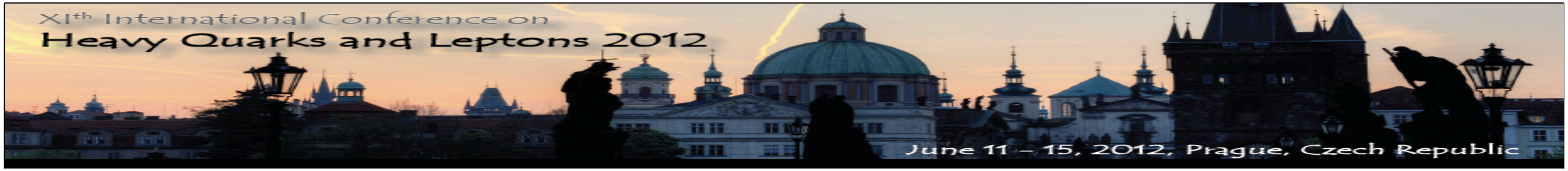


The study of geo-neutrinos

Sandra Zavatarelli INFN Genova (Italy)

Why is it now feasible to study geo-ν?

Two fundamental advances occurred in the last years :

✓The progresses on understanding neutrino properties and propagation (i.e. recent results on θ13 by Daya Bay and RENO..)

✓The existence of extremely low background neutrino detectors, in particular scintillators (like Kamland, Borexino) more suited to detect medium-low energy neutrinos

=> Our understanding of solar fusion has now been proven by measuring the different components of the solar ν fluxes (Borexino: ^{7}Be,^{8}B, pep, limits on CNO,pp)

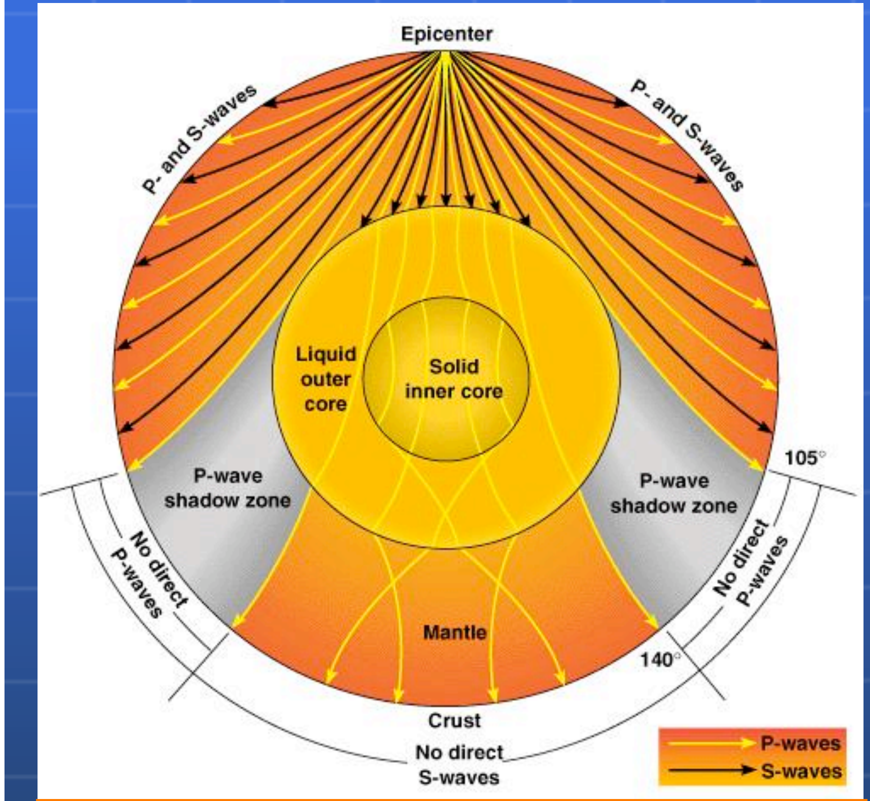
So if thanks to neutrinos we are now able to get closer insights into deep stellar core… why do not extend this approach to the Earth study?

Outline

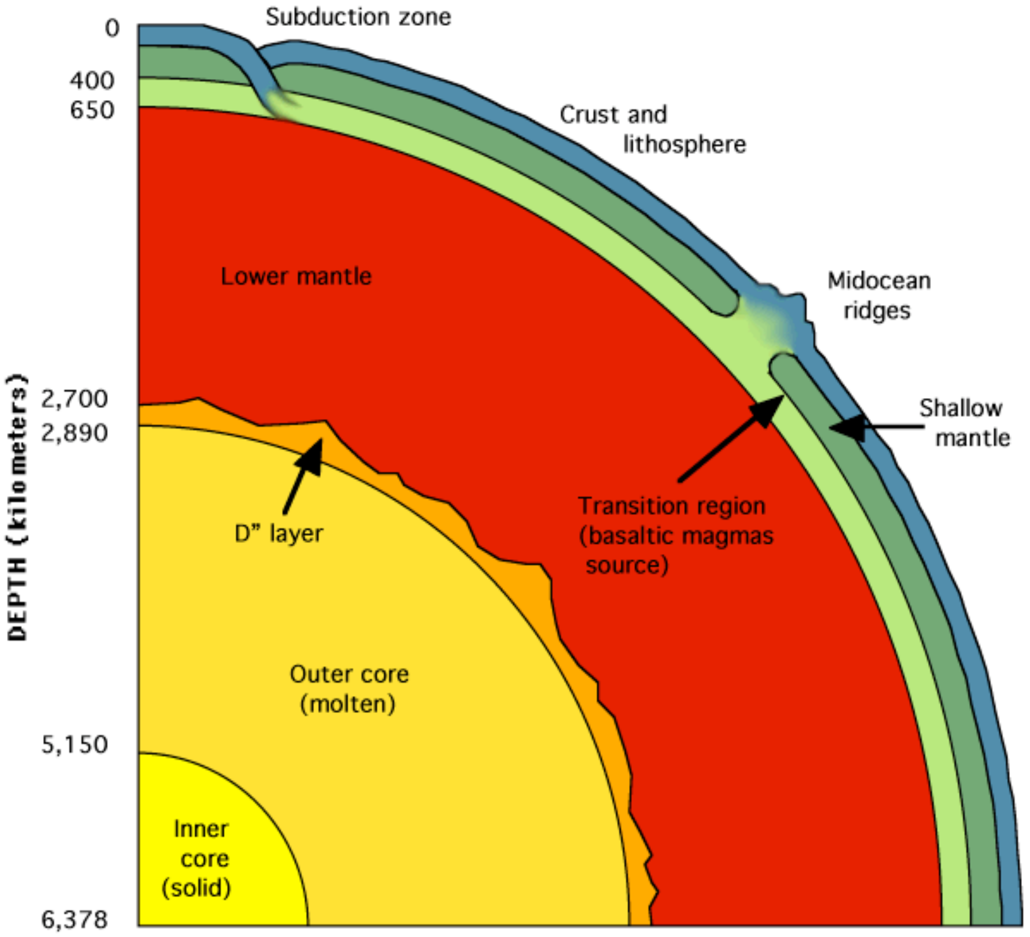
- ✓ The Earth: what we know and the many open issues..
- ✓ Earth antineutrinos (Geo-ν): what they could help to understand…
- ✓ Running experiments and last news!
- ✓ Combined analysis
- ✓ The future

The Earth: Geophysical approach

Sismology -> Mechanical layers



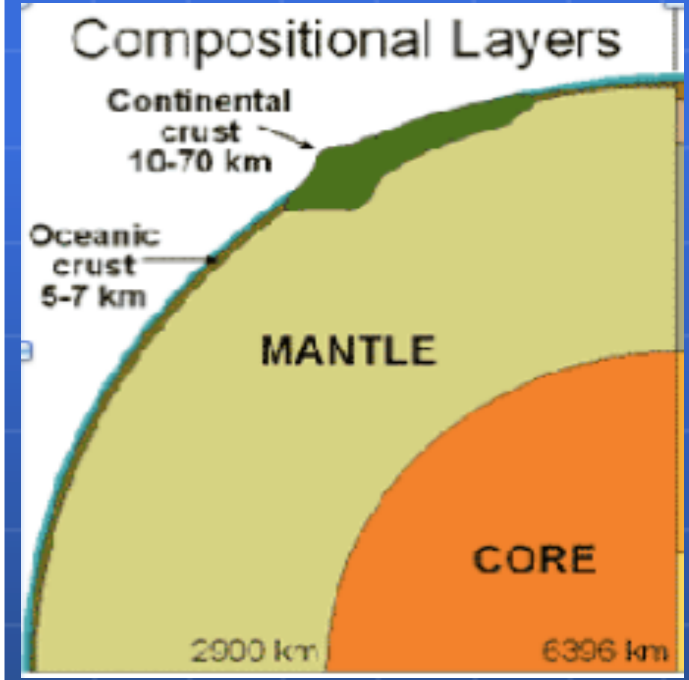
P – primary, longitudinal waves
S – secondary, transverse/shear waves



Discontinuities in the waves propagation and velocity -> structure & density profile

No info about the chemical composition of the Earth

The Earth: Geochemical approach



1) Direct rock samples

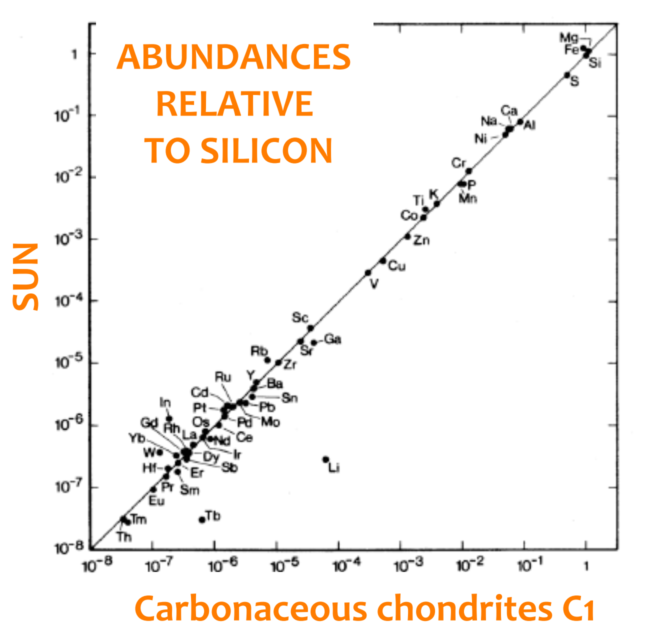
* surface and bore-holes (max. 12 km);

* mantle rocks brought up by tectonics and **vulcanism;**

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

2) Cosmochemistry:

-Meteorites: Carbonaceous chondrites/ Enstatite chondrites + Sun

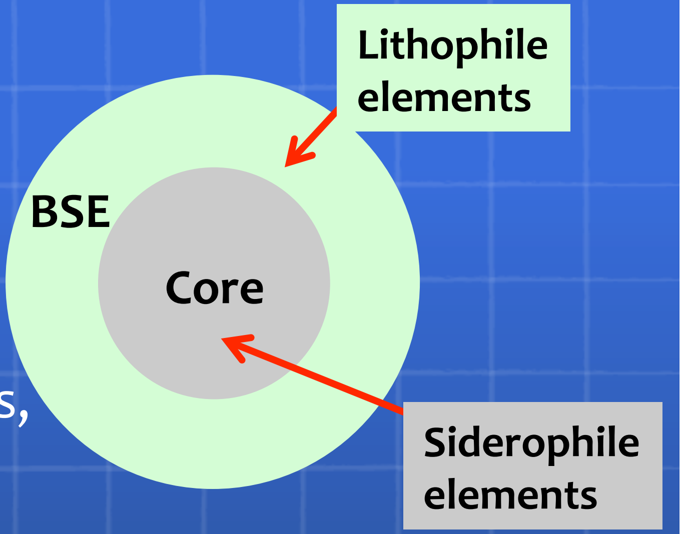


=> Geochenical models: carbonaceous :McDonough & Sun 1995, Lyubetskaya & Korenaga 200
enstatic: Javoy 2010)

Ratios of element abundances more stable in different models with respect to absolute abundances: $Th/U \sim 3.9$, $K/U \sim 1.1410^4$

Geochemical models : the BSE models

- ✓The BSE describes the primordial non metallic Earth that followed planetary accretion and core separation prior to its differentiation into a mantle and crust
- ✓Different authors proposed a range of BSE models based on different constraints(carbonaceous chondrites, enstatite chondrites..)


Lithophile elements

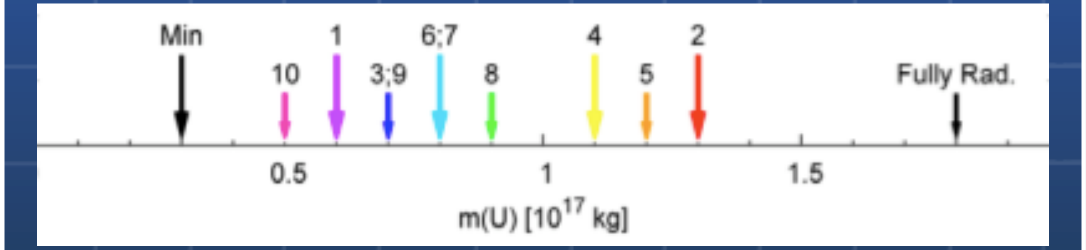
BSE

Core

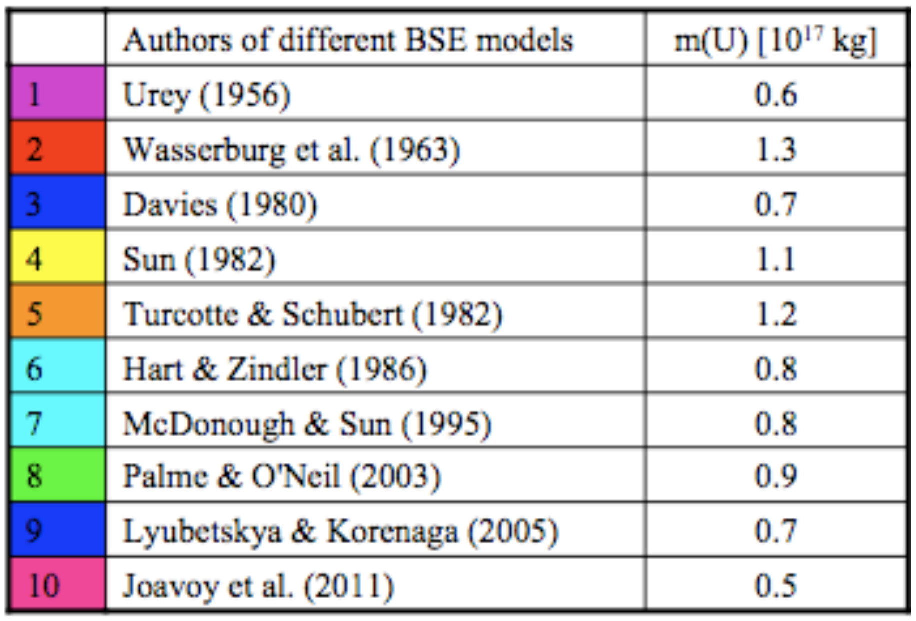
Siderophile elements

Example: the U content

U/Th/K are refractory, litophile



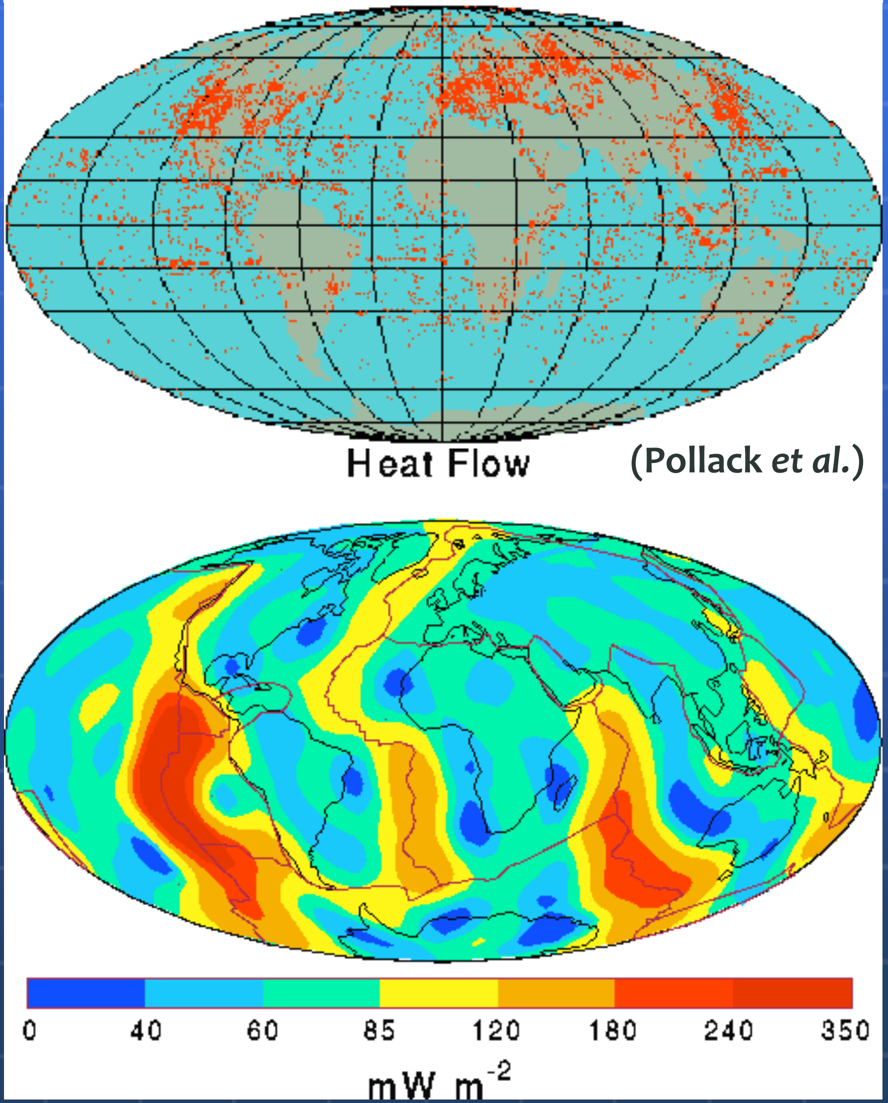
Spread: a factor 2.6!!!!!



	Authors of different BSE models	m(U) [10^{17} kg]
1	Urey (1956)	0.6
2	Wasserburg et al. (1963)	1.3
3	Davies (1980)	0.7
4	Sun (1982)	1.1
5	Turcotte & Schubert (1982)	1.2
6	Hart & Zindler (1986)	0.8
7	McDonough & Sun (1995)	0.8
8	Palme & O'Neil (2003)	0.9
9	Lyubetskya & Korenaga (2005)	0.7
10	Joavoy et al. (2011)	0.5

Earth surface heat flux

Bore-hole measurements



(Pollack *et al.*)

Conductive heat flow : ~ 60 mW/m^2

From bore-hole temperature gradients

Total surface heat flux:

- (31 ± 1) TW (Hofmeinster& Criss 2005)
- (46 ± 3) TW (Jaupart er all 2007)
- (47 ± 2) TW (Davies and Davies 2010)

(same data , different analysis)

Systematic errors:
Different assumption concerning the role of fluids in the zone of mid ocean ridges

Sources of Earth heat: an open issue!!

Necessary energy supply: U = H (heat flow) x t (Earth age)~ $5\ 10^{30}$ J

U_G~ GM^2/R~ $4\ 10^{32}$ J, U_{chem}~ 0.1 eV x N_{at}~$6\ 10^{31}$ J, U_{nucl}~ 1 MeV x N_{nucl} ~ $6\ 10^{30}$ J => All ok!!!!!

- **Total heat flow ("measured"): 31±1 or 46±3 or 47±2 TW**
- **Urey ratio = radioactive heat production/ total heat loss**

geophysics (mantle convection models): mantle Urey ~ 0.7
geochemistry (bulk composition models): mantle Urey ~ 0.3
Discrepancy!

Radiogenic total : 10- 29 TW !!!

→ Linked to convection, plate tectonics…

- Other heat sources (possible deficit up to 47-10 = 37 TW!)
  - Residual heat and secular cooling;
  - gravitational contraction and extraterrestrial impacts in the past;
  - mantle differentiation and recrystallisation;
  - ^{40}K in the core;
  - nuclear reactor; (BOREXINO rejects a power > 3 TW at 95% C.L.)

IMPORTANT MARGINS
FOR ALL DIFFERENT MODELS OF THE EARTH HEAT SOURCES

Geo-ν a unique direct probe of the Earth interior

The Earth shines in anti-ν ($\Phi_\nu \sim 10^6$ cm^{-2} s^{-1})

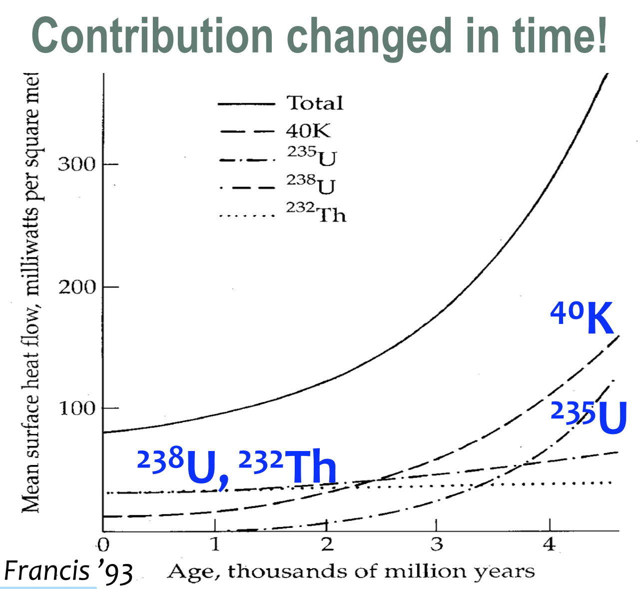
$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- + 6\,\bar{\nu}_e + 51.7$ MeV

$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- + 4\,\bar{\nu}_e + 42.8$ MeV

$^{40}K \rightarrow {}^{40}Ca + e^- + 1\,\bar{\nu}_e + 1.32$ MeV

$^{235}U \rightarrow {}^{207}Pb + 7\,\alpha + 4\,e^- + 4\,\bar{\nu}_e + 46.4$ MeV

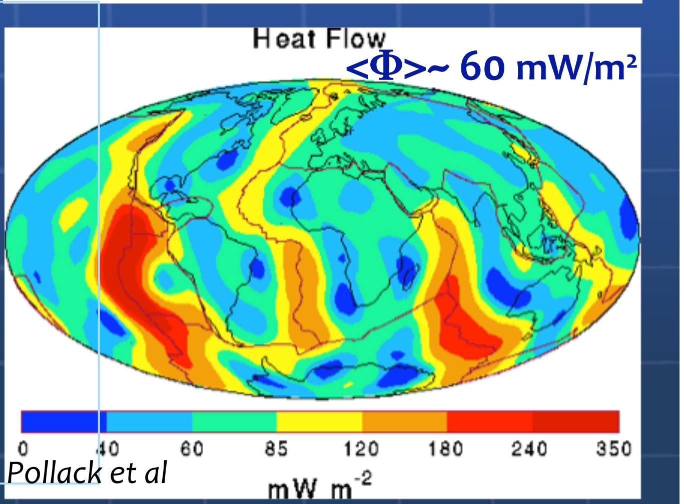
✓**Released heat and anti-neutrinos flux in a well fixed ratio!**


Contribution changed in time!

Francis '93

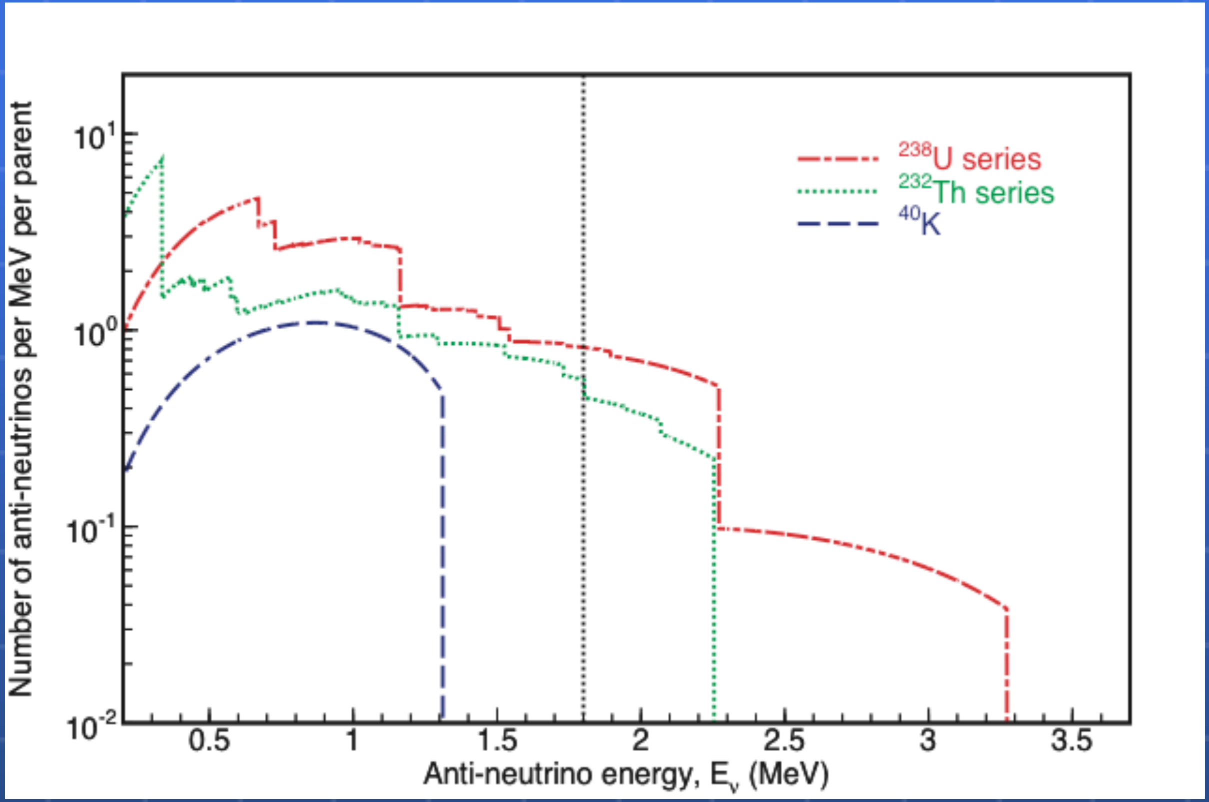
Open questions:

- *What is radiogenic contribution to the Earth energy budget?*
- *What is the distribution of the radiogenic elements?*
  - *How much in the crust and how much in the mantle?*
  - *Core composition: energy source driving the geo- dynamo? ^{40}K ? Geo-reactor (Herndon 2001)?*
- *Are the standard geochemical models (BSE) correct?*



Pollack et al

Geoneutrinos energy spectra



The probability to detect electron antineutrino :

$$P_{ee} = P(\overline{\nu}_e \to \overline{\nu}_e) = \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12}\sin^2\left(\frac{\delta m^2 L}{4E}\right)\right) + \sin^4\theta_{13}$$

Effect of $\theta_{13} \neq 0$: 5%

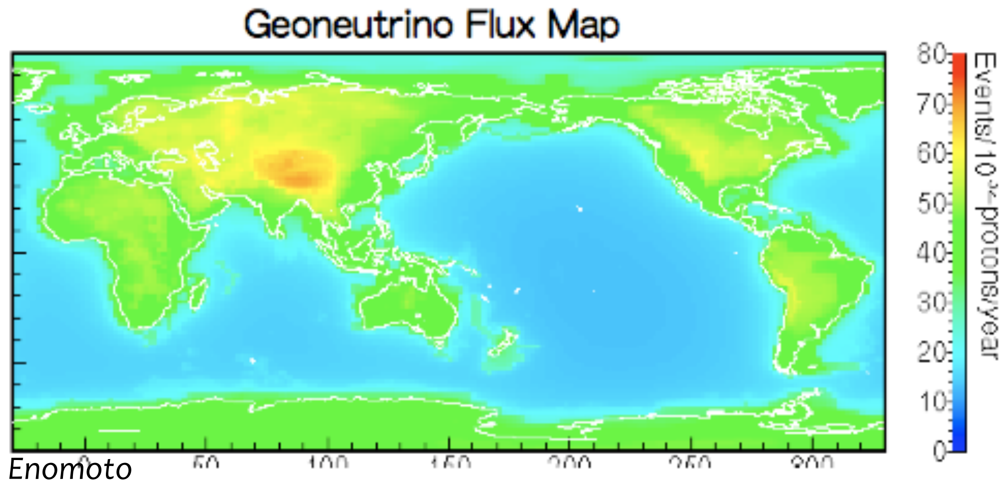
For geoneutrinos we can use average survival probability

Pee (3 flavors) = 0.551 $\pm$ 0.015 *(Fiorentini et al 2012 arXiv: 1204.1923v1)*

Geo-ν: expected fluxes

Models based on:

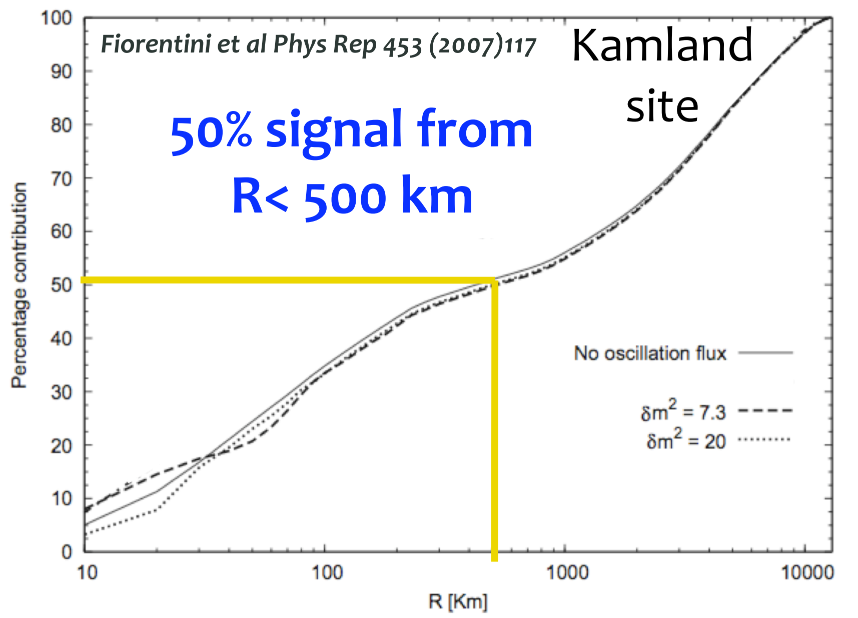
- Data on crustal thickness and composition
- Bulk Silicate Earth composition hypothesis (BSE)



Enomoto

Flux not homogeneous!! Strong contribution from local geology…..

Need of a precise evaluation of the local contribution and of multi-site measurements!!
- Continental sites
- Oceanic sites

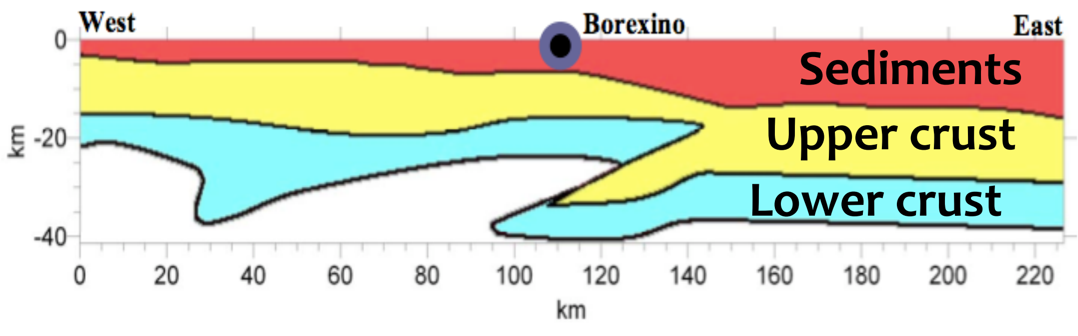


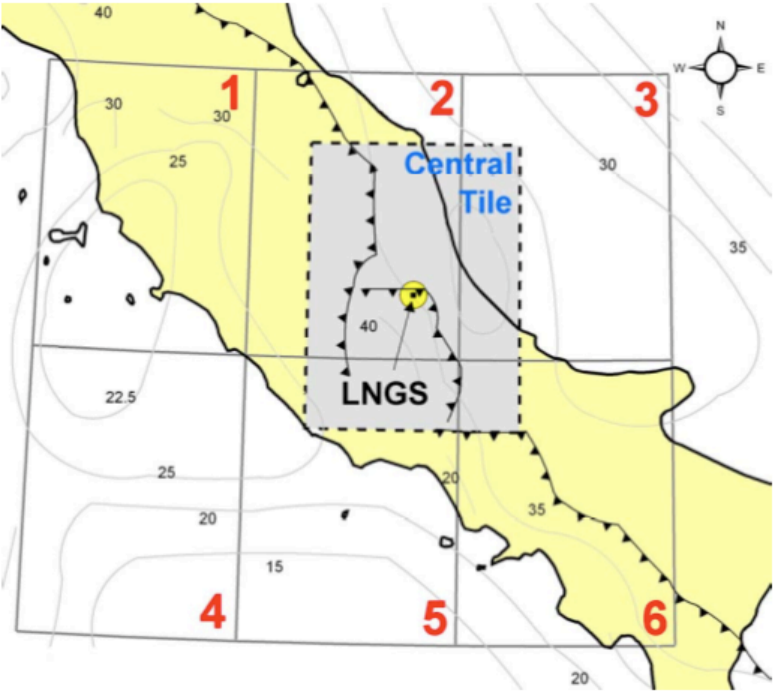
Fiorentini et al Phys Rep 453 (2007)117

Kamland site

50% signal from R< 500 km

Geo-ν fluxes at LNGS : an example of local geology study (Coltorti et al., Geo.Cosm. Acta 75(2011)2271)





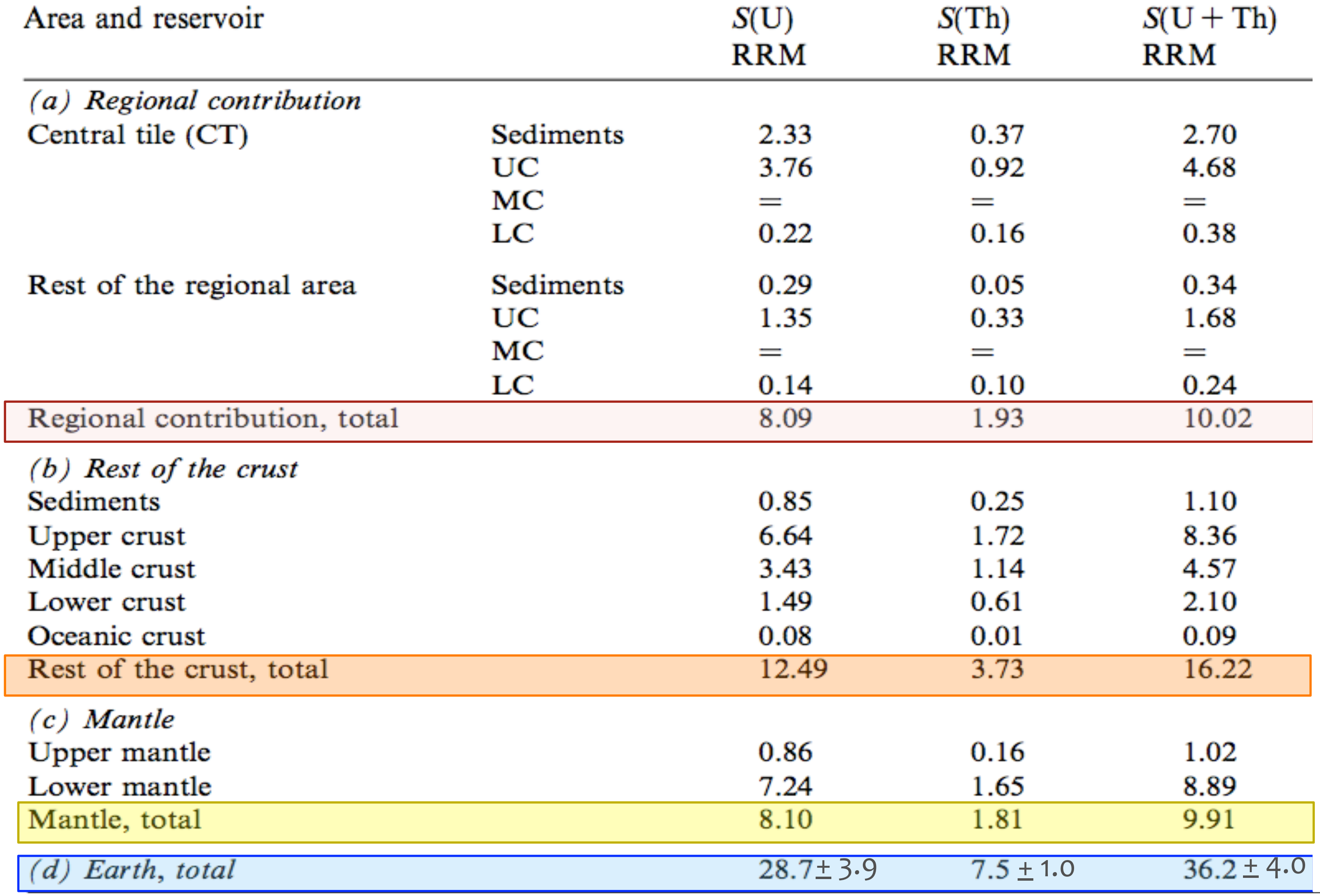
- ✓U and Th abundances of more than 50 samples belonging to sedimentary cover analized by means of ICP-MS and NaI(Tl) gamma spectroscopy;
- ✓U and Th content in the upper and lower crust from Valsugana and Ivrea-Verbano area outcrops;
- ✓On the central tile 6 reservoirs have been taken into account (4 sedimentary layers , upper crust and lower crust) while only 3 on the rest of regional area (sediments, upper crust and lower crust)

By using the available seismic profile as weel as stratigrafic records from a number of exploration wells a 3 D models over an area of 2° x 2° was developed down to the Moho depht for a total of 10^6 1 km^3 volume cells.

Geo-ν fluxes at LNGS (Coltorti et al., Geo.Cosm. Acta 75(2011)2271)

Total fluxes : S(U)= (28.7 ± 3.9) TNU, S(Th)=(7.5 ± 1.0) TNU

Units:
1 TNU = 1 event / year / 10^{32} protons



Area and reservoir		S(U) RRM	S(Th) RRM	S(U + Th) RRM	
(a) Regional contribution					
Central tile (CT)	Sediments	2.33	0.37	2.70	
	UC	3.76	0.92	4.68	
	MC	=	=	=	
	LC	0.22	0.16	0.38	
Rest of the regional area	Sediments	0.29	0.05	0.34	
	UC	1.35	0.33	1.68	
	MC	=	=	=	
	LC	0.14	0.10	0.24	
Regional contribution, total		8.09	1.93	10.02	27.8 %
(b) Rest of the crust					
Sediments		0.85	0.25	1.10	
Upper crust		6.64	1.72	8.36	
Middle crust		3.43	1.14	4.57	
Lower crust		1.49	0.61	2.10	
Oceanic crust		0.08	0.01	0.09	
Rest of the crust, total		12.49	3.73	16.22	44.8 %
(c) Mantle					
Upper mantle		0.86	0.16	1.02	
Lower mantle		7.24	1.65	8.89	
Mantle, total		8.10	1.81	9.91	27.4 %
(d) Earth, total		28.7 ± 3.9	7.5 ± 1.0	36.2 ± 4.0	

Geo-ν detection

Prompt:

$\nu + p \to e^+ + n$

$E_{e+} = E_\nu - 0.78$ MeV

E_{thr}=1.8 MeV

Minimum det. energy: 2x 511 keV

Delayed (τ~256 μs):

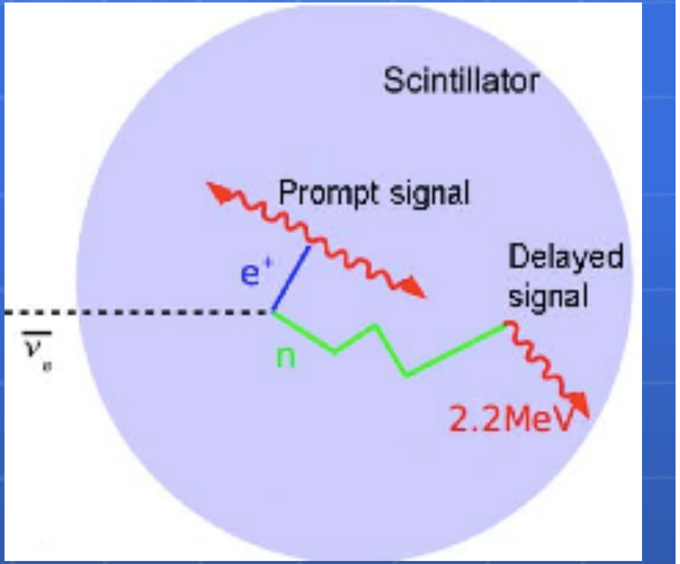
$n + p \to d + \gamma$

Detected energy: 2.2 MeV

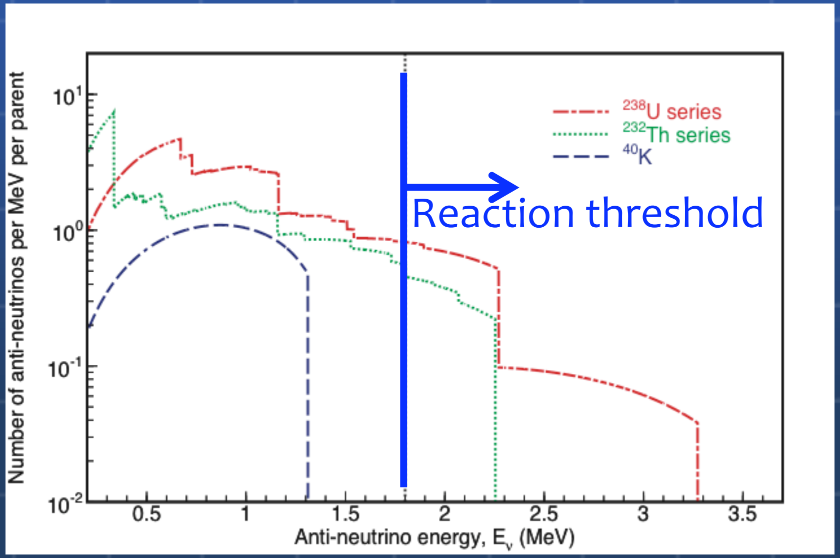
Geoneutrinos energy range

$T_{geo\text{-}\nu}$ = 1.8 – 3.3 MeV

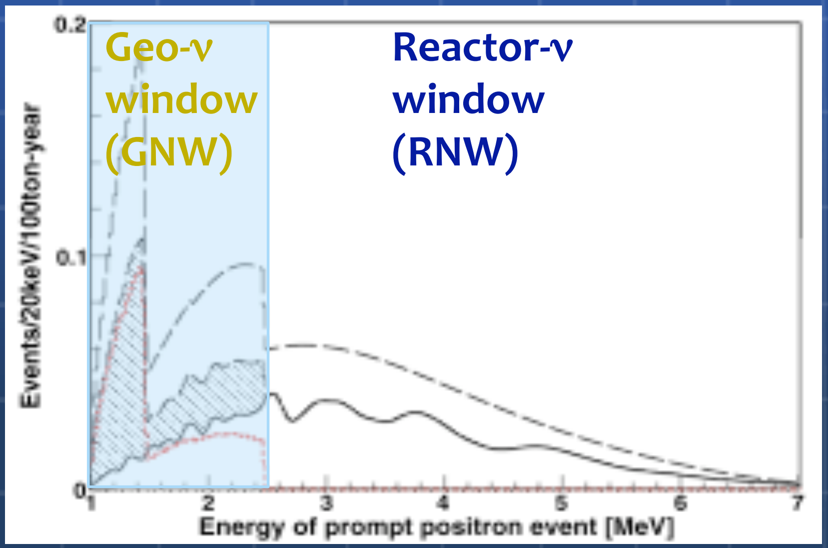
$E_{visible}$ ~ 1 – 2.6 MeV



Geo-ν energy spectrum



Expected positron energy spectrum in BX



The most important backgrounds

Reactor antineutrinos

Kamland site: *the reactors operation records, including thermal power generation, fuel burn-up and exchange and enrichments log are provided by the Consortium of Japanese electric power companies*

S(reactors)/S(geo) ~ 5 in geo-ν window

Borexino site:

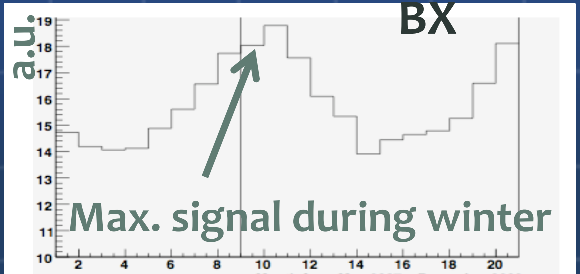
Contacts with IAEA and EDF:

-Thermal powers for each European reactors are known on a monthly base;

-Expected signal @ LNGS evaluated with a dedicated code

-S(reactors)/S(geo) ~ 0.4

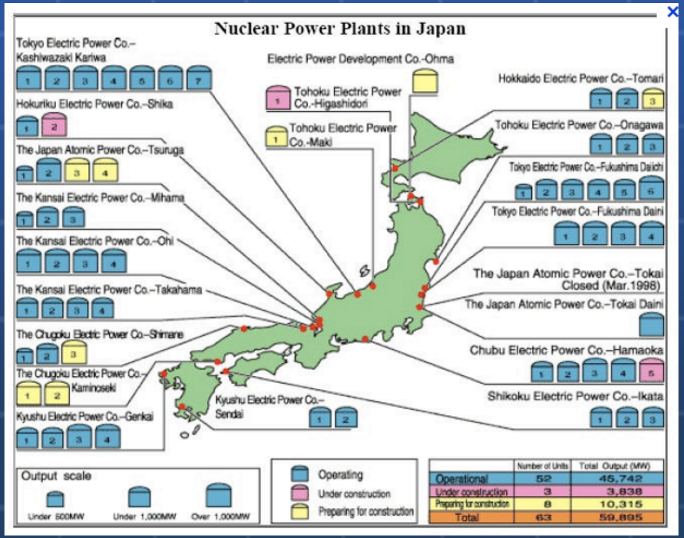
Flux sys. uncertainty ~6%



Max. signal during winter

Effect of $\theta_{13} \neq 0$:

Up to 10%



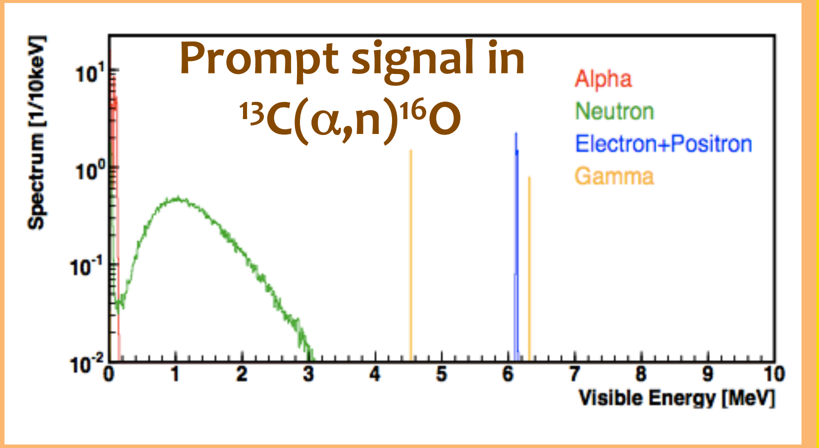
HQL 2012, Prague

Sandra Zavatarelli, INFN Genova Italy

The most important backgrounds

Background mimicking the anti-ν interactions:

Internal contamination: $^{13}C(\alpha,n)^{16}O$



- α particles are emitted in the U an Th chains
- ^{210}Po α emitter

(KL ~ 5000 cpd/t, now~250 cpd/t, BX~12 cpd/t)

- ^{13}C low abundance: $^{13}C/^{12}C$~1.1 %
- KL: S(α,n)/S(geo)~ 1.5 ; BX: 0.3%

Random coincidences

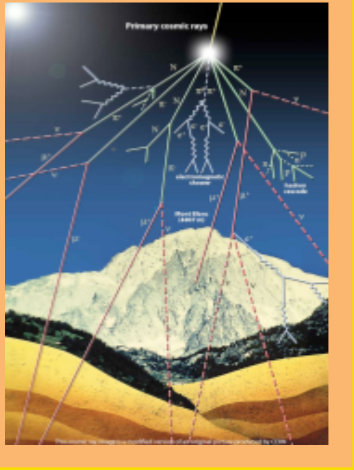
- Mostly due to U/Th chains high energy decays and external backgrounds;
- KL: S(rnd)/S(geo)~ 72% ; BX: S(rnd)/S(geo)~2%.

Muon correlated events: fast neutrons & cosmogenic ^{9}Li and ^{8}He decay via *β-n reactions*

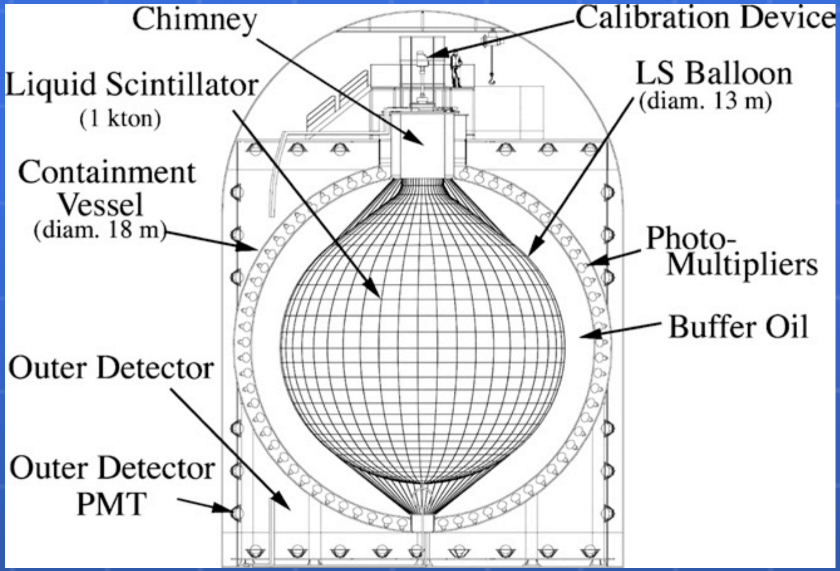
$^{9}Li \rightarrow 2\,\alpha + e^{-} + n + \nu$; $^{8}He \rightarrow {}^{7}Li + n + e^{-} + \gamma$

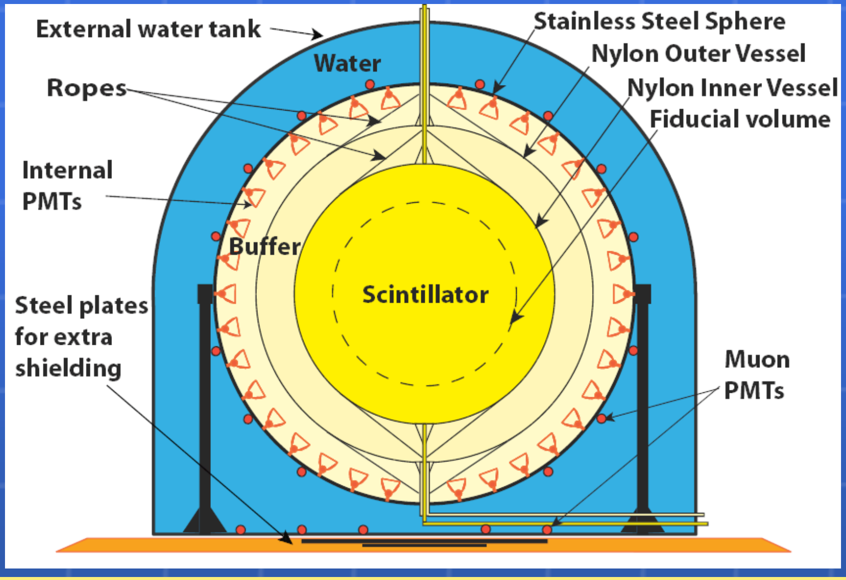
τ~ 150 ms

- by applying a 2 s detector veto after scintillator muons-> negligible!!



Running experiments





Kamland: OCEANIC CRUST

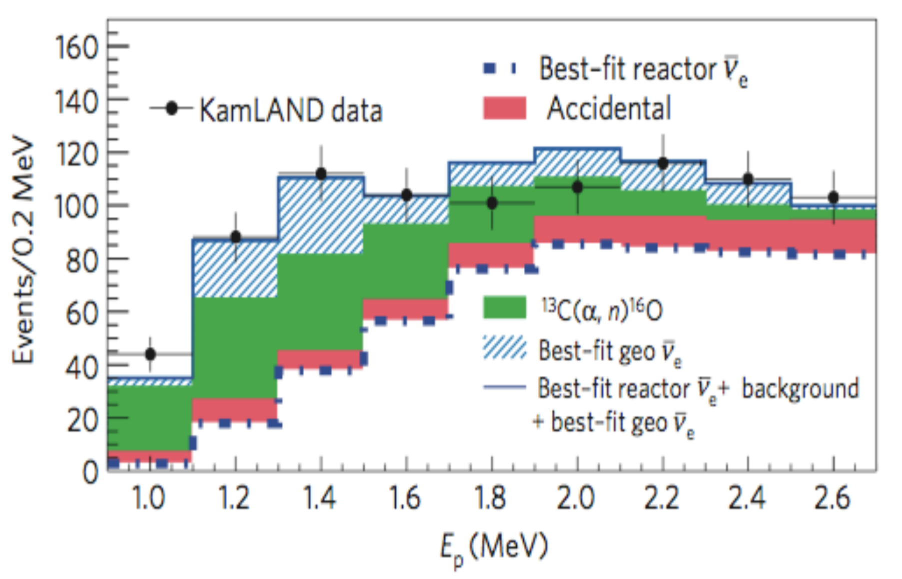
- originally build to measure reactor antineutrinos;
- 1000 tons;
- 2700 m.w.e. rock overburden;
- $\Phi\mu \sim 5.4\ \mathrm{m}^{-2}\,\mathrm{h}^{-1}$;
- The first excess due to geoneutrinos measured in 2005 (Araki et al. Nature 436);
- 99.997 CL observation in 2011 (Gando et al, Nature Geoscience 1205) in 4132 ton y:

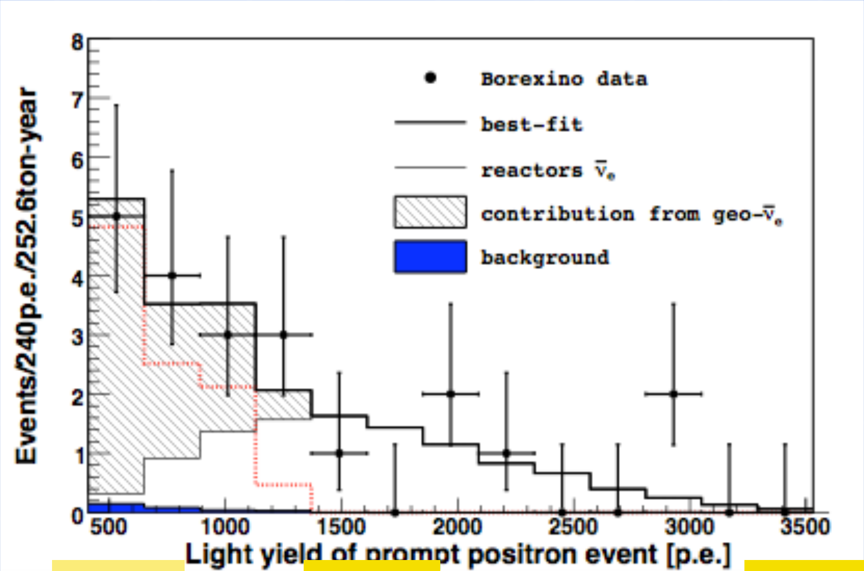
Borexino @ LNGS, Italy

CONTINENTAL CRUST

- originally build to measure neutrinos from the Sun – extreme radiopurity needed and achieved;
- 280 tons;
- 3600 m.w.e. rock overburden, $\Phi\mu \sim 1\mathrm{m}^{-2}\mathrm{h}^{-1}$;
- DAQ started in 2007;
- observation at 99.997 CL in 2010 (Bellini et al, PLB 687) in 252.6 ton y:

KamLand (2002 – 2009)   Borexino (2007 – 2009)





~1 MeV   ~3 MeV   ~7 MeV

Period	Mar 02- Nov. 09
Tot. Ev. [gν e.w.]	841
Reactors ev.	485 ± 27
^{13}C (α,n)^{16}O	165 ± 18
Geo-ν ev.	111 $^{+45}_{-43}$
Accidental ev.	80 ± 0.1

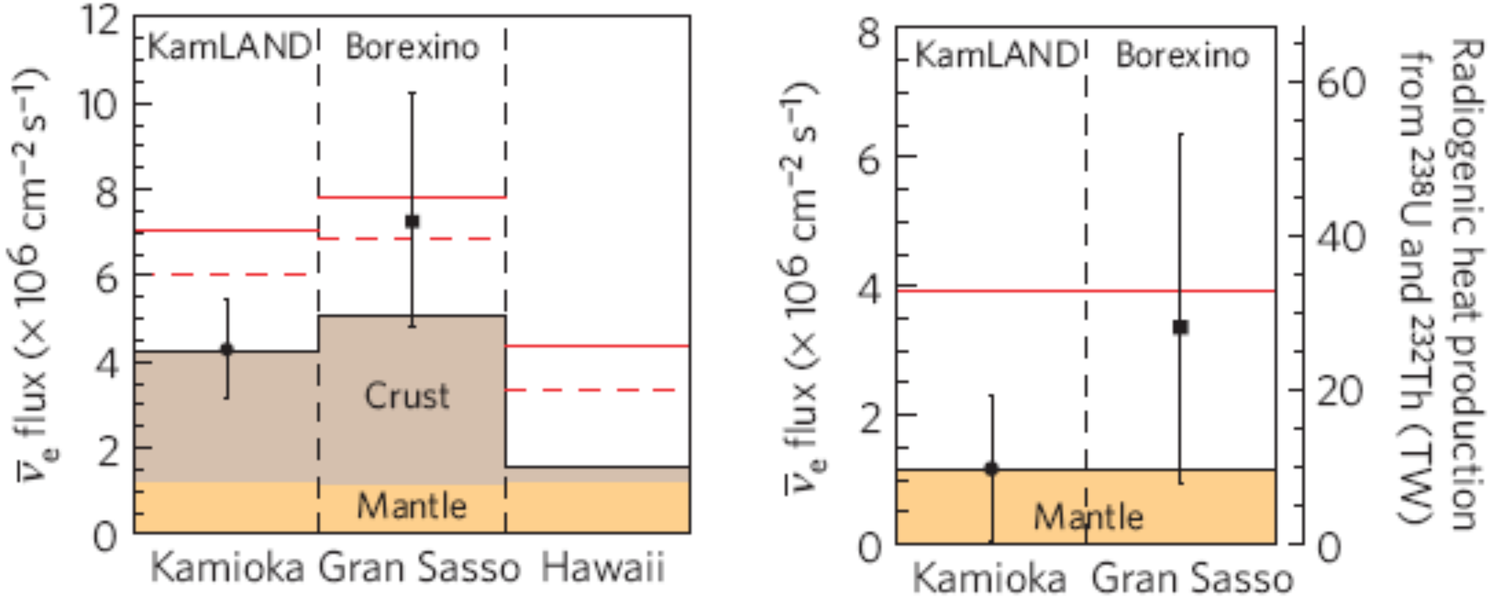
Period	Dec.07 – Dec.09
Tot ev [full sp.]	21
Reactors ev.	10.7 $^{+4.3}_{-3.4}$
Geo-n ev.	9.9 $^{+4.1}_{-3.4}$
Background ev.	0.4 ±0.05

A. Gando *et al.*, Nature Geoscience **1205** (2011).

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

Experimental results analysis

A. Gando *et al*., Nature Geoscience 1205 (2011)



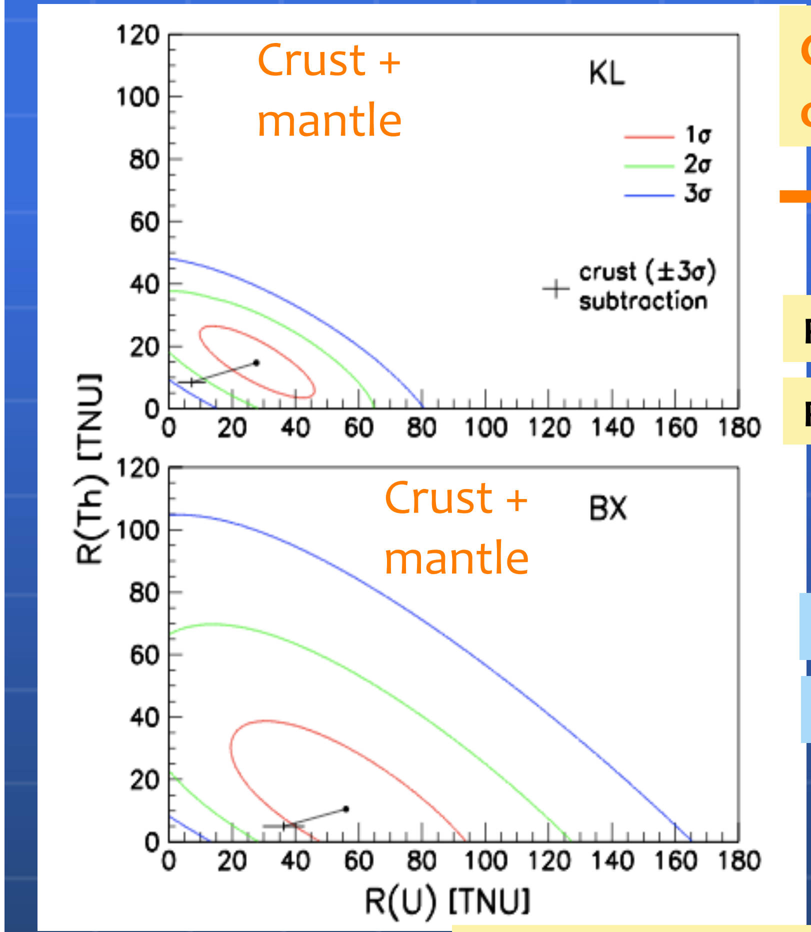
Fully radiogenic model : all Earth heat (i.e. 44 TW) is due to radioactive decays

------------- homogeneous mantle

- - - - - - - sunken layer hyphotesis

- **Homogeneous fully radiogenic model excluded at 97% CL**
- **Mantle contribution observed** (with low statistical significance..);

U/Th in the mantle (G. Fiorentini et al, 2012 arXiv:1204.1923)



Geological models of the crust

KL site

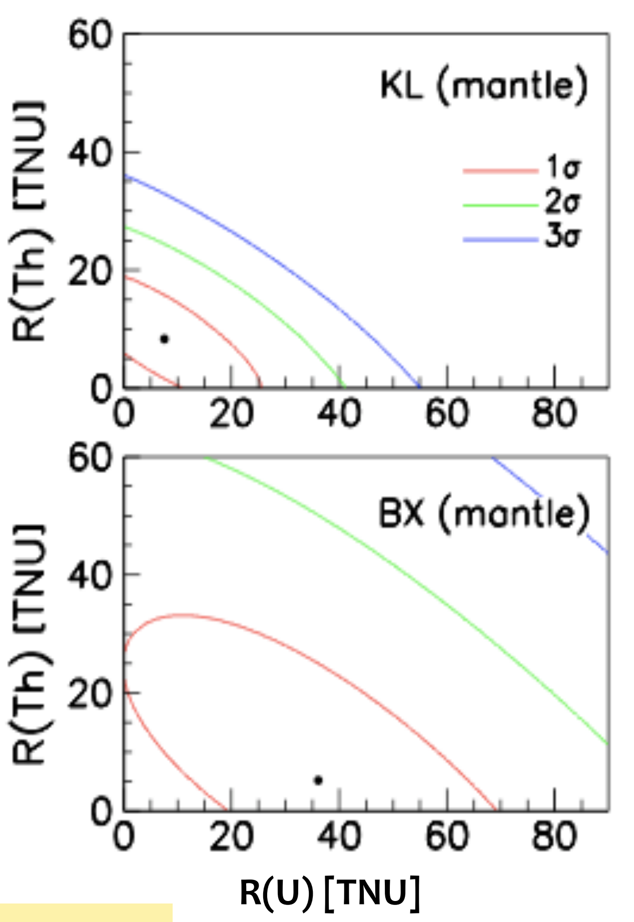
$R_{Cr}(U)=(20.2 \pm 1.4)$ TNU

$R_{Cr}(Th)=(6.5 \pm 0.5)$ TNU

BX site

$R_{Cr}(U)=(19.9 \pm 2.2)$ TNU

$R_{Cr}(Th)=(5.5 \pm 0.5)$ TNU

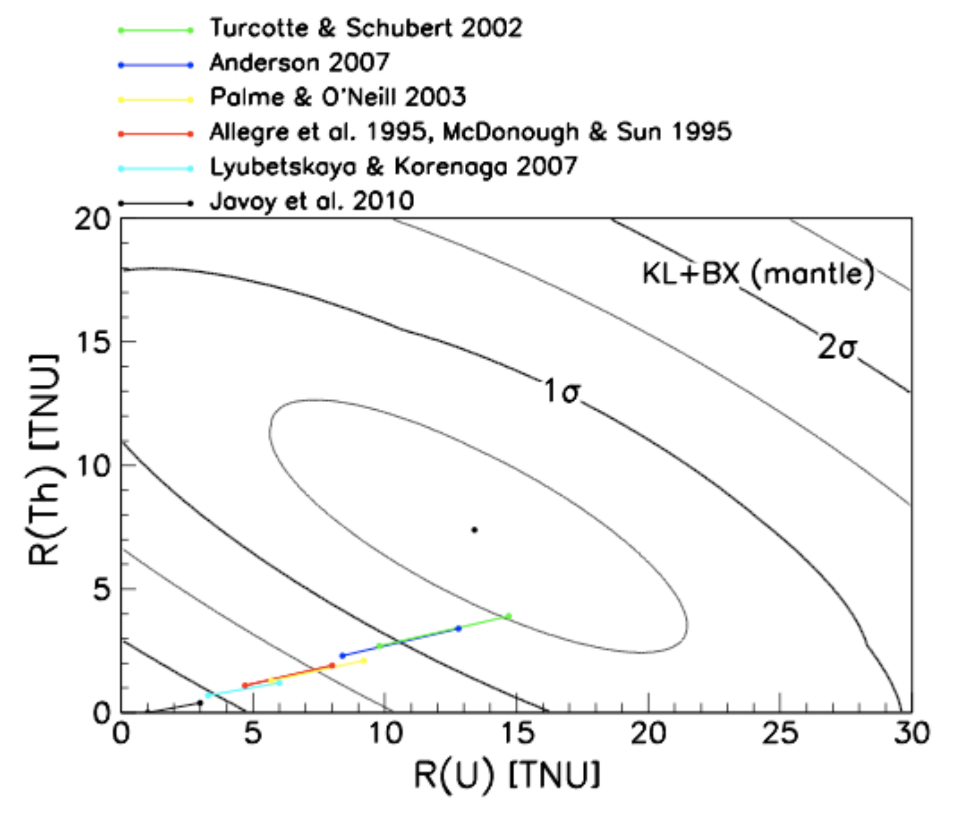


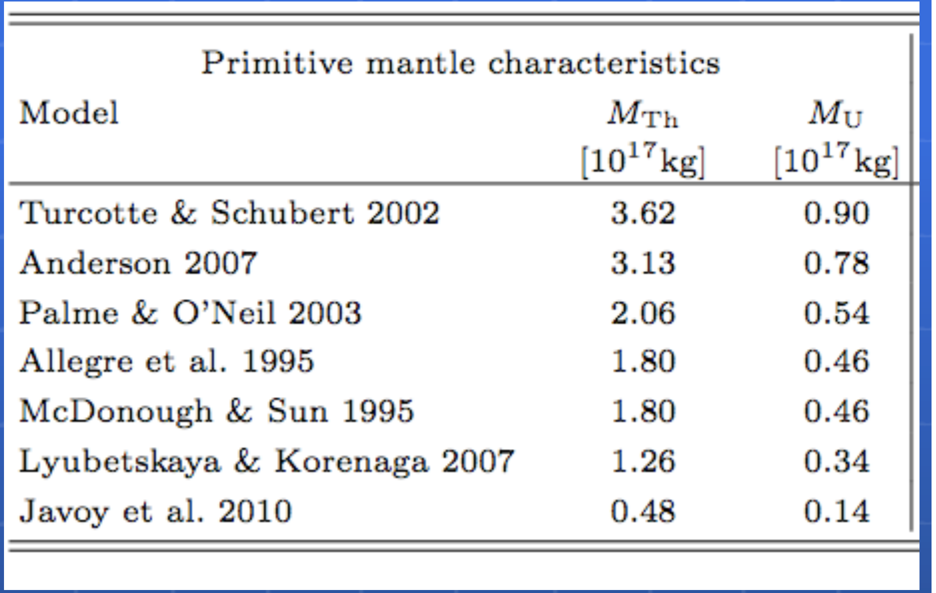
R(mantle) = R(total,exp) - R(crust,theo)

- Allowed regions in KL and Bx largely overlap;
- The hyphotesis of no mantle signal is disfavoured at ~ 1.7 σ in KL and 2 σ in BX

U/Th in the mantle (G. Fiorentini et al, 2012 arXiv:1204.1923)

Site independent mantle flux -> combined analysys





Primitive mantle characteristics

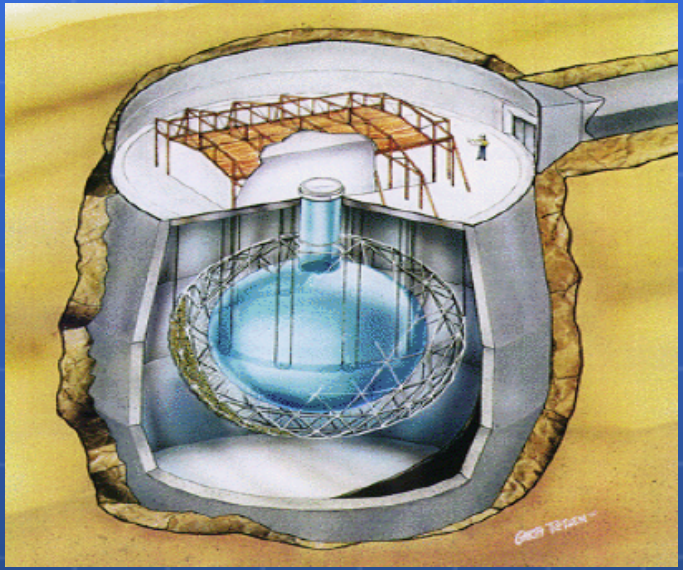
Model	M_{Th} $[10^{17}\mathrm{kg}]$	M_{U} $[10^{17}\mathrm{kg}]$
Turcotte & Schubert 2002	3.62	0.90
Anderson 2007	3.13	0.78
Palme & O'Neil 2003	2.06	0.54
Allegre et al. 1995	1.80	0.46
McDonough & Sun 1995	1.80	0.46
Lyubetskaya & Korenaga 2007	1.26	0.34
Javoy et al. 2010	0.48	0.14

By marginalizing Th/U € [1.7,3.9]:
Rate (U + Th from mantle): 23 ± 10 TNU

Best estimate for the mantle geo-v flux by using inputs from particle physics (KL, BX, oscillation data) and from Earth science (crustal data and Th/U ratio)

- Crustal contribution subtracted & neutrino oscillations considered;
- null mantle contribution excluded at 2.4 σ C.L.
- data prefer mantle model with high radiogenic content and disfavour at ~ 2σ those with low content.

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)

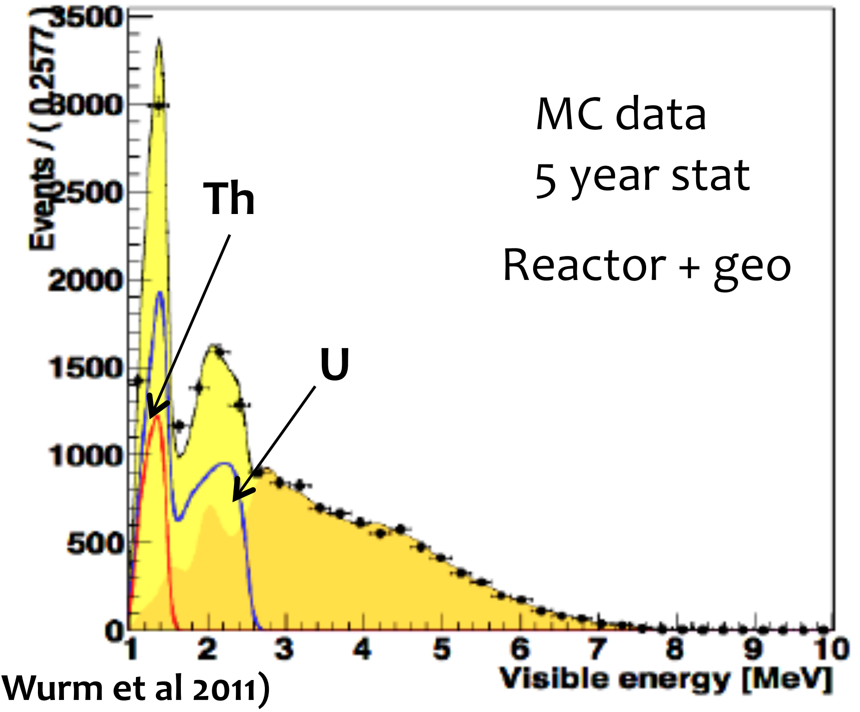
Placed on an old continental crust:
80% of the signal from the crust
(Fiorentini et al., 2005)

BSE: 28-38 events/per year

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



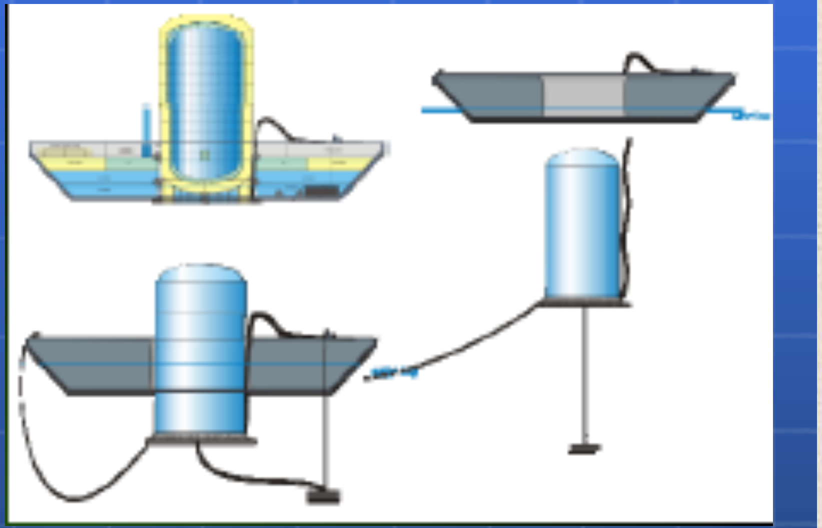
(Wurm et al 2011)

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

Hanohano at Hawaii

Hawaii Antineutrino Observatory (HANOHANO = "magnificent” in Hawaiian



Project for a 5-10 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 Hawaii 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

Summary

- ✓ A new interdisciplinary field is born;
- ✓ Collaboration among geologists and physicists is a must;
- ✓ The geo-neutrinos have already been successfully detected;
- ✓ The combined results from different experimental sites have stronger impact –> multi-site measurements are crucial!
- ✓ The first geologically significant results are starting to appear;
- ✓ New measurements (now in Japan the reactors are off!) and the new generation experiments are needed for geologically highly significant results….

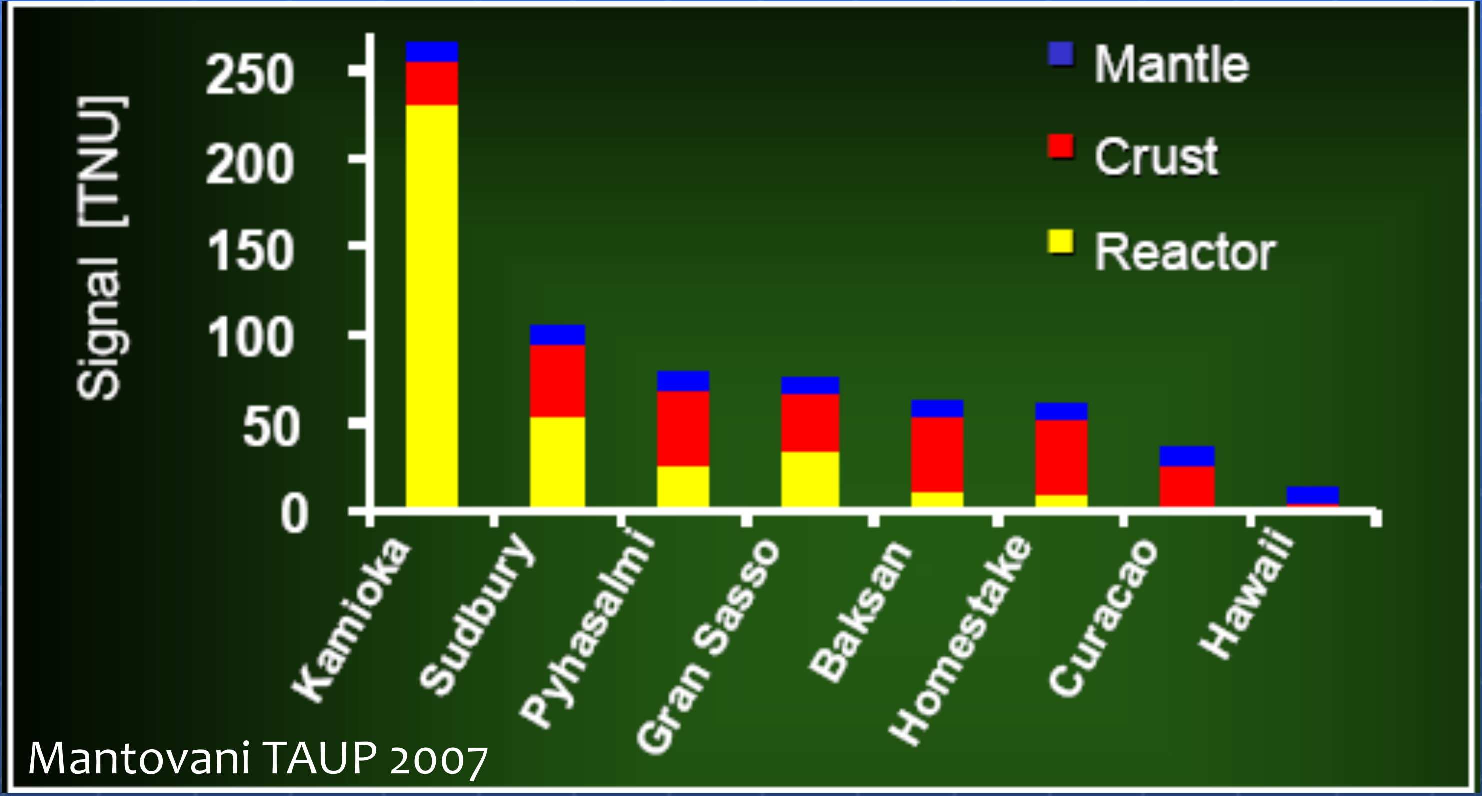
THANK YOU!!!


The Borexino Collaboration


XIth International Conference on
Heavy Quarks and Leptons 2012
June 11 – 15, 2012, Prague, Czech Republic

Backup slides

Running and planned experiments



Mantovani TAUP 2007

KL: signal time variation

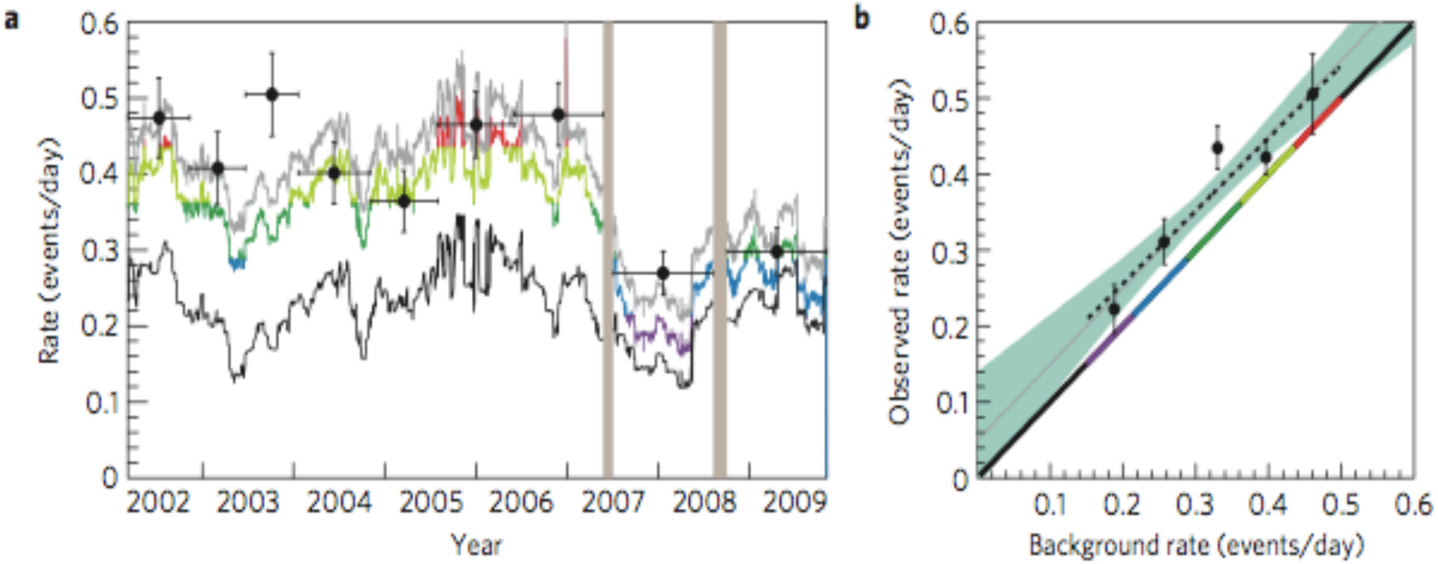
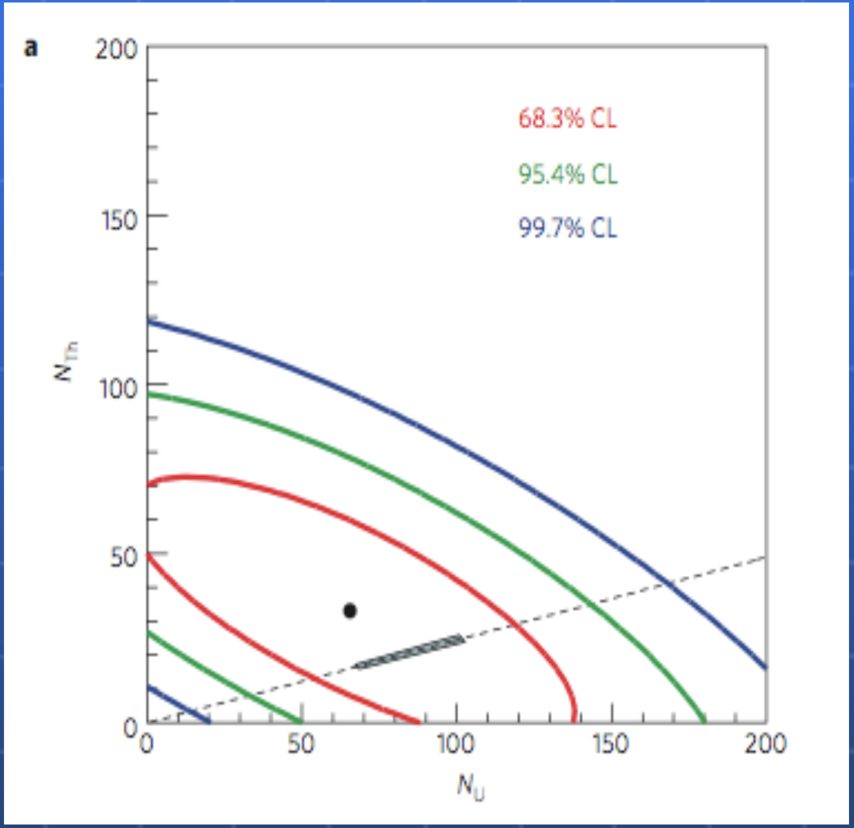


Figure 2 | Event-rate correlation. a, Expected and measured rates at KamLAND for $\overline{\nu}_e$ s with energies between 0.9 MeV and 2.6 MeV. The points indicate the measured rates, whereas the curves show the expected rates for reactor $\overline{\nu}_e$ s, reactor $\overline{\nu}_e$ s + other backgrounds, and reactor $\overline{\nu}_e$ s + backgrounds + geoneutrinos. The vertical bands correspond to data periods not used owing to high noise resulting from purification activities. **b**, Measured $\overline{\nu}_e$ event rates plotted against the expected rate from reactor $\overline{\nu}_e$ s + other backgrounds. The dotted line is the best linear fit. The shaded region is the $\pm 1\sigma$ fit envelope. The error bars are statistical only.

KL: U and Th signal



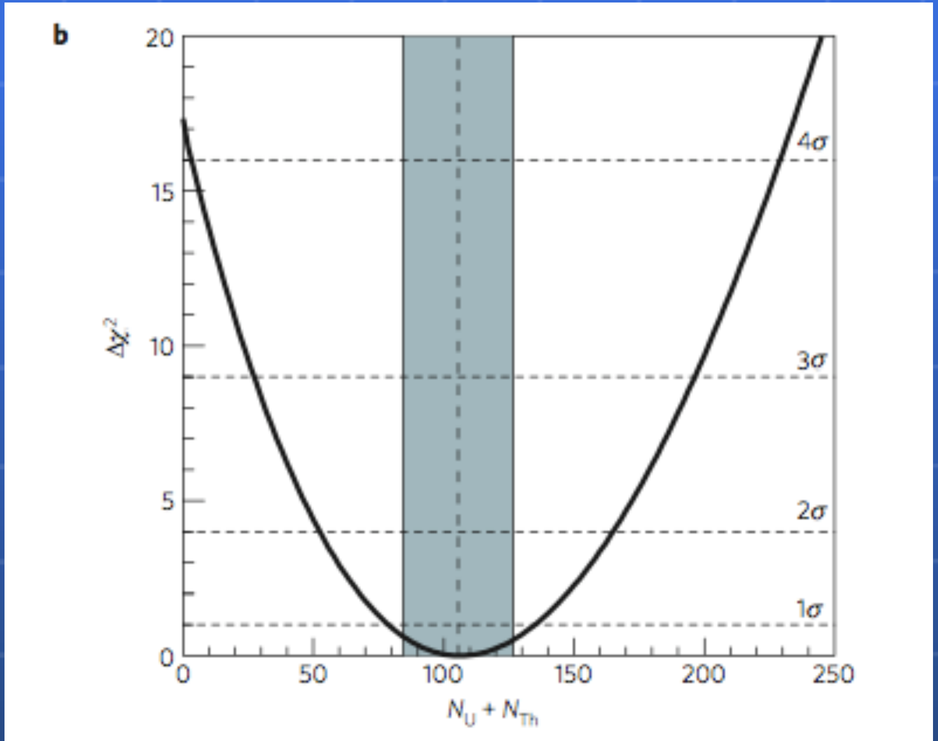
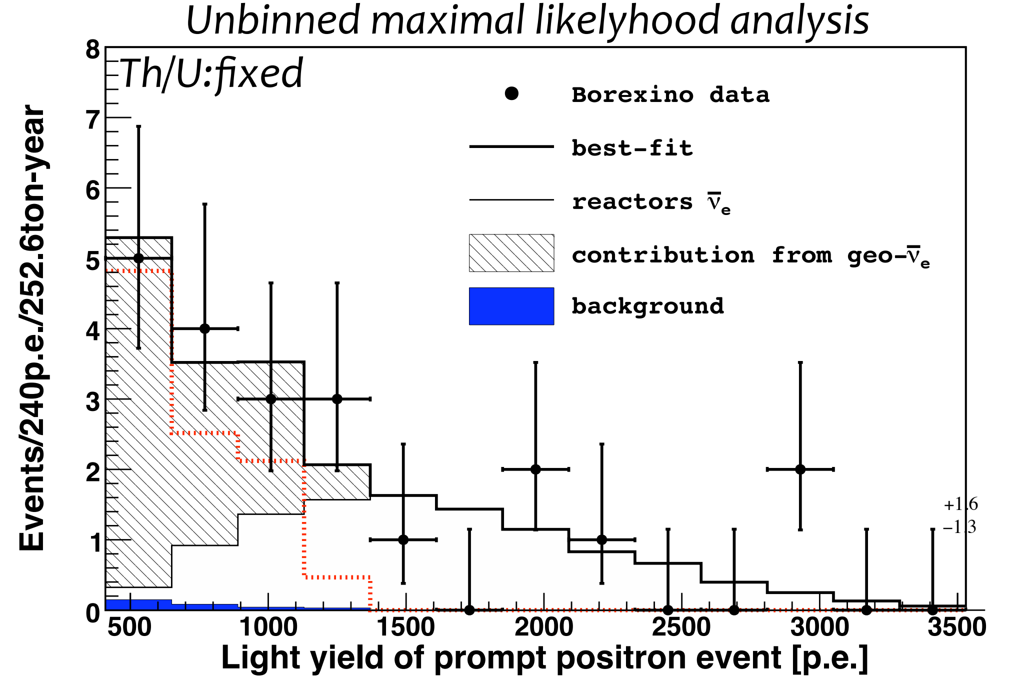


Figure 3 | CL of geoneutrino events. a, CL contours and best-fit point for the observed geoneutrino event rates. The small shaded region is favoured by the reference model[4]. The dashed line is the locus of points expected from the BSE model of ref. 5, Th:U = 3.9. **b**, $\Delta\chi^2$-profile from the fit to the total number of geoneutrino events discussed in the text. In this case the Th:U ratio is fixed at 3.9. The BSE model prediction is represented by the shaded band[5].

BX: the observation of the geo-ν signal

Phys.Lett.B 687 (2010) 299-304



Our best estimates are:

$$N_{geo} = 9.9^{+4.1\;+14.6}_{-3.4\;-8.2}$$

$$N_{react} = 10.7^{+4.3\;+15.8}_{-3.4\;-8.0}$$

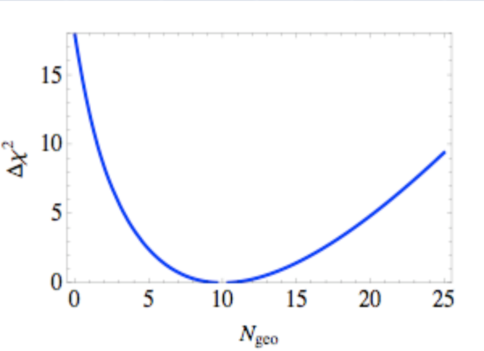
@ 99.73% C.L

@ 68.3% C.L

Background in the geo-ν energy window: **0.31 ± 0.05**

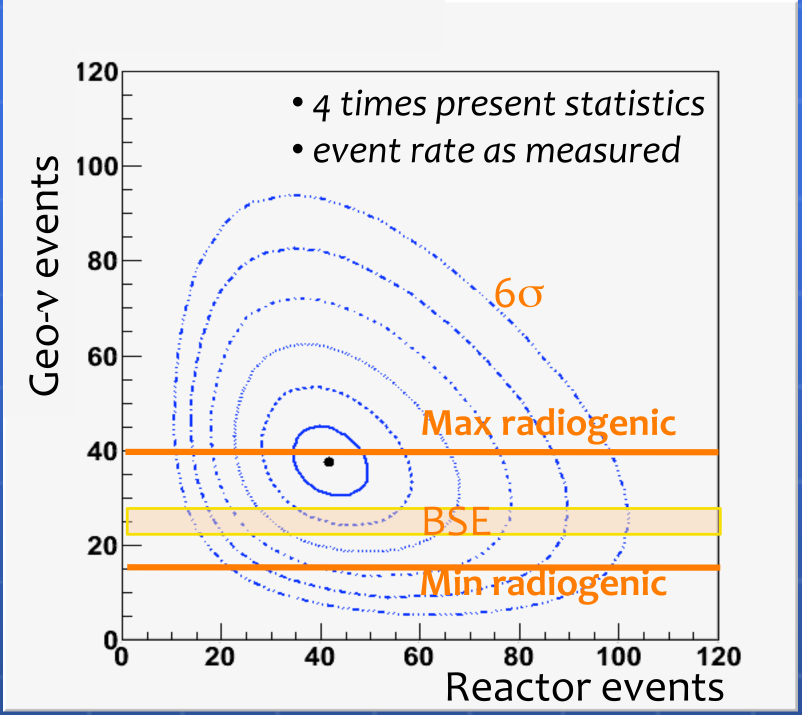
- *By studing the profile of the likelyhood respect to N_{geo}:*

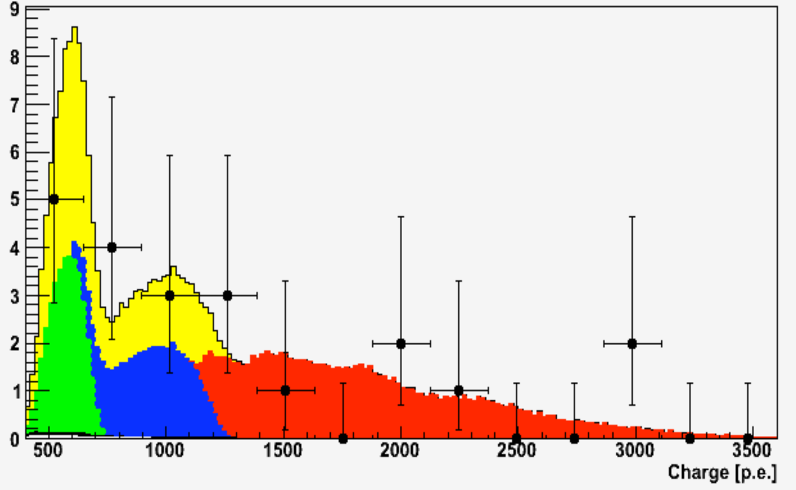
Null geo-ν hypothesis rejected at 4.2 σ



Geo-ν (U+Th) flux [10^6 cm^{-2} s^{-1}]	
Borexino	$7.2^{+2.9}_{-2.4}$
BSE (Mant.2004)	$4.6^{+0.5}_{-0.9}$
Max. rad. Earth	7.2
Min. rad. Earth	2.9

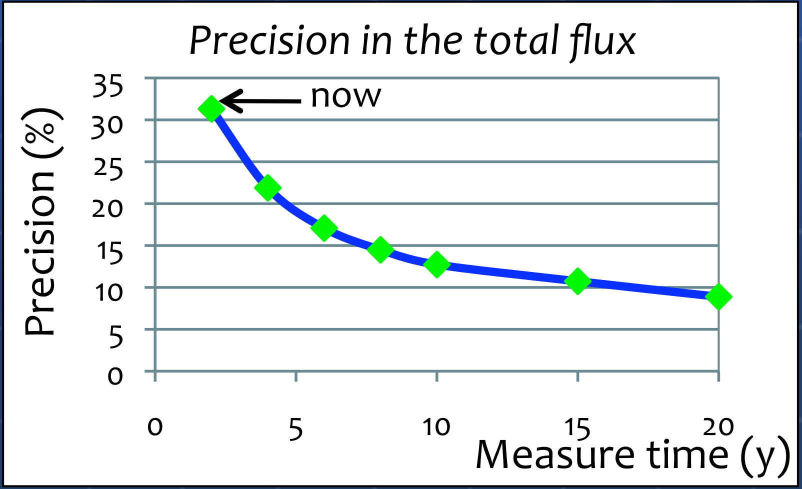
Geo-ν: future BX results

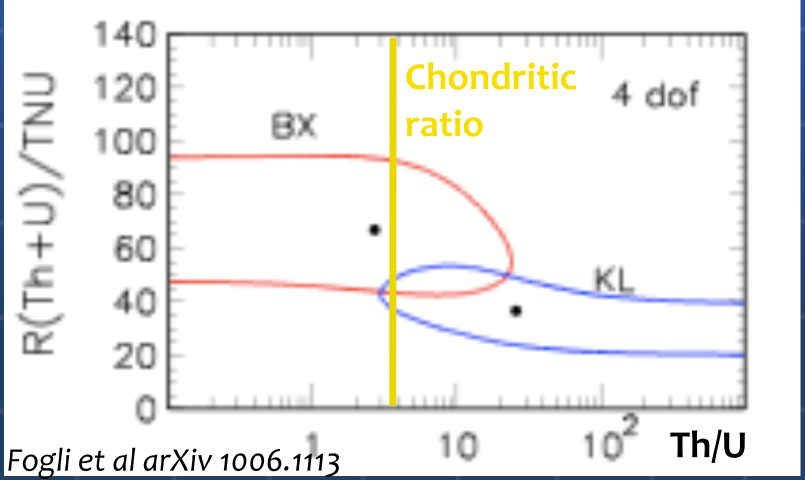




U/Th ratio free:

- *Difficult to constrain with enough precision by a single exp. (if detector size ≤ kton)*
- *Better results through combined analysis:*





Fogli et al arXiv 1006.1113

Geo-ν: the background in BX

Geo-ν expected signal (BSE) = 2.5 cpy/100 t

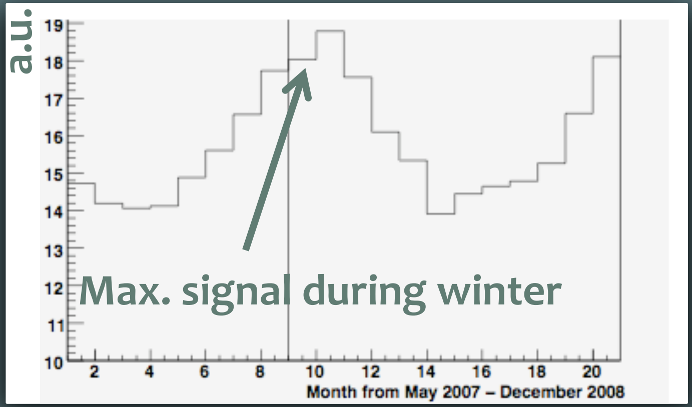
Reactor antineutrinos

✓ Overall rate: 5.0 ± 0.3 cpy/100 t
✓ Rate in the GNW: 2.0 ±0.1 cpy/100 t

We are in contact with IAEA and EDF:

-Thermal powers for each European reactors are known on a monthly base;

-Expected signal @ LNGS evaluated with a dedicated code (sys. uncertainty: 5.4%)



Signal (BSE)/(Reactor background) ~ 1.25 In the GNW

Cosmogenic/enviromental background

✓ Overall rate: 0.14 ± 0.02 cpy/100 t
✓ Rate in the GNW: 0.12 ±0.01 cpy/100 t

Muon correlated events

Cosmogenic ^{9}Li and ^{8}He decay via β-n

- τ~ 150 ms
- 2 s detector veto after scintillator muons
- Residual background: 0.03±0.02 cpy/100 t

Radiogenic $^{13}C(\alpha,n)^{16}O$

- ^{210}Po a emitter: 12 cpd/100 t
- ^{13}C low abundance: $^{13}C/^{12}C$~1.1 %
- Background: 0.014±0.001 cpy/100 t

Random coincidences

Searching for events in a window of 2 ms-2 s:
0.080 ±0.001 cpy/100t

Signal(BSE)/(non anti-ν Background) ~ 21

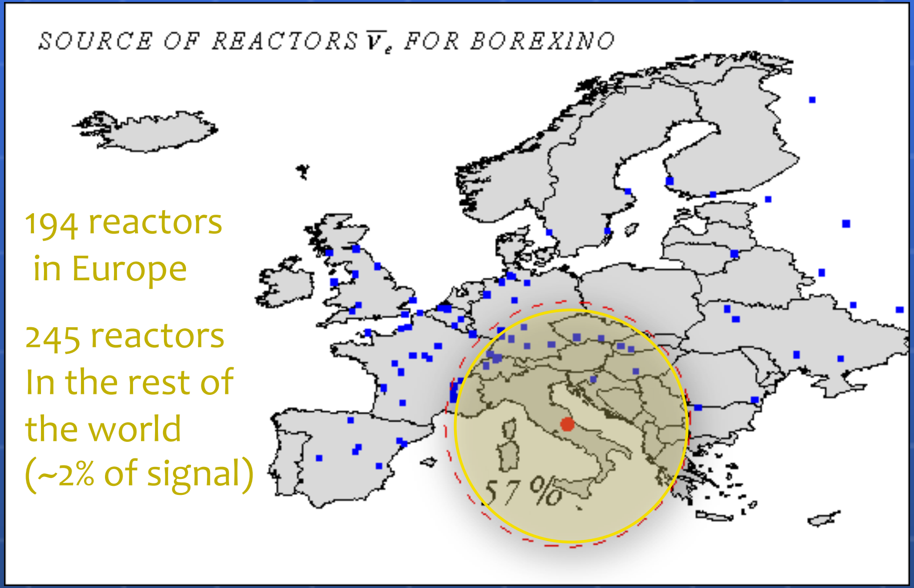
Geo-ν signal: non anti-ν backgrounds

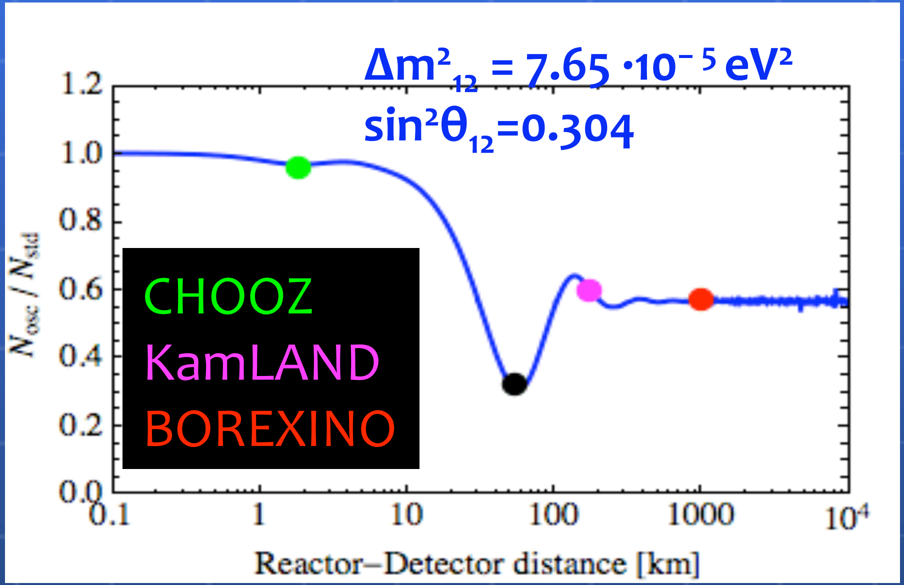
Background source	events/(100 ton-year)
Cosmogenic ^{9}Li and ^{8}He	0.03 ± 0.02
Fast neutrons from μ in Water Tank (measured)	< 0.01
Fast neutrons from μ in rock (MC)	< 0.04
Non-identified muons	0.011 ± 0.001
Accidental coincidences	0.080 ± 0.001
Time correlated background	< 0.026
(γ,n) reactions	< 0.003
Spontaneous fission in PMTs	0.003 ± 0.0003
(α,n) reactions in the scintillator [^{210}Po]	0.014 ± 0.001
(α,n) reactions in the buffer [^{210}Po]	< 0.061
TOTAL	**0.14 ± 0.02**

Expected : 2.5 geo-ν/(100ton-year) (assuming BSE)

BX: The detection of the European reactor anti-

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



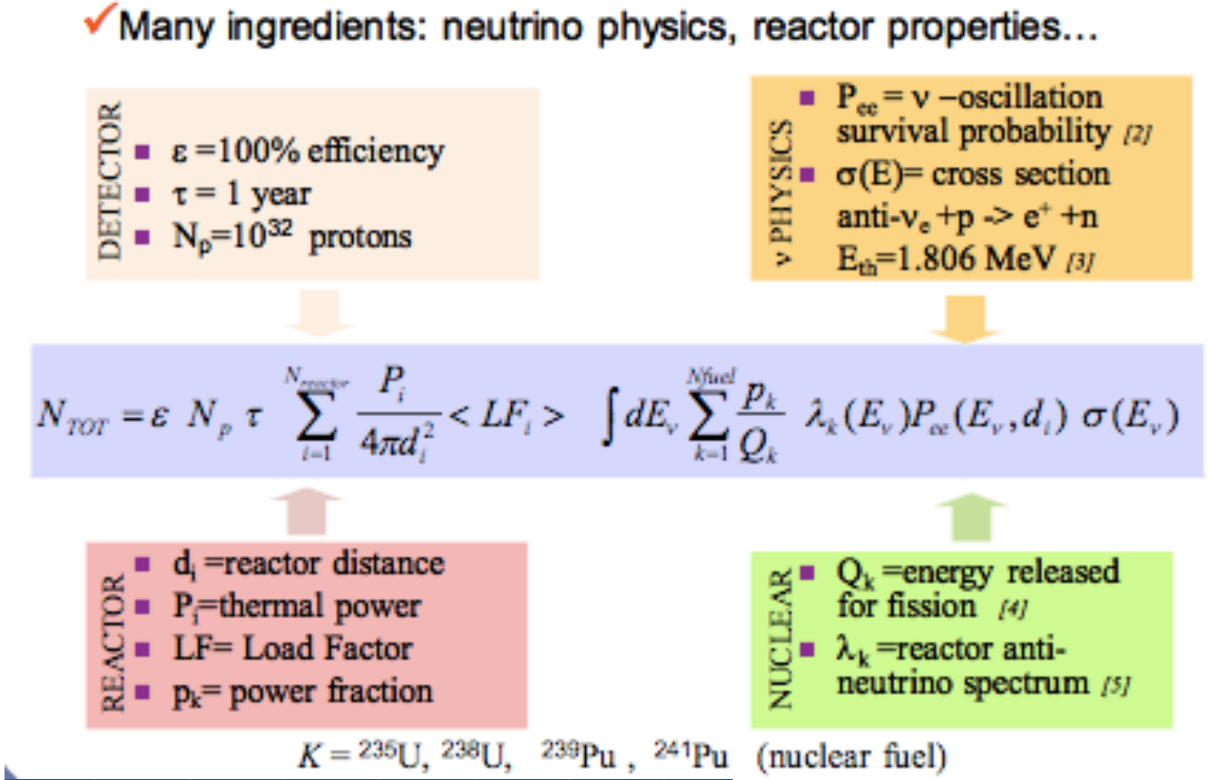


Mean baseline ~ 1000 km

- 6 events observed in the RNW
- 16.3 ± 1.1 events expected (no osc.)

- The non oscillation hypothesis is excluded at 99.60 C.L.
- Geo-reactor power in the Earth core < 3TW @ 95% C.L.

The reactors anti-ν expected signal



✓ Many ingredients: neutrino physics, reactor properties…

DETECTOR
- ε =100% efficiency
- τ = 1 year
- $N_p = 10^{32}$ protons

ν PHYSICS
- P_{ee} = ν –oscillation survival probability [2]
- $\sigma(E)$= cross section anti-ν_e +p -> e^+ +n E_{th}=1.806 MeV [3]

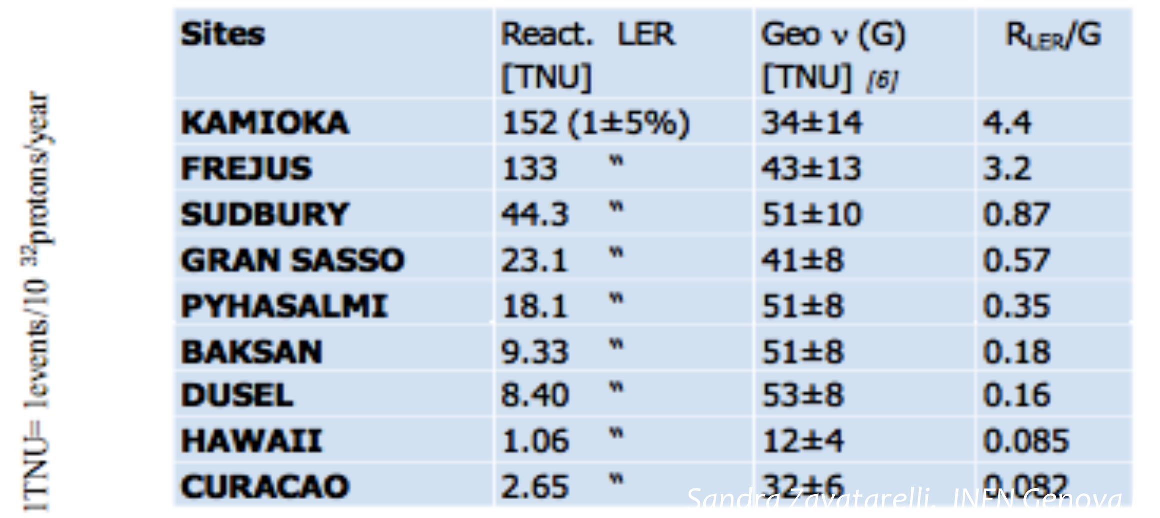
$$N_{TOT} = \varepsilon\ N_p\ \tau \sum_{i=1}^{N_{reactor}} \frac{P_i}{4\pi d_i^2} < LF_i > \int dE_\nu \sum_{k=1}^{Nfuel} \frac{p_k}{Q_k}\ \lambda_k(E_\nu) P_{ee}(E_\nu, d_i)\ \sigma(E_\nu)$$

REACTOR
- d_i =reactor distance
- P_i=thermal power
- LF= Load Factor
- p_k= power fraction

NUCLEAR
- Q_k =energy released for fission [4]
- λ_k =reactor anti-neutrino spectrum [5]

$K = {}^{235}$U, ^{238}U, ^{239}Pu , ^{241}Pu (nuclear fuel)

B. Ricci
TAUP 2012



1TNU= 1events/10^{32}protons/year

Sites	React. LER [TNU]	Geo ν (G) [TNU] [6]	R_{LER}/G
KAMIOKA	152 (1±5%)	34±14	4.4
FREJUS	133 "	43±13	3.2
SUDBURY	44.3 "	51±10	0.87
GRAN SASSO	23.1 "	41±8	0.57
PYHASALMI	18.1 "	51±8	0.35
BAKSAN	9.33 "	51±8	0.18
DUSEL	8.40 "	53±8	0.16
HAWAII	1.06 "	12±4	0.085
CURACAO	2.65 "	32±6	0.082

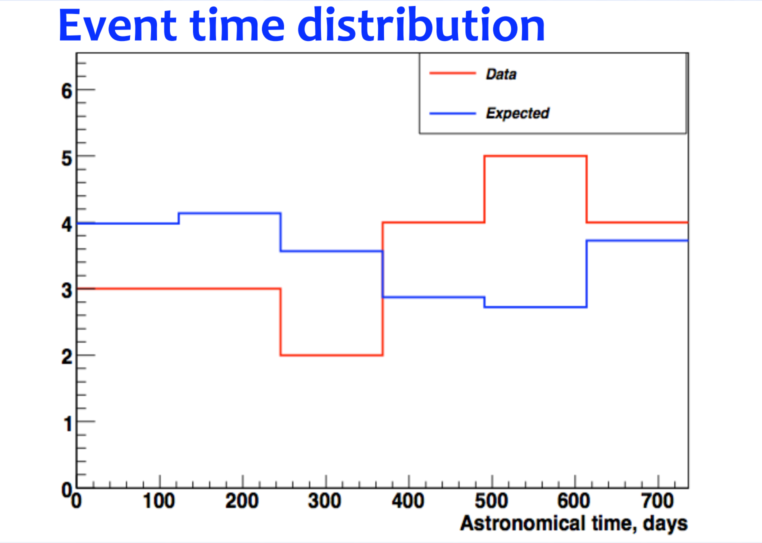
BX: the selected events

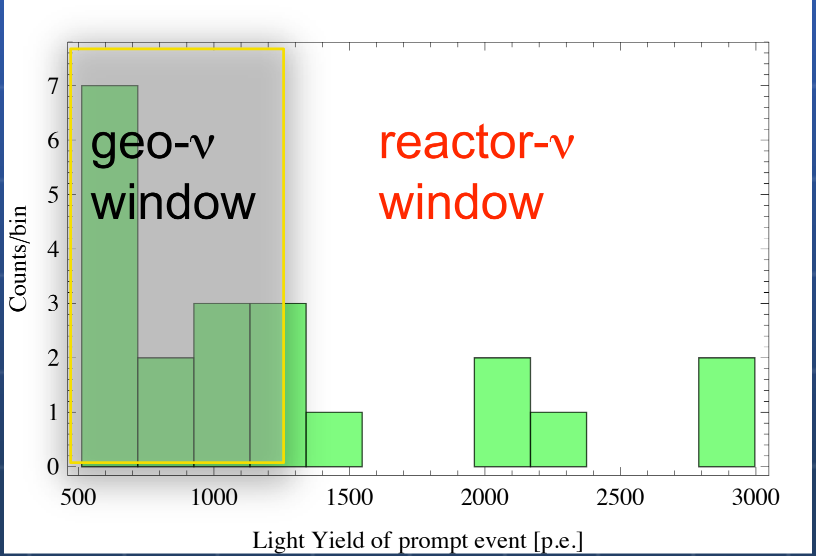
Data set : Dec. 2007- Dec.2009

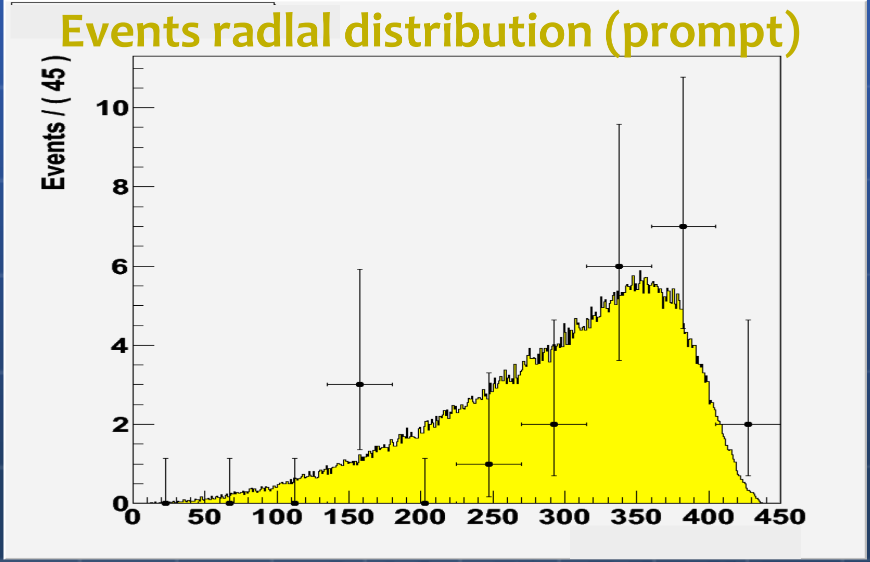
21 selected antinu candidates in 252.6 tons y

Selection cuts – ε (with MC): 0.85 ± 0.01

- Light yield prompt event> 410 p.e.
- 700 p.e .< light yield delayed event< 1250 p.e.
- $\Delta R < 1$m
- 20 μs < Δt < 1280 μs
- R_{IV}-R_{prompt} >0.25 m


Event time distribution




Events radlal distribution (prompt)