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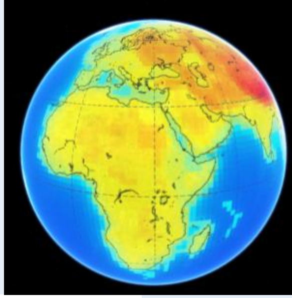
A refined reference Earth model for the geo-neutrino studies at Borexino

Viacheslav Chubakov

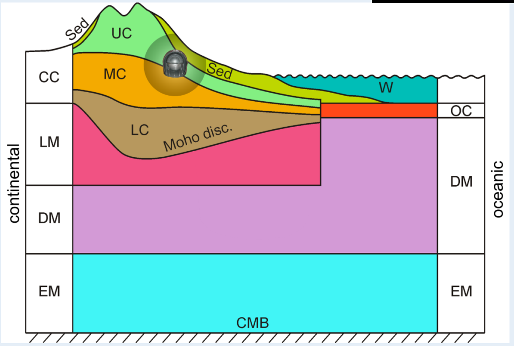
TUTORI: Prof. Giovanni Fiorentini, PhD. Fabio Mantovani

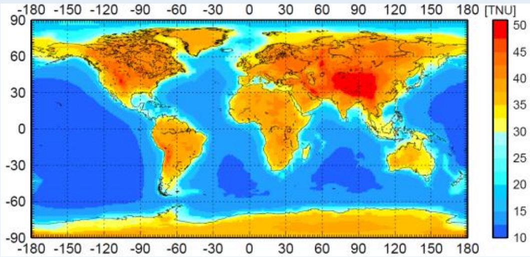
Università di Ferrara

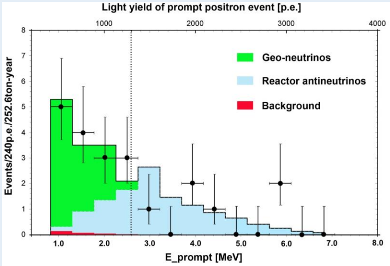
Summary

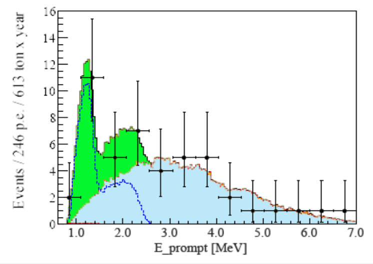


- Introduction:
  - geoneutrino properties
  - why do we need a refined reference Earth model (RRM)
- Main ingredients of RRM
  - Global model of crust
  - Model of mantle
  - Local model of crust around LNGS
- Antineutrino background from reactors
- Geoneutrino measurements of Borexino
- Conclusions









Geo-neutrinos: anti-neutrinos from the Earth

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

- Earth emits (mainly) antineutrinos $\Phi_{\bar{\nu}} \sim 10^6\,\mathrm{cm^{-2}s^{-1}}$ whereas Sun shines in neutrinos.
- A fraction of geoneutrinos from U and Th (not from ^{40}K) are above threshold for inverse β on protons: $\bar{\nu} + p \rightarrow e^+ + n - 1.8\ \mathrm{MeV}$
- Different components can be distinguished due to different energy spectra: e. g. anti-n with highest energy are from Uranium.
- Signal unit: 1 TNU = one event per 10^{32} free protons per year.

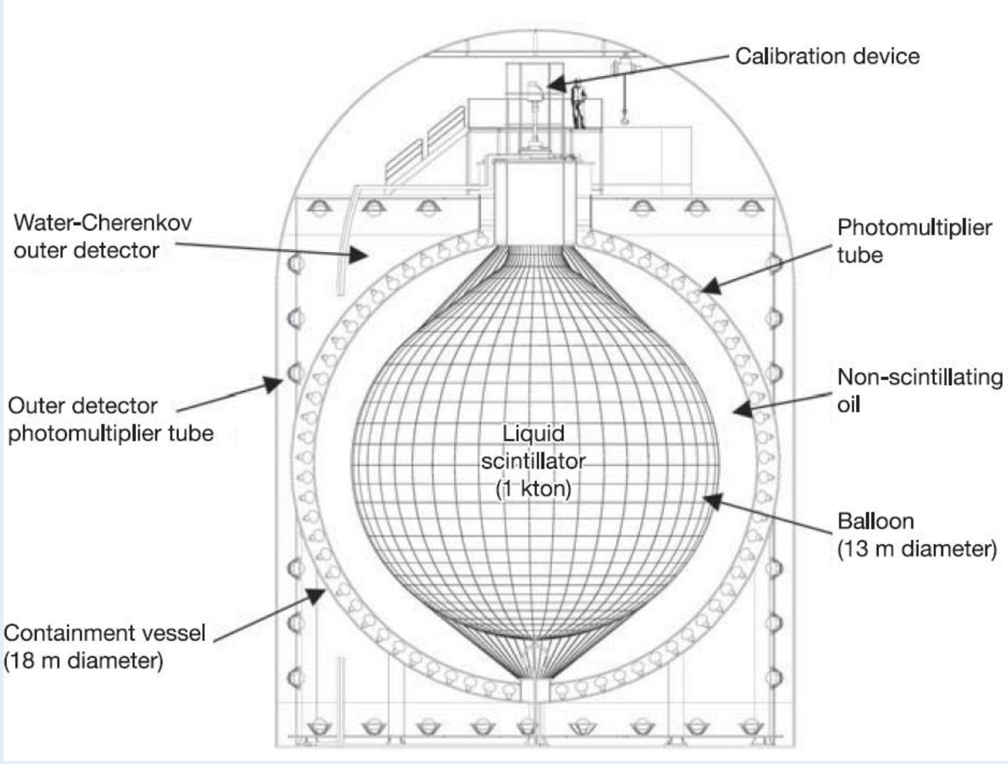
Running experiments: KamLAND and Borexino

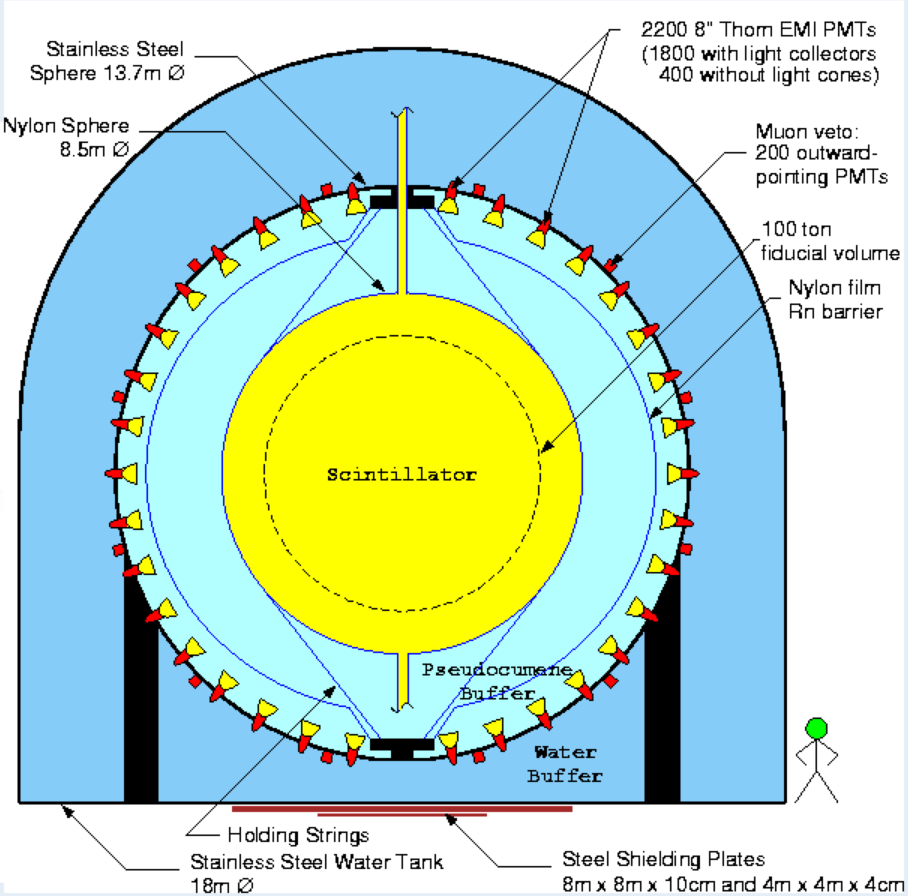
Kamioka
Liquid
Scintillator
ANtineutrino
Detector

1 kton LS, surrounded by 1845 PMT's

Borexino
placed at Gran Sasso National Laboratories

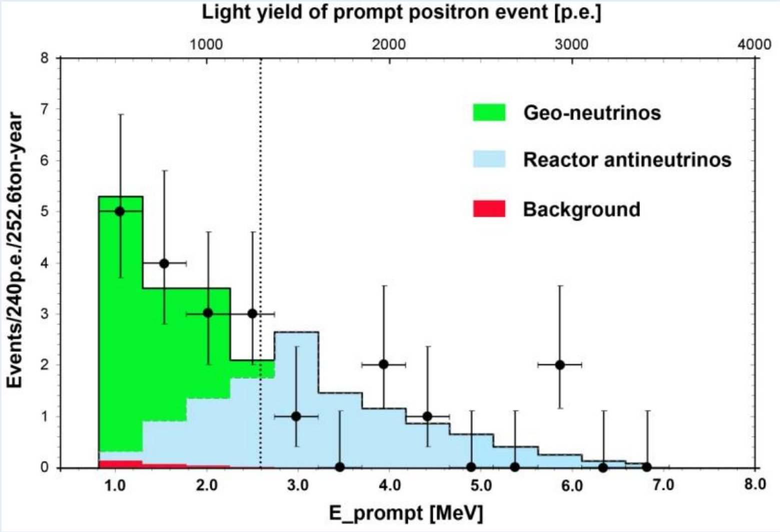
300 ton LS, surronded by 2200 PMT's



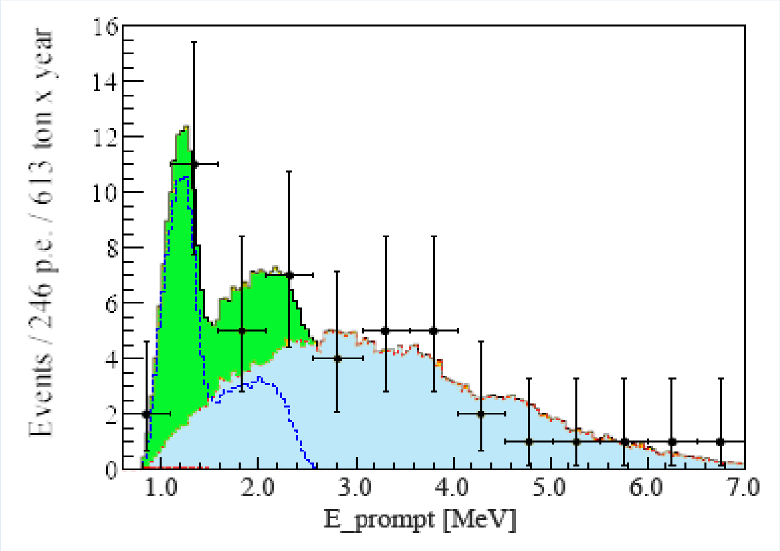


Geo-neutrino measurements by Borexino

Period	Dec. 07 – Dec. 09	
Exposure p.yr	0.15×10^{32}	
	events	TNU
Total (full sp.)	21	
Reactors	$10.7_{-3.4}^{+4.3}$	64_{-22}^{+26}
Geo-n	$9.9_{-3.4}^{+4.1}$	69_{-22}^{+28}
Background	$0.4_{-0.05}^{+0.05}$	



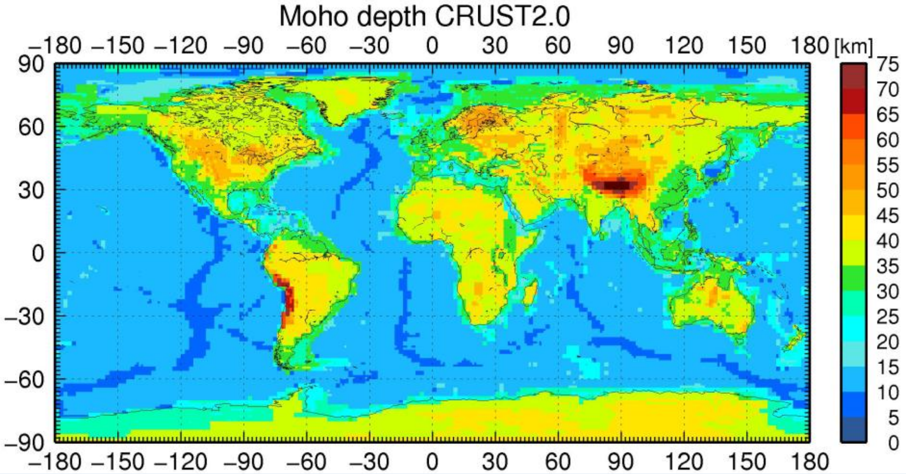
Period	Dec. 02 – Aug. 12	
Exposure p.yr.	0.37×10^{32}	
	events	TNU
Total (full sp.)	46	
Reactors	$31.2_{-6.1}^{+7.0}$	$84.5_{-16.9}^{+19.3}$
Geo-nu	14.3 ± 4.4	38.8 ± 12
Background	0.70 ± 0.18	



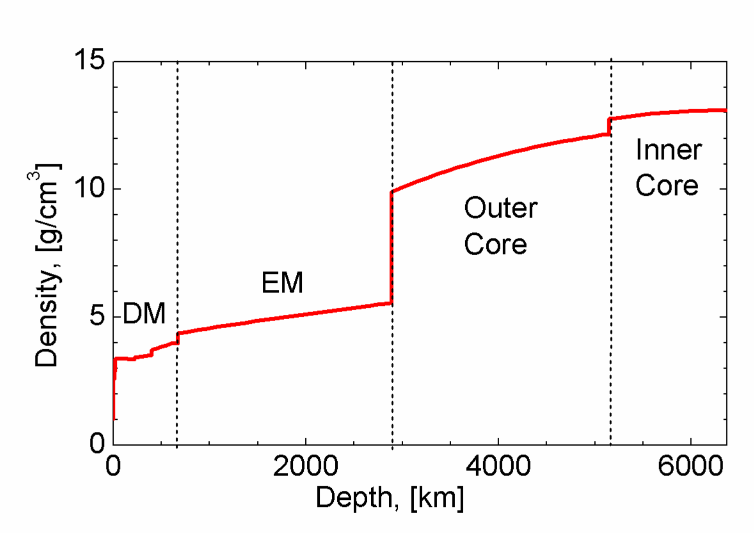
* Bellini et al. Physics Letters B 687, 2010; Bellini et al. arXiv:1303.2571, 2013.

Previous reference Earth models (RM)

Crust and mantle were treated as two separate reservoirs. In particular, the mantle was conventionally described as a spherically uniform shell between the crust and the core.



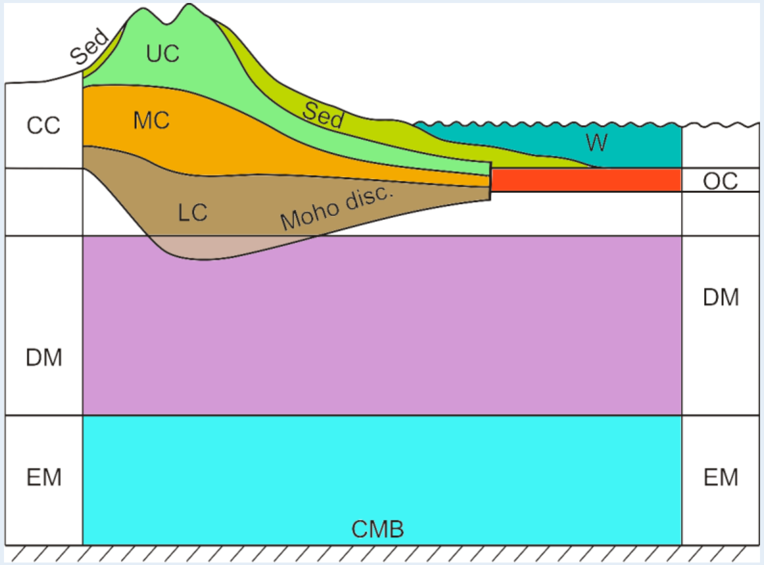
1) Crust:
    a) geophysical properties (thickness, density, etc.) were based on 2º×2º CRUST2.0 map;
    b) composition was adopted from the world wide average abundances.



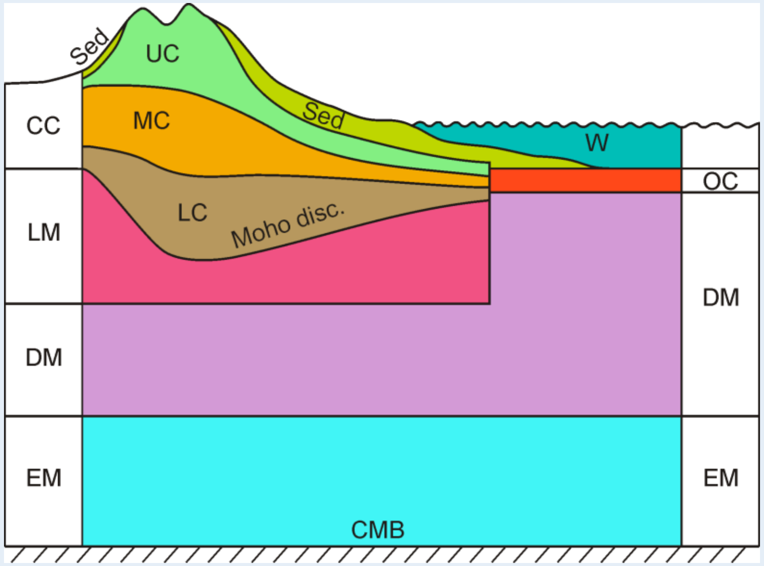
2) Mantle structure was based on PREM (Preliminary Earth Reference Model, a 1-D seismologically based global model)

3) Core is considered to have negligible amounts of K, Th and U.

Structure of RM



Structure of RRM

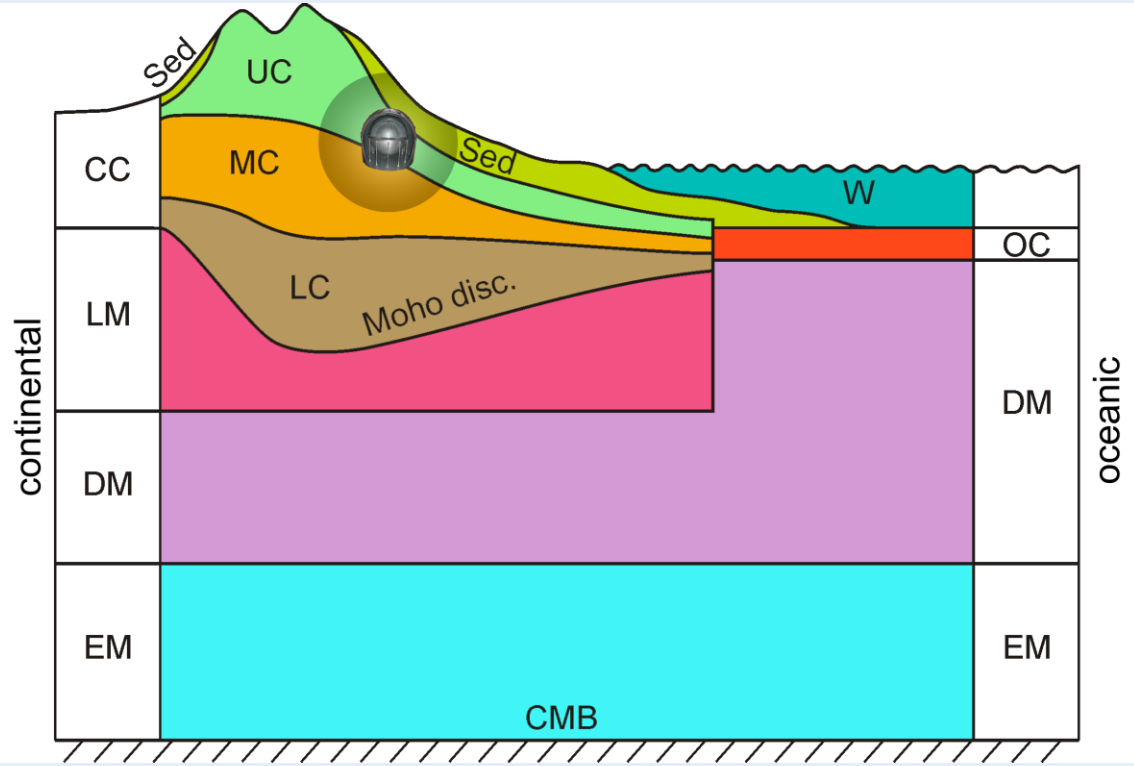


Geoneutrino signal at LNGS predicted by different RM

Reference	$S_{\text{Gran Sasso}}$, TNU
Mantovani et al. 2004	40.5 ± 6.5
Fogli et al., 2006	40.5 ± 2.9
Enomoto et al. 2007	43.1
Dye, 2010	42.0 ± 7.2

Towards a Refined Reference Earth Model (RRM)*

The main updates of the RRM



- An updated 1°x1° sedimentary layer
- Combination of 3 models for crust thickness
- New compilations of HPEs abundances in OC, Seds, UC
- New approach in the evaluation of U and Th abundances (and their uncertainties) in MC and LC based on seismic arguments
- Heterogeneous topography of crust bottom
- Introduction of CLM
- Propagation of uncertainties by using Monte Carlo simulation

*In collaboration with: Y. Huang, W. F. McDonough, R. L. Rudnick (Maryland Univ.)

Structure of RRM and its uncertainties

1) Topography and bathymetry are adopted from a standard database (ETOPO-5)

2) Sedimentary layer - a global 1°×1° sediment map [Laske and Masters, 1997]

3) Continental crust:

   a. Upper crust

   b. Middle crust

   c. Lower crust

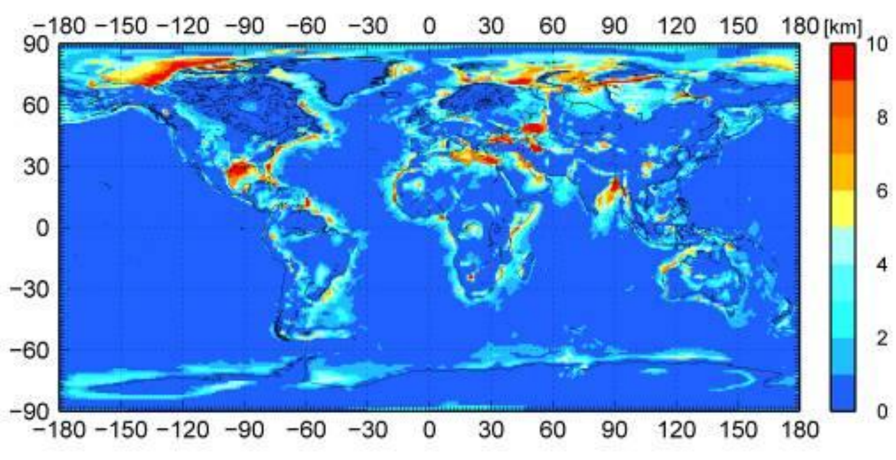
4) Oceanic crust

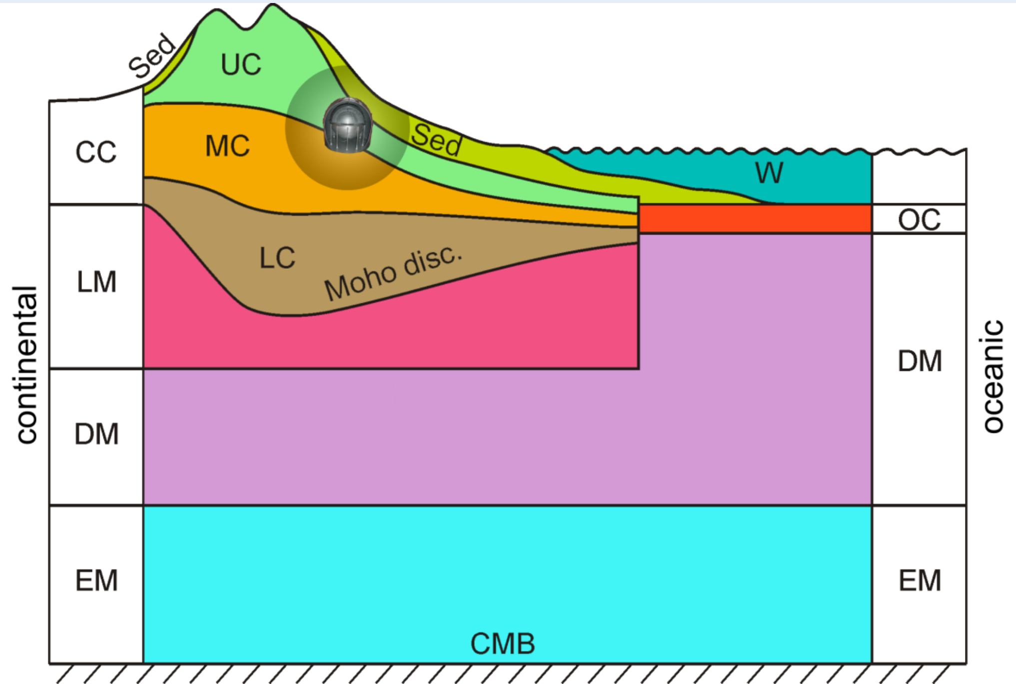
5) Lithospheric mantle, depth of CLM base is 175±75 km

6) Depleted mantle

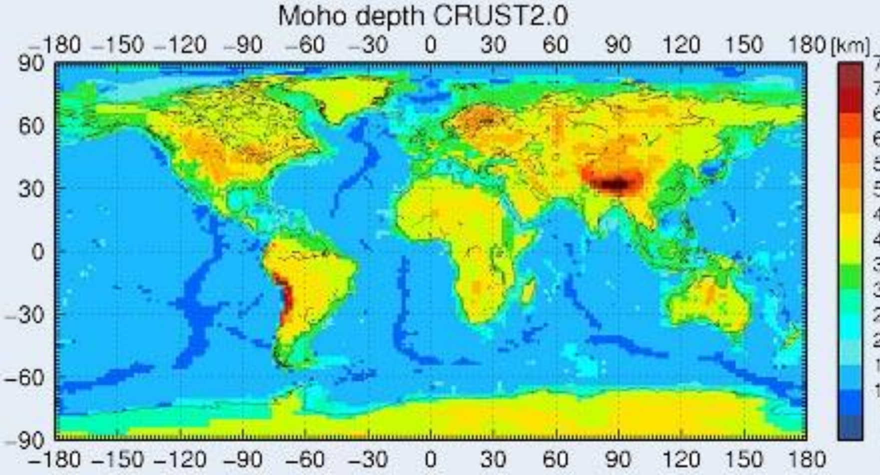
7) Enriched mantle – 17% of the total mantle mass (Arevalo et al.[2012])

Thickness of sediments (1°x1°)

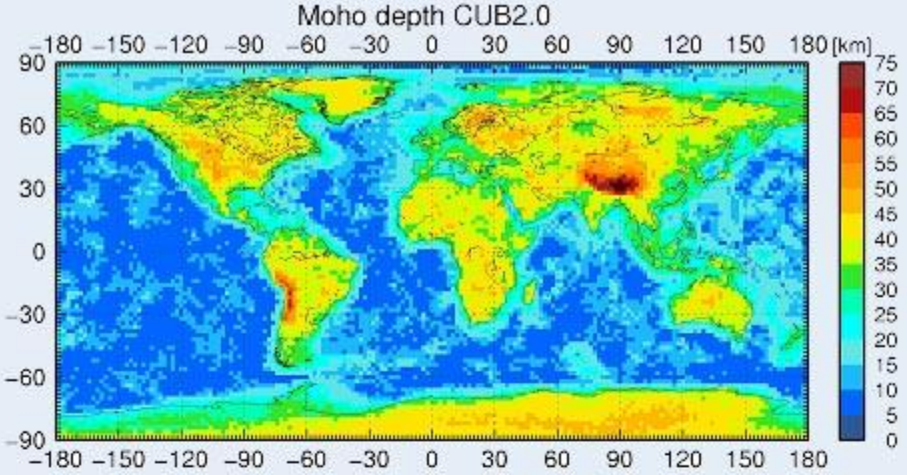




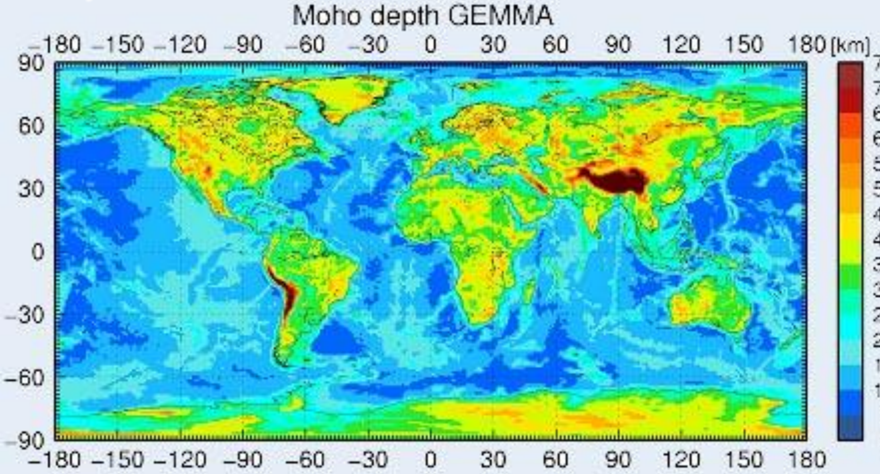
Crust thickness of RRM



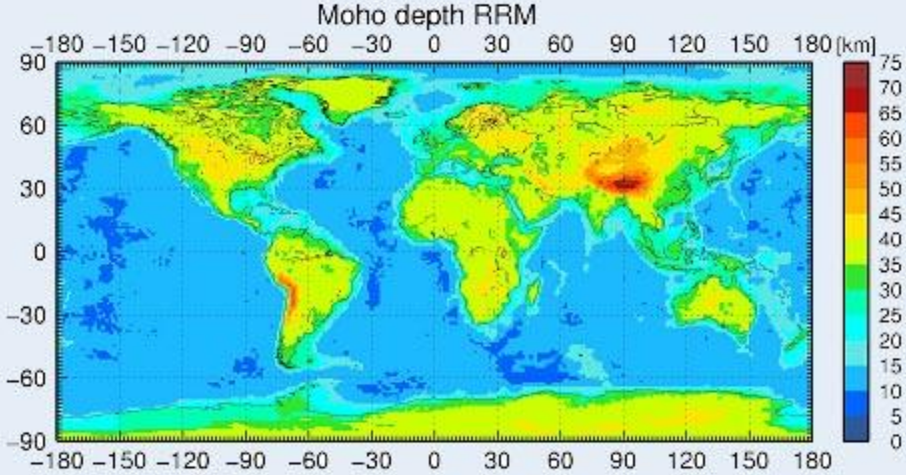
CRUST2.0 (Bassin et al., 2000), 2°×2° resolution model based on reflection and refraction seismic body waves



CUB2.0 (Shapiro and Ritzwoller 2002), 2°×2° resolution model based on surface wave dispersion

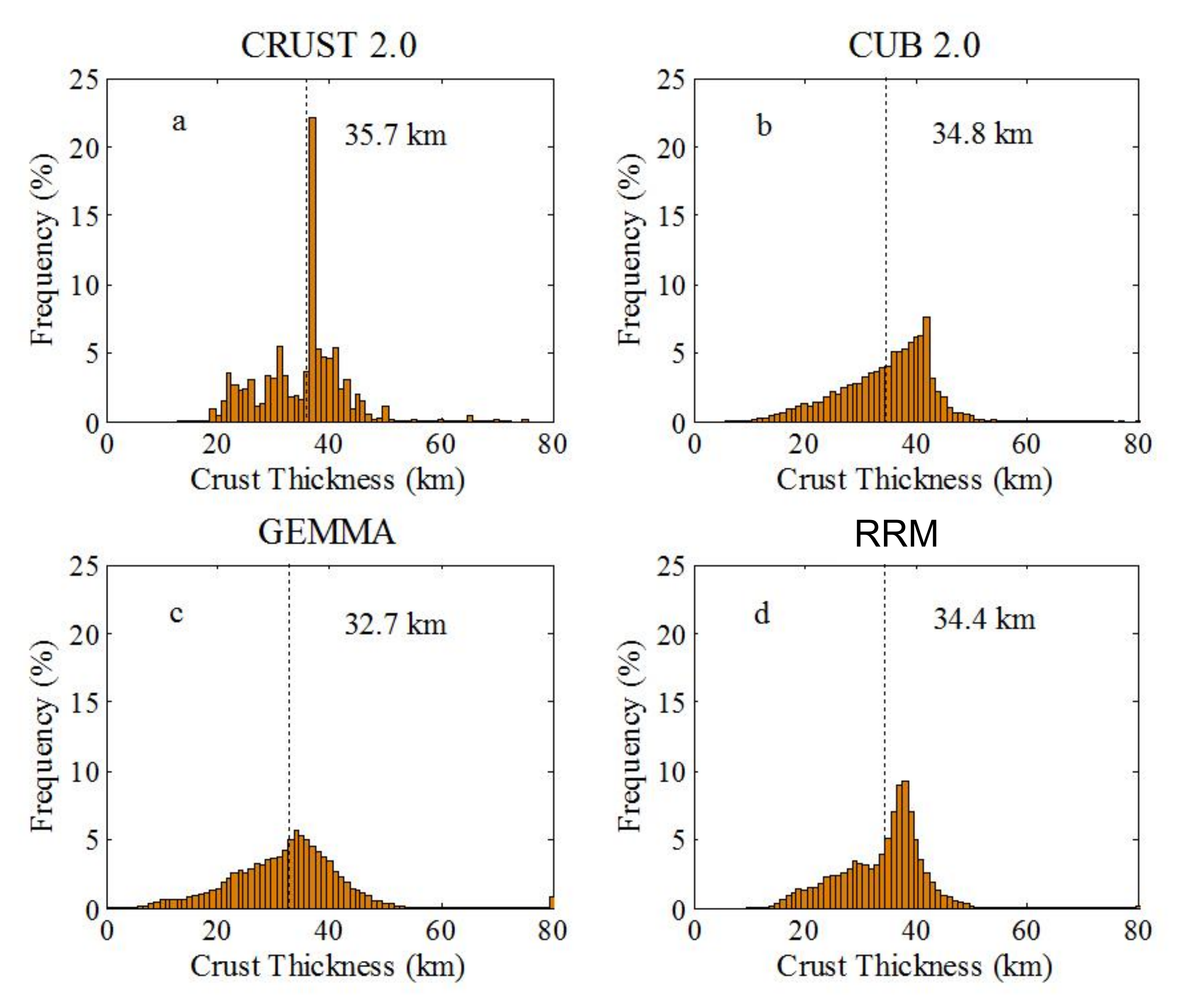


GEMMA (Reguzzoni, Tselfes, 2009; Reguzzoni, Sampietro, 2012) – GOCE Exploitation for Moho Modeling and Applications, the first global high-resolution map (0.5°×0.5°) of Moho depth
Based on gravity field measurements

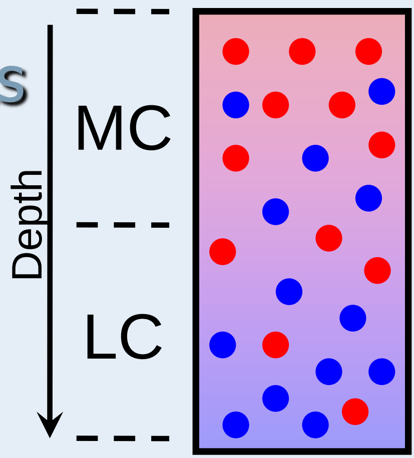


RRM thickness and its associated uncertainty of each 1°×1° crustal voxel is obtained as the mean and the half-range of the three models:

Distributions of CC thickness in three global crustal models and the RRM



U and Th in MC and LC : felsic and mafic components

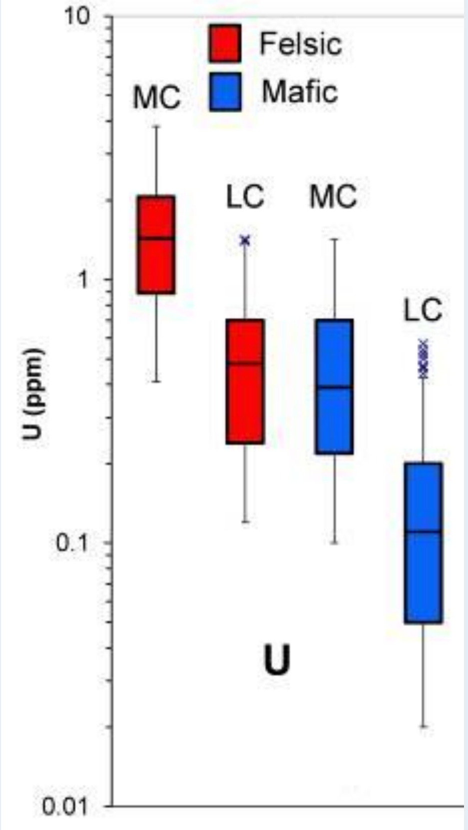


- In the previous models the abundances of U and Th in MC and LC were affected by large uncertainties, often obtained by average of different compilations.
- In MC and LC we can recognize two components: felsic and mafic rocks.

	Fraction	Chemic. Properties	
Felsic	Decrease with depth	Acid	High SiO_2
Mafic	Increase with depth	Basic	Low SiO_2

- We compile a database with thousands of published data obtained by ICPMS/γray measurements on samples.

		Uranium		**Thorium**	
		n°	*a* [ppm]	n°	*a* [ppm]
MC	Fels.	**368**	$\mathbf{1.4_{-0.6}^{+1.0}}$	**428**	$\mathbf{8.3_{-4.1}^{+8.2}}$
	Mafic	**233**	$\mathbf{0.4_{-0.2}^{+0.4}}$	**257**	$\mathbf{0.6_{-0.3}^{+0.6}}$
LC	Fels.	**108**	$\mathbf{0.4_{-0.2}^{+0.4}}$	**133**	$\mathbf{3.9_{-2.5}^{+7.4}}$
	Mafic	**236**	$\mathbf{0.1_{-0.1}^{+0.1}}$	**258**	$\mathbf{0.3_{-0.2}^{+0.5}}$

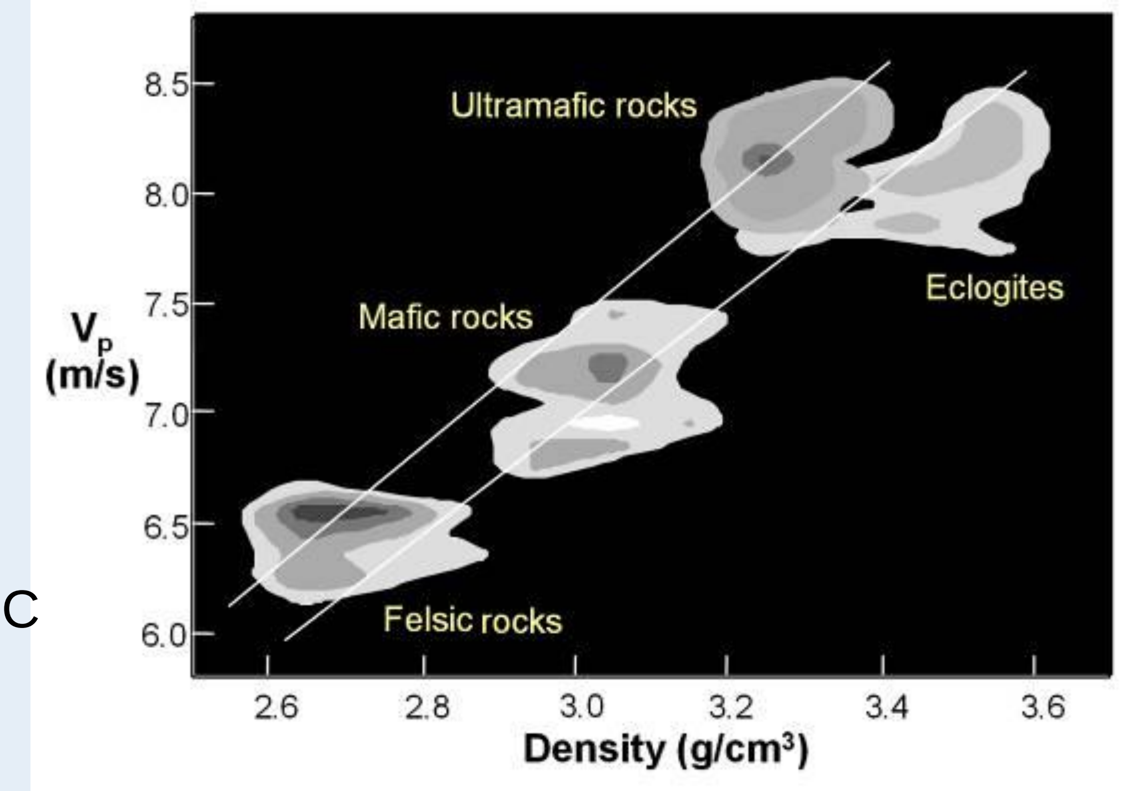


Seismic argument for estimating Felsic/Mafic in MC and LC

- Felsic and mafic rocks can be distinguished on the basis of P and S waves velocities

- Ultrasonic velocity measurements of deep crustal rocks provide a link between seismic velocity and lithology.

- The fractions of **felsic** (**f**) and **mafic** (**m**) rocks in the MC and LC of RRM are estimated solving:



$$
\begin{cases}
f + m = 1 \\
v_C = m v_m + f\, v_f \\
a = m a_m + f\, a_f
\end{cases}
$$

v_C = seismic velocity measured in MC and LC reported in worldwide crustal model CRUST2.0
$v_{f;m}$ = lab. measurements of felsic and mafic rock velocity
$a_{f;m}$ = U (and Th) abundance in felsic and mafic rocks
a = U (and Th) abundance in MC and LC

		n° data	v_p (km/s)
MC	Fels.	77	6.3 ± 0.2
	Mafic	57	7.0 ± 0.2
LC	Fels.	29	6.5 ± 0.2
	Mafic	44	7.2 ± 0.2

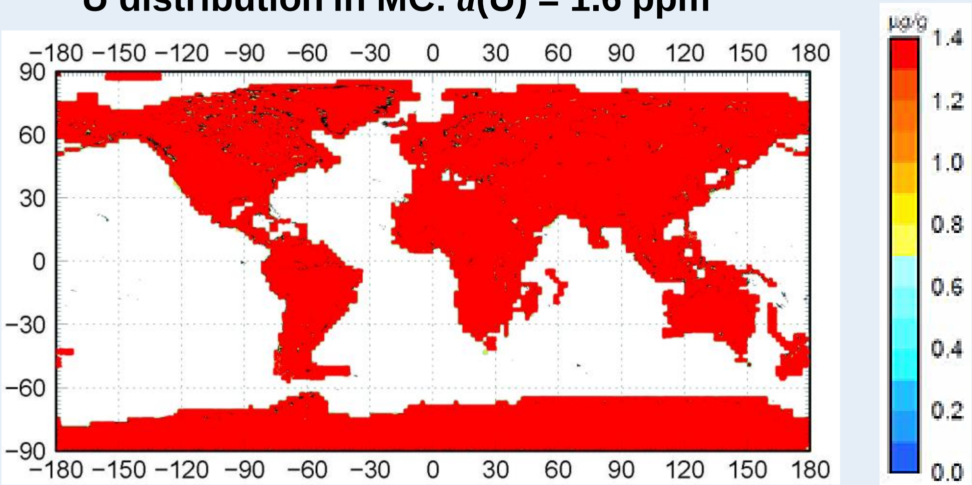
U content in the MC and LC: RM vs RRM

In the RM* the MC and LC were composed by tiles (2°x2°) with different thickness but homogeneous content of U: in RRM the U (Th) distribution is heterogeneous

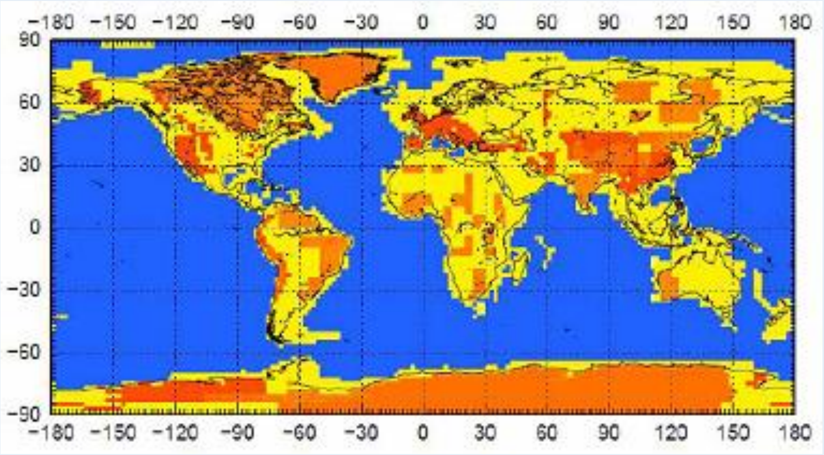
Reference Model*

Refined Reference Model**

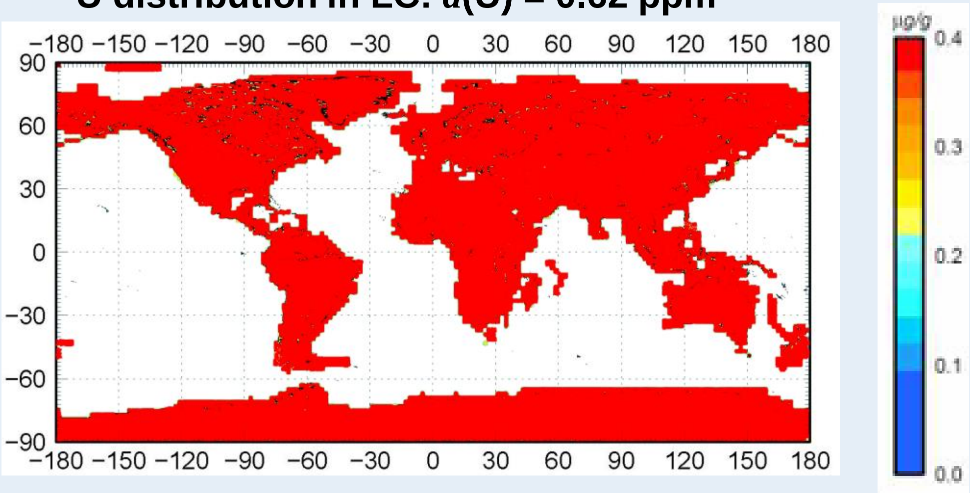
U distribution in MC: a(U) = 1.6 ppm



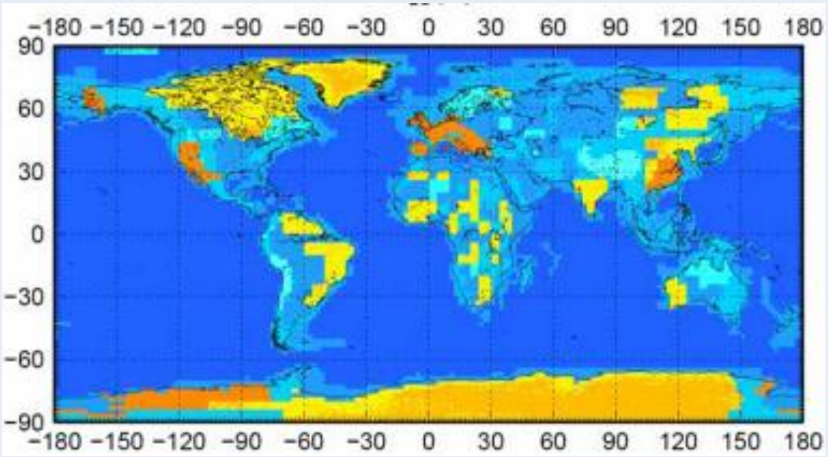
U distribution in MC: <a(U)> = 1.0 ppm



U distribution in LC: a(U) = 0.62 ppm



U distribution in LC: <a(U)> = 0.16 ppm

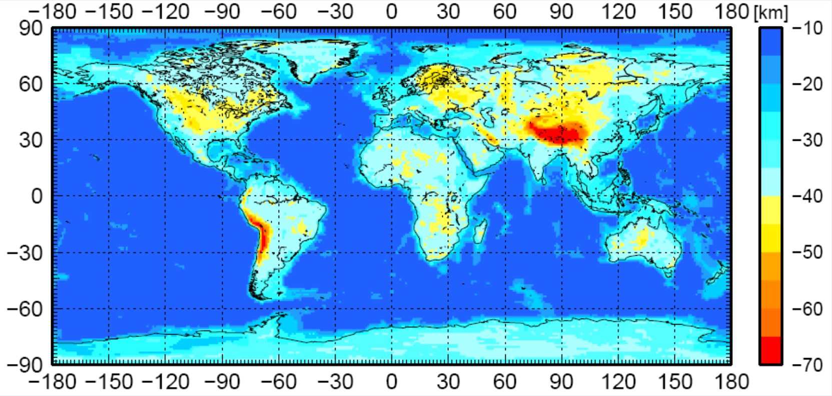


*** Mantovani et al. Phys. Rev. D 69, 2004**

**** This results are obtained by using only the v_p data**

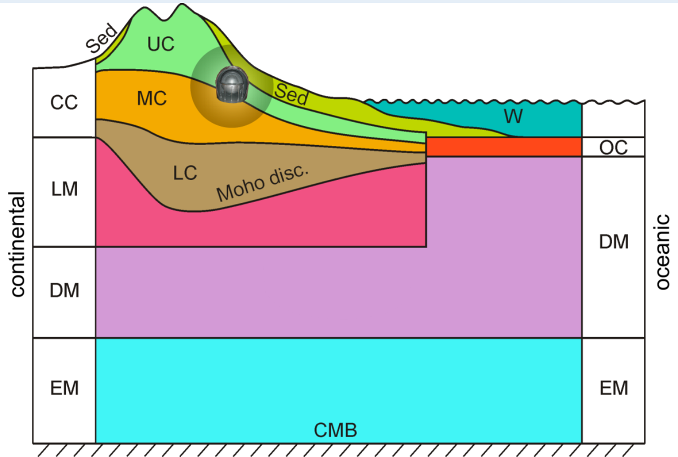
Mantle

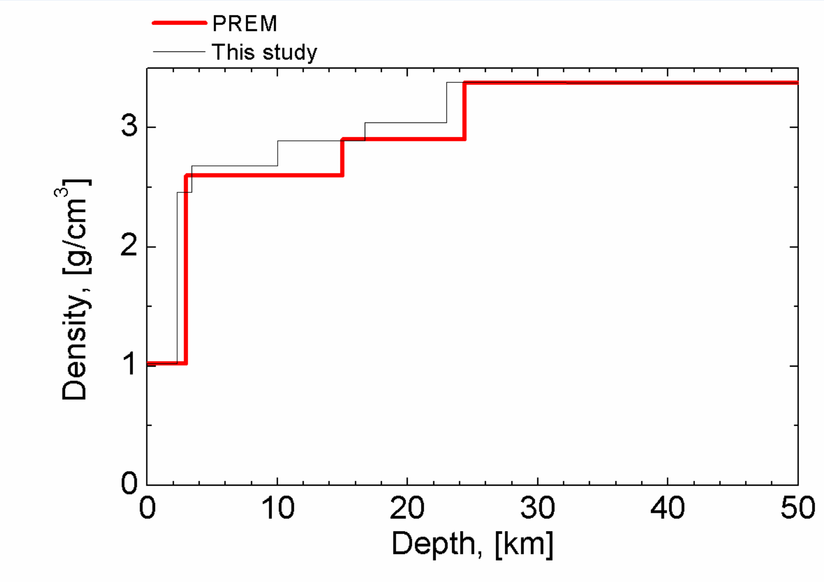
1) Heterogeneous topography of the mantle is considered



2) Continental lithospheric mantle is treated as separated reservoir with depth 175±75 km

3) Enriched mantle is assumed to contain 17% of the total mantle mass (Arevalo et al.[2012])

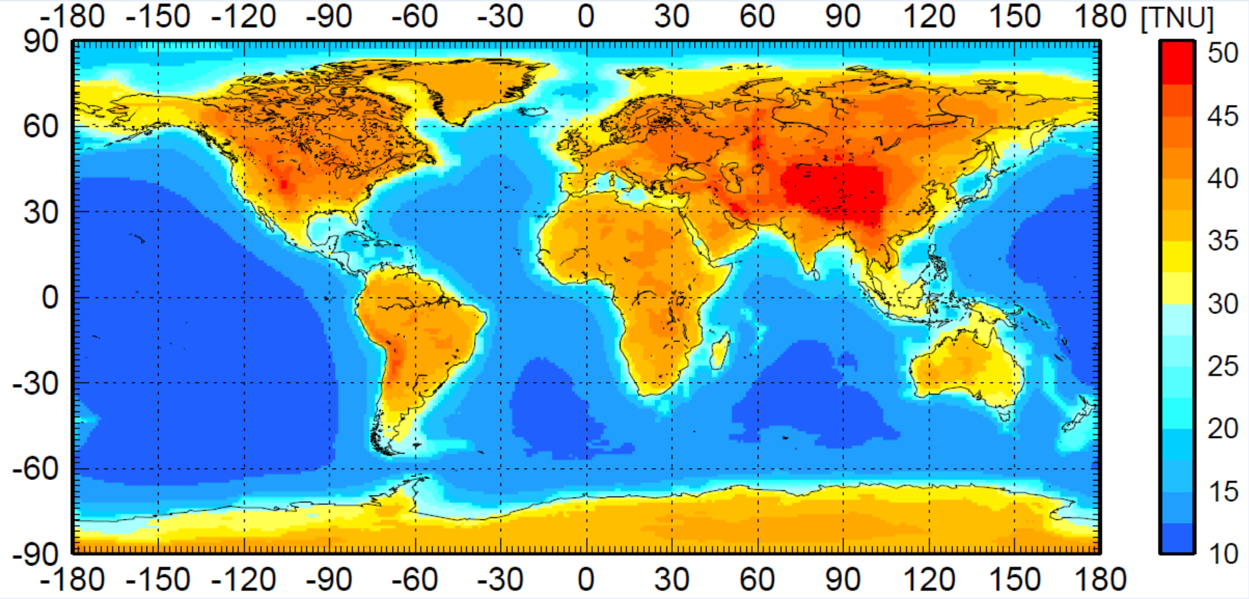




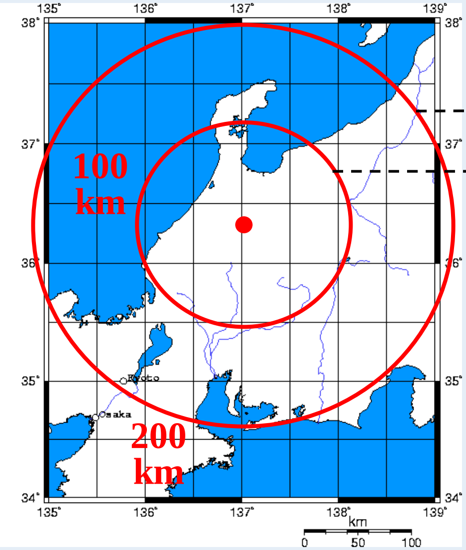
Calculated geoneutrinos signal at LNGS

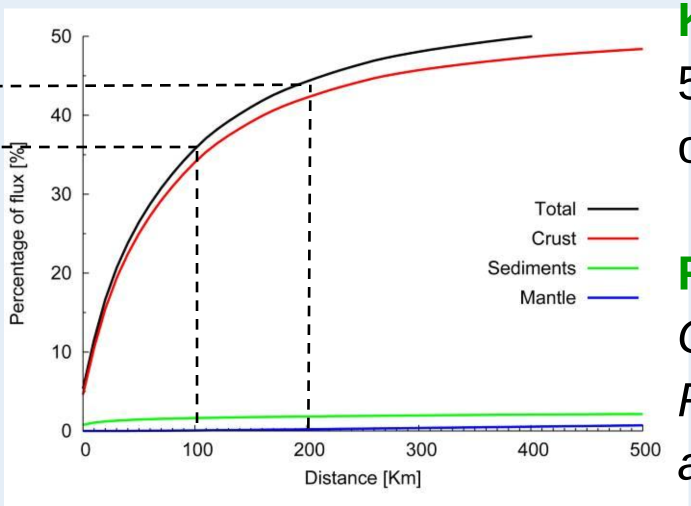
	Borexino (42.45 N, 13.57 E)		
	S(U)	S(Th)	S(U+Th)
Bulk Crust	$21.4_{-4.6}^{+5.2}$	$6.8_{-1.4}^{+2.3}$	$29_{-5.0}^{+6.0}$
CLM	$1.4_{-1.0}^{+2.7}$	$0.4_{-0.3}^{+1.0}$	$2.2_{-1.3}^{+3.1}$
Total LS	$23.6_{-5.2}^{+6.8}$	$7.6_{-1.8}^{+2.9}$	$31.9_{-5.8}^{+7.3}$
DM	4.1	0.8	4.9
EM	2.7	0.8	3.5
Grand Total	$40.2_{-5.8}^{+7.3}$		--

Geoneutrino signal at Earth's surface



Why regional geology is relevant?



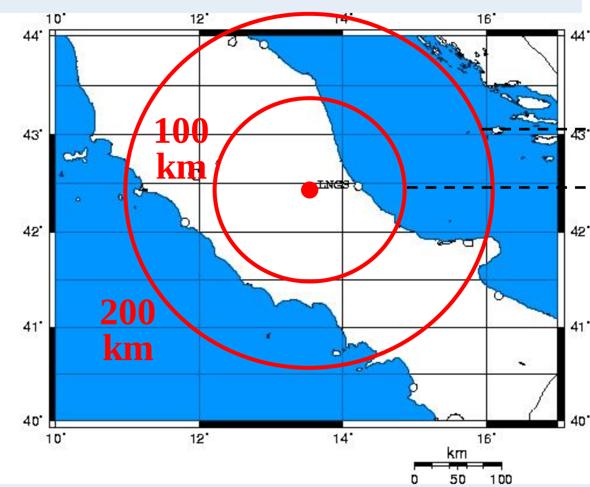


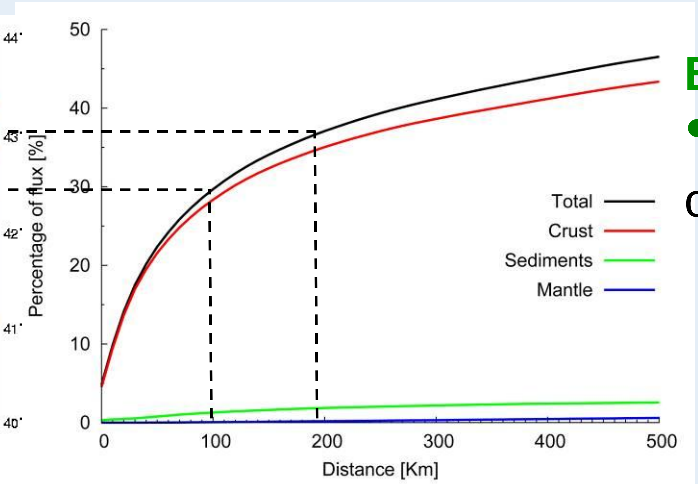
KamLAND at Kamioka:

50% of the total signal is originated from within 600 km

Refined Reference Model:

G. Fiorentini et al. – Physical Review D72 – 2005 – arXiv:hep-ph/0501111





Borexino at Gran Sasso:

- 50% of the total signal is originated from within 900 km

The regional contribution has to be controlled/determined by study of regional geology, if one wants to extract the global information brought in by geo-n's

Refining of the Reference Model for Gran Sasso

- The reference model [Mantovani et al. 2004] predicts for Borexino:

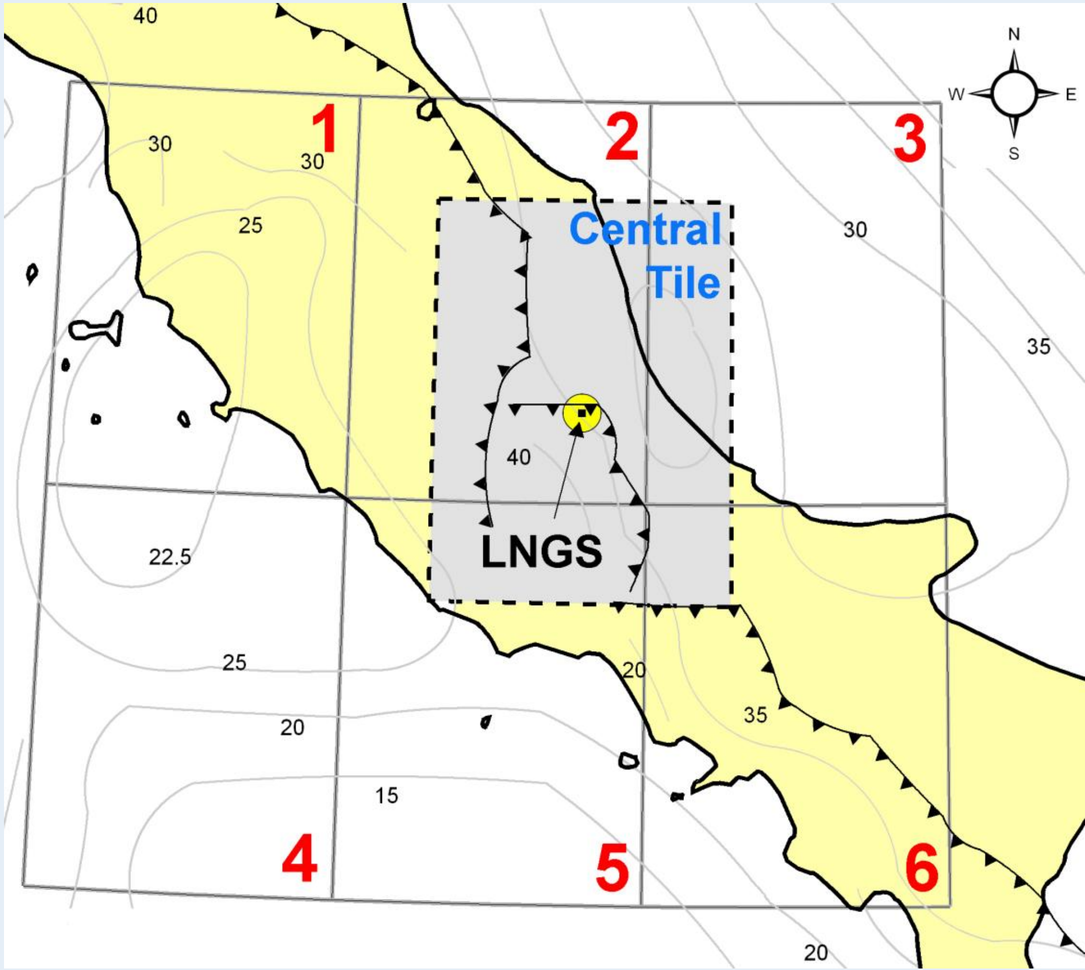
S_{Crust} = 32 TNU

- The 6 2°x2° tiles near Borexino contributes:

S_{reg} = 15.6 TNU

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

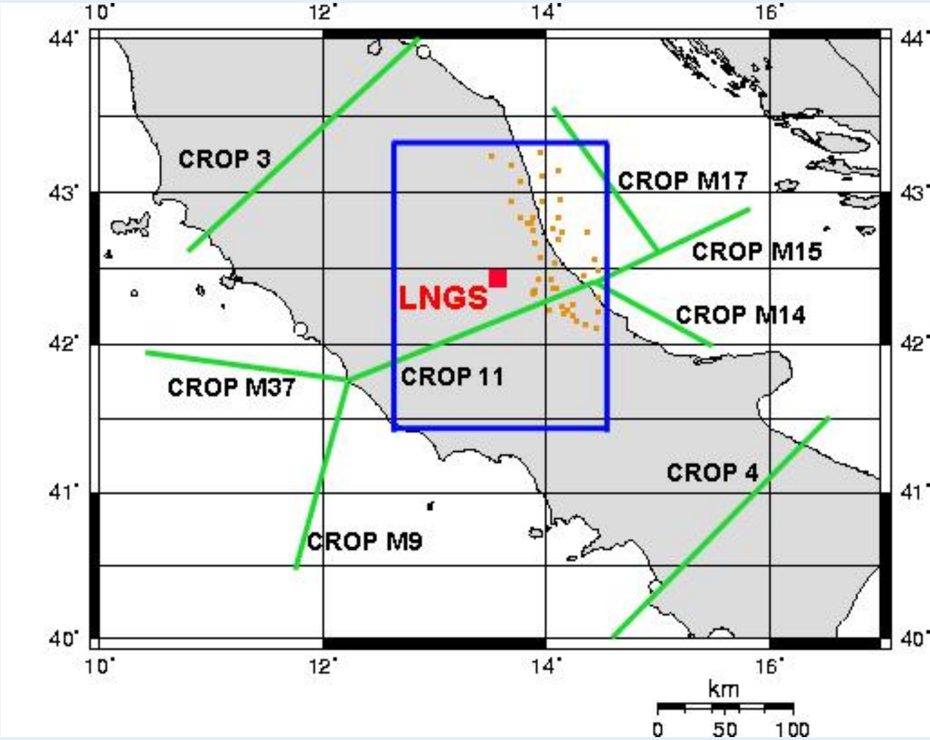
S_{CT} = 12.3 TNU



3D model of the central tile

Input:

- Data of CROP seismic sections
- Data from 38 deep oil and gas wells

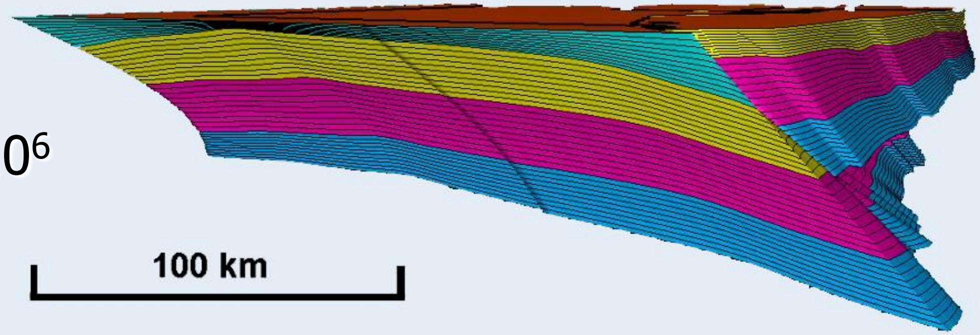


Identify six reservoirs:

- Sediments:
  - Cenozoic terrigenous units
  - Meso-Cenozoic Basinal Carbonate units
  - Mesozoic Carbonate units
  - Permian and Paleozoic clastic units
- Upper crust
- Lower crust

Output:

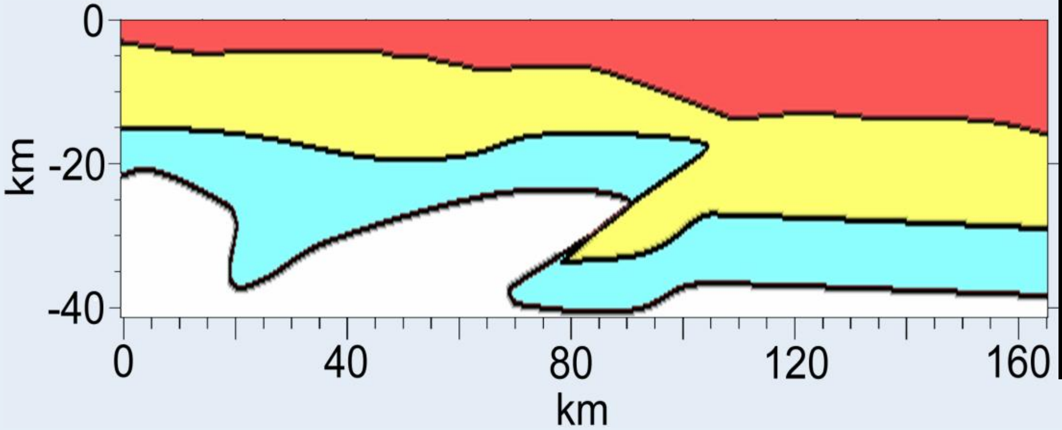
- A 3D dimensional model, built on 10^6 2 km^3 cells



The sedimentary cover of the central tile

Average thickness of different reservoirs in Reference and 3D model

(the total thickness is almost the same)



Layer	3D model, [km]	Ref. Model, [km]
Sediments	13	0.5
Upper crust	13	10
Middle crust	/	10
Lower Crust	8	10.5
Total	34	31

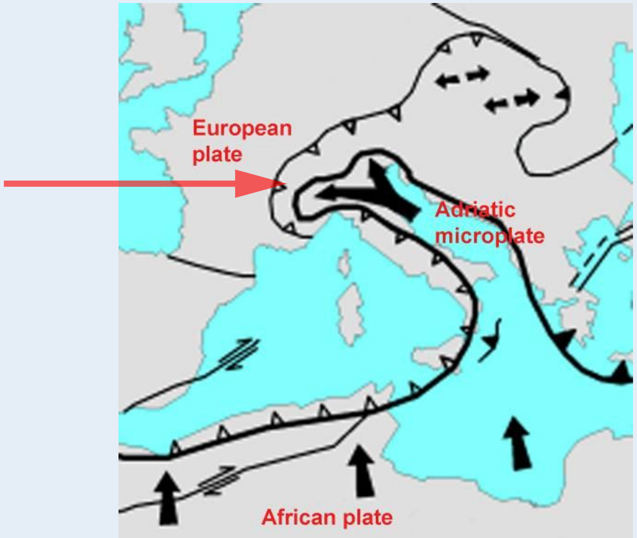
Measured U and Th content in representative samples of the sedimentary cover:

Reservoir	Volume, [%]	*a*(U), [ppm]	*a*(Th), [ppm]
Mesozoic Carbonate units	74.6	0.31 ± 0.19	0.21 ± 0.19
Cenozoic terrigenous	18.0	2.28 ± 0.62	8.31 ± 2.45
Permian and Paleozoic clastic	5.4	2.44 ± 0.70	8.76 ± 2.52
Meso-Cenozoic Basinal Carbonate	1.9	2.08 ± 1.47	1.62 ± 1.76

The total signal from the Central Tile

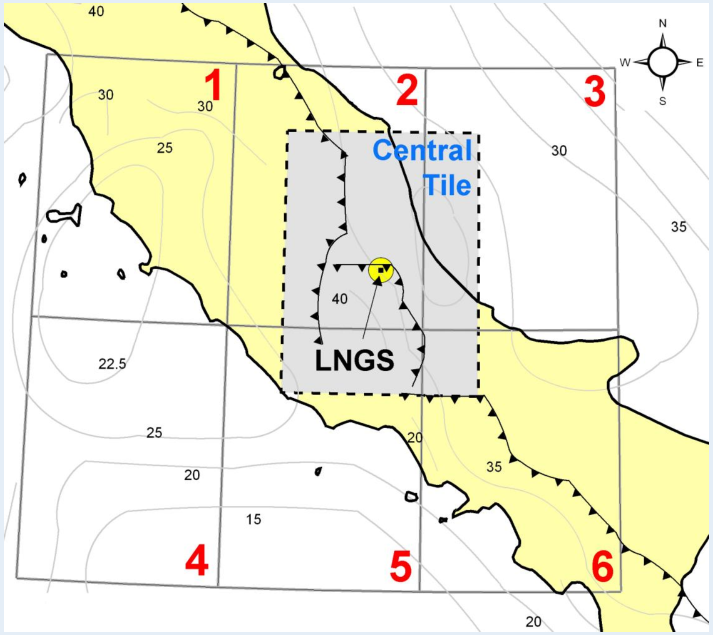
- U and Th content in the Central Tile:

Representative samples from outcropping Adriatic Crust on Western Alps and measured U and Th content



- The total geo-neutrino signal from the Central Tile at Gran Sasso:

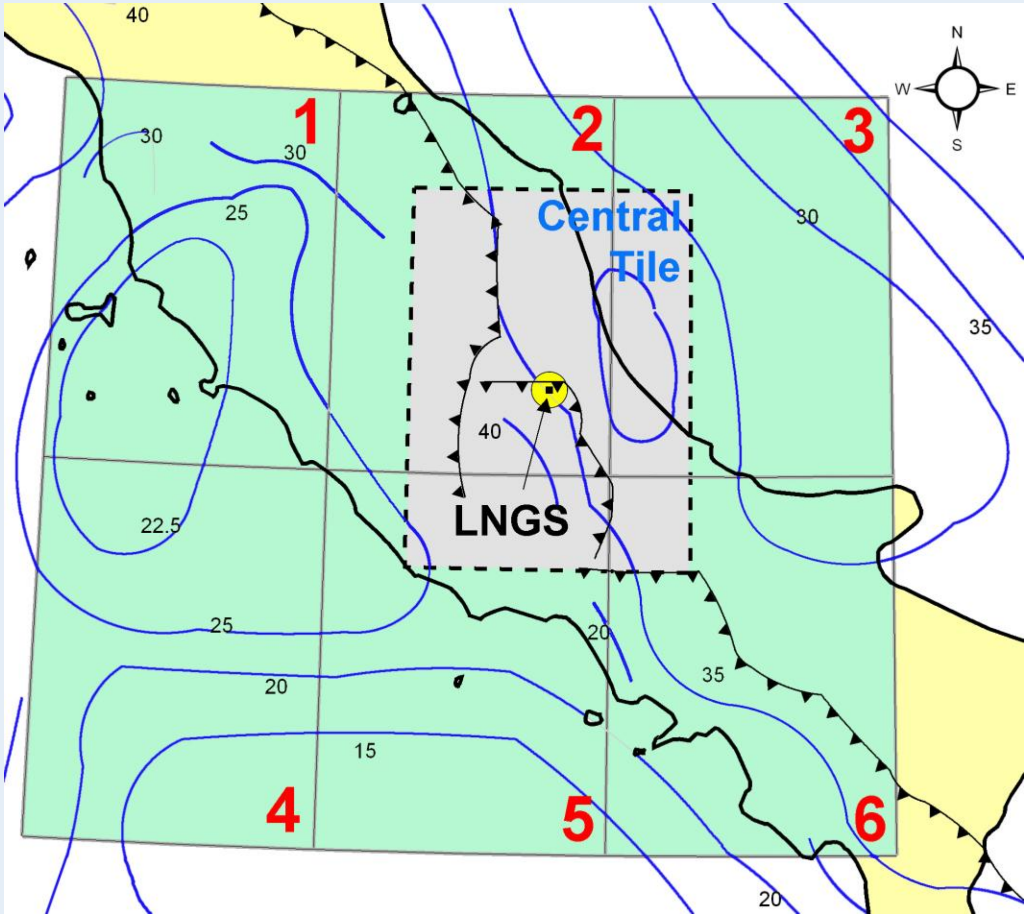
Reservoir	Signal from **Ref. Model** [TNU]	Signal from **3D model** [TNU]
Sediments	0.5	2.7
Crust	11.8	5.1
Total	**12.3**	**7.8**



The rest of the regional contribution

We consider the region out of the central tile and refine the model by using:

- Data of the main CROP seismic sections
- Depth conversion velocities of the crustal stratigraphic layers
- Detailed measurements of Moho depth



By using the deduced U and Th abundance, the signal from the refined out-region is:

S_{Out} = 2.3 TNU

To be compared with that estimated in Ref.:

S_{Out} = 3.3 TNU

Geoneutrino signal from local geology

Area and reservoir	S_{RM}(U+Th), [TNU]	S_{RRM}(U+Th), [TNU]
Central Tile, 3D Model	12.3	7.8 ↓
Rest of the regional area	3.3	2.3 ↓
Regional Contribution, total	15.6	10.0 ± 1.3 ↓

Total geoneutrino signal at LNGS

$$S_{geo}\,(\mathrm{Crust}) = S_{geo}\,(\mathrm{LOC}) + S_{geo}\,(\mathrm{ROC})$$

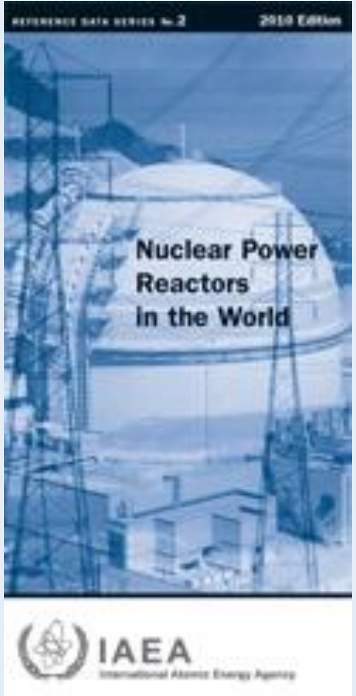
	Borexino (42.45 N, 13.57 E)		
	S(U)	S(Th)	S(U+Th)
LOC	8.1 ± 1.0	1.9 ± 0.3	10.0 ± 1.3
ROC	$10.3_{-2.2}^{+2.6}$	$3.2_{-0.7}^{+1.1}$	$13.7_{-2.3}^{+2.8}$
CLM	$1.4_{-1.0}^{+2.7}$	$0.4_{-0.3}^{+1.0}$	$2.2_{-1.3}^{+3.1}$
DM	4.1	0.8	4.9
EM	2.7	0.8	3.5
Grand Total	$34.3_{-2.9}^{+4.4}$		--

Data Source: IAEA files

- International Atomic Energy Agency

http://www.iaea.org/programmes/a2/

- On June, description and history of each core are published, referring to previous year.



2010 Edition

Nuclear Power
Reactors
in the World

IAEA

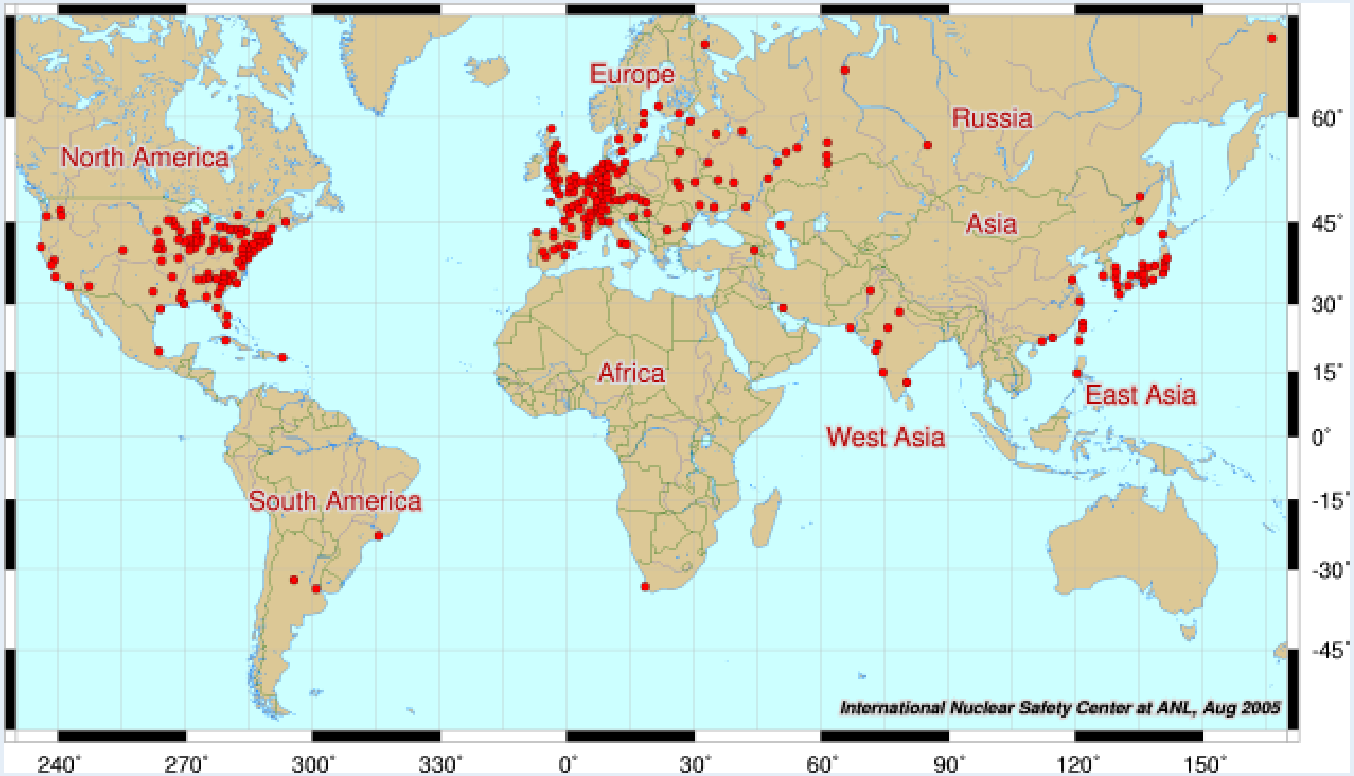
IAEA

2010 Edition

OPERATING
EXPERIENCE
WITH
NUCLEAR POWER
STATIONS
IN MEMBER STATES IN
2009

- Data on: thermal power, electrical capacity, electrical Load Factor, fuel enrichment…

Nuclear power plants in the world

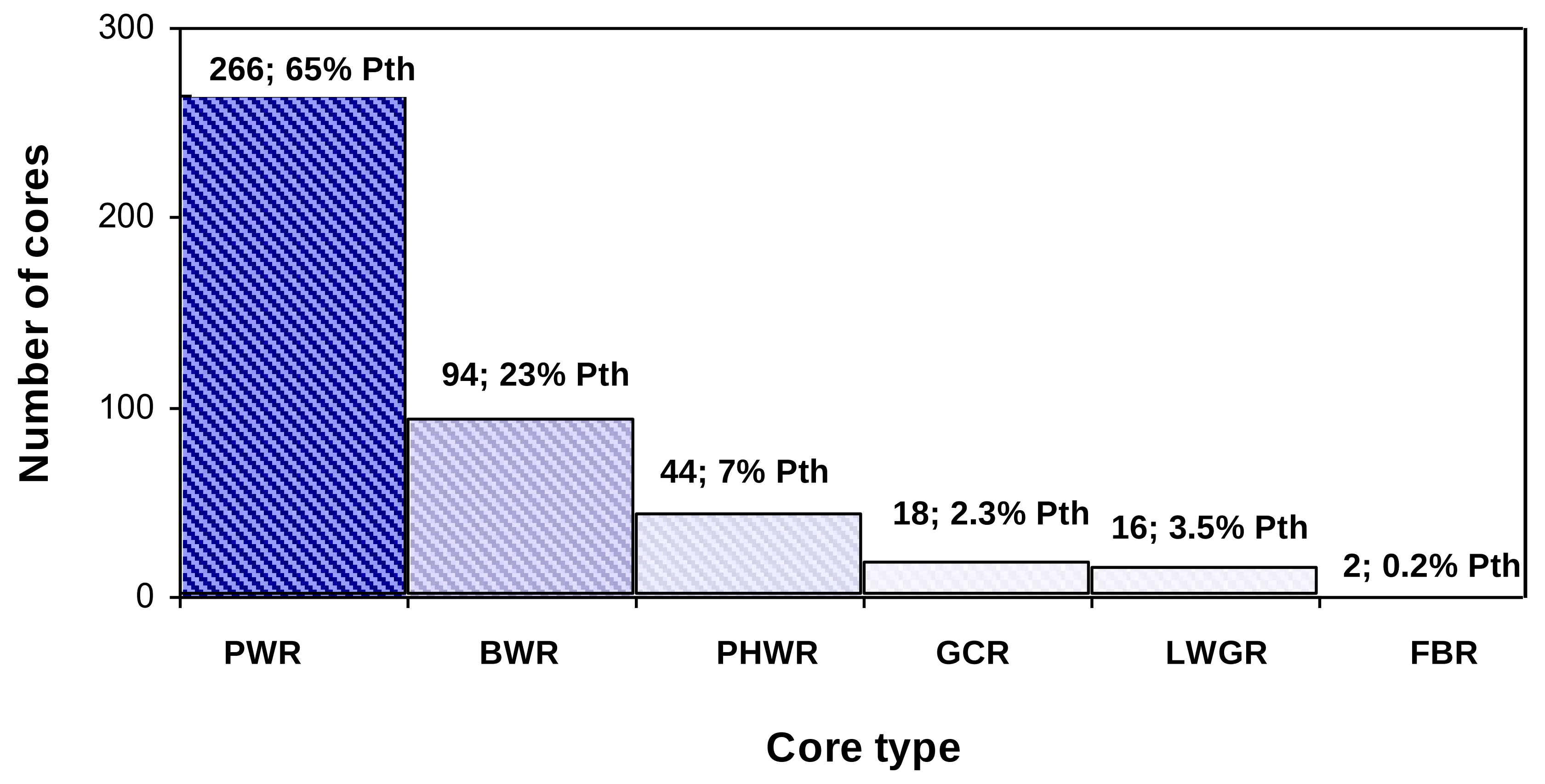


International Nuclear Safety Center at ANL, Aug 2005

	#cores	P_{th} [GW]
Europe + Russia	197	519
North America	122	353
Japan+ Korea	76	201
Others	45	75
Total:	440	1148

- Mean thermal power for core: 2.6 GWth

Reactors by type



PWR	Pressurized (light) Water Reactor
BWR	Boiling Water Reactor
PHWR	Pressurized Heavy Water Reactor (includes 47 CANDU reactors)

GCR	Gas Cooled Reactor
LWGR	Light Water Graphite mod.
FBR	Fast Breeder Reactor

Signal calculation

DETECTOR

- ε=100% detection efficiency
- τ =1 year
- N_p=10^32

ν PHYSICS

- P_{ee}= survival probability
- σ(E)= cross section
  anti-ν_e +p -> e^+ +n
  E_{th}=1.806 MeV
  (calculation from Vissani and Strumia 2003)

$$N_{TOT} = \varepsilon\ N_p\ \tau \sum_{i=1}^{N_{reactor}} \frac{P_i}{4\pi d_i^2} < LF_i >_{2009} \int dE_\nu \sum_{k=1}^{Nfuel} \frac{p_k}{Q_k}\ \lambda_k(E_\nu) P_{ee}(E_\nu, d_i)\ \sigma(E_\nu)$$

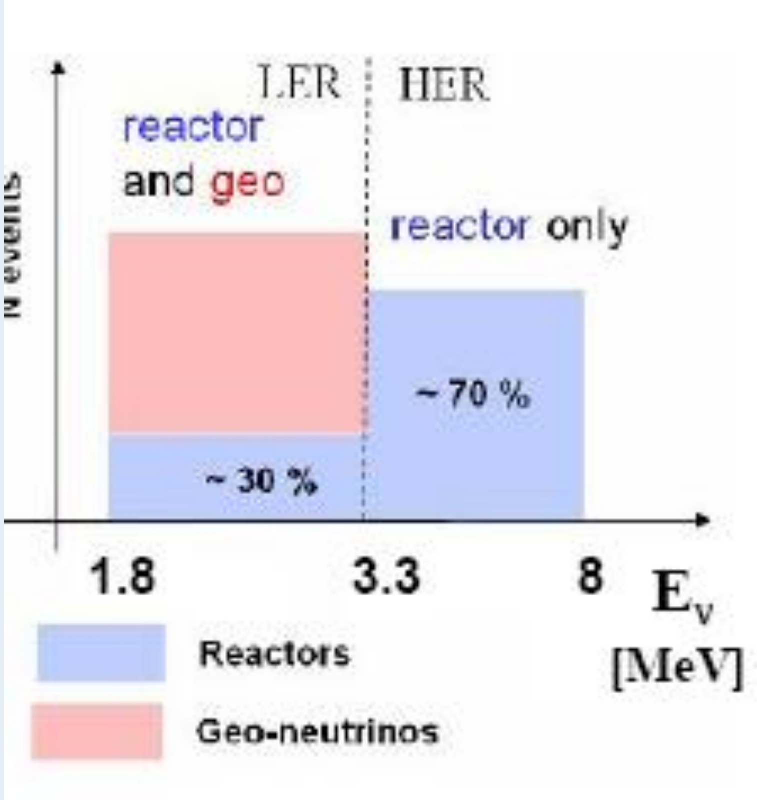
REACTOR

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

NUC. PHYS.

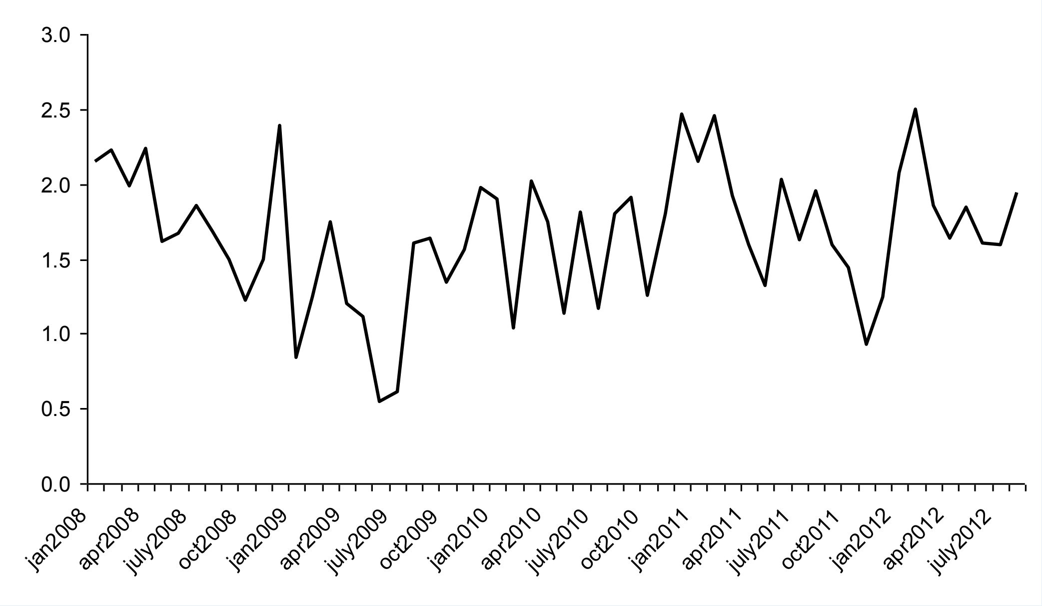
- Q_k =energy released for fission
- λ_k =reactor anti-neutrino spectrum

Reactor antineutrino signal at LNGS

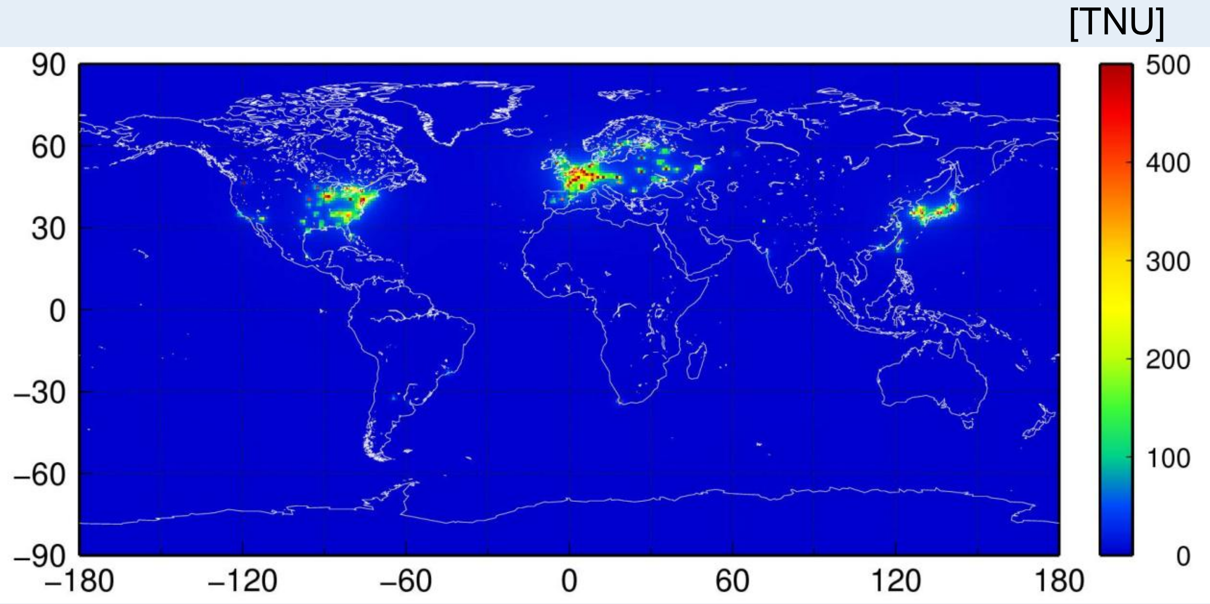


	S_{react}, TNU
LER	23.6 ± 1.2
HER	65.2 ± 3.3
Total	88.8 ± 4.4

Monthly evolution of the reactor antineutrino event rate at LNGS

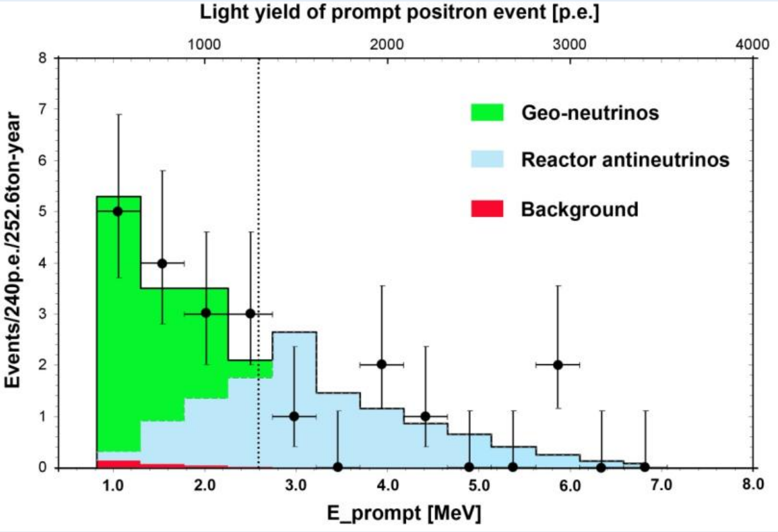


Reactor antineutrino signal in geoneutrino energy window

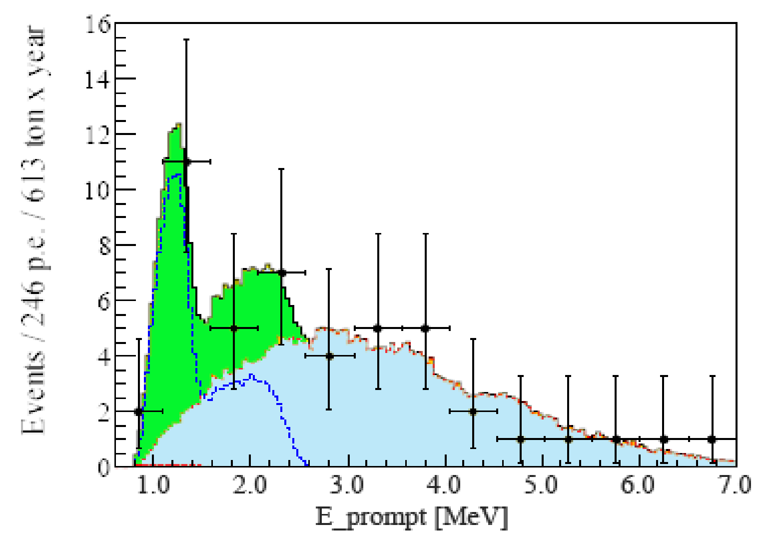


Geo-neutrino measurements by Borexino

Period	Dec. 07 – Dec. 09	
Exposure p.yr	0.15×10^{32}	
	events	TNU
Total (full sp.)	21	
Reactors	$10.7_{-3.4}^{+4.3}$	64_{-22}^{+26}
Geo-n	$9.9_{-3.4}^{+4.1}$	69_{-22}^{+28}
Background	$0.4_{-0.05}^{+0.05}$	

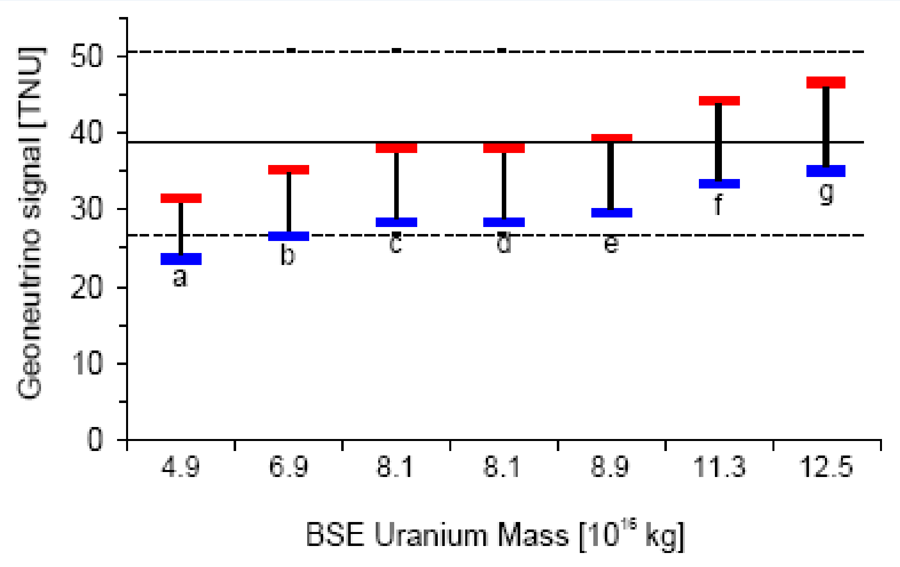


Period	Dec. 02 – Aug. 12	
Exposure p.yr.	0.37×10^{32}	
	events	TNU
Total (full sp.)	46	
Reactors	$31.2_{-6.1}^{+7.0}$	$84.5_{-16.9}^{+19.3}$
Geo-nu	14.3 ± 4.4	38.8 ± 12
Background	0.70 ± 0.18	



* Bellini et al. Physics Letters B 687, 2010; Bellini et al. arXiv:1303.2571, 2013.

Borexino (2013): geological implications



Geoneutrino signal S_{geo} in Borexino (solid line) 1σ uncertainty (dashed lines) S_{geo}(LOC + ROC+mantle) according to RRM and seven BSE models:

a) Javoy et al. 2010

b) Lyubetskaya and Korenaga 2007

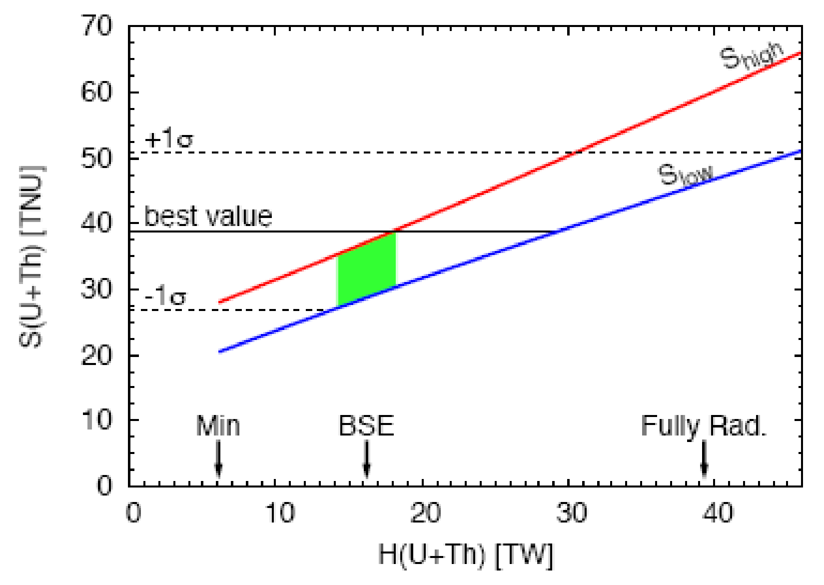
c) McDonough and Sun 1995

d) Allegre et al. 1995

e) Palme and O'Neil 2004

f) Anderson 2007

g) Turcotte and Schubert 2002



🟩 region allowed by BSE $m(U) = 0.8 \cdot 10^{17}$ kg [McDonough and Sun, 1995], region between lines contains all models consistent with geochemical and geophysical data

Conclusions

1) With the aim of estimation of the total geoneutrino signal at Borexino and its associated uncertainties the detailed global and local models of crust were developed.

2) The geoneutrino signal at Borexino for the new reference Earth model was calculated: $S_{\mathrm{geo}\text{-}\nu} = 34.3^{+4.4}_{-2.9}$ TNU

3) For the first time thickness of crust was evaluated from 3 different geological models, abundances in the middle and lower continental crust were calculated by using seismic arguments, continental lithospheric mantle is treated as a separate geochemical reservoir.

4) The antineutrino background from nuclear reactors was examined. Operating experience of all commercial nuclear reactors in the last four years was collected. Different power fractions for 3 main types of reactor’s fuel burn cycles were considered.

Written articles

1. Y. Huang, V. Chubakov, F. Mantovani, R. L. Rudnick, W. F. McDonough . A reference Earth model for the heat producing elements and associated geoneutrino flux. Geochem. Geophys. Geosyst. 2013.
2. Borexino Collaboration. Lifetime measurements of ^{214}Po and ^{212}Po with the CTF liquid scintillator detector at LNGS. Physical Review C, 2012.
3. M. Coltorti, R. Boraso, F. Mantovani, M. Morsilli, G. Fiorentini, A. Riva, G. Rusciadelli, R. Tassinari, C. Tomei, G. Di Carlo, V. Chubakov. U and Th content in the Central Apennines continental crust: a contribution to the determination of the geo-neutrinos flux at LNGS. Geochimica et Cosmochimica Acta vol. 75, n. 9, 2271-2294, 2011.
4. G. Fiorentini, V. Chubakov, F. Mantovani, B. Ricci. Radiogenic contribution to Earth’s heat flow studied throught geo-neutrinos. XIV International Workshop on “Neutrino Telescopes”. 15-18 March 2011, Venice.
5. G. Fiorentini, M. Lissia,F. Mantovani, V. Chubakov. Geo-neutrinos and radiogenic contribution to Earth’s heat flow, AIP Conference Proceedings, 2010.

THANK YOU FOR YOUR ATTENTION

Participation in the conferences

1. The XXV International Conference on Neutrino Physics and Astrophysics
   3-9 June 2012 (Neutrino) – Kyoto (Japan).
   Title: Reactor antineutrinos in the world.
2. 12th International Conference on Topics in Astroparticle and Underground Physics
   5-9 September 2011 (TAUP) – Munich (Germany).
   Title: Towards a refined reference Earth model for geo-neutrinos.
3. Center for Theoretical Underground Physics and Related Areas
   21 June 2011 (CETUP) – Dakota State University – South Dakota (US).
   Title: Geoneutrinos: Global Crust Model and LNGS Study.
4. Carpathian Summer School of Physics 2010
   20 June – 3 July, 2010, Sinaia, Romania.
5. International Neutrino Summer School 2010
   23-31 August, 2010, Yokohama, Japan
6. 89^0 Congresso SIMP: L'evoluzione del sistema terra dagli atomi ai vulcani
   13-15 September 2010, Ferrara, Italy
7. IV International Neutrino Geoscience 2010 Conference
   6-8 October, 2010, Laboratori Nazionali del Gran Sasso, Italy

THANK YOU FOR YOUR ATTENTION