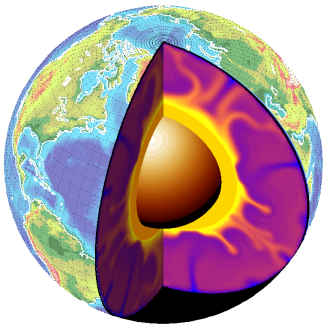
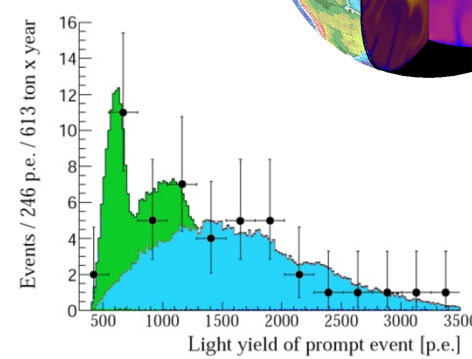
Anti-neutrinos from the Earth: status and perspectives

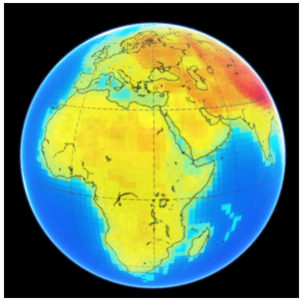
B. Ricci
Dept. of Physics and Earth Science and INFN-Ferrara
Neutrino Telescopes, Venice 2-6 March 2015



Summary:

- ✓ Antineutrinos from the Earth: what are they?
- ✓ How can we measure them ?
- ✓ KamLAND and Borexino results and geological implications
- ✓ Geoneutrinos prediction
- ✓ What's next



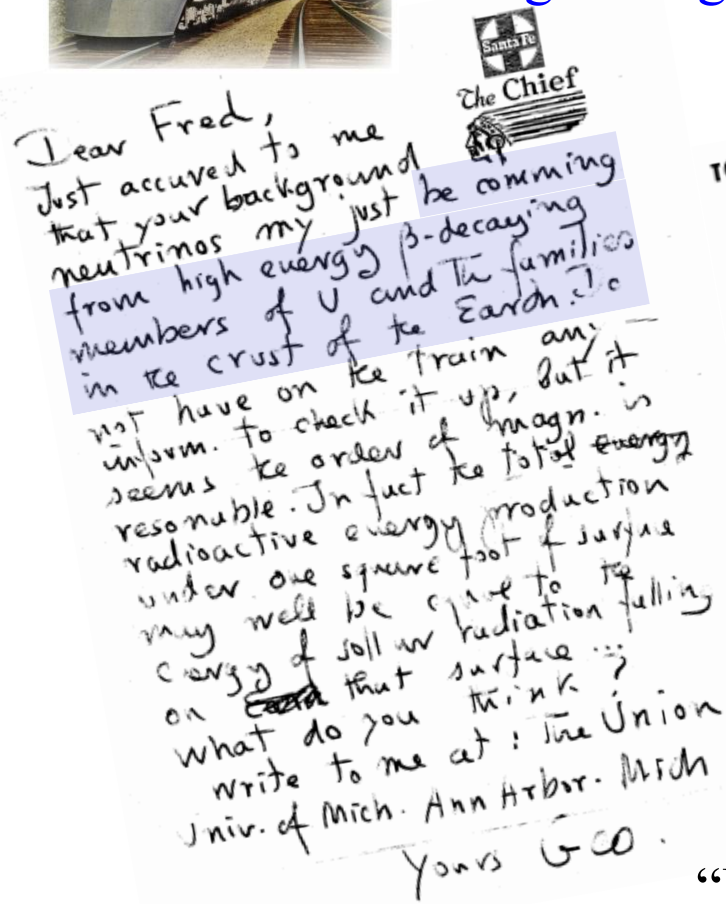


Thanks to: F. Mantovani, G. Fiorentini, M. Baldoncini, V. Strati, G. Xhixa, I. Callegari

POSTER

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

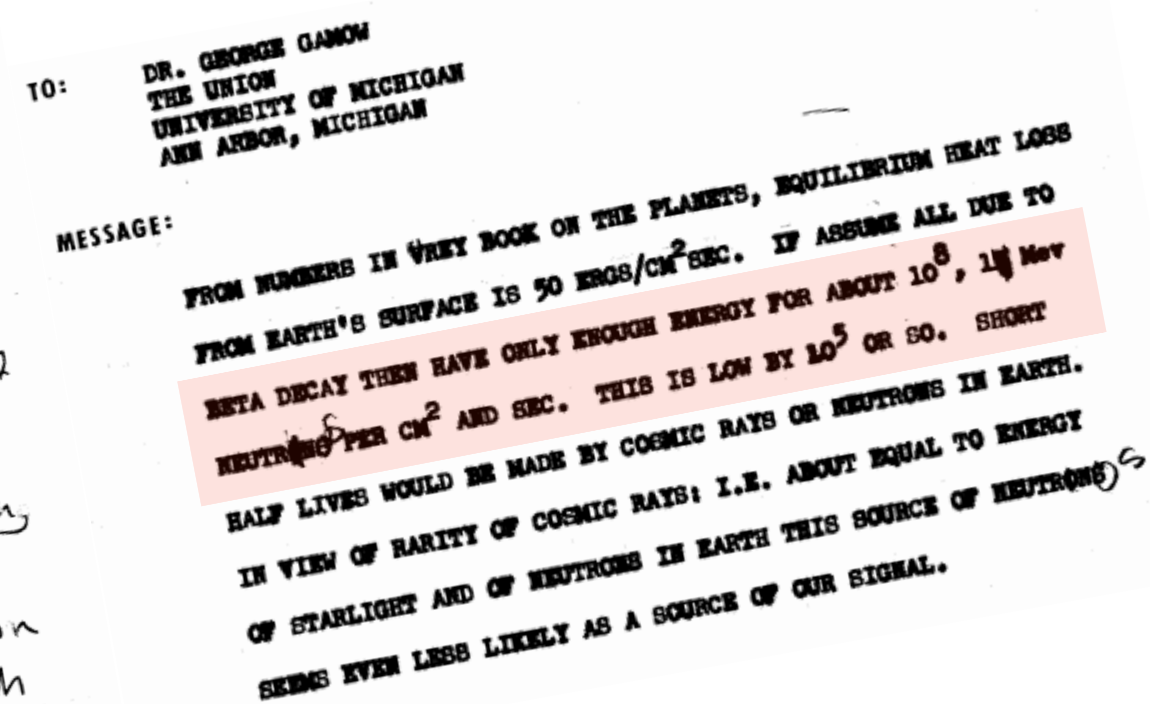
In 1953 G. Gamow wrote to F. Reines: “It just occurred to me that your background may just be coming from high energy beta-decaying members of U and Th families in the crust of the Earth.”



Santa Fe

The Chief

Dear Fred,
Just accured to me
that your background
neutrinos my just be comming
from high energy β-decaying
members of U and Th families
in the crust of the Earth. 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~~ energy
radioactive energy production
under one square foot of surface
may well be equal to the
energy of sollar 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 10^5 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 NEUTRONS 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.”

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	$T_{1/2}$ $[10^9\ \mathrm{yr}]$	$E_{\max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar\nu}$ $[\mathrm{kg}^{-1}\mathrm{s}^{-1}]$	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}

Review paper: *Fiorentini et al. – Phys. Rep. 453, 117 (2007)*

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

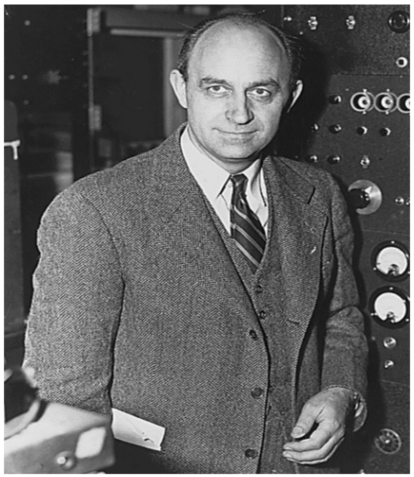
- A fraction of geo-neutrinos from U and Th (not from ^{40}K) are above threshold for inverse β on protons: $\bar\nu + p \to e^+ + n - 1.8\ \mathrm{MeV}$

- Geoneutrinos originating from U and Th can be distinguished through their energy spectra : e. g. anti-ν with highest energy are from Uranium (E_{max}=3.3 MeV)

1 TNU = one event / 10^{32} free protons / year

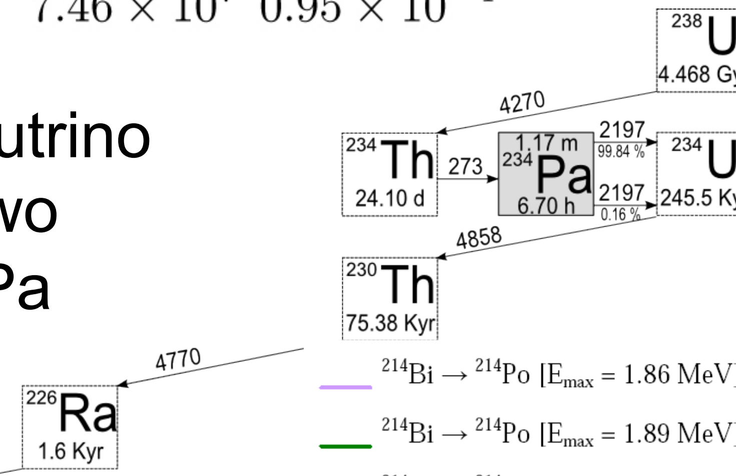
U decay chain and geo-neutrino spectra

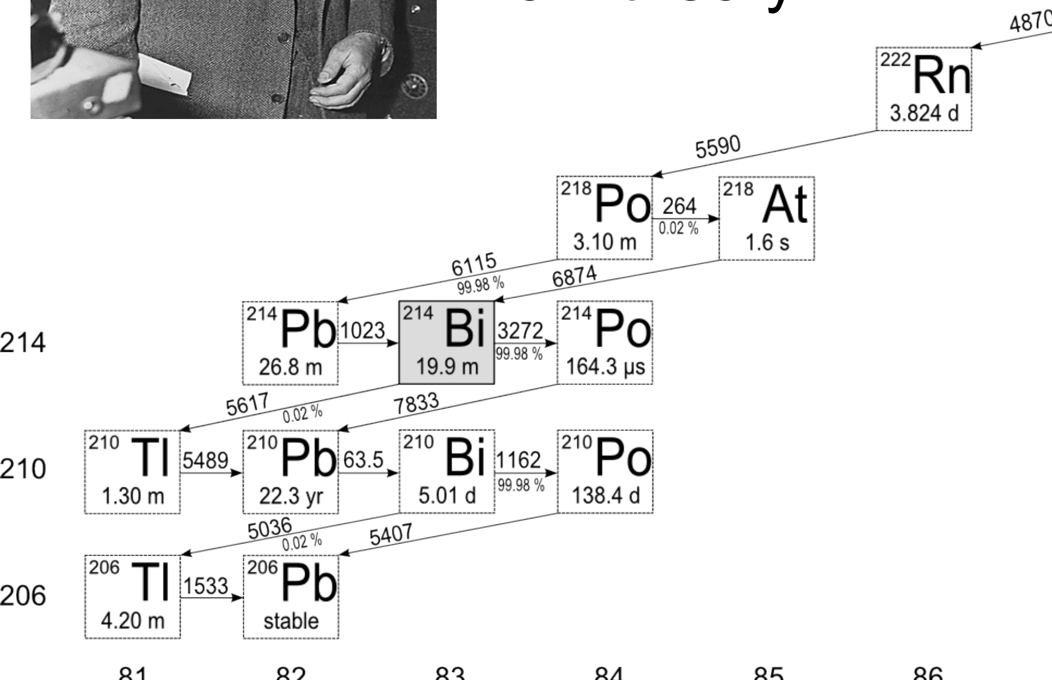
Decay	$T_{1/2}$ [10^9 yr]	$E_{\max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$\mathrm{kg}^{-1}\mathrm{s}^{-1}$]	ε_H [W/kg]
$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,{}^{4}\mathrm{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^{7}	0.95×10^{-4}

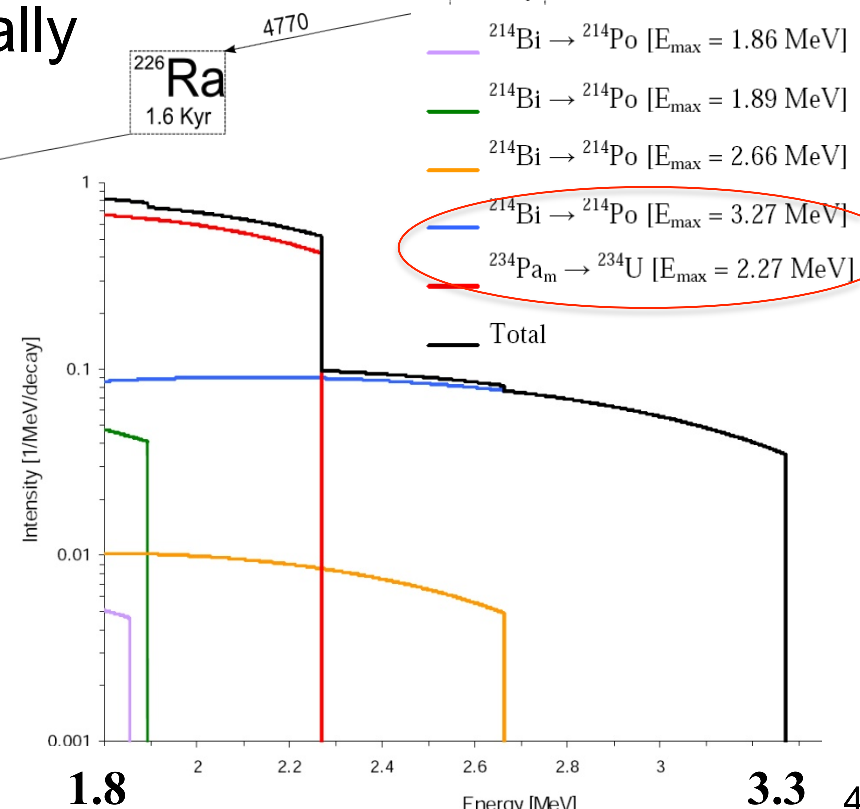


-98% of uranium geo-neutrino signal comes from just two transitions: ^{214}Bi and ^{234}Pa

-spectrum is essentially from theory

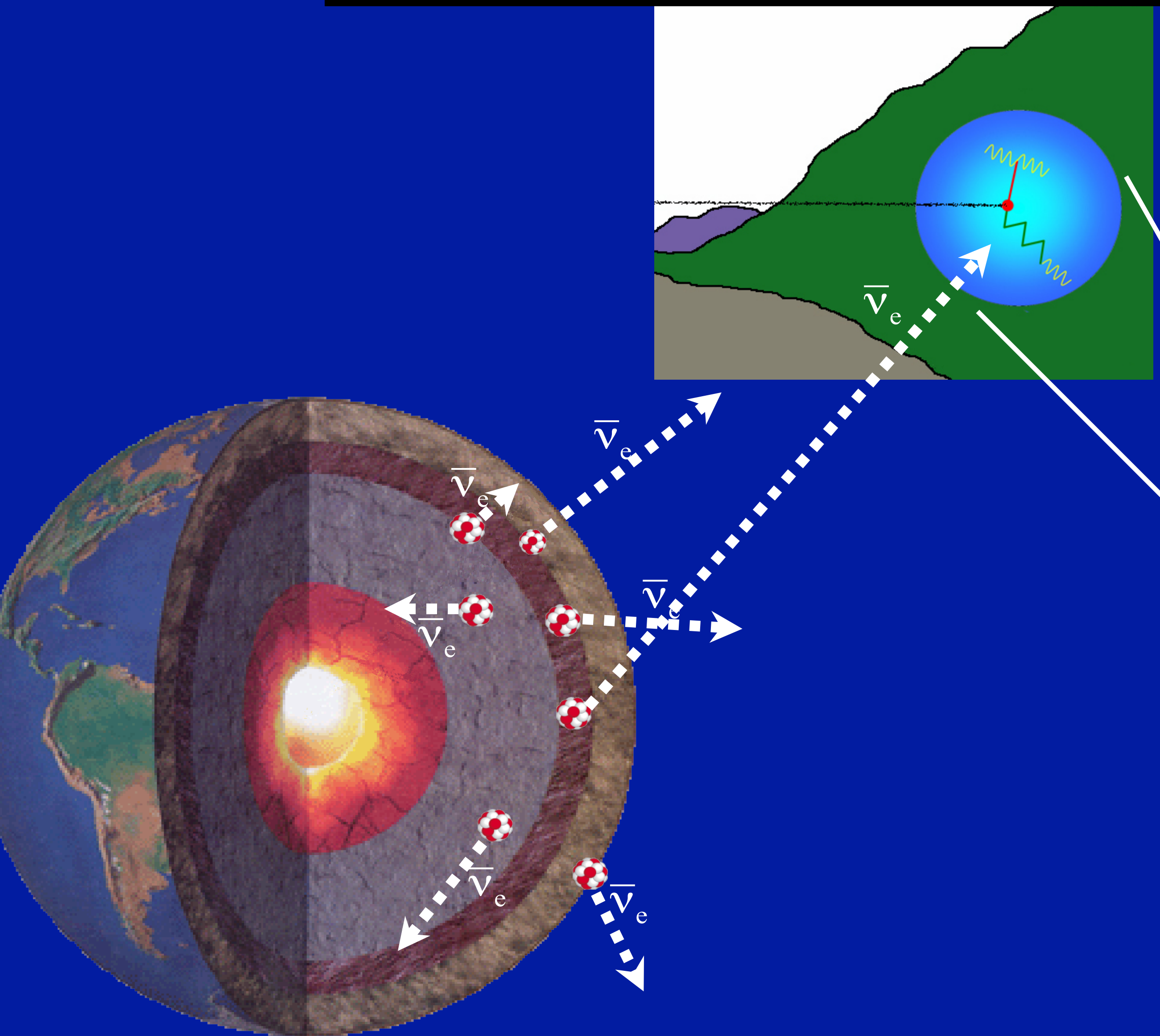






Detection of antineutrinos from Earth

$$\bar{\nu}_e + p \rightarrow n + e^+ - 1.8\ \mathrm{MeV}$$



KamLAND (Japan)

1 kTon LS – t_0 = 2002

Borexino (Italy)

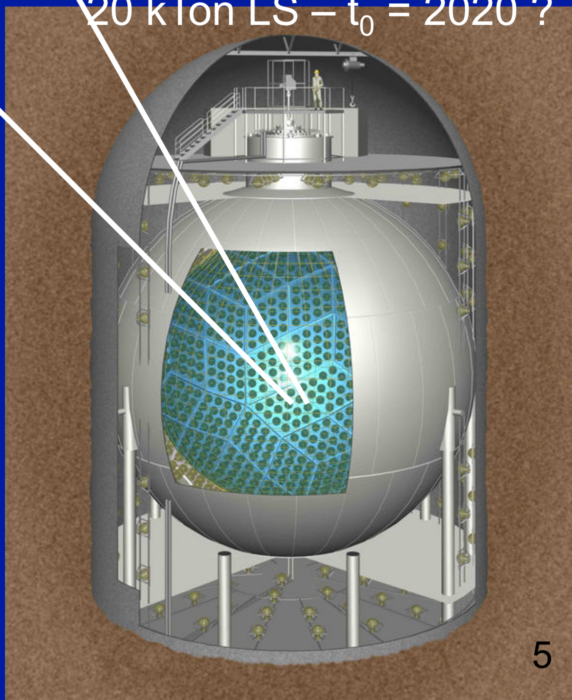
0.3 kTon LS – t_0 = 2007

SNO+ (Canada)

1 kTon LS – t_0 = 2015 ?

JUNO (China)

20 kTon LS – t_0 = 2020 ?



Detection of antineutrinos from Earth

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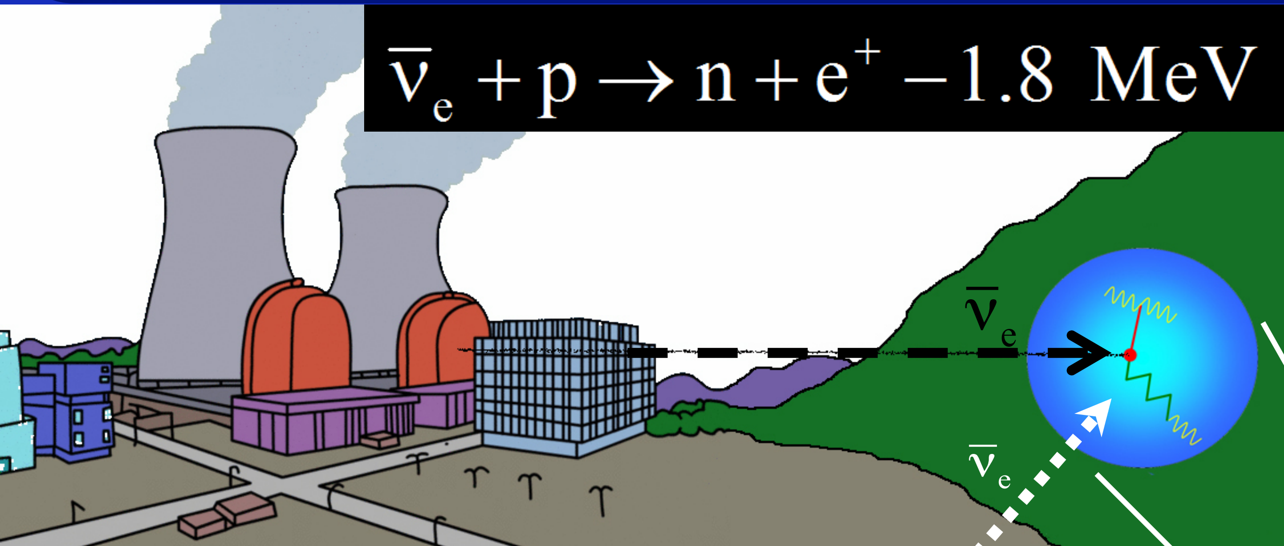

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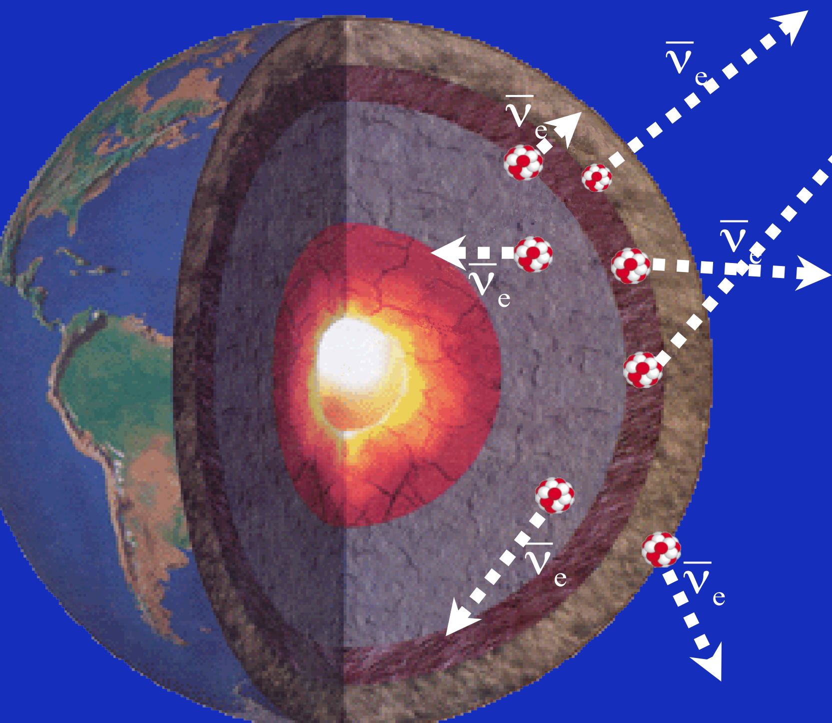
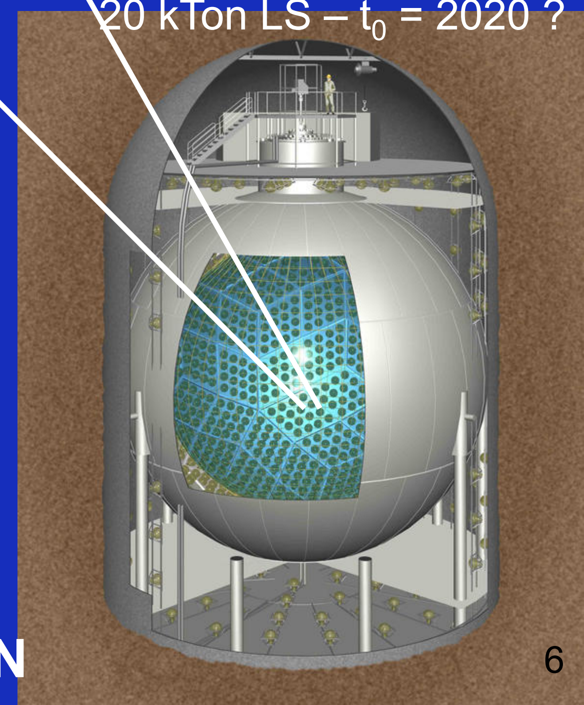
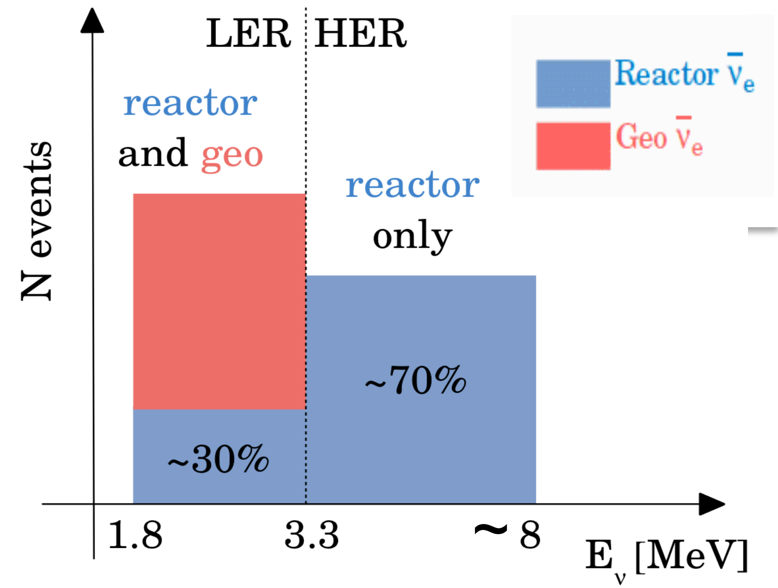


REACTOR ANTI NEUTRINOS ARE THE MOST IMPORTANT SOURCE OF BACKGROUND IN GEONU DETECTION

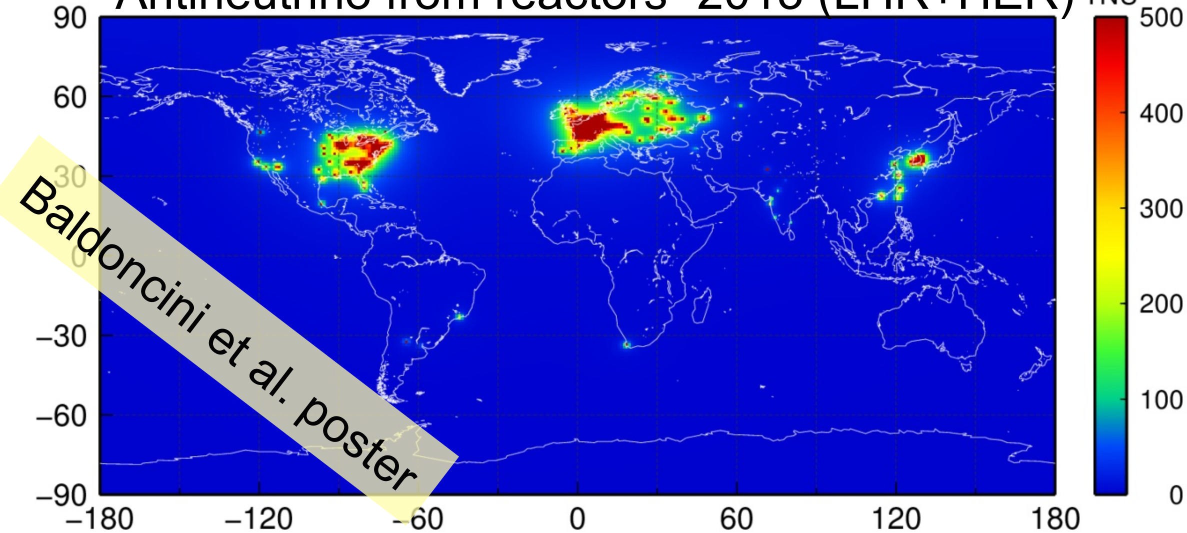


Antineutrinos from reactors

- Reactor antinu and geonu spectra are partially overlapped
- R signal in the HER is crucial for modeling the reactor contribution in the LER, and therefore for extracting information on geoneutrinos.
- Reactor antinu signal calculation requires several ingredients (production, propagation and detection)



Antineutrino from reactors -2013 (LHR+HER)

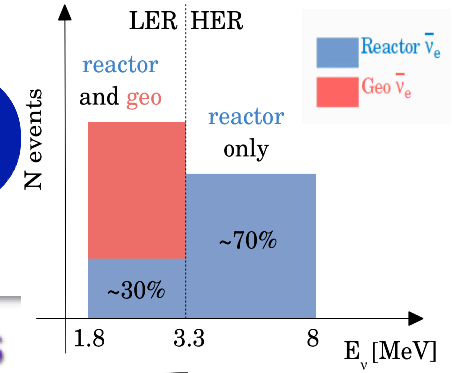


- R signal changes according to the different reactor operational conditions (IAEA-PRIS)
- A worldwide map* of reactor antinu signal using updated data
- Total uncertainty is ~ **3%** (main from $\mathbf{sen^2\theta_{12}}$)

*Baldoncini et al. arXiv:1411.6475

Baldoncini et al. poster

A group shot…



Reactor anti-ν and geo-ν at different sites

R_{FER} = total reactor anti-ν_e signal

R_{LER} = reactor anti-ν_e signal in the geo-ν energy window (LER)

G = geo-ν signal

SITE	EXPERIMENT	R [TNU]	R_{LER} [TNU]	G [TNU][7]	R_{LER}/G
LNGS	BOREXINO	$83.3^{+2.0}_{-1.9}$	$22.2^{+0.6}_{-0.6}$	$40.3^{+7.3}_{-5.8}$	0.6
KAMIOKA	KAMLAND	$65.3^{+1.7}_{-1.6}$	$18.3^{+0.6}_{-1.0}$	$31.5^{+4.9}_{-4.1}$	0.6
		$625.9^{+14.5}_{-13.2}$ [a]	$168.5^{+5.7}_{-6.3}$ [a]		5.3
SUDBURY	SNO+	$190.9^{+4.6}_{-4.2}$	$47.8^{+1.7}_{-1.4}$	$45.4^{+7.5}_{-6.3}$	1.1
DONGKENG	JUNO	$95.3^{+2.6}_{-2.4}$	$26.0^{+2.2}_{-2.3}$	$39.7^{+6.5}_{-5.2}$	0.7
		1566^{+111}_{-100} [b]	$354.5^{+44.5}_{-40.6}$ [b]		8.9
GUEMSEONG	RENO-50	1128^{+75}_{-67}	$178.4^{+20.8}_{-19.6}$	$38.3^{+6.1}_{-4.9}$	4.7
HAWAII	HANOHANO	$3.4^{+0.1}_{-0.1}$	$0.9^{+0.02}_{-0.02}$	$12.0^{+0.7}_{-0.6}$	0.1
PYHÄSALMI	LENA	$66.1^{+1.6}_{-1.5}$	$17.0^{+0.5}_{-0.4}$	$45.5^{+6.9}_{-5.9}$	0.4
HOMESTAKE	/	$30.4^{+0.7}_{-0.7}$	$8.0^{+0.2}_{-0.2}$	$48.7^{+8.3}_{-6.9}$	0.2

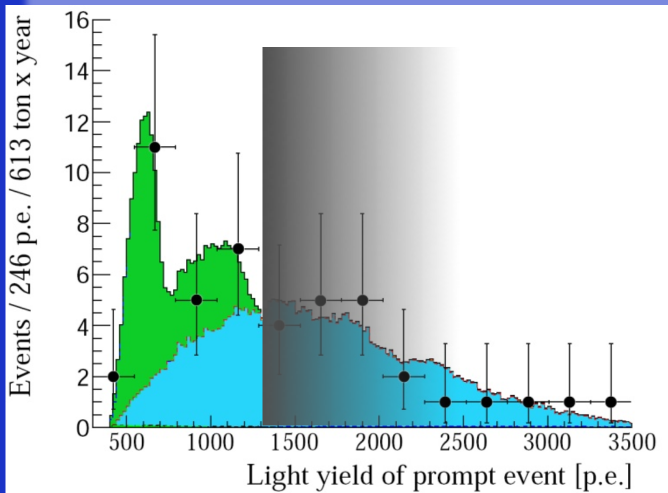
[a] 2006 reactor operational data

[b] 2013 reactor operational data plus Yangjiang (17.4 GW) and Taishan (18.4 GW) nuclear power stations operating with a 80% average annual load factor.

Baldoncini et al. arXiv:1411.6475

www.fe.infn.it/antineutrino

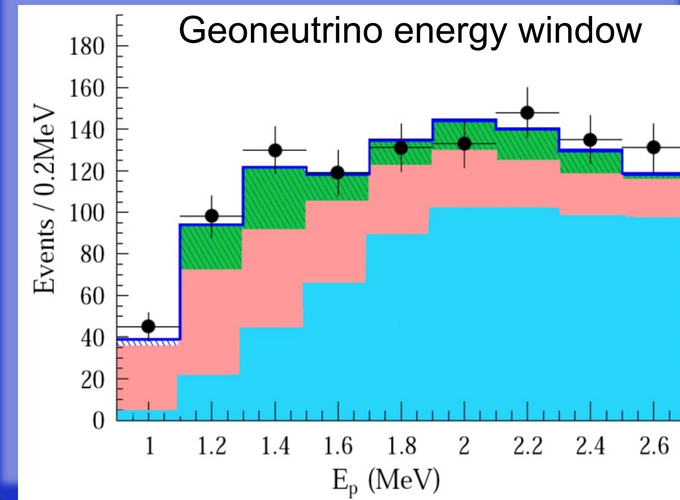
Borexino and KamLAND results



Geoneutrinos

Background

Reactor antineutrinos



Borexino

- Period: 2007 – 2012
- Geo-ν events: 14^{+4}_{-4}
- Signal: 39 ± 12 TNU

KamLAND

- Period: 2002 – 2012
- Geo-ν events: 116^{+28}_{-27}
- Signal: 30 ± 7 TNU

* arXiv:1303.2571v2
Borexino collaboration - Physics Letters B 722 (2013)

** arXiv:1303.4667v2
KamLAND collaboration - Phys. Rev. D 88 (2013)

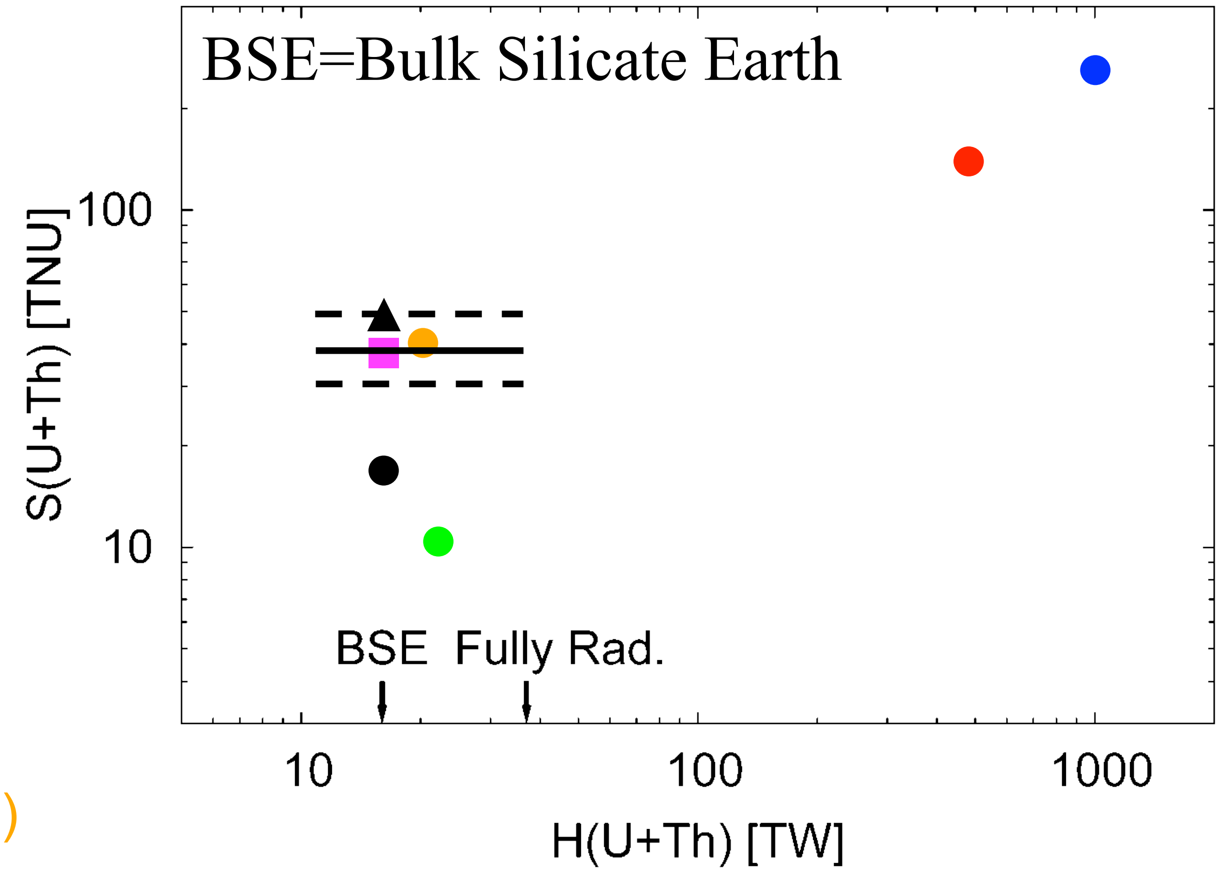
Geoneutrino signal: an historical perspective

Models assuming uniform U distribution in the Earth:

- Eder (Nucl. Phys. 1966)
- Marx (Cz. J. Phys 1969)
- Kobayashi (GRL 1991)

Model with an uniform distribution of U in the continental crust:

- Krauss et al. (Nature 1984)



BSE model with different U distribution between crust and mantle:

- Rothschild et al. (1998)
- ▲ Raghavan et al. (1998)

■ 2° x 2° crustal model with BSE constraint (papers after 2004)

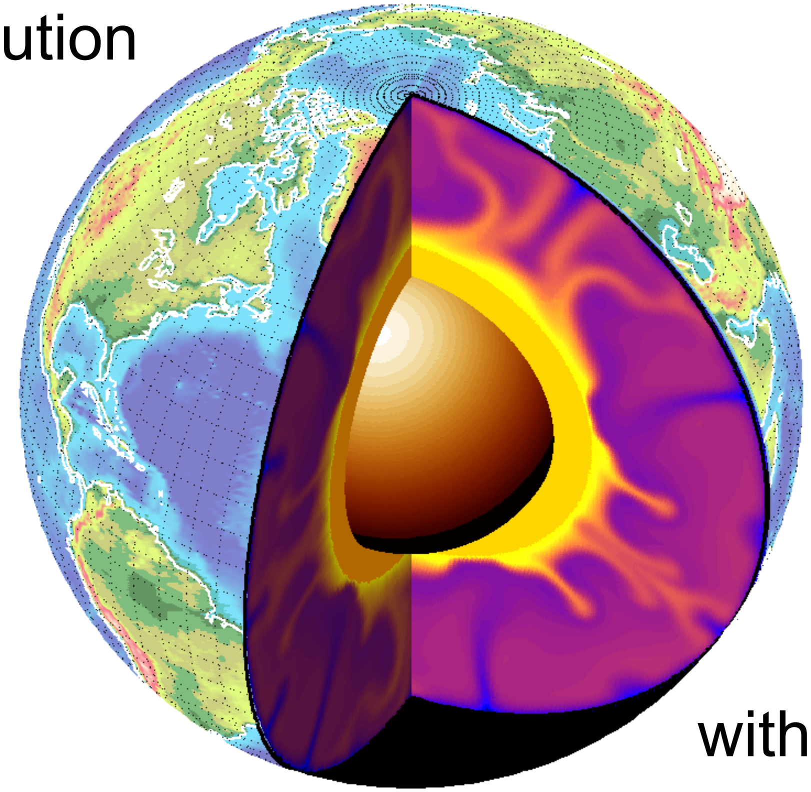
KamLAND and Borexino measurements

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?

3 - How much U and Th in the mantle?



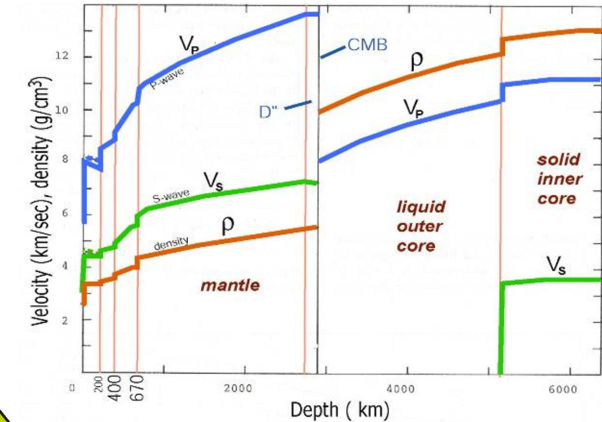
4 - What is hidden in the Earth's core? (geo-reactor, ^{40}K, …)

5 - Is the standard geochemical model (BSE) consistent with geo-neutrino data?

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

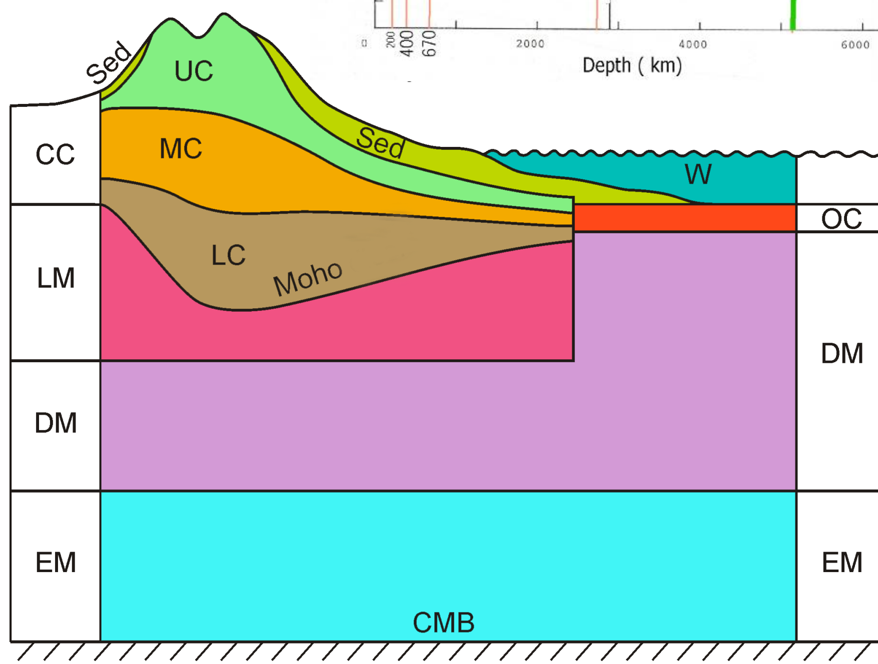
Terra Incognita

- Deepest hole is about 12 km
- Samples from the crust (and the upper portion of mantle) are available for geochemical analysis.
- Seismology reconstructs density profile (not composition) throughout all Earth.



Recent novelties*:

- a refined geophysical structure of Continental Crust and new compilations of geochemical data
- a new approach for evaluating the composition of Middle Crust and Lower Cr.
- the contributions from Lithospheric Mantle and from 3 classes of BSE compositional models (cosmochemical, geochemical and geodynamical)

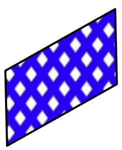


* Sràmek et al. 2012 + Huang et al. 2013

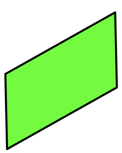
KL and BX results and radiogenic heat

In the plane (S,H), a region containing all models consistent with geochemical and geophysical data can be defined:

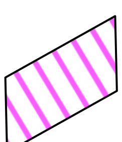
- ✓ the "slope" is universal
- ✓ the intercept depends on the site
- ✓ the width depends on the site (crust effect)



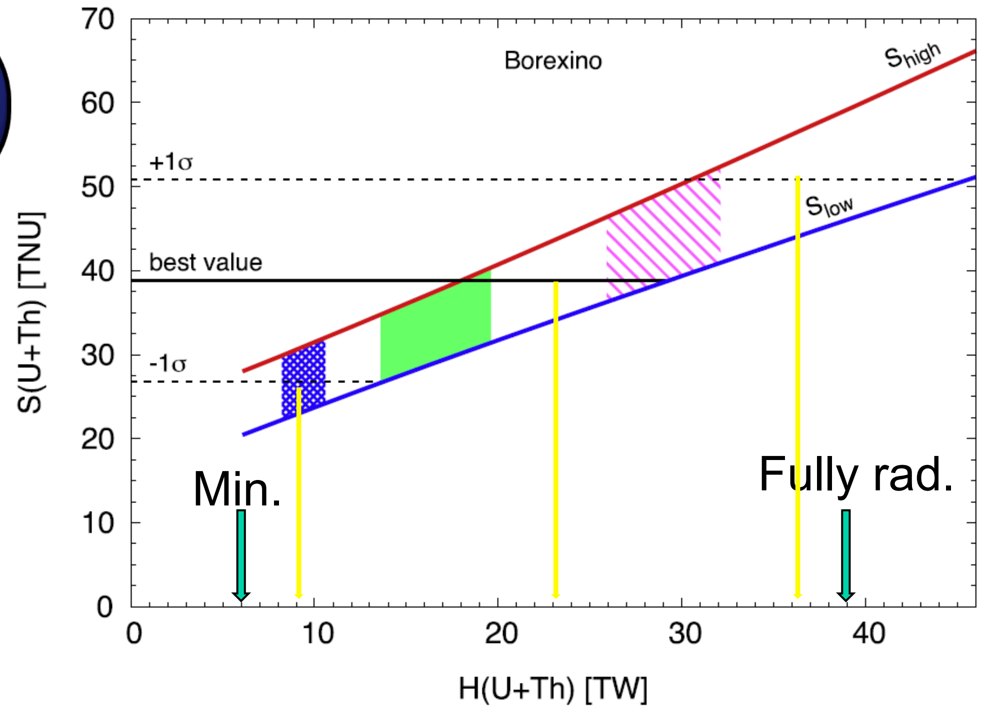
Cosmochemical BSE models:
$m_{PRIM}(U) = 0.5 \pm 0.1\ 10^{17}$ kg
Th/U = 3.5

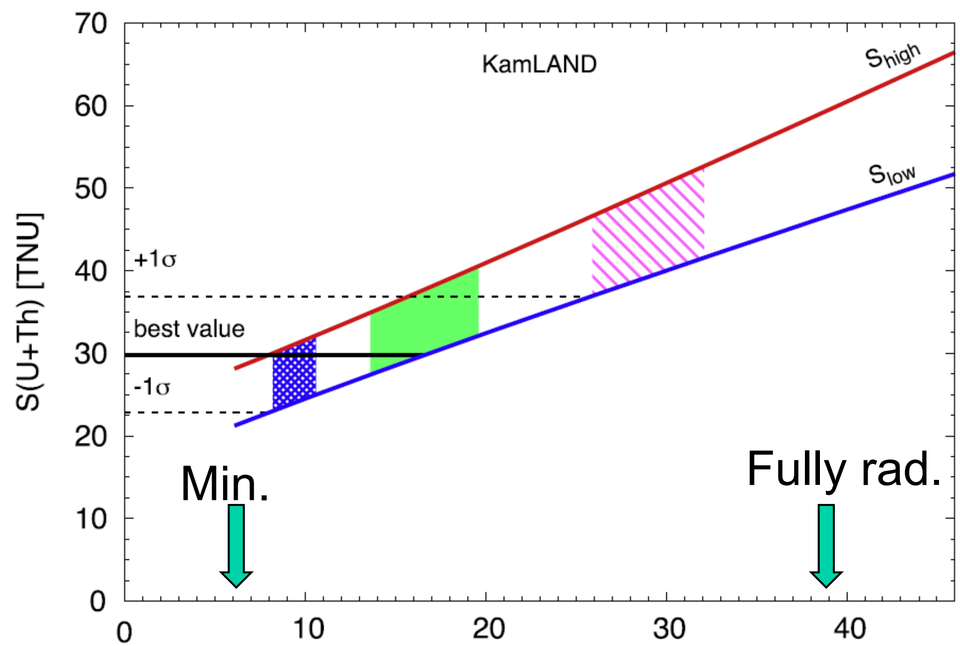


Geochemical BSE models:
$m_{PRIM}(U) = 0.8 \pm 0.2\ 10^{17}$ kg
Th/U = 4



Geodynamical BSE models:
$m_{PRIM}(U) = 1.4 \pm 0.2\ 10^{17}$ kg
Th/U = 4





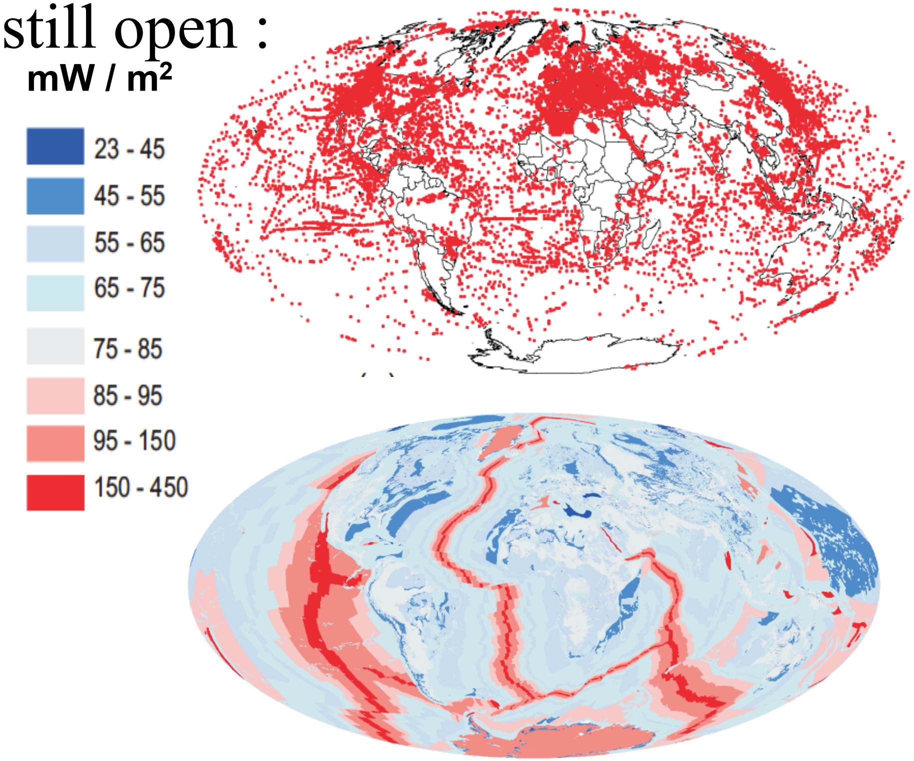
* Bellini et al 2013 – arXiv:1310.3732

Implications of KL and BX on terrestrial radiogenic heat

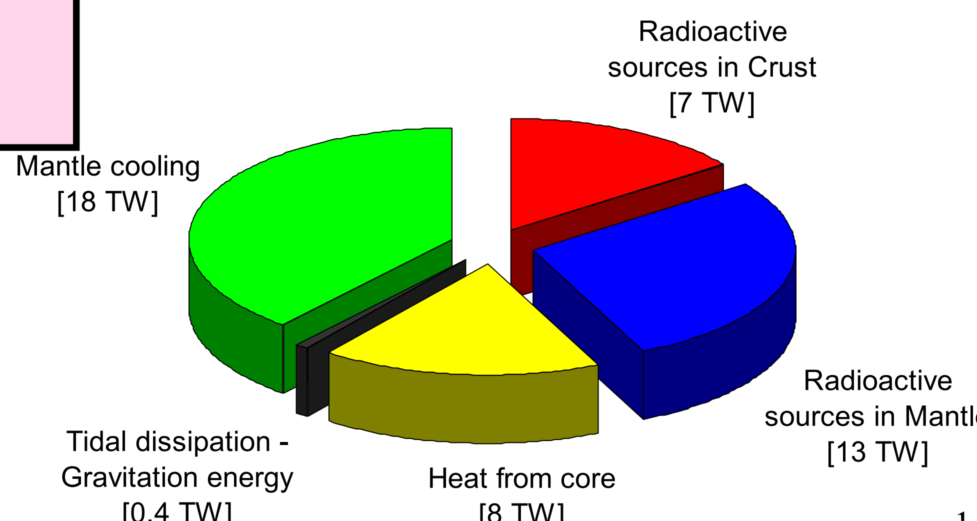
-Debate about the terrestrial heat flow still open :

	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
Davies and Davies [2010]	47 ± 2

- New results based on ~40.000 measurements in deep bore-holes (55% more than used in previous estimates)
- Heat loss through the sea floor is estimated by half space model.

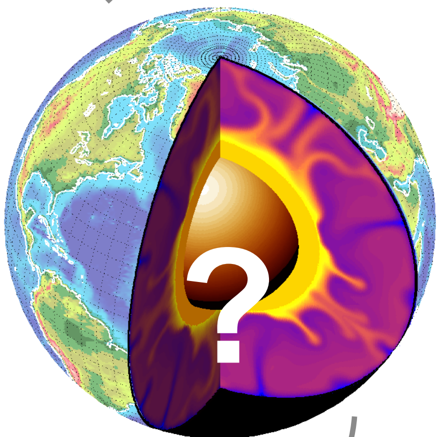


	H(U+Th) [TW]*
KamLAND	13 ± 9
Borexino	23 ± 14



* Bellini et al 2013 - Prog Part Nucl Phys - arXiv:1310.3732

How to look into the deep Earth?



- If one wants to extract the global information brought in by geo-ν's, the contribution from regional geology (~500x500 km^2) and crust has to be controlled.
- For each element (U, Th) the expected geo-neutrino signal S in one site on the Earth's surface is the sum of three contributions:

$$S_{Expected} = S_{LOCal} + S_{Far\ Field\ Crust} + S_{Mantle}$$

$$S_{Mantle} = S_{Measured} - (S_{LOCal} + S_{Far\ Field\ Crust})$$

Fiorentini et al. – 2012 – Physical Review D 86, 033004

Multi-site “view” of the mantle

$$S_{LOCal} + S_{Far\ Field\ Crust} = S_{Crust}$$

	LOC [TNU][1]	FFC [TNU][2]	Crust total [TNU]
KamLAND	17.7 ± 1.4	7.3 ± 1.4	25.0 ± 2.0
Borexino	9.7 ± 1.3	13.7 ± 2.5	23.4 ± 2.8

$$S_{Measured} - S_{Crust} = S_{Mantle}$$

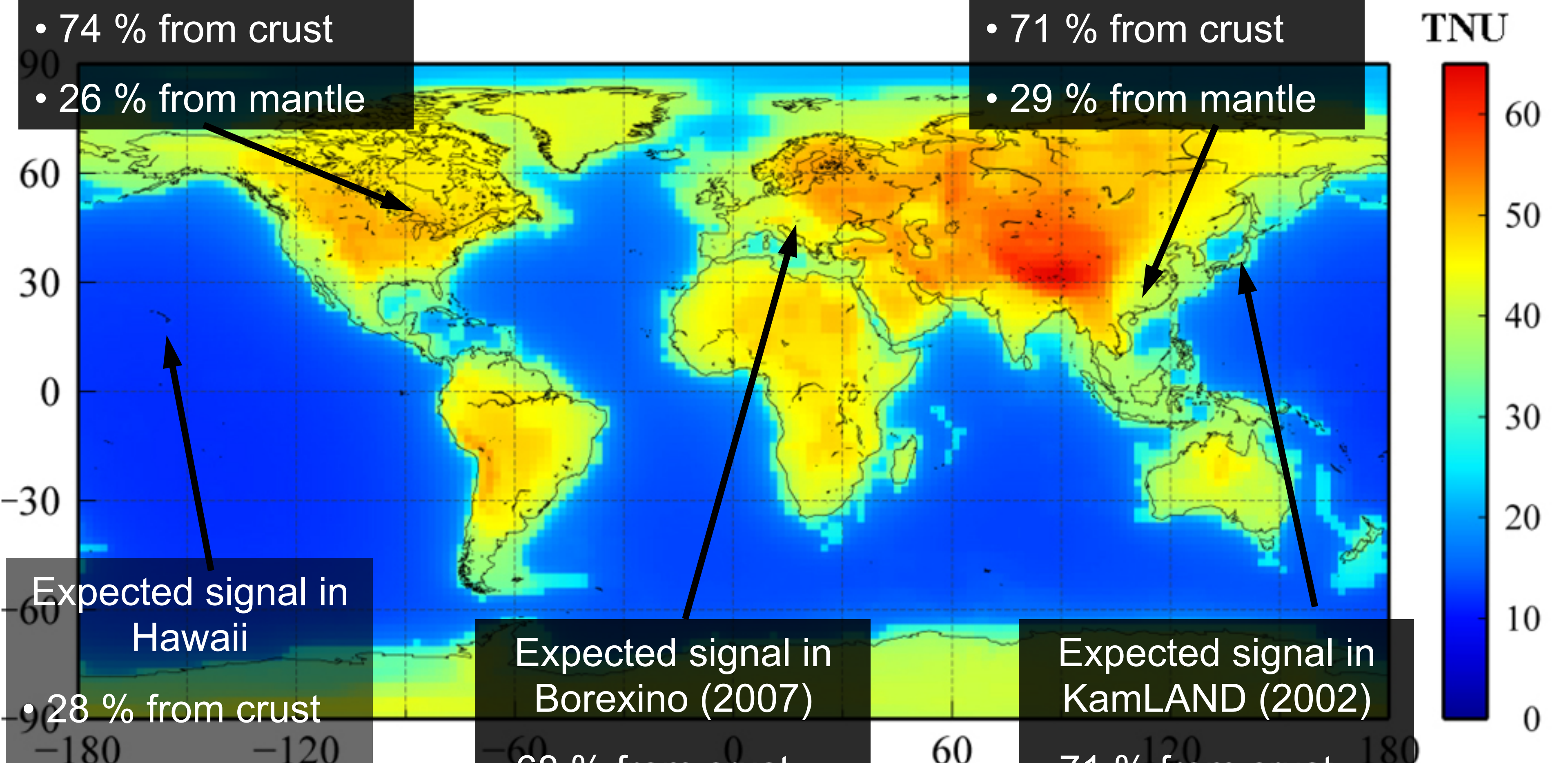
Preliminary

	2013 data [TNU]	Crust [TNU]	Mantle [TNU]
KamLAND	31.1 ± 7.3	25.0 ± 2.0	6.1 ± 7.6
Borexino	38.8 ± 12.0	23.4 ± 2.8	15.4 ± 12.3[3]

The best fit value for the mantle signal common for both sites is $S_{Mantle} = (14.1 \pm 8.1)$ TNU [3]

[1]Fiorentini et al. 2012; [2]Huang et al. 2013; [3]Borexino coll PLB2013

Geoneutrino signal around the world*



Expected signal in SNO+ (2015?)

- 74 % from crust
- 26 % from mantle

Expected signal in JUNO (2020?)

- 71 % from crust
- 29 % from mantle

Expected signal in Hawaii

- 28 % from crust
- 72 % from mantle

Expected signal in Borexino (2007)

- 68 % from crust
- 32 % from mantle

Expected signal in KamLAND (2002)

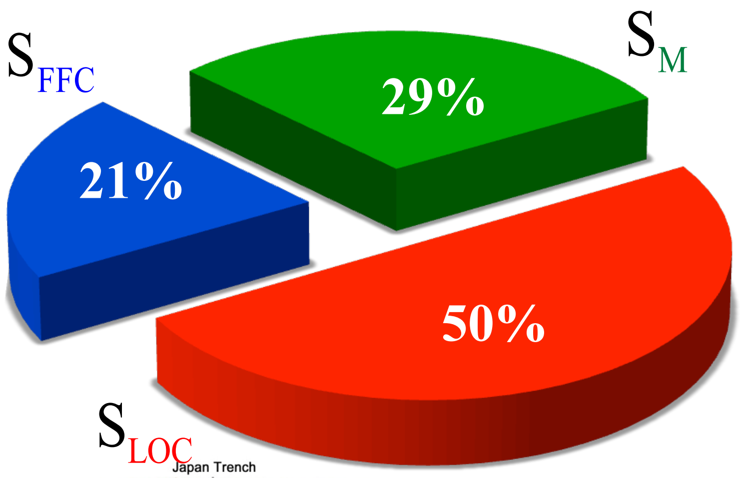
- 71 % from crust
- 29 % from mantle

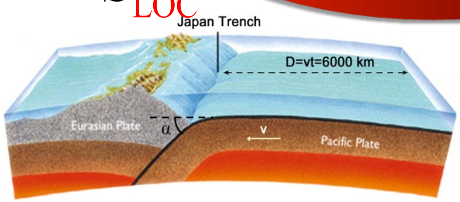
* Huang, Y., et al. - Geochem Geophy Geosy – 2013 - arXiv:1301.0365v2

KamLAND: theory vs experiment

For each element (U, Th) the expected geo-neutrino signal S in one site on the Earth's surface is the sum of three contributions:

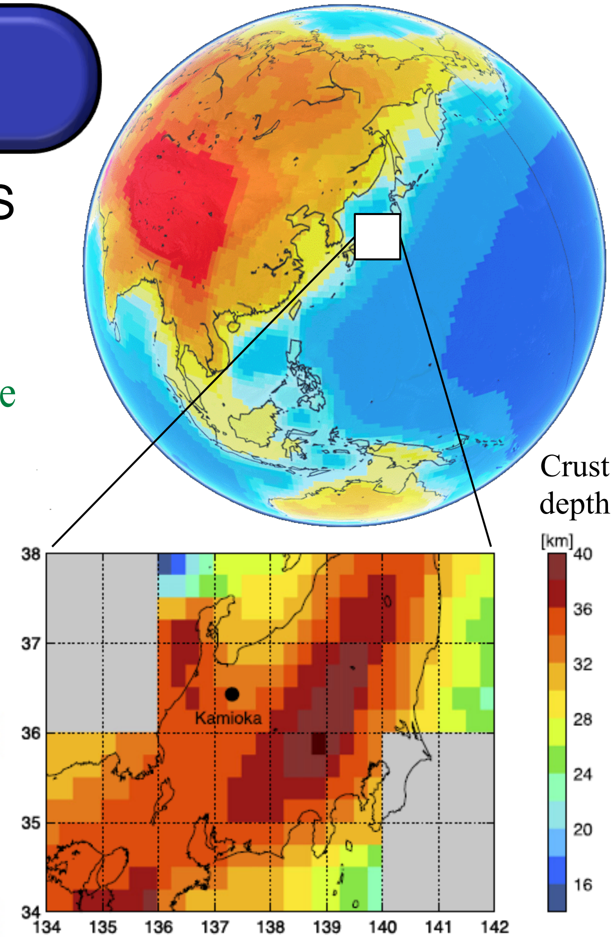
$$S_{Expected} = S_{LOCal} + S_{Far\ Field\ Crust} + S_{Mantle}$$





Contributions to the S_{LOC} in KamLAND are given by U and Th in:

	S(TNU)
Local geology	14.4 ± 1.0
Subducting slab	2.9 ± 0.9
Crust of Japan Sea	0.4 ± 0.1
Total S_{LOC}	17.7 ± 1.4



~ 500 km x 500 km

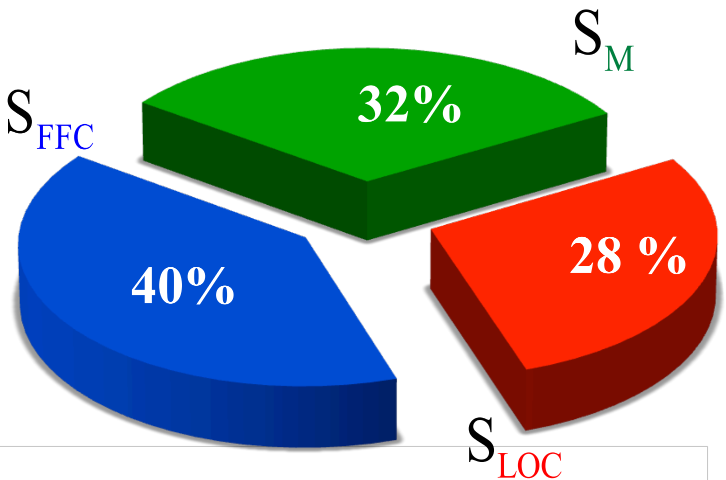
	LOC[1]	FFC[2]	CLM[2]	Mantle[2]	Total (theory)	Experiment (KL 2013)[3]
S(U+Th) [TNU]	17.7 ± 1.4	7.3 ± 1.4	1.6 ± 1.6	8.8	35.4 ± 2.5	30 ± 7

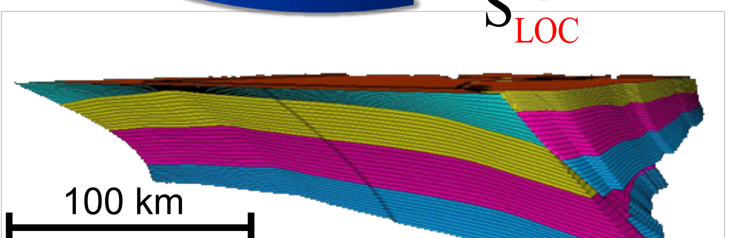
Including a refined local model, in Enomoto et al. (2007) the expected signal in KamLAND is 35.2 TNU.

[1] Fiorentini et al. - 2012
[2] Huang, Y., et al. - 2013 - arXiv:1301.0365v2
[3] KamLAND collaboration – PRD 88 - 2013

Borexino: theory vs experiment

$$S_{Expected} = S_{LOCal} + S_{Far\ Field\ Crust} + S_{Mantle}$$

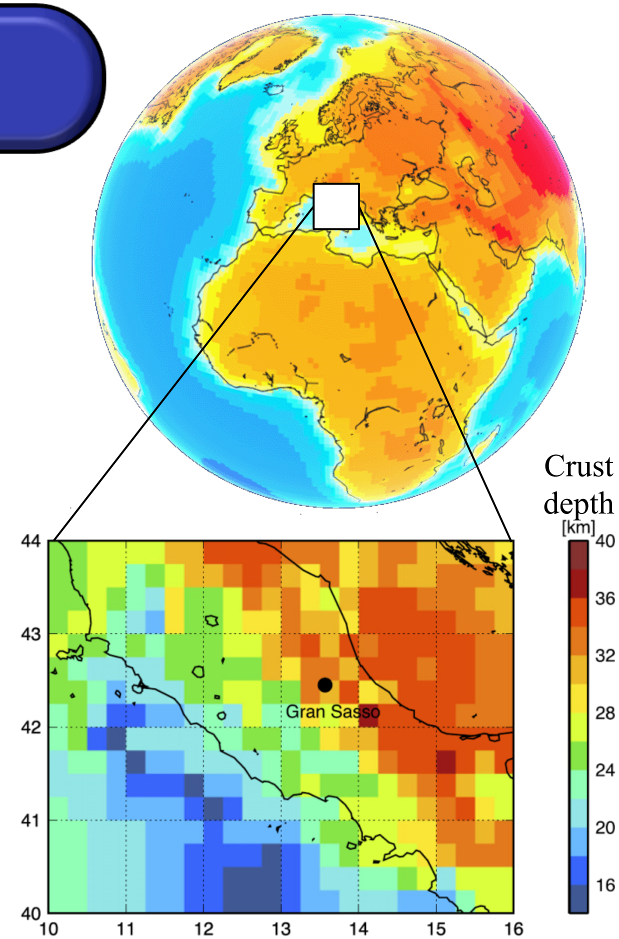




3D model of the crust around Gran Sasso Lab

Contributions to the S_{LOC} Borexino are given by U and Th in:

	S_{LOC} (TNU)
Sediments	2.9 ± 0.3
Loc UC	6.2 ± 1.2
Loc LC	0.6 ± 0.2
Total S_{LOC}	9.7 ± 1.3

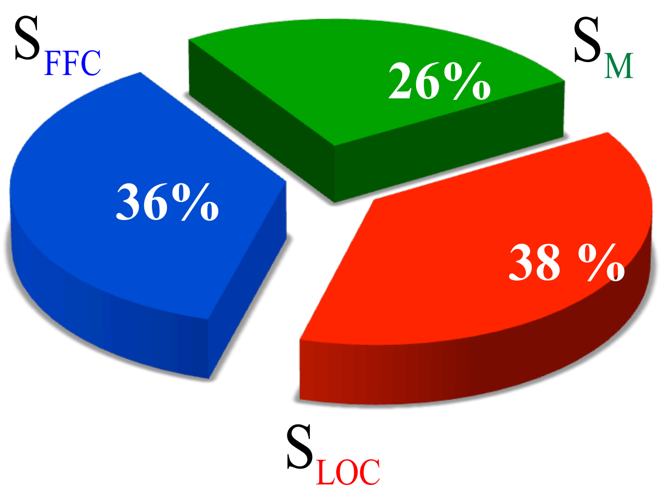


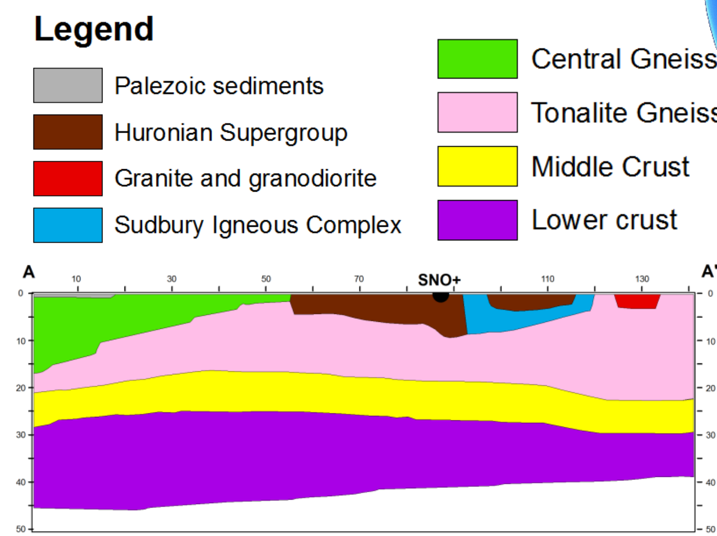
	LOC[1]	FFC[2]	CLM[2]	Mantle[2]	Total (theory)	Experiment (BX 2013)[3]
S(U+Th) [TNU]	9.7 ± 1.3	13.7 ± 2.5	2.2 ± 2.2	8.7	34.3 ± 3.6	39 ± 12

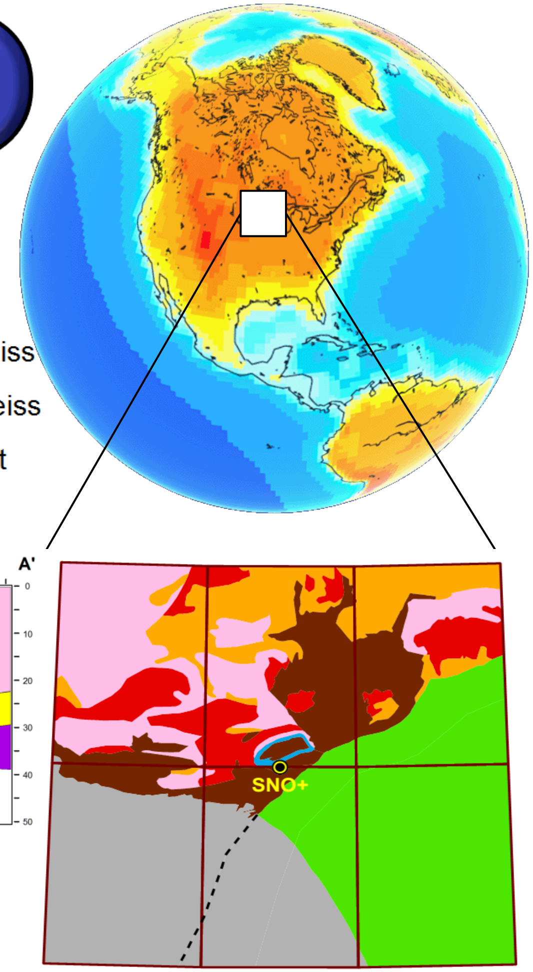
[1] Fiorentini et al. – 2012 // [2] Huang, Y., et al. - 2013 - arXiv:1301.0365v2 // [3] Borexino collaboration – PLB 722 - 2013

SNO+: theory vs experiment

$$S_{\text{Expected}} = S_{\text{LOCal}} + S_{\text{Far Field Crust}} + S_{\text{Mantle}}$$





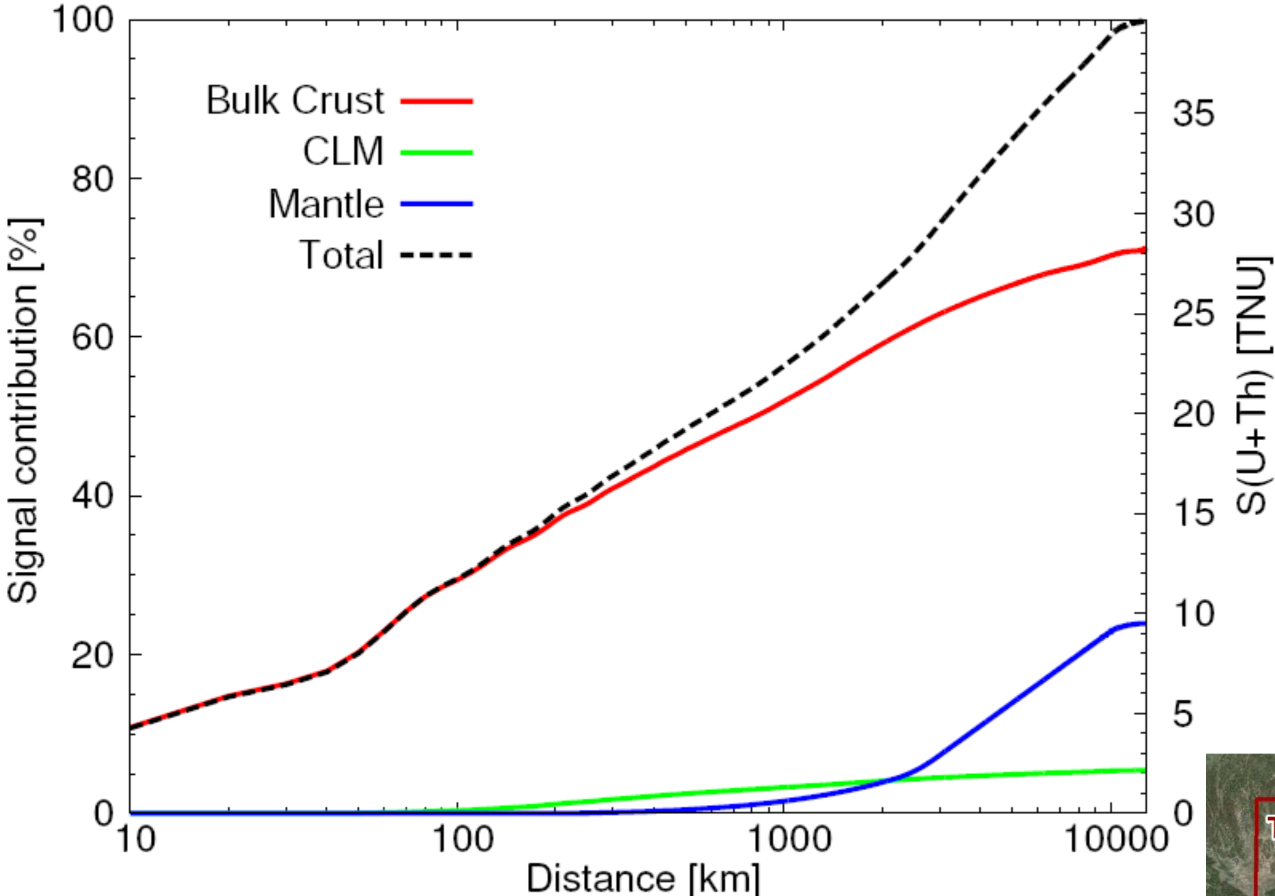


- The local UC is divided into 7 dominant lithologic units
- 3146 samples used for estimating U and Th abundance in UC
- Local 3D geophysical model based on ~400 seismic control points

	LOC[1]	FFC[2]	CLM[2]	Mantle[2]	Total Expected	Experiment
S(U+Th) [TNU]	15.6 ± 4.3	15.1 ± 2.6	2.1 ± 2.1	8.7	41.5 ± 5.4	(2015?)

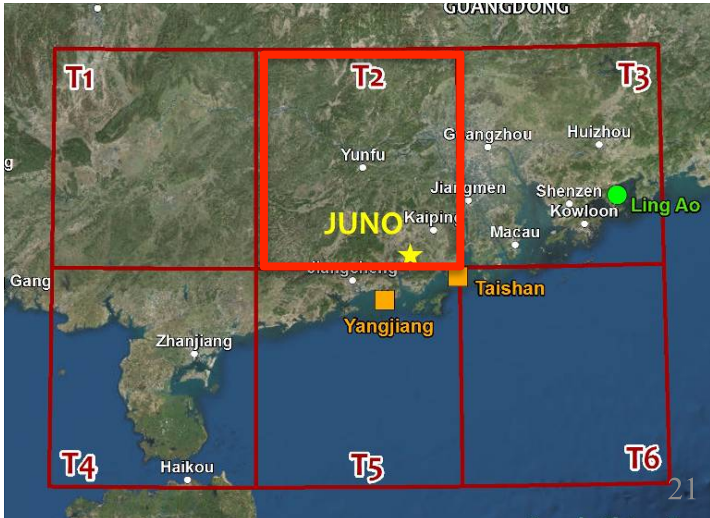
[1] Huang, Y., et al. - 2014 - arXiv:1404.6692 // [2] Huang, Y., et al. - 2013 - arXiv:1301.0365v2

Geoneutrinos signal in JUNO



Crustal Tiles

Tile	S (U+Th)
T1	$0.53^{+0.13}_{-0.10}$
T2	$10.77^{+2.09}_{-1.78}$
T3	$1.48^{+0.33}_{-0.25}$
T4	$0.38^{+0.09}_{-0.07}$
T5	$3.16^{+0.56}_{-0.49}$
T6	$1.02^{+0.23}_{-0.17}$

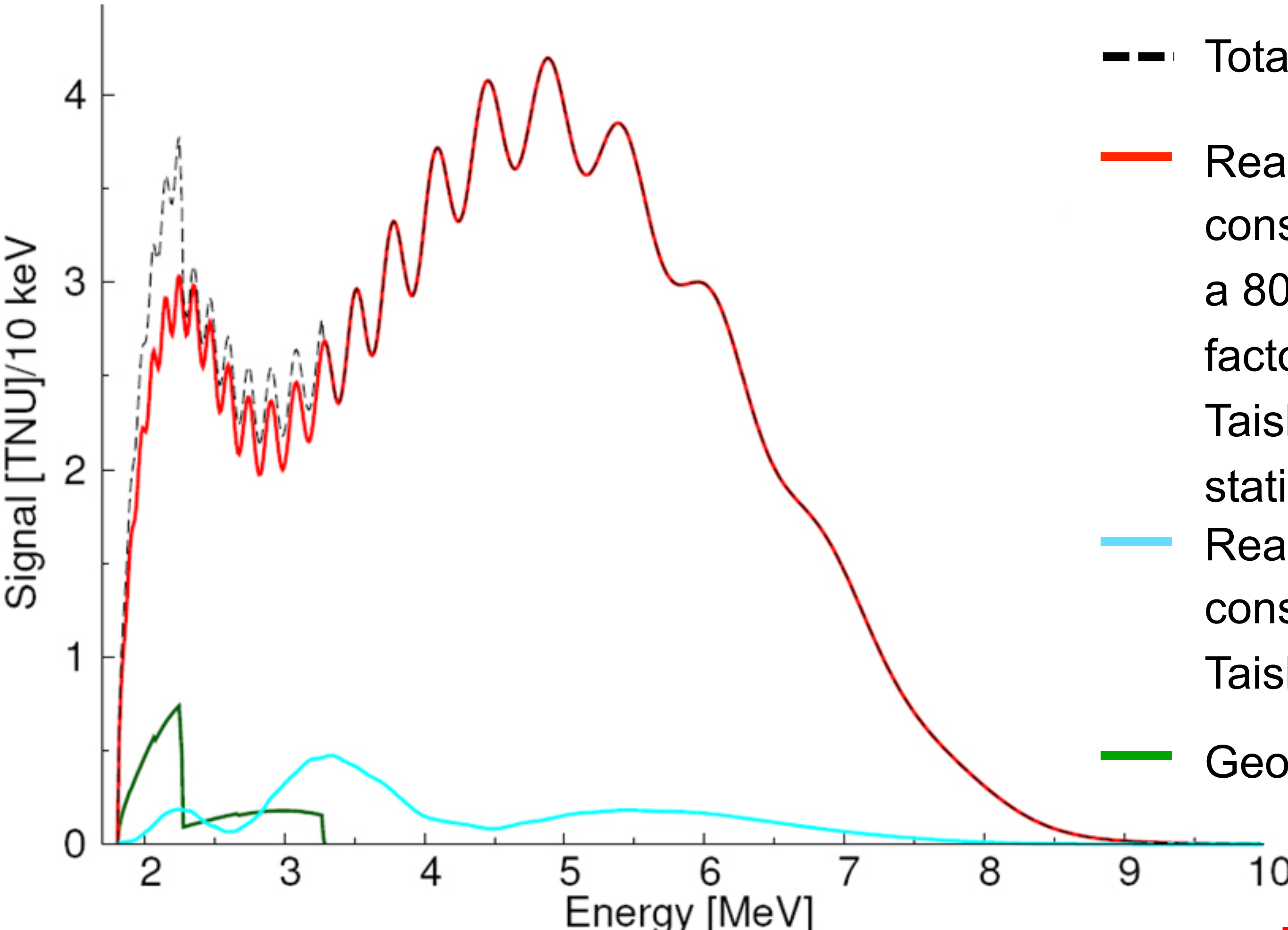


-The 50% of the total signal comes from U and Th in the crust of the region within 860 km from the detector.

-T2 tile contributes with 27% of the total

V. Strati et al. arXiv:1412.3324,

Reactors antineutrinos and geoneutrinos in JUNO



Total (— + —)

Reactor antineutrinos considering as operating with a 80% annual average load factor the Yangjiang and Taishan nuclear power stations (R_{ON})

Reactor antineutrinos considering Yangjiang and Taishan switched off (R_{OFF})

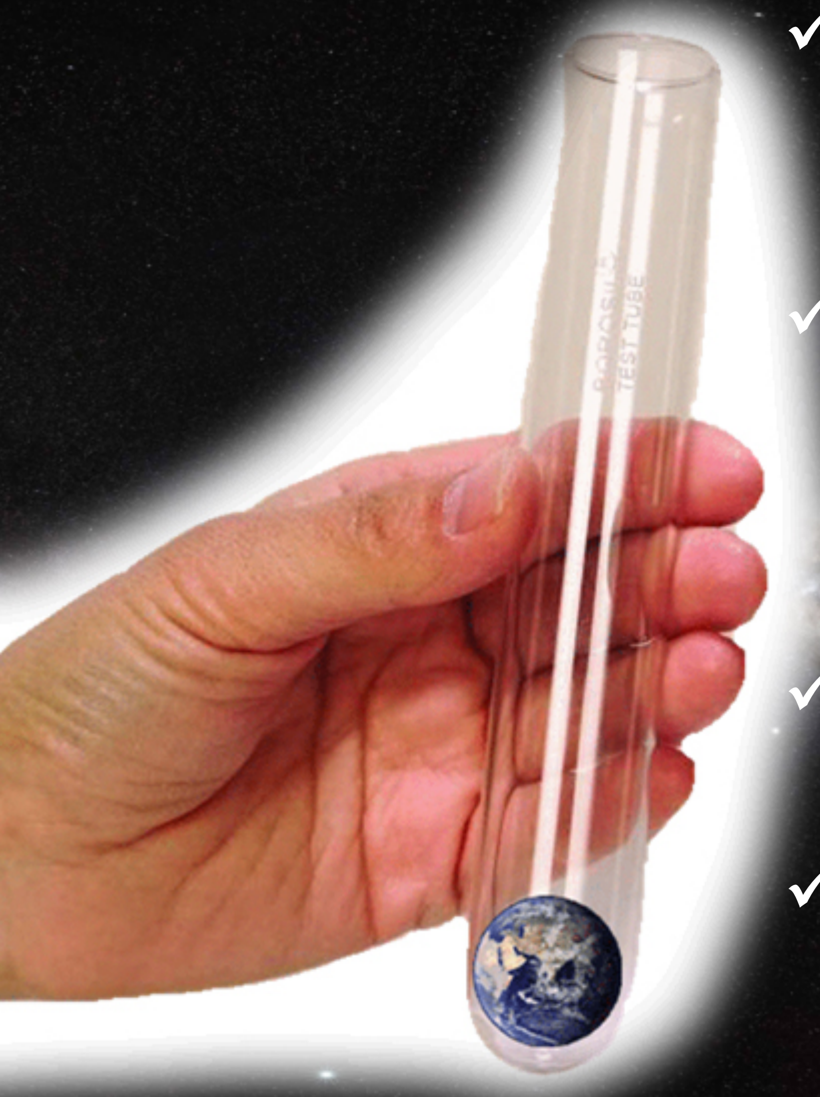
Geoneutrinos

- $R_{LER\text{-}ON}/G = 8.9$
- $R_{LER\text{-}OFF}/G = 0.7$

In the R_{OFF} scenario, JUNO is an excellent experiment for geoneutrino measurements

Strati et al.– arXiv:1412.3324
Baldoncini et al – arXiv:1411.6475

Conclusions



- ✓ Geoneutrinos represent an unique probe for studying the Earth interior
- ✓ Two independent experiments, far ~10^4 km each other, measure a geo-nu signal in agreement with the expectations
- ✓ A big effort in geoneutrino signal calulation
- ✓ Future experiments are needed to better determine the radioactive content of the deep Earth

⇨ Geoneutrinos = fruitful connection between geology and physics (Neutrino Geoscience 2015, Paris 15-17 June)