Improved geoneutrino results from Borexino
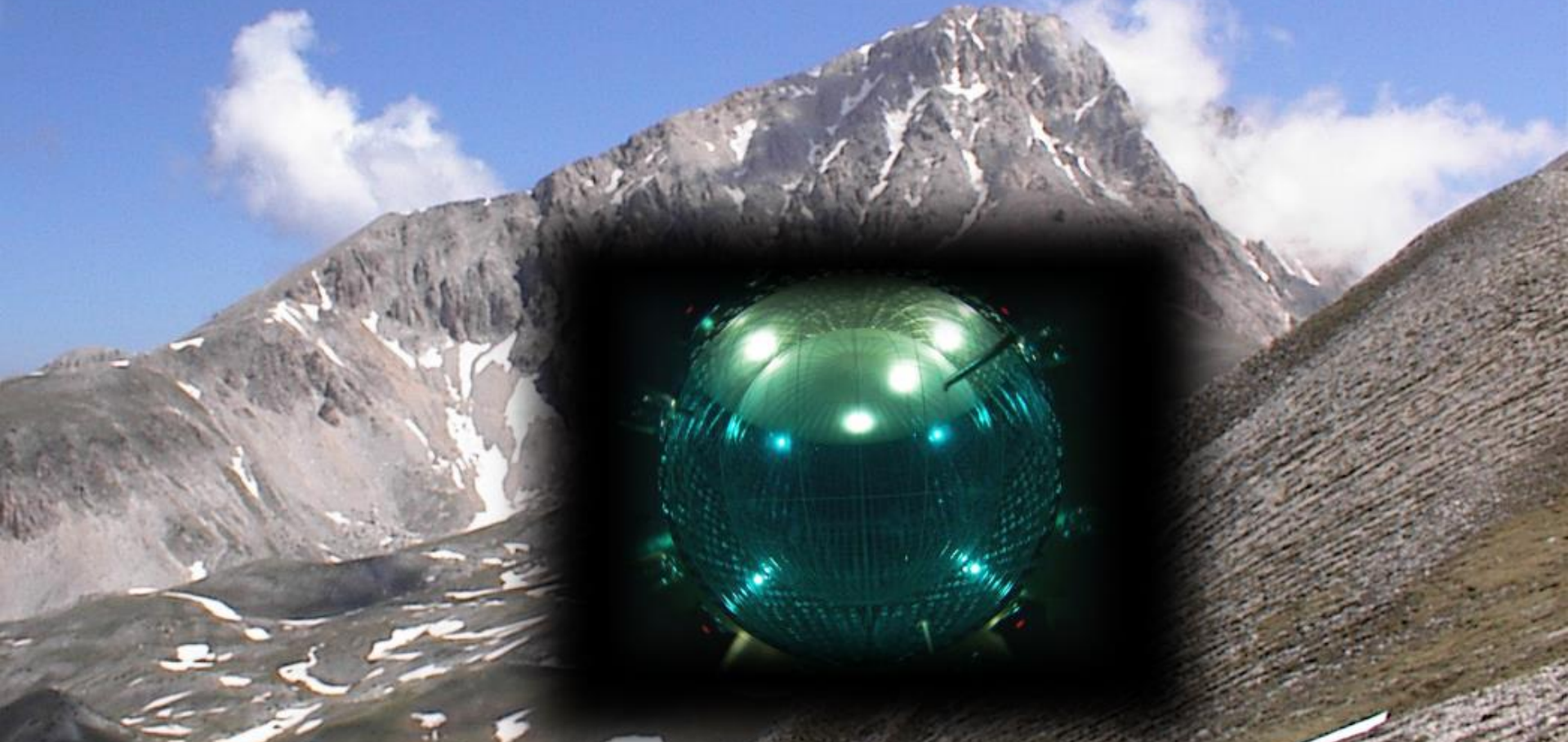
Fabio Mantovani on behalf of the Borexino Collaboration

mantovani@fe.infn.it - www.fe.infn.it/radioactivity/

Università degli Studi di Ferrara

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Summary

- Geoneutrinos and the heat power from the Earth

- Borexino geoneutrino results

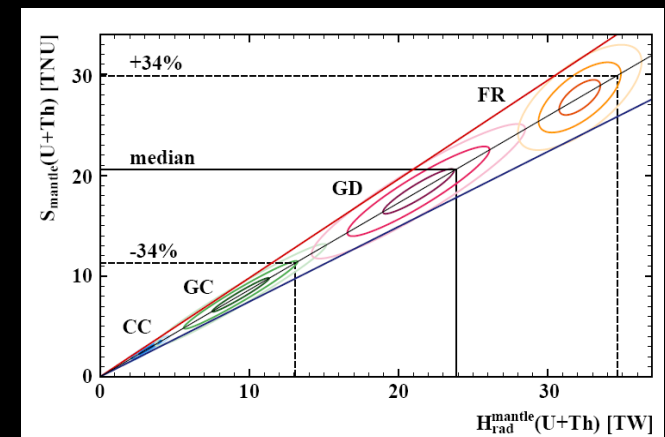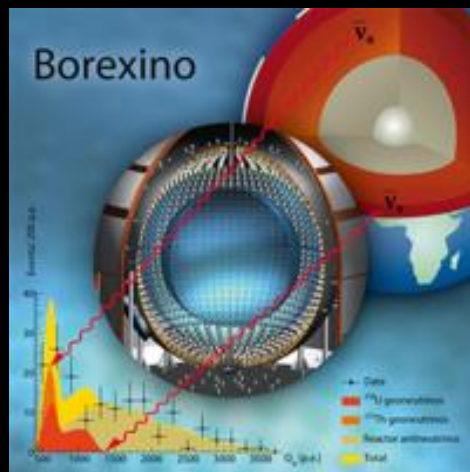- Geological implications of Borexino measurements
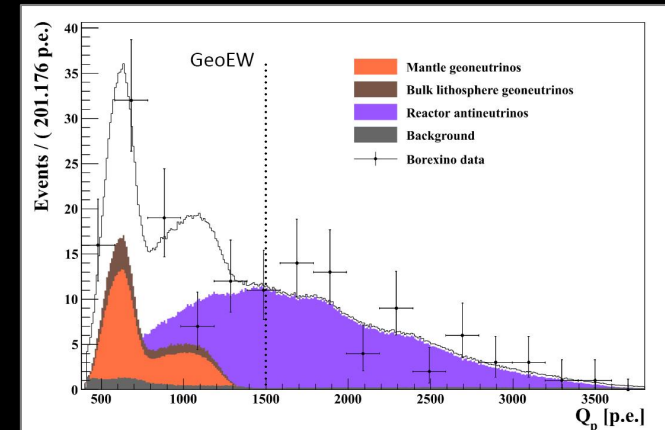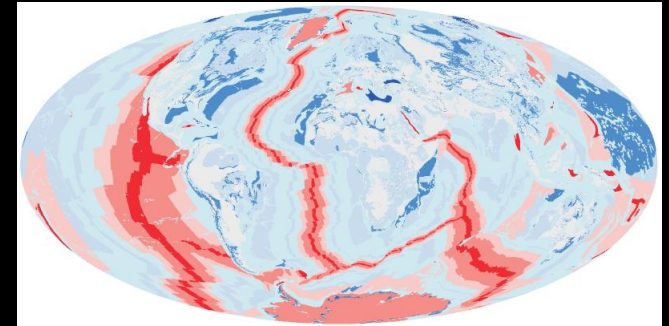
PHYSICAL REVIEW D **101,** 012009 (2020)

Editors' Suggestion   Featured in Physics

Comprehensive geoneutrino analysis with Borexino

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

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

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

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

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

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

Open questions about natural radioactivity in the Earth

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

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

3 - At which thermal conditions the Earth initially is formed?
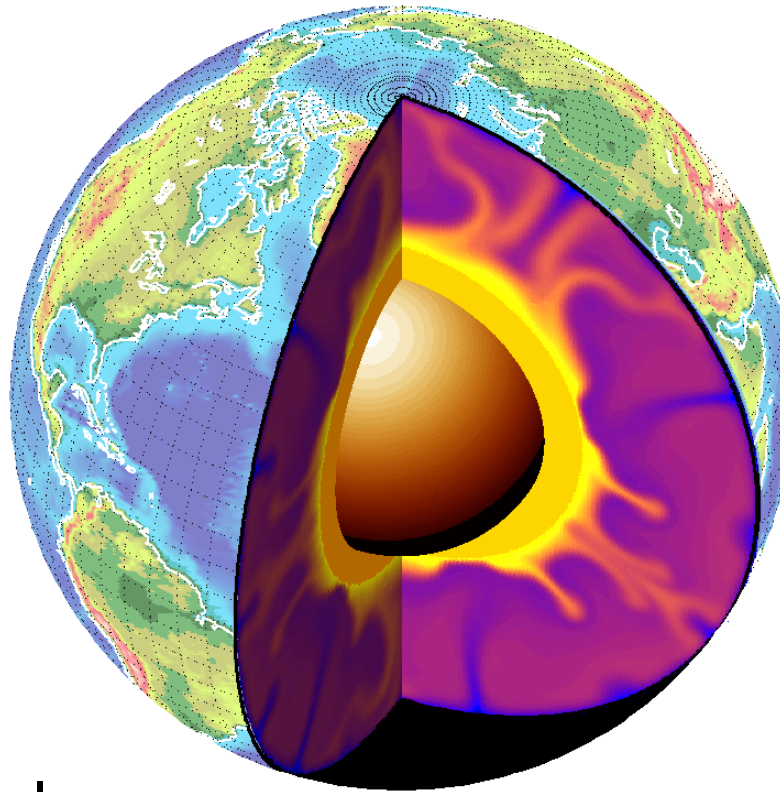
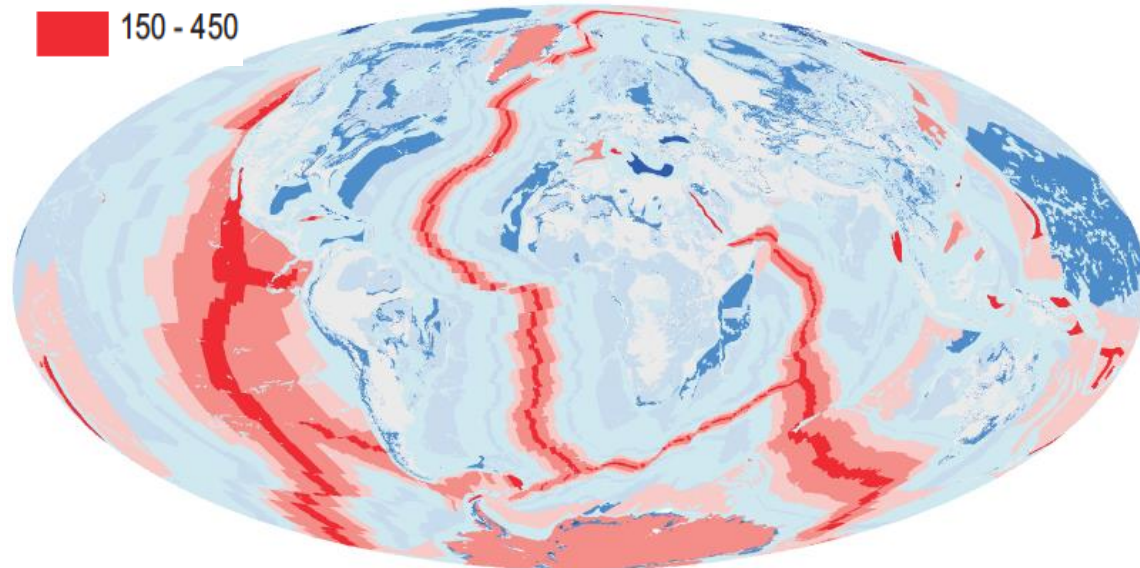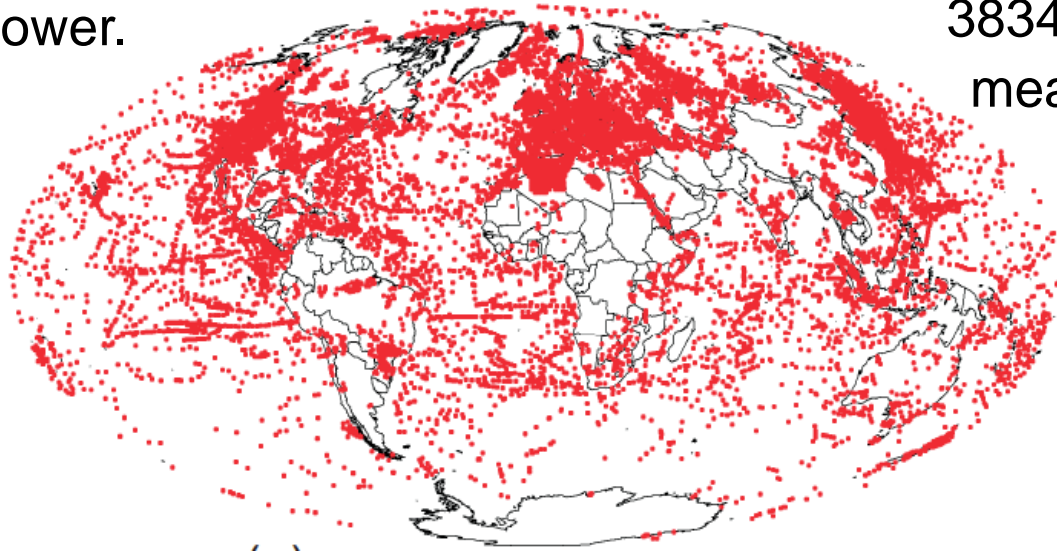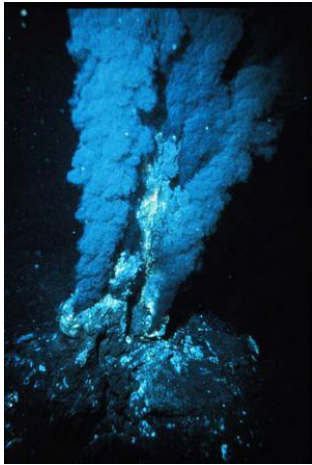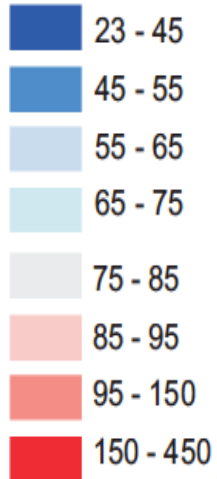**4 -** What is hidden in the Earth's core? (geo-reactor, ^{40}K, …)

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

Heat power from the Earth

- Oceanic floors release ~70% of the total terrestrial power.

- Input dataset: 38347 heat flow measurements

mW / m² *

■	23 - 45
■	45 - 55
■	55 - 65
■	65 - 75
■	75 - 85
■	85 - 95
■	95 - 150
■	150 - 450

Global heat loss [TW] according to different studies	
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
Davies and Davies [2010]	47 ± 2
Jaupart et al. [2015]	46 ± 3

* Davies and Davies, 2010 - Solid Earth 1(1):5-24 · 2010

Origin of the heat from Earth' interior

Neglecting tidal dissipation and gravitation contraction (<0.5 TW), heat comes from:

Secular Cooling (SC): cooling down caused by the initial hot environment of early formation's stages

Radiogenic Heat (RH) due to naturally occurring decays of Heat Producing Elements, HPEs (U, Th and K) inside our planet.
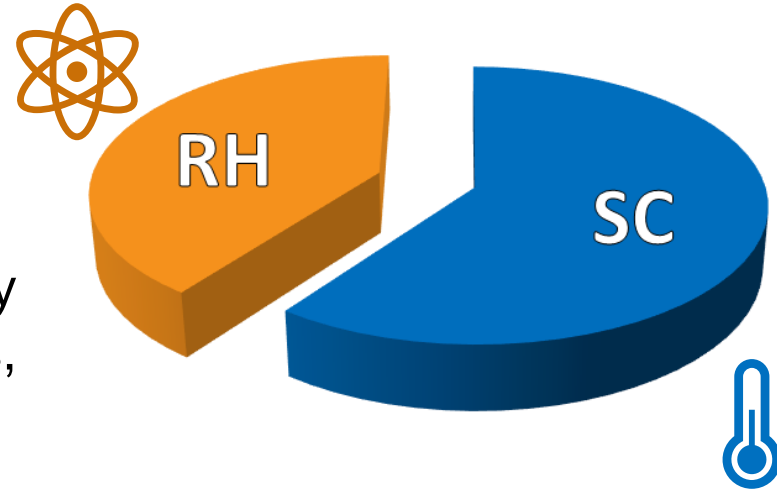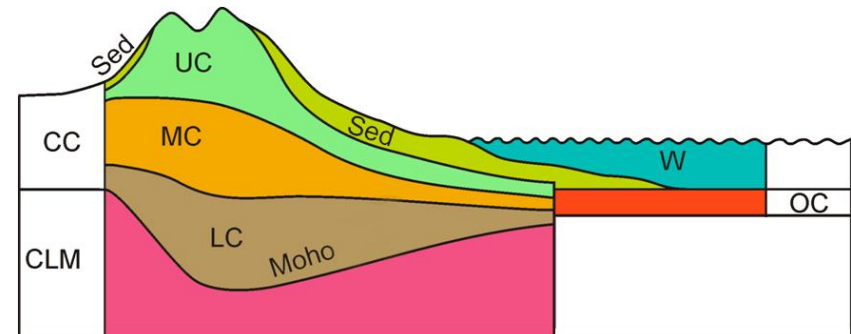

Convective Urey ratio UR$_{CV}$:
mantle heat generation vs mantle heat loss

H$_{Rad\ Mantle}$ affected the dynamical process of Earth interior

$$\mathbf{UR_{CV}} = \frac{H_{Rad} - H_{Rad\ Continental\ Crust}}{H_{Tot} - H_{Rad\ Continental\ Crust}} = \frac{H_{Rad\ Mantle}}{H_{Tot} - H_{Rad\ Continental\ Crust}}$$

K, Th and U distributed in the sediments (Sed), upper (UC), middle (MC) and lower (LC) continental crust give ~7 TW

Radioactivity in the Lithosphere

The Lithosphere (Thick$_{ContLith}$ ~ 140 km) is the superficial portion of the Earth including the Crust and the Continental Lithospheric Mantle (CLM)
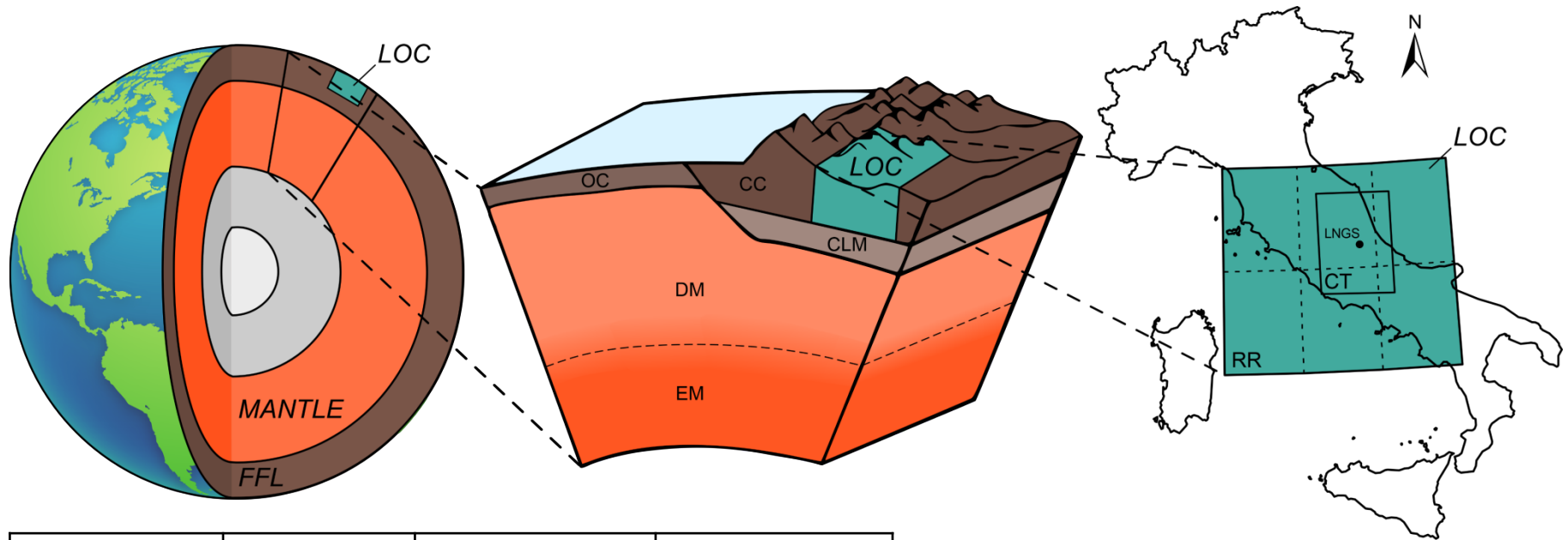
	Mass (U) [10^{16} kg]	Mass (Th) [10^{16} kg]	H(U+Th+K) [TW]
Bulk Crust	$2.8^{+0.6}_{-0.5}$	$12.3^{+3.2}_{-2.1}$	$7.2^{+1.2}_{-1.0}$
CLM	$0.3^{+0.5}_{-0.2}$	$1.5^{+2.9}_{-0.9}$	$0.8^{+1.1}_{-0.6}$
Lithosphere	$3.3^{+0.8}_{-0.6}$	$14.3^{+4.8}_{-2.8}$	$8.4^{+1.7}_{-1.2}$

• The **mass** of the Lithosphere is ~ 2% of the Earth's mass.

• It contains ~ 40% and ~45% of the **U** and **Th** masses, respectively.

• It produces ~18% of the total **heat** flux.
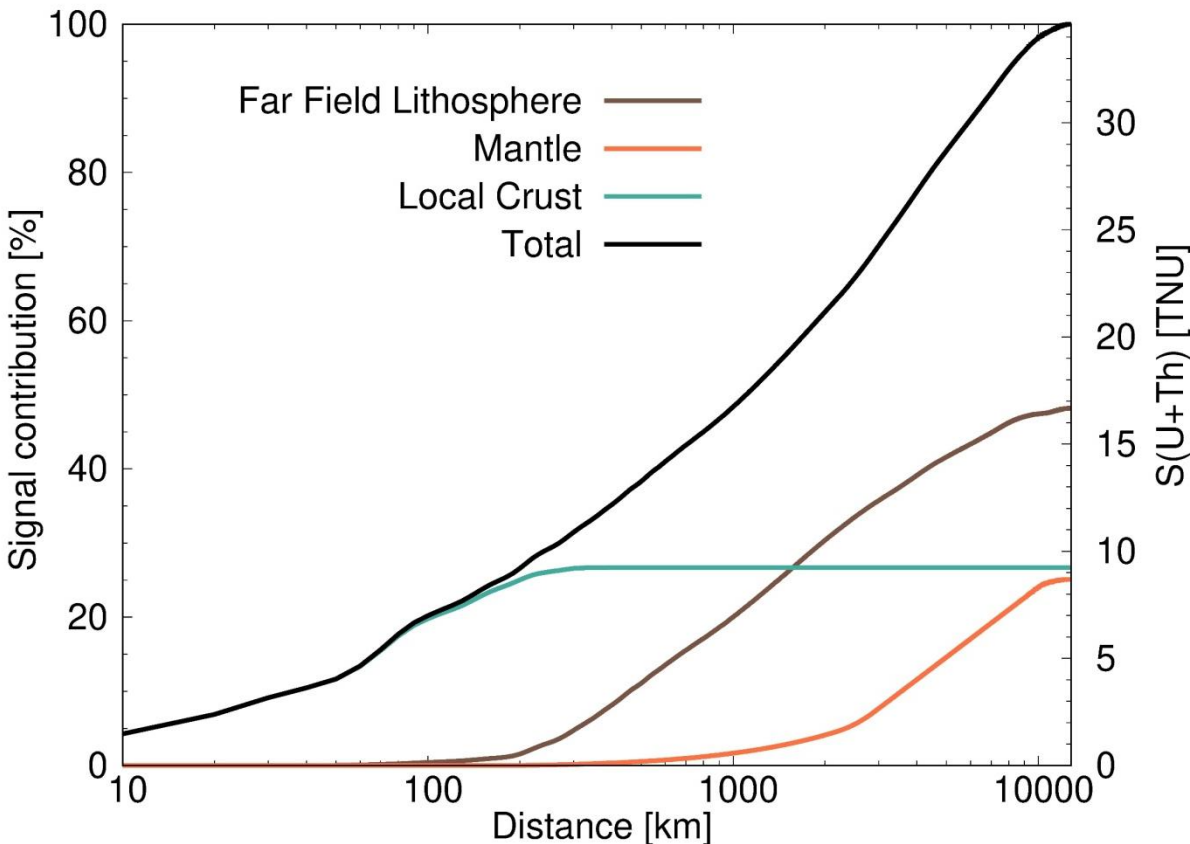
S (U + Th) [TNU]

LOC	9.2 ± 3.7
FFL	$16.7^{+3.8}_{-3.1}$
Mantle	8.7 ± 0.8
Bulk Lithosphere	$25.9^{+4.7}_{-4.3}$

- **40%** of the total signal comes from U and Th in the regional crust that lies within ~550 km of the detector.
- At **~150** km from Borexino, the signal from the LOC can be considered the only contribution to the total signal
- The signal from the **LOC** is comparable with the Mantle signal.

Borexino experiments and geoneutrinos
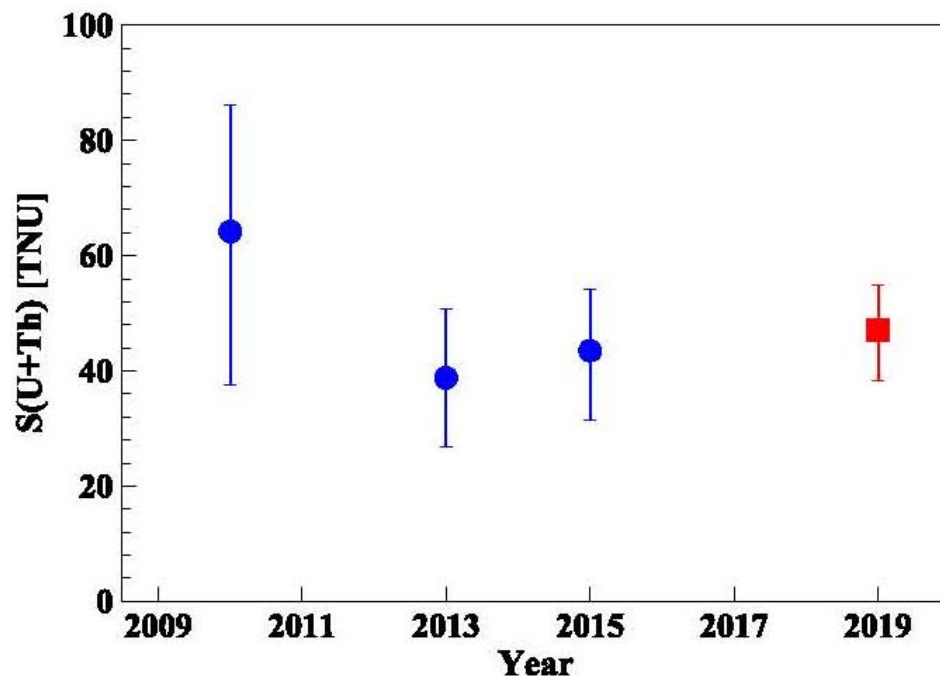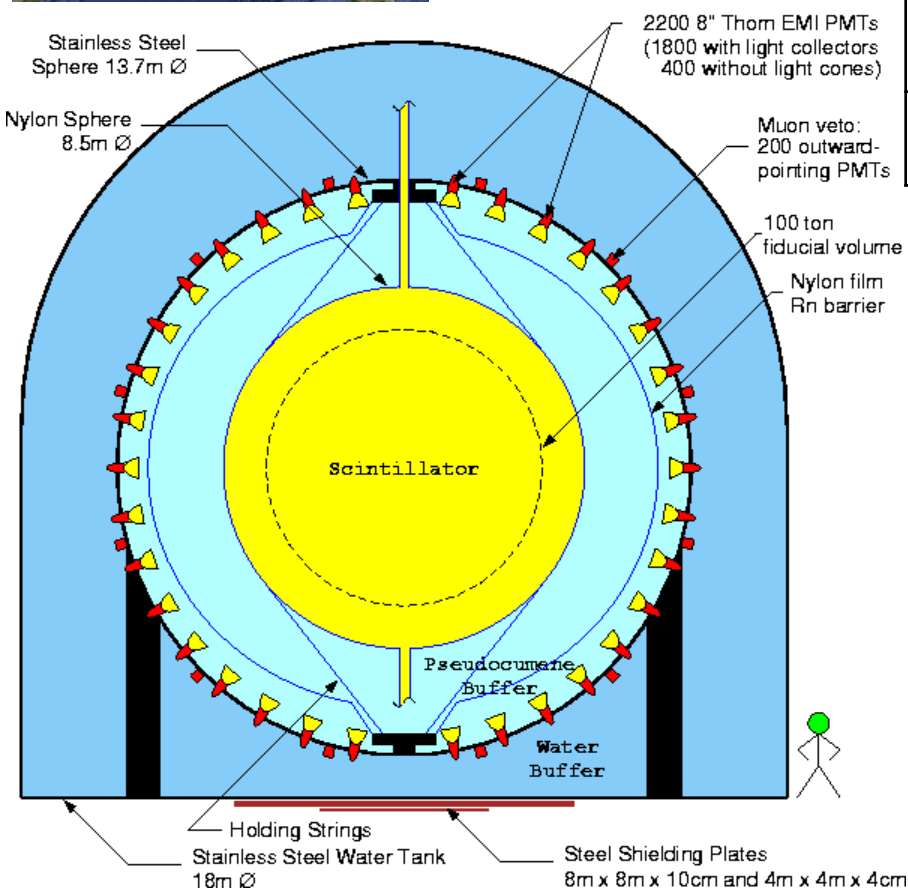
Borexino
@ LNGS
278 ton PC LS
~2200 8" PMTs
6×10^{28} free prot/ton
$a(^{238}U) < 9.4 \times 10^{-20}$ g/g
$a(^{232}Th) < 5.7 \times 10^{-19}$ g/g

	Live time (days)	Fid. Expos. 10^{31} free prot x yr	Geo-nu events
2010	537	1.52	$9.9^{+4.1}_{-3.4}$
2013	1353	3.7 ± 0.2	$14.3^{+4.4}_{-4.4}$
2015	2056	5.5 ± 0.3	$23.7^{+6.5}_{-5.7}$ (stat) $^{+0.9}_{-0.6}$ (sys)
2019	3263	12.9 ± 0.5	$52.6^{+9.4}_{-8.6}$ (stat) $^{+2.7}_{-2.1}$ (sys)

Stainless Steel Sphere 13.7m Ø

Nylon Sphere 8.5m Ø

2200 8" Thorn EMI PMTs (1800 with light collectors 400 without light cones)

Muon veto: 200 outward-pointing PMTs

100 ton fiducial volume

Nylon film Rn barrier

Scintillator

Pseudocumene Buffer

Water Buffer

Holding Strings
Stainless Steel Water Tank 18m Ø

Steel Shielding Plates 8m x 8m x 10cm and 4m x 4m x 4cm

Main improvements in data selection

- Improved muon vetoes: for internal muons a cylindrical veto is applied, and the dead times are tuned according to the muon's probability to form spallation products (^{9}Li, ^{8}He, ^{12}B).

- The tagging efficiency is increased including double cluster events (i.e. fast ^{212}Bi-^{212}Po coincidence is tagged)

- Since the detector's shape change in time, a dynamical fiducial volume cut permitted to include prompt events up to 10 cm from inner vessel.
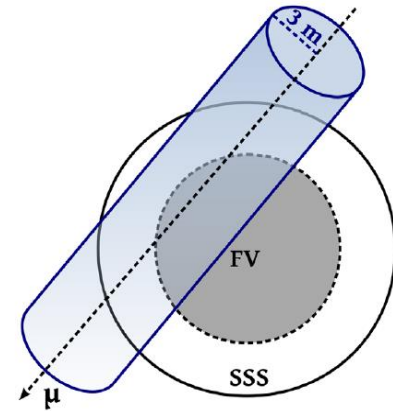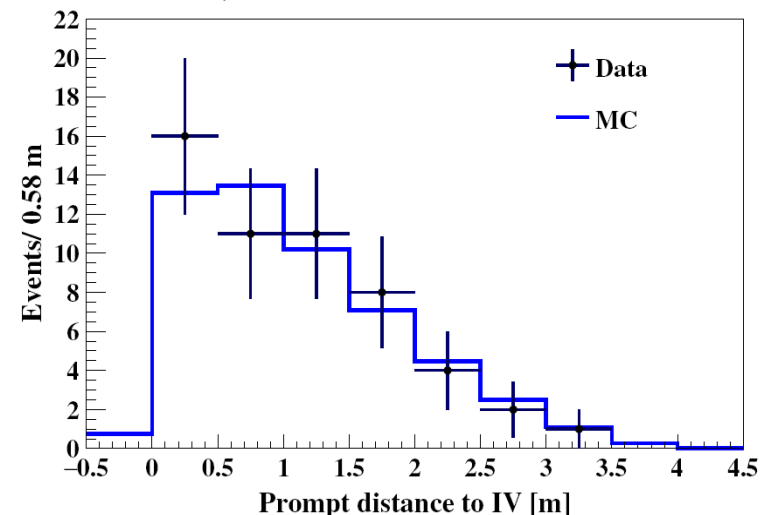
Exposure increases by factor 2 respect 2015 Borexino analysis

Events with Q_p < 1500 p.e. (~ Geo-ν + Rea-ν energy window)
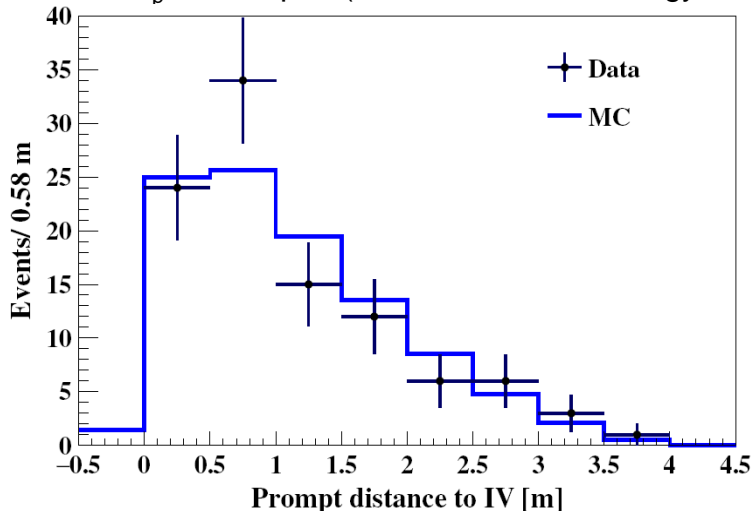
Events with Q_p > 1500 p.e. (~ Rea-ν energy window)

Background in Borexino

TABLE XV. Summary of the expected number of events from non-antineutrino backgrounds in the antineutrino candidate sample (exposure $\mathcal{E}_p = (1.29 \pm 0.05) \times 10^{32}$ protons × yr). The limits are 95% C.L.

Background Type	Events
^{9}Li background	3.6 ± 1.0
Untagged muons	0.023 ± 0.007
Fast n's (μ in WT)	<0.013
Fast n's (μ in rock)	<1.43
Accidental coincidences	3.846 ± 0.017
(α, n) in scintillator	0.81 ± 0.13
(α, n) in buffer	<2.6
(γ, n)	<0.34
Fission in PMTs	<0.057
^{214}Bi-^{214}Po	0.003 ± 0.001
Total	8.28 ± 1.01

• In 3262.74 days BX measured 154 antineutrinos candidates in the effective exposure, after cuts.

• Estimated constrained **background events**: 8.3 ± 1.0

• In GeoEW [1.8-3.3 MeV] the reconstructed **reactor events** are 39.5 ± 0.7.

• Assuming a Th/U = 3.9, the **geoneutrino events** are $52.6^{+9.6}_{-9.0}$

• Considering the effective exposure $\varepsilon' = 1.12 \ 10^{32}$ free protons x yr, one can calculate the signal in TNU:

$$S[TNU] = N_{Eve} * (10^{32}/ \varepsilon')$$
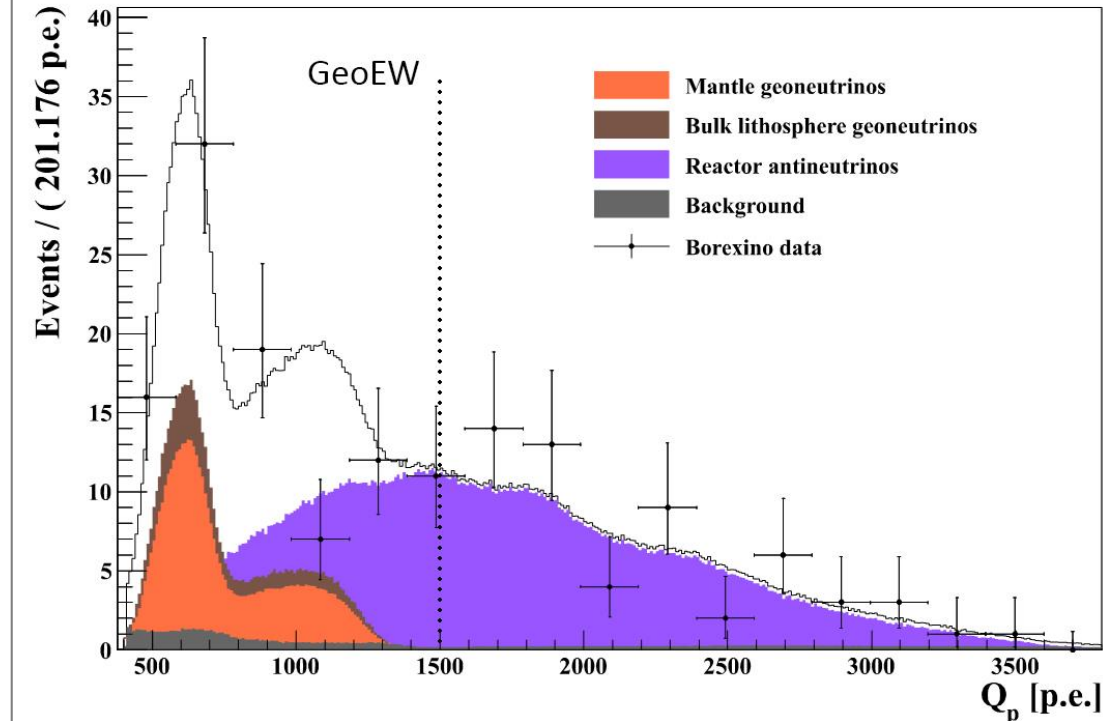
• Constraining the contribution from the **bulk lithosphere** (28.8 ± 5.6 events), the **extracted mantle** events are $23.7^{+10.7}_{-10.1}$

$$(S_{Man}(U + Th) = 21.2^{+9.5}_{-9.0} \ (Stat) \ ^{+1.1}_{-0.9} \ (Sys) \ TNU)$$

$$S \ (U+Th) = 47.0 \ ^{+8.4}_{-7.7} \ (Stat) \ ^{+2.4}_{-1.9} \ (Sys) \ TNU$$

Bulk Silicate Earth (BSE) and mantle radiogenic power

The BSE describes the primordial non-metallic Earth condition that followed planetary accretion and core separation, prior to its differentiation into a mantle and crust.

Cosmochemical Model (CC)

- Enstatitic meteorites

- $H_{Mantle}(K, Th, U) = 1.2 - 4.7$ TW

Geochemical Model (GC)

- Carbonaceous meteorites

- $H_{Mantle}(K, Th, U) = 9.7 - 13.6$ TW

Geodynamical Model (GD)

- Earth dynamics

- $H_{Mantle}(K, Th, U) = 23.0 - 26.9$ TW

Fully radiogenic (FR)

- Terrestrial heat is fully accounted by radiogenic production

- $H_{Mantle}(K, Th, U) = 36.5 - 39.8$ TW

$$S_{Mantle}(U+Th) = 21.2\,^{+9.5}_{-9.0}\,(Stat)\,^{+1.1}_{-0.9}\,(Sys)\ TNU$$
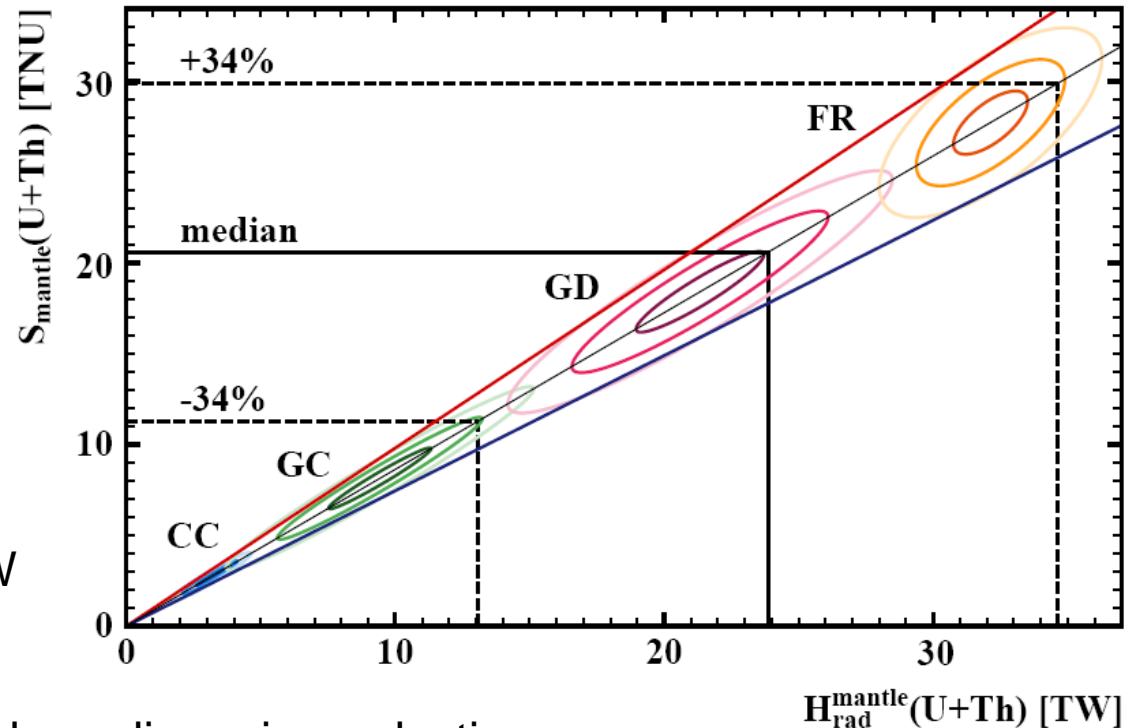
BSE models according to different authors:

J = M. Javoy et al., EPSL 293, (2010).

L&K = T. Lyubetskaya and J. Korenaga, J. Geoph. Res. Sol. Earth, 112 (2007)

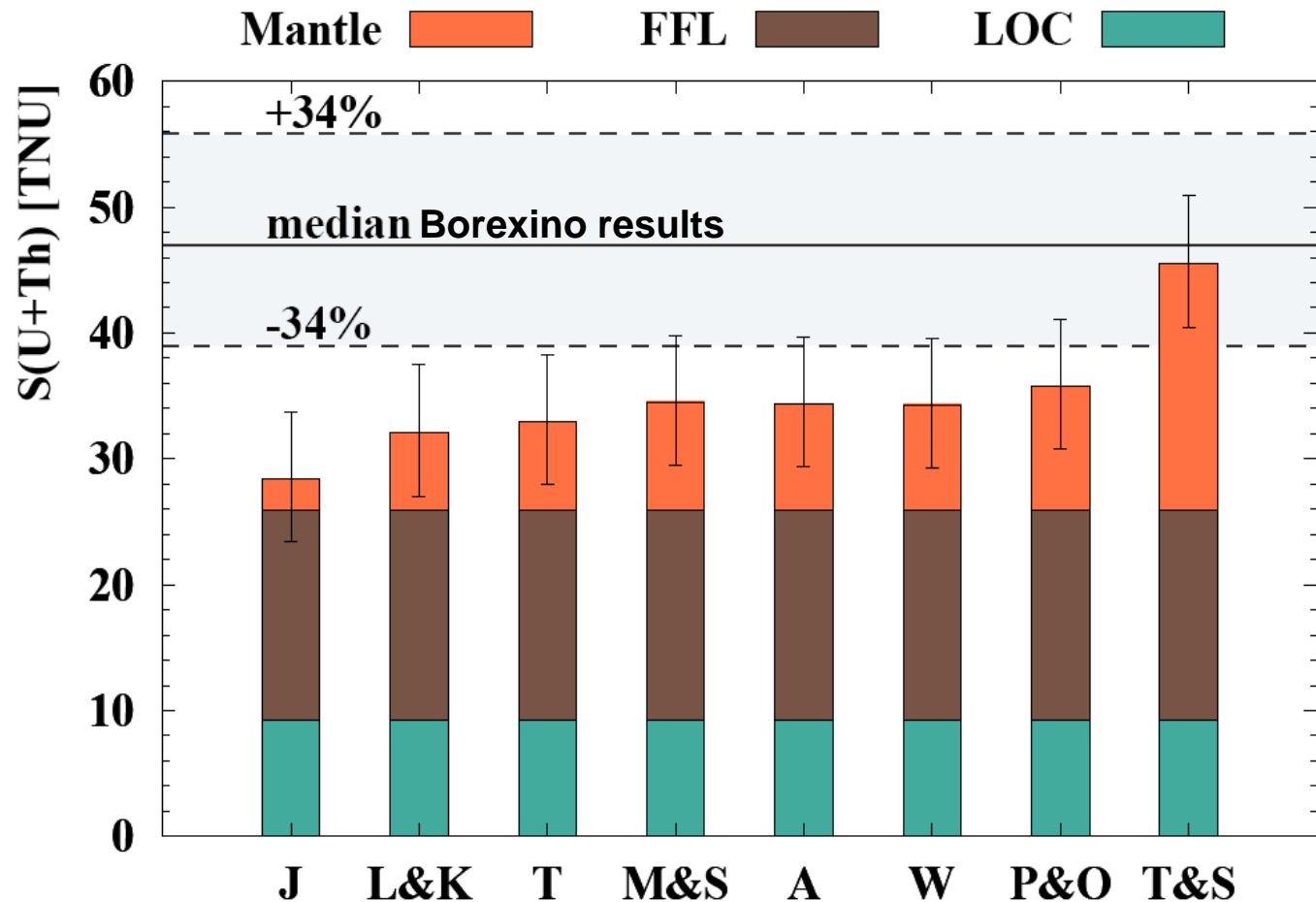**T** = S. Taylor, Proc. Lunar Planet. Sci. Conf. 11, 333 (1980)

M&S = W. F. McDonough and S. Sun, Chem. Geol. 120, (1995)

A = D. L. Anderson, Cambridge University Press, (2007)

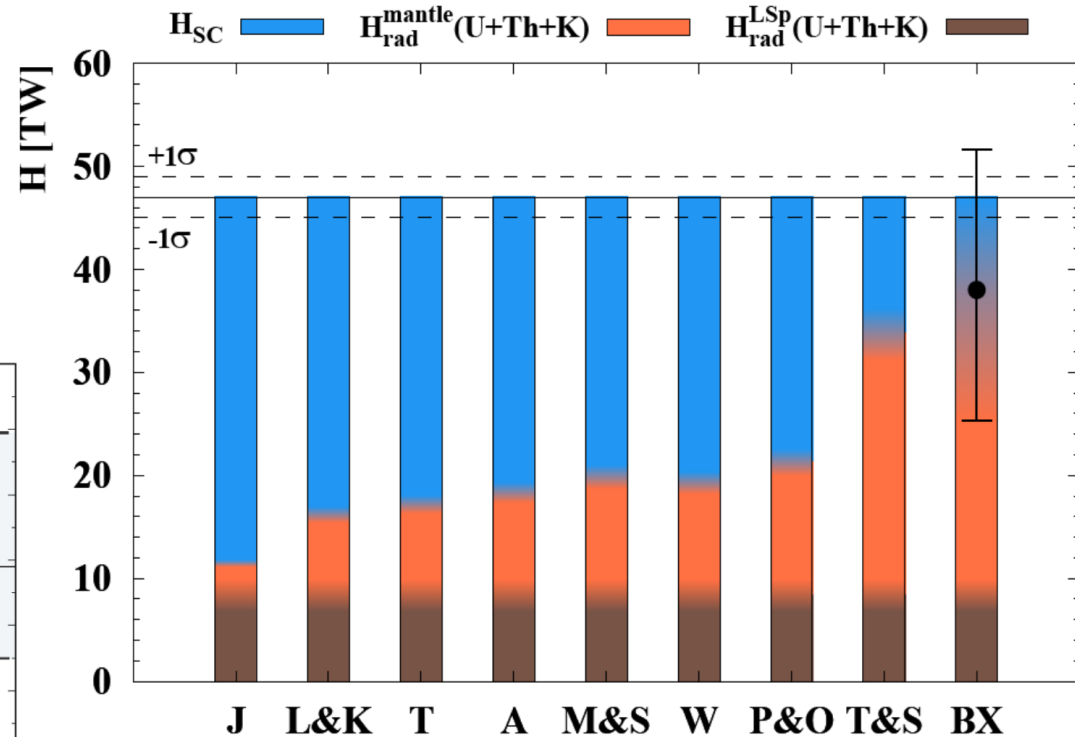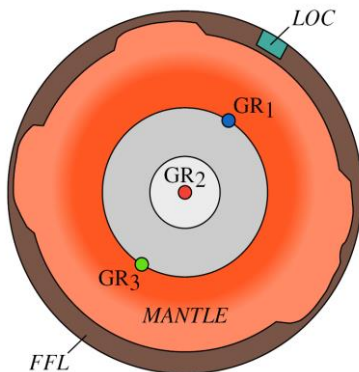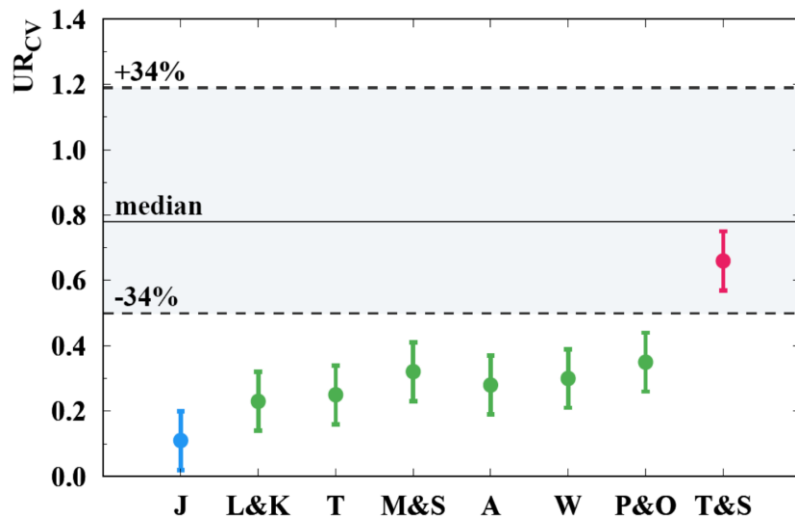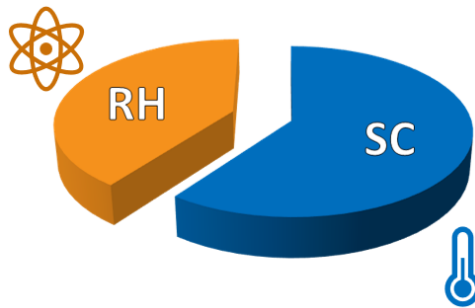**W** = H. S. Wang et al., Icarus 299, (2018)

P&O = H. Palme and H. O'Neill, Treatise of Geochemistry, (2003)

T&S = D. L. Turcotte and G. Schubert, Cambridge University Press, (2002)

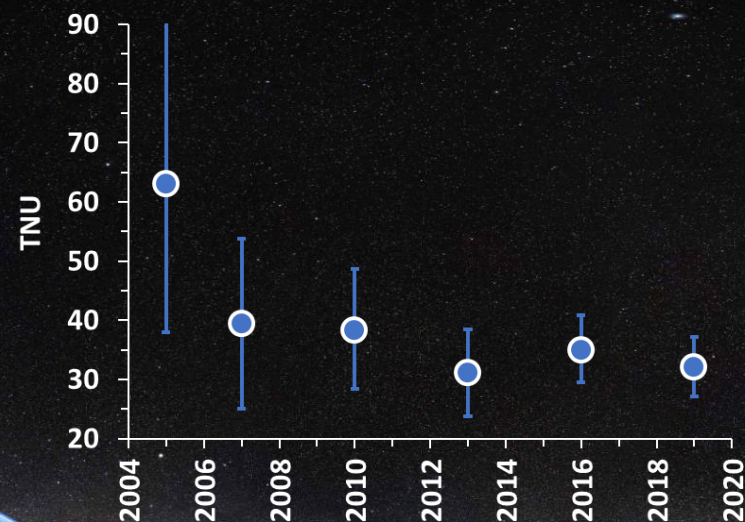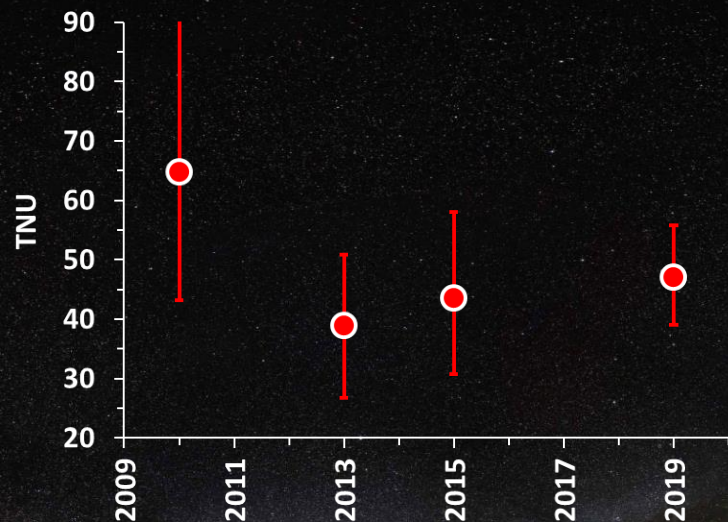The observations favor geological models that predict a relatively high concentration of radioactive elements in the mantle.

• Borexino estimates a high probability (~ 85%) that the radioactive decays produce more than half of the total Earth's heat.

• A hypothetical 2.4 TW georeactor at Earth's center is excluded at 95% C.L.

Borexino and KamLAND results 2019

Borexino

- Period:
2007 – 2019

- Geo-ν events:
$52.6^{+7.4}_{-6.3}$

- Signal:
$47.0^{+8.7}_{-7.9}$ TNU

- Expected Signal with Geochemical BSE:
$34.6^{+5.5}_{-5.0}$ TNU

KamLAND*

- Period:
2002 – 2019

- Geo-ν events:
$168.8^{+26.3}_{-26.5}$

- Signal: 32 ± 5 TNU

- Expected Signal with Geochemical BSE: 35.3 ± 2.7 TNU

Take away 4 highlights

- Geoneutrino signal measured by Borexino $S(U + Th) = 47.0 ^{+8.4}_{-7.7}$ (Stat) $^{+2.4}_{-1.9}$ (Sys) TNU is obtained with an optimized data selection, which improved detection efficiency (87 ± 1.5 %)

- Borexino observes a geoneutrino mantle signal $S_{Man}(U + Th) = 21.2^{+9.5}_{-9.0}$ (Stat) $^{+1.1}_{-0.9}$ (Sys) TNU , with a null observation excluded at a 99.0% CL

- Borexino estimates a radiogenic power from (U+Th) in the mantle $H_{Mantle}(U+Th) = 24.6 ^{+11.1}_{-10.4}$ TW Adding contributions from lithosphere and from K, the obtained total radiogenic power is $H_{Rad} = 38.2 ^{+13.6}_{-12.7}$ TW.

- Borexino measurements show a ~ 2.4 σ tension with BSE models which predict the lowest U and Th mantle abundances