A sample-based crustal model for the Borexino geoneutrino signal

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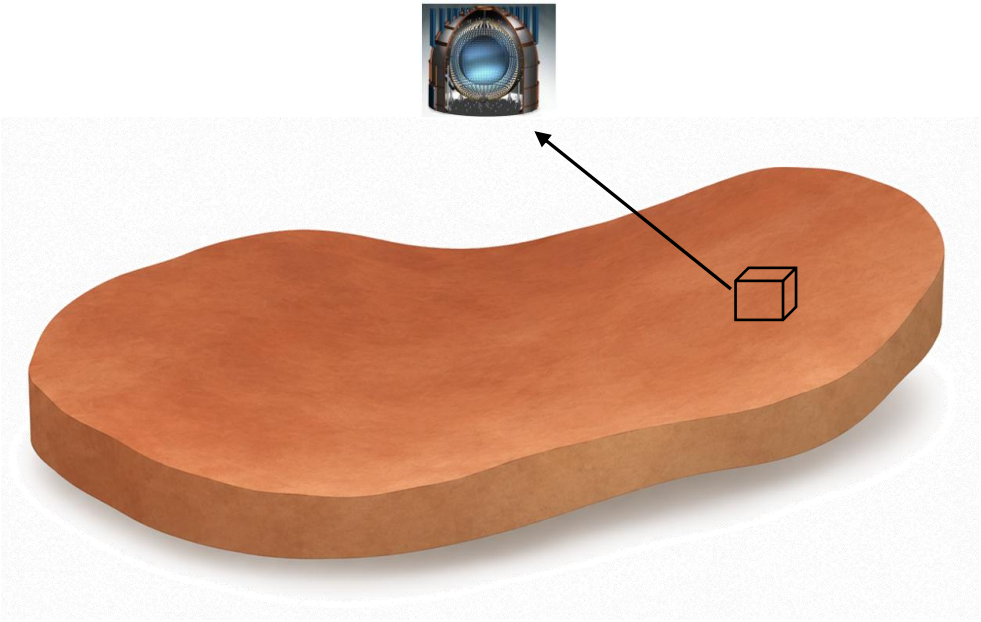
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Outline

- Geological setting and geochemical dataset
- U and Th of the sedimentary cover and crystalline crust
- Comparison with the previous model
- From abundances to the local signal to the lithospheric signal and to the mantle radiogenic power
- Take home messages



Unitary geoneutrino signal



$$S(X,\vec{r}) = N_p \cdot T \cdot \varepsilon_{\bar{\nu}_e} \cdot \eta \cdot \int dE_{\bar{\nu}} \cdot \sigma(E_{\bar{\nu}}) \cdot S_p(X, E_{\bar{\nu}}) \cdot \int d^3r' \cdot P_{ee}(|\,\boldsymbol{r}-\boldsymbol{r}'\,|, E_{\bar{\nu}}) \cdot \frac{\rho(\boldsymbol{r}')}{4\pi\,|\,\boldsymbol{r}-\boldsymbol{r}'\,|^2} a(X,\boldsymbol{r}')$$

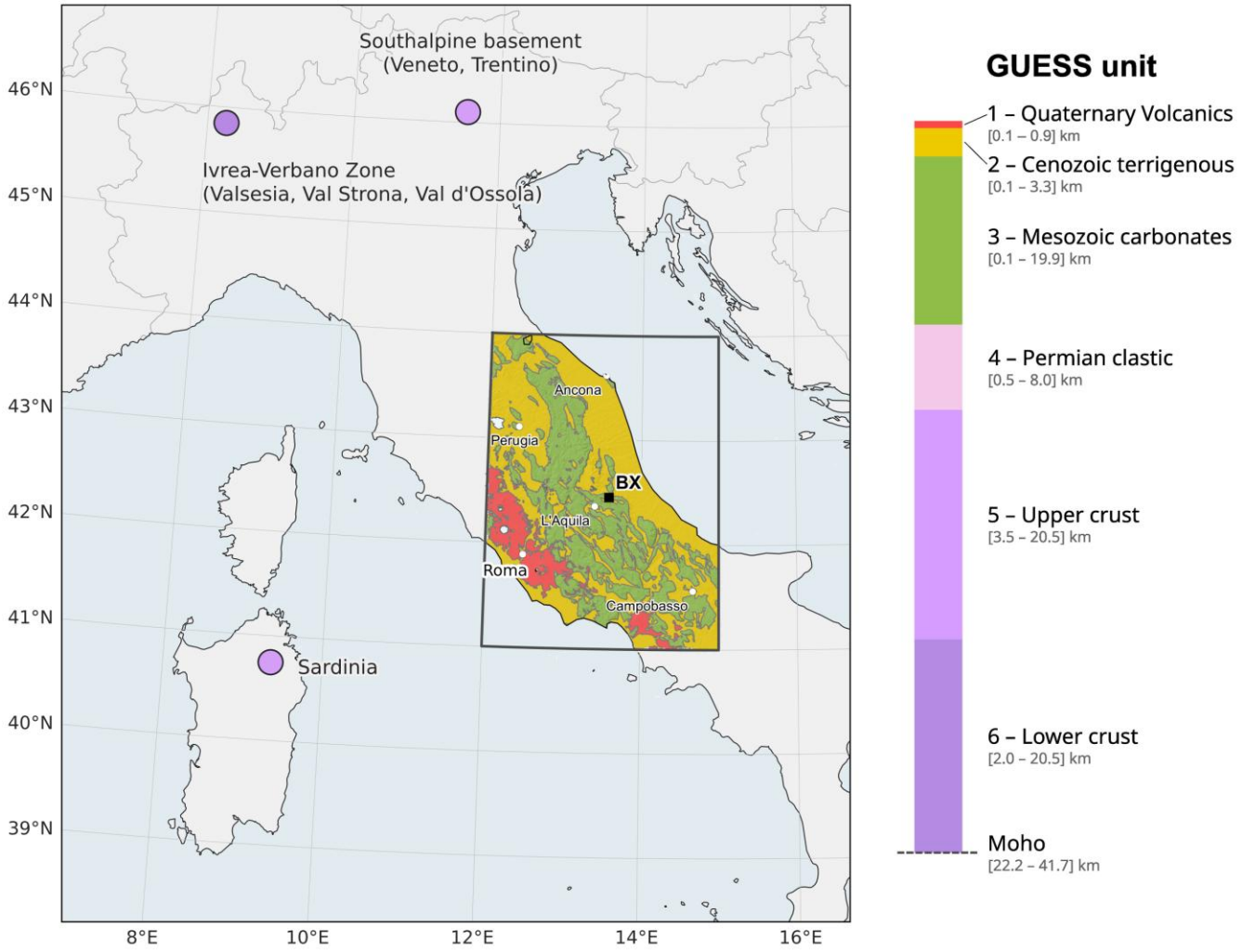
G = Response factor



$$S(X) = G \cdot a(X)$$

Response factor G: signal at the detector from a unit with unitary abundance (1 µg/g), summing all voxels: it holds geometry, density and neutrino physics.

Geological setting



The tile lies in a **complex tectonic setting**, whit the **Moho deepens from ~22 to ~42 km**.

The **crystalline basement** is overlain by a **sedimentary cover** dominated by **Mesozoic carbonates up to ~20 km thick**, which **hosts the Borexino detector**.

The **Quaternary volcanics** of the **Roman Magmatic Province** are **rich in U and Th** but only **0.1–0.9 km thick**.

The crystalline **upper crust (UC) and lower crust (LC) do not crop out** anywhere within the tile.

The **UC** is sampled on the European side in the basement of **Sardinia** and, on the Adriatic side, in the **Southalpine basement** of Veneto and Trentino.

The **LC** is sampled only in the **Ivrea-Verbano Zone**, in outcrops (Valsesia, Val Strona) and in the **ICDP-DIVE boreholes** (Val d'Ossola).

The geochemical dataset

- The geochemical base grows **from 57 samples in Coltorti et al. (2011) to 1671 in this study.**
- **Sedimentary cover and volcanics**: sampled in **Tuscany, Umbria and Marche**, complemented by Coltorti et al. (2011)[1] in the **Gran Sasso** area.
- **Upper crust**: sampled in the Variscan basement of **Sardinia** and in the **Southalpine basement**, complemented by Coltorti et al. (2011)[1] in **Valsugana**.
- **Lower crust**: sampled exclusively in the **Ivrea-Verbano Zone**, from outcrops and from the **ICDP-DIVE**[2] drill cores (Val d'Ossola).

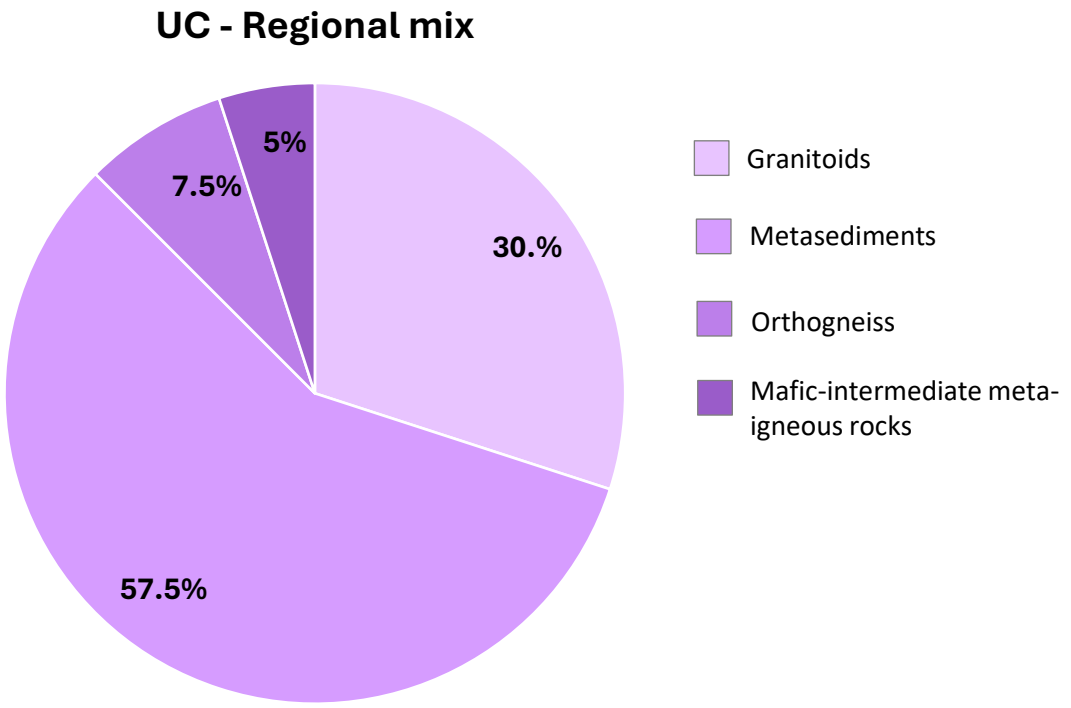
Unit	Main lithologies	Original GUESS	Coltorti et al. (2011)[1]	ICDP-DIVE, Ivrea-Verbano[2]	Total
1 Quaternary volcanics	Pyroclastics, Dykes, Tephrites, Lava	108	–	–	**108**
2 Cenozoic terrigenous sediments	Sandstones, Siltstones, Clays, Marls	550	4	–	**554**
3 Mesozoic carbonates	Limestones, Marl, Argillite, Radiolarite	432	24	–	**456**
4 Permian clastic unit	Phyllites, Metaconglomerates, Quartzites	30	–	–	**30**
5 Upper crust	Granite, Tonalite, Orthogneiss, Paragneiss	452	20	–	**472**
6 Lower crust	Metagabbro, Diorite, Stronalite, Paragneiss	11	9	31	**51**
Total		**1583**	**57**	**31**	**1671**

Original data: Callegari et al. (2013); Kaçeli Xhixha et al. (2016); Raptis et al. (2022); Strati et al. (2015). Published dataset: Strati et al. (2026), Zenodo, https://doi.org/10.5281/zenodo.21353553

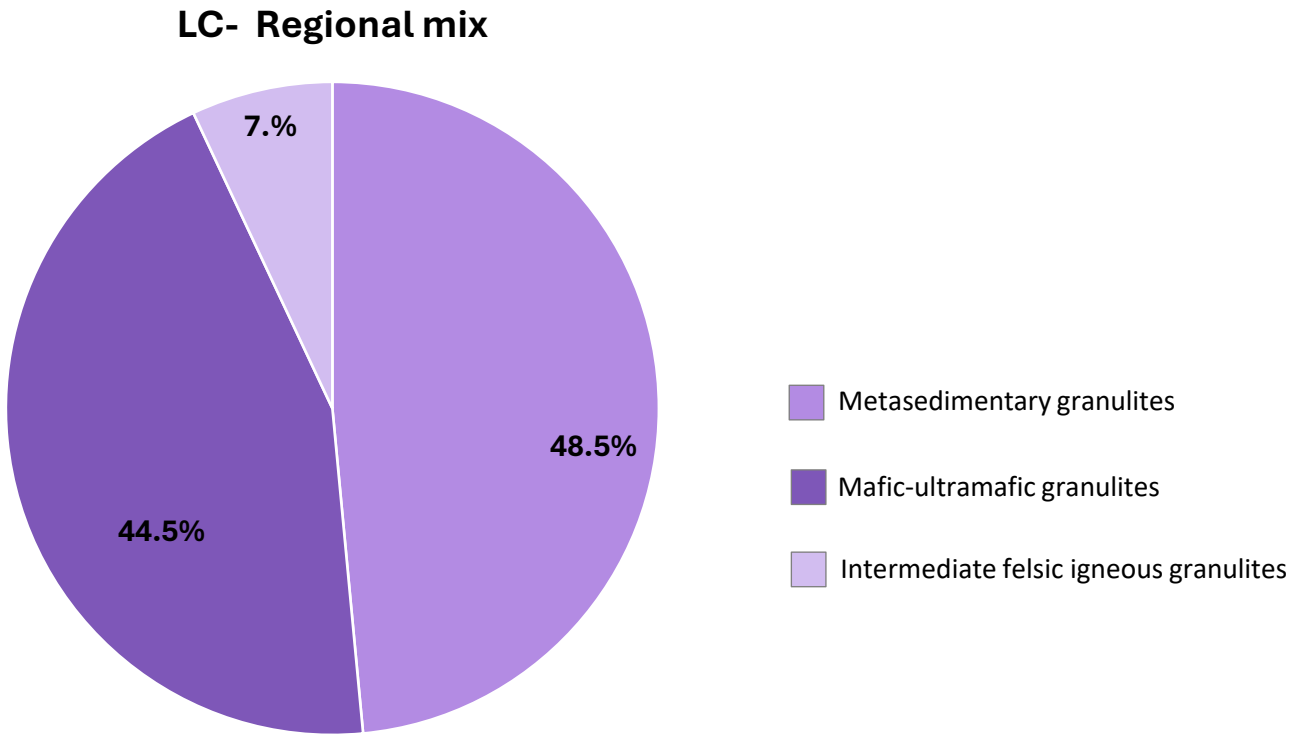
[1] Coltorti et al. (2011), Geochim. Cosmochim. Acta, 75(9), 2271–2294.

[2] Lemke et al. (2025). Thermal property data of drill cores of ICDP project DIVE (5071) and surface samples in the Ivrea-Verbano Zone [Dataset]. GFZ Data Services. https://doi.org/10.5880/ICDP.5071.005

Crystalline crust: proportions of the macrogroups



- Neither the UC nor the LC crops out in the tile, so each is modelled as a mixture of **petrogenetic macrogroups**: rock families with a common origin and similar geochemistry.
- The U and Th abundances of each unit are the weighted mean of its macrogroups, so the **proportions** are a key input.



- Two macrogroups dominate each unit: **metasediments** and **granitoids** in the **UC** (**87.5%**), **metasedimentary** and **mafic-ultramafic granulites** in the LC (**93%**).

[1]Sinigoi, S., Quick, J. E., Demarchi, G., & Klötzli, U. (2011). The role of crustal fertility in the generation of large silicic magmatic systems triggered by intrusion of mantle magma in the deep crust. Contributions to Mineralogy and Petrology, 162(4), 691–707. https://doi.org/10.1007/s00410-011-0619-2

[2]Caggianelli, A., Prosser, G., Festa, V., Langone, A., & Spiess, R. (2013). From the upper to the lower continental crust exposed in Calabria. Geological Field Trips, 5(1.2), 1–49. https://doi.org/10.3301/GFT.2013.02

Statistical treatment of U and Th abundances

Input: 11 sample populations

1671 samples → **4 sedimentary units** + **7 crystalline macrogroups**; each measurement carries its **own MDA**, values below it are **non-detects**, kept as such

↓

Outlier removal

Tukey rule, **1.5 × IQR**, **sedimentary units only**; out in one element → **removed for both**

↓

Minimum Detectable Activity (MDA)[1]: fraction of non-detects

counted on the cleaned population; decides, **per population and per element**, how the frequency distribution is derived

↓ ↓

≤ 50%: censored ML fit[2]

normal vs log-normal; **higher likelihood**, if normal has **P(x<0) < 5%**

> 50%: bounded estimate[2]

log-uniform between **lowest detected value** and **highest MDA**

↓ ↓

Th–U correlation

Th regressed on U over detected pairs; propagated when **$R^2 > 0.50$** (sedimentary units); crystalline units use the macrogroup **spread correlation ρ**

↓

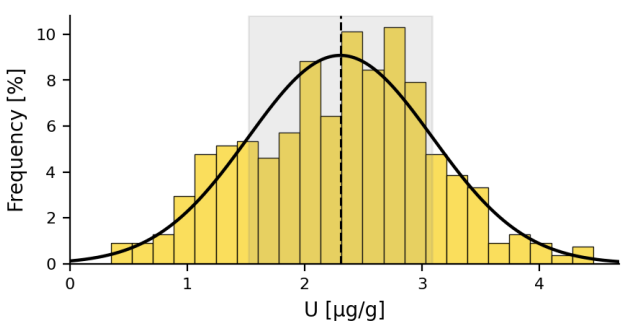
Reference value ± 1σ per population

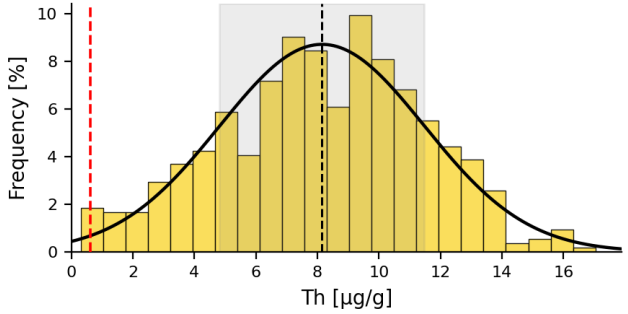
fit parameters, not sample statistics → unit distributions and crustal mixtures

[1] Helsel, D. R., & Cohn, T. A. (1988). Estimation of descriptive statistics for multiply censored water quality data. Water Resources Research, 24(12), 1997–2004.
[2] Limpert, E., & Stahel, W. A. (2011). Problems with using the normal distribution – and ways to improve quality and efficiency of data analysis. PLoS ONE, 6(7), e21403.

Statistical treatment: two representative cases

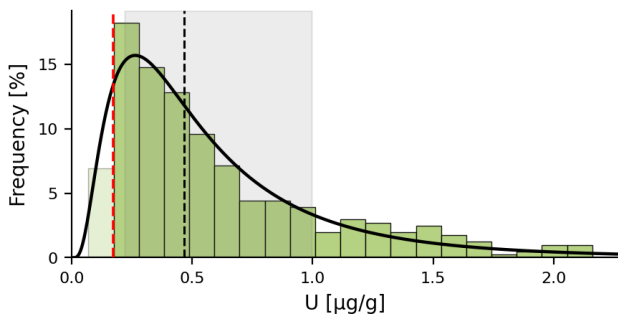
Unit 2 – Cenozoic terrigenous

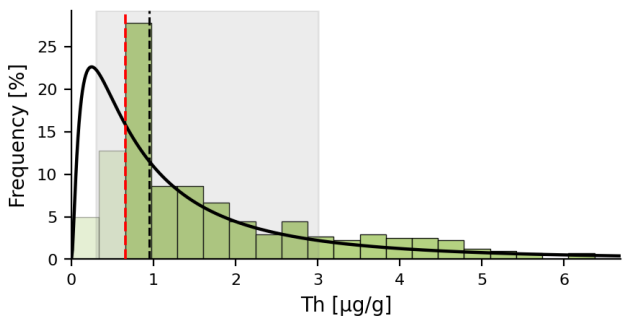


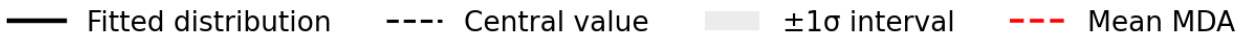


- **Data:** nearly all values are **detected**; only a few Th values lie below the MDA.
- **Fit:** the histograms are **symmetric**, so the **normal** has the higher likelihood.
- **Result:** **U = 2.3 ± 0.8 µg/g** and **Th = 8.2 ± 3.3 µg/g**; the central value is the **mean**, with a **symmetric ±1σ** well above the MDA.

Unit 3 – Mesozoic carbonates





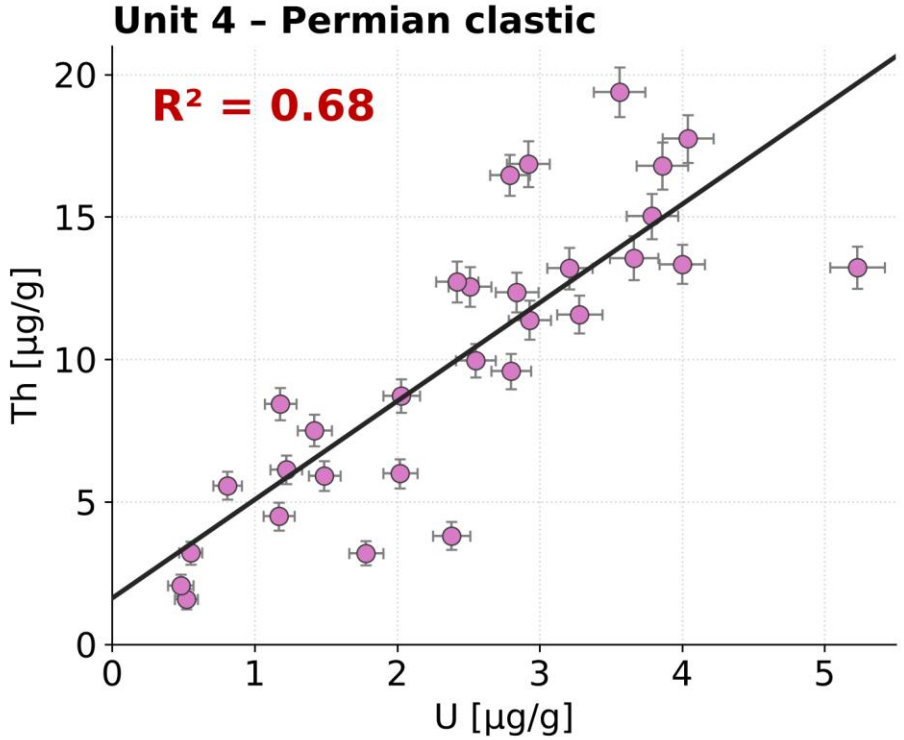


- **Data:** many values lie **near or below the MDA**
- **Fit:** the histograms are **right-skewed**, so the **log-normal** is adopted.
- **Result:** **U = 0.47** $^{+0.53}_{-0.25}$ **µg/g** and **Th = 0.94** $^{+2.06}_{-0.65}$ **µg/g**; the central value is the **median**, with an **asymmetric ±1σ** from the fit.

U and Th of the sedimentary cover

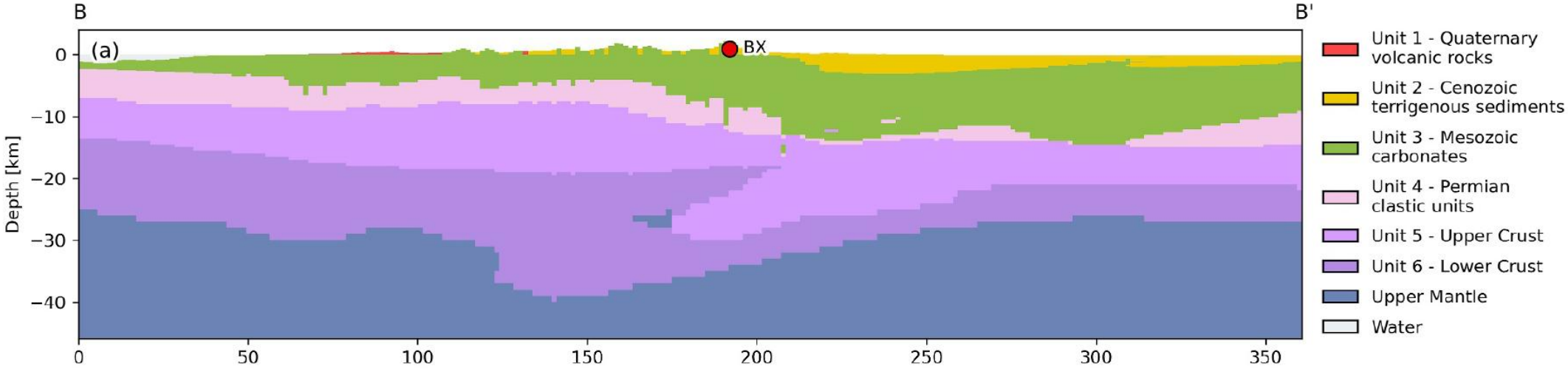
Unit	N	U [µg/g]	Th [µg/g]	Th/U	R^2
1 Quaternary volcanics	97	$9.3^{+4.3}_{-2.9}$	48 ± 26	5.2	0.49
2 Cenozoic terrigenous	543	2.3 ± 0.8	8.2 ± 3.3	3.6	0.44
3 Mesozoic carbonates	406	$0.47^{+0.53}_{-0.25}$	$0.94^{+2.06}_{-0.65}$	2.0	0.32
4 Permian clastic unit	30	2.4 ± 1.2	10.1 ± 5.1	4.2	0.68

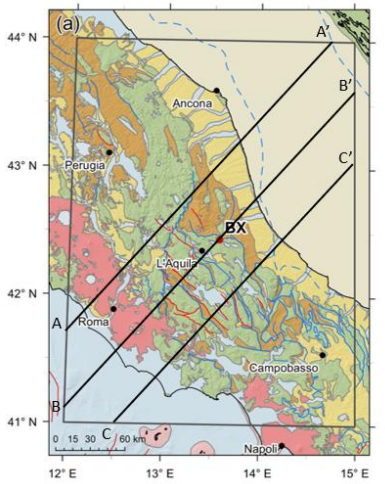
N = samples after outlier removal. R^2 = Th–U correlation over the samples with both elements detected.



- U varies by about a **factor of 20** between the **carbonates** and the **volcanics**.
- **Th/U** is highest in the **volcanics** and lowest in the **carbonates**.
- The **terrigenous sediments** and the **Permian clastic unit** have **similar U and Th**.
- Only in the **Permian clastic unit** are U and Th **correlated enough** to be **propagated together**.

U and Th of the upper and lower crust





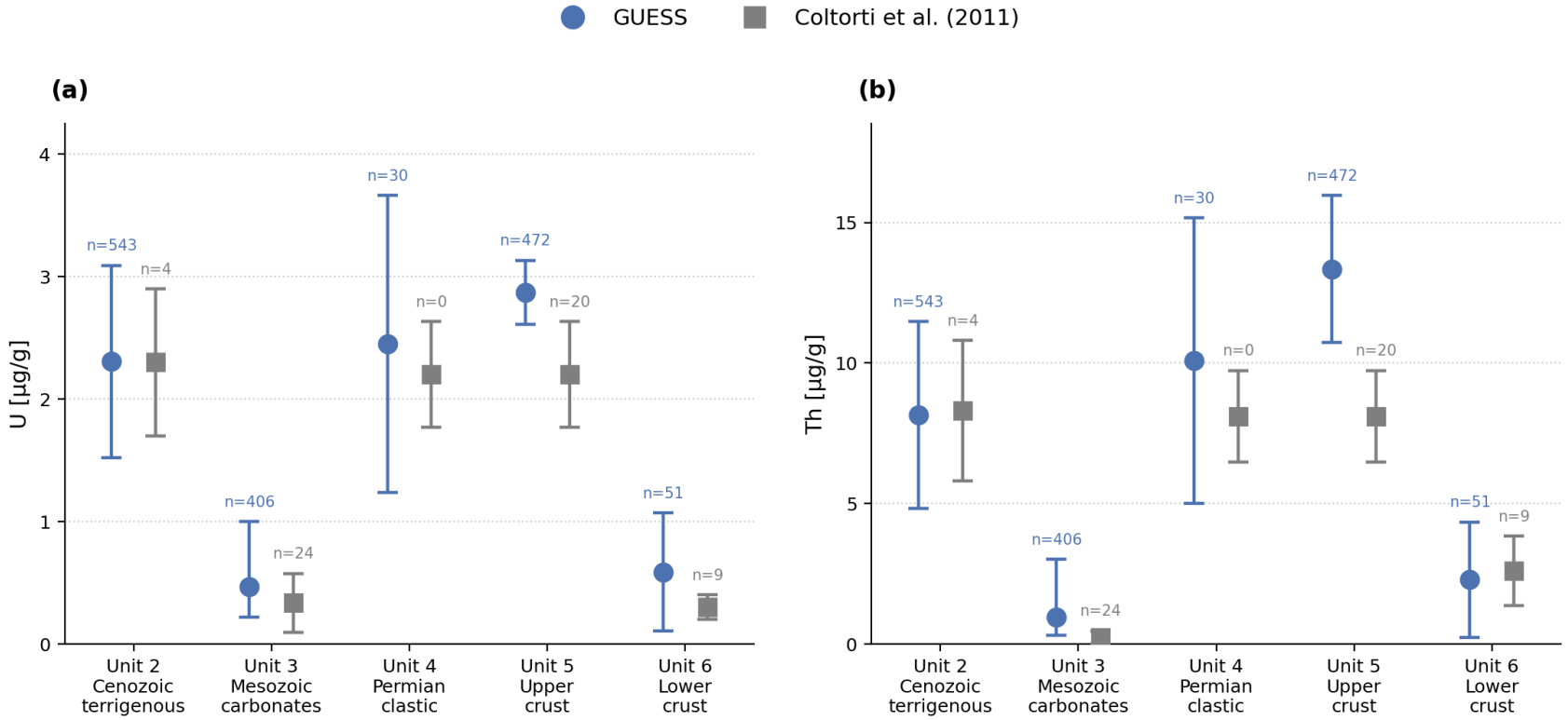
Upper crust (UC)			
Macrogroup	**N**	**U [µg/g]**	**Th [µg/g]**
Bulk UC	**472**	**2.9 ± 0.3**	**13.3 ± 2.6**
Global UC, Huang et al. (2013)[1]	–	*2.7 ± 0.6*	*10.5 ± 1.0*
Lower crust (LC)			
Bulk LC	**51**	**0.6 ± 0.5**	**2.3 ± 2.1**
Global MC + LC average, Huang et al. (2013)[1]	–	$0.57^{+0.30}_{-0.18}$	$2.9^{+2.2}_{-1.2}$

- This is expected for a Variscan basement, **rich** in **metasediments** and **granitoids**. The main rock families have **similar U and Th**, so the bulk value **barely depends on their proportions**.

- The **metasedimentary granulites** carry **most of the U and Th**, so the bulk value **depends on their proportion**.

[1] Huang, Y., Chubakov, V., Mantovani, F., Rudnick, R. L., & McDonough, W. F. (2013). A reference Earth model for the heat-producing elements and associated geoneutrino flux. Geochemistry, Geophysics, Geosystems, 14(6), 2003–2029. doi:10.1002/ggge.20129. MC + LC average: mean of their middle and lower crust.

Comparison with the previous model



- **Sedimentary cover:** the carbonates are higher in GUESS but still compatible, and the Permian clastic unit now has **30 samples of its own** instead of the upper-crust values.
- **Upper crust: Higher, especially in Th**, but **compatible within 2σ**. **Four petrogenetic macrogroups on 472 samples** instead of **two reservoirs, felsic and mafic, on 20**.
- **Lower crust: Compatible within 1σ**. The **uncertainty is larger** because it is the **weighted spread of the macrogroups**: it reflects **how different the rock families are**, not only how many samples we have.

From abundances to signal: propagating the distributions

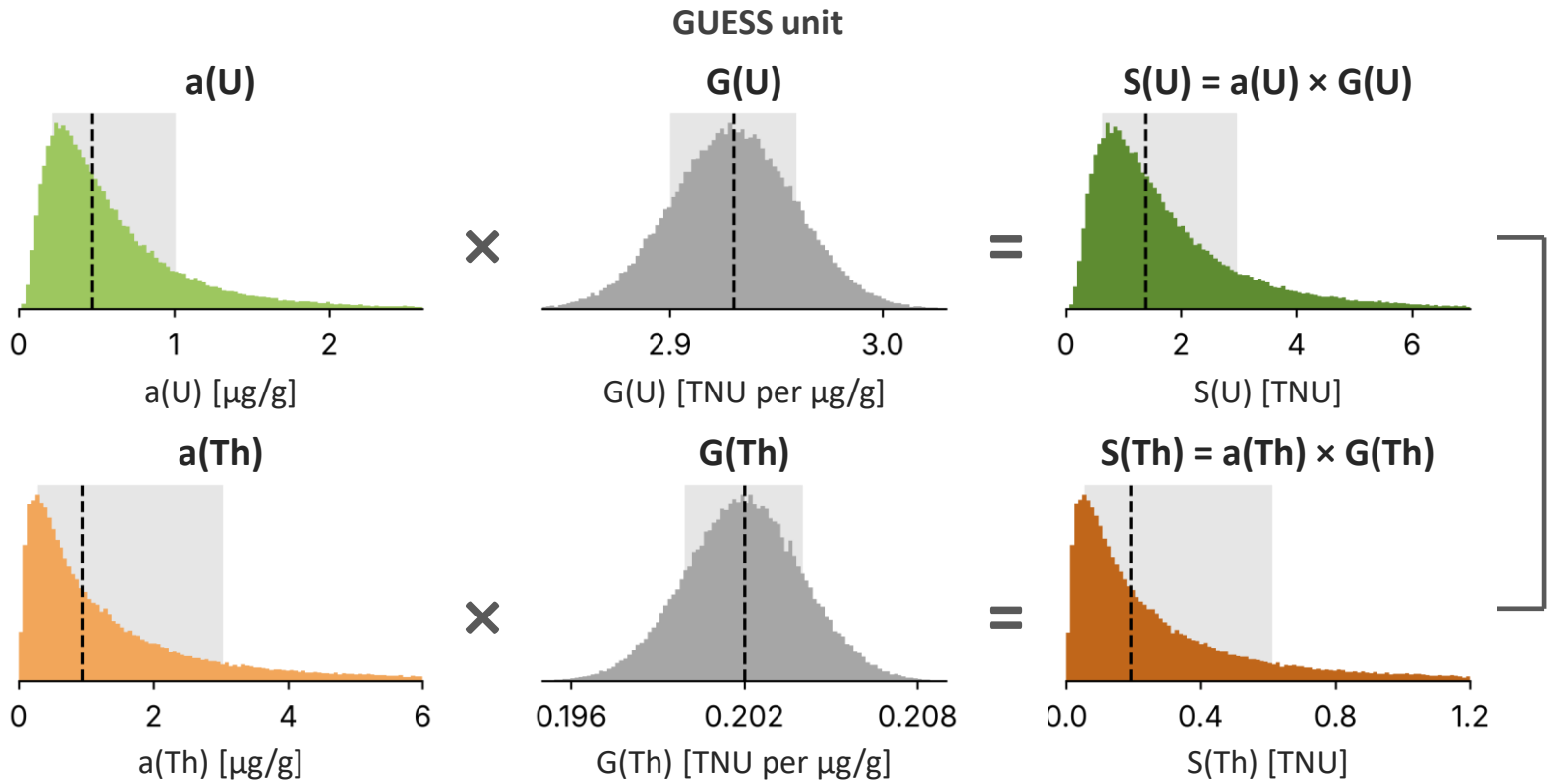
G
response factors
(Fabio's talk)

×

a(U), a(Th)
abundances, 1671 samples

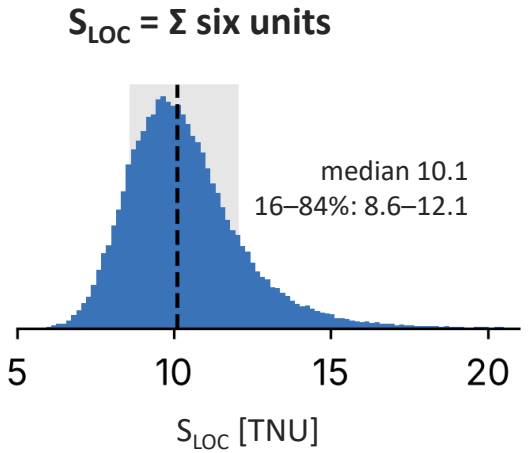
=

S_{LOC}
Local signal



S = S(U) + S(Th)

repeat for all six GUESS units and add



- A **Monte Carlo** draws a(U), a(Th) and G **10^5 times** and sums the six units (**S = a(U)·G(U) + a(Th)·G(Th)) draw by draw.**

[1] Rossi, L., Capponi, M., Conti, P., Elek, N. I., Ermini, A., Raptis, K. G. C., et al. (2026). A geophysical crustal model of Central Italy for geoneutrino prediction at Borexino. Earth and Space Science, in press.

Local signal: results by unit

Component	Volume [10^3 km^3]	S(U) [TNU]	S(Th) [TNU]	S(U+Th) [TNU]
Unit 1 – Quaternary volcanics	1.2	$(6.7^{+3.1}_{-2.1}) \times 10^{-3}$	$(2.4 \pm 1.3) \times 10^{-3}$	$(9.2^{+3.3}_{-2.5}) \times 10^{-3}$
Unit 2 – Cenozoic terrigenous	55.8	$0.39^{+0.14}_{-0.13}$	0.10 ± 0.04	0.49 ± 0.14
Unit 3 – Mesozoic carbonates	**585.1**	$\mathbf{1.4^{+1.5}_{-0.7}}$	$\mathbf{0.19^{+0.42}_{-0.13}}$	$\mathbf{1.7^{+1.7}_{-0.8}}$
Unit 4 – Permian clastic unit	285.1	1.2 ± 0.6	0.34 ± 0.17	1.5 ± 0.7
Unit 5 – Upper crust (UC)	795.7	3.9 ± 0.4	1.3 ± 0.3	5.2 ± 0.6
Unit 6 – Lower crust (LC)	737.0	$0.71^{+0.59}_{-0.58}$	0.20 ± 0.18	0.90 ± 0.76
Local crust (LOC)	n.a.	$7.8^{+1.7}_{-1.2}$	$2.2^{+0.5}_{-0.4}$	$\mathbf{10.1^{+2.0}_{-1.5}}$

- The **upper crust** gives about **half** of the local signal; the **lower crust**, with a similar volume, only **≈ 9%**.
- The **carbonates** are **poor in U and Th** but host the detector: they give **1.7 TNU**, as much as the Permian clastic unit.
- The **sedimentary cover** (Units 1–4) gives about **35%** of the local signal, the **crystalline crust** about **60%**.

From the lithospheric signal to the mantle signal

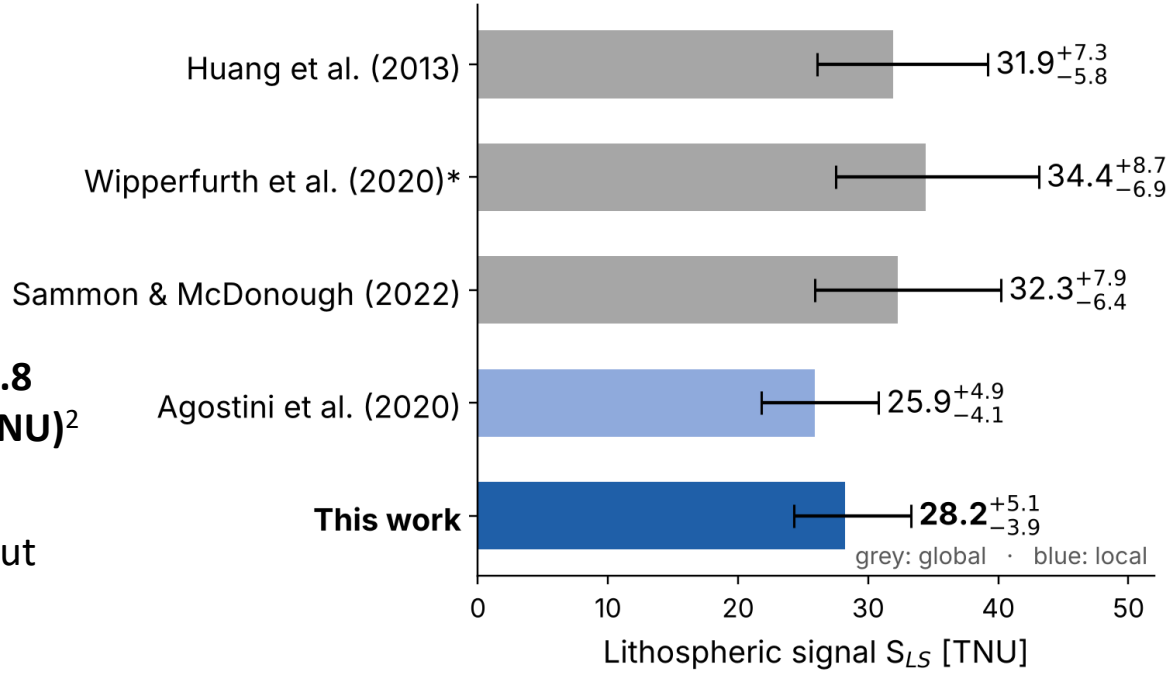
S_{LOC} $10.1\,^{+2.0}_{-1.5}$ TNU
local signal

+

S_{ROL} $17.8\,^{+4.6}_{-3.4}$ TNU
rest of lithosphere (RRM)[1]

=

S_{LS} $28.2\,^{+5.1}_{-3.9}$ TNU
total lithosphere



- Adding to the local signal the signal of the **rest of the lithosphere (17.8 TNU)**[1] gives S_{LS}; subtracting it from the **Borexino measurement (47 TNU)**[2] gives the **mantle signal S_M**.
- The rest of the lithosphere gives about **63%** of S_{LS}; the local crust about **36%**.
- Both **local models** predict a **lower lithospheric signal** than the global models, because the crust around the detector is dominated by the **sedimentary cover**, carbonates above all.

S_{exp} $47.0\,^{+8.6}_{-8.1}$ TNU
Borexino measurement[2]

−

S_{LS} $28.2\,^{+5.1}_{-3.9}$ TNU
total lithosphere

=

S_M $18.4\,^{+9.6}_{-9.7}$ TNU
mantle signal

- The mantle signal is **compatible** with the published Borexino value[2], **$21.2^{+9.6}_{-9.0}$ TNU**, within **0.3σ**.

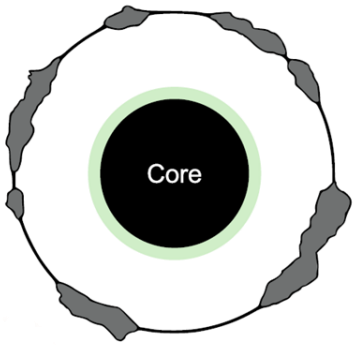
[1] Refined Reference Model: Huang, Y., et al. (2013), G-cubed, 14(6), 2003–2029, doi:10.1002/ggge.20129; far-field crust (87%) + continental lithospheric mantle (13%), as in Agostini et al. (2020).
[2] Agostini, M., et al. (Borexino Collaboration) (2020). Comprehensive geoneutrino analysis with Borexino. Physical Review D, 101(1), 012009. doi:10.1103/PhysRevD.101.012009
FiWipperfurth, S. A., Šrámek, O., & McDonough, W. F. (2020), JGR Solid Earth, 125, e2019JB018433; Sammon, L. G., & McDonough, W. F. (2022), EPSL, 593, 117684; Huang et al. (2013); Agostini et al. (2020).

From mantle signals to radiogenic power

- β combines **nuclear and neutrino inputs** with one assumption, the mantle **Th/U = 3.7**; it then depends only on **how U and Th are distributed** in the mantle.
- We adopt the mean of the two scenarios, **β = 0.86 TNU/TW**, in the **linear relation** (Bellini et al., 2022):

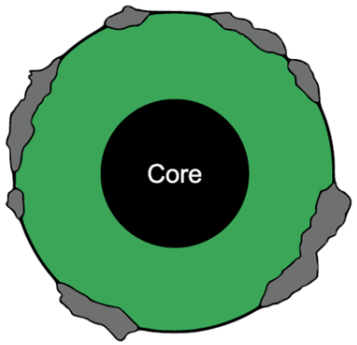
$$S_M(U+Th) = \beta \cdot H_M(U+Th)$$

LOW SCENARIO

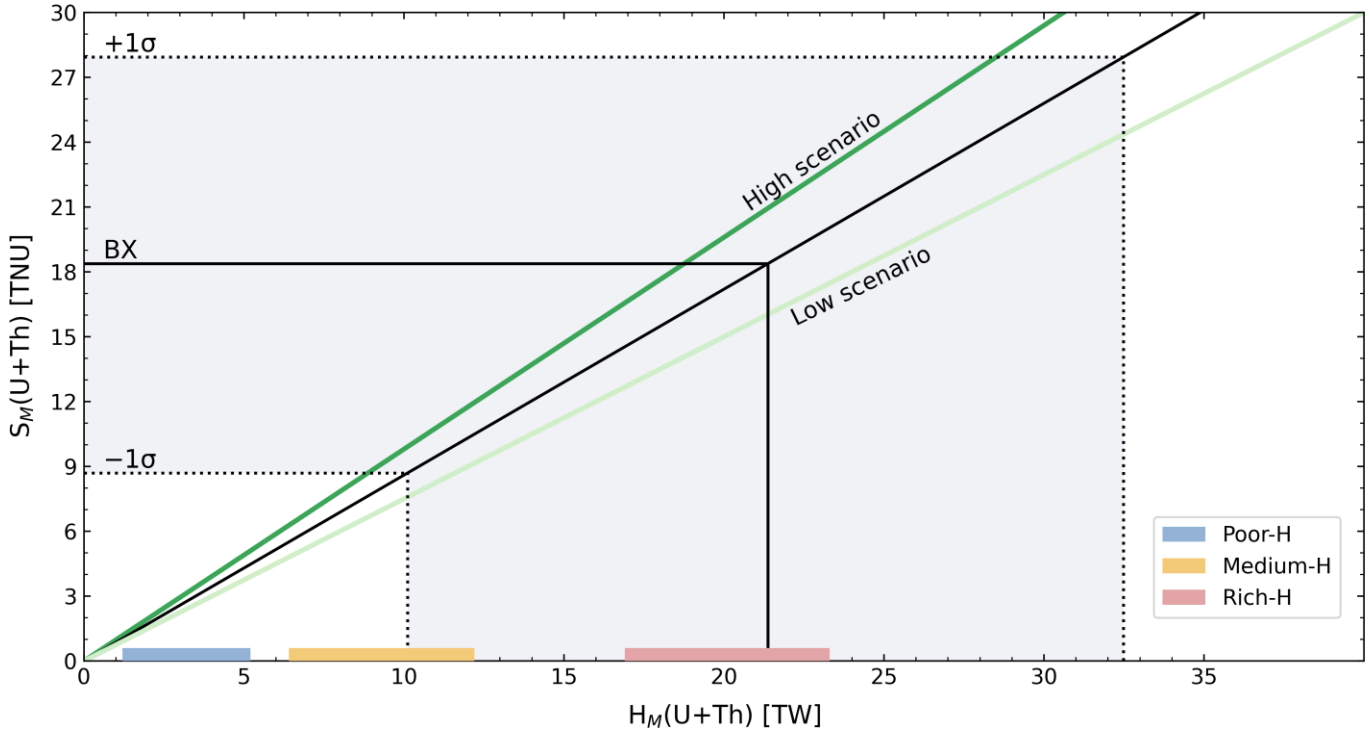


$\beta = 0.75$

HIGH SCENARIO



$\beta = 0.98$



H_M(U+Th) = 21 ± 11 TW

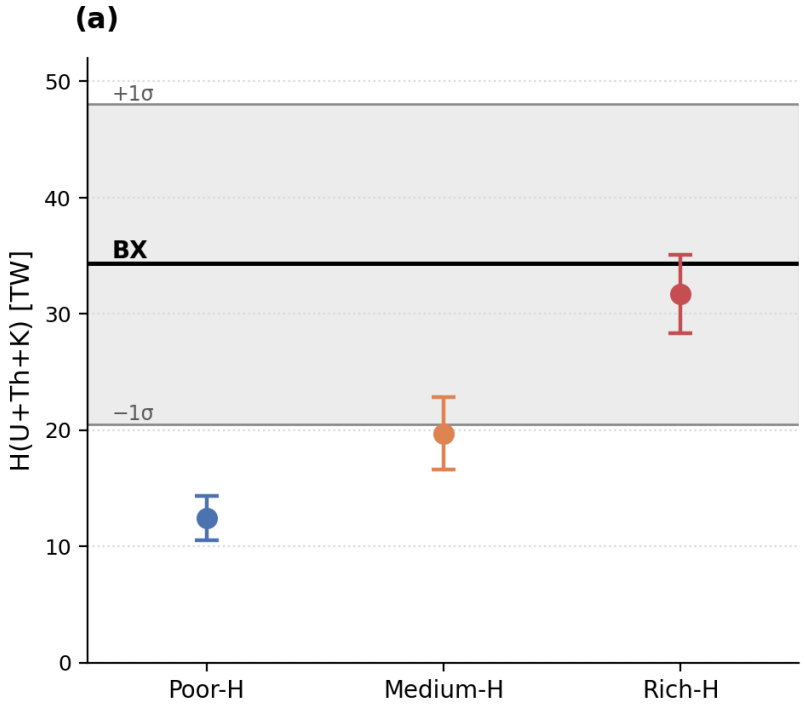
	Poor-H	Medium-H	Rich-H
H_M(U+Th) [TW]	$3.2^{+2.0}_{-2.1}$	9.3 ± 2.9	$20.2^{+3.2}_{-3.3}$
S_M(U+Th) [TNU]	$2.8^{+2.4}_{-1.9}$	$8.0^{+4.0}_{-3.2}$	$17.4^{+5.7}_{-4.7}$

Bellini et al. (2022), Geoneutrinos and geoscience: an intriguing joint-venture (arXiv:2109.01482, IRIS UniFe)

Energy heat budget

- Assuming the contribution from ^{40}K to be **18%** of the total mantle radiogenic heat, and summing the well-constrained contribution from the **lithosphere**[3], we obtain **H(U+Th+K) = 34 ± 14 TW**.
- It **agrees with the rich-H class**[1] and is **consistent within 2σ** also with the **medium-H** and **poor-H** classes.
- Of the surface heat loss[2], radioactivity supplies **34 TW** (26 in the mantle, 8 in the lithosphere); the remaining **12 ± 14 TW** is the **secular cooling** of mantle and core.

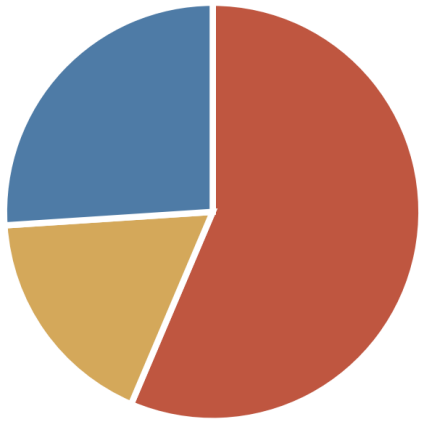
Borexino vs Bulk Silicate Earth classes[1]



Surface heat loss Q = 46 ± 3 TW (Jaupart et al., 2015)[2]

Secular cooling

$C = Q - H = 12 \pm 14$ TW



Mantle radiogenic

$H_M(U+Th+K) = 26 \pm 14$ TW

Lithosphere

$H_{LS}(U+Th+K) = 8.1^{+1.9}_{-1.4}$ TW

Lithospheric radiogenic power: Agostini et al. (2020)[3]

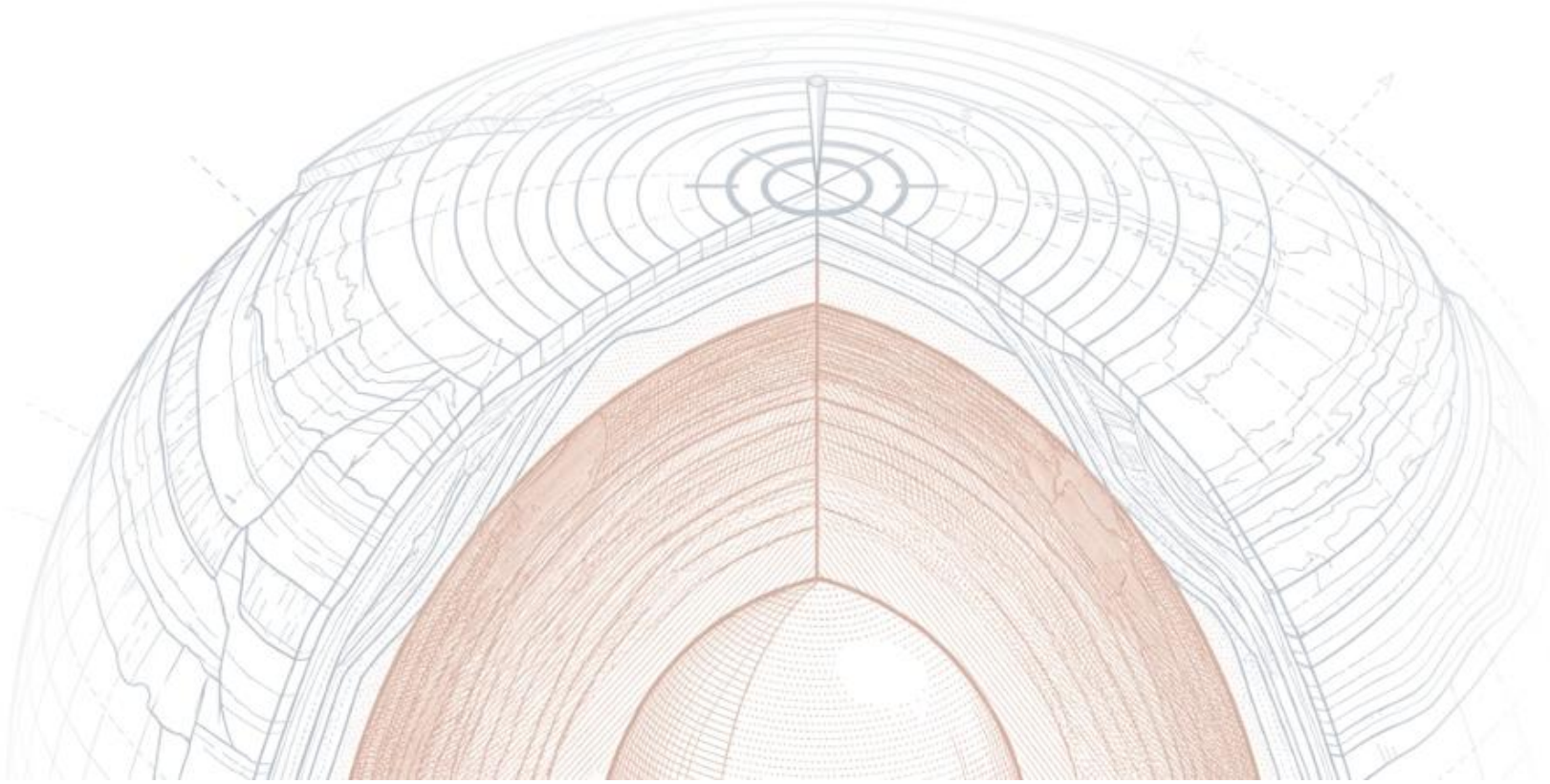
[1] Bellini, G., Inoue, K., Mantovani, F., Serafini, A., Strati, V., & Watanabe, H. (2022). Geoneutrinos and geoscience: An intriguing joint-venture. La Rivista del Nuovo Cimento, 45(1), 1–105. doi:10.1007/s40766-021-00026-7
[2] Jaupart, C., Labrosse, S., Lucazeau, F., & Mareschal, J.-C. (2015). Temperatures, heat, and energy in the mantle of the Earth. Treatise on Geophysics, 7, 223–270. doi:10.1016/B978-0-444-53802-4.00126-3
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Conclusions & perspectives

- U and Th are assigned to every GUESS unit from **1671 rock samples**, **1583** of them original, with **fitted distributions** and **propagated uncertainties**.
- The local crust gives **$10.1^{+2.0}_{-1.5}$ TNU** and the lithosphere **$28.2^{+5.1}_{-3.9}$ TNU**: an **ordinary basement** lies under a **carbonate cover poor in U and Th**.
- The volcanics are the **richest unit** but give **less than 0.01 TNU**, so they **cannot explain** the high Borexino signal.
- The mantle signal is **$18.4^{+9.6}_{-9.7}$ TNU** and the mantle radiogenic power **26 ± 14 TW**, which **confirms the previous Borexino result**.
- A more precise result needs a **joint analysis of several detectors** (Borexino, KamLAND, SNO+, JUNO), each with its **own local model**.

Manuscript: Refining the Local Geoneutrino Signal at Borexino: A New Look at the Mantle Radiogenic Power — Strati et al. (2026), Geochemistry, Geophysics, Geosystems: under review.

Thank you



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