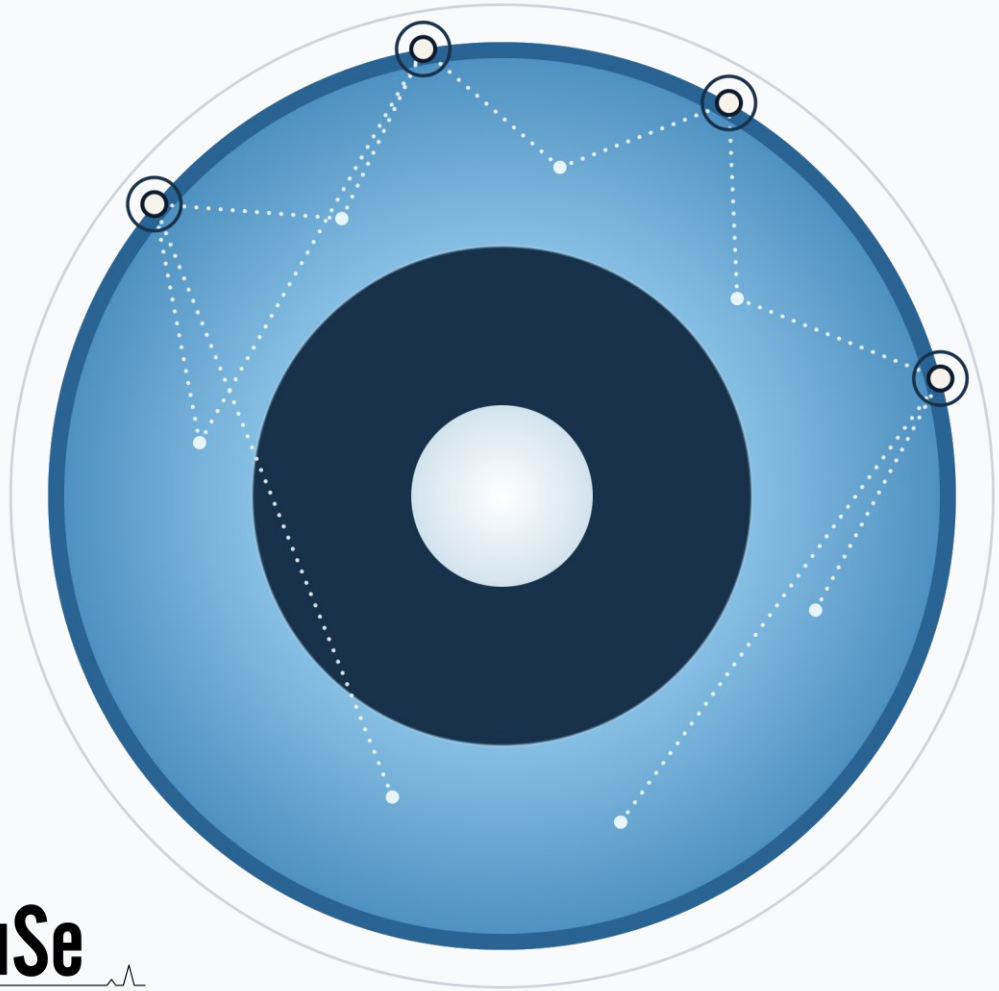
NEUTRINO GEOSCIENCE 2026
Zhuhai, China (16–19 November 2026)

How radioactive is the Earth?

A multi-site geoneutrino perspective

Virginia Strati – strati@fe.infn.it
M. Albèri, E. C. Esen, G. Hasnain, F. Mantovani,
K. G. C. Raptis, N. I. Elek

University of Ferrara · INFN Ferrara



FERRARIAE UNIVERSITAS · EX LABORE FRUCTUS · 13 91

INFN
Istituto Nazionale di Fisica Nucleare

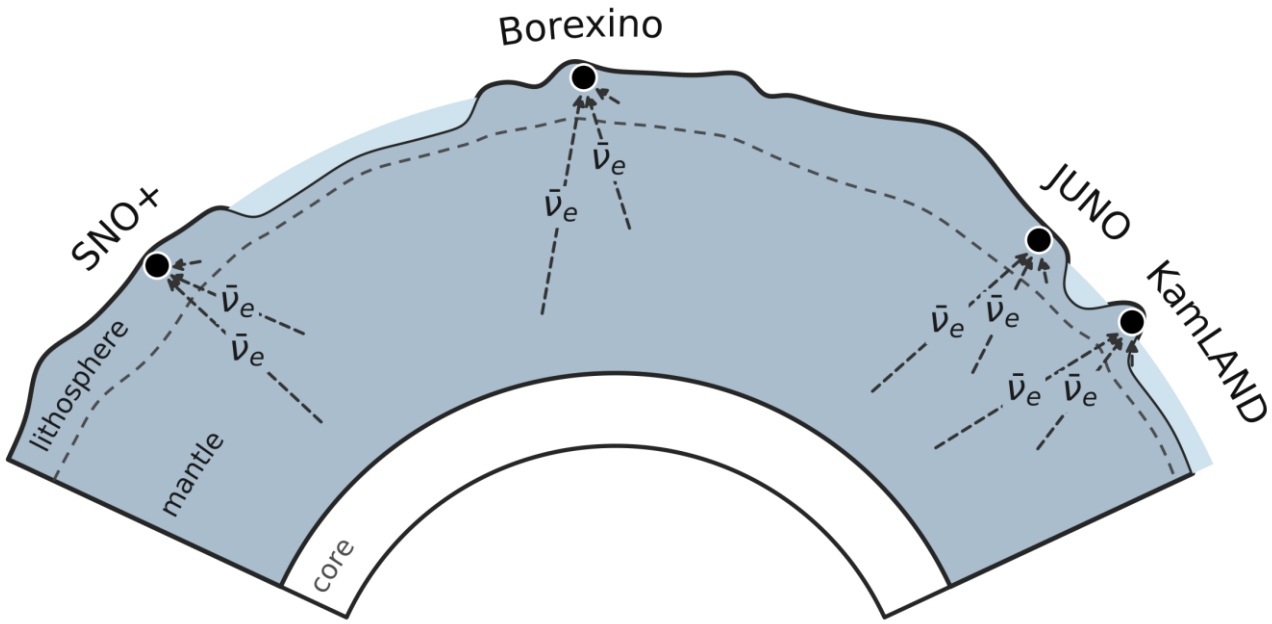
Laboratory for Nuclear Technologies — Applied to the Environment —

FUNDAMENTAL PHYSICS · SEISMOLOGY · AI · EXPERIMENTS

FuSe
TESTING FUNDAMENTAL PHYSICS WITH SEISMOLOGY

Geoneutrinos enter the multi-site era

- **Four experiments on the Earth:** KamLAND, Borexino, SNO+ and JUNO measure geoneutrinos each from its own observatory, on three continents and on very different lithospheres
- **A gap to fill:** only two sites, KamLAND and Borexino, had been combined before[1]
- Combining four sites brings **new challenges**, since the experiments differ in how they analyze the data and their uncertainties are partly correlated



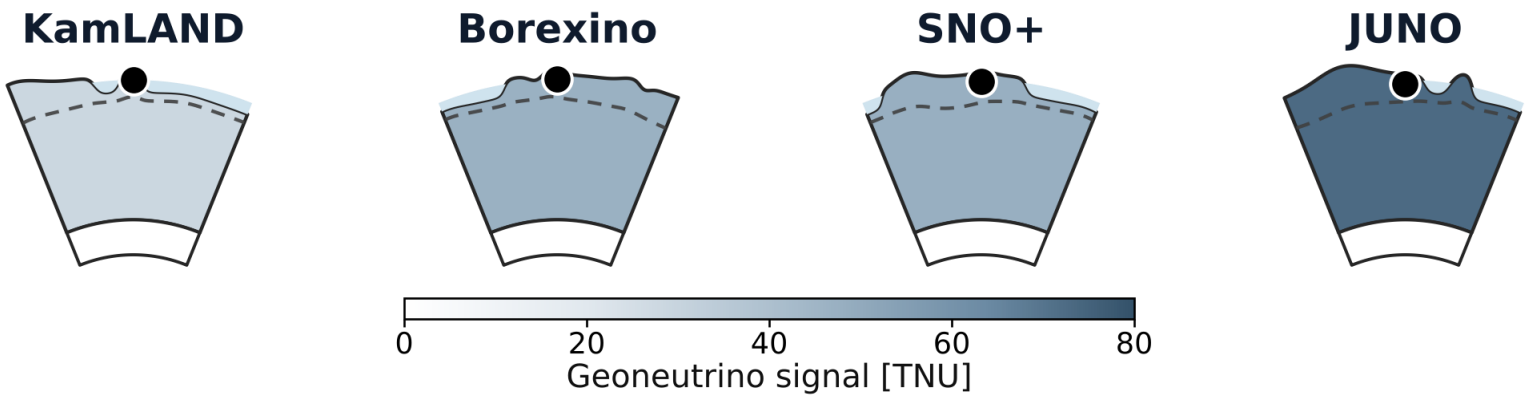
What we learn about the mantle's radioactivity from these 4 experiments?

What does its value imply for Earth's heat budget?

[2]Bellini, G., Inoue, K., Mantovani, F., Serafini, A., Strati, V., Watanabe, H., 2022. Geoneutrinos and geoscience: an intriguing joint-venture. Riv. Nuovo Cimento 45, 1–105. https://doi.org/10.1007/s40766-021-00026-7

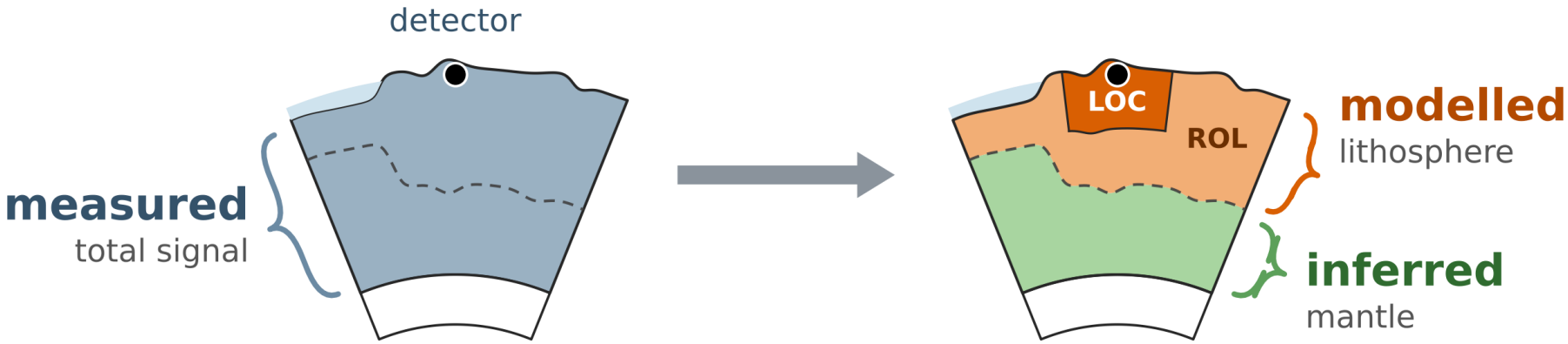
Four detectors and four geoneutrino signals

Detector	KamLAND[1]	Borexino[2]	SNO+[3]	JUNO[4]
Overburden [m.w.e.]	2700	3800	5900	1800
Scintillator mass [kton]	1	0.278	0.78	20
Data taking [MM/YYYY]	03/2002–12/2020	12/2007–04/2019	05/2022–07/2025	08/2025–05/2026
Live time [d]	5227	3263	685.2	207.2
Geoneutrino events	174^{+29}_{-28}	$52.6^{+9.4}_{-8.6}$ (stat) $^{+2.7}_{-2.1}$ (sys)	35 ± 9	439 ± 66
Th/U signal ratio	free	0.27 (fixed)	$0.26^{+0.14}_{-0.07}$	0.29 ± 0.03
S_{exp}(U+Th) [TNU]	$\mathbf{28.6^{+5.1}_{-4.8}}$	$\mathbf{47.0^{+8.6}_{-8.1}}$	$\mathbf{48^{+14}_{-12}}$	**73 ± 11**



[1] Abe, S., et al. (KamLAND Collaboration), 2022. Abundances of uranium and thorium elements in Earth estimated by geoneutrino spectroscopy. Geophys. Res. Lett. 49, e2022GL099566. https://doi.org/10.1029/2022GL099566
[2] Agostini, M., et al. (Borexino Collaboration), 2020. Comprehensive geoneutrino analysis with Borexino. Phys. Rev. D 101, 012009. https://doi.org/10.1103/PhysRevD.101.012009
[3] SNO+ Collaboration (Abreu, M., et al.), 2026. Measurement of reactor antineutrino oscillations with 1.46 ktonne-years of data at SNO+. arXiv:2511.11856v4. https://doi.org/10.48550/arXiv.2511.11856
[4] JUNO Collaboration (Adam, T., et al.), 2026. Measurement of neutrino oscillation parameters at JUNO and indication of the neutrino mass ordering. arXiv:2609.37895v1. https://doi.org/10.48550/arXiv.2609.37895

From the measured signal to the mantle

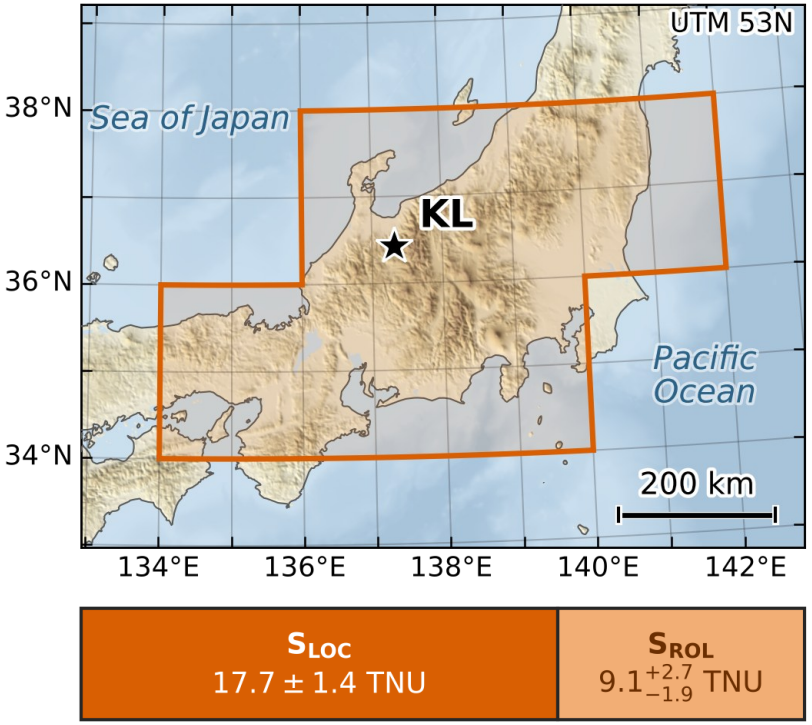


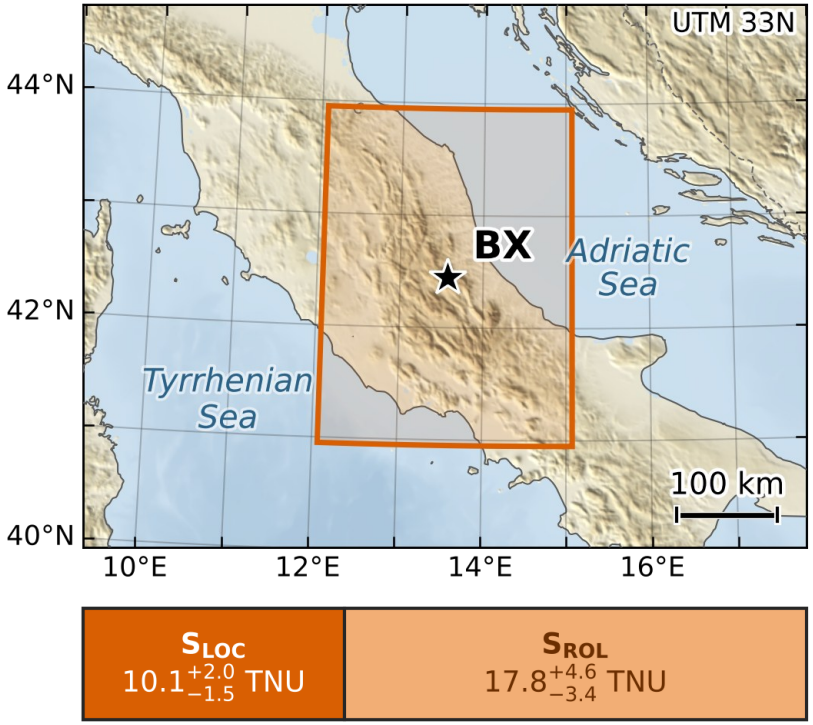
$$S_{exp} = S_{LOC} + S_{ROL} + S_M \quad \Rightarrow \quad S_M = S_{exp} - S_{LOC} - S_{ROL}$$

- **Two lithospheric components:** the LOcal Crust (LOC), within a few hundred kilometers of the detector, and the Rest Of the Lithosphere (ROL), the far-field crust and the continental lithospheric mantle.
  At each site LOC and ROL are not correlated.
- **LOC:** at each site a dedicated model with regional geophysical and geochemical data is used for calculating the signal contribution. *LOC are not correlated among the sites*.
- **ROL:** the same model (Refined Reference Model - RRM[1]) is adopted to evaluate the signal from the region complementary to each LOC region. *The ROL is 100% correlated among the sites*

[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. Geochem. Geophys. Geosyst. 14, 2003–2029. https://doi.org/10.1002/ggge.20129

Local models: KamLAND and Borexino





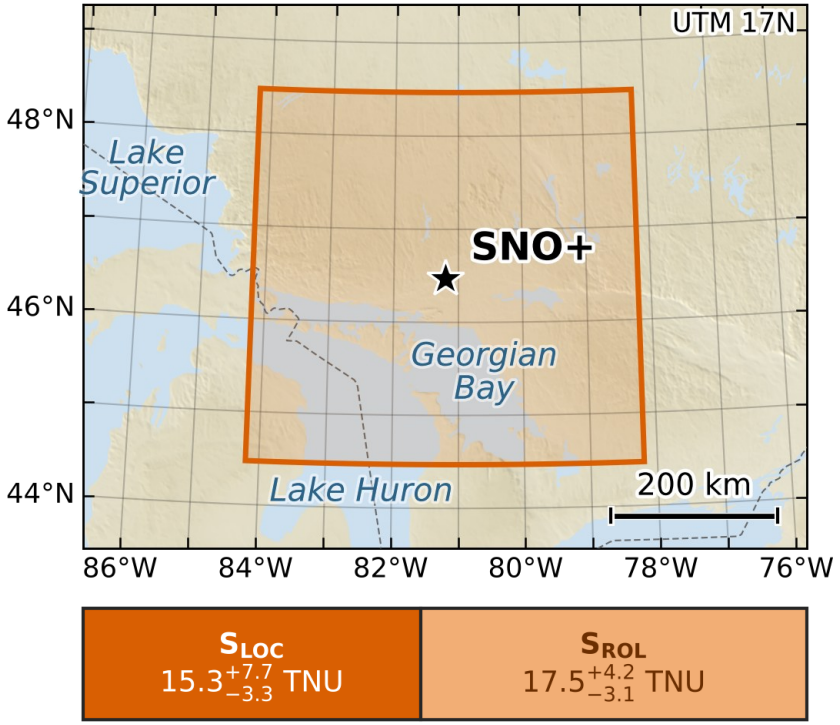
- **KamLAND** (island arc of Japan): six staggered 2°×2° tiles. The model adds the subducting slab and the Japan Sea to an upper crust depleted in heat-producing elements relative to the average continental crust[1,2]. S_{LOC} is about **66%** of the lithospheric signal
- **Borexino** (central Apennines): 3°×3° region around the detector. A sedimentary cover dominated by Mesozoic carbonates rests on an upper and a lower crust[3]**.** S_{LOC} is about **36%** of the lithospheric signal

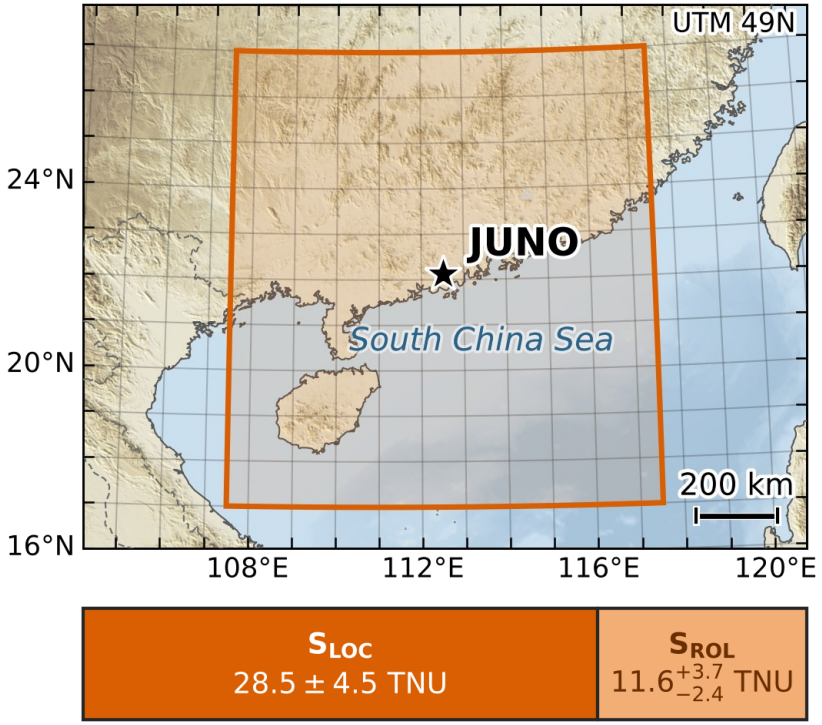
[1] Fiorentini, G., Fogli, G.L., Lisi, E., Mantovani, F., Rotunno, A.M., 2012. Mantle geoneutrinos in KamLAND and Borexino. Phys. Rev. D 86, 033004. https://doi.org/10.1103/PhysRevD.86.033004

[2] Bellini, G., Inoue, K., Mantovani, F., Serafini, A., Strati, V., Watanabe, H., 2022. Geoneutrinos and geoscience: an intriguing joint-venture. Riv. Nuovo Cimento 45, 1–105. https://doi.org/10.1007/s40766-021-00026-7

[3] Strati, V., Abdelkader, M., Albèri, M., Albertella, A., Capponi, M., Conti, P., Ermini, A., Esen, E.C., Hasnain, G., Mantovani, F., Raptis, K.G.C., Reguzzoni, M., Rossi, L., Salvini, R., Sampietro, D., Elek, N.I., 2026. Refining the local geoneutrino signal at Borexino: a new look at the mantle radiogenic power. Submitted to Geochem. Geophys. Geosyst.

Local models: SNO+ and JUNO





- **SNO+** (Sudbury, Canada): 6°×4° region on the Archean Superior craton, near the Sudbury impact structure and the Proterozoic Huronian Supergroup[1]. S_{LOC} is about **47%** of the lithospheric signal
- **JUNO** (Cathaysia block, South China): 10°×10° region, with Mesozoic granites widespread in the upper crust (JULOC model)[2]. S_{LOC} is about **71%** of the lithospheric signal

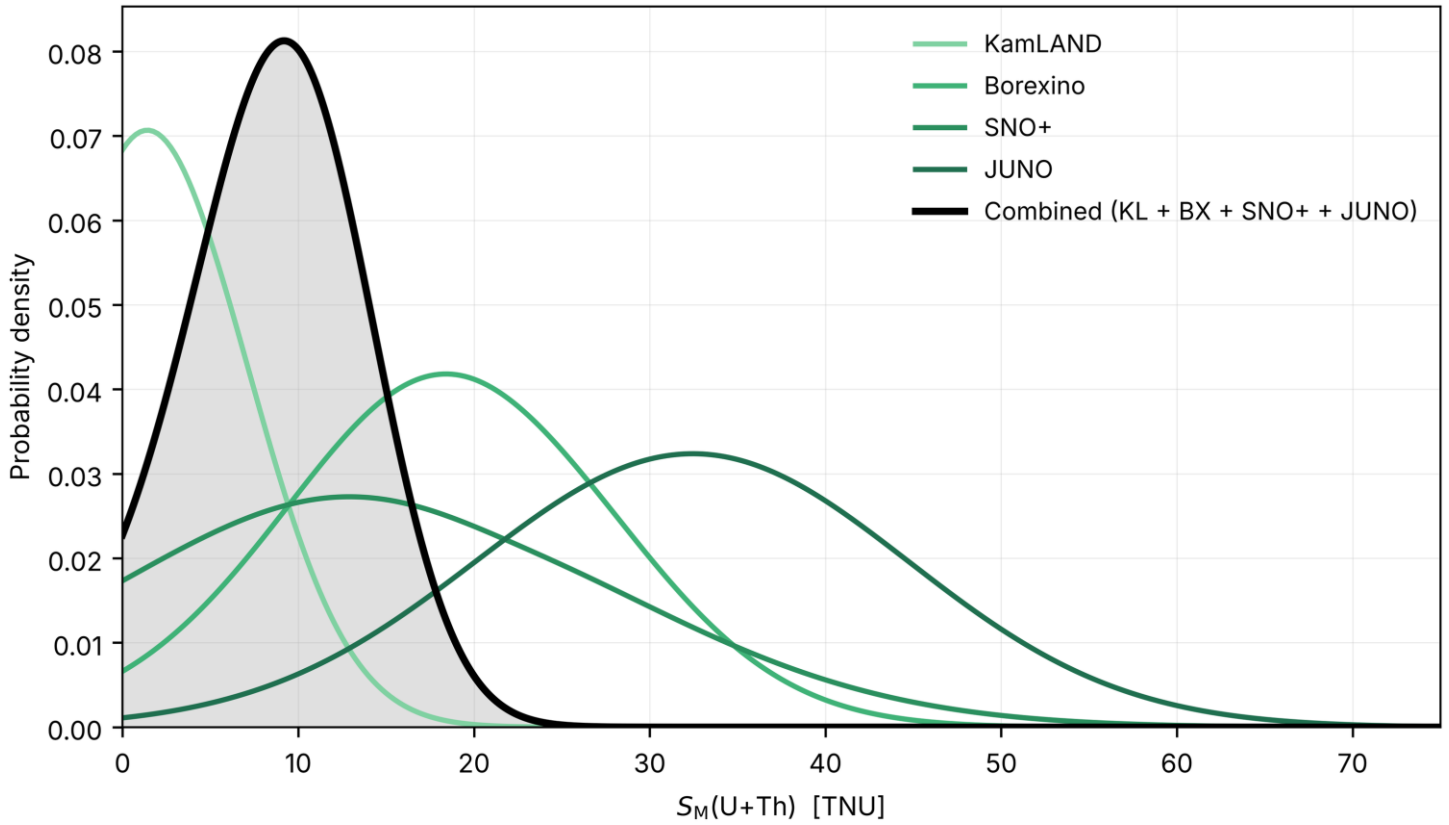
[1] Strati, V., Wipperfurth, S.A., Baldoncini, M., McDonough, W.F., Mantovani, F., 2017. Perceiving the crust in 3-D: a model integrating geological, geochemical, and geophysical data. Geochem. Geophys. Geosyst. 18, 4326–4341. https://doi.org/10.1002/2017GC007067

[2] Gao, R., Li, Z., Han, R., Wang, A., Li, Y., Xi, Y., Liu, J., Mao, X., Sun, Y., Xu, Y., 2020. JULOC: a local 3-D high-resolution crustal model in South China for forecasting geoneutrino measurements at JUNO. Phys. Earth Planet. Inter. 299, 106409. https://doi.org/10.1016/j.pepi.2019.106409

Four residuals, one common mantle

- **Input PDFs**: S_{exp}, S_{LOC} and S_{ROL} are rebuilt from their published central values and 68% intervals
- Each site: $S_{exp} - S_{LOC} - S_{ROL}$ gives a residual PDF, the **mantle signal** as seen from that site

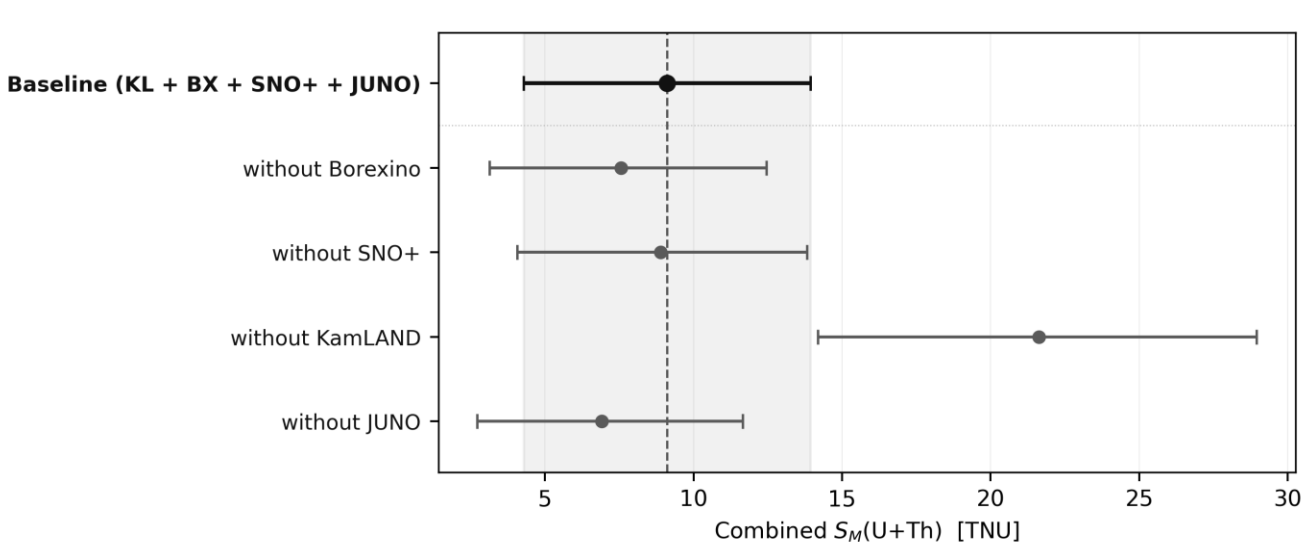
	KamLAND	Borexino	SNO+	JUNO	Combined
S_M(U+Th) [TNU]	$4.4^{+4.5}_{-3.0}$	$18.8^{+9.4}_{-9.0}$	$16.8^{+13.7}_{-10.5}$	32.4 ± 12.3	**9.1 ± 4.8**



- **One mantle for all**: the four sites see the same S_M. Each curve says how plausible a value is for one site. The combined PDF (black) is the product of the four residual PDFs
- **Prior $S_M \geq 0$**: the mantle cannot give a negative signal. The prior removes 8% of the combined PDF.

Compatibility with one common mantle

- **χ^2**: measures how much the four residuals scatter around the combined value. Divided by the degrees of freedom (number of sites − 1), it gives the reduced χ^2, 1 on average when the scatter comes only from the uncertainties
- **p-value**: how often chance alone would give a χ^2 at least this large if the four sites saw the same mantle

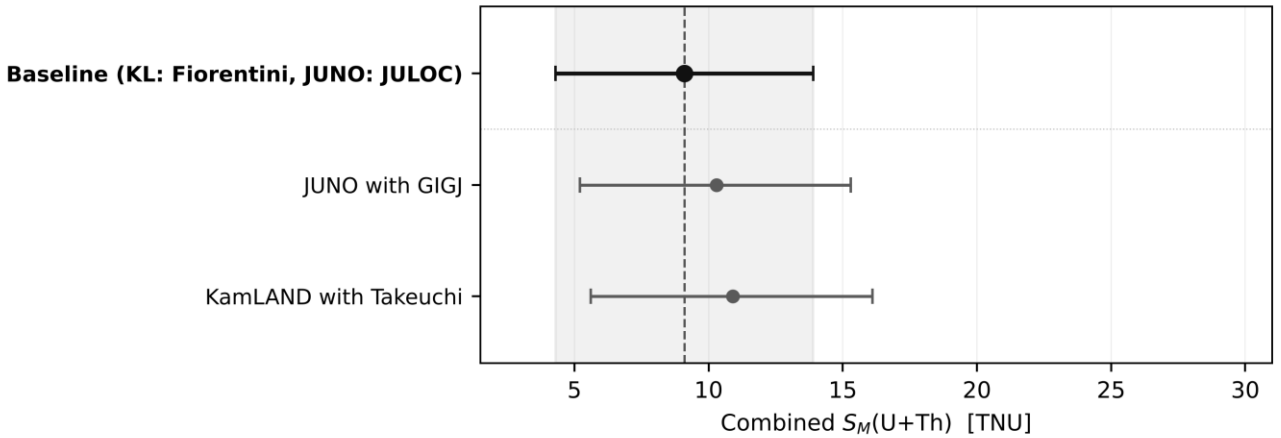


	χ^2/dof	reduced χ^2	p
Baseline (KL + BX + SNO+ + JUNO)	**7.1/3**	**2.4**	**0.07**
without Borexino	5.9/2	2.9	0.05
without SNO+	7.0/2	3.5	0.03
without KamLAND	1.2/2	0.6	0.54
without JUNO	3.0/2	1.5	0.22

- **Four sites**: the χ^2 and the p-value indicate that the four residuals are compatible with one common mantle
- **Without Borexino or SNO+**: the χ^2 hardly changes and p stays low. These two sites add little to the scatter
- **Without KamLAND or JUNO**: the χ^2 drops and p rises. The scatter comes from these two sites
- **Combined S_M**: compared with the baseline, removing KamLAND or JUNO moves it to 22 and 7 TNU, respectively

Sensitivity to the local crustal models

- **Alternative local models**: we tested them for KamLAND and JUNO, replacing one local model at a time



	χ^2/dof	reduced χ^2	p	KamLAND–JUNO difference
Baseline (KL: Fiorentini, JUNO: JULOC)	**7.1/3**	**2.4**	**0.07**	**2.4σ**
JUNO with GIGJ	12.4/3	4.1	0.006	3.4σ
KamLAND with Takeuchi	5.9/3	2.0	0.12	2.2σ

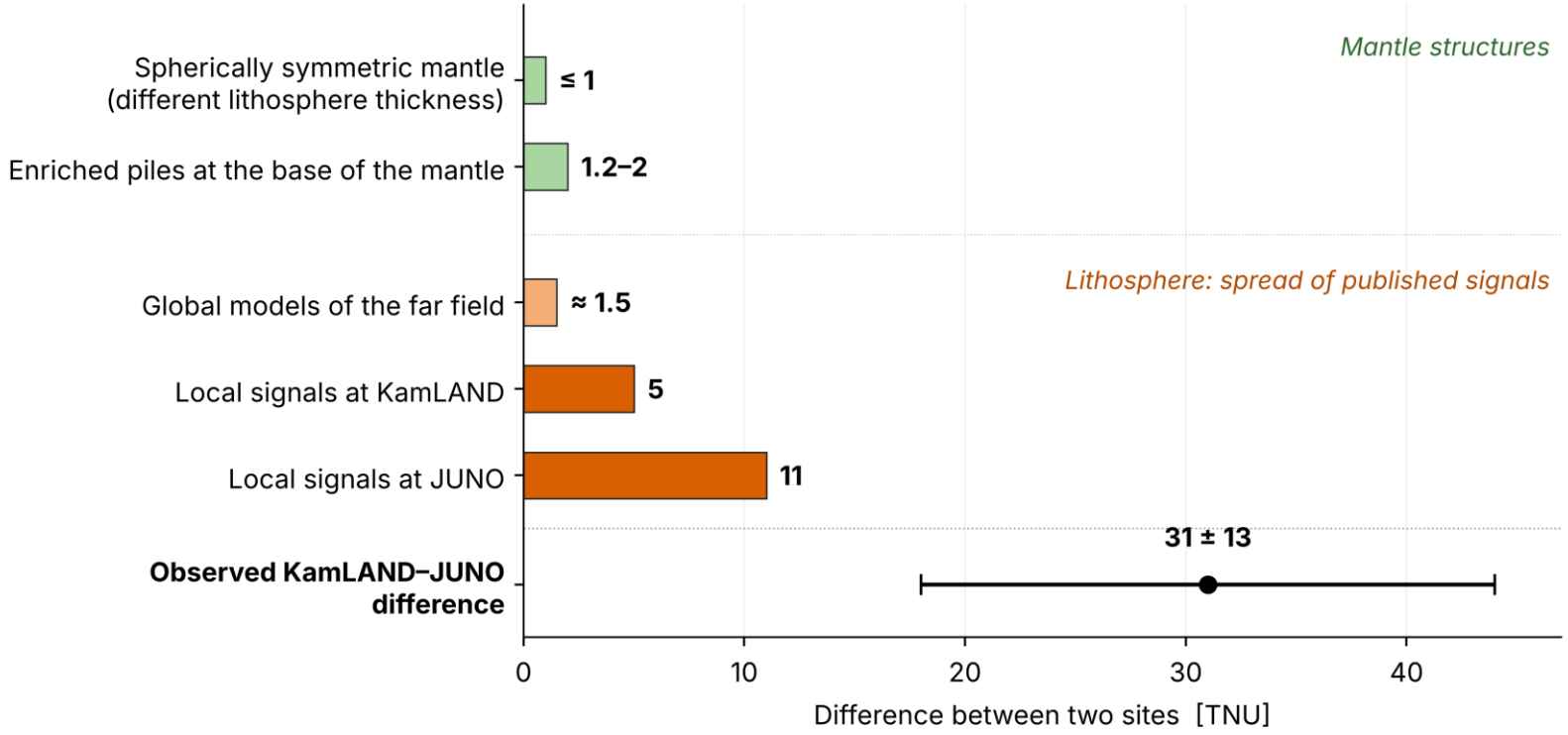
- **JUNO with GIGJ**[1] (local geophysical model with global abundances) the combined S_M hardly moves (10.3 TNU), but the KamLAND–JUNO difference grows from 2.4σ to 3.4σ and one common mantle becomes unlikely (p = 0.006)
- **KamLAND with Takeuchi et al. 2019**[2]: the lithospheric signal ($26.3^{+4.3}_{-4.0}$ TNU) is close to the baseline ($27.0^{+3.4}_{-2.4}$ TNU) and the sites still agree (p = 0.12). Its uncertainty is not established: the authors bound it between about 3% and more than 60%. Our rough, indicative estimate is 20%

[1] Reguzzoni, M., Rossi, L., Baldoncini, M., et al., 2019. GIGJ: a crustal gravity model of the Guangdong Province for predicting the geoneutrino signal at the JUNO experiment. J. Geophys. Res. Solid Earth 124, 4231–4249. https://doi.org/10.1029/2018JB016681

[2] Takeuchi, N., Ueki, K., Iizuka, T., Nagao, J., Tanaka, A., Enomoto, S., Shirahata, Y., Watanabe, H., Yamano, M., Tanaka, H.K.M., 2019. Stochastic modeling of 3-D compositional distribution in the crust with Bayesian inference and application to geoneutrino observation in Japan. Phys. Earth Planet. Inter. 288, 37–57. https://doi.org/10.1016/j.pepi.2019.01.002

What drives the KamLAND–JUNO difference?

- **The question**: the residuals of KamLAND and JUNO differ by 31 ± 13 TNU (2.4σ). It could be a statistical fluctuation, or come from the mantle or the lithospheric models

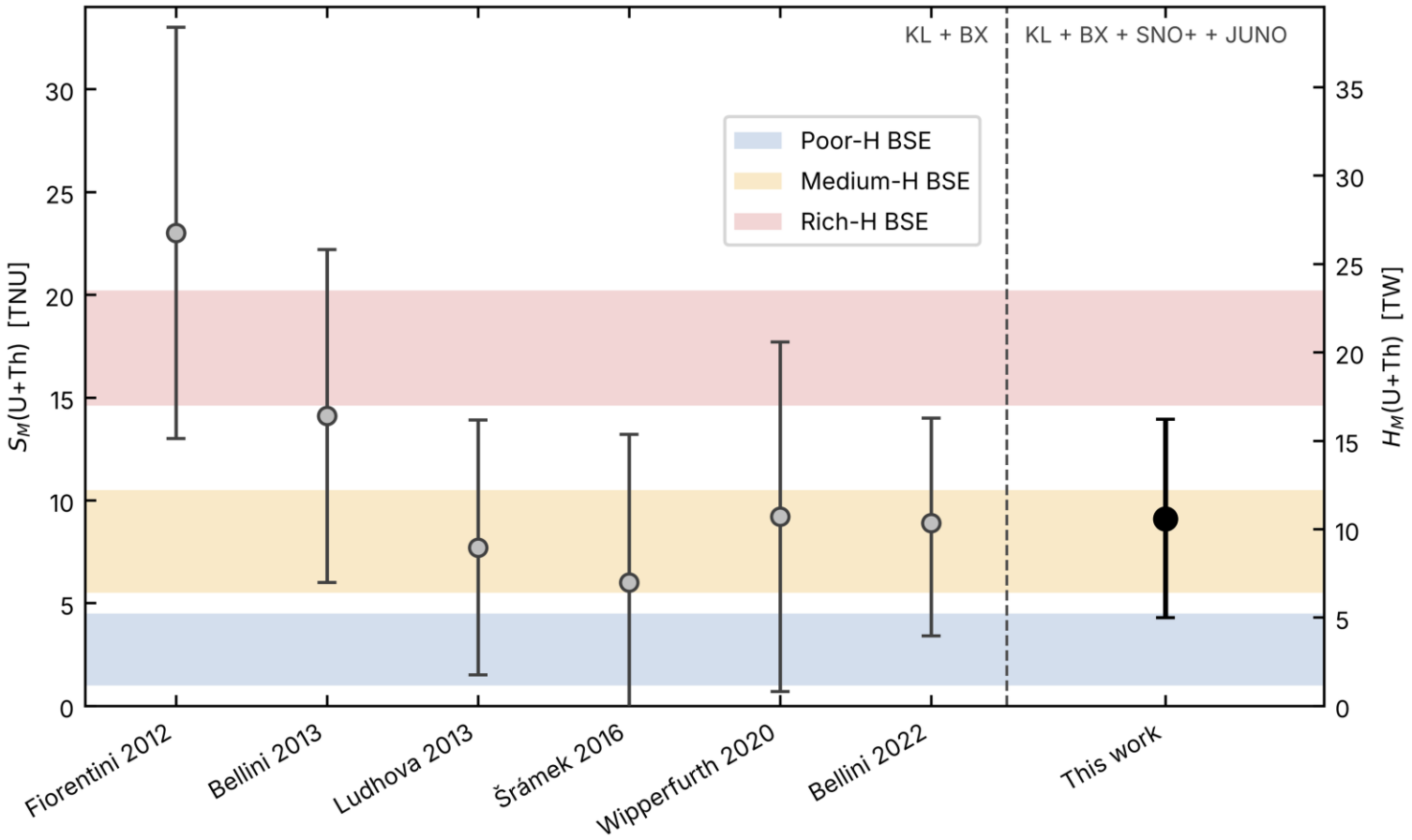


- **Not the mantle**: the structures proposed for the mantle put at most about 2 TNU between two sites[1,2], less than a tenth of the difference
- **Not the far field**: the global models agree within about 1.5 TNU[3]

- **The local crust**: published local signals differ by 5 TNU at KamLAND and 11 TNU at JUNO[4].
  It is the first term to improve.

[1] Šrámek, O., et al., 2013. Earth Planet. Sci. Lett. 361, 356–366
[2] Xu, Z., et al. (OBD Consortium), 2026. arXiv:2606.13273
[3] Bellini, G., et al., 2022. Riv. Nuovo Cimento 45, 1–105
[4] McDonough, W.F., Watanabe, H., 2023. Geophys. Monogr. 276, 1–23

From two sites to four: the mantle signal

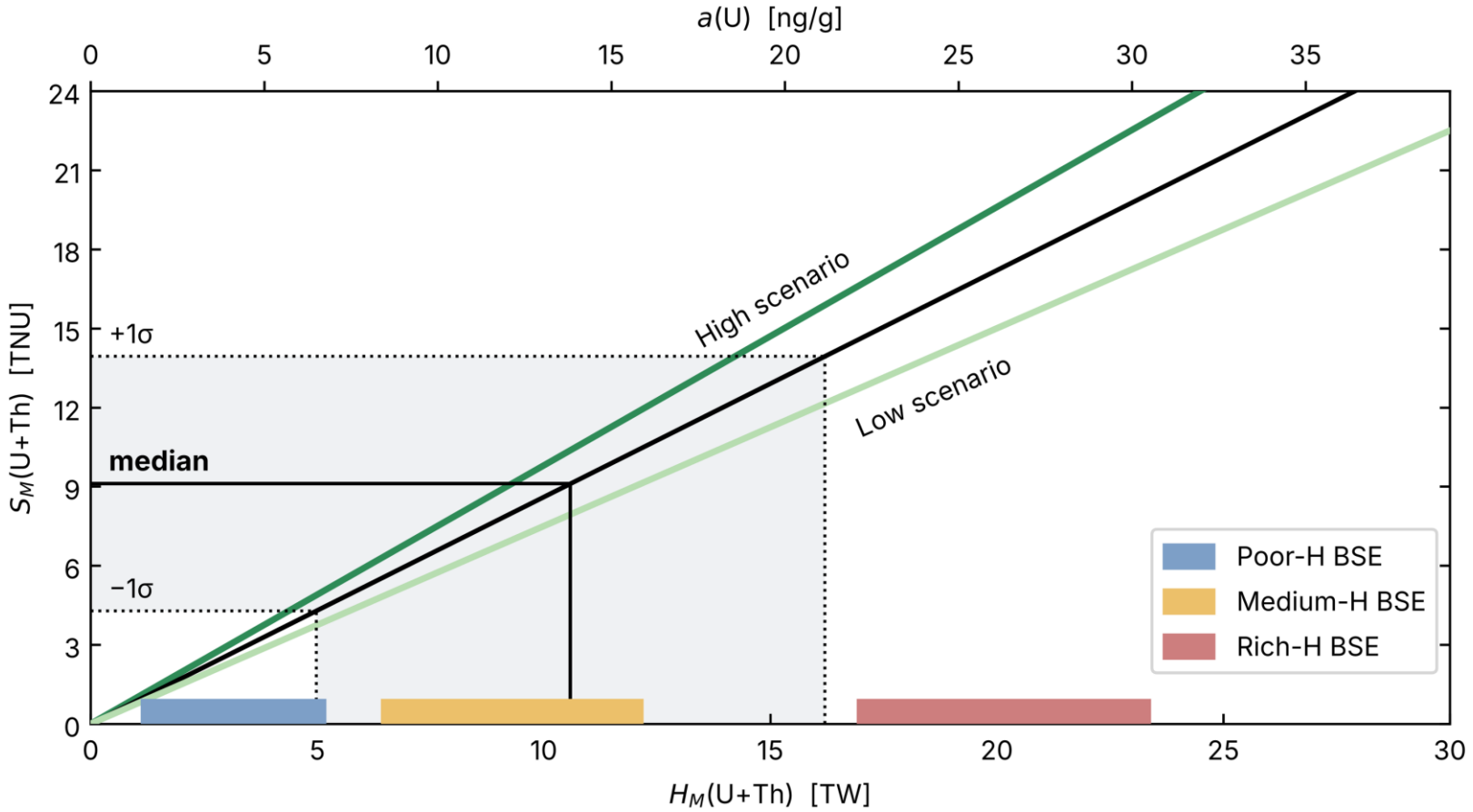


- **Two sites, 2012–2022**: six combinations of KamLAND and Borexino. S_M was 23 ± 10 TNU in 2012 and settled between 6 and 9 TNU as data accumulated and the lithospheric models were refined
- **Four sites, this work**: S_M = 9.1 ± 4.8 TNU, within that sequence and with the narrowest interval obtained so far

- **Bulk Silicate Earth** (mantle plus lithosphere) **classes**[1]: the mantle signal expected by compositional models of the Earth that are poor, intermediate or rich in heat-producing elements. The result is closest to Medium-H BSE (0.2σ), with Poor-H BSE at 1.2σ and Rich-H BSE at 1.5σ
- **A mantle without U and Th**, which would give S_M = 0, is disfavored at about 1.5σ

[1]Bellini, G., et al., 2022. Riv. Nuovo Cimento 45, 1–105

From mantle signal to power and uranium



- **From signal to power**[1]: for a spherically symmetric mantle $S_M = \beta H_M(U+Th)$. β depends only on how deep U and Th sit: shallower sources give more signal for the same power
- **Three scenarios**: β = 0.98 TNU/TW for a homogeneous mantle, 0.75 for U and Th in a thin layer above the core, 0.86 as the central value

- **Mantle radiogenic power**: $H_M(U+Th)$ = 10.6 ± 5.6 TW for the central β, between 9.3 and 12.1 TW over the range of β
- **Mantle abundances**: the same signal gives an average a(U) = 14 ± 7 ng/g and a(Th) = 51 ± 27 ng/g, with the Th/U ratio fixed at 3.7

[1] Bellini, G., Inoue, K., Mantovani, F., Serafini, A., Strati, V., Watanabe, H., 2022. Geoneutrinos and geoscience: an intriguing joint-venture. Riv. Nuovo Cimento 45, 1–105. https://doi.org/10.1007/s40766-021-00026-7

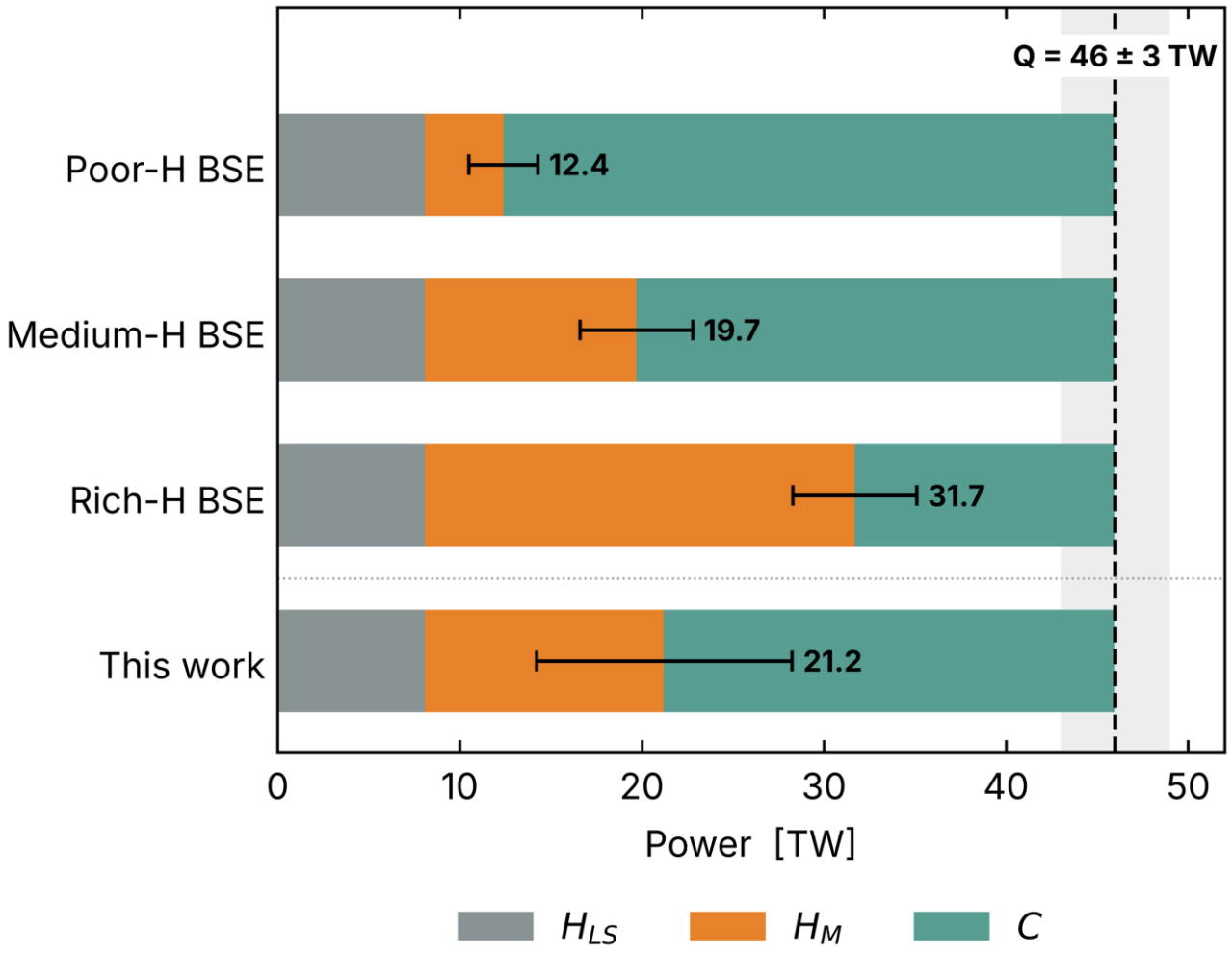
How much uranium is in the Earth?

Quantity	This work	Compared with
BSE uranium mass $M_{BSE}(U)$	$8.7^{+3.0}_{-2.9} \times 10^{16}$ kg	Poor-H BSE: $5.2 \pm 0.9 \times 10^{16}$ kg Medium-H BSE: $8.2 \pm 1.3 \times 10^{16}$ kg Rich-H BSE: $13.3 \pm 1.5 \times 10^{16}$ kg
Mantle uranium abundance - a(U)	14 ± 7 ng/g, < 26 ng/g at 95% C.L.	Depleted mantle of mid-ocean ridges: 3–8 ng/g

- **Uranium mass**: with no uranium in the core, BSE holds $M_{BSE}(U)$, 0.2σ from Medium-H BSE, 1.2σ above Poor-H BSE and 1.4σ below Rich-H BSE
- **Upper limit**: a(U) < 26 ng/g at 95% C.L., about the abundance expected for a Rich-H BSE mantle
- **Mantle abundance**: a(U) = 14 ± 7 ng/g is two to four times the 3–8 ng/g of the depleted mantle that feeds mid-ocean ridges[1]. The result points to, but does not yet require, a part of the mantle that ridge basalts do not sample
- **Budget, not distribution**: a uniform mantle and one with its excess uranium in a thin layer above the core fit the same signal, with a(U) = 12 and 16 ng/g

[1] Workman, R.K., Hart, S.R., 2005. Earth Planet. Sci. Lett. 231, 53–72. https://doi.org/10.1016/j.epsl.2004.12.005; Salters, V.J.M., Stracke, A., 2004. Geochem. Geophys. Geosyst. 5, Q05B07. https://doi.org/10.1029/2003GC000597; Arevalo, R., Jr., McDonough, W.F., Stracke, A., Willbold, M., Ireland, T.J., Walker, R.J., 2013. Geochem. Geophys. Geosyst. 14, 2265–2285. https://doi.org/10.1002/ggge.20152

Heat budget: about half is radiogenic

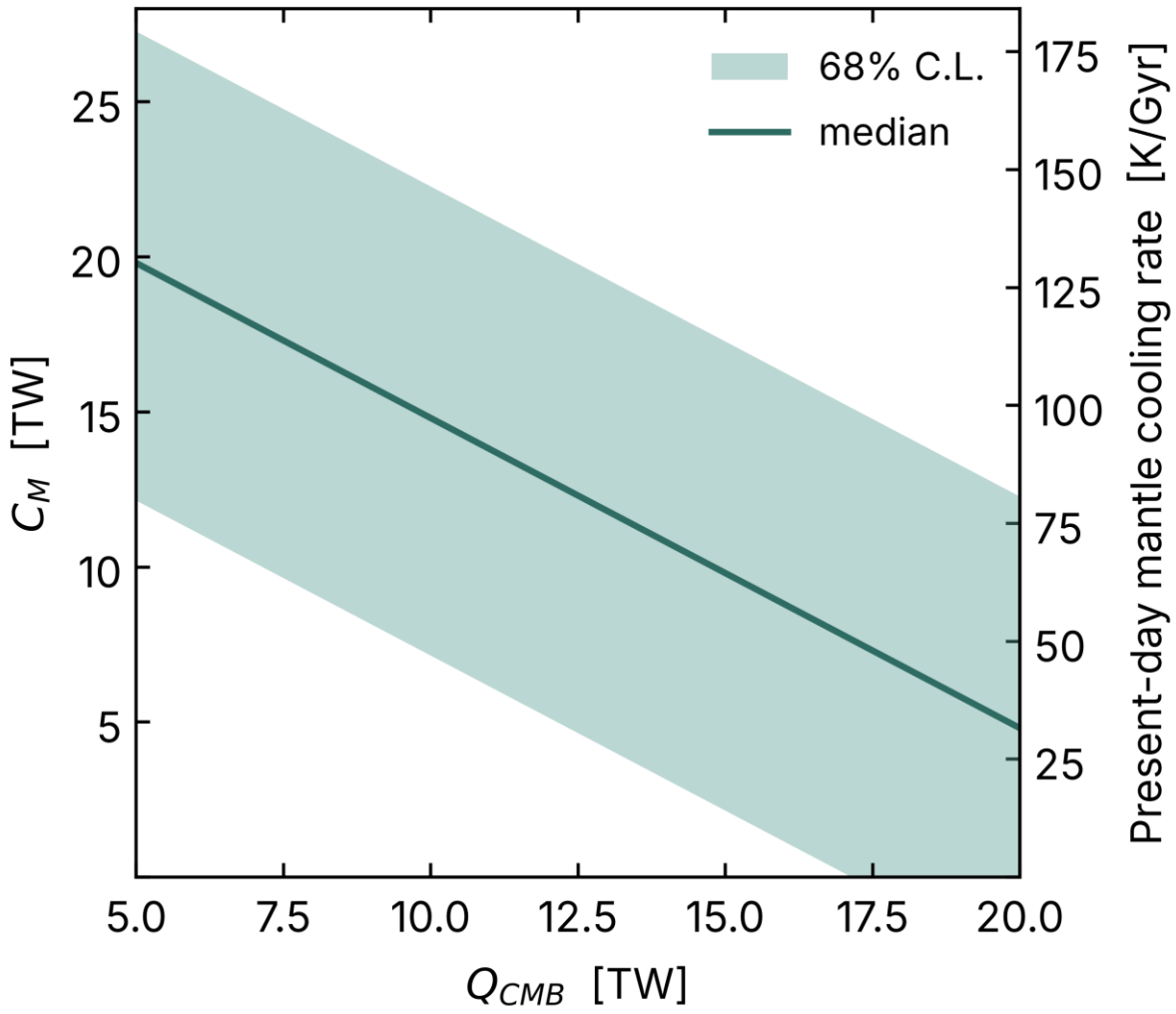


- **Lithosphere and mantle**: $H_{LS} = 8.1^{+1.9}_{-1.4}$ TW in the lithosphere and H_M(U+Th+K) = 12.9 ± 6.9 TW in the mantle. Potassium is included: in the mantle it is fixed at 18% of the power[2]
- **Radiogenic power**: H(U+Th+K) = $21.2^{+7.1}_{-7.0}$ TW, about half of the surface heat loss Q = 46 ± 3 TW[1] (H/Q = 0.46)
- **Secular cooling**: the rest, C = 25^{+7}_{-8} TW, is heat that the Earth has kept since its formation. An Earth heated by radioactivity alone is excluded at 3.3σ

[1] Jaupart, C., Labrosse, S., Lucazeau, F., Mareschal, J.-C., 2015. Temperatures, heat, and energy in the mantle of the Earth. In: Schubert, G. (Ed.), Treatise on Geophysics, second ed., vol. 7. Elsevier, pp. 223–270. https://doi.org/10.1016/B978-0-444-53802-4.00126-3

[2] Agostini, M., et al. (Borexino Collaboration), 2020. Comprehensive geoneutrino analysis with Borexino. Phys. Rev. D 101, 012009. https://doi.org/10.1103/PhysRevD.101.012009

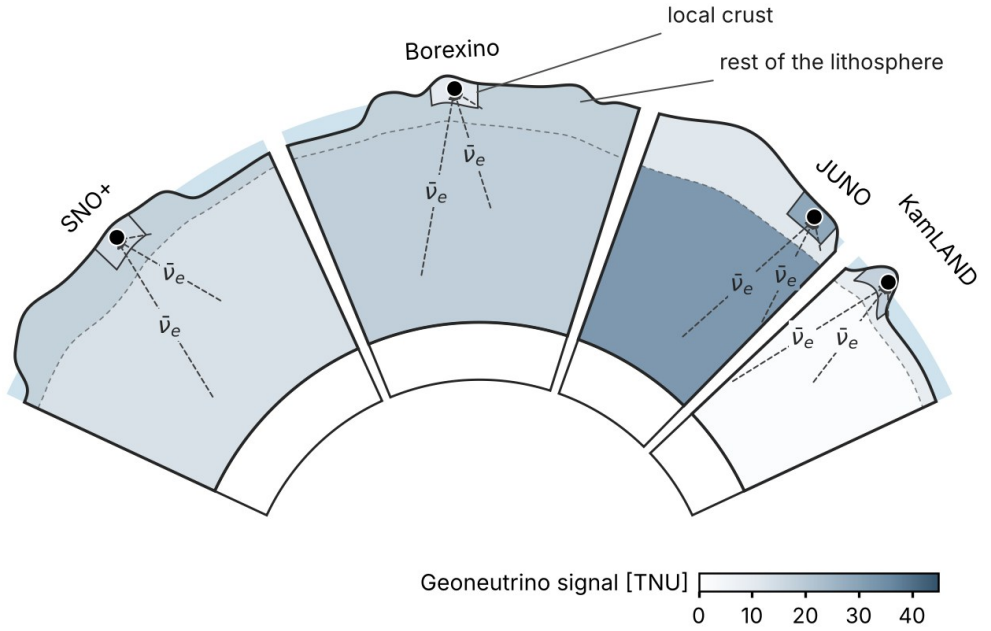
Mantle cooling and the core heat loss

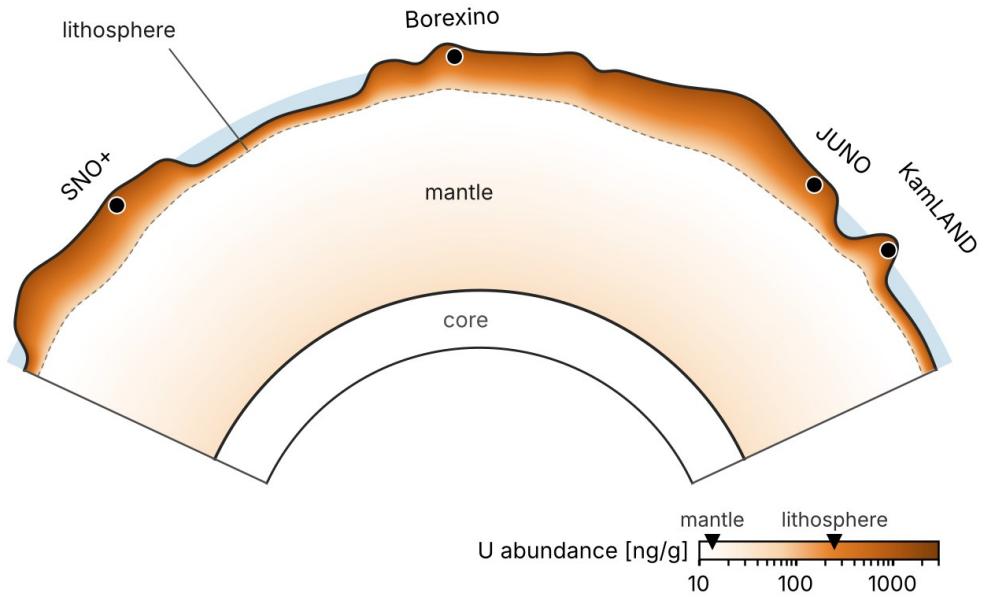


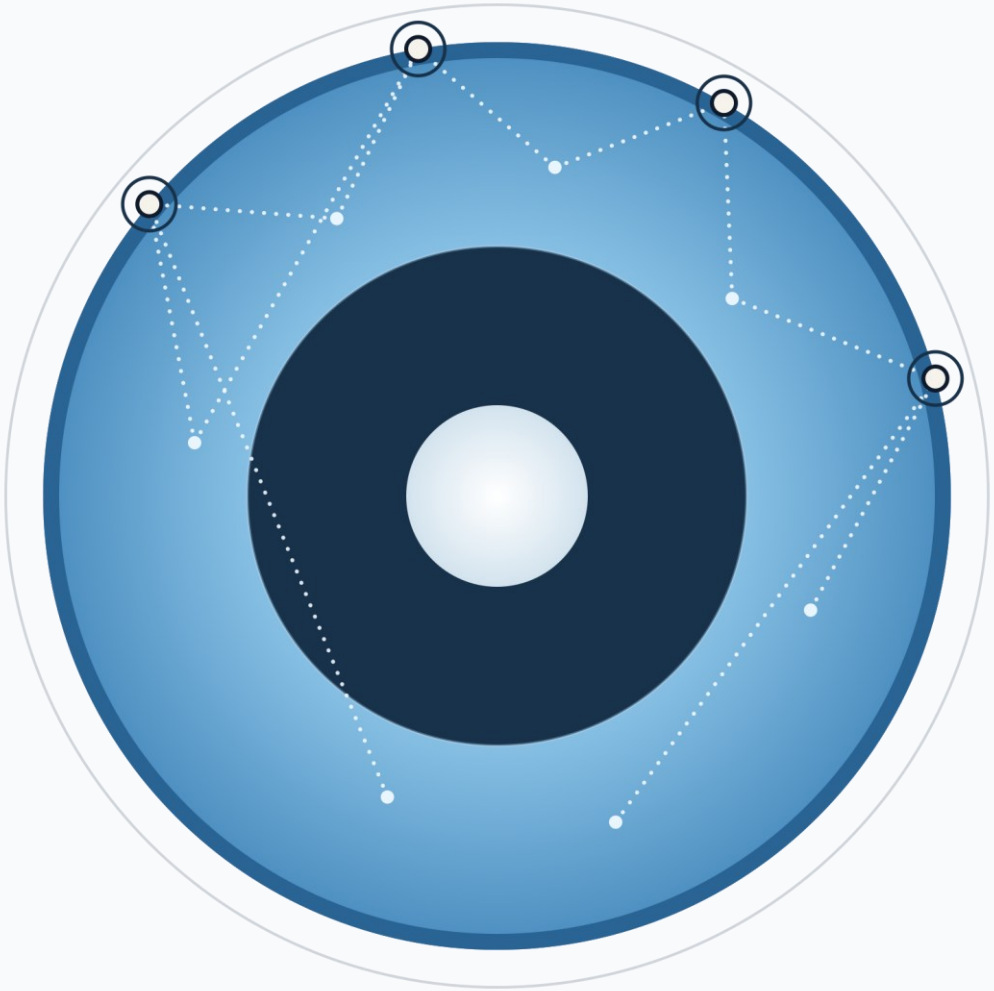
- The **secular cooling C** is shared by the mantle (C_M) and the core Q_{CMB}, which geoneutrinos cannot separate.
- **Core heat loss is poorly known**: published Q_{CMB} spans about 5 to 17 TW, as wide as the 68% interval of H(U+Th+K). It limits the mantle cooling as much as the geoneutrino measurement does
- **For Q_{CMB} = 10 TW** the mantle is cooling with a probability of 97.5%, at a present-day rate of about 100 K/Gyr
- **Outlook**: once the mantle signal is narrowed, the question could turn from how radioactive the Earth is to how much heat its core loses

Conclusions

- **Four sites, one mantle**: KamLAND, Borexino, SNO+ and JUNO are compatible with one common mantle signal (p = 0.07), S_M(U+Th) = 9.1 ± 4.8 TNU.
- **KamLAND and JUNO** differ by 2.4σ, a difference that no proposed mantle structure can produce
- **Uranium**: the mantle holds a(U) = 14 ± 7 ng/g, two to four times the depleted mantle. The Earth is closest to the Medium-H BSE class (0.2σ)
- **Heat**: about half of the surface heat loss is radiogenic (H/Q = 0.46). An Earth heated by radioactivity alone is excluded at 3.3σ
- **Future prospects**: more JUNO data, new sites (ocean bottom, Jinping) and detectors sensitive to ^{40}K geoneutrinos are the next steps







Thank you

Virginia Strati · strati@fe.infn.it

University of Ferrara · INFN Ferrara

Neutrino Geoscience 2026
Zhuhai, China (16–19 November 2026)

FERRARIAE UNIVERSITAS · EX LABORE FRUCTUS · 13 91

INFN
Istituto Nazionale di Fisica Nucleare

Laboratory for Nuclear Technologies — Applied to the Environment

FUNDAMENTAL PHYSICS · SEISMOLOGY · EXPERIMENTS · AI

FuSe
TESTING FUNDAMENTAL PHYSICS WITH SEISMOLOGY