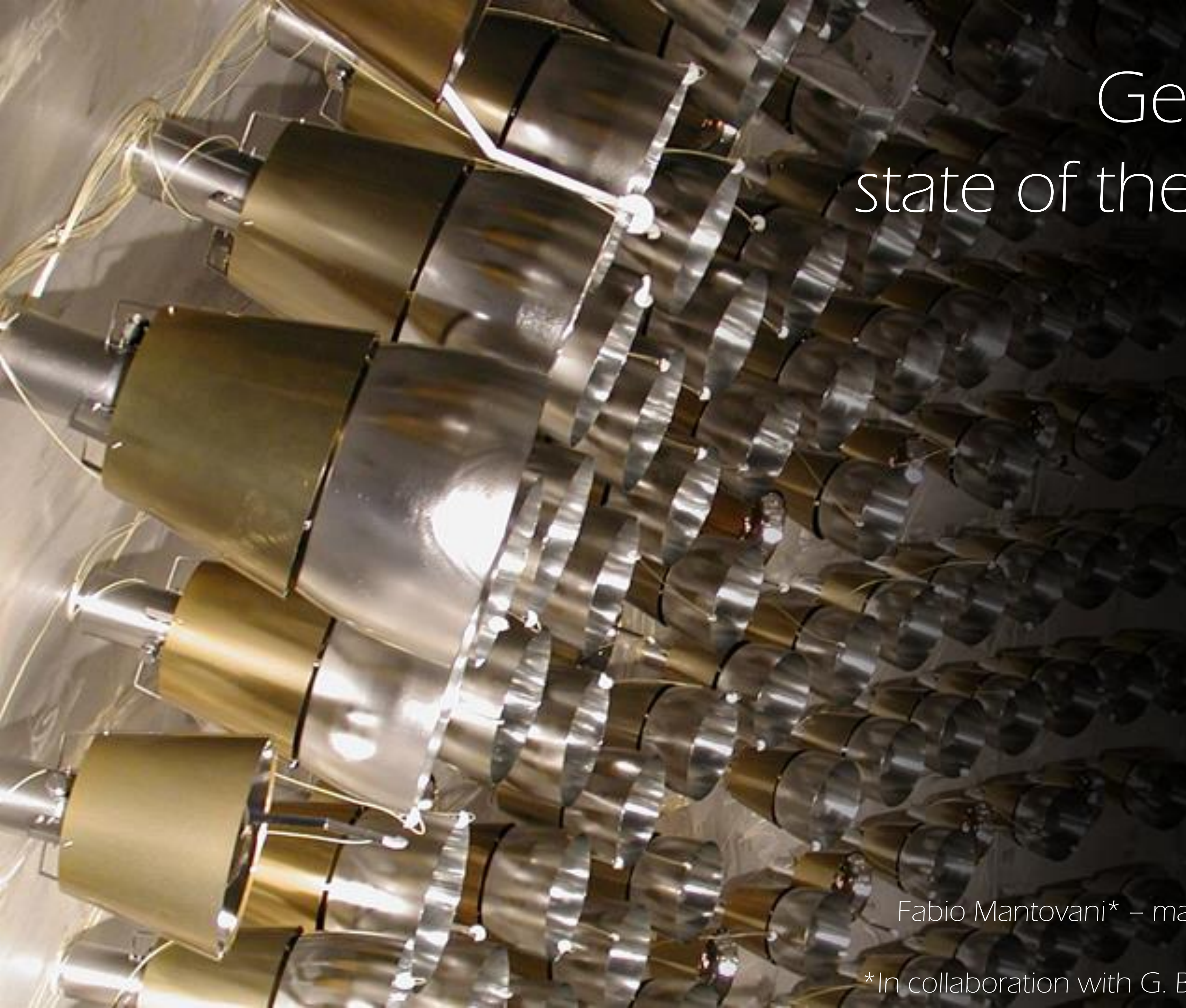
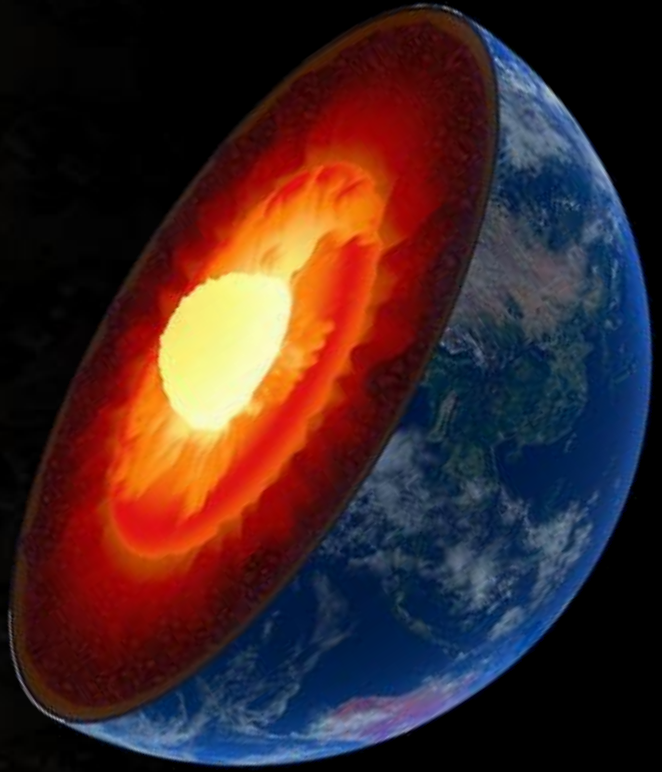


Geoneutrino: state of the art and prospects



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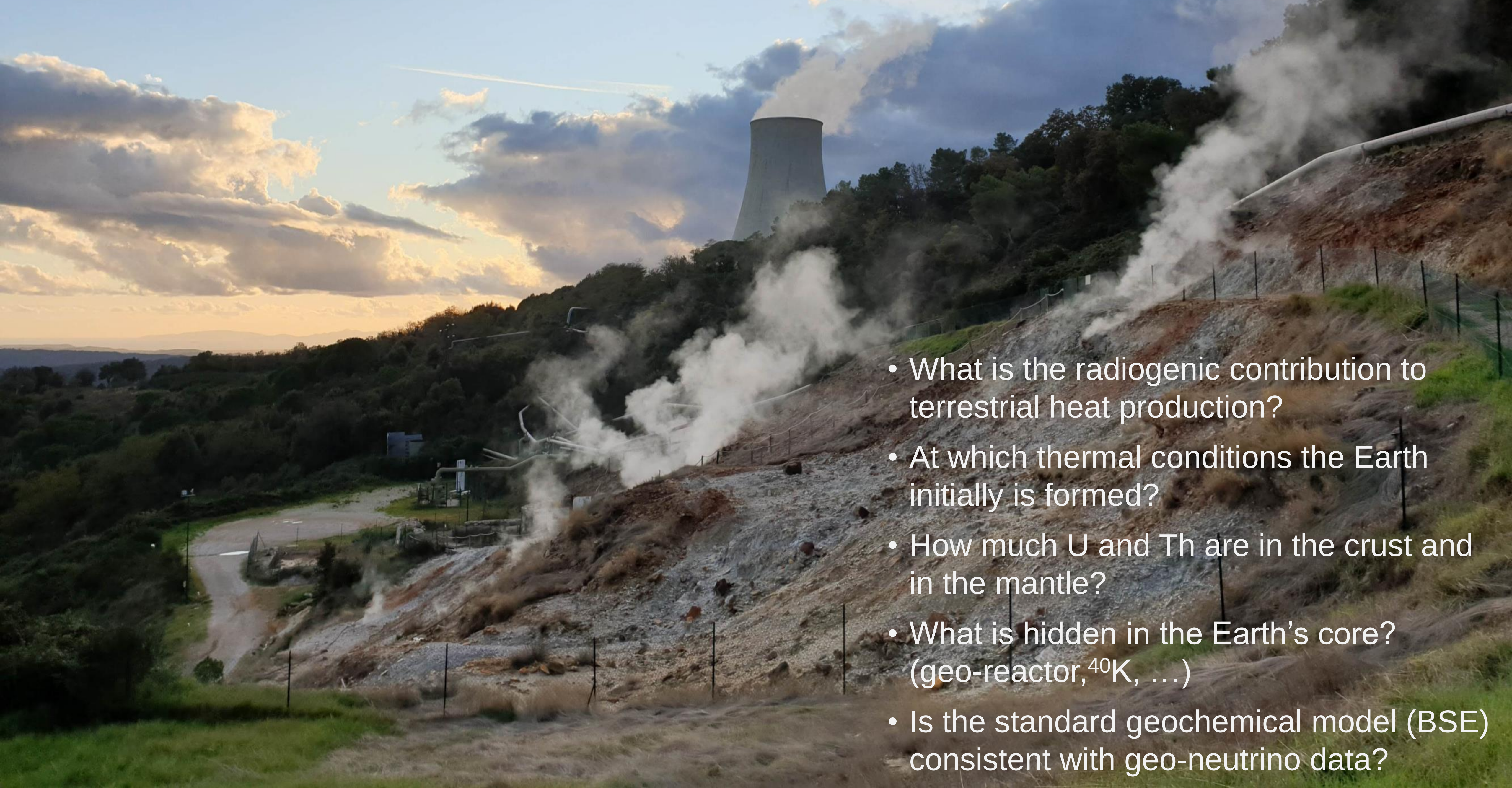
*In collaboration with G. Bellini, K. Inoue, A. Serafini, V. Strati, H. Watanabe

Outline

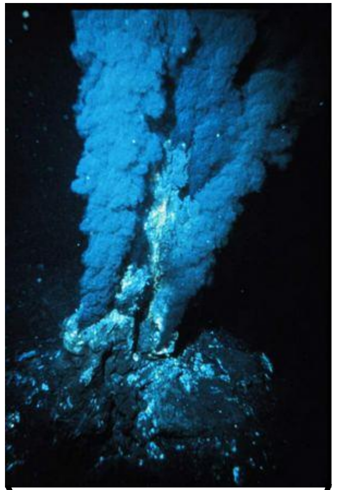
- Terrestrial heat power Earth and geoneutrinos
- KamLAND and Borexino results
- Mantle geoneutrino signals from multi-site detection
- Understanding the Earth’s heat budget with geoneutrinos
- Perspectives for future detectors

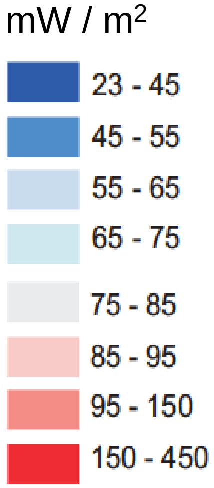
Open questions about natural radioactivity in the Earth

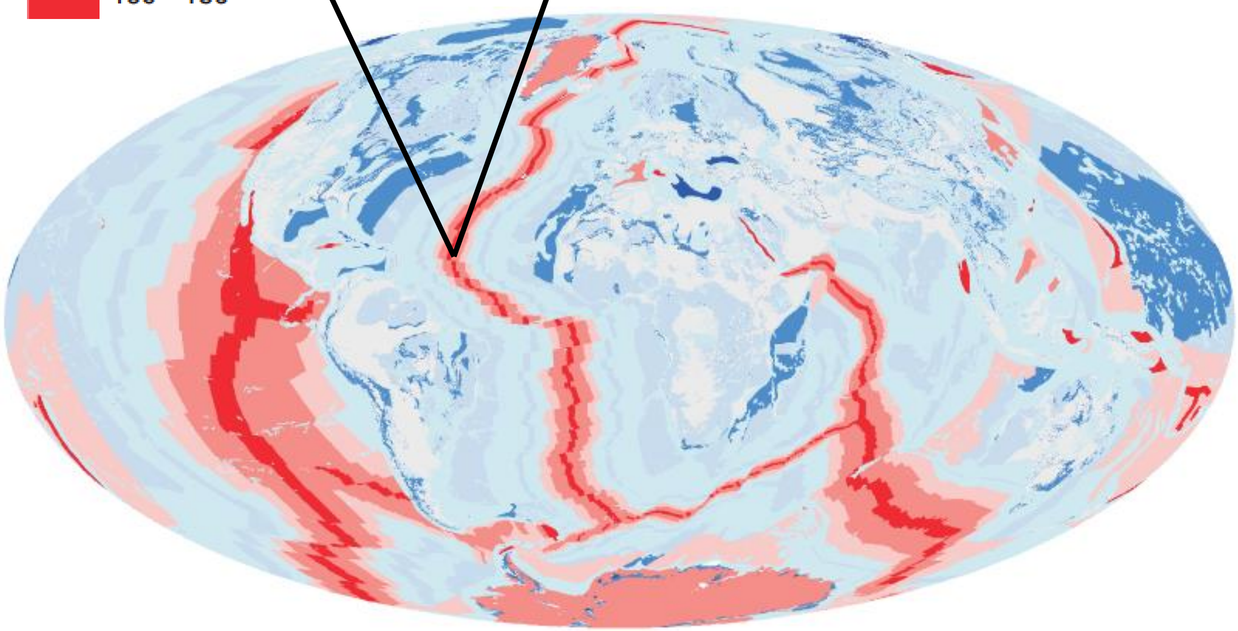


- What is the radiogenic contribution to terrestrial heat production?
- At which thermal conditions the Earth initially is formed?
- How much U and Th are in the crust and in the mantle?
- What is hidden in the Earth's core? (geo-reactor, ^{40}K, …)
- Is the standard geochemical model (BSE) consistent with geo-neutrino data?

Heat power of the Earth



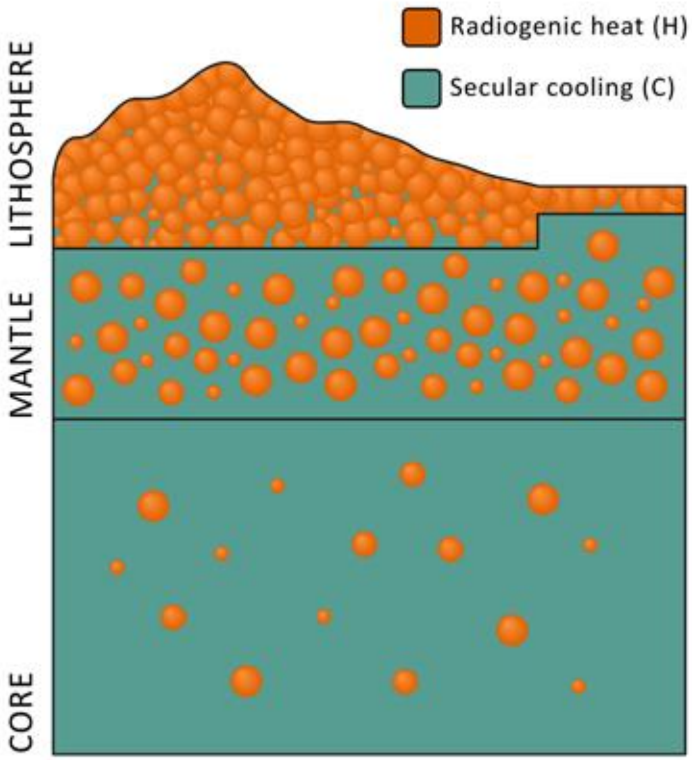




- Heat power of the Earth Q [30-49 TW] is the equivalent of ~ 10^4 nuclear power plants.
- The conduction is not the only way of Earth's cooling: convective motions are responsible for significant fraction of surface heat loss.
- The quantitative assessment of heat transport by hydrothermal circulation remains a difficult task.
- Heat flow observations are sparse, non-uniformly distributed and not reliable in the oceans.

REFERENCE	Continents	Oceans	Total
	q_{CT} [mW m^{-2}]	q_{OCS}[mW m^{-2}]	Q (TW)
Williams et al., 1974	61	92	43 ± 6
Davies, 1980	55	95 ± 10	41 ± 4
Sclater et al., 1980	57	99	42
Pollack et al., 1993	65 ± 2	101 ± 2	44 ± 1
Hofmeister and Criss, 2005	61	65	31 ± 1
Jaupart et al., 2015	65	107	46 ± 2
Davies and Davies, 2010	**71**	**105**	**47 ± 2**
Davies, 2013	65	96	45
Lucazeau, 2019	66.7	89.0	44

Earth's heat budget



- H_{CC} = radiogenic power of the continental crust
- H_{CC} = radiogenic power of the continental crust
- H_{CLM} = radiogenic power of the continental lithospheric mantle

$$C = Q - H$$

$$C_M = Q - H - C_C$$

$$H_M = H - H_{LS} - H_C$$

$$H_{LS} = H_{CC} + H_{OC} + H_{CLM}$$

$$U_R = \frac{H - H_{CC}}{Q - H_{CC}}$$

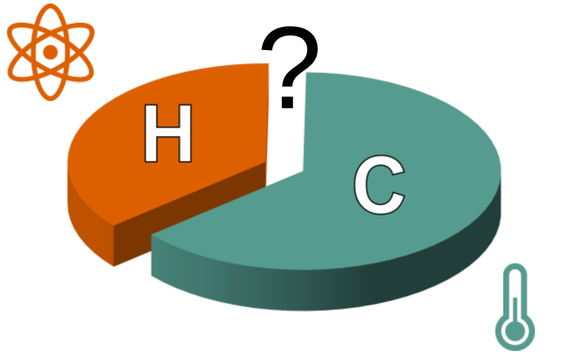
	Range [TW]	Adopted [TW]
H	[10 ; 37]	19.3 ± 2.9
H_{LS}	[6 ; 11]	$8.1^{+1.9}_{-1.4}$
H_M	[0 ; 31]	$11.0^{+3.3}_{-3.4}$
H_C	[0 ; 5]	0

	Range [TW]	Adopted [TW]
C	[8 ; 39]	28 ± 4
C_{LS}	~ 0	0
C_M	[1 ; 29]	17 ± 4
C_C	[5 ; 17]	11 ± 2

- The mass of the lithosphere (~ 2% of the Earth's mass) contains ~ 40% of the total estimated HPEs and it produces H_{LS} ~ 8 TW.
- Radiogenic power of the mantle H_M and the contributions to C from mantle (C_M) and core (C_C) are model dependent.
- U_R is defined as convective Urey ratio.

Neglecting tidal dissipation and gravitation contraction (<0.5 TW), the two contributions to the total heat loss (Q) are:

- Secular Cooling (C): cooling down caused by the initial hot environment of early formation's stages
- Radiogenic Heat (H) due to naturally occurring decays of Heat Producing Elements, HPEs (U, Th and K) inside our planet.



Geo-neutrinos: anti-neutrinos from the Earth

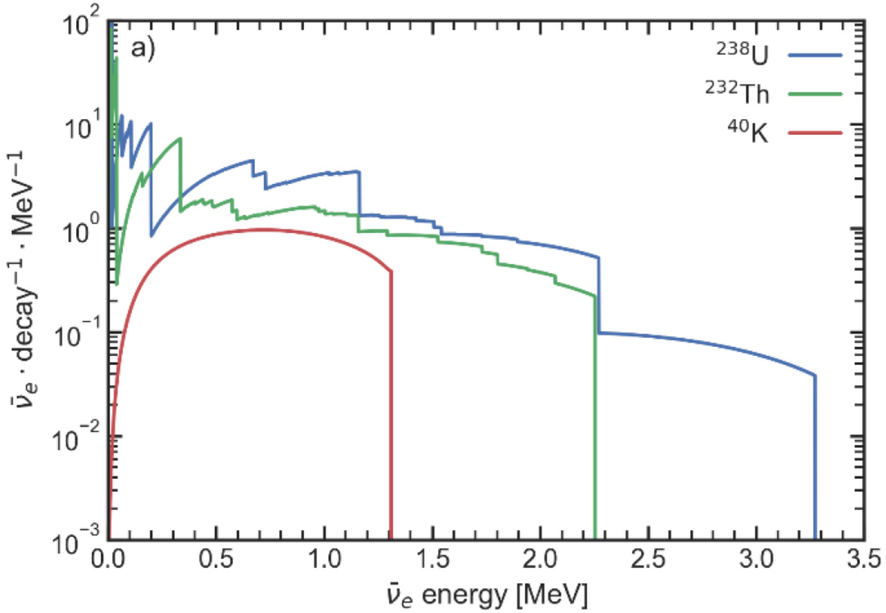
U, Th and ^{40}K in the Earth release heat together with anti-neutrinos, in a well-fixed ratio:

Decay	$T_{1/2}$ [10^9 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}

- 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:

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

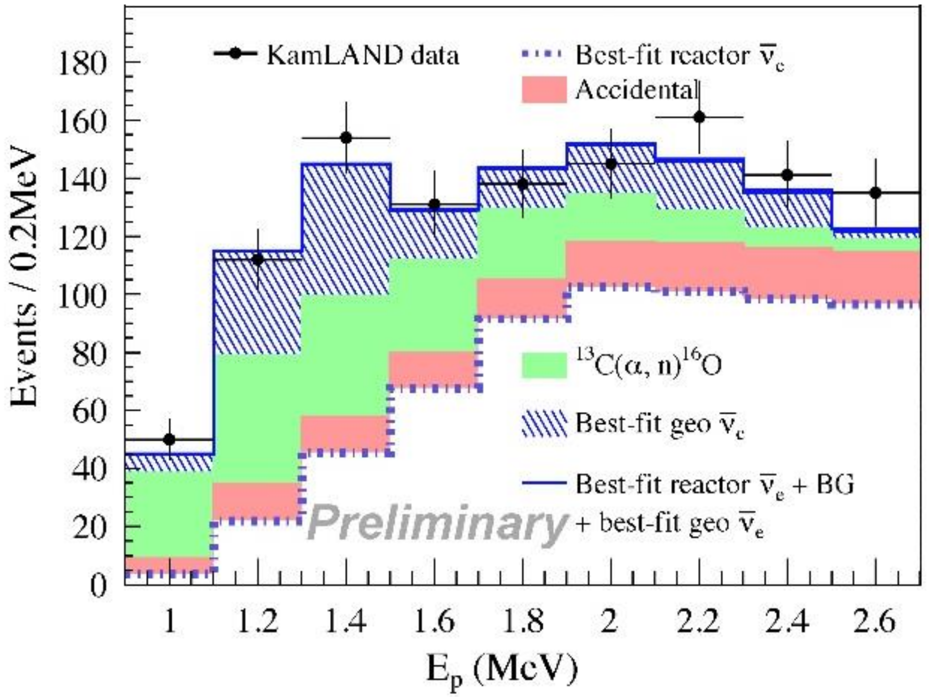
- Different components can be distinguished due to different energy spectra: e. g. anti-ν with highest energy are from U
- Signal unit: **1 TNU** = one event per 10^{32} free protons/year

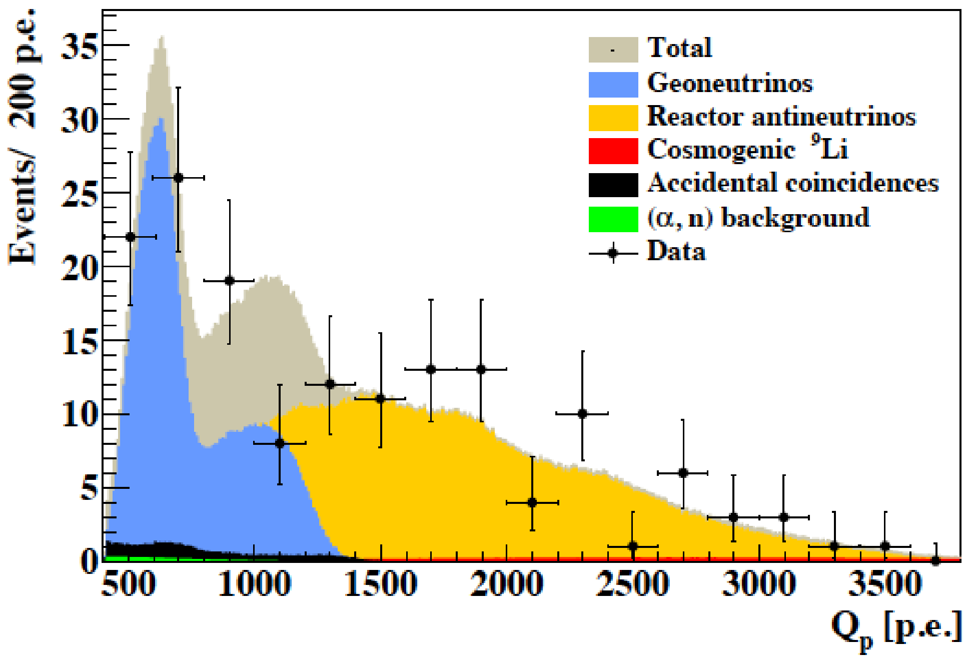


Borexino and KamLAND geoneutrino results

- KamLAND is 1 kTon liquid scintillator detector surrounded by 1325 17” PMTs and 554 20” PMTs.
- The ratio S_{rea} / S_{geo} changed drastically during the data taking.

Data taking	2002-2019
Reactors events	629.0 ± 34.4
Tot bkg events	337.9 ± 23.7
Geo-ν events (U+Th)	$168.8^{+26.3}_{-26.5}$
S(U+Th) [TNU]	32.1 ± 5.0

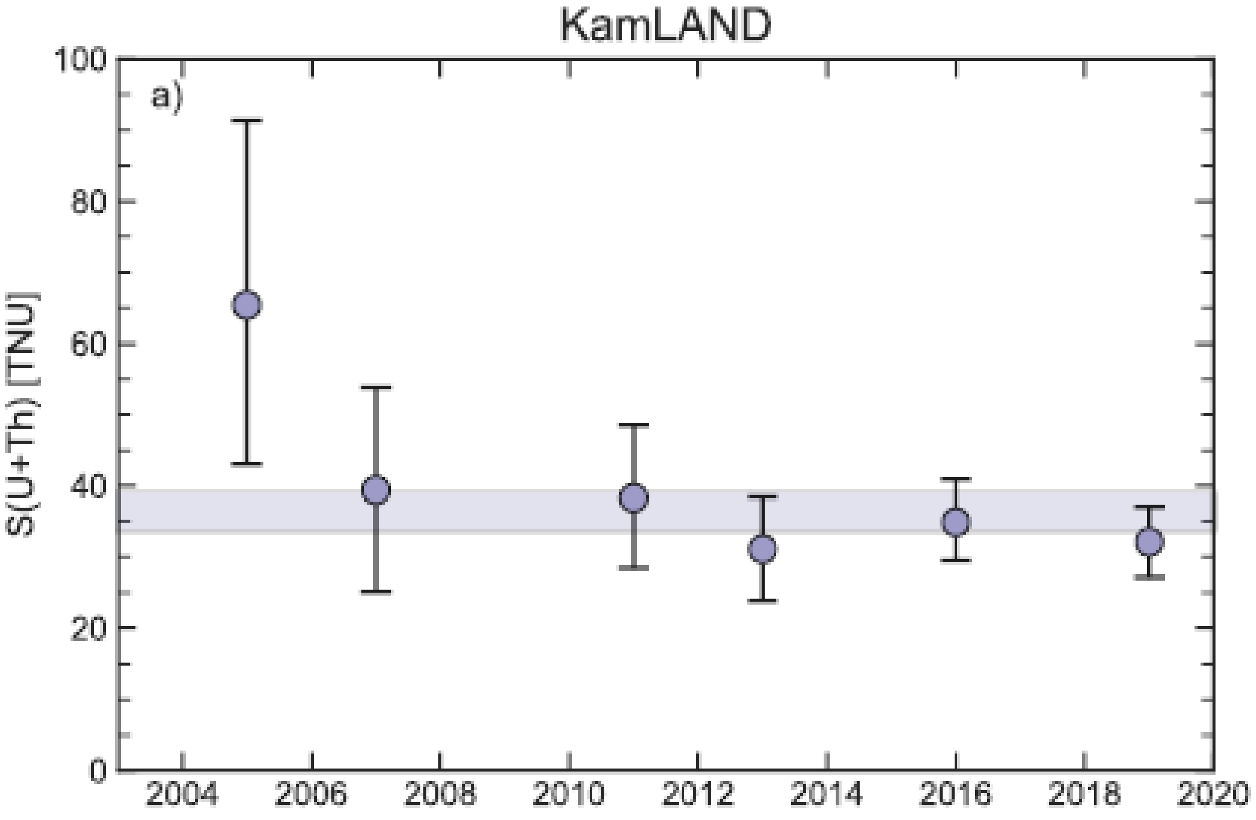


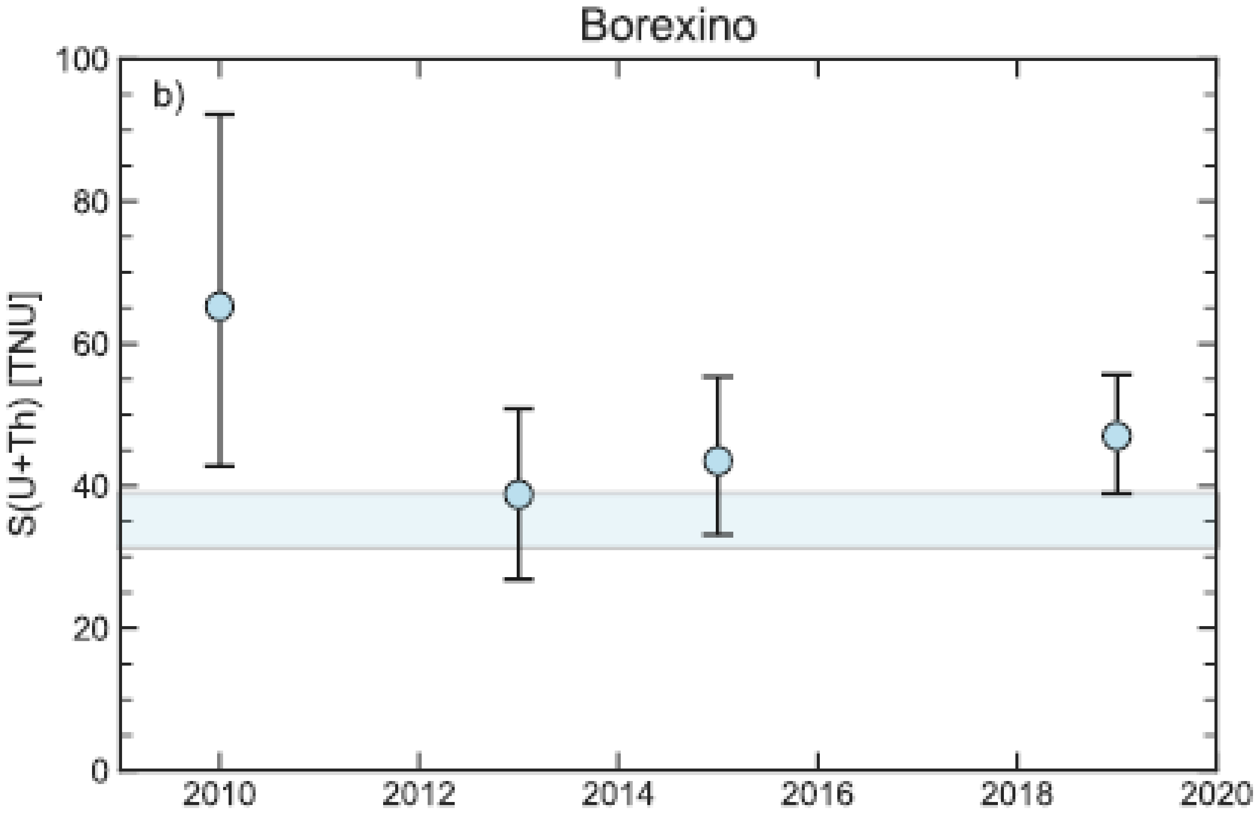


Data taking	2007-2019
Reactors events	39.5 ± 0.7
Tot bkg events	8.3 ± 1.0
Geo-ν events (U+Th)	$52.6^{+9.6}_{-9.0}$
S(U+Th) [TNU]	$47.0^{+8.6}_{-8.1}$

- Borexino is 0.3 kTon liquid scintillator detector surrounded by ~2200 8” PMTs.
- The ratio S_{rea} / S_{geo} fluctuated regularly in a range of ± 25% during the data taking.

Timeline of KamLAND and Borexino geoneutrino results



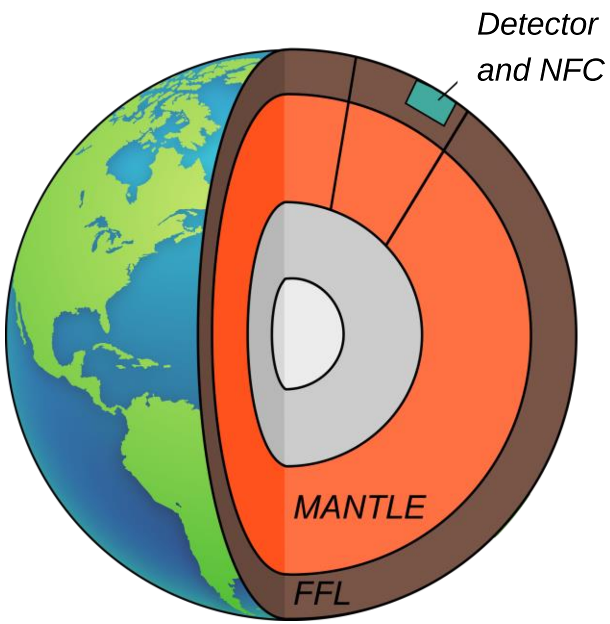


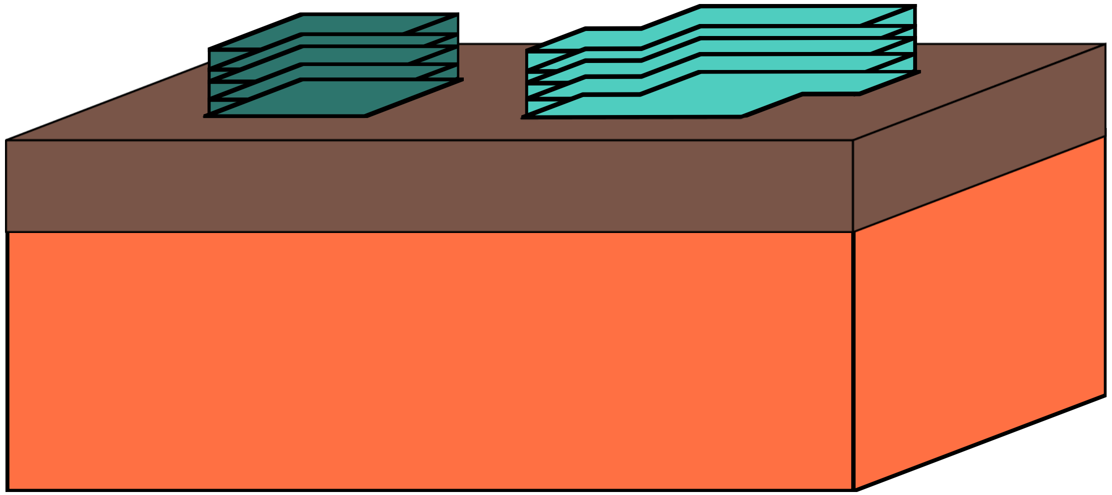
- In 2005 KamLAND collaboration published the first geoneutrino observation.
- Horizontal bars traces the expected signal at 1σ C.L.
- In the second decade of the 21st century the results published with greater statistical significance highlighted the necessity of geophysical and geological models for understanding geoneutrino signal.

Mantle geoneutrino signals from multi-site detection

The **Far Field Lithosphere (FFL)** is the superficial portion of the Earth including the Far Field Crust (FFC) and the Continental Lithospheric Mantle (CLM).

U and Th distributed in the **Near Field Crust (NFC)** gives a significant contribution to the signal (~ 50% of the total).





$$S^i_M(U+Th) = S^i_{Exp}(U+Th) - S^i_{FFC}(U+Th) - S^i_{CLM}(U+Th) - S^i_{NFC}(U+Th)$$

The geological models need to comply with the following constraints:

- **FFC** model needs to be unique for *i* detectors for avoiding systematic biases.
- **NFC** should be built with geochemical and/or geophysical information typical of the local regions.
- **NFC** must be geometrically complementary to the FFC.
- All geoneutrino signal contributions should be separately reported together with their uncertainties.

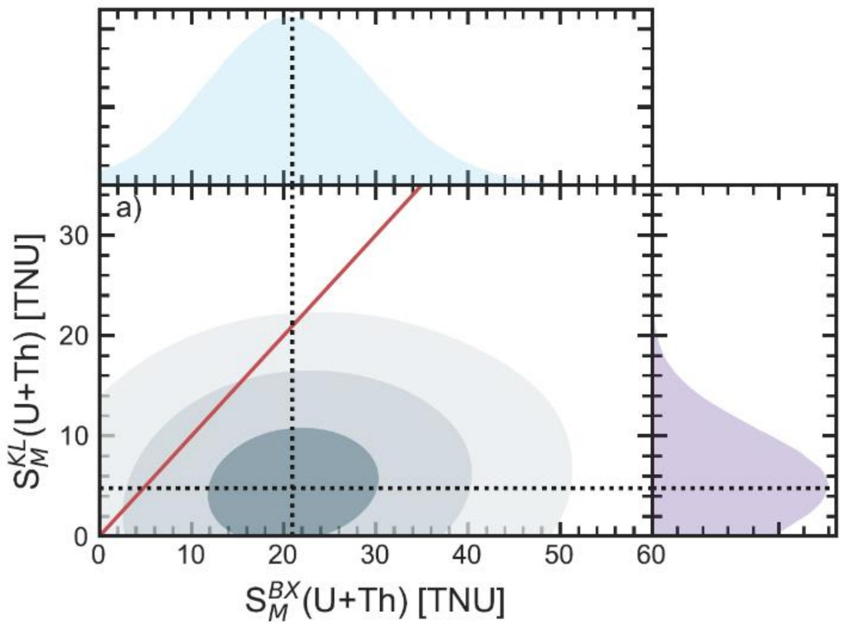
Mantle geoneutrinos from KamLAND and Borexino

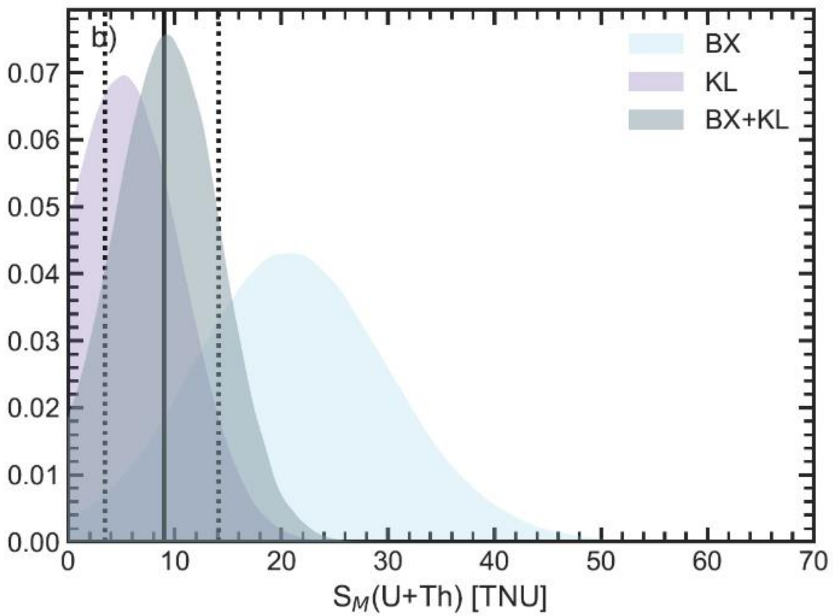
- The FFC and the CLM signals of KL and BX are fully correlated, since they are derived from the same geophysical and geochemical model,.
- S_{NFC}^{BX}(U+Th) and S_{NFC}^{KL}(U+Th) are considered uncorrelated.
- Using only the experimental signals published by BX and KL collaborations without any spectral information, the PDFs of experimental KL and BX signals are reconstructed.

	S_{Exp}(U+Th) [TNU]	S_{NFC}(U+Th) [TNU]	S_{FFC}(U+Th) [TNU]	S_{CLM}(U+Th) [TNU]	S_{M}(U+Th) [TNU]
KL	32.1 ± 5.0	17.7 ± 1.4	$7.3^{+1.5}_{-1.2}$	$1.6^{+2.2}_{-1.0}$	$4.8^{+5.6}_{-5.9}$
BX	$47.0^{+8.6}_{-8.1}$	9.2 ± 1.2	$13.7^{+2.8}_{-2.3}$	$2.2^{+3.1}_{-1.3}$	$20.8^{+9.4}_{-9.2}$
KL+BX	-	-	-	-	$8.9^{+5.1}_{-5.5}$

- The joint distribution S_M^{KL+BX}(U+Th) can be inferred from the PDFs by requiring that S_M^{KL}(U+Th) = S_M^{BX}(U+Th), obtaining the combined mantle geoneutrino signal:

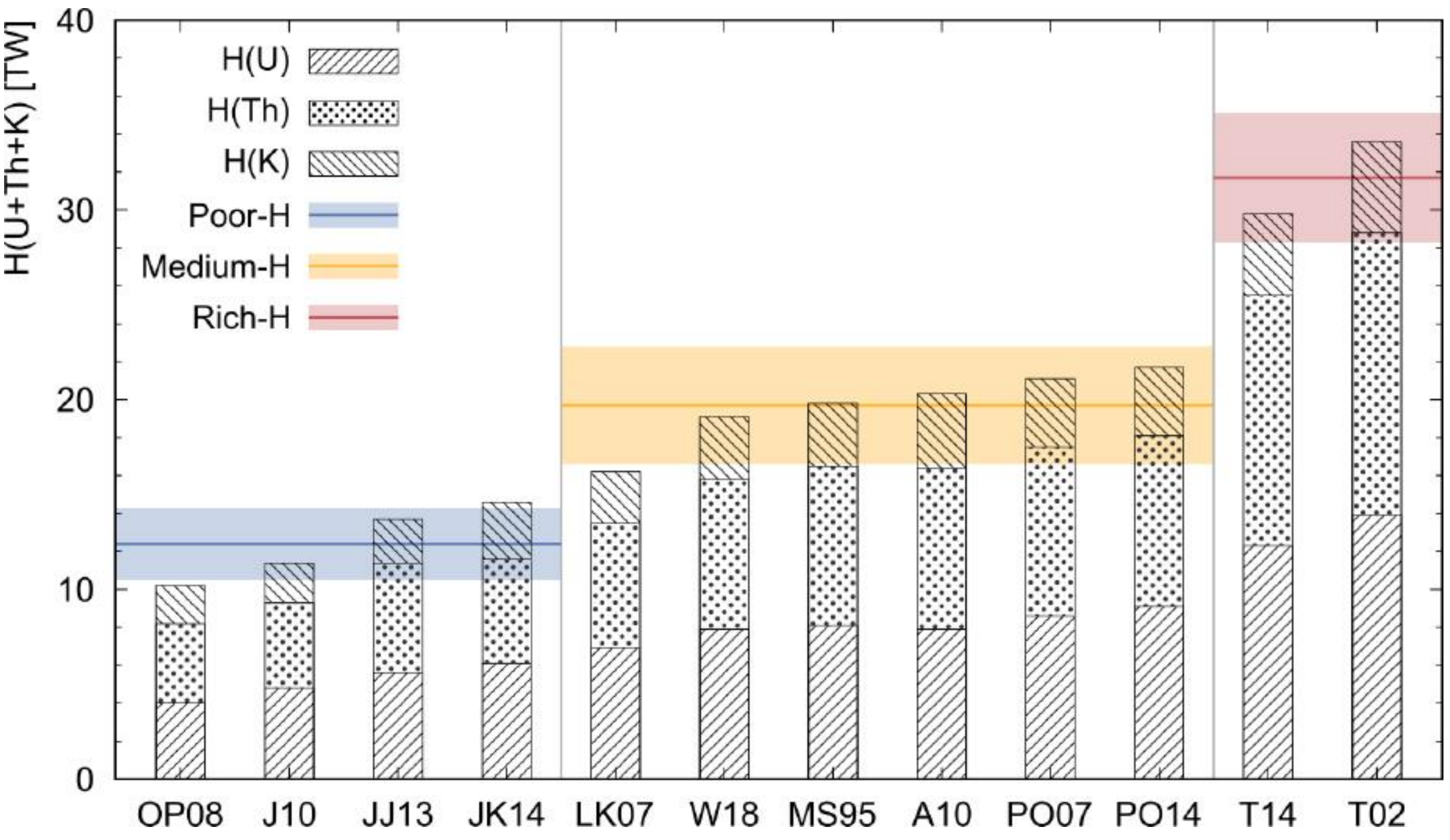
$$S_M^{KL+BX}(U+Th) = 8.9^{+5.1}_{-5.5}\ \text{TNU}$$





Bulk Silicate Earth Models

- The BSE describes the primordial, non-metallic Earth condition that followed planetary accretion and core separation, prior to its differentiation into a mantle and lithosphere.
- Different authors* proposed a range of BSE models based on different constraints (carbonaceous chondrites, enstatite chondrites, undepleted mantle, etc.)



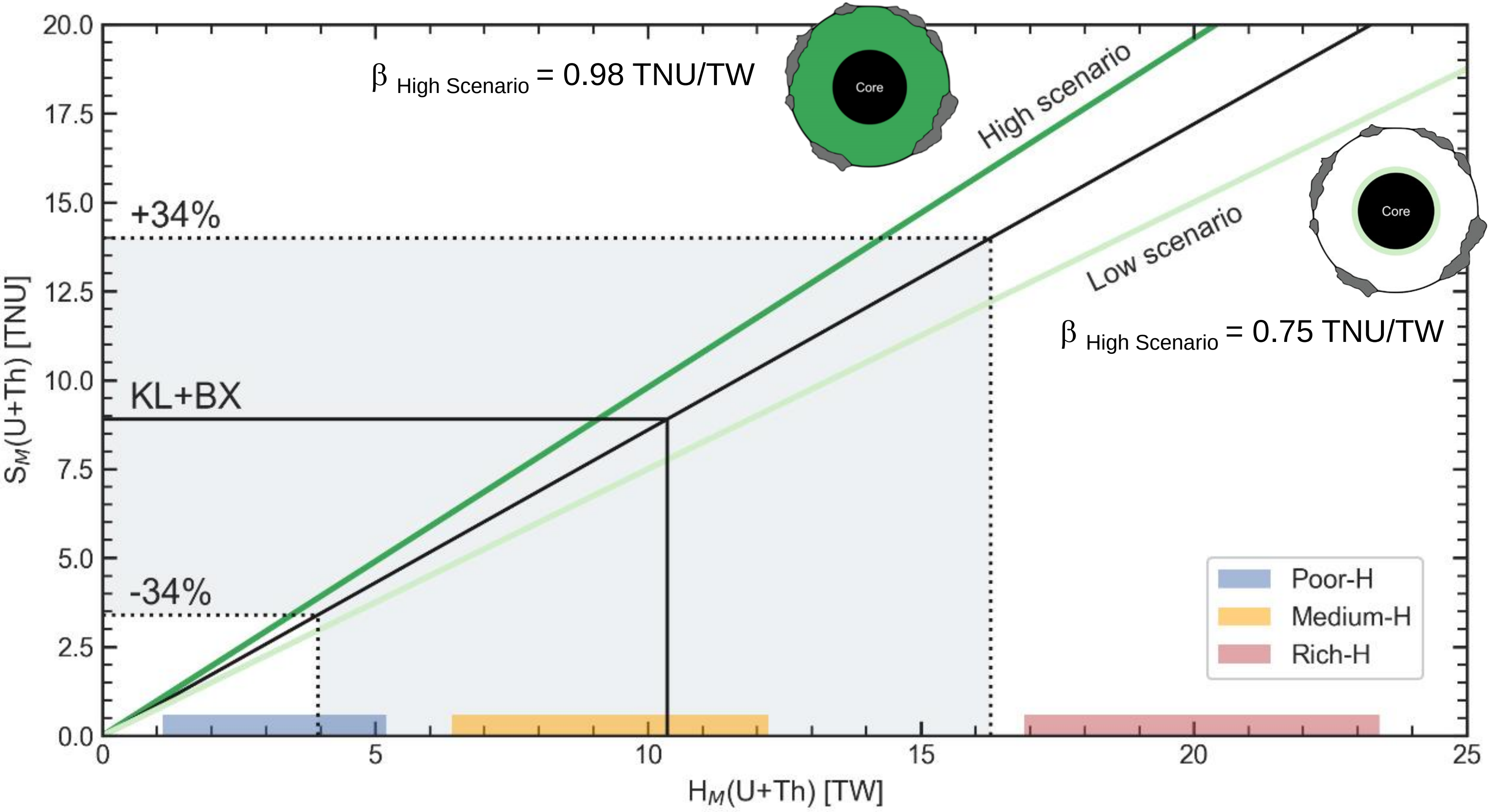
	Poor	Medium	Rich
H(U+Th+K) [TW]	12.4 ± 1.9	19.7 ± 3.1	31.7 ± 3.4

** The codes reported in the plot are explicitly indicated in the back slide.*

Mantle radiogenic power from U and Th

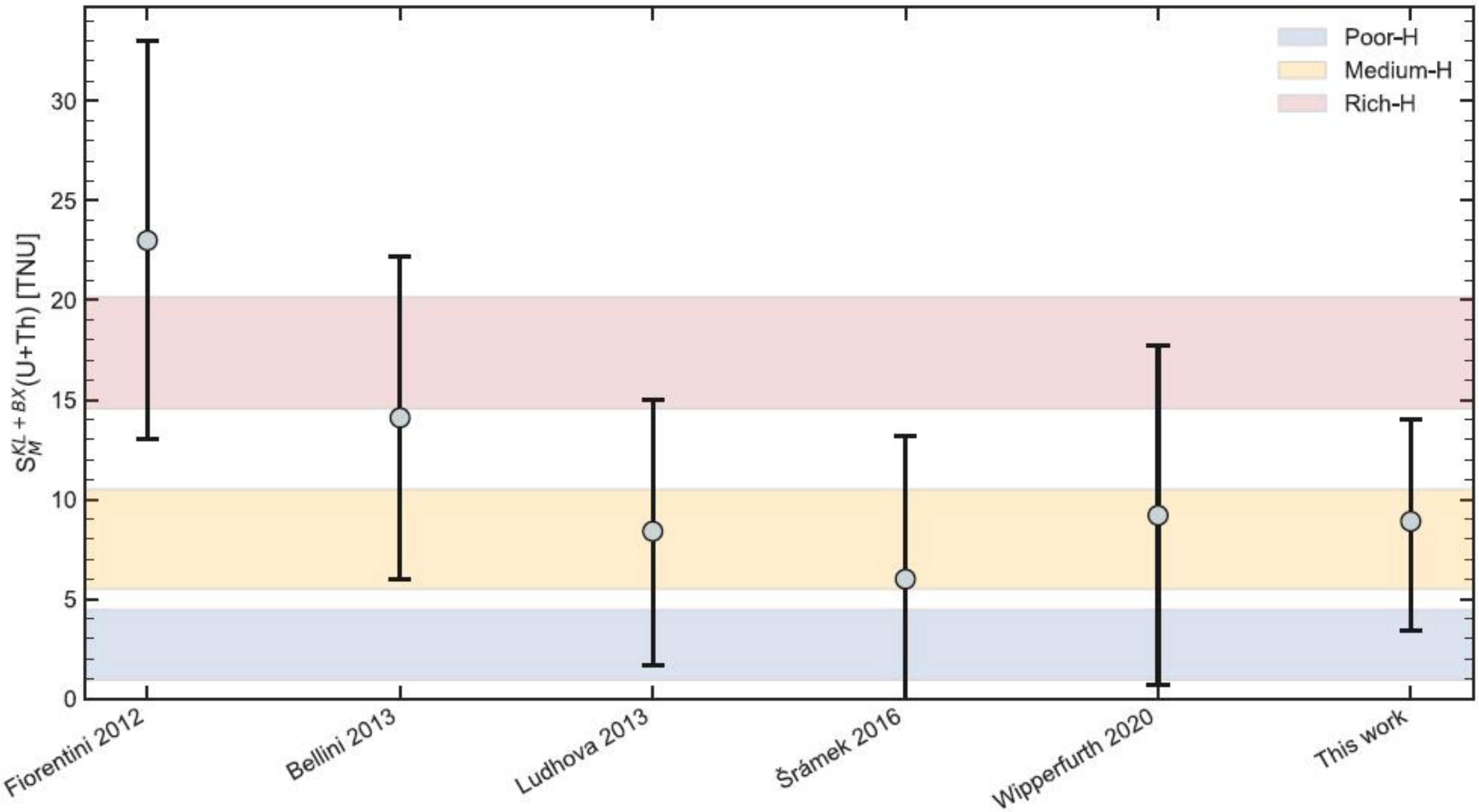
Since H_{LS} (U+Th)= $6.9_{-1.2}^{+1.6}$ TW is independent from the BSE model, the discrimination capability of the combined geoneutrino measurement among the different BSE models can be studied in the space S_M(U+Th) vs H_M(U+Th):

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

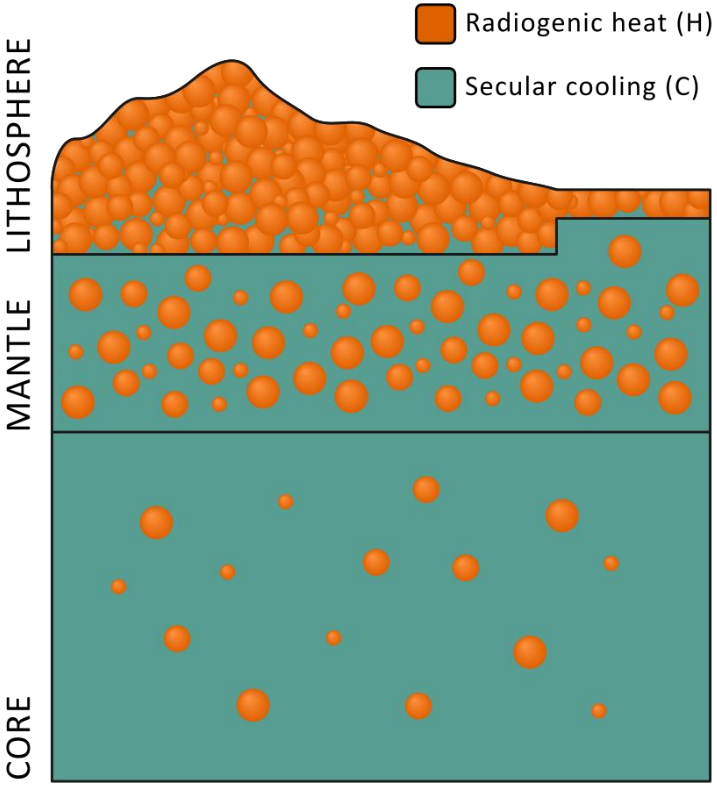


	Poor	Medium	Rich	KL+BX
H_M(U+Th) [TW]	$3.2^{+2.0}_{-2.1}$	9.3 ± 2.9	$20.2^{+3.2}_{-3.3}$	$10.3^{+5.9}_{-6.4}$

Collection of the geoneutrino mantle signals



Understanding the Earth's heat budget with geoneutrinos



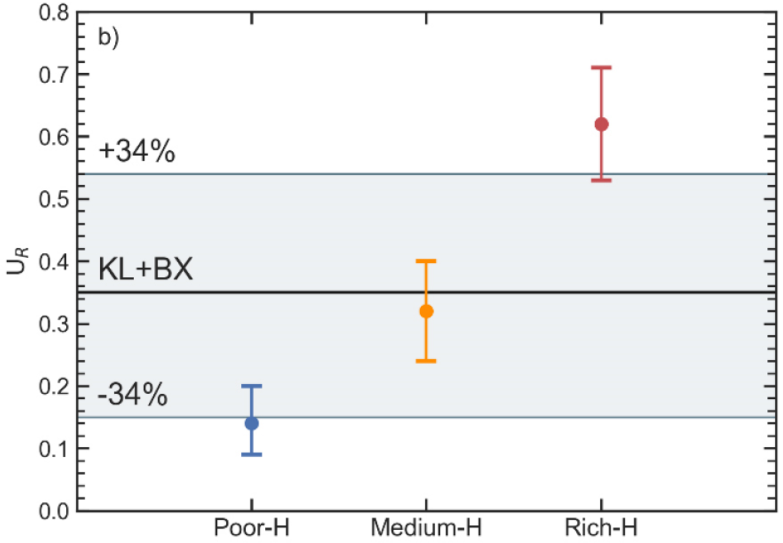
$$C = Q - H$$

$$C_M = Q - H - C_C$$

$$H_M = H - H_{LS} - H_C$$

$$H_{LS} = H_{CC} + H_{OC} + H_{CLM}$$

$$U_R = \frac{H - H_{CC}}{Q - H_{CC}}$$



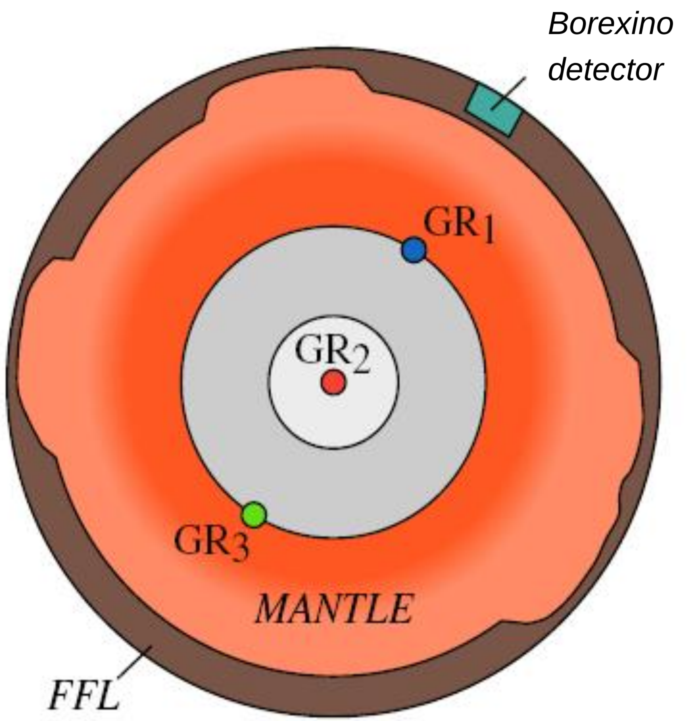
The combined geoneutrino analysis of KL and BX results constraint:

- the ratio of heat production over heat loss
- the Urey ratio $U_R^{KL+BX} = 0.35^{+0.19-0.20}$

	Adopted	**Combined KL + BX**
Q [TW]	**47 ± 2**	
H_{LS}(U+Th+K) [TW]	$8.1^{+1.9}_{-1.4}$	
H_M(U+Th+K) [TW]	$11.3^{+3.3}_{-3.4}$	$12.5^{+7.1}_{-7.7}$
H [TW]	**19.3 ± 2.9**	$\mathbf{20.8^{+7.3}_{-7.9}}$
C [TW]	**28 ± 4**	**26 ± 8**

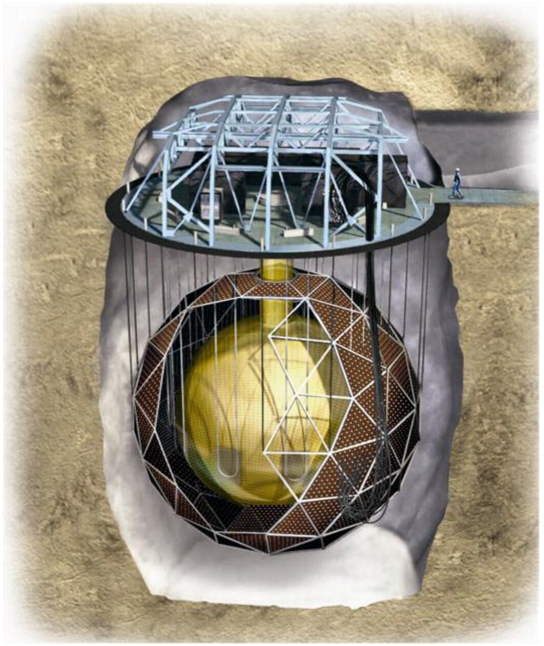
Georeactor investigation

- A possible existence of GeoReactor (GR), i.e., natural nuclear fission reactor in the Earth interior, was first suggested by Herndon in 1993.
- Different models suggest the existence of natural nuclear reactors at different depths: at the center of the core, at the inner core boundary, and the core-mantle boundary.
- Borexino collaboration tested the GR hypothesis by performing the spectral fit after constraining the expected number of reactor antineutrino events.



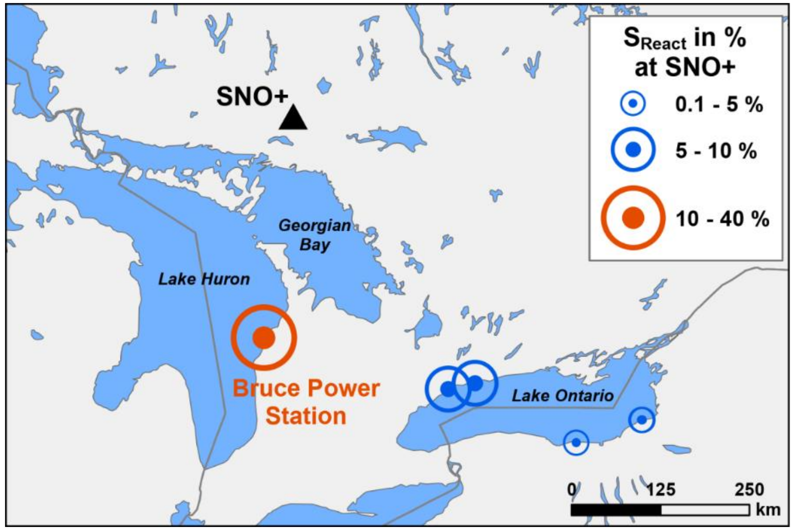
	GR1	GR2	GR3
Distance from BX	2900 km	6371 km	9842 km
GR power excluded at 95% CL	0.5 TW	2.4 TW	5.7 TW

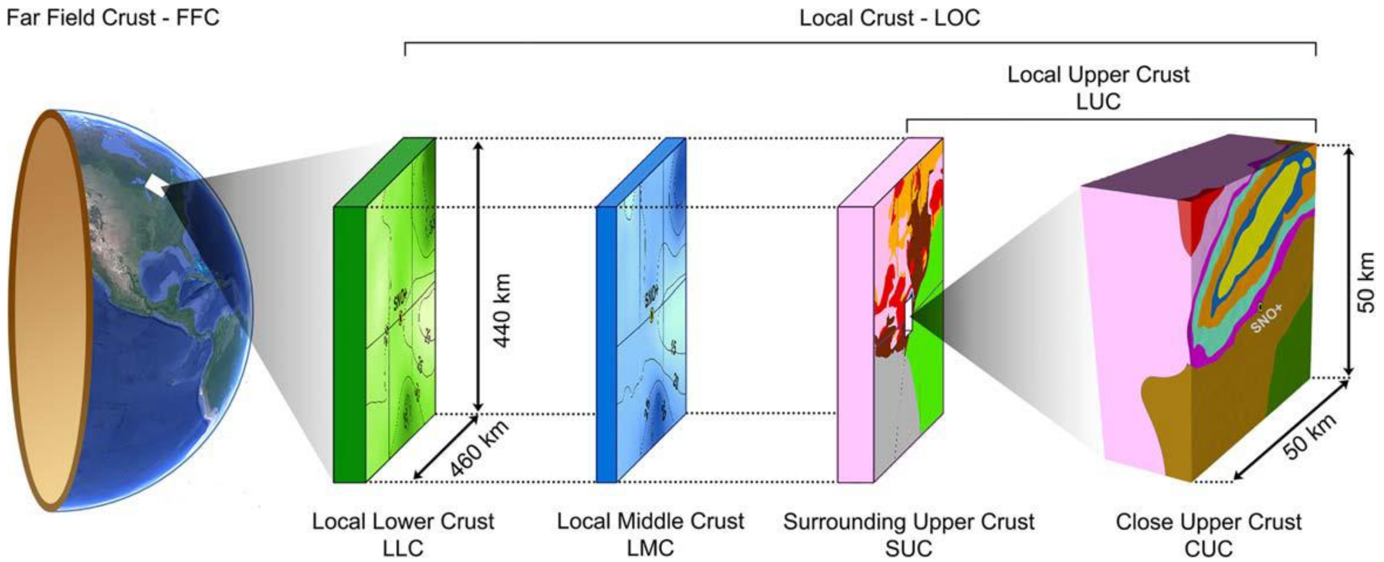
Expected geoneutrino signal at SNO+



- Deepest underground detector (~ 5800 mwe)
- 780 tons of LS detector with ~ 9300 PMTs
- Expected react-ν in [1.8-3.3 MeV] = $48.5^{+1.8}_{-1.5}$ TNU (S_{rea} / S_{geo} ~ 1.2)

	S(U+Th) [TNU]
Wipperfurth et al., 2020 (using global crustal models)	$50.2^{+9.7}_{-8.1}$
	$46.2^{+9.3}_{-7.7}$
	$46.8^{+9.3}_{-7.8}$
Strati et al., 2017 (combining global crustal model and local geological data)	$41.8^{+9.6}_{-6.2}$



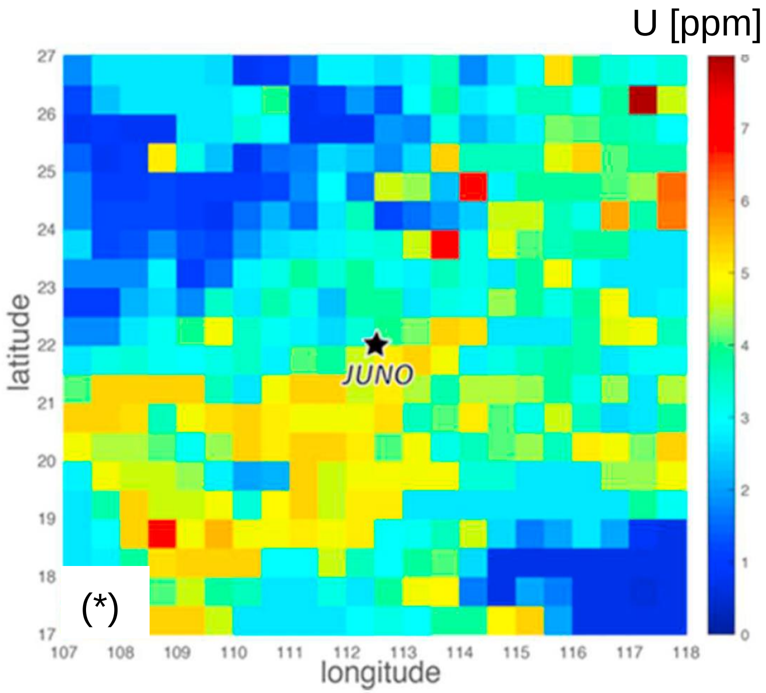


Expected geoneutrino signal at JUNO

- JUNO is a 20 kton LS detector surrounded by ~18.000 20" PMT
- Expected geo-ν ~ 400 events/year (~ 40 TNU)
- Expected react-ν in [1.8-3.3 MeV] ~ 260 TNU (S_{rea} / S_{geo} ~ 7)

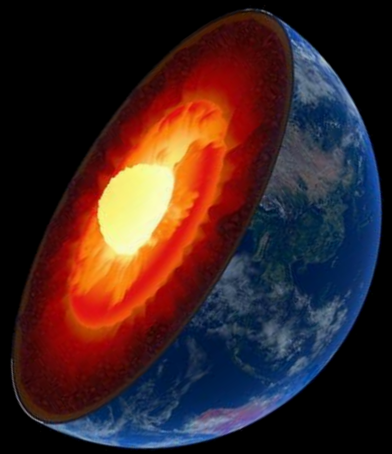
	N° of cores	Thermal power/core
Yangjiang	6	2.9 GW
Taishan	2	4.6 GW

	S(U+Th) [TNU]
Strati et al., 2015 (using global crustal model)	$39.7^{+6.5}_{-5.2}$
Wipperfurth et al., 2020 (using global crustal models)	$41.3^{+7.5}_{-6.3}$
	$41.2^{+7.6}_{-6.4}$
	$40.05^{+7.4}_{-6.2}$
Gao et al., 2020 (*) (combining global crustal model and local geological data)	$49.1^{+5.6}_{-5.0}$

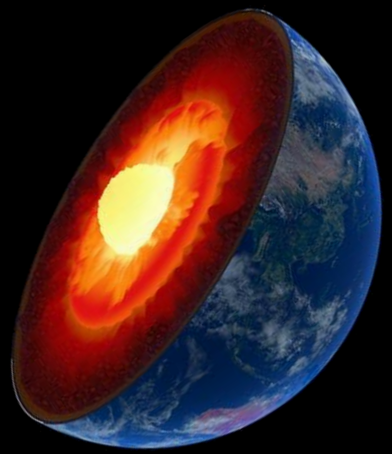


Take-away messages

- To deeply understand the experimental geoneutrino results, the use of refined geological models is essential
- The mantle radiogenic power H_M (U+Th)= $10.3^{+5.9}_{-6.4}$ TW from combined KL+BX geoneutrino analysis agrees with medium-H BSE models.
- The presence of georeactor P_{GR} = 2.4 TW in the center of the Earth is excluded at 95% C.L.
- Very soon we will investigate the deep Earth with KL, BX, SNO+ and JUNO results: the era of "multi-site detection" of geoneutrinos is definitely open

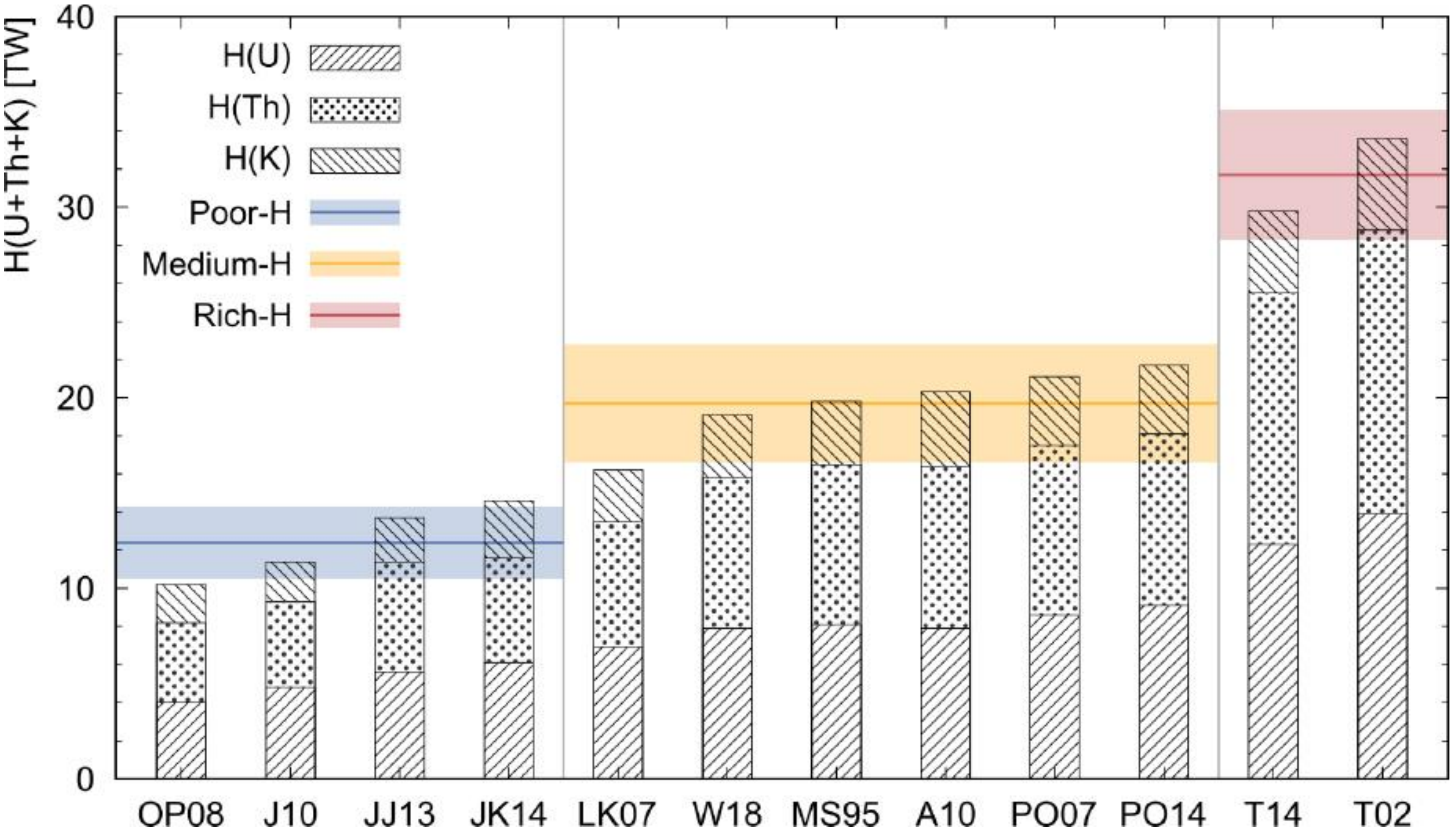


Thank you



Back up slide

Reference	Code
Jackson and Jellinek, 2013	JJ13
O’Neill and Palme, 2008	OP08
Javoy and Kaminski, 2014	JK14
Javoy et al., 2010	J10
McDonough and Sun, 1995	MS95
Lyubetskaya and Korenaga, 2007	LK07
Palme and O’Neill, 2007	PO07
Arevalo, 2010	A10
Wang et al., 2018	W18
Palme and O’Neill, 2014	PO14
Turcotte, 2002*	T02
Turcotte, 2014	T14



	Poor	Medium	Rich
H(U+Th+K) [TW]	12.4 ± 1.9	19.7 ± 3.1	31.7 ± 3.4