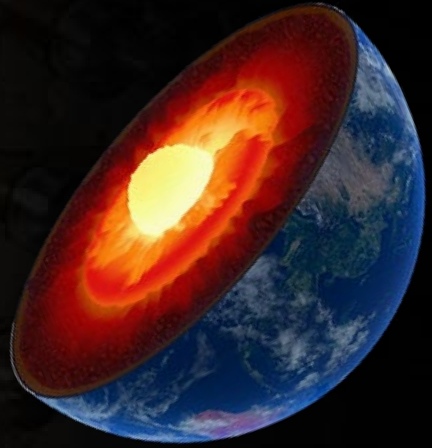
Revealing the Earth's interior with geoneutrinos



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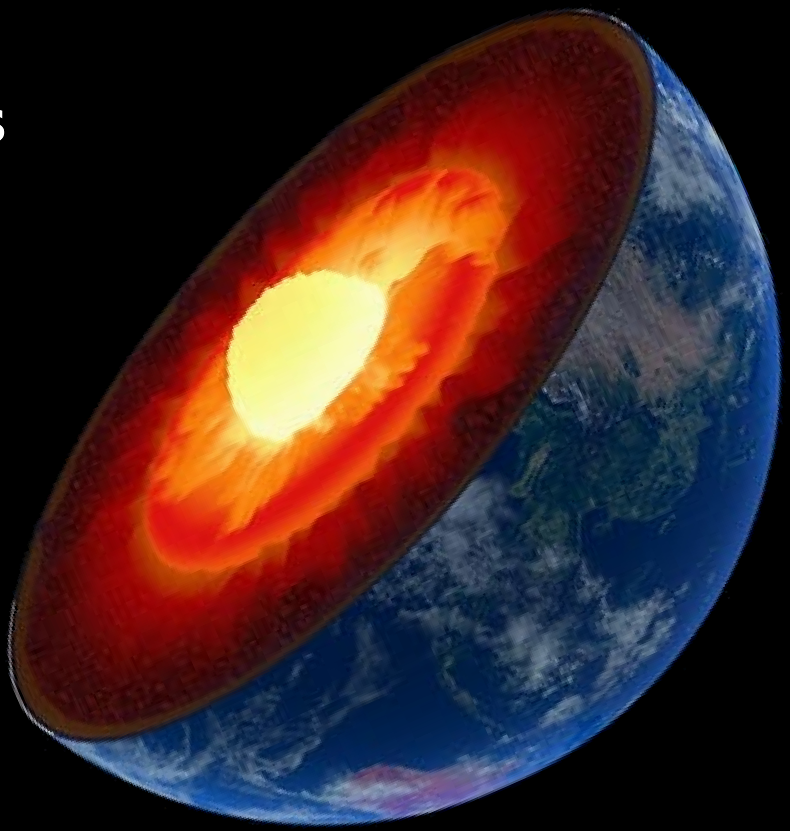
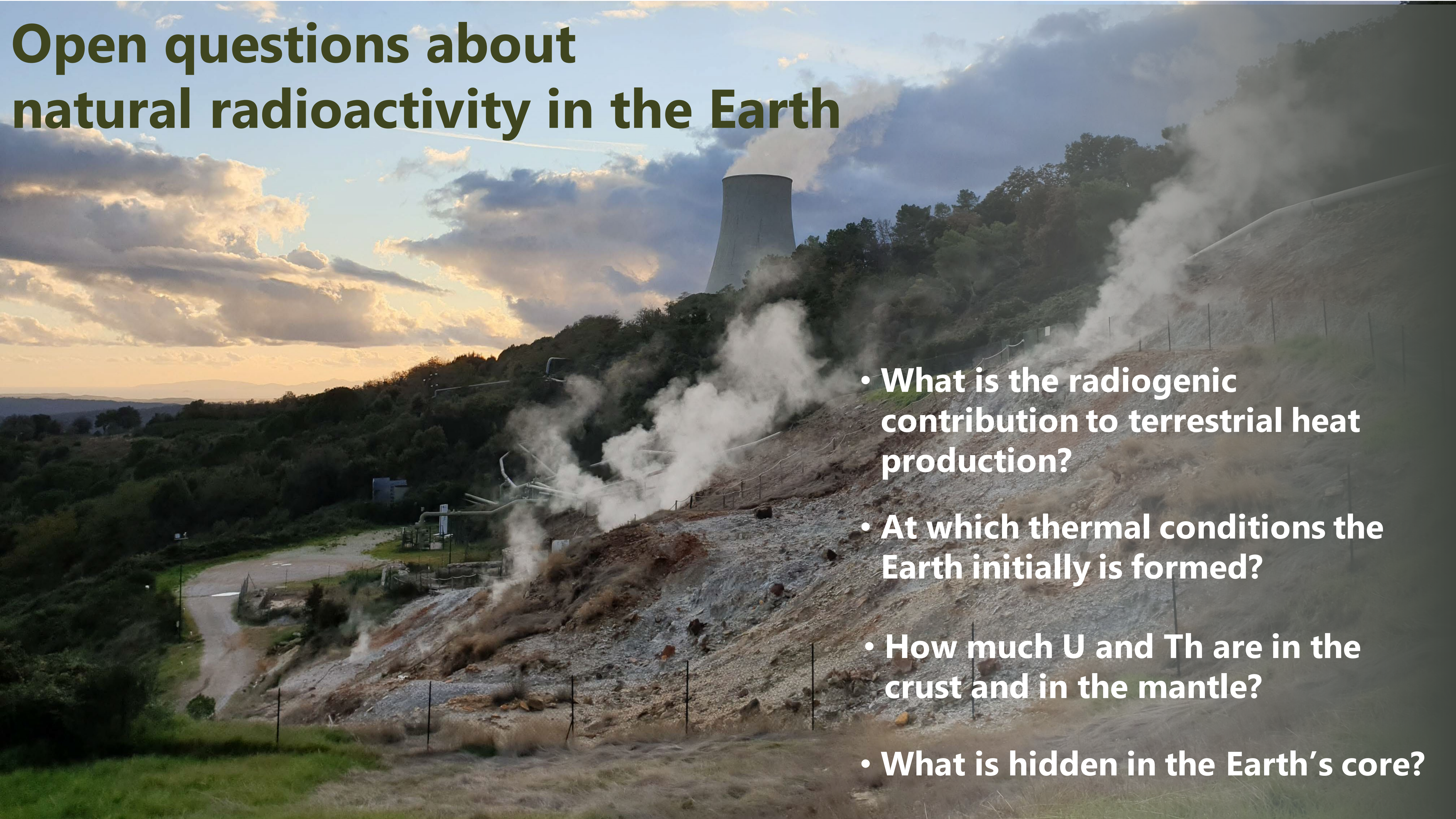
Multi-messenger Tomography of the Earth 2023
4-7 July 2023 - Paris

Outline

- Natural radioactivity and Heat power in the Earth: open questions
  Virginia Strati
- Overview of experimental results on geoneutrinos
  Livia Ludhova
- What can we learn from geoneutrinos results?
  Virginia Strati
- Perspectives and challenges for geoneutrino experiments
  Fabio Mantovani
- JUNO's perspectives for geoneutrinos
  Yury Malyshkin

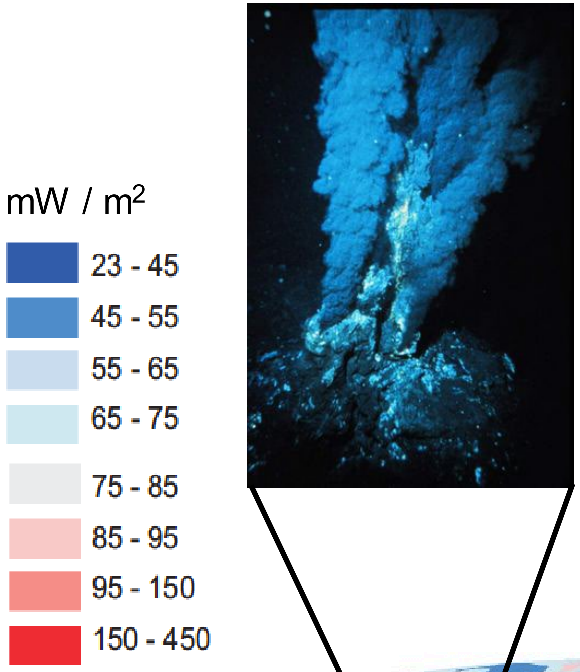




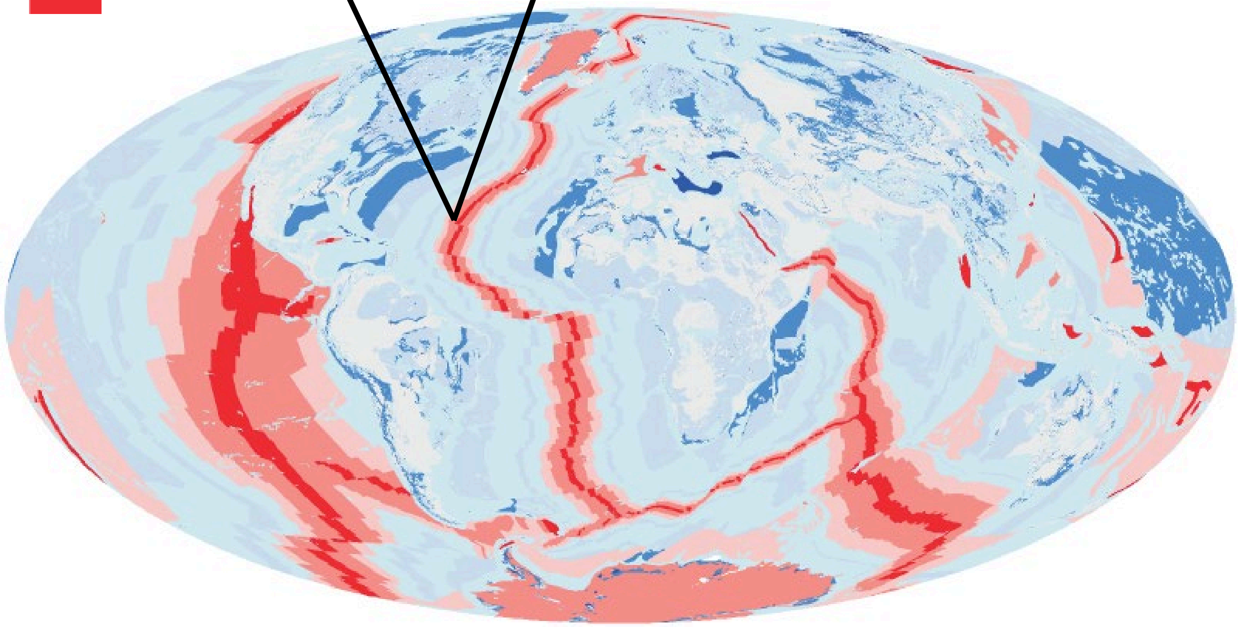
Open questions about natural radioactivity in the Earth

- 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?

Heat power of the Earth



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



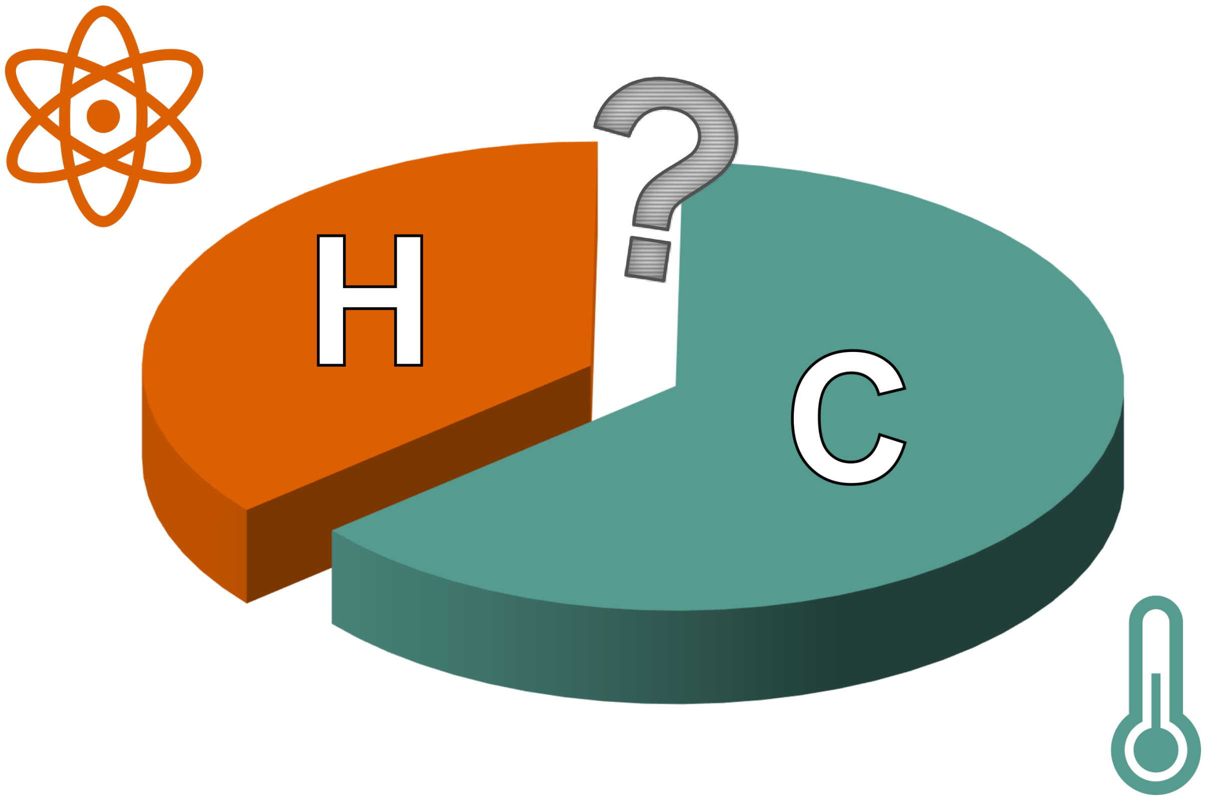
REFERENCE	Continents	Oceans	Total
	q_{CT} [mW m^{-2}]	q_{OCS}[mW m^{-2}]	Q (TW)
Williams et al., 1974	61	92	43 ± 6
Davies, 1980	55	95 ± 10	41 ± 4
Sclater et al., 1980	57	99	42
Pollack et al., 1993	65 ± 2	101 ± 2	44 ± 1
Hofmeister and Criss, 2005	61	65	31 ± 1
Jaupart et al., 2015	65	107	46 ± 2
Davies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

The Earth's heat sources

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), i.e. U, Th and K, inside our planet.

- The Urey ratio is a key parameter that can be seen as the ratio of **H** over **Q**. It measures the efficiency of the Earth's convective engine in evacuating heat generated by radioactive decays.

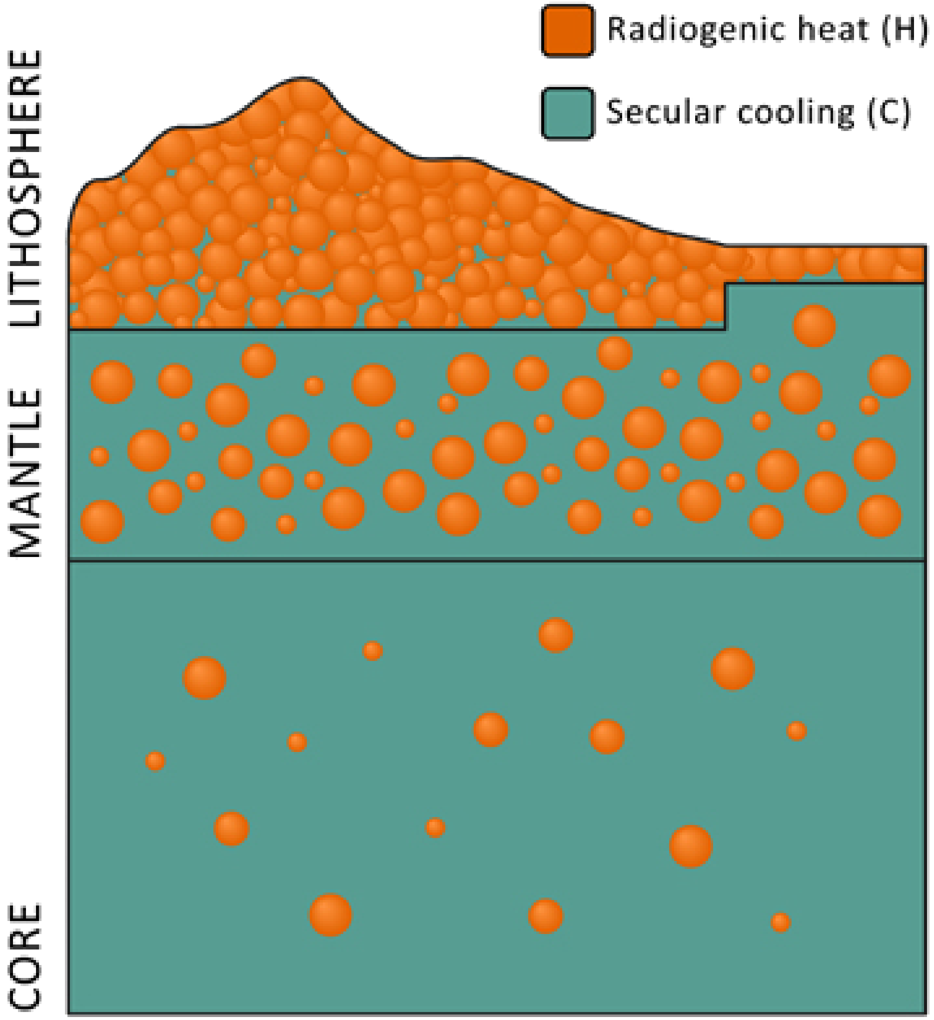


$$U_R = \frac{H}{Q} \ (Bulk\ Earth)$$

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

H_{CC} : radiogenic power of the continental crust

The Earth's budget



- H_{CC} = radiogenic power of the continental crust
- H_{OC} = radiogenic power of the oceanic 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 HPEs: $\mathbf{H_{LS} \sim 8}$ **TW**.
- Radiogenic power of the **mantle** H_M and the contributions to C from mantle (C_M) and core (C_C) are model dependent.

The building blocks of the Bulk Silicate Earth

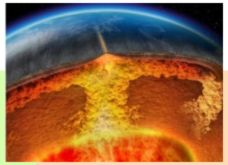
- The **Bulk Silicate Earth** (**BSE**) describes the primordial non-metallic Earth condition that followed planetary accretion and core separation, prior to its differentiation into a mantle and crust.
- We can tempt to naively build the BSE in the image and likeness of a primitive meteorite: every year 10^4 kg of meteorites falling to the ground
- The **chondrites** are undifferentiated rocky meteorites: they represents the initial «cocktail» of the Solar System

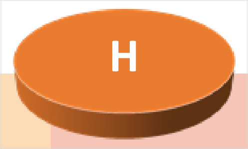
CARBONACEOUS (**CI**):
composition close to Solar photosphere - high concentration of oxides

ENSTATITE (**EH**) **:**
Isotopic composition more similar to the terrestrial samples - high metallic iron content

References	Chondrite	$a_{BSE}(U)$ [ng g^{-1}]
Jackson and Jellinek [160]	CI-EH	14 ± 3
O'Neill and Palme [67]	CI-EH	10
Javoy and Kaminski [157]	EH	15 ± 2
Javoy et al. [101]	EH	12 ± 2
McDonough and Sun [38]	C	20 ± 4
Lyubetskaya and Korenaga [161]	C	17 ± 3
Palme and O'Neill 2007	C	22 ± 3
Arevalo 2010	C	20 ± 4
Wang et al. 2018	C	20 ± 2
Palme and O'Neill [162]	C	23 ± 3
Turcotte 2002*	CI-EH	35 ± 4
Turcotte 2014	CI-EH	31

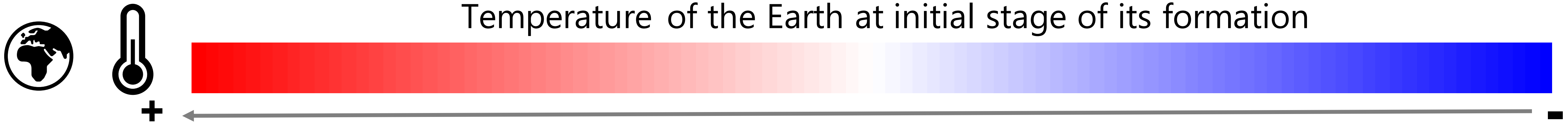
Different models of Bulk Silicate Earth





	CC	GC	GD	FR
	COSMOCHEMICAL	**GEOCHEMICAL**	**GEODYNAMICAL**	**FULLY RADIOGENIC**
	• Enstatites chondrites • Sufficiently high iron content to explain the metallic core	• Chondritic compositions for refractory lithophile elements • Constraints from terrestrial samples	• Energetics arguments of mantle convection • Observed surface heat loss	• The terrestrial heat (47 TW) is assumed to be fully accounted by radiogenic production
H (U+Th+ K) [TW]	**11**	**20**	**34**	**47**
M (U) [10^{16} kg]	5	8	14	20

Temperature of the Earth at initial stage of its formation



Geo-neutrinos: anti-neutrinos from the Earth

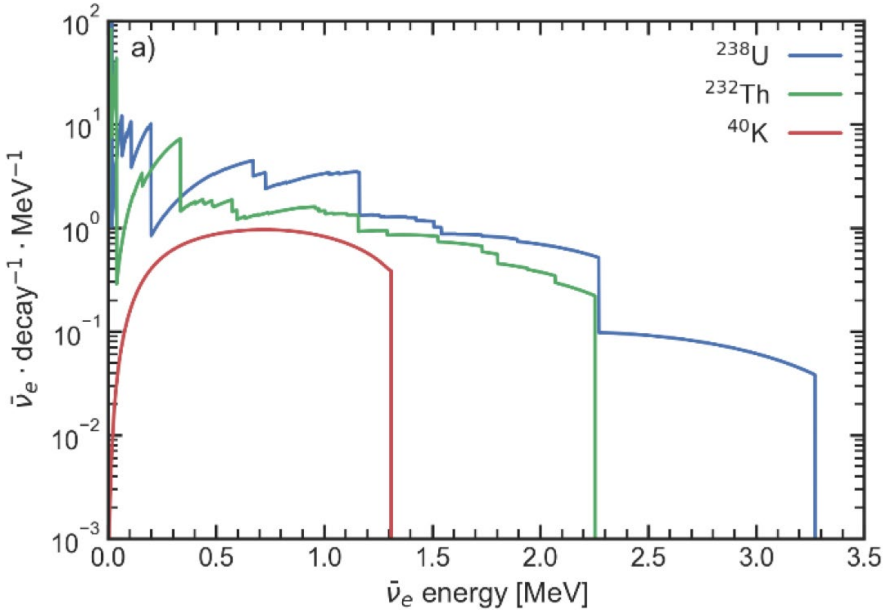
U, Th and ^{40}K in the Earth release heat together with anti-neutrinos, in a **well-fixed ratio**:

Decay	$T_{1/2}$ [10^9 yr]	E_{max} [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$kg^{-1}s^{-1}$]	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 $\Phi_{\bar{\nu}} \sim 10^6\,cm^{-2}s^{-1}$ 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:

$$\bar{\nu} + p \rightarrow e^+ + n - 1.806\ MeV$$

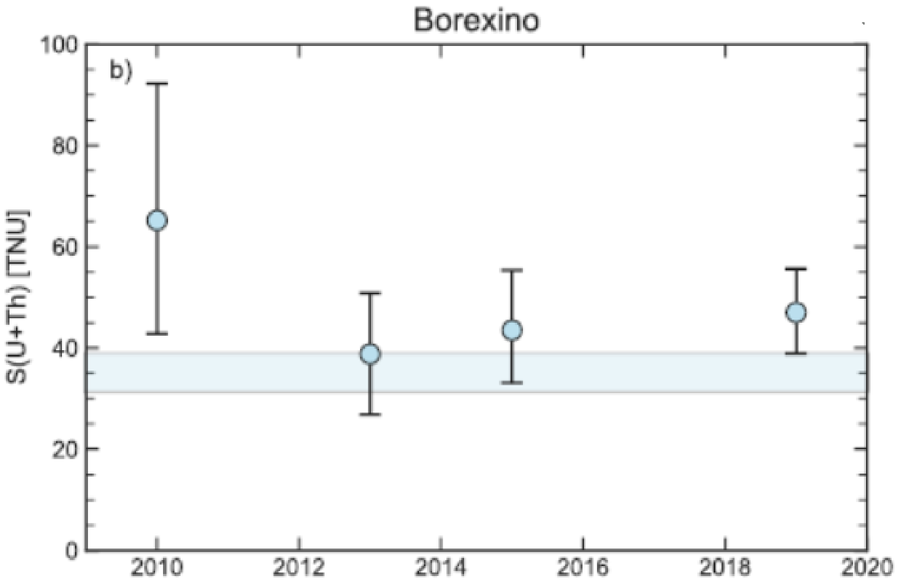
- Different components can be distinguished due to different energy spectra: e. g. anti-ν with highest energy are from U
- Signal unit: **1 TNU** = one event per 10^{32} free protons/year



Borexino geoneutrino results

Borexino

- Period: 2007 – 2019
- Geo-ν events: $52.6^{+7.4}_{-6.3}$
- Signal: $47.0^{+8.7}_{-7.9}$ TNU

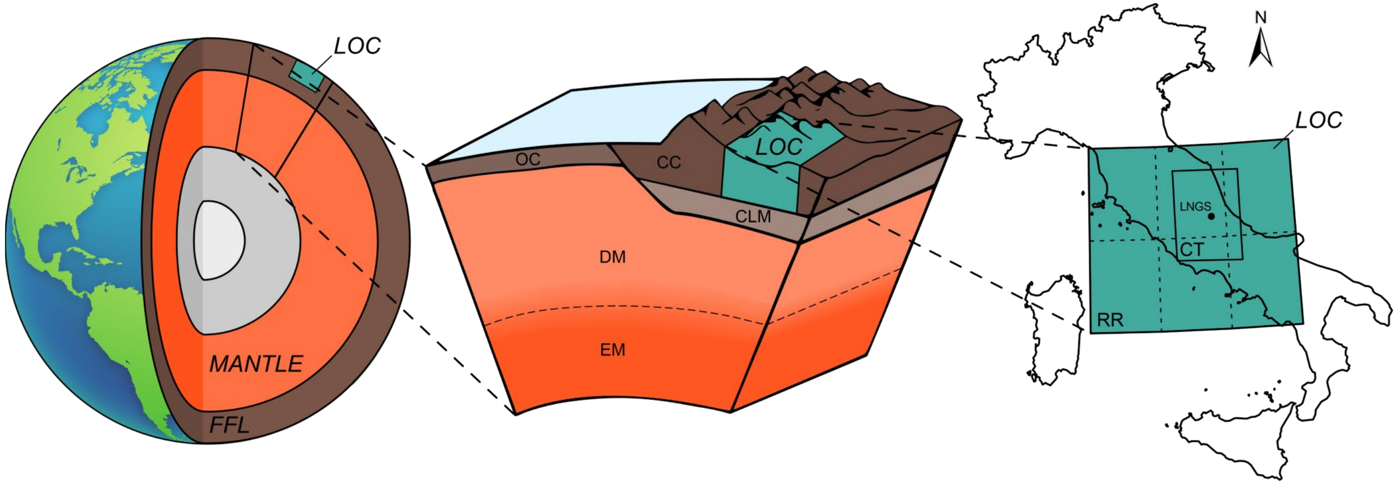


- Horizontal bars traces the **expected signal** at 1σ C.L.
- In the second decade of the 21st century the results published with greater statistical significance highlighted the necessity of **geophysical and geological models** for understanding geoneutrino signal.

Borexino collaboration, 2020 - PRD – 101 (1)

Mantle geoneutrino signals from experimental signal

$$S^i_{Exp}(U+Th) = S^i_M(U+Th) + S^i_{FFL}(U+Th) + S^i_{LOC}(U+Th)$$



- U and Th distributed in the **Local Crust (LOC)** (i.e. ~ 500 km within the detector) gives a significant contribution to the signal (~ 50% of the total).

$$S^i_M(U+Th) = S^i_{Exp}(U+Th) - S^i_{FFL}(U+Th) - S^i_{LOC}(U+Th)$$

- The signal of **the Far Field Lithosphere (FFL)** is modeling based on global reference model.
- The **Local Crust (LOC)** modeling should be built with geochemical and/or geophysical information typical of the local regions.

$S_{LOC}(U+Th)$	9.2 ± 1.2 TNU
$S_{FFL}(U+Th)$	$16.3^{+4.8}_{-3.7}$ TNU

Measurements vs models

S_{Exp} (U+Th) = $47.0^{+8.6}_{-8.1}$ 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)

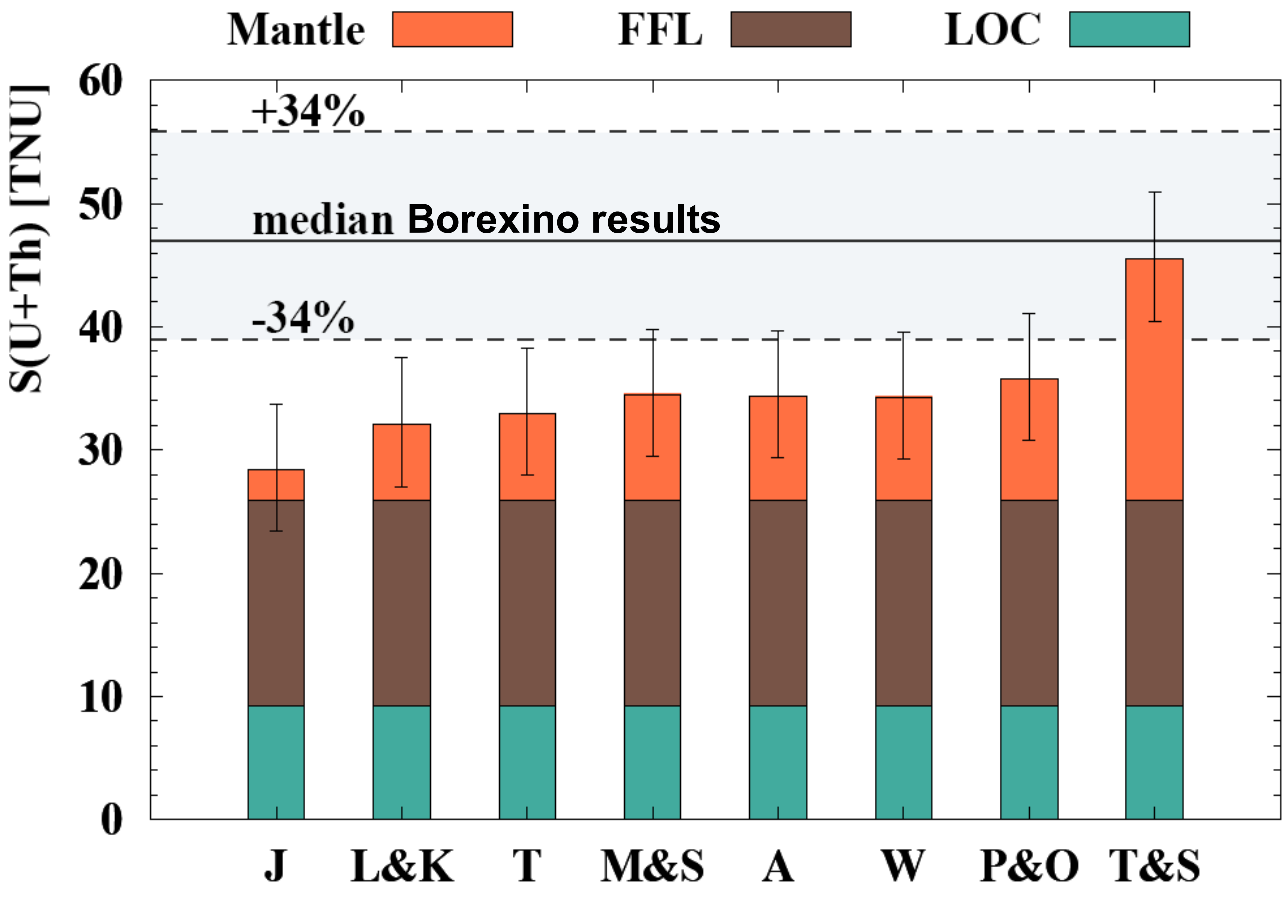
M&S = W. F. McDonough and S. Sun, Chem. Geol. 120, (1995)

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

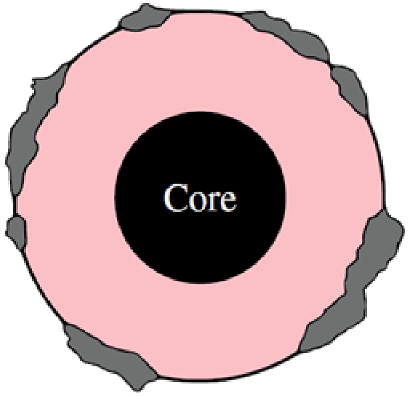
Mantle radiogenic power (BX)

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

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

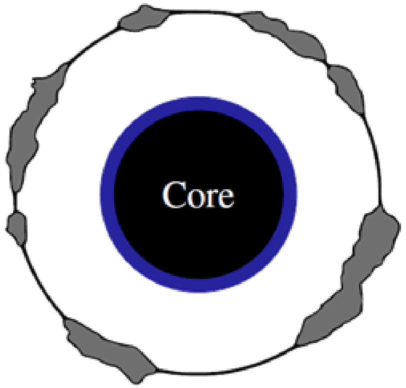
High scenario

β = 0.98 TNU/TW



Low scenario

β = 0.75 TNU/TW



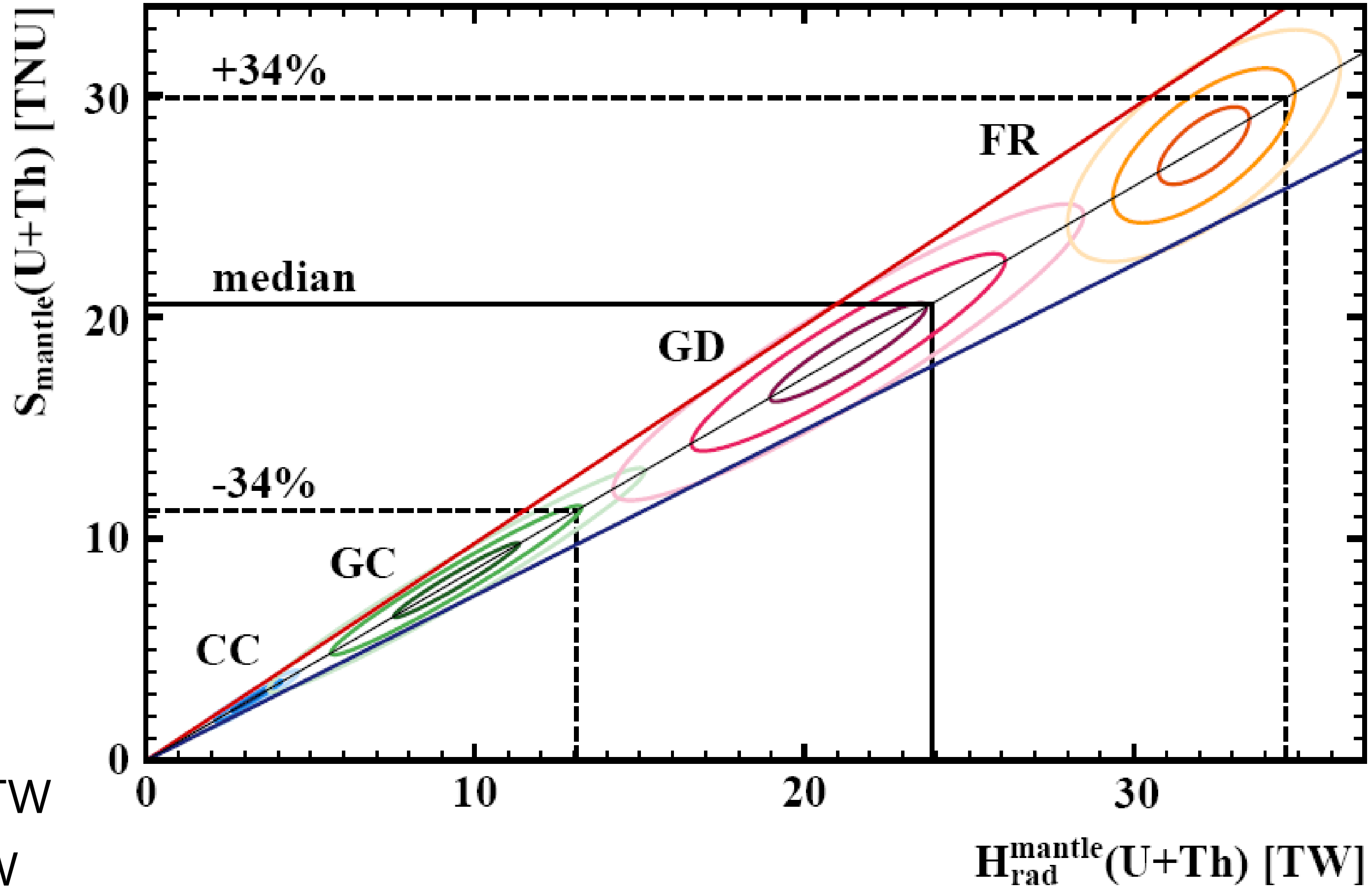
Cosmochemical Model (CC) H_M(U + Th) = 0.7 – 3.8 TW

Geochemical Model (GC) H_M(U + Th) = 7.5 – 10.9 TW

Geodynamical Model (GD) H_M(U + Th) =19.8 – 23.3 TW

Fully radiogenic (FR) H_M(U + Th) = 30.5 – 34.0 TW

S_{Mantle} (U+Th) = $21.2^{+9.6}_{-9.0}$ TNU



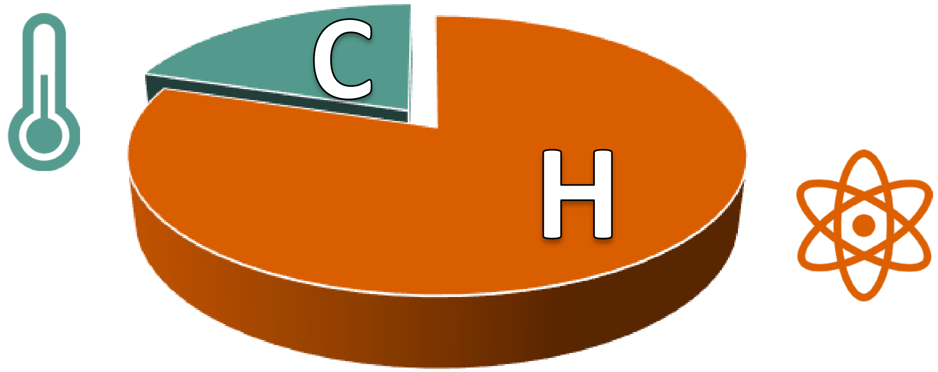
H_{Mantle} (U+Th) = $24.6^{+11.1}_{-10.4}$ TW

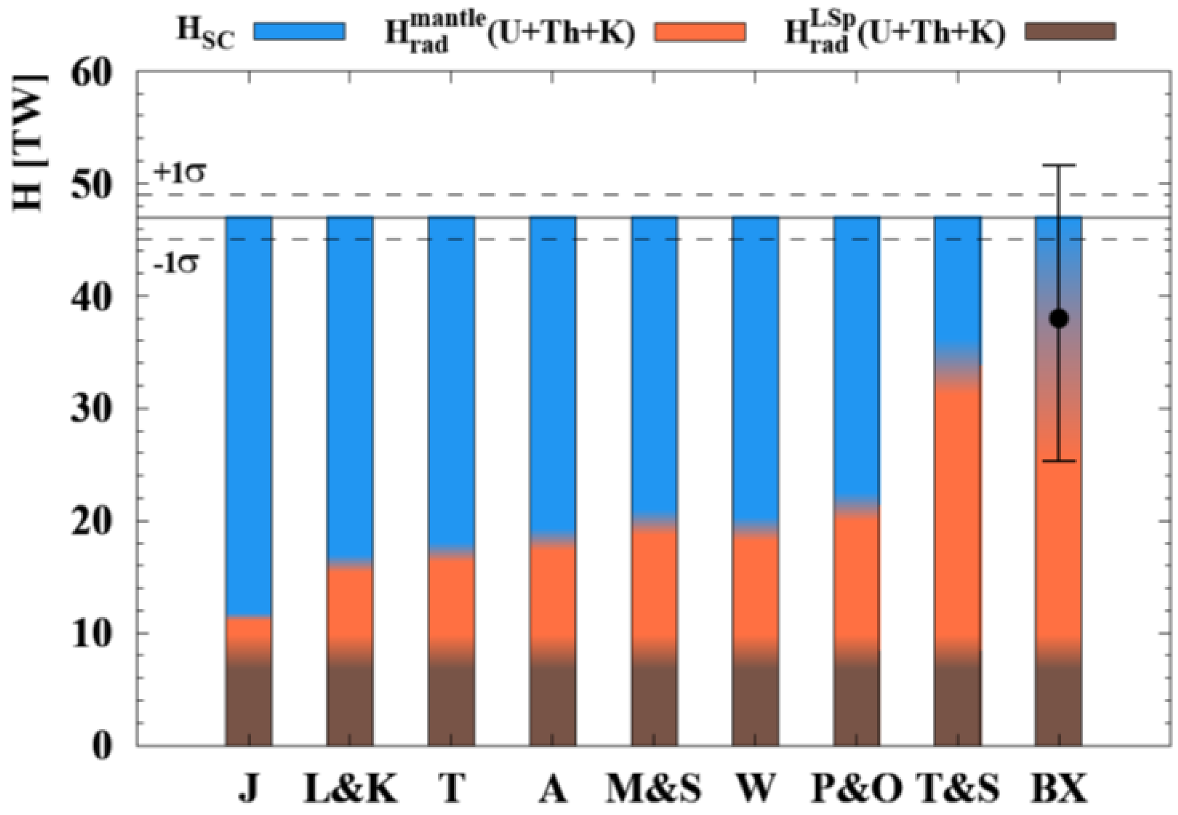
Earth's heat budget (BX)

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

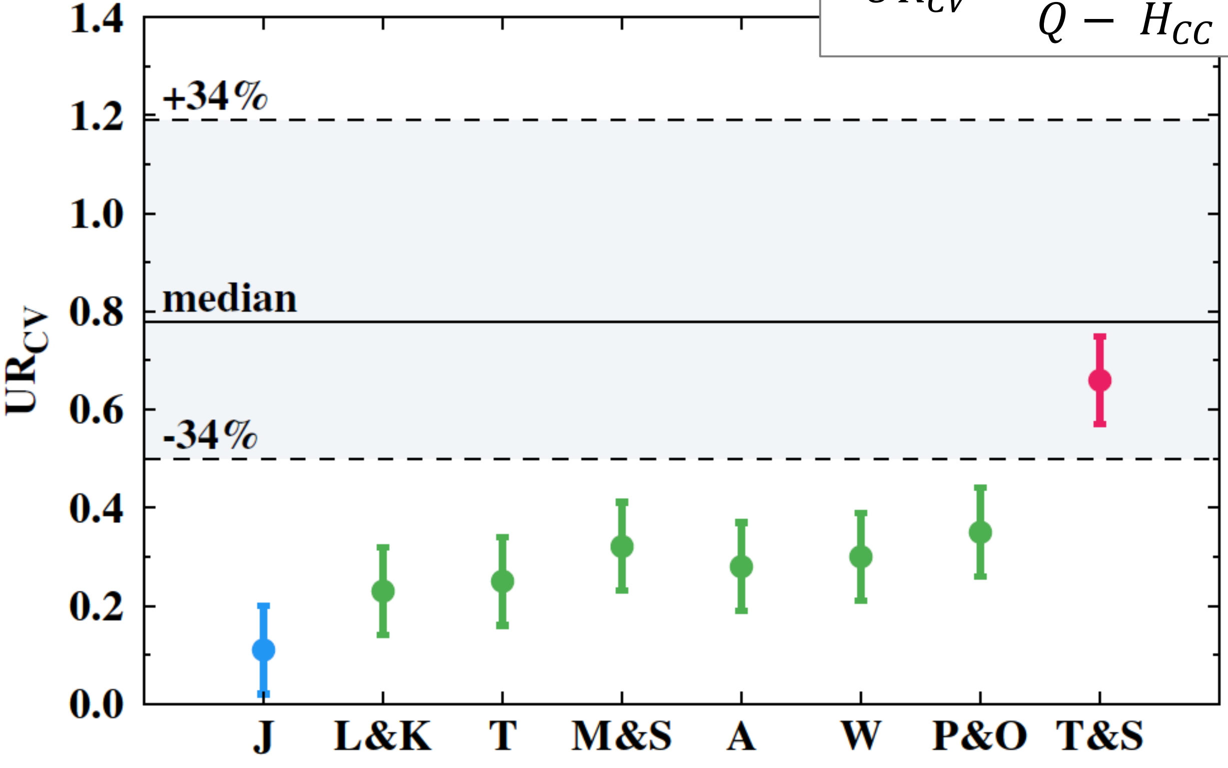
Assuming the contribution from ^{40}K to be 18% of the total mantle radiogenic heat

H_{Earth} (U+Th+K) = $38.2^{+13.6}_{-12.7}$ TW





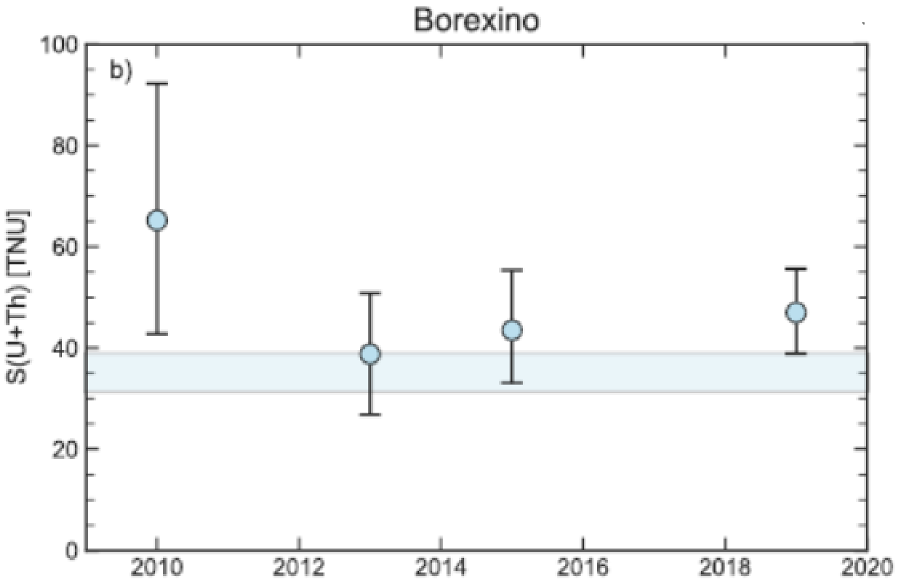
$$UR_{CV} = \frac{H - H_{CC}}{Q - H_{CC}}$$

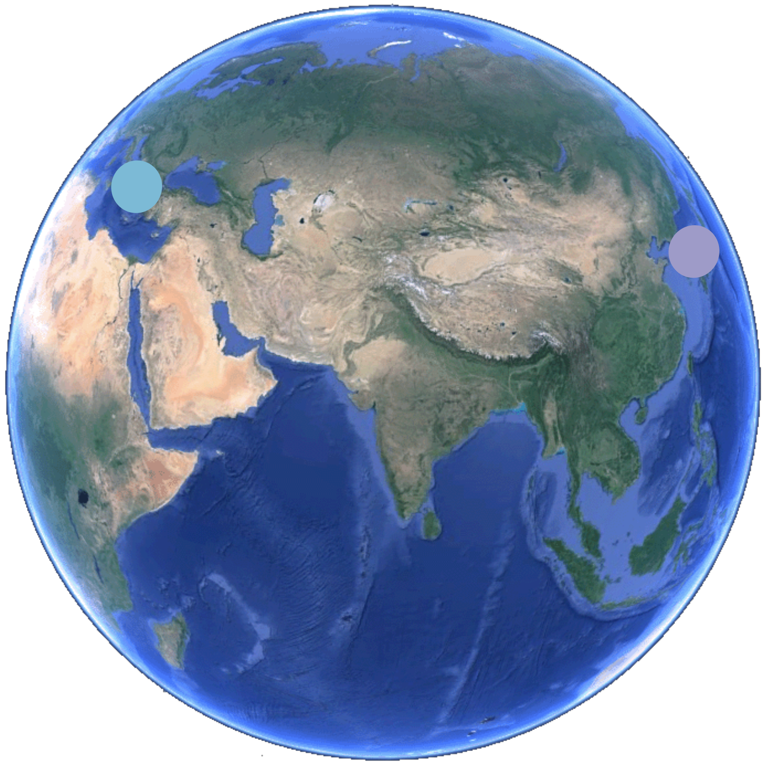


Borexino and KamLAND geoneutrino results

Borexino

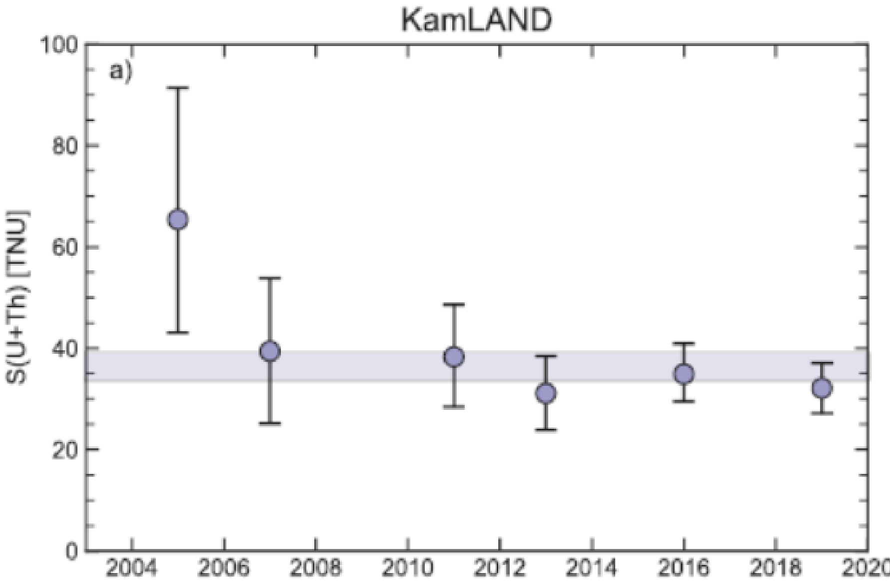
- Period: 2007 – 2019
- Geo-ν events: $52.6^{+7.4}_{-6.3}$
- Signal: $47.0\ ^{+8.7}_{-7.9}$ TNU





KamLAND

- Period: 2002 – 2019
- Geo-ν events: $168.8^{+26.3}_{-26.5}$
- Signal: 32 ± 5 TNU



- 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.

Borexino collaboration, 2020 - PRD – 101 (1)

KamLAND collaboration, 2019 – NGS Prague 2019

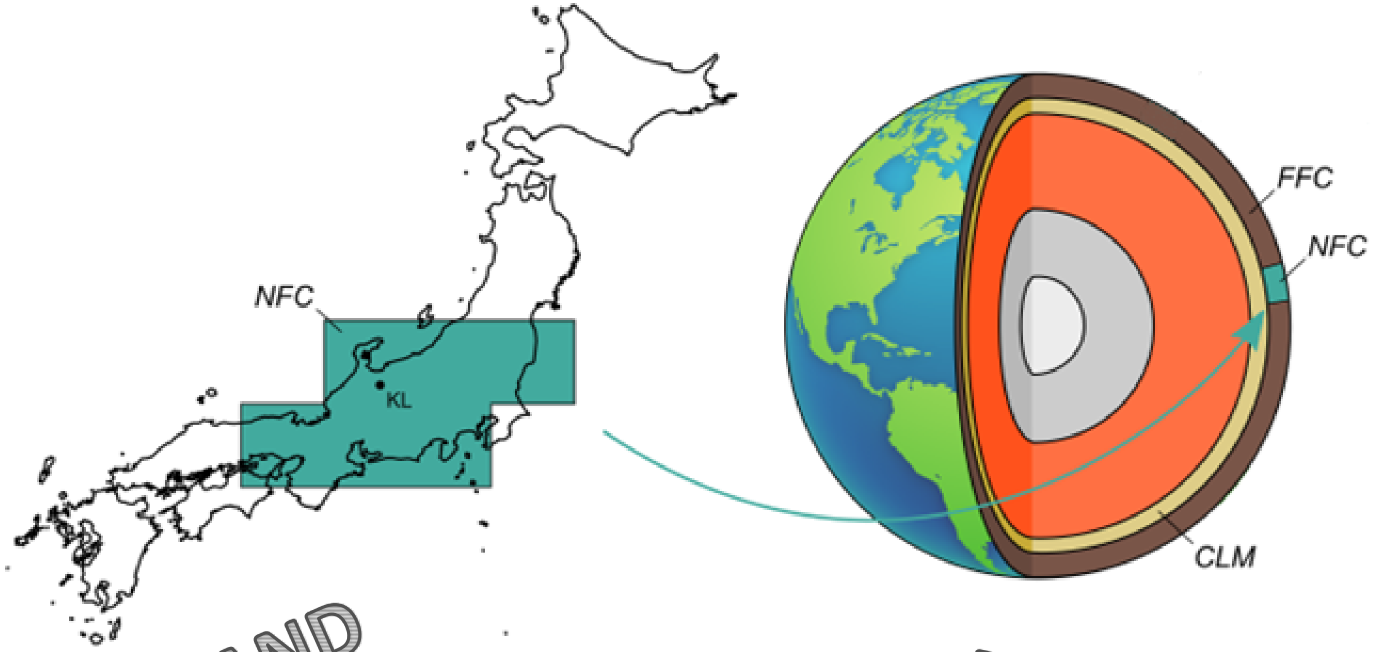
Mantle geoneutrinos (KL)

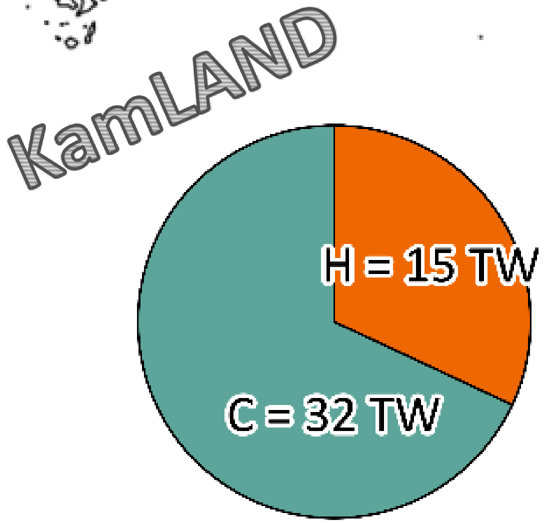
$$S_{M}^{KL}(U+Th) = S_{Exp}^{KL}(U+Th) - S_{NFC}^{KL}(U+Th) - S_{FFC}^{KL}(U+Th) - S_{CLM}^{KL}(U+Th)$$

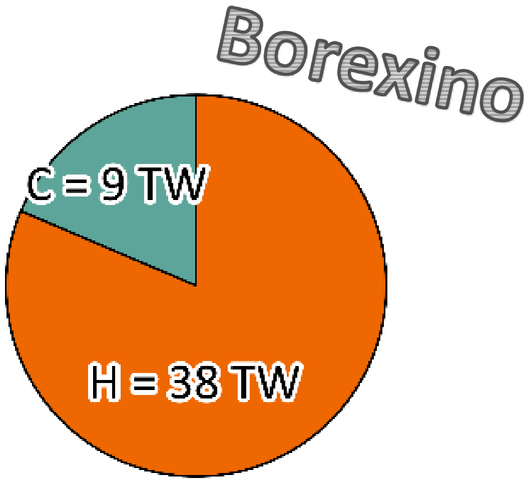
	KamLAND
S_{NFC} (U+Th) [TNU]	17.7 ± 1.4
S_{FFC} (U+Th) [TNU]	$7.3^{+1.5}_{-1.2}$
S_{CLM} (U+Th) [TNU]	$1.6^{+2.2}_{-1.0}$

S_{M}^{KL}(U+Th) = $4.8^{+5.6}_{-5.9}$ TNU

S_{M}^{BX}(U+Th) = $21.2^{+9.6}_{-9.0}$ TNU





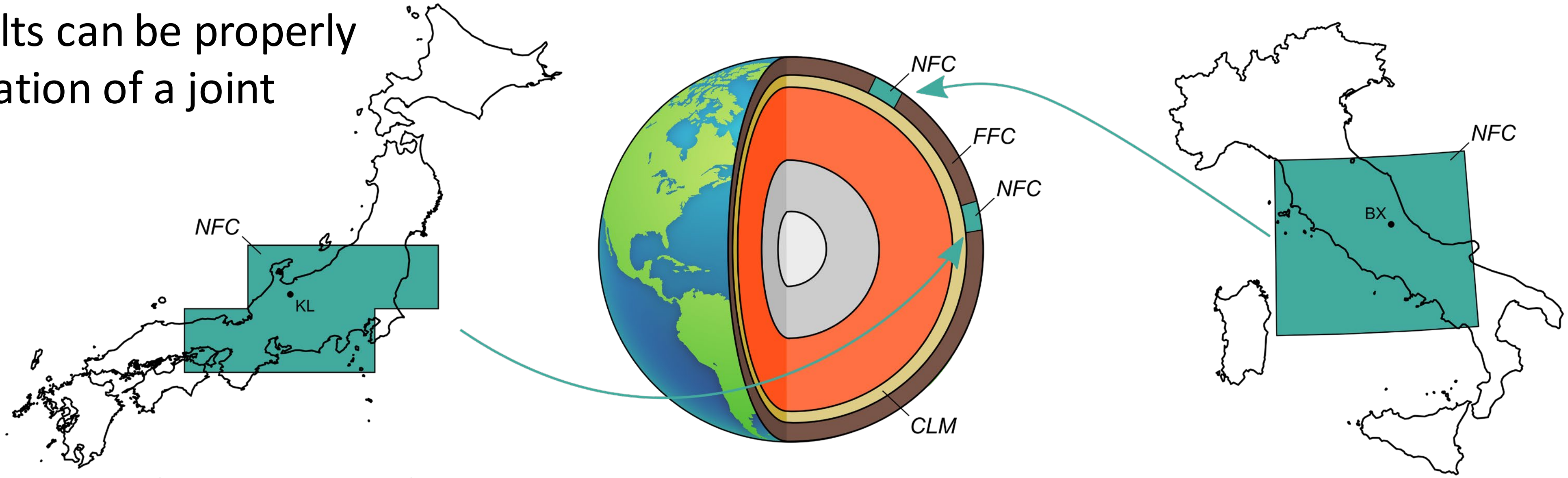


Combined mantle geoneutrinos (KL + BX)

$$S_M^{KL}(U+Th) = S_{Exp}^{KL}(U+Th) - S_{NFC}^{KL}(U+Th) - S_{FFC}^{KL}(U+Th) - S_{CLM}^{KL}(U+Th)$$

$$S_M^{BX}(U+Th) = S_{Exp}^{BX}(U+Th) - S_{NFC}^{BX}(U+Th) - S_{FFC}^{BX}(U+Th) - S_{CLM}^{BX}(U+Th)$$

- Assuming the site-independence of the mantle signal, the results can be properly combined in the estimation of a joint bivariate PDF.



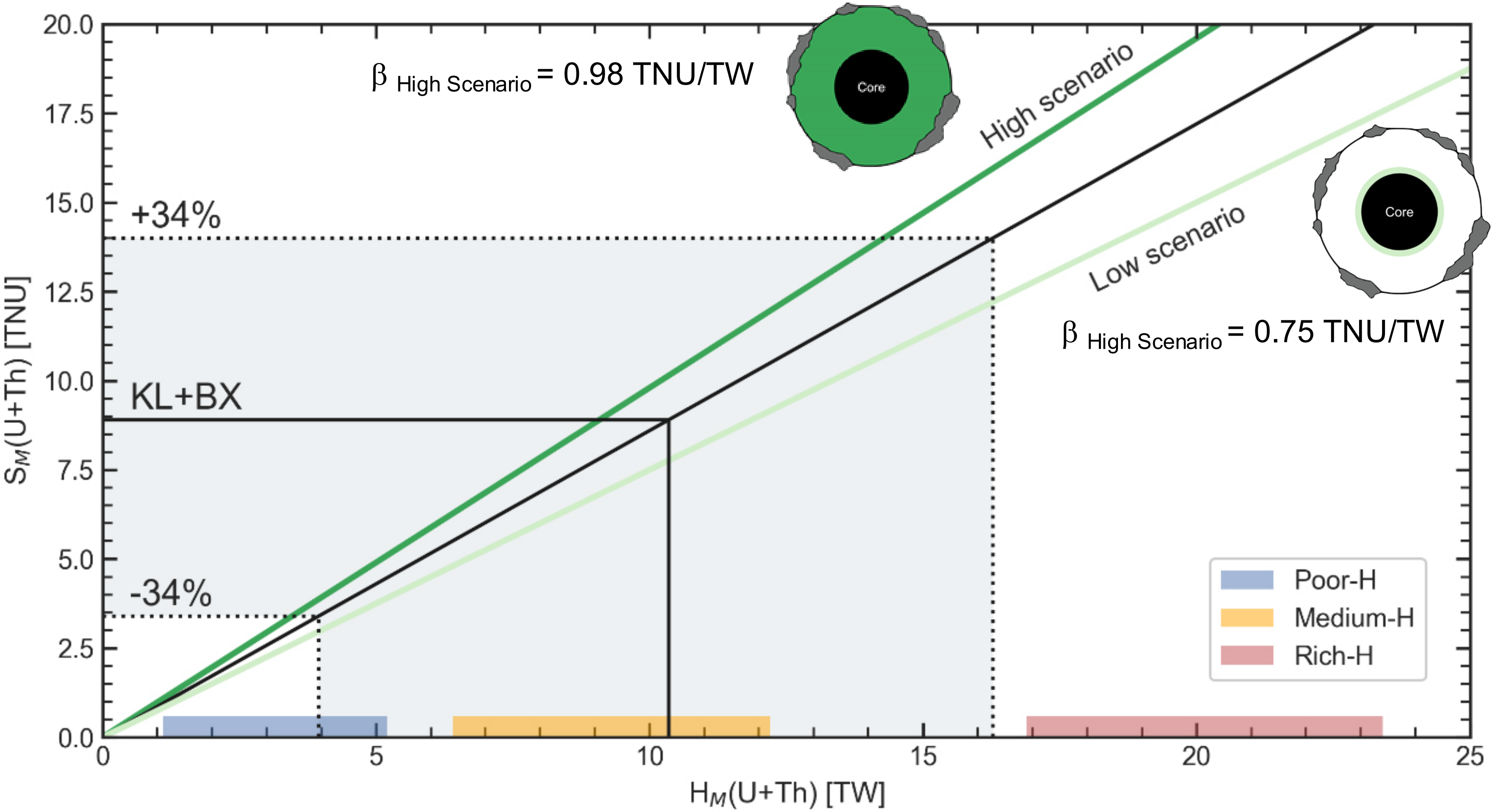
	KamLAND	Borexino
S_{NFC} (U+Th) [TNU]	17.7 ± 1.4	9.2 ± 1.2
S_{FFC} (U+Th) [TNU]	$7.3^{+1.5}_{-1.2}$	$13.7^{+2.8}_{-2.3}$
S_{CLM} (U+Th) [TNU]	$1.6^{+2.2}_{-1.0}$	$2.2^{+3.1}_{-1.3}$

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

For more details see Fabio's talk

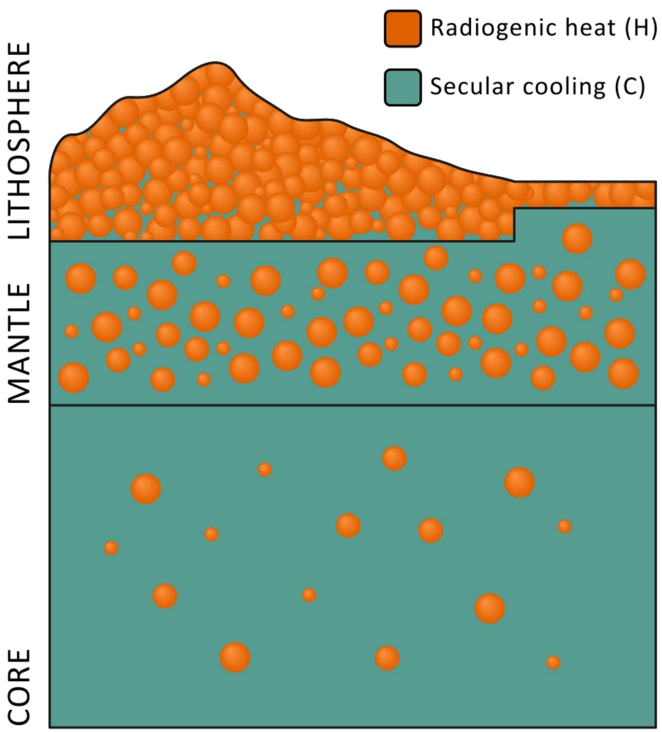
Mantle radiogenic power (KL+BX)

Class	References
Poor – H	Jackson and Jellinek, 2013
	O'Neill and Palme, 2008
	Javoy and Kaminski, 2014
	Javoy et al., 2010
Medium - H	McDonough and Sun, 1995
	Lyubetskaya and Korenaga, 2007
	Palme and O'Neill, 2007
	Arevalo, 2010
	Wang et al., 2018
	Palme and O'Neill, 2014
Rich - H	Turcotte, 2002
	Turcotte, 2014



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

Earth's heat (BX + KL)



$$C = Q - H$$

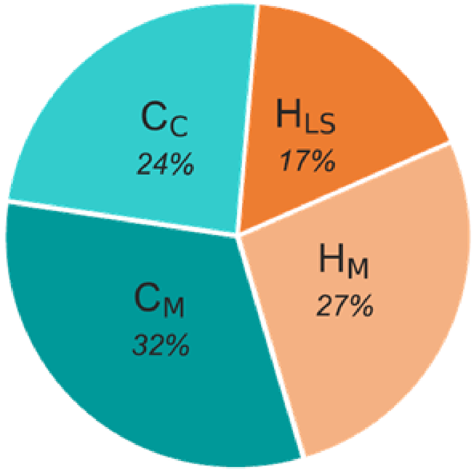
$$C_M = Q - H - C_C$$

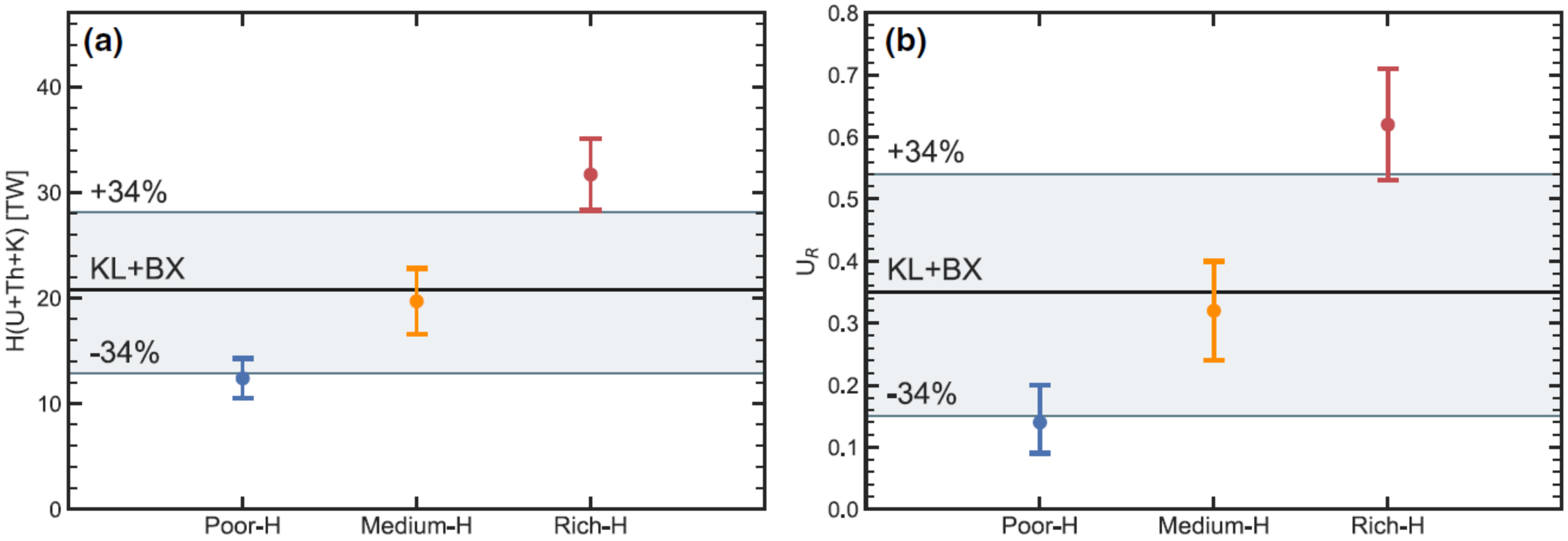
$$H_M = H - H_{LS} - H_C$$

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

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

	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]	$12.5^{+7.1}_{-7.7}$
H [TW]	$\mathbf{20.8^{+7.3}_{-7.9}}$
C [TW]	**26 ± 8**





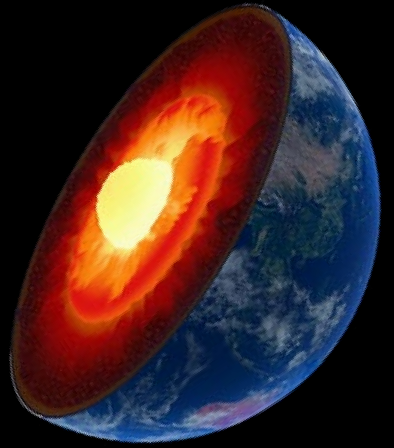
Take-away messages

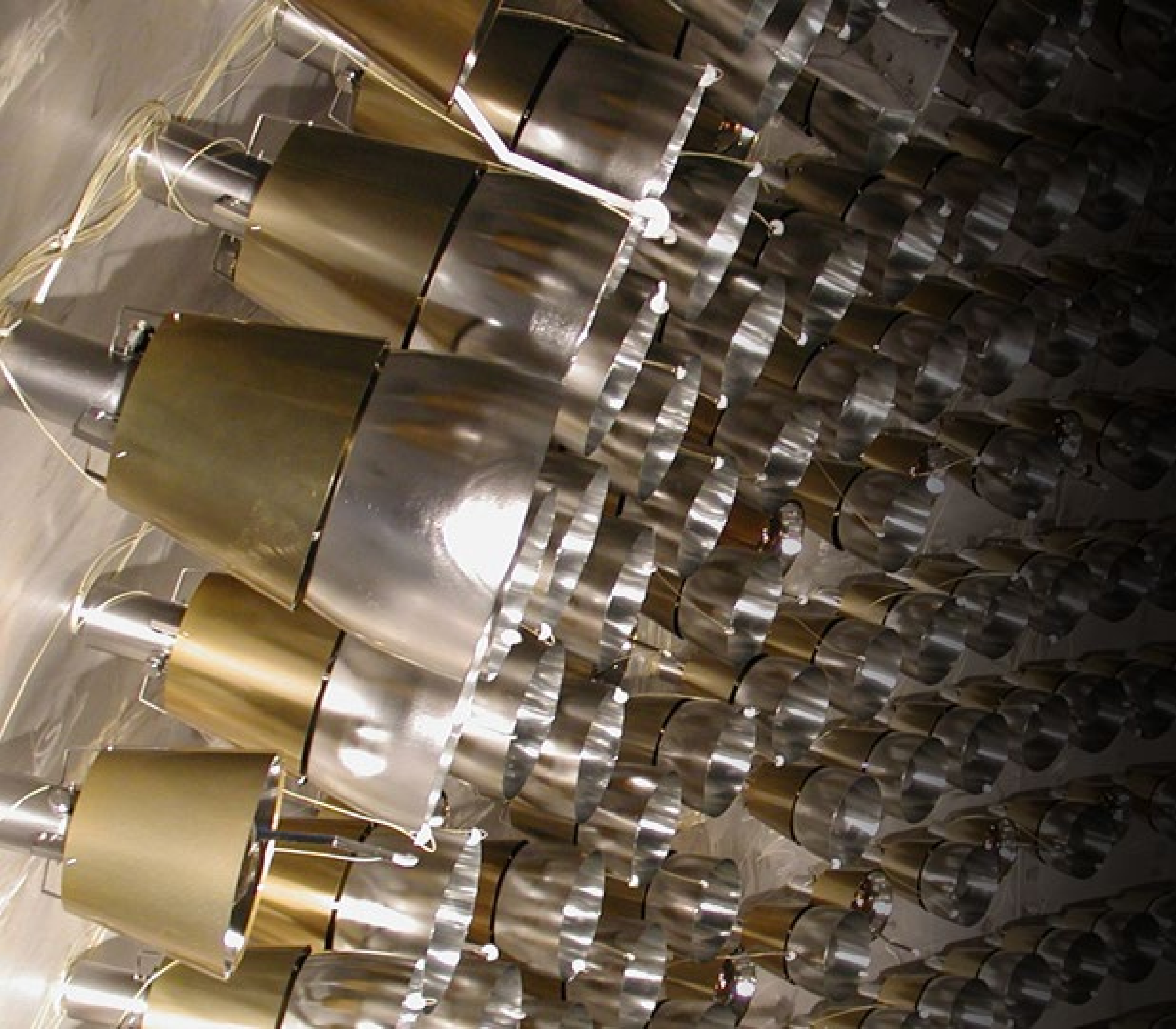
- To deeply understand the experimental geoneutrino results, the use of refined geological models is essential
- The Borexino (KamLAND) observations favor geological models that predict a relatively high (low) concentration of radioactive elements in the mantle
- The combined mantle measurements (BX + KL) falls within the prediction of the Medium-H models
- The era of "multi-site detection" of geoneutrinos is definitely open…

References:

Bellini, G., K. Inoue, F. Mantovani, A. Serafini, V. Strati & H. Watanabe (2021) Geoneutrinos and geoscience: an intriguing joint-venture. *La Rivista del Nuovo Cimento,* 45**,** 1-105

Agostni et al. (2020) Comprehensive geoneutrino analysis with Borexino. Physical Review D, 101.





Thank you