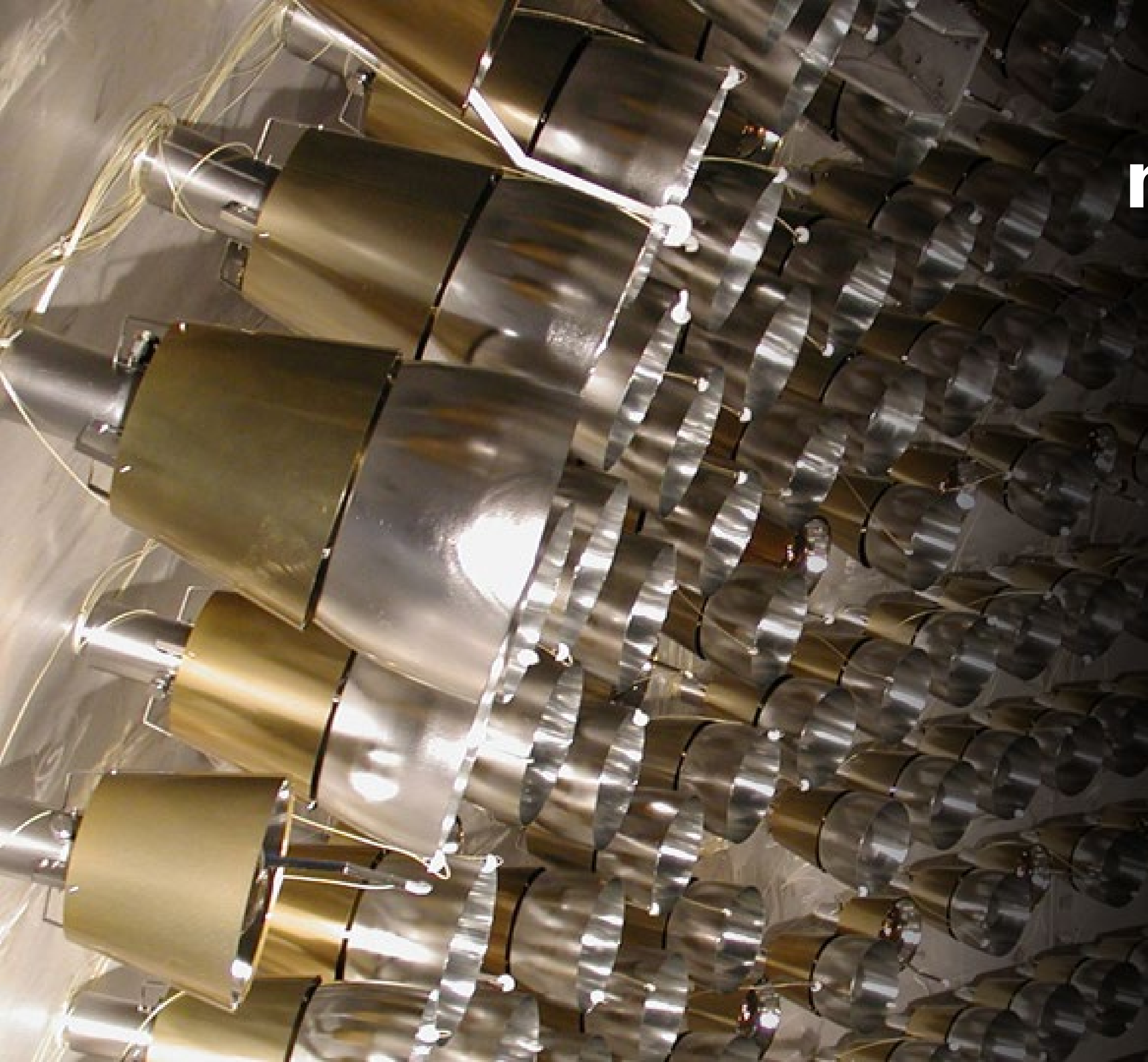
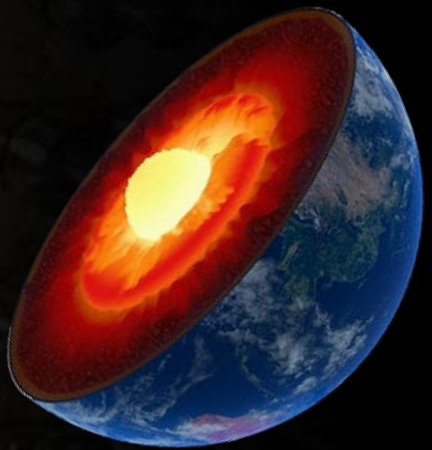


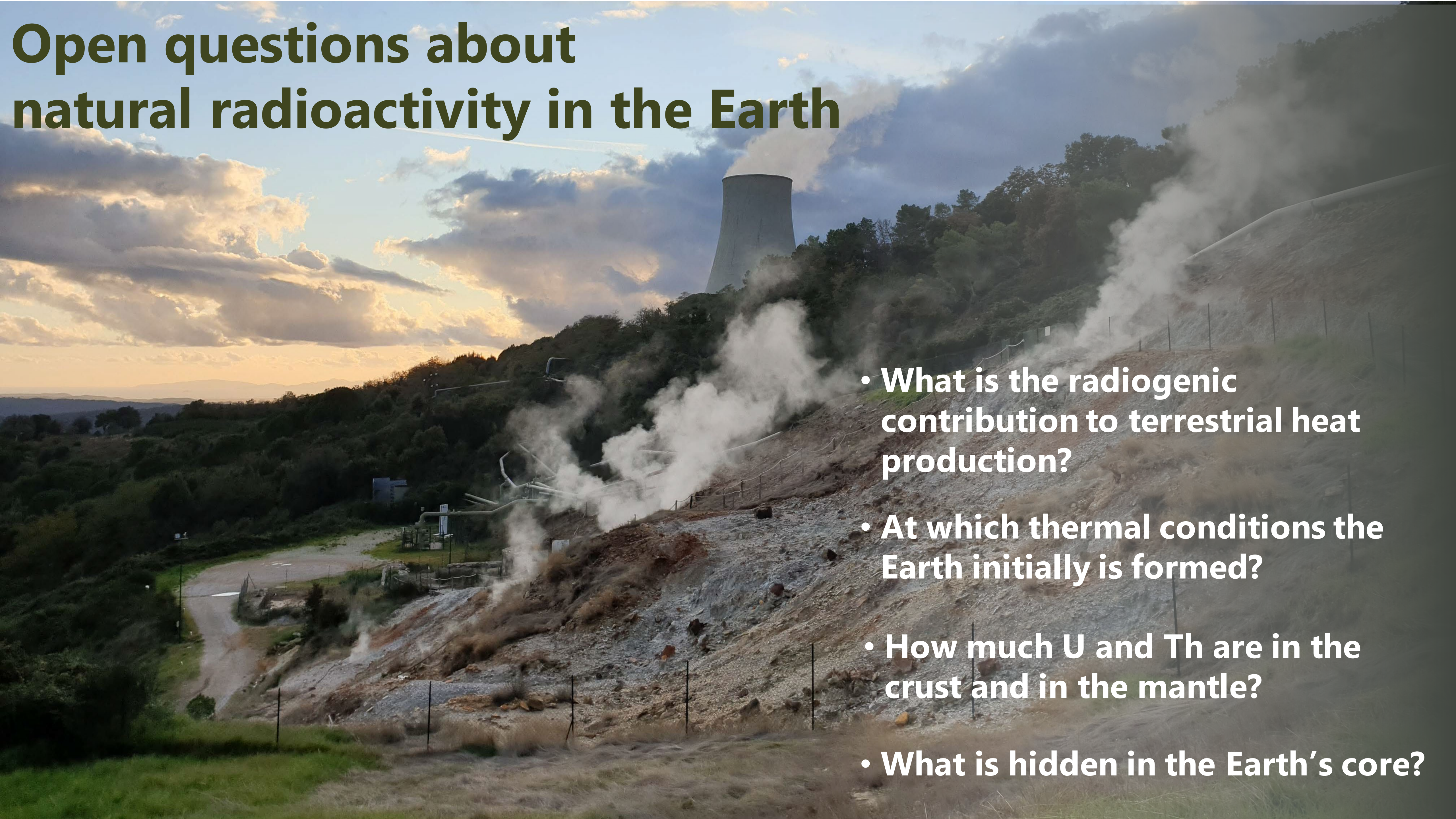
Geoneutrinos: messengers from the inaccessible Earth



Virginia Strati
University of Ferrara – INFN Ferrara
strati@fe.infn.it

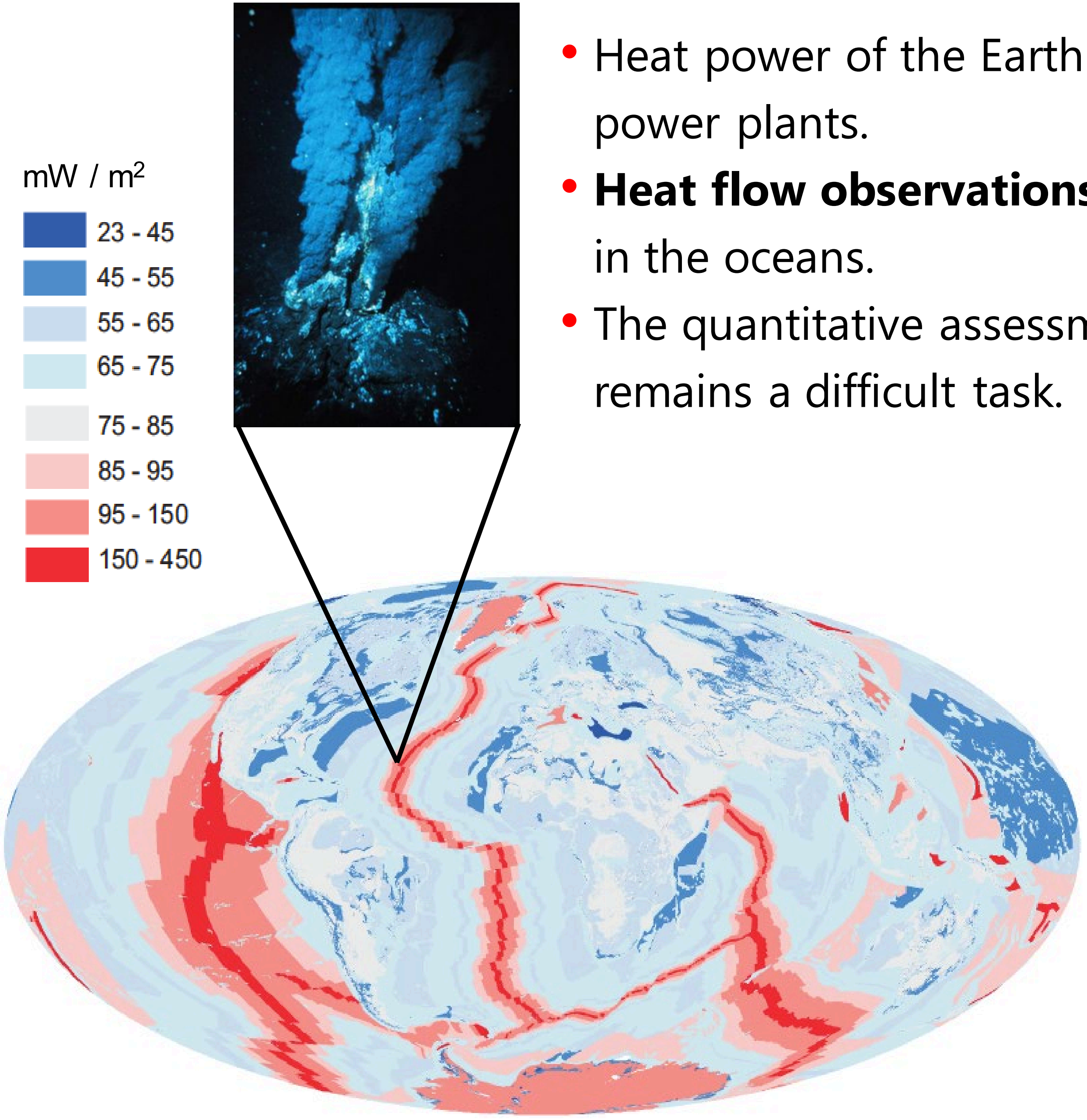
Applied Antineutrino Physics Workshop 2023
18 - 21 September 2023 - York

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



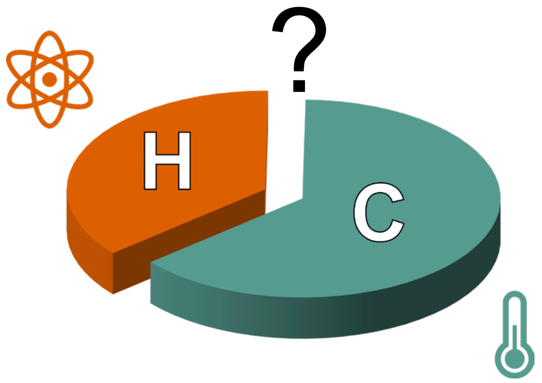
- Heat power of the Earth **Q [30-49 TW]** is the equivalent of ~ 10^4 nuclear power plants.
- **Heat flow observations** are sparse, non-uniformly distributed and not reliable in the oceans.
- The quantitative assessment of heat transport by **hydrothermal circulation** remains a difficult task.

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

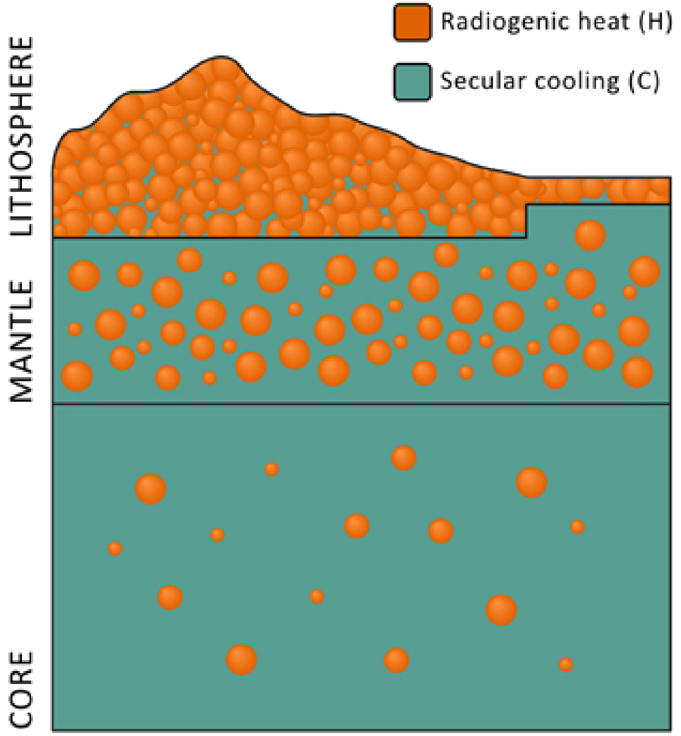
Earth's heat budget

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 mass of the **lithosphere** (~ 2% of the Earth's mass) contains ~ 40% of the total estimated HPEs and it produces $\mathbf{H_{LS} \sim 8\ TW}$.
- Radiogenic power of the **mantle** H_M and the contributions to C from mantle (C_M) and core (C_C) are model dependent.



- 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

$$C = Q - H$$

$$C_M = Q - H - C_C$$

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

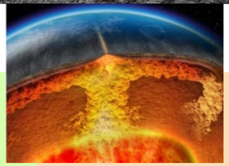
$$H_{LS} = H_{CC} + H_{OC} + H_{CLM}$$

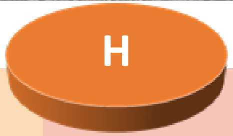
$$U_R = \frac{H - H_{CC}}{Q - H_{CC}}$$

	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

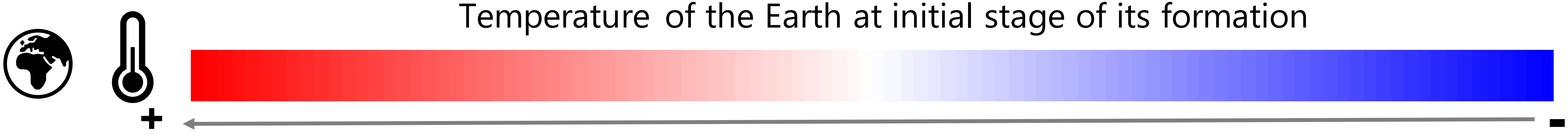
Different models of the Bulk Silicate Earth*





	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



*Bulk Silicate Earth: Lithosphere + Mantle

Geo-neutrinos: anti-neutrinos from the Earth

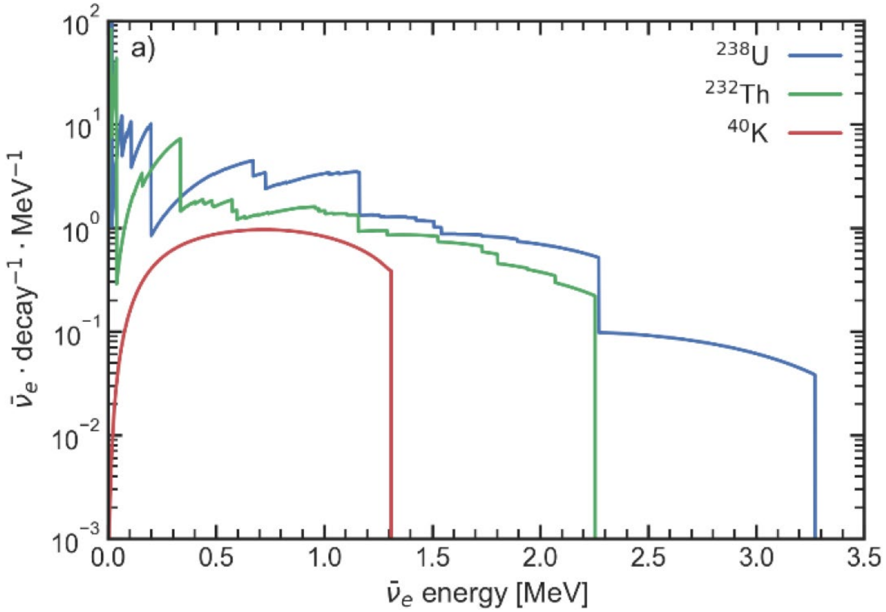
U, Th and ^{40}K in the Earth release heat together with anti-neutrinos, in a **well-fixed ratio**:

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

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

- 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 and KamLAND experiments

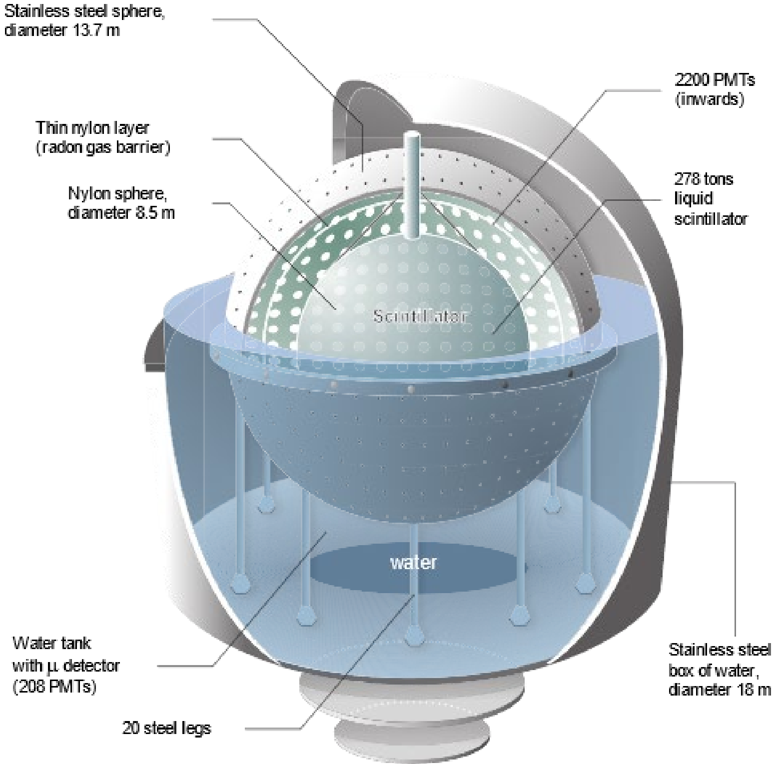
Borexino

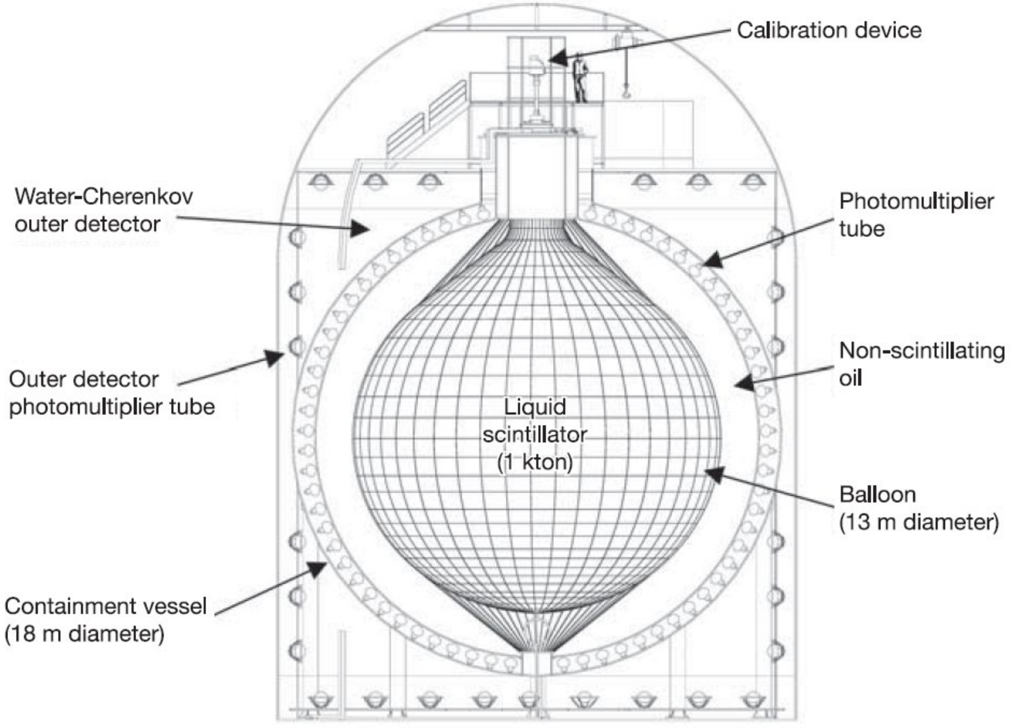
Gran Sasso National Laboratories
-1400 m (3800 MWE)

300 ton Liquid Scintillator
~2200 8″ PMTs

KamLAND

Kamioka mine
-1000 m (2700 MWE)
1 kton Liquid Scintillator
1325 17″ PMTs and
554 20″ PMTs





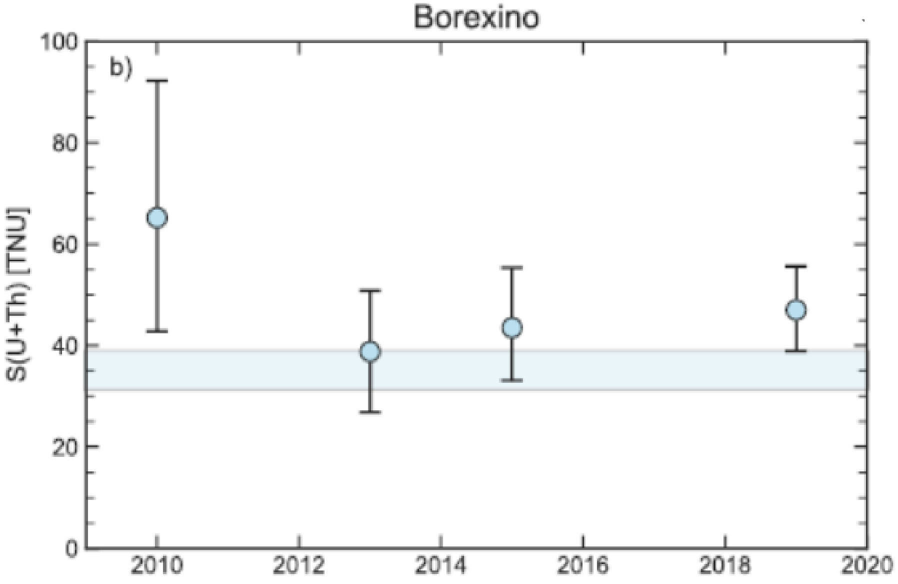
Borexino and KamLAND geoneutrino results

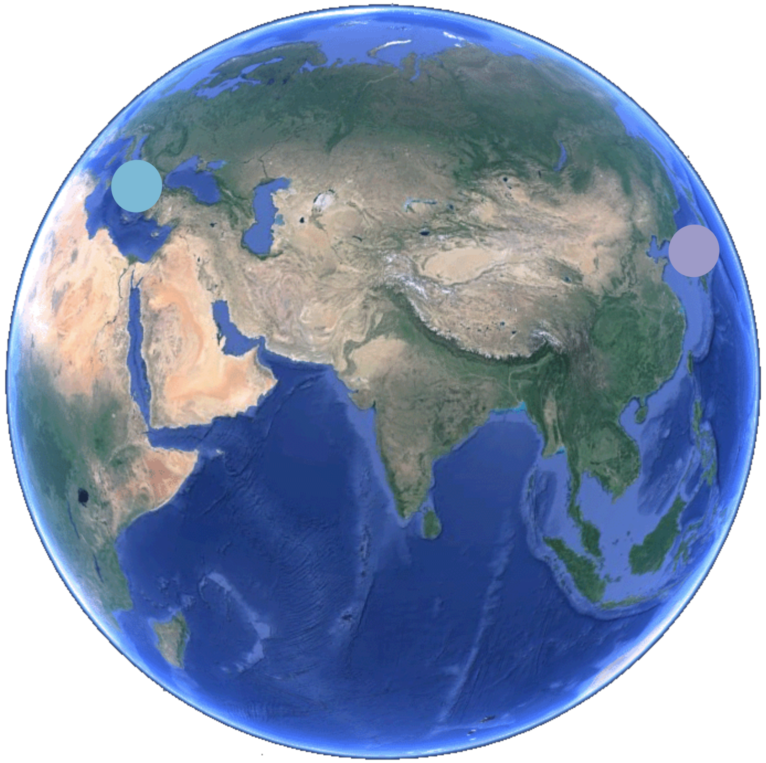
Borexino

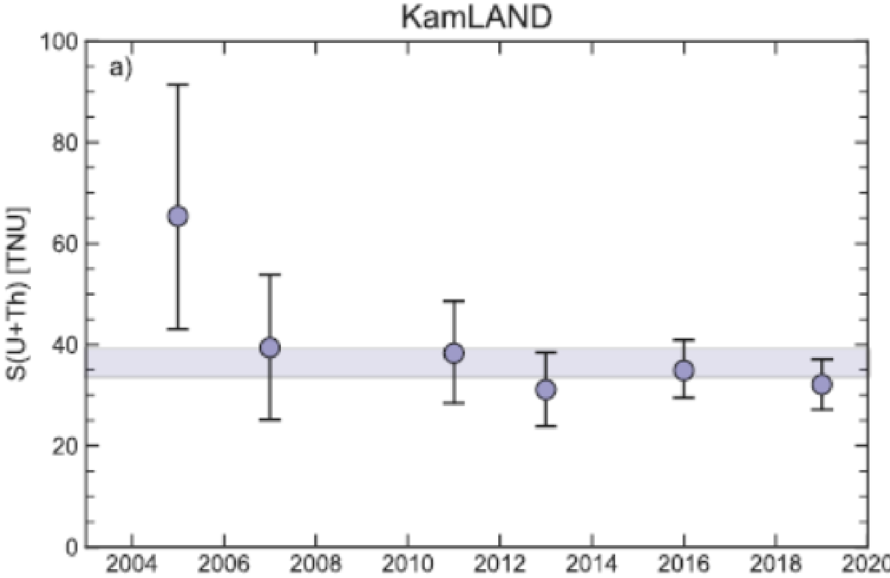
- Period: 2007 – 2019
- Geo-ν events: $52.6^{+7.4}_{-6.3}$
- Signal: $47.0^{+8.7}_{-7.9}$ TNU

KamLAND

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







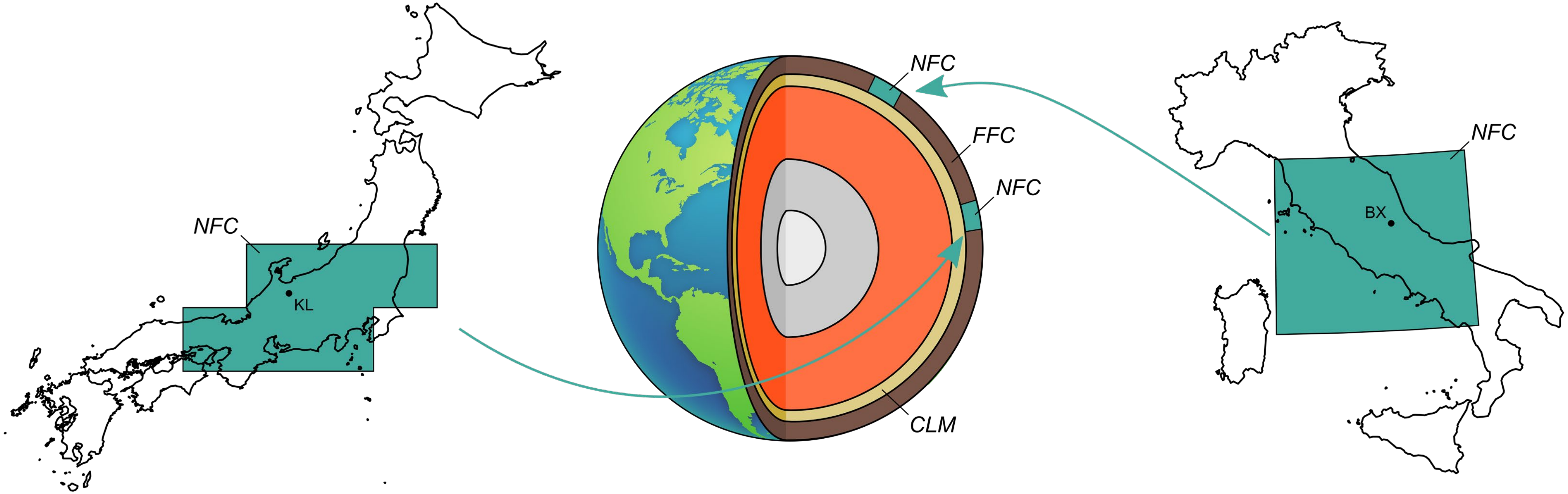
- Horizontal bars traces the **expected signal** at 1σ C.L.
- In the second decade of the 21st century the results published with greater statistical significance highlighted the necessity of **geophysical and geological models** for understanding geoneutrino signal.

Borexino collaboration, 2020 - PRD – 101 (1)

KamLAND collaboration, 2019 – NGS Prague 2019

Mantle geoneutrino signals from experimental signal

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



- U and Th distributed in the **Near Field Crust (NFC)** (i.e. ~ 500 km within the detector) gives a significant contribution to the signal (~ 50% of the total). The modeling of the **NFC** should be built with local geochemical and/or geophysical information
- The signal of **the Far Field Crust (FFC)** and of the **Continental Lithospheric Mantle** (**CLM**) is modeling based on global reference models.

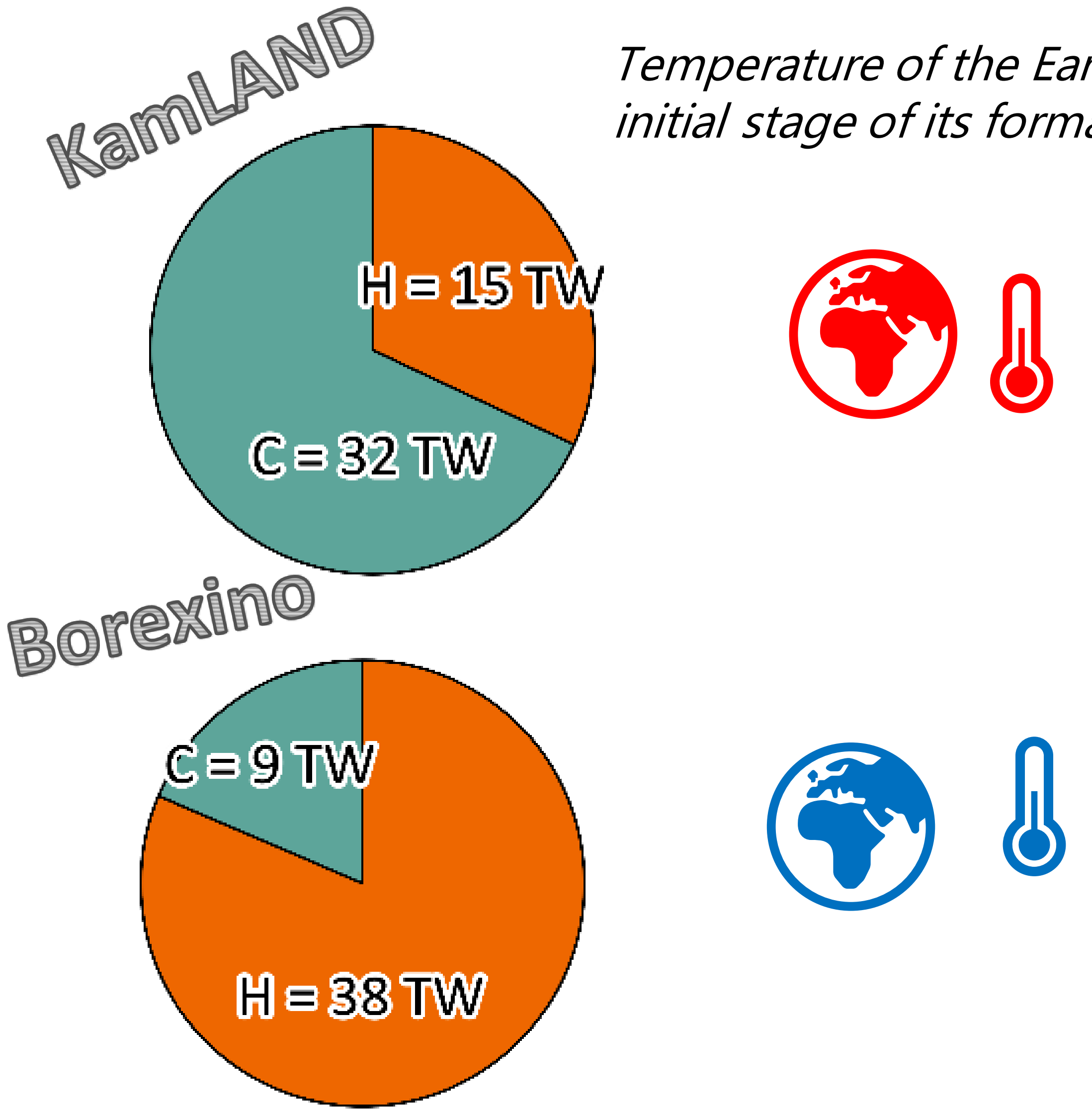
Mantle geoneutrinos (KL)

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

	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]	$1.6^{+2.2}_{-1.0}$	$2.2^{+3.1}_{-1.3}$

$$S^{KL}_M(U+Th) = 4.8^{+5.6}_{-5.9}\ \text{TNU}$$

$$S^{BX}_M(U+Th) = 21.2^{+9.6}_{-9.0}\ \text{TNU}$$



Temperature of the Earth at initial stage of its formation

Combined mantle geoneutrinos (KL + BX)

The joint distribution $S_M^{KL+BX}(U+Th)$ can be inferred from the mantle signal's PDFs of the two experiments by requiring that:

$$S_M^{KL}(U+Th) = S_M^{BX}(U+Th)$$

$$4.8^{+5.6}_{-5.9} \qquad 20.8^{+9.4}_{-9.2}$$

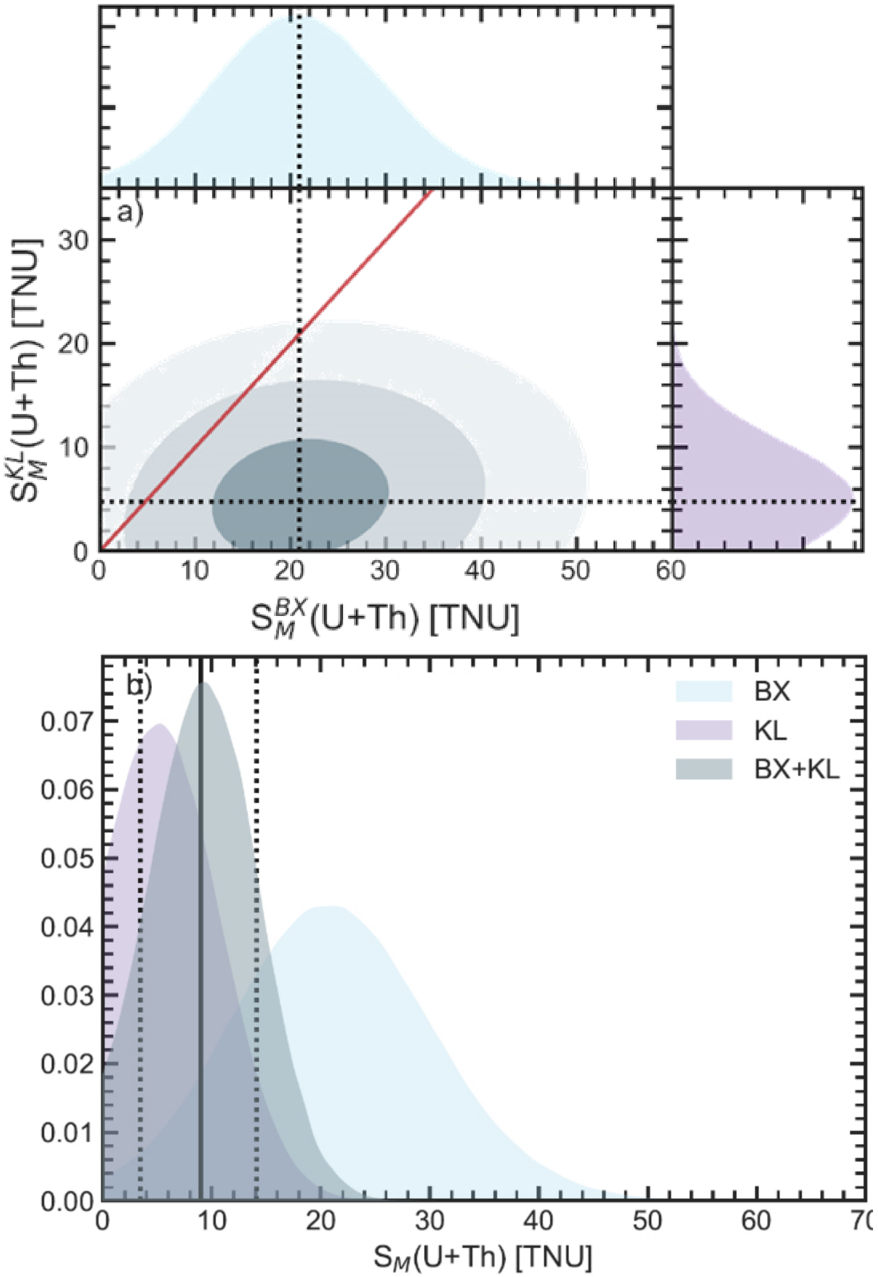
$$S_M^{KL+BX}(U+Th) = 8.9^{+5.1}_{-5.5}\ TNU$$

Where correlations need to be properly accounted for:

» $S_{FFC}^{KL}(U+Th) \propto S_{FFC}^{BX}(U+Th)$

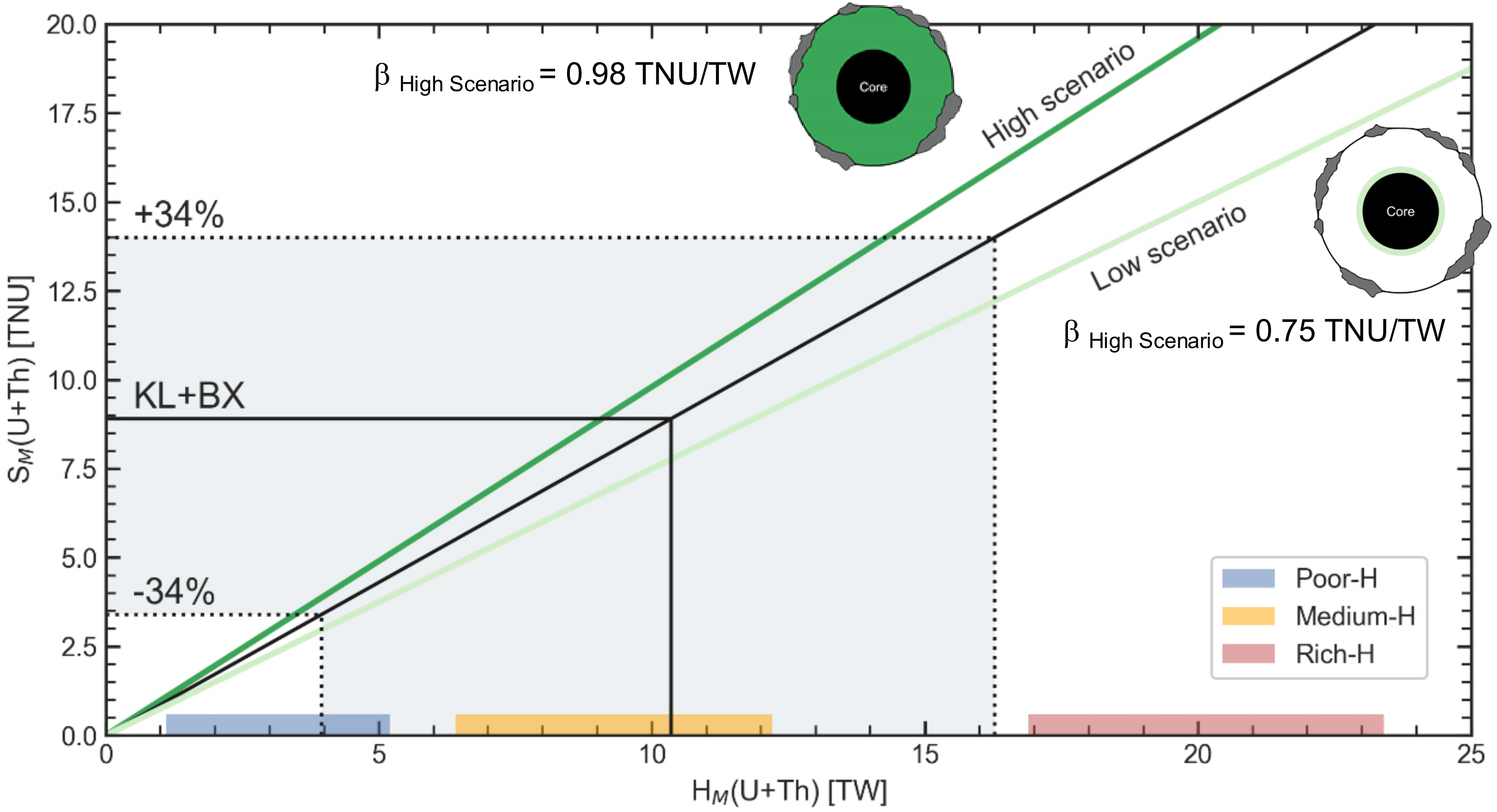
» $S_{CLM}^{KL}(U+Th) \propto S_{CLM}^{BX}(U+Th)$

are fully correlated, since they are derived from the same geophysical and geochemical model



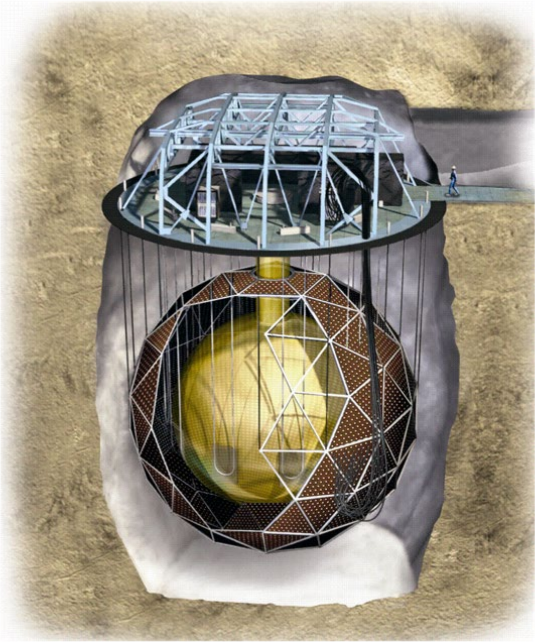
Mantle radiogenic power (KL+BX)

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



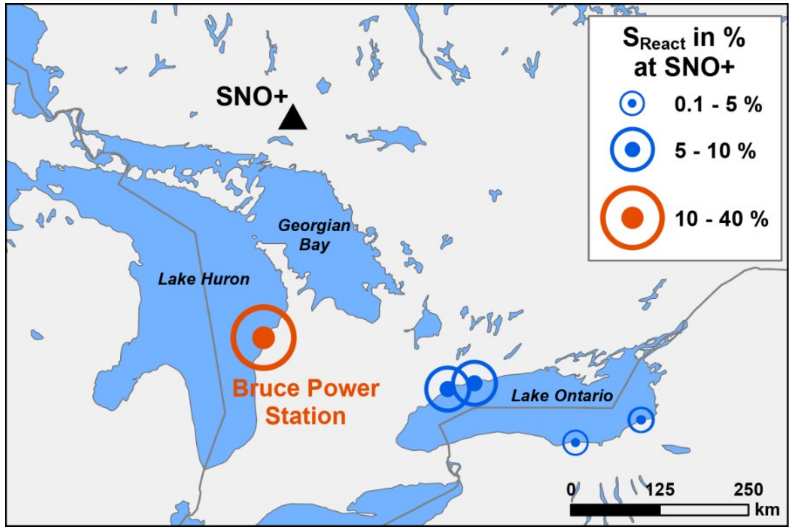
	Poor	Medium	Rich	KL+BX
H_M(U+Th) [TW]	$3.2^{+2.0}_{-2.1}$	9.3 ± 2.9	$20.2^{+3.2}_{-3.3}$	$10.3^{+5.9}_{-6.4}$

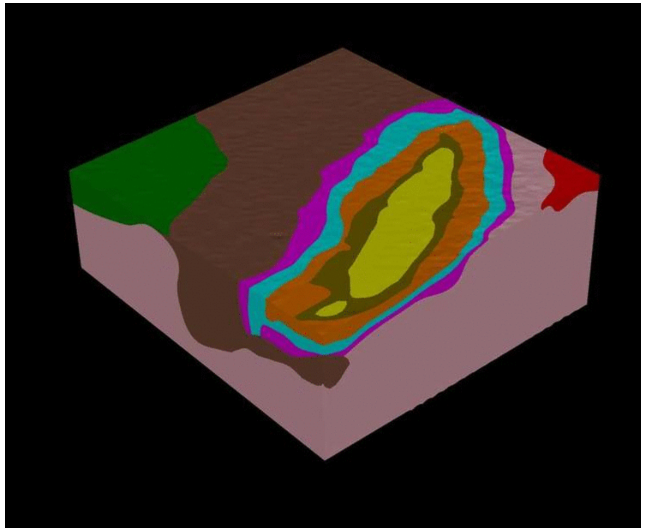
Expected geoneutrino signal at SNO+



- 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)	$41.8^{+9.6}_{-6.2}$

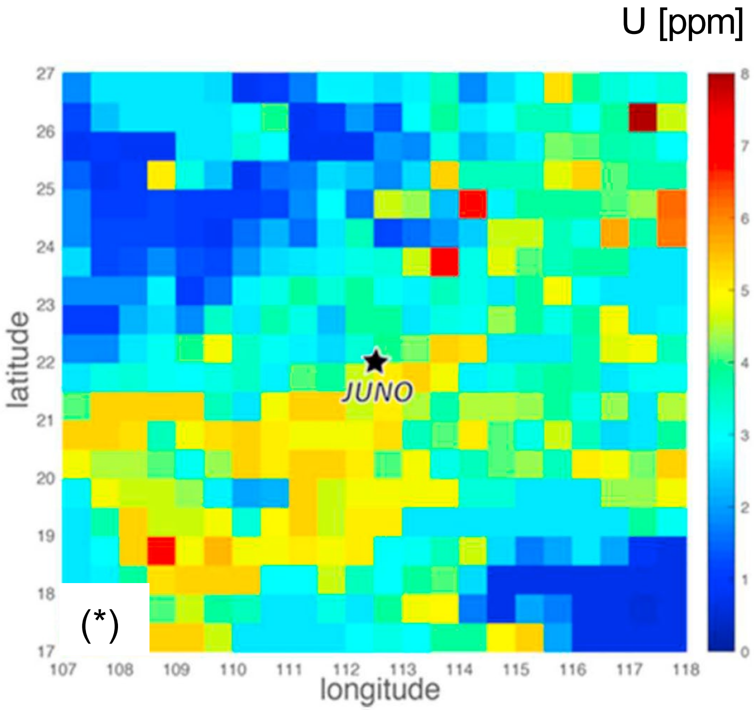




Expected geoneutrino signal at JUNO

- 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



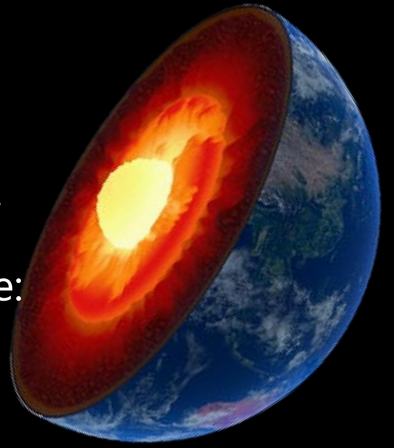
	S(U+Th) [TNU]
Strati et al., 2015 (using global crustal model)	$39.7^{+6.5}_{-5.2}$
Wipperfurth et al., 2020 (using global crustal models)	$41.3^{+7.5}_{-6.3}$
	$41.2^{+7.6}_{-6.4}$
	$40.0^{+7.4}_{-6.2}$
Gao et al., 2020 (*) (combining global crustal model and local geological data)	$49.1^{+5.6}_{-5.0}$

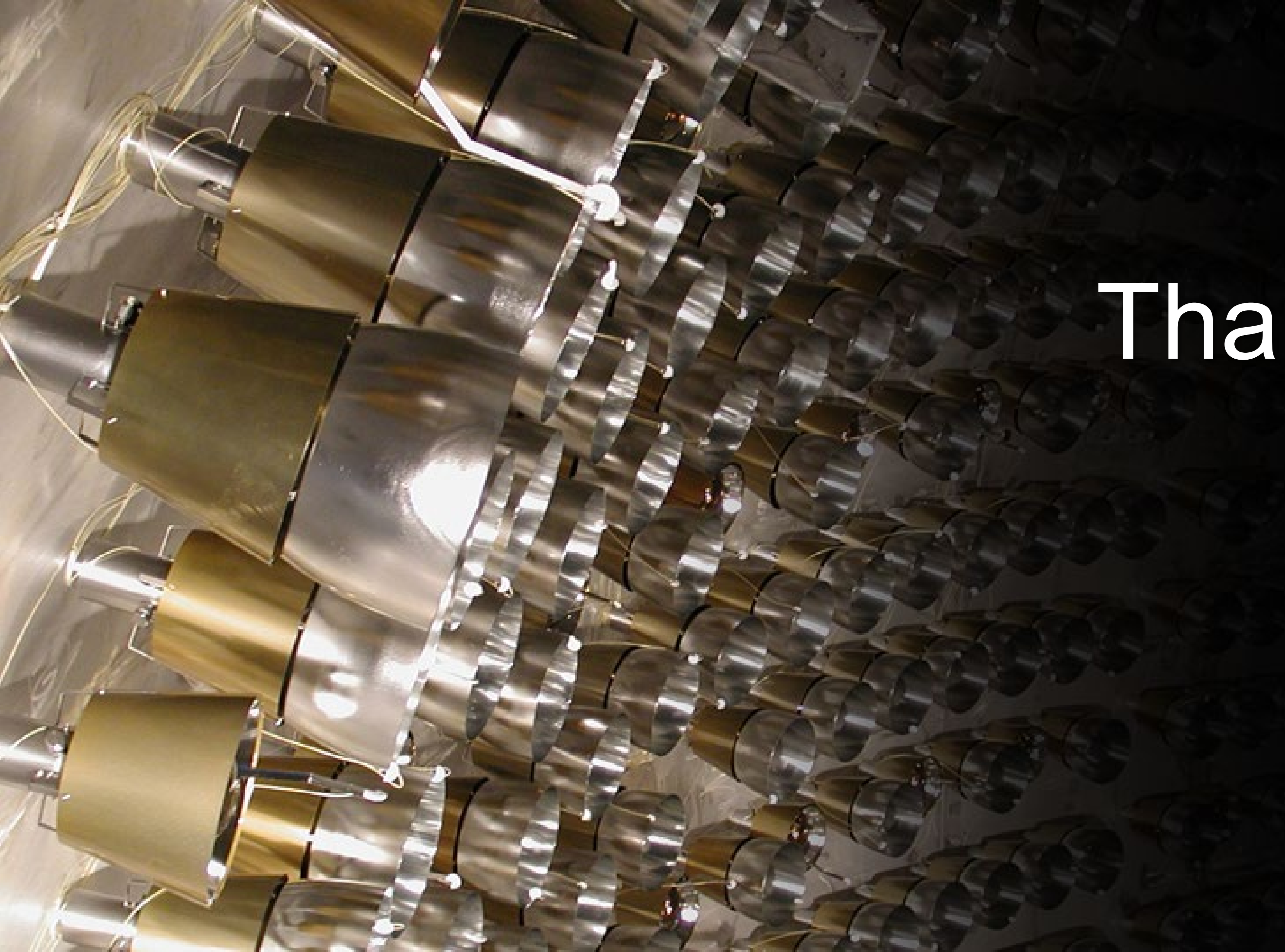
Take-away messages

- To deeply understand the experimental geoneutrino results, the use of refined geological models is essential
- The 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…

For more information:

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





Thank you