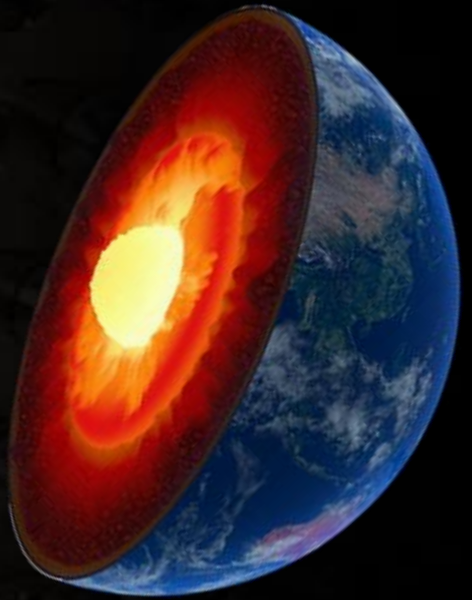
Geoneutrinos

State of the art and prospects



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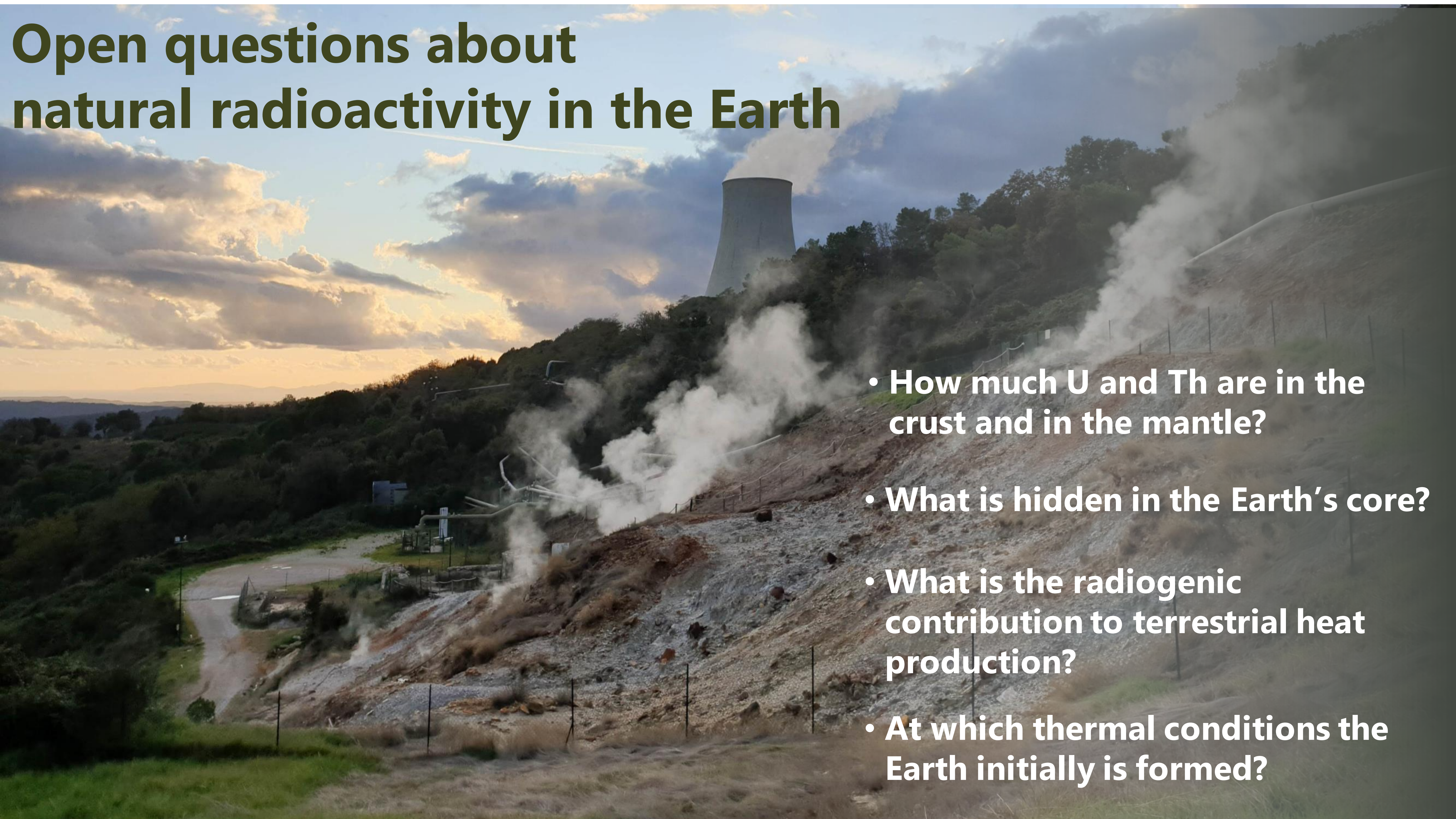
Outline

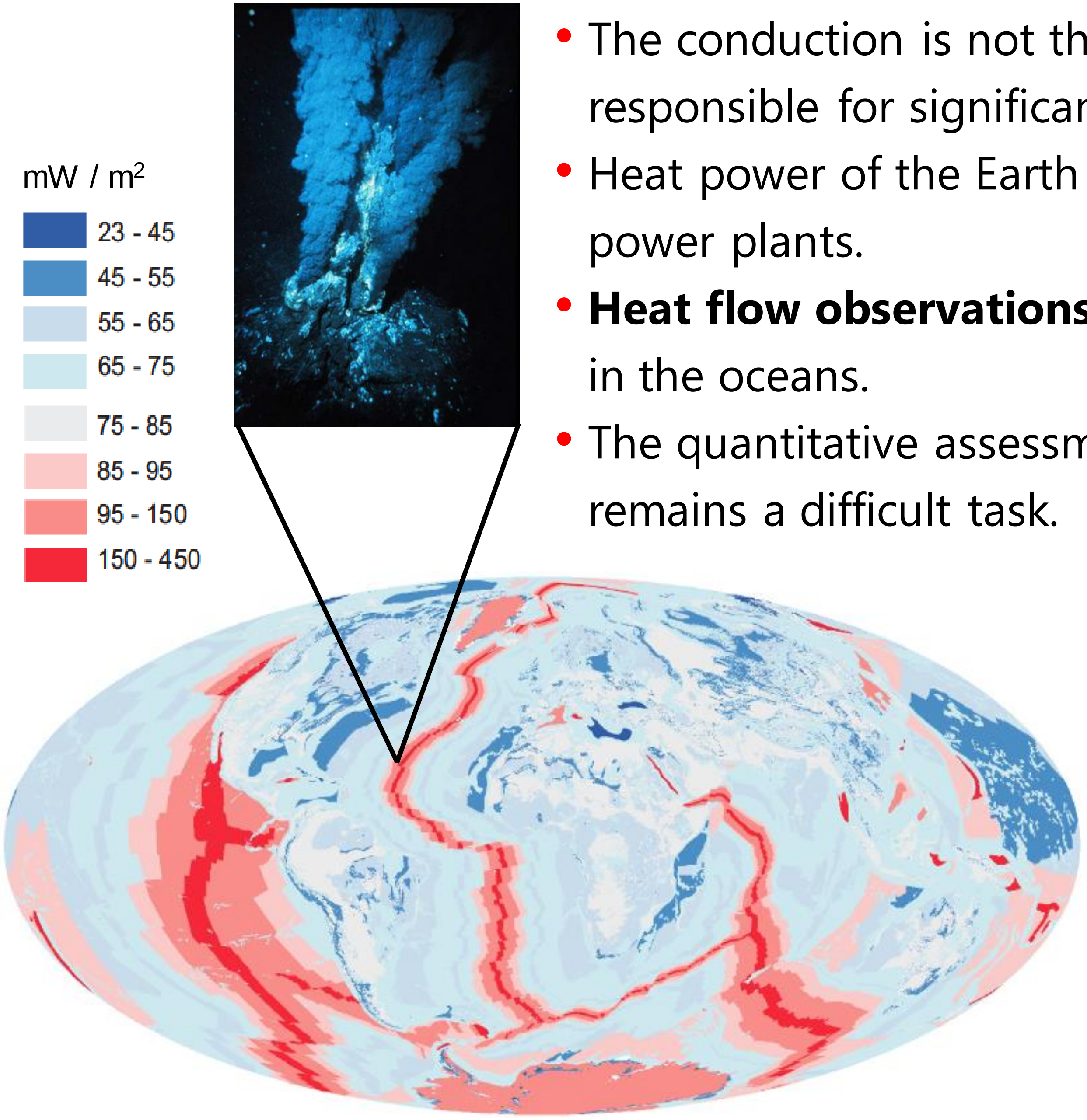
- Terrestrial heat power of the Earth and geoneutrinos
- Borexino and KamLAND experiments
- Mantle geoneutrino signals from Borexino experimental data
- Understanding the Earth’s heat budget with geoneutrinos
- Perspectives for future detectors

Open questions about natural radioactivity in the Earth



- How much U and Th are in the crust and in the mantle?
- What is hidden in the Earth's core?
- What is the radiogenic contribution to terrestrial heat production?
- At which thermal conditions the Earth initially is formed?

Heat power of the Earth



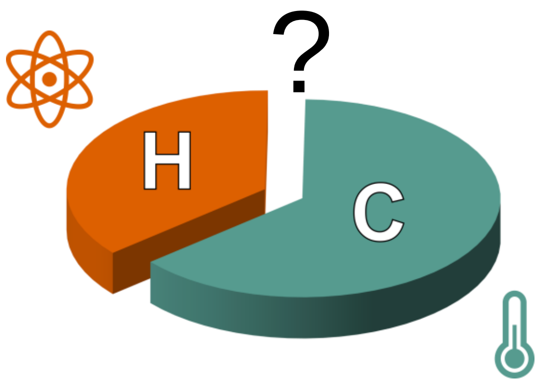
- The conduction is not the only way of Earth's cooling: **convective motions** are responsible for significant fraction of surface heat loss.
- Heat power of the Earth **Q [30-49 TW]** is the equivalent of ~ 10^4 nuclear power plants.
- **Heat flow observations** are sparse, non-uniformly distributed 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

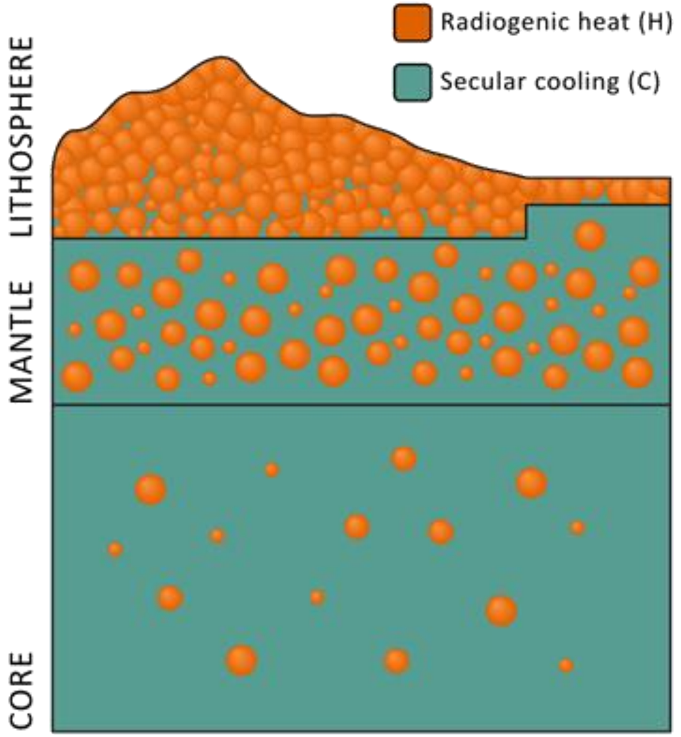
Earth's heat budget

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_{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

Geo-neutrinos: anti-neutrinos from the Earth

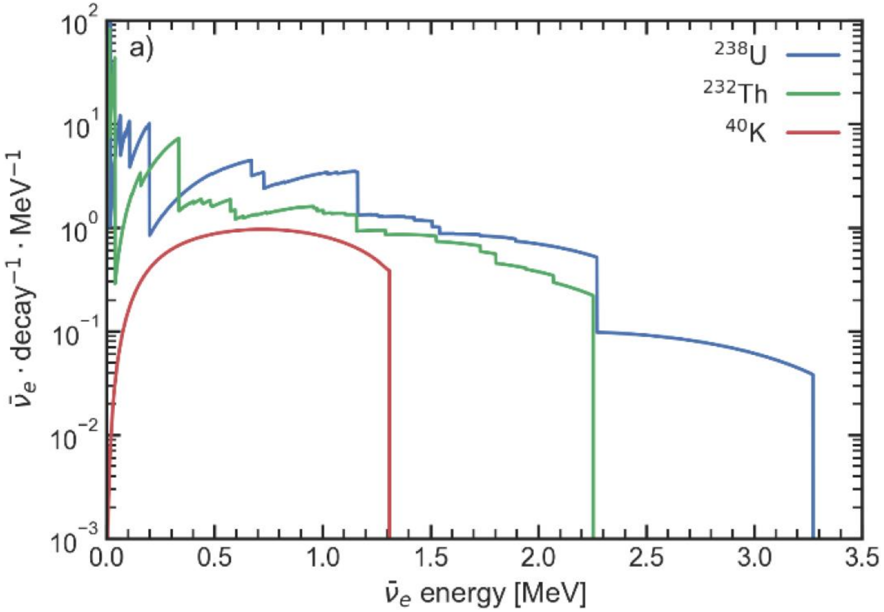
U, Th and ^{40}K in the Earth release heat together with anti-neutrinos, in a well-fixed ratio:

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

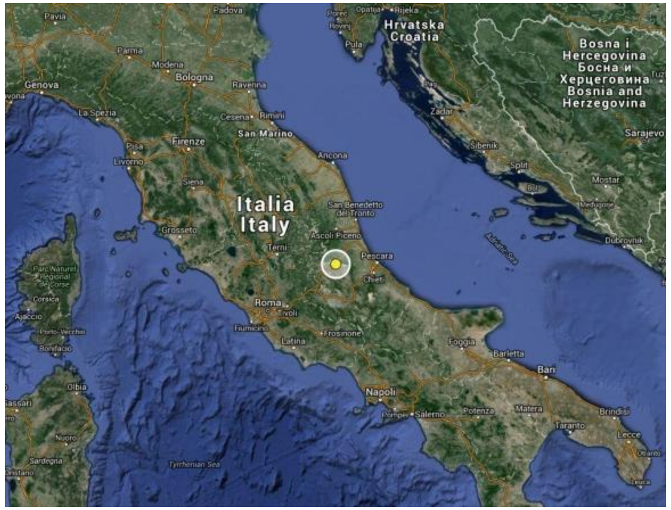


Borexino and KamLAND experiments

Borexino

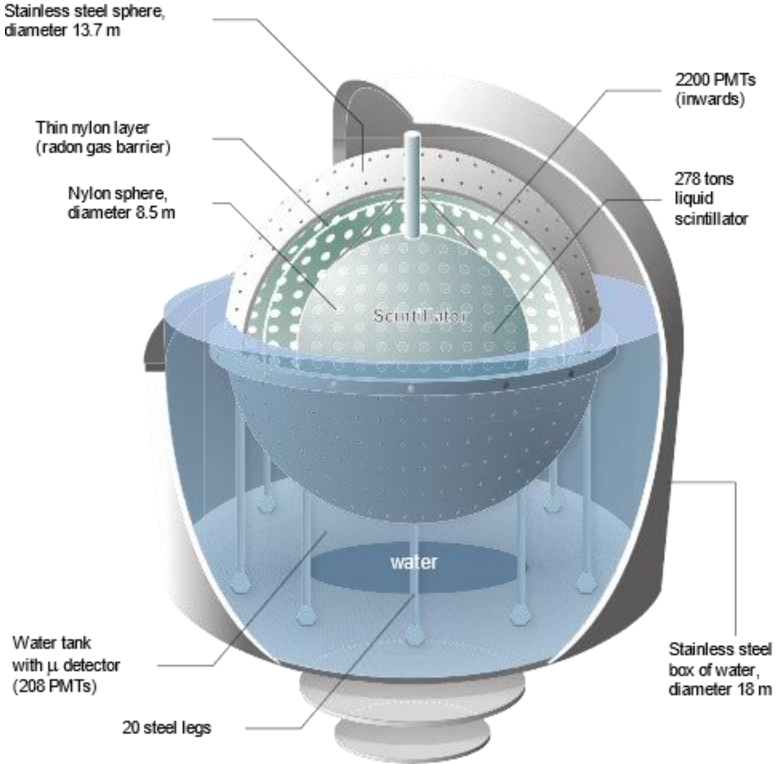
Gran Sasso National Laboratories
-1400 m (3800 MWE)

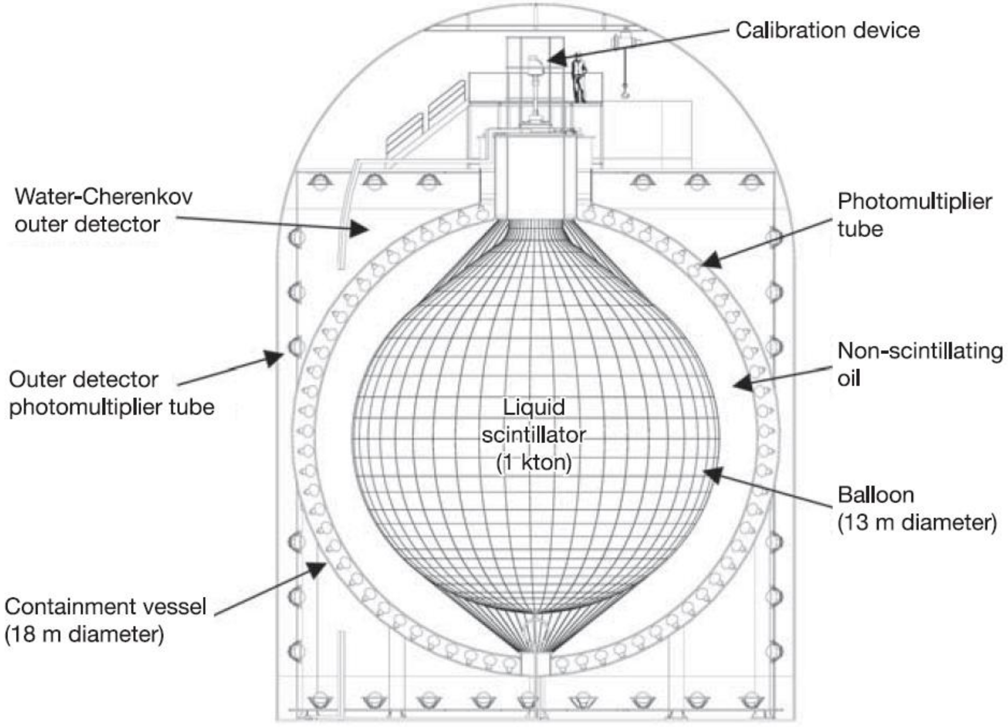
300 ton LS
~2200 8″ PMTs



KamLAND

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





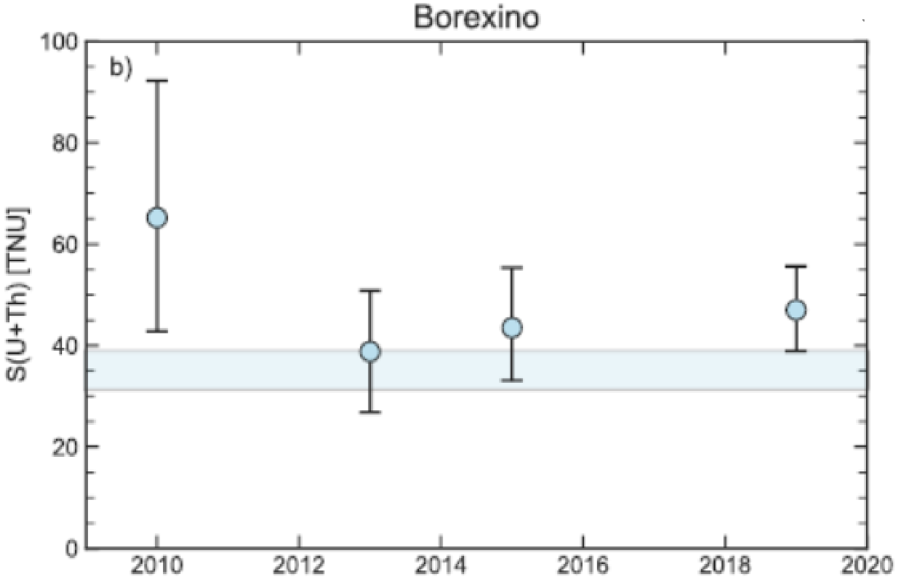
Borexino and KamLAND geoneutrino results

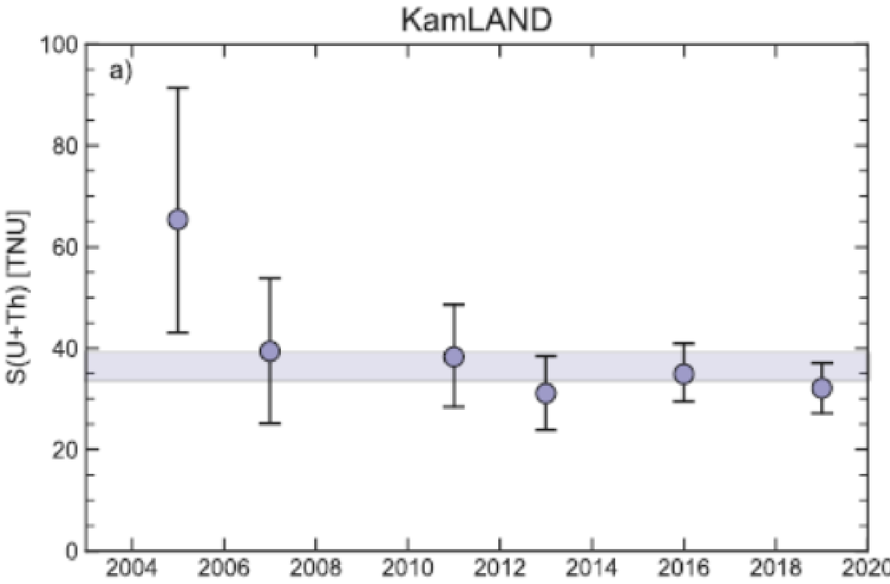
Borexino

- 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





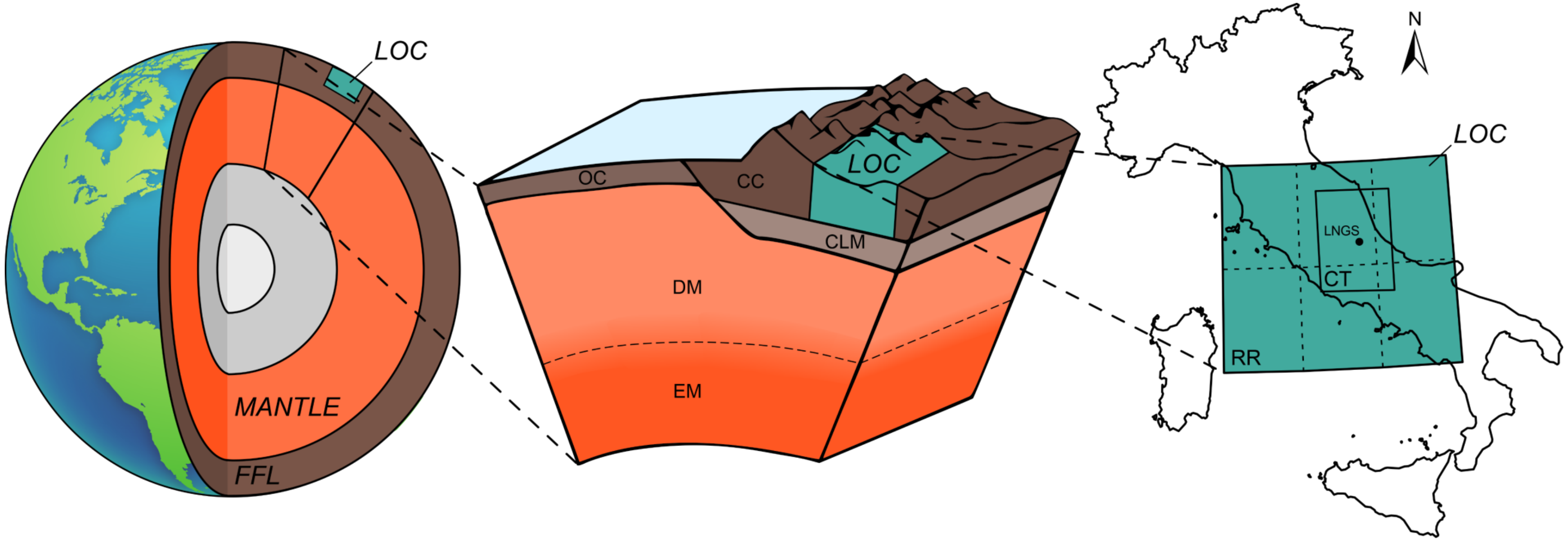
- Horizontal bars traces the **expected signal** at 1σ C.L.
- In the second decade of the 21st century the results published with greater statistical significance highlighted the necessity of **geophysical and geological models** for understanding geoneutrino signal.

Borexino collaboration, 2020 - PRD – 101 (1)

KamLAND collaboration, 2019 – NGS Prague 2019

Mantle geoneutrino signals from experimental signal

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



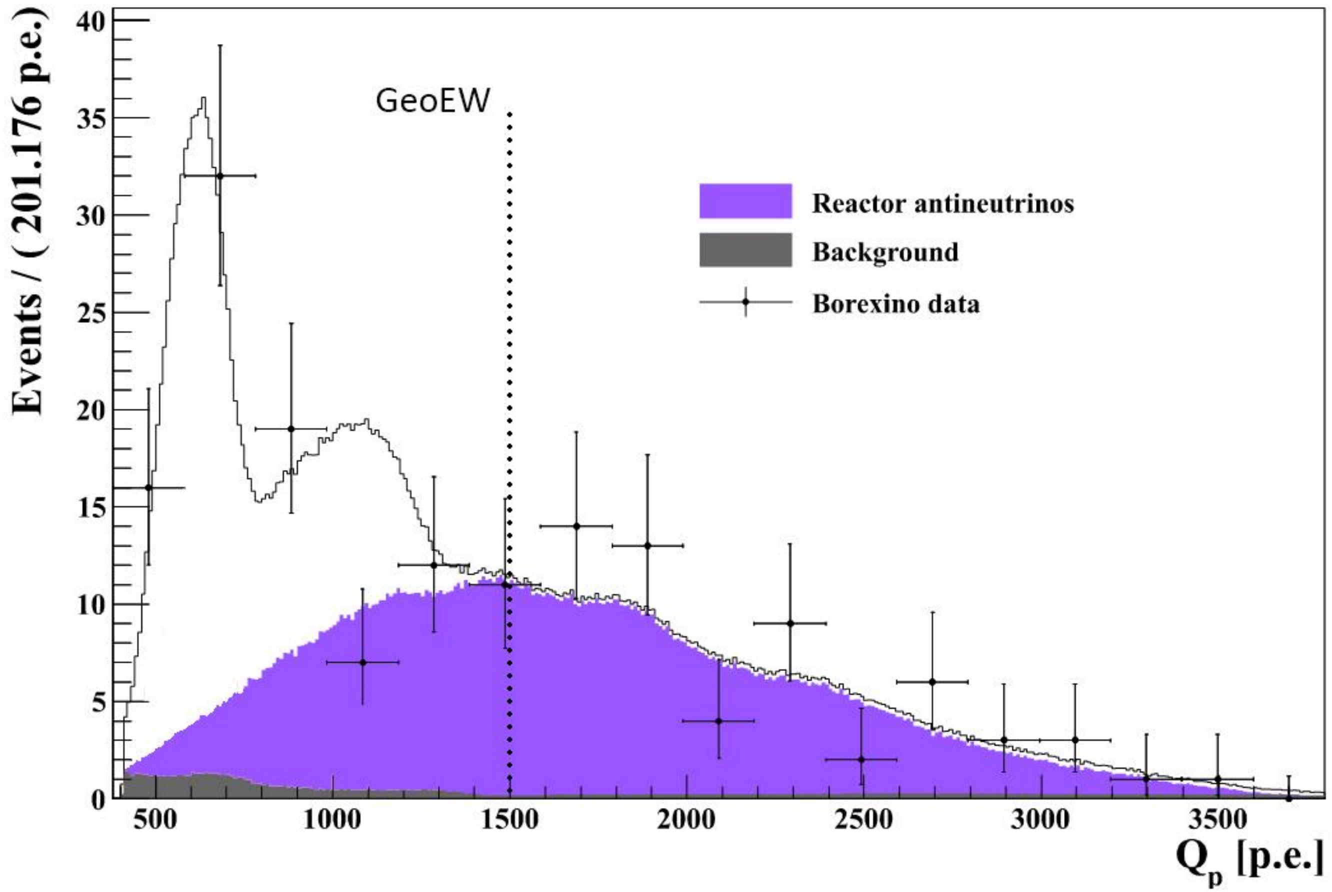
- U and Th distributed in the **Local Crust (LOC)** (i.e. ~ 500 km within the detector) gives a significant contribution to the signal (~ 50% of the total).

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

- 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.

Borexino geoneutrino spectra

- In 3262.74 days BX measured 154 antineutrinos candidates in the effective exposure, after cuts.
- Estimated constrained **background events**: 8.3 ± 1.0
- In GeoEW [1.8-3.3 MeV] the reconstructed **reactor events** are 39.5 ± 0.7.



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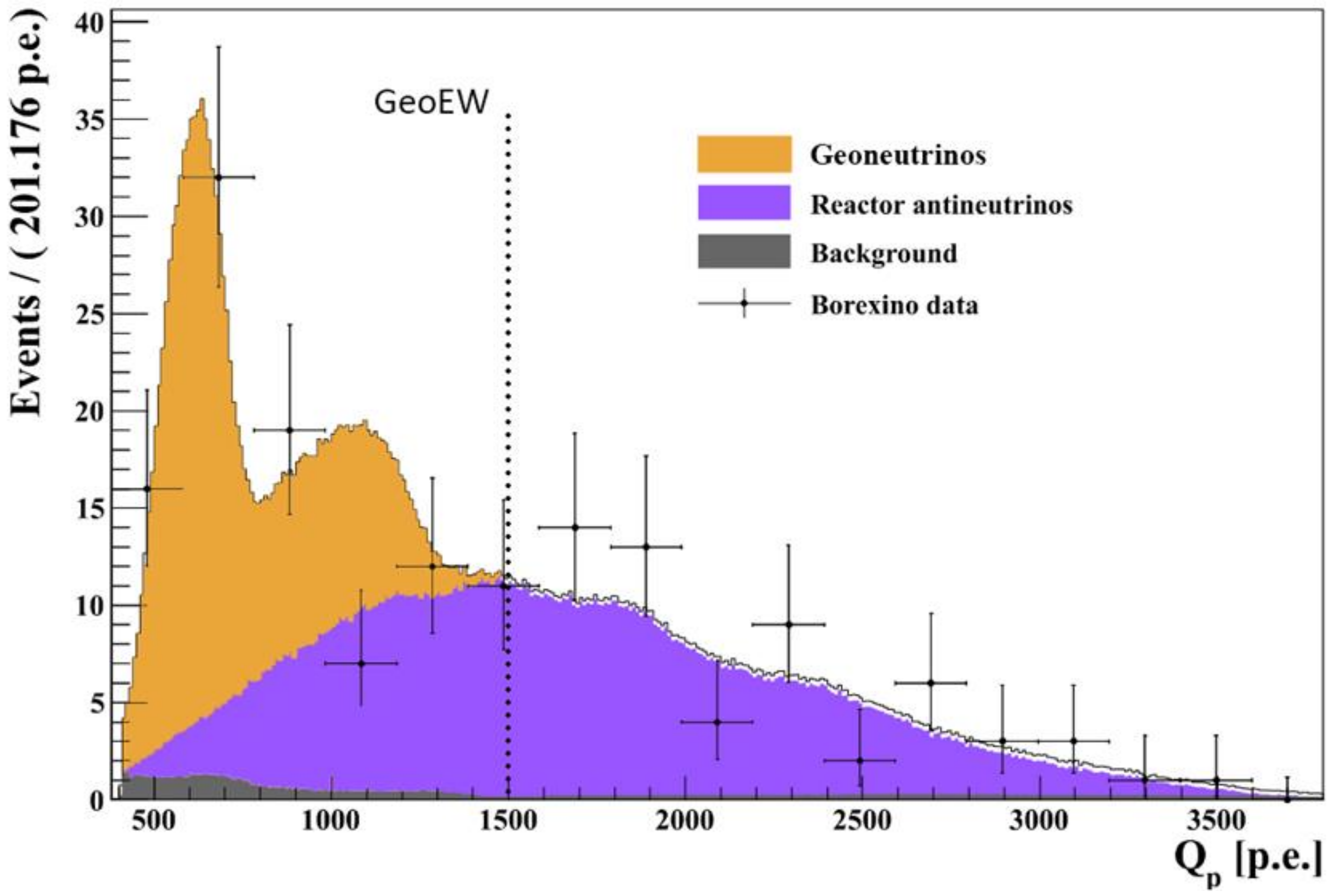
- Assuming a Th/U = 3.9, the **geoneutrino events** are $52.6^{+9.6}_{-9.0}$
- Considering the effective exposure $\varepsilon' = 1.12\ 10^{32}$ free protons x yr, one can calculate the signal in TNU:

$S\ [TNU] = N_{Eve} * (10^{32} / \varepsilon')$ → $S\ (U+Th) = 47.0\ ^{+8.4}_{-7.7}\ (Stat)\ ^{+2.4}_{-1.9}\ (Sys)\ TNU$



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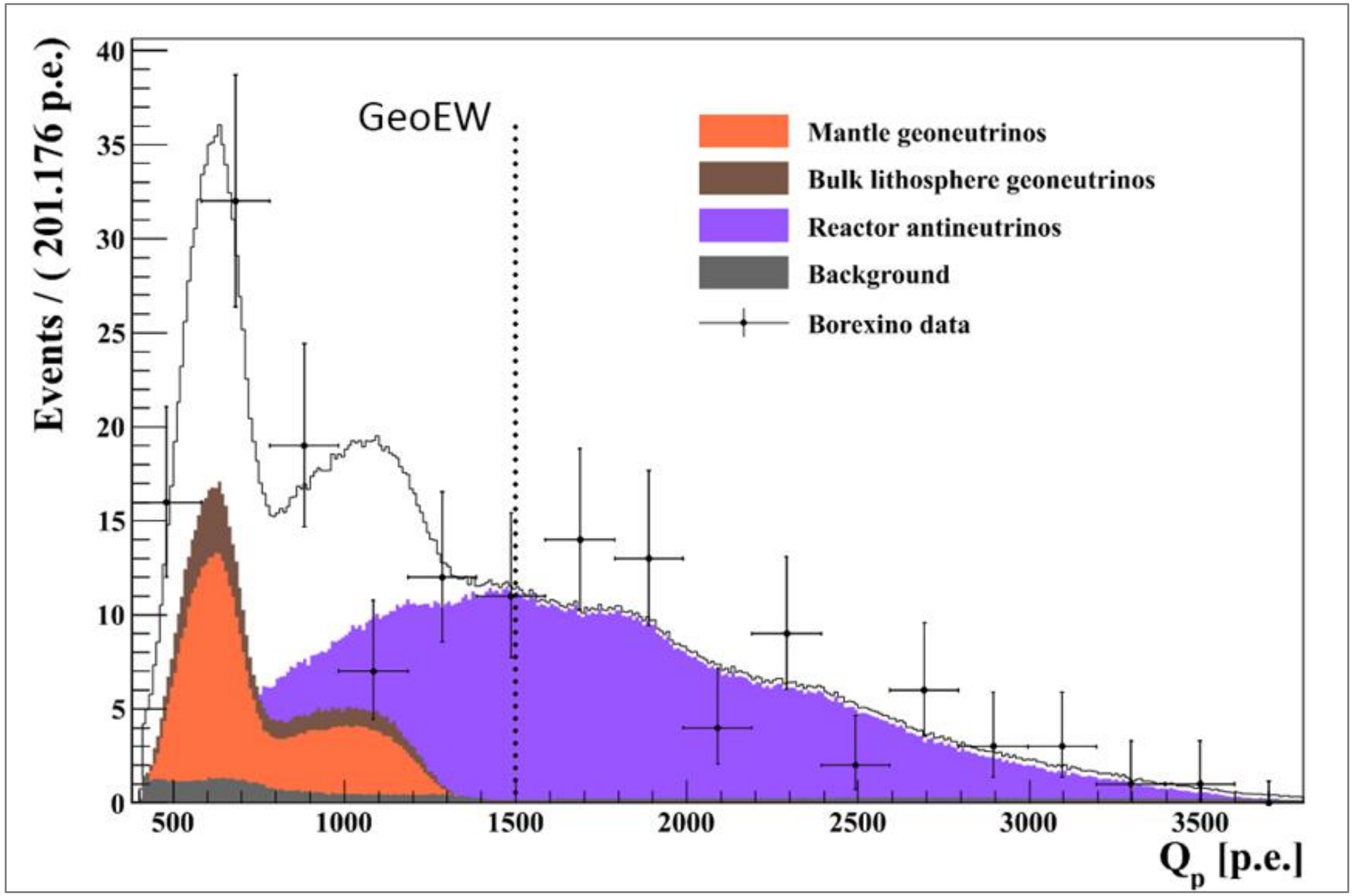

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- Constraining the contribution from the **bulk lithosphere** (28.8 ± 5.6 events), the **extracted mantle** events are $23.7^{+10.7}_{-10.1}$ → $S_M(\mathrm{U+Th}) = 21.2^{+9.5}_{-9.0}\ (\mathrm{Stat})\ ^{+1.1}_{-0.9}\ (\mathrm{Sys})\ \mathrm{TNU})$

Measurements vs models

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.

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)

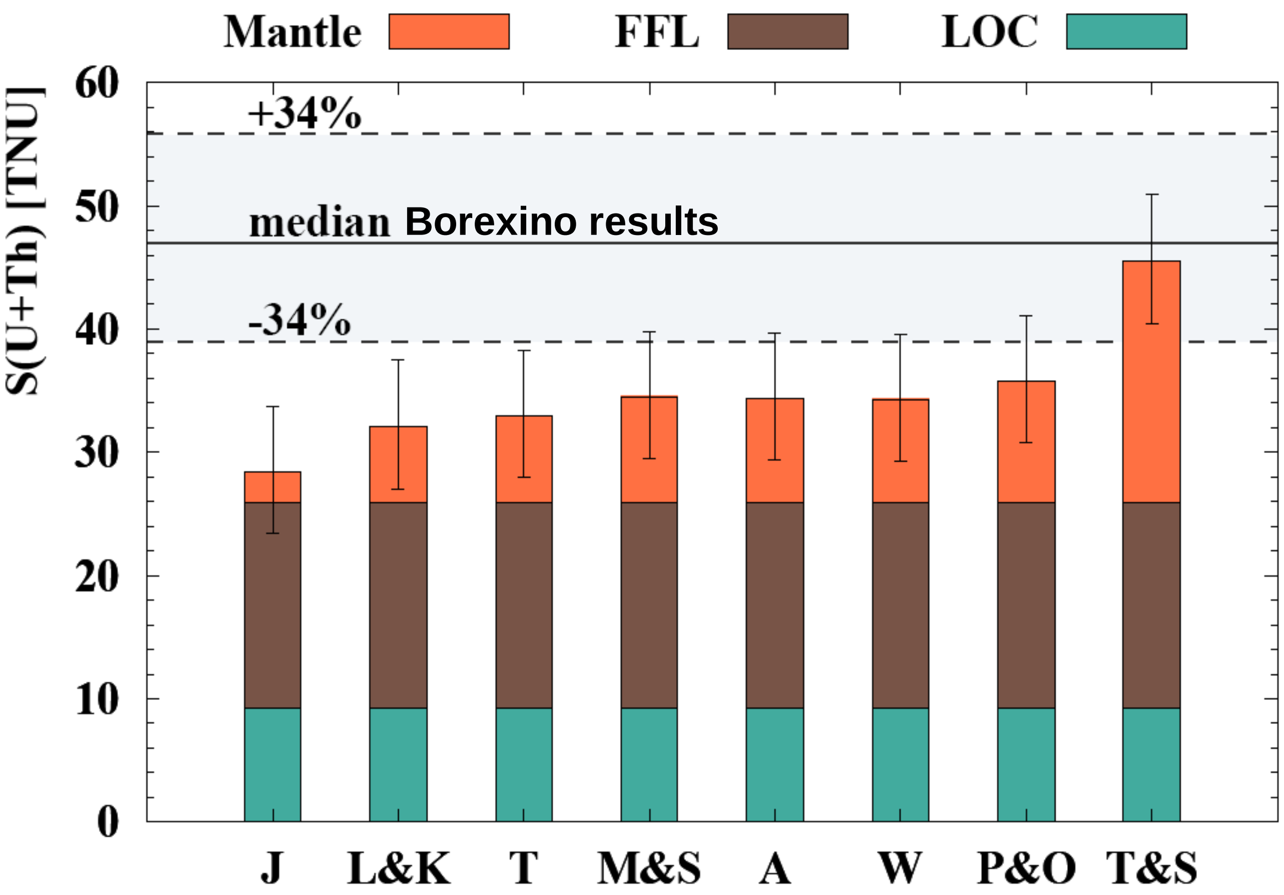
M&S = W. F. McDonough and S. Sun, Chem. Geol. 120, (1995)

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

Cosmochemical Model (CC)

- Enstatitic meteorites
- H_{Mantle}(K, Th, U) = 0.7 – 3.8 TW

Geochemical Model (GC)

- Carbonaceous meteorites
- H_{Mantle}(K, Th, U) = 7.5 – 10.9 TW

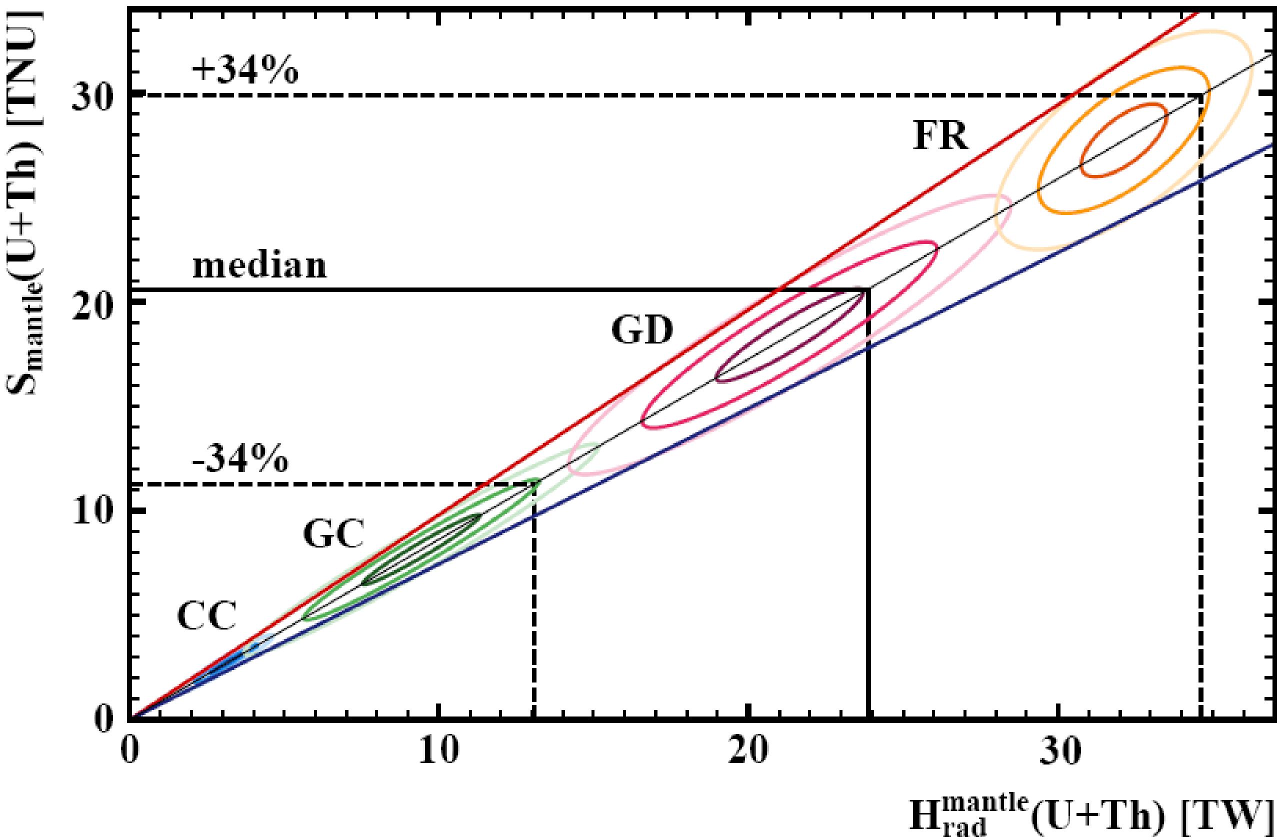
Geodynamical Model (GD)

- Earth dynamics
- H_{Mantle}(K, Th, U) =19.8 – 23.3 TW

Fully radiogenic (FR)

- Terrestrial heat is fully accounted by radiogenic production
- H_{Mantle}(K, Th, U) = 30.5 – 34.0 TW

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



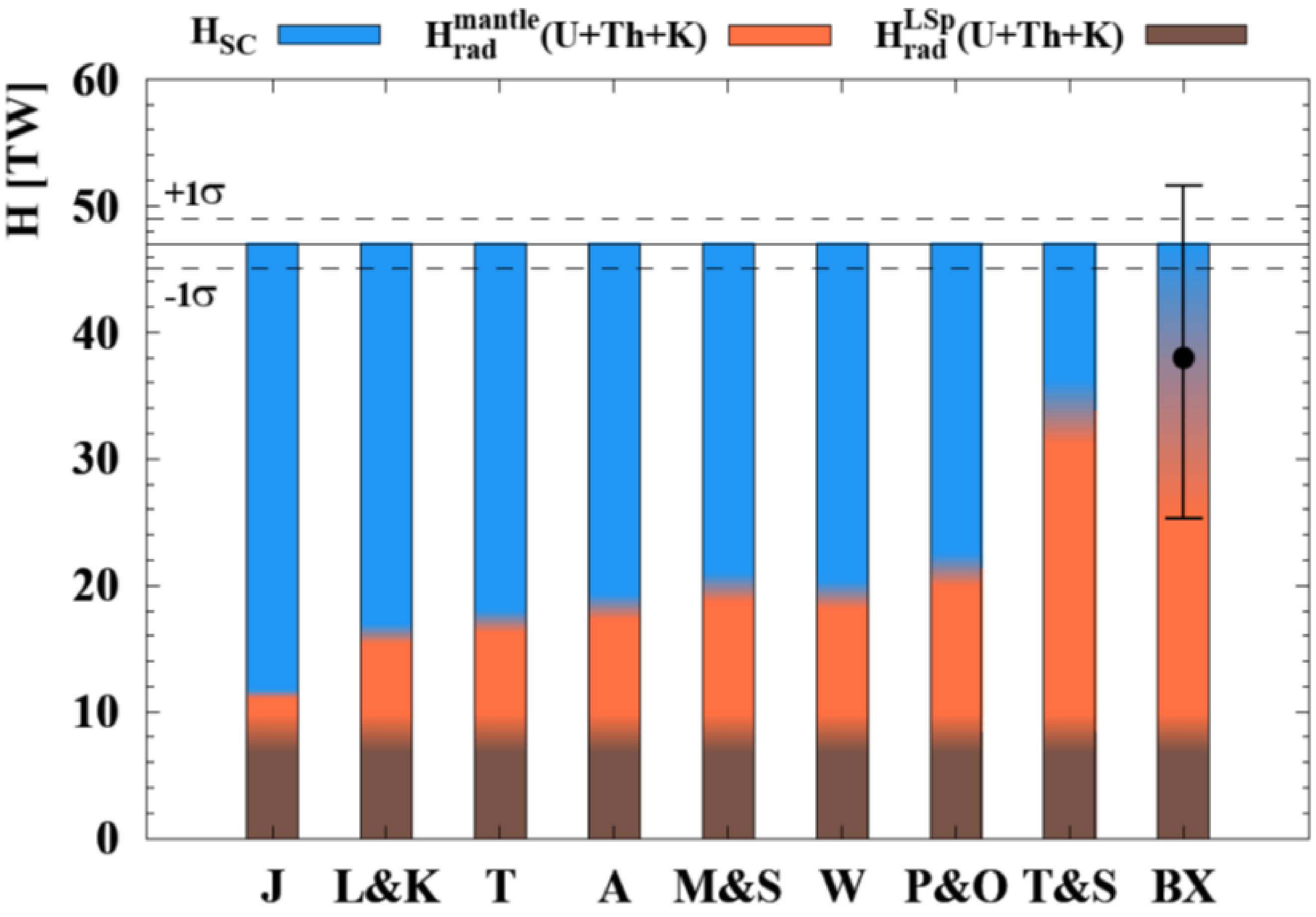
H_{Mantle} (U+Th) = 24.6 $^{+11.1}_{-10.4}$ TW

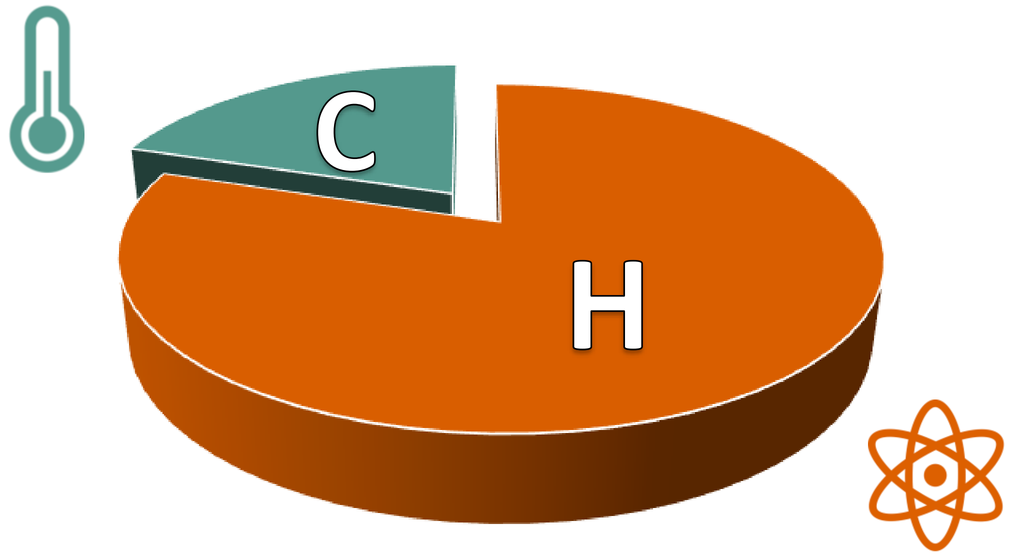
H_{Mantle} (U+Th+ K) = 30.0 $^{+13.5}_{-12.7}$ TW

Earth's heat power

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

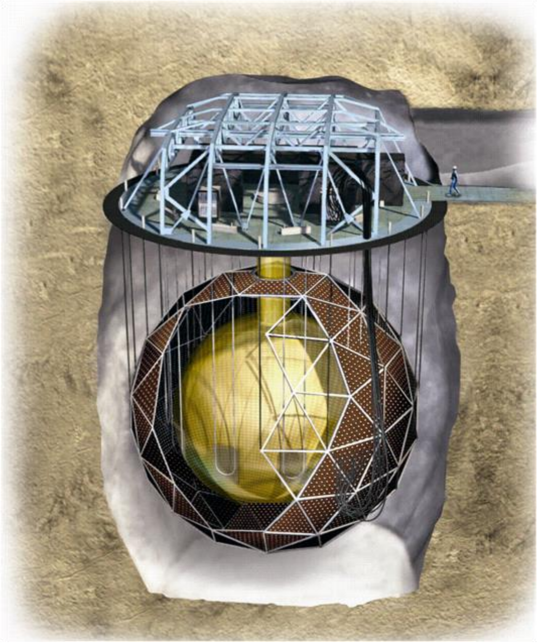
H_{Earth} (U+Th+ K) = $38.2^{+13.6}_{-12.7}$ TW





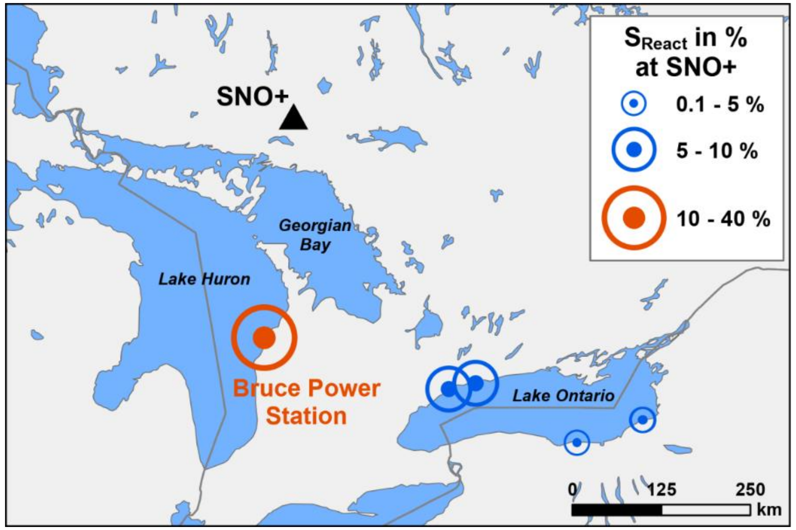
- Borexino estimates a high probability (~ 88 %) that the radioactive decays produce more than half of the total Earth's heat.

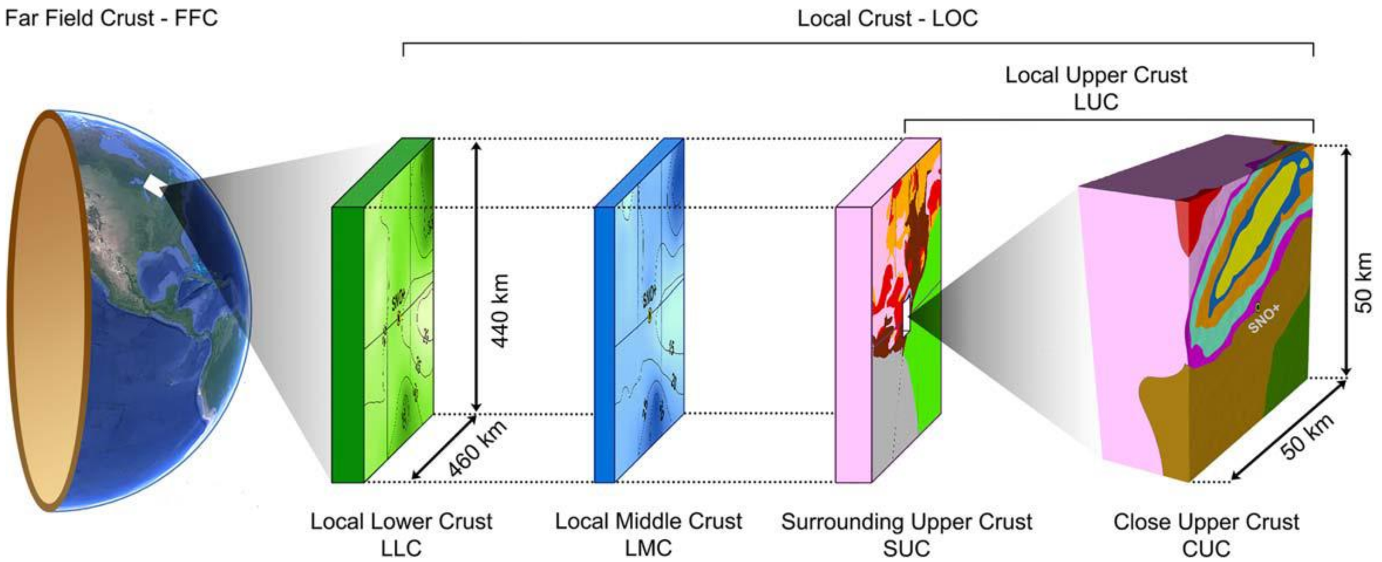
Expected geoneutrino signal at SNO+



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



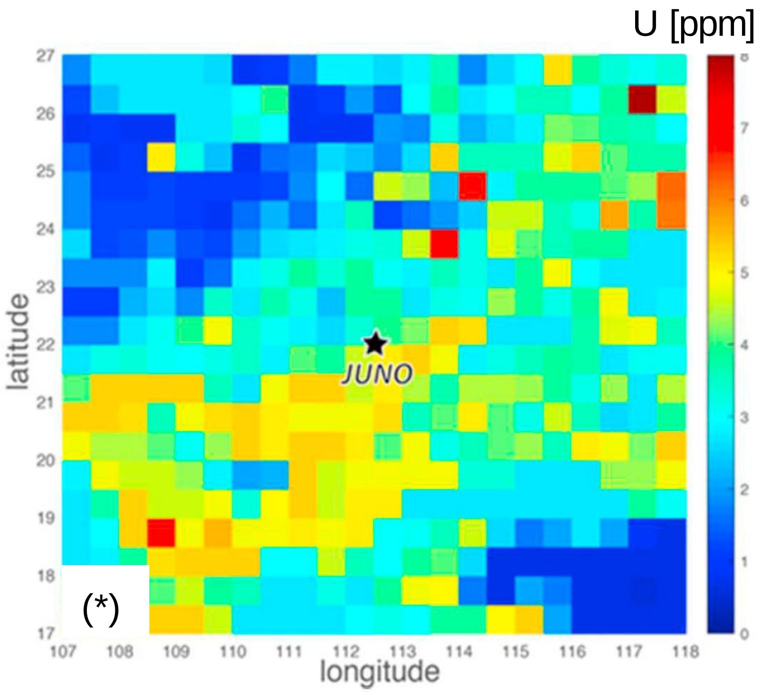


Expected geoneutrino signal at JUNO

- 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)

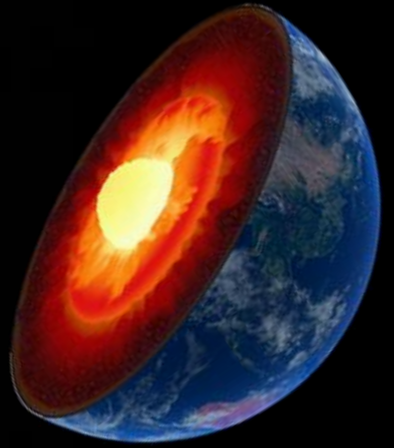
	N° of cores	Thermal power/core
Yangjiang	6	2.9 GW
Taishan	2	4.6 GW

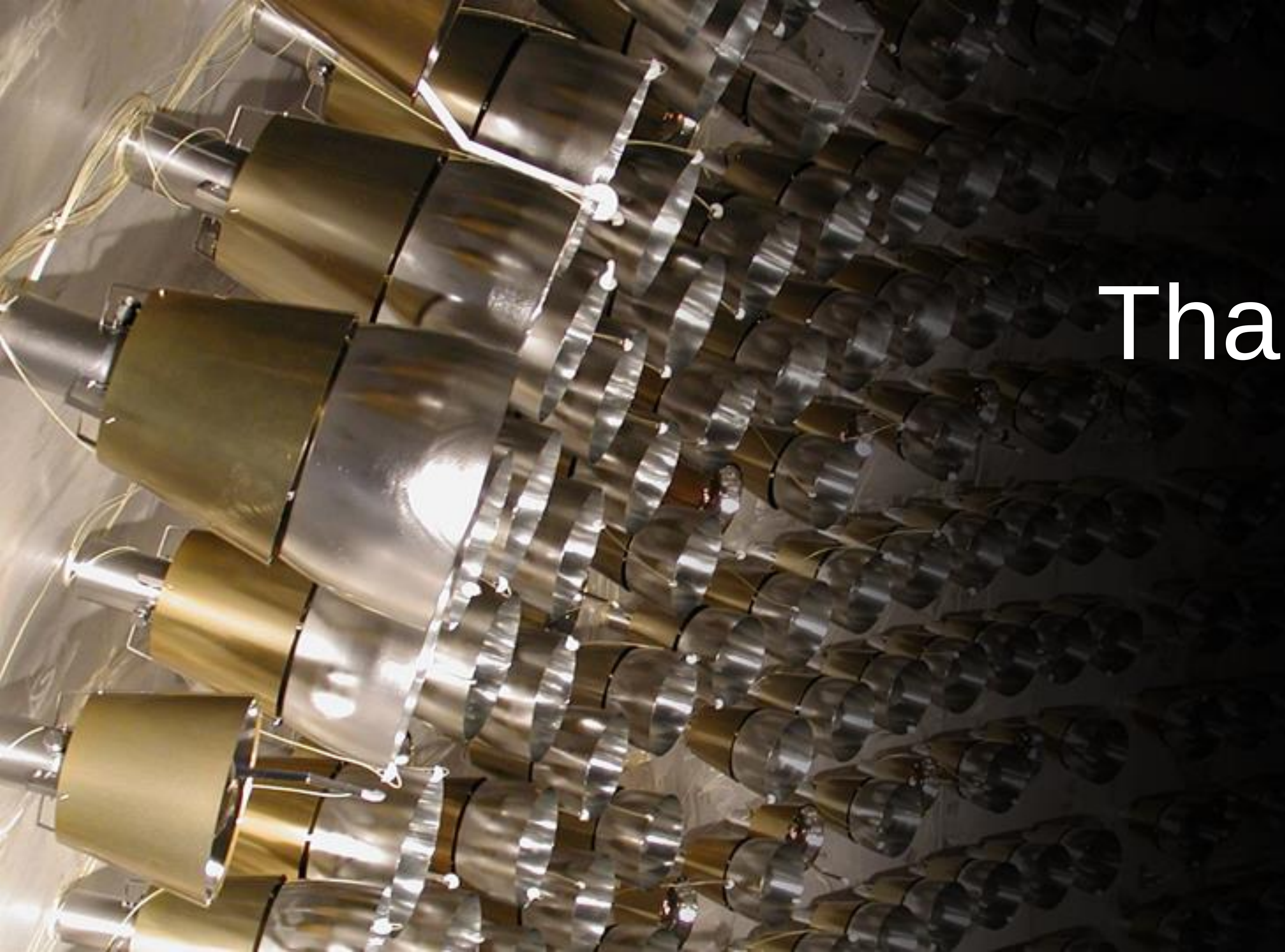
	S(U+Th) [TNU]
Strati et al., 2015 (using global crustal model)	$39.7^{+6.5}_{-5.2}$
Wipperfurth et al., 2020 (using global crustal models)	$41.3^{+7.5}_{-6.3}$
	$41.2^{+7.6}_{-6.4}$
	$40.0^{+7.4}_{-6.2}$
Gao et al., 2020 (*) (combining global crustal model and local geological data)	$49.1^{+5.6}_{-5.0}$



Take-away messages

- To deeply understand the experimental geoneutrino results, the use of refined geological models is essential
- The Borexino observations favor geological models that predict a relatively high concentration of radioactive elements in the mantle.
- The mantle radiogenic power H_M (U+Th)= $10.3^{+5.9}_{-6.4}$ TW from Borexino geoneutrino analysis agrees with BSE geodynamical model
- 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