Investigating Earth's mantle with antineutrinos

A. Serafini [a, +], G. Bellini [b], K. Inoue [c, d], F. Mantovani [e], V. Strati [e], H. Watanabe [c, d]

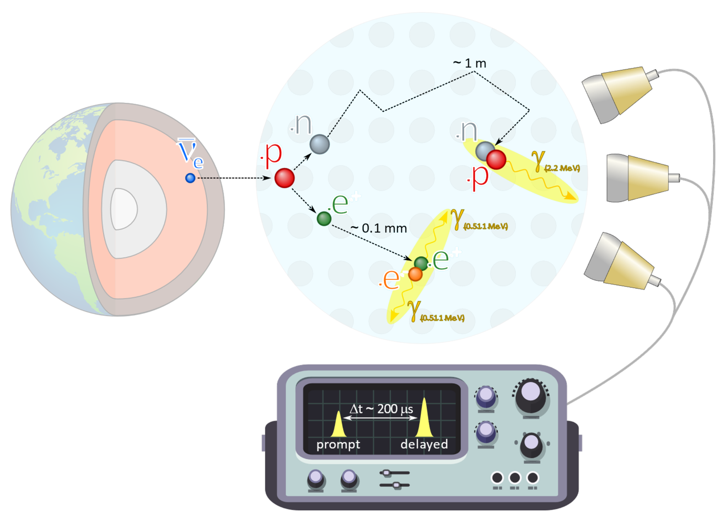
[a] Department of Physics and Astronomy, University of Padua and INFN, 35131 Padua, Italy
[b] Department of Physics, University of Milan and INFN, 20133 Milan, Italy
[c] Research Center for Neutrino Science, Tohoku University, Sendai 980-8578, Japan
[d] Institute for the Physics and Mathematics of the Universe, Tokyo University, Kashiwa 277-8568, Japan
[e] Department of Physics and Earth Sciences, University of Ferrara and INFN, 44122 Ferrara, Italy
[+] Correspondence: andrea.serafini@infn.it

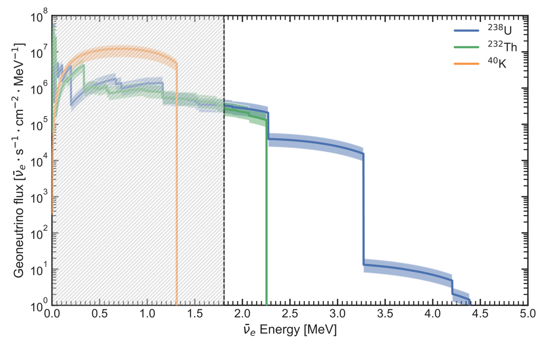
Neutrino2022
XXX International Conference on Neutrino Physics and Astrophysics

Geoneutrinos and geoscience: an intriguing joint-venture
Bellini G., K. Inoue, F. Mantovani, A. Serafini, V. Strati, H. Watanabe
La Rivista del Nuovo Cimento, 45, 1-105 (2022)

KamLAND and Borexino results

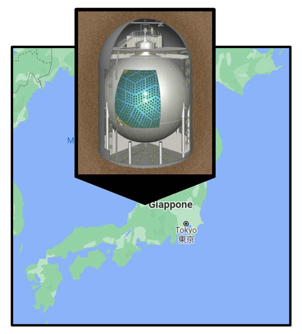
Geoneutrinos, the electron antineutrinos originating from the β⁻ emitters inside our planet, are a precious tool for exploring the inner Earth. While decaying, the radioisotopes belonging to ^{238}U and ^{232}Th decay chains and ^{40}K release **geoneutrinos** and **energy**, dissipated as heat, in a **well-fixed ratio**.





Uranium (U) and thorium (Th) geoneutrinos are detected via **Inverse Beta Decay** on free protons inside big **liquid scintillator detectors**. The measurement of the geoneutrino **flux at surface** permits to estimate the U and Th content of our planet's mantle and in turn to derive its **radiogenic heat production**.

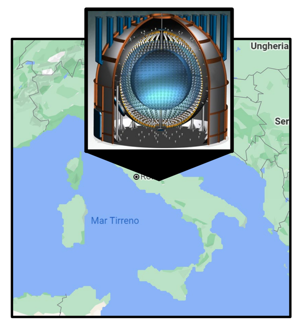
The only two running experiments in the world capable of measuring geoneutrinos are Borexino and KamLAND.



KamLAND is a **1 kton** liquid scintillator detector situated in **Japan**, in the Kamioka mine. It is surrounded by 1325 17" PMTs and 554 20" PMTs.

Latest results[1]:

Data-taking: 2002-2019			
	U	Th	U+Th
Events [#]	$138.0^{+22.3}_{-20.5}$	$34.1^{+5.4}_{-5.1}$	$168.8^{+26.3}_{-26.5}$
Signal [TNU]	$26.1^{+4.2}_{-3.9}$	$6.6^{+1.1}_{-1.0}$	$\mathbf{32.1^{+5.0}_{-5.0}}$



Borexino is **0.3 kton** liquid scintillator detector situated in **Italy**, at the Laboratori Nazionali del Gran Sasso. It is surrounded by ~2200 8" PMTs.

Latest results[2]:

Data-taking: 2007-2019			
	U	Th	U+Th
Events [#]	$41.1^{+7.5}_{-7.1}$	$11.5^{+2.2}_{-1.9}$	$52.6^{+9.6}_{-9.0}$
Signal [TNU]	$36.3^{+6.7}_{-6.2}$	$10.5^{+2.1}_{-1.7}$	$\mathbf{47.0^{+8.6}_{-8.1}}$

[1] Watanabe, H. *Geo-neutrino Measurement with KamLAND* in Neutrino Geoscience 2019.

[2] Agostini, M., *Comprehensive geoneutrino analysis with Borexino*. Physical Review D, 2020

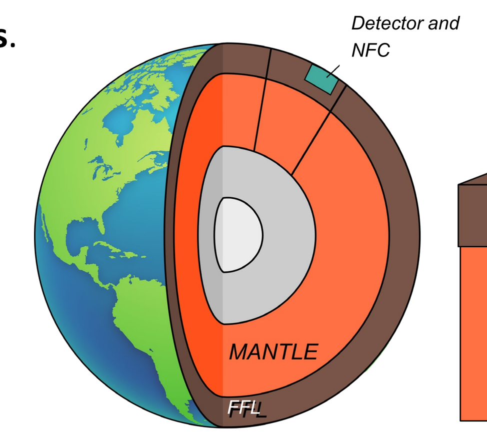
1 TNU = 1 antineutrino event measured over 1 year by a detector containing 10^{32} free protons target, assuming 100% detection efficiency.

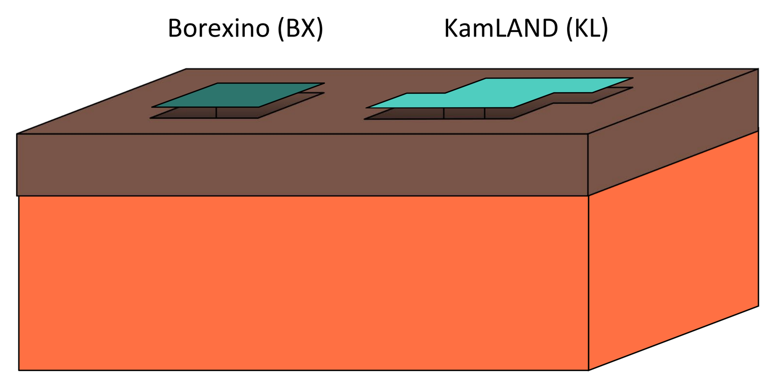
Geophysical and geochemical modelling

The geoneutrino signal can be modeled as the **sum** of **different components**.

The **Near Field Crust (NFC)** is the 6°x 4° portion of the crust surrounding the detector. U and Th distributed in the NFC can contribute up to ~ 50% of the total geoneutrino signal.

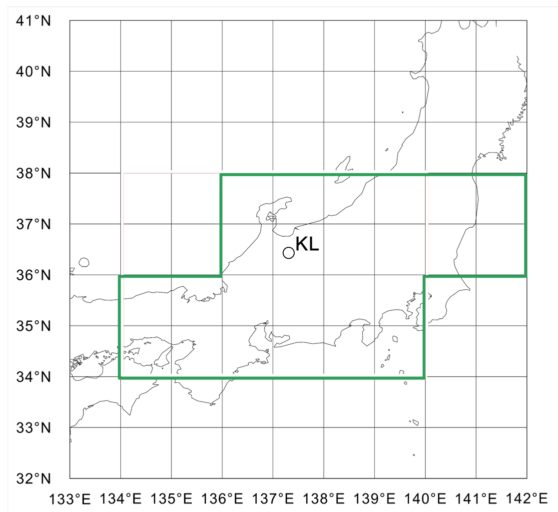
The **Far Field Lithosphere (FFL)** is the superficial portion of the Earth complimentary to the NFC. It includes the Far Field Crust (FFC) and the Continental Lithospheric Mantle (CLM).





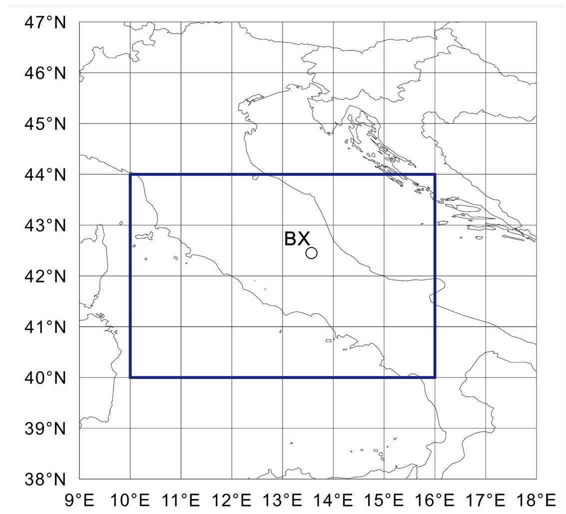
Different for different detectors — Common to detectors

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



KamLAND (KL)	S(U+Th) [TNU]
NFC [3]	17.7 ± 1.4
FFC [4]	$7.3^{+1.5}_{-1.2}$
CLM [4]	$1.6^{+2.2}_{-1.0}$

[3] Fiorentini, G., *Mantle geoneutrinos in KamLAND and Borexino*. Physical Review D, 2012



Borexino (BX)	S(U+Th) [TNU]
NFC [2]	9.2 ± 1.2
FFC [4]	$13.7^{+2.8}_{-2.3}$
CLM [4]	$2.2^{+3.1}_{-1.3}$

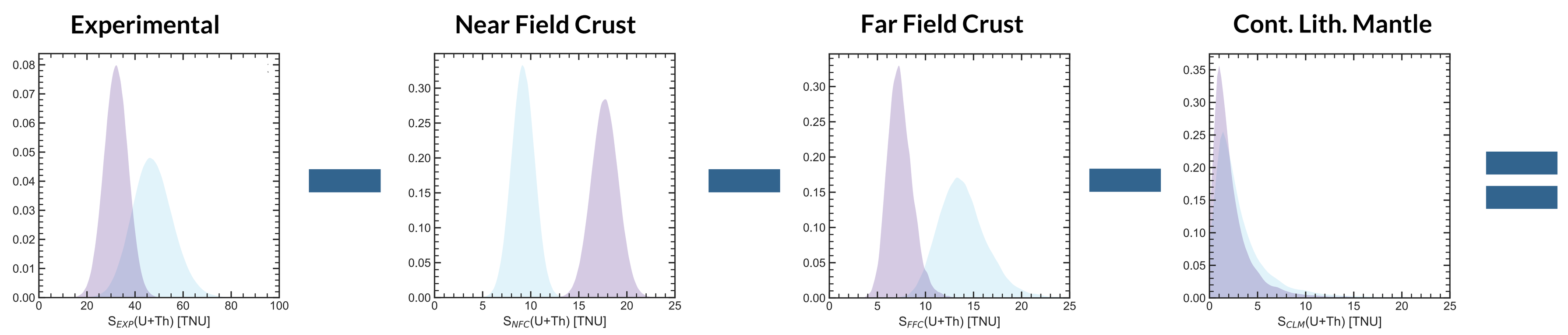
[4] Huang, Y., *A reference Earth model for the heat producing elements [...]*. Geochem Geophys, 2013

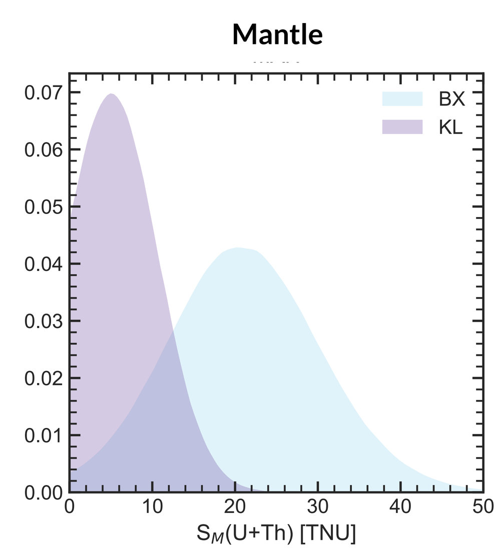
Geoneutrino mantle signal extraction

The mantle signals $S^{BX}_M(U+Th)$ and $S^{KL}_M(U+Th)$ can be inferred by subtracting the estimated lithospheric components from the experimental total signals using their reconstructed PDFs:

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

$$S^{BX}_M(U+Th) = S^{BX}_{Exp}(U+Th) - S^{BX}_{NFC}(U+Th) - S^{BX}_{FFC}(U+Th) - S^{BX}_{CLM}(U+Th) = 20.8^{+9.4}_{-9.2} \text{ TNU}$$



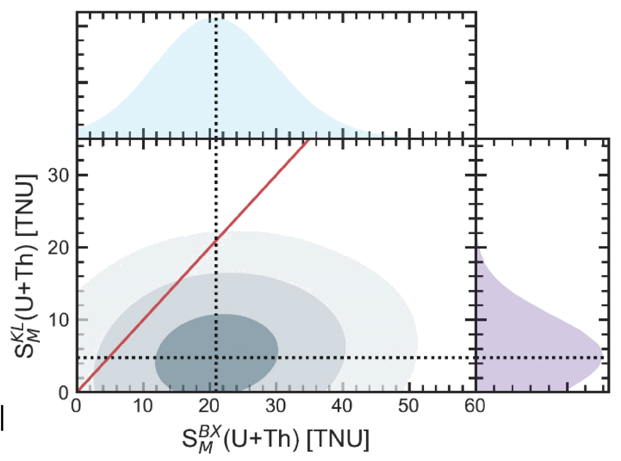


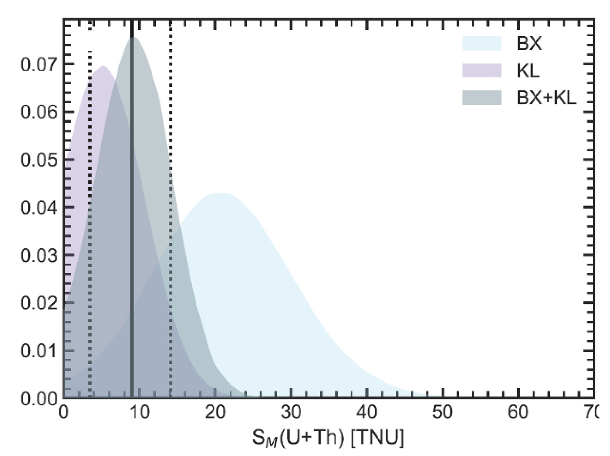
Under the assumption of site-independent mantle signal, the joint distribution $S^{KL+BX}_M(U+Th)$ can be inferred by requiring that the estimated signals $S^{BX}_M(U+Th) = S^{KL}_M(U+Th)$ are two observations of the same underlying quantity $S^{KL+BX}_M(U+Th) = 8.9^{+5.1}_{-5.5}$ TNU.

Correlations need to be properly accounted for:

- » $S^{KL}_{FFC}(U+Th) \propto S^{BX}_{FFC}(U+Th)$
- » $S^{KL}_{CLM}(U+Th) \propto S^{BX}_{CLM}(U+Th)$

As they are derived from the same geophysical and geochemical model





Implications for Earth Science

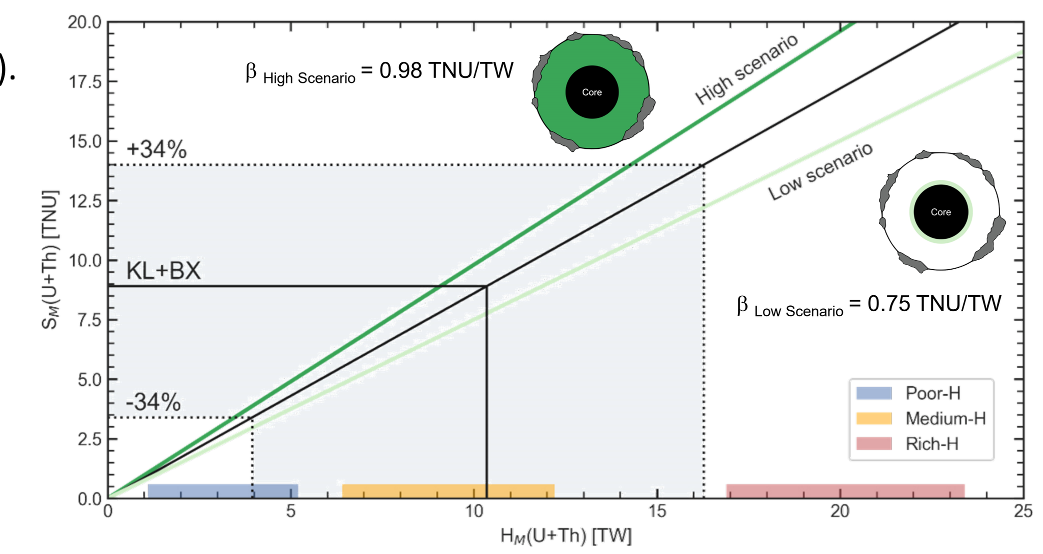
In literature there is a wide range of **Earth compositional models** based on different constraints (composition of meteorites, geochemical/geodynamical observations, etc.).

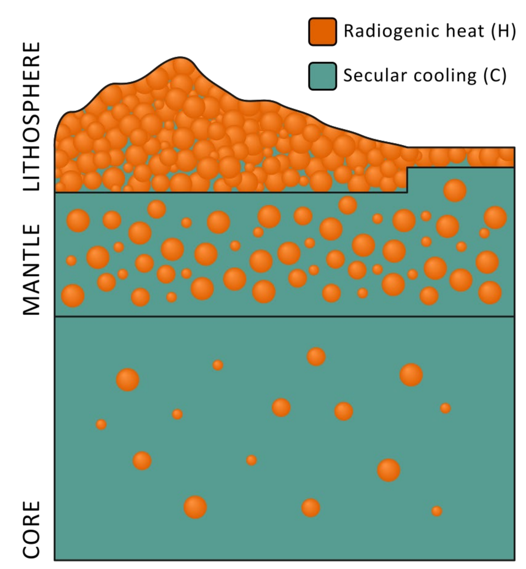
Models can be grouped based on their expected **radiogenic heat production (H)** in **poor-H**, **medium-H** and **rich-H models.**

Assuming that the U and Th abundances in the mantle are radial, non-decreasing function of the depth, the obtained mantle signal $S^{KL+BX}_M(U+Th)$ can be used to estimate the radiogenic heat production of the mantle $H_M(U+Th)$:

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

✓ Our estimate $H_M(U+Th) = 10.3^{+5.9}_{-6.4}$ **TW** falls in the 68% coverage range of the medium-H models and it is compatible at 1σ level with the Poor-H models



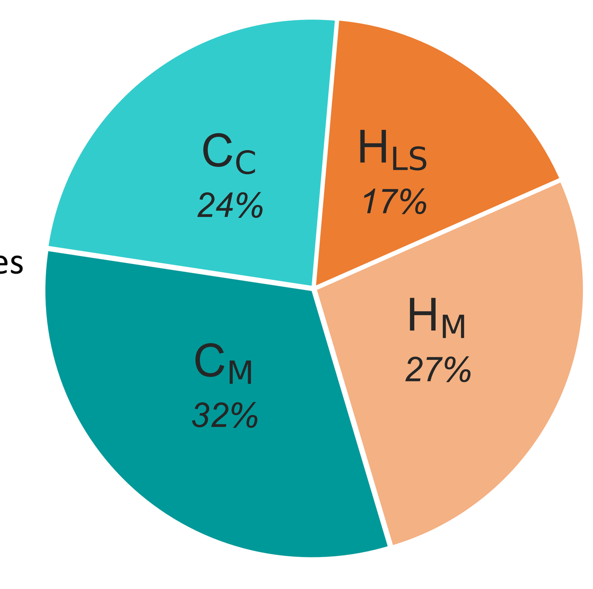


Radiogenic heat (H) is not the only source contributing to the well-established total heat power (Q) of the Earth of 47 ± 2 TW[5]. A large contribution to Q comes from the indeterminate slow **secular cooling (C)** of our planet.

✓ By combining our estimate for H_M with the geochemical knowledge on the lithosphere $H_{LS} = 8.1^{+1.9}_{-1.6}$ TW[4] it is possible to derive a picture of the sources of Earth's heat budget:

$C = Q - H$
$C_M = Q - H - C_C$
$H_M = H - H_{LS} - H_C$
$H_{LS} = H_{CC} + H_{OC} + H_{CLM}$

Q [TW]	H_{LS} [TW]	H_M [TW]	H [TW]	C [TW]
47 ± 2	$8.1^{+1.9}_{-1.6}$	$12.5^{+7.1}_{-7.7}$	$\mathbf{20.8^{+7.3}_{-7.9}}$	$\mathbf{26 \pm 8}$



[5] Davies, J.H. and D.R. Davies, *Earth's surface heat flux*. Solid Earth, 2010