Geo-neutrino measurements with Borexino

Xuefeng Ding

Physics Department, Princeton University, Princeton, NJ 08542, USA
*Now at Experiment Physics Division, Institute of High Energy Physics, Chinese Academy of Sciences, Shijingshan District, Beijing 100049, China

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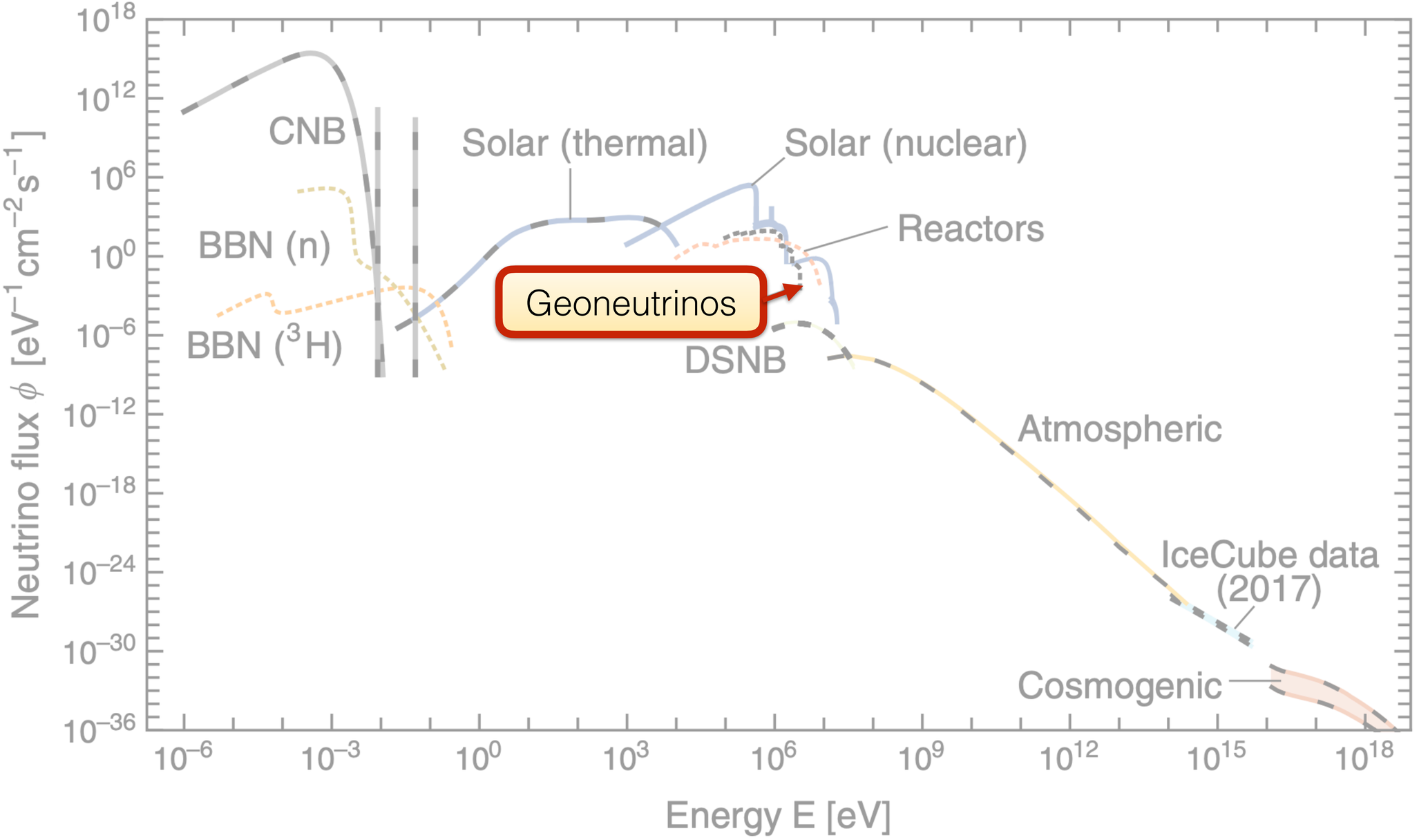
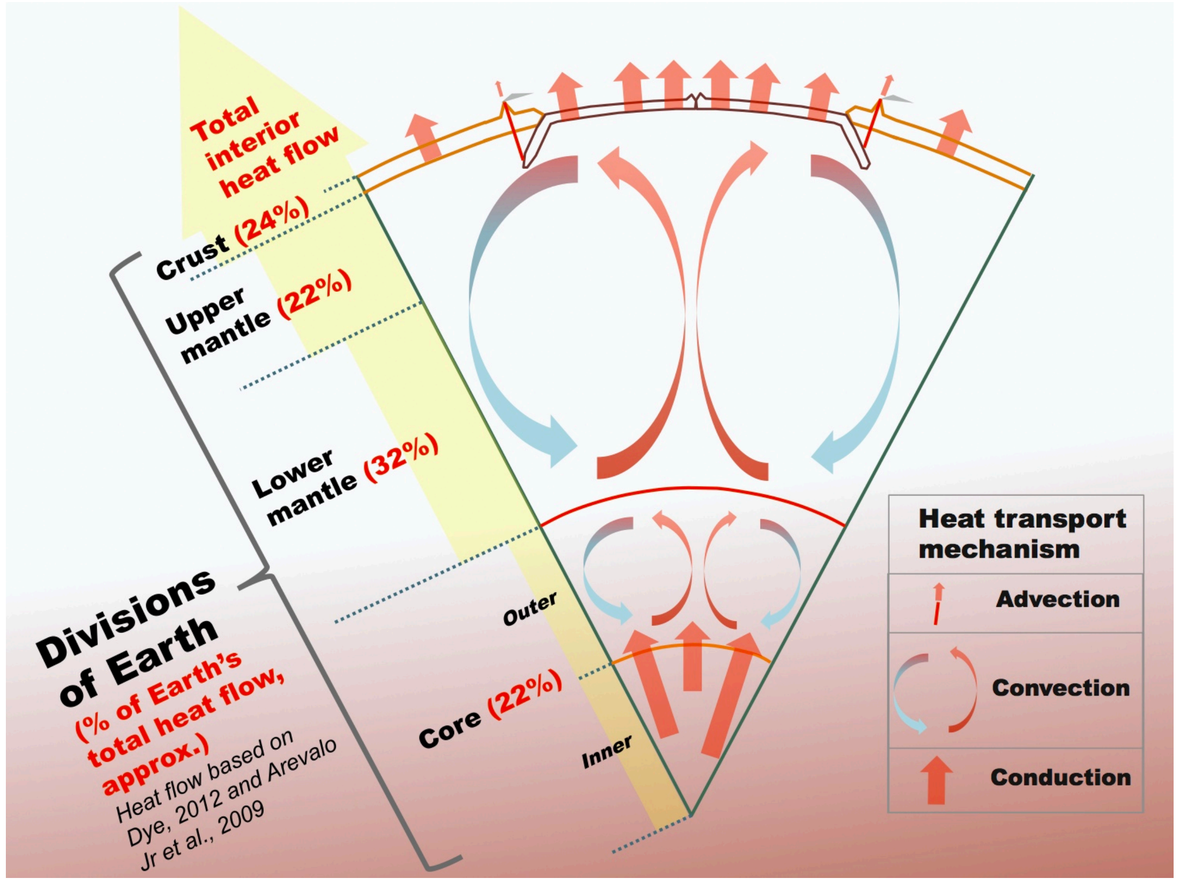


Grand unified neutrino spectrum at Earth: Sources and spectral componentsEdoardo Vitagliano, Irene Tamborra, and Georg Raffelt
Rev. Mod. Phys. 92, 045006 – Published 9 December 2020



Geo-neutrinos: New messengers of the Mantle

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 8e^{-} + 6\bar{\nu}_e + 51.7\ \mathrm{MeV} \quad (1)$$

$$^{235}\mathrm{U} \rightarrow {}^{207}\mathrm{Pb} + 7\alpha + 4e^{-} + 4\bar{\nu}_e + 46.4\ \mathrm{MeV} \quad (2)$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4e^{-} + 4\bar{\nu}_e + 42.7\ \mathrm{MeV} \quad (3)$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^{-} + \bar{\nu}_e + 1.31\ \mathrm{MeV}\ (89.3\%) \quad (4)$$

$$^{40}\mathrm{K} + e^{-} \rightarrow {}^{40}\mathrm{Ar} + \nu_e + 1.505\ \mathrm{MeV}\ (10.7\%) \quad (5)$$

BOREX*: SOLAR NEUTRINO EXPERIMENT VIA WEAK NEUTRAL AND CHARGED CURRENTS IN BORON-11

T. KOVACS, J. MITCHELL, P. RAGHAVAN, R. S. RAGHAVAN

AT&T Bell Laboratories, Murray Hill, U.S.A.

S. J. FREEDMAN

Argonne National Laboratory, Argonne, U.S.A.

J. KAY, C. E. LANE, R. I. STEINBERG

Drexel University, Philadelphia, U.S.A.

C. CATTADORI, A. DONATI

Laboratori Nazionali del Gran Sasso, Assergi, Italy

S. PAKVASA

University of Hawaii at Manoa, Honolulu, U.S.A.

M. DEUTSCH, P. ROTHSCHILD

Massachusetts Inst. of Technology, Cambridge, U.S.A.

C. ARPESELLA, G. BELLINI, S. BONETTI, M. CAMPANELLA, P. INZANI, I. MANNO, E. MERONI†, G. RANUCCI, F. RAGUSA

Milano University and INFN, Milano, Italy

and

G. CECCHET, A. DE BARI, M. GALLORINI, A. PEROTTI

Pavia University and INFN, Pavia, Italy

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Abstract. Borex, an experiment to observe solar neutrinos using boron-loaded liquid scintillation techniques, is being developed for operation at the Gran Sasso underground laboratory. It aims to observe the spectrum of electron type ^{8}B solar neutrinos via charged current inverse β-decay of ^{11}B and the total flux of solar neutrinos regardless of flavor by excitation of ^{11}B via the weak neutral current.

BOREX @ 1989
NC+CC+ES, but too large for LNGS

Four basic reactions may be observed in Borex:

(a) $\nu + {}^{11}\mathrm{B} \rightarrow \nu' + [{}^{11}\mathrm{B}^*(E_i) \rightarrow {}^{11}\mathrm{B} + \gamma(E_i)]$; NC

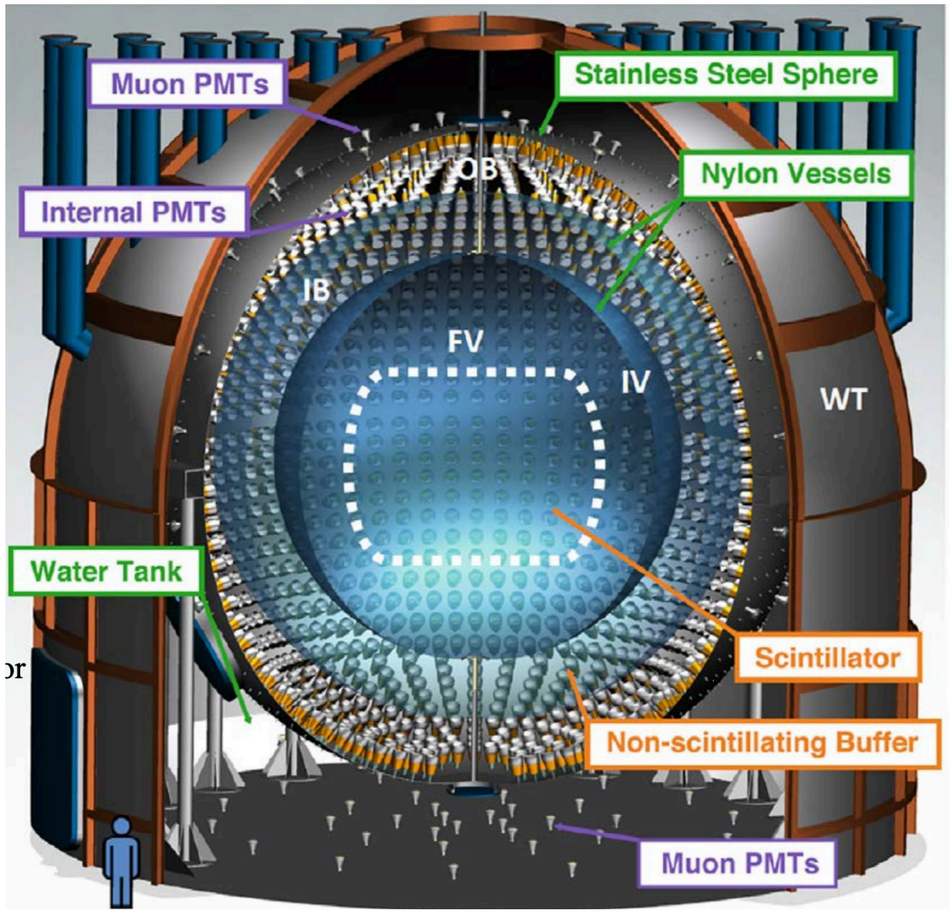
(b) $\nu_e + {}^{11}\mathrm{B} \rightarrow e^- + [{}^{11}\mathrm{C}^*(E_i') \rightarrow \gamma(E_i') + [{}^{11}\mathrm{C} \rightarrow {}^{11}\mathrm{B} + e^+ + \nu_e]]$; CC

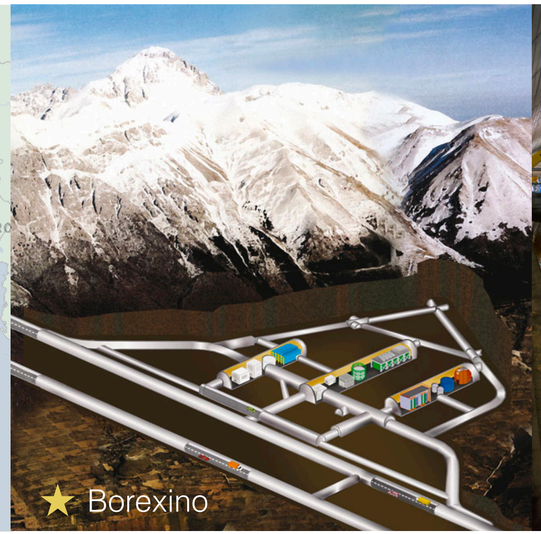
(c) $\nu + e^- \rightarrow \nu + e^-$; ES

(d) $\bar{\nu}_e + p \rightarrow e^+ + n$ followed by $n + {}^{10}\mathrm{B} \rightarrow \alpha + {}^{7}\mathrm{Li} + 0.48\ \mathrm{MeV}\gamma$. IBD

The Borexino Collaboration

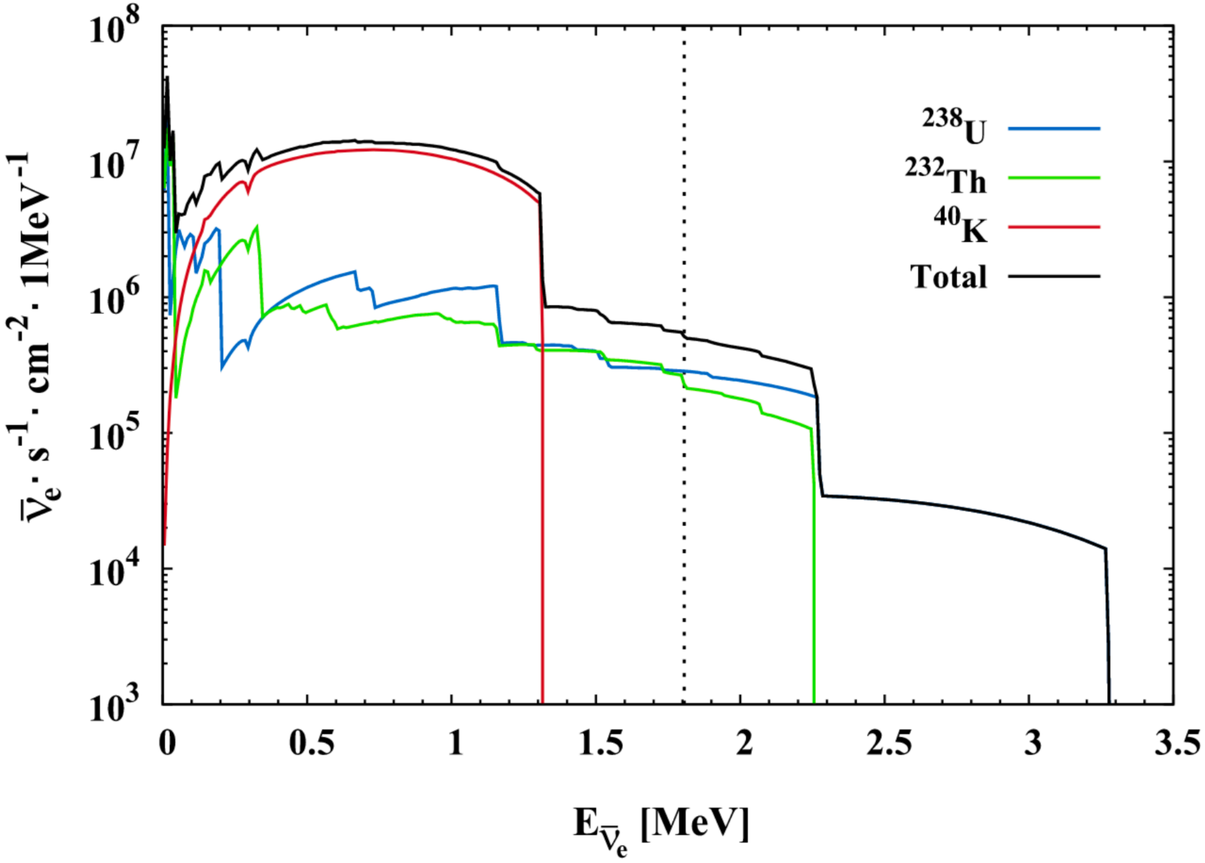
The Borexino Detector

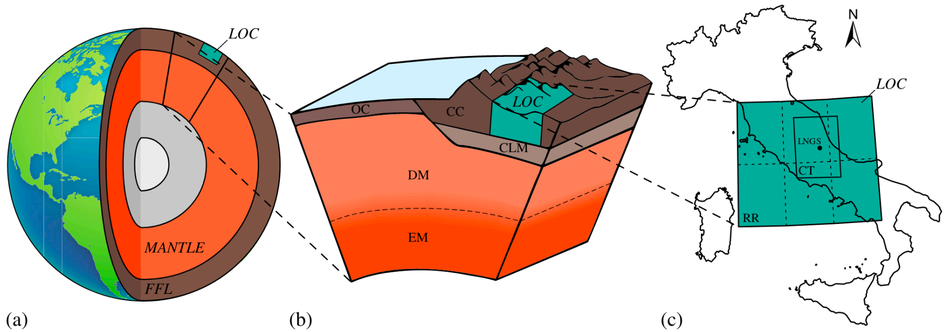


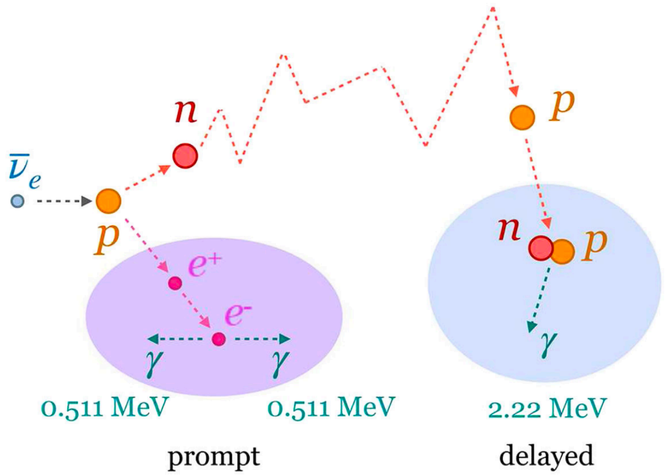


- Located at hall C of LNGS, Italy.
- Active volume 280 tons of liquid scintillator

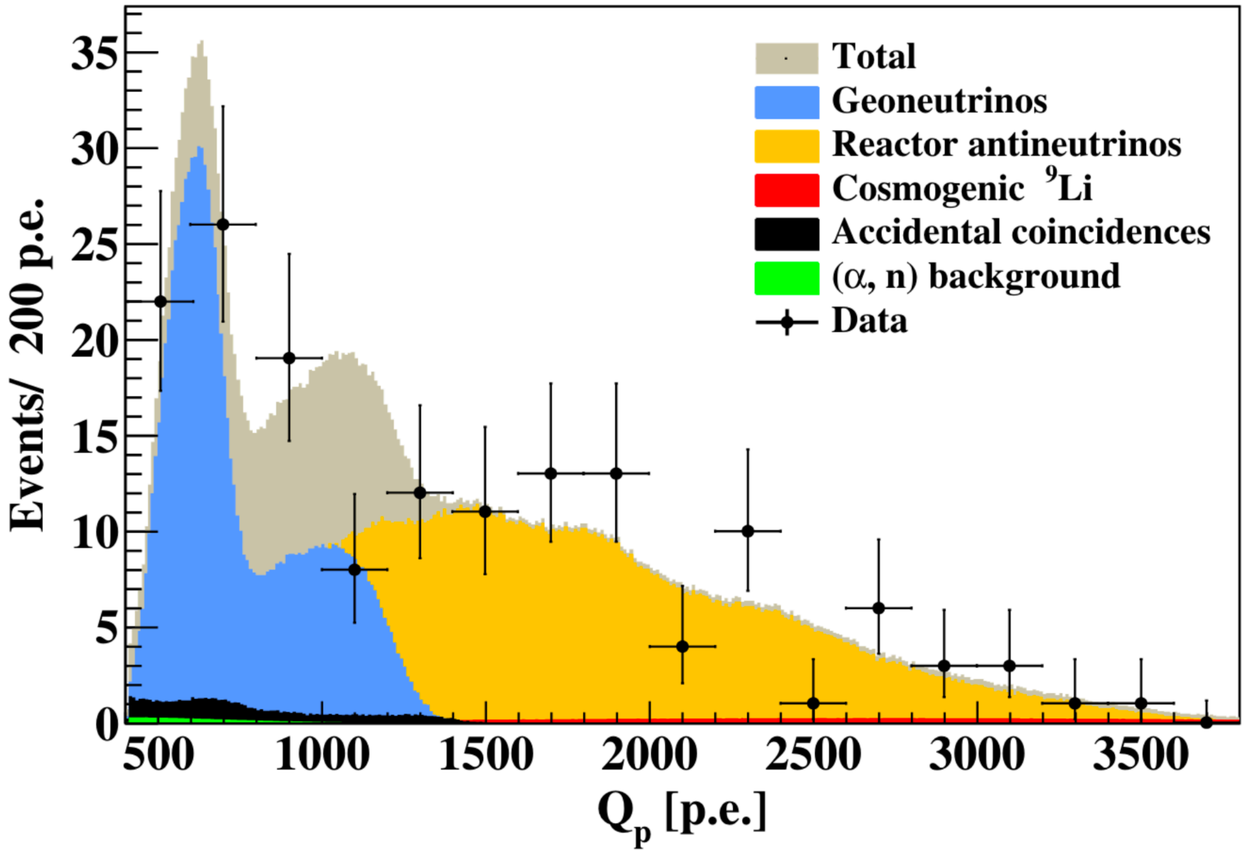
Geo-ν Signal seen by Borexino

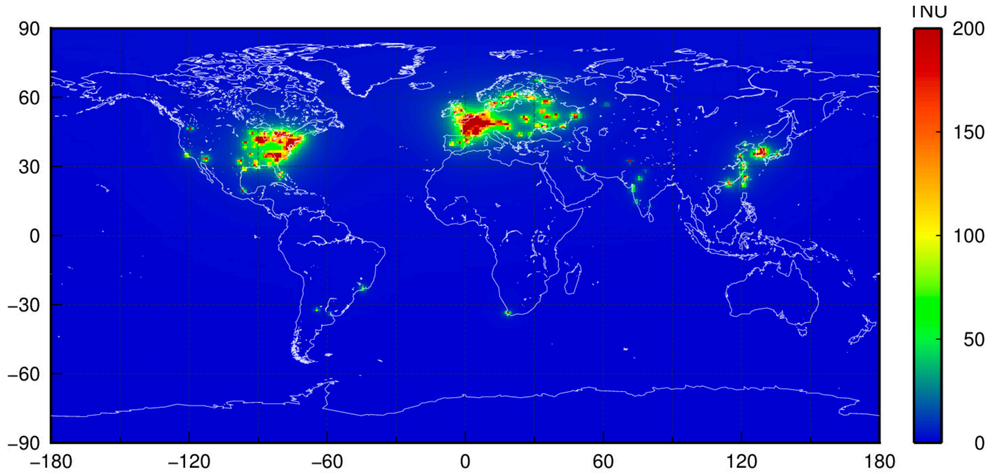






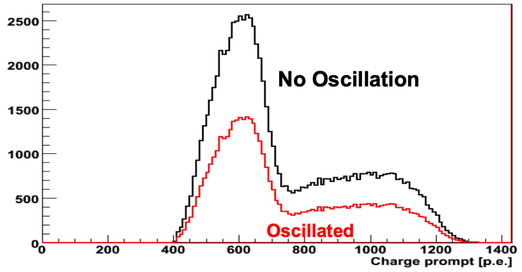
Backgrounds — Reactor neutrinos



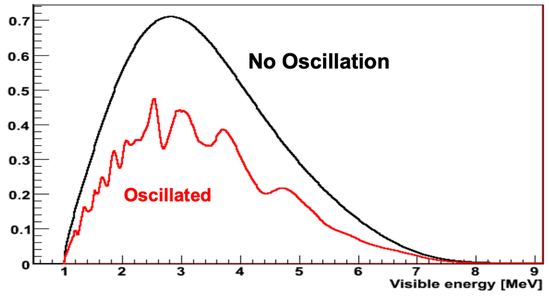


Baldoncini, Marica, Ivan Callegari, Giovanni Fiorentini, Fabio Mantovani, Barbara Ricci, Virginia Strati, and Gerti Xhixha. "Reference Worldwide Model for Antineutrinos from Reactors." *Physical Review D* 91, no. 6 (March 2, 2015): 065002. https://doi.org/10.1103/PhysRevD.91.065002.

Geoneutrinos



Reactor antineutrinos at LNGS



Summary of Cuts (eff. ~87%)

Charge of prompt

Q_p > 408 pe

- Prompt spectrum starts at 1 MeV
- 5% energy resolution @ 1 MeV

Charge of delayed

Q_d > 700 (860) – 3000 pe

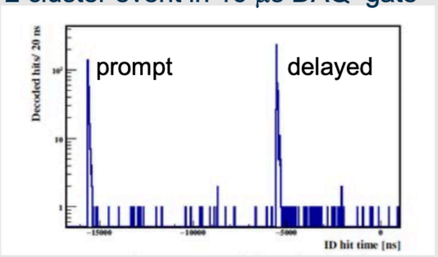
- Neutron captures on proton (2.2 MeV) and in about 1% of cases on **^{12}C (4.95 MeV)**
- Spill out effect at the nylon inner vessel border
- Radon correlated ^{214}Po($\alpha + \gamma$) decays from ^{214}Bi and ^{214}Po fast coincidences

Time correlation

dt = (2.5-12.5) μs + (20-1280) μs

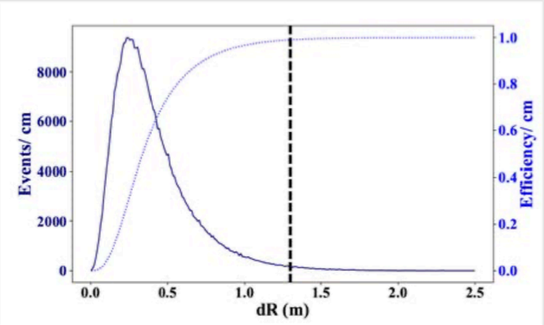
Neutron capture $\tau = (254.5 \pm 1.8)$ μs

2 cluster event in 16 μs DAQ gate



Space correlation

dR < 1.3 m

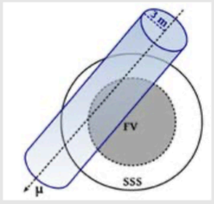


Muon veto

2s || 1.6 s : ^{9}Li(β + n)

2 ms: neutrons

- Several veto categories
- Strict and special muon tags



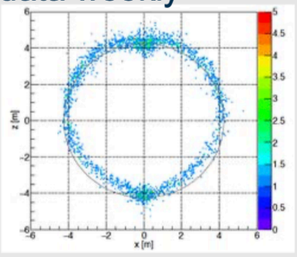
- Whole detector
- **Cylinder**

Only 2.2% exposure loss

Dynamic Fiducial Volume

> 10 cm from IV (prompt)

- Exposure vs accidental bgr
- IV has a leak: shape reco from the data weekly



Multiplicity

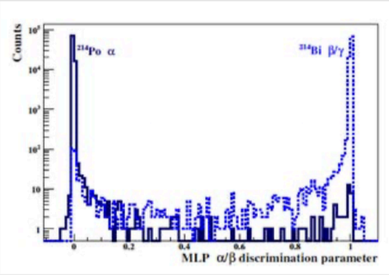
No event with Q >400 pe ±2 ms around promt/delayed

- Suppressing undetected cosmogenic background, mostly multiple neutrons
- Negligible exposure loss

α/β discrimination

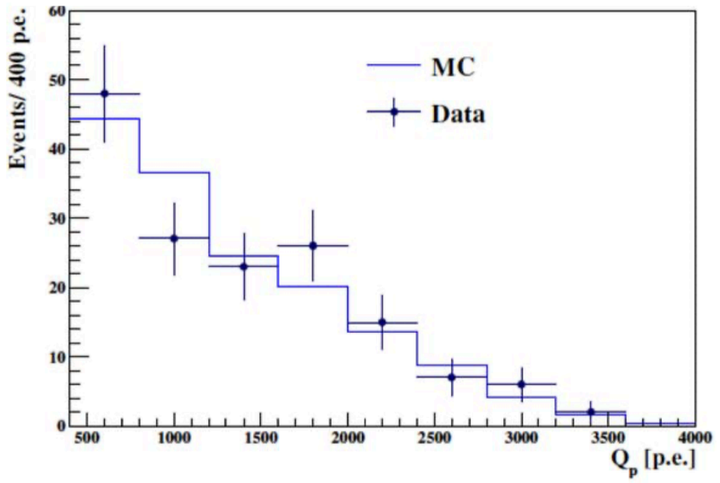
$MLP_{delayed}$ > 0.8

- Radon correlated ^{214}Po(α+γ)

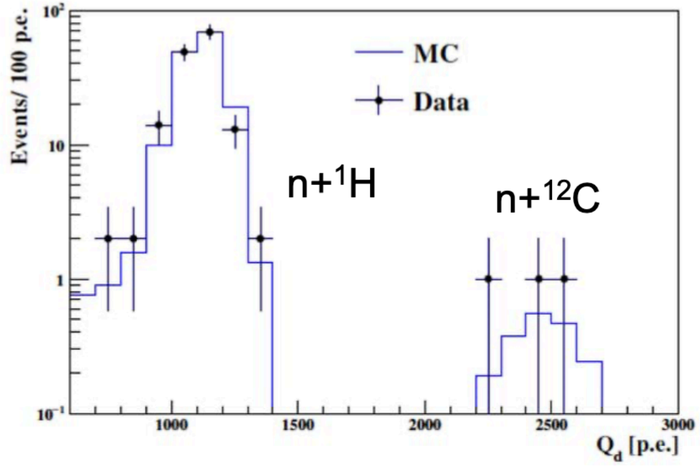


Events after cut

Prompt charge spectrum

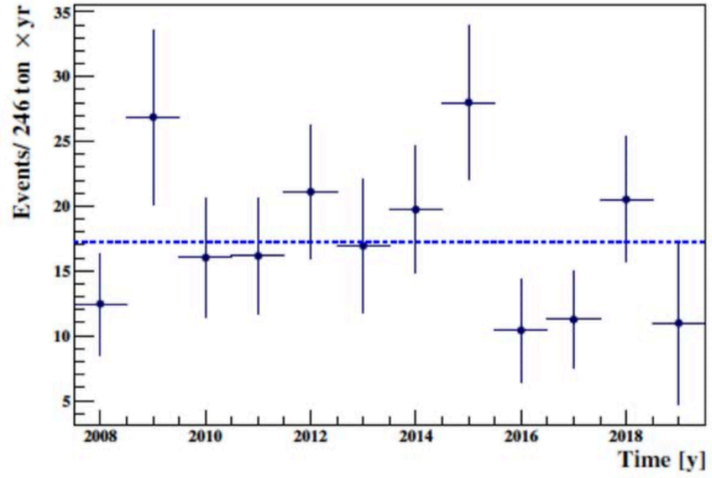


Delayed charge spectrum

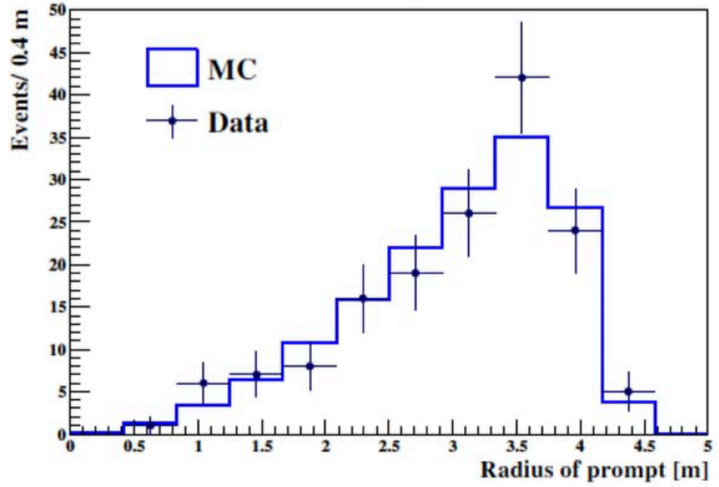


- December 9, 2007 to April 28, 2019
- 3262.74 days of data taking
- Average FV = (245.8 ± 8.7) ton
- **Exposure = (1.29 ± 0.05) x 10^{32} proton x year**
- Including systematics on position reconstruction and muon veto loss, for 100% detection eff.

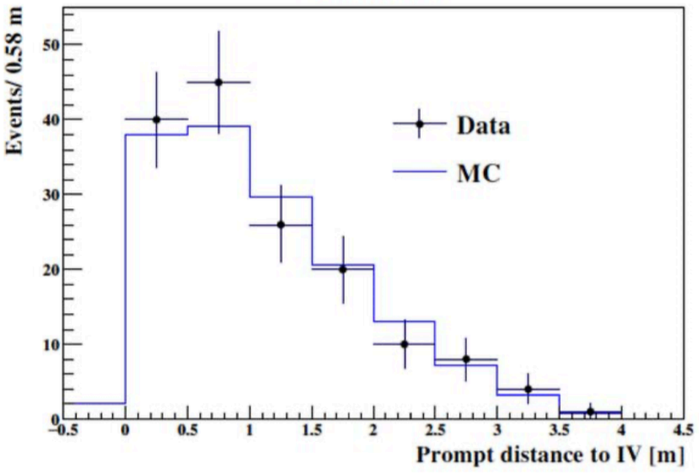
Distribution in time



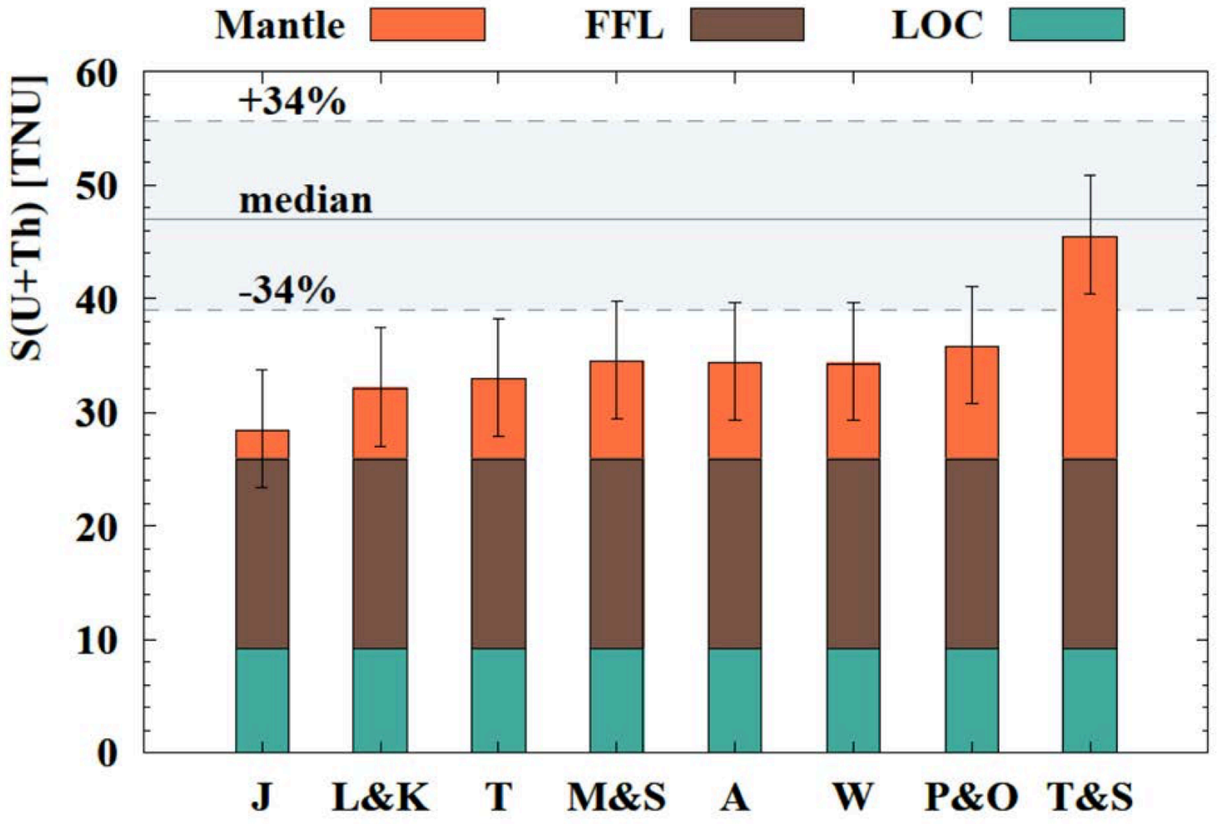
Radial distribution



Distance to the Inner Vessel



Results $47.0^{+8,4}_{-7.7}(stat)^{+2,4}_{-1.9}(sys)TNU$



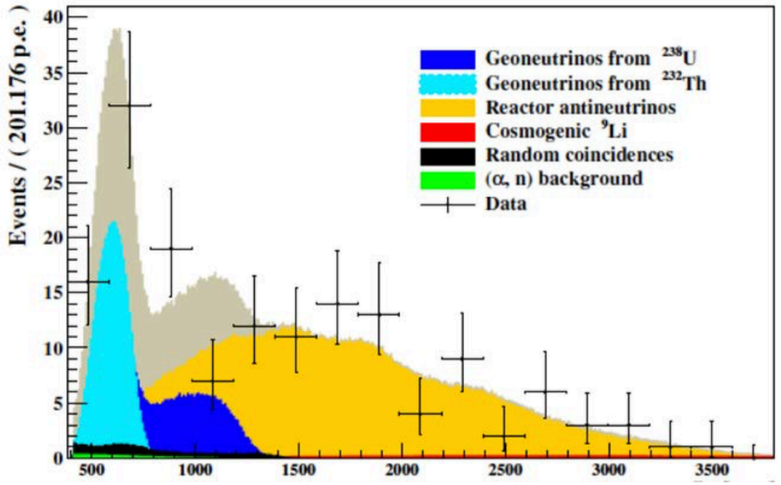
LOC = local crust = (9.2 ± 1.2) TNU

FFL = far-field lithosphere = ($4.0^{+1.4}_{-1.0}$) TNU

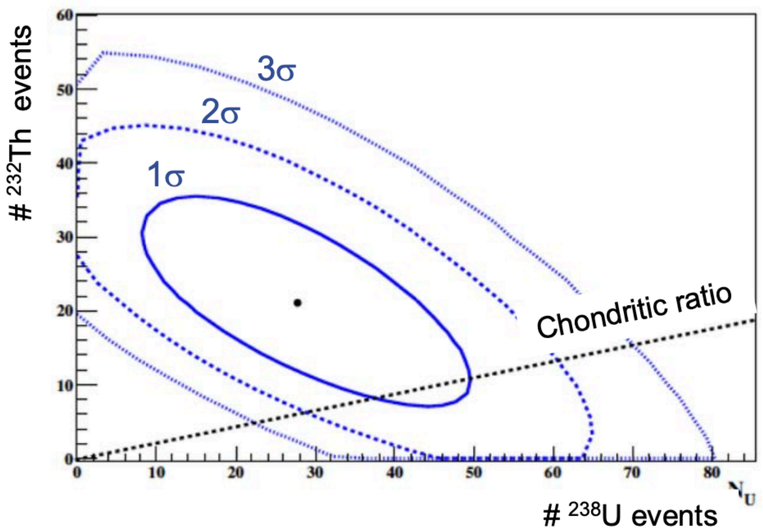
MANTLE (U + Th abundances) = BSE model – LITHOSPHERE

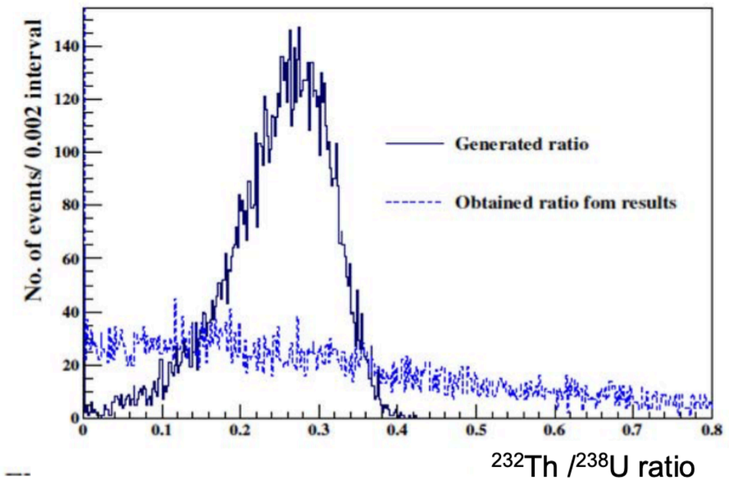
J: Javoy at al., 2010
L&K: Lyubetskaya and Korenaga, 2007
T: Taylor, 1980
M&S: Mc Donough and Sun, 1995
A: Anderson, 2007
W: Wang, 2018
P&O: Palme and O'Neil, 2003
T&S: Turcotte and Schubert, 2002

Separate fit of ^{238}U and ^{232}Th

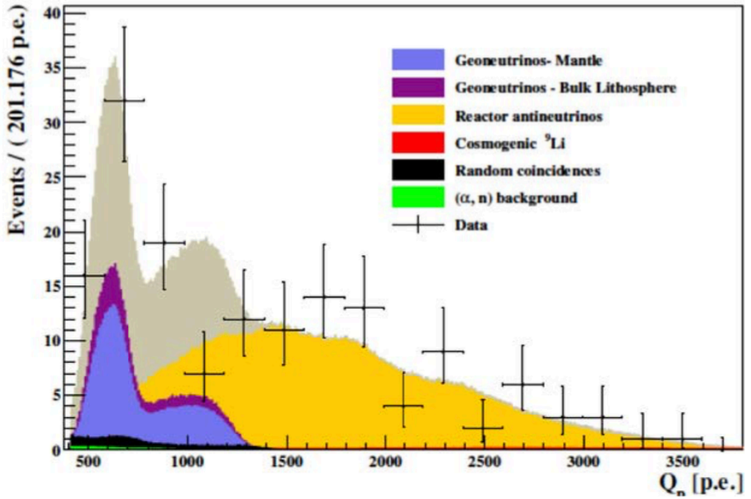


Prompt charge [photoelectrons]: 1 MeV ~500 photoelectrons

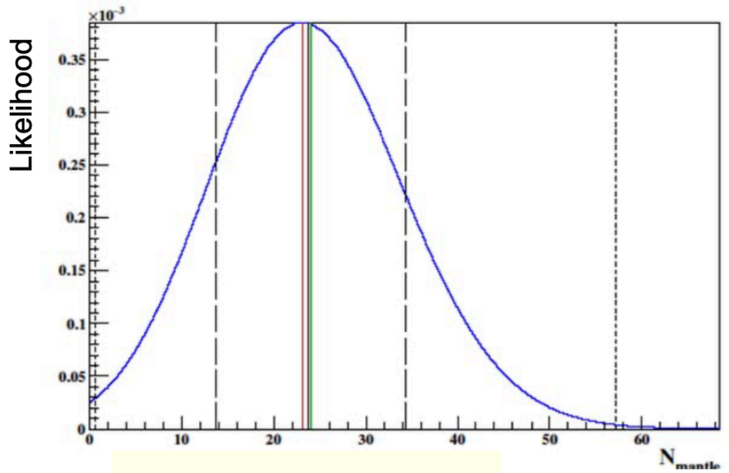




Significance to mantle geo-ν: 2.3 sigma

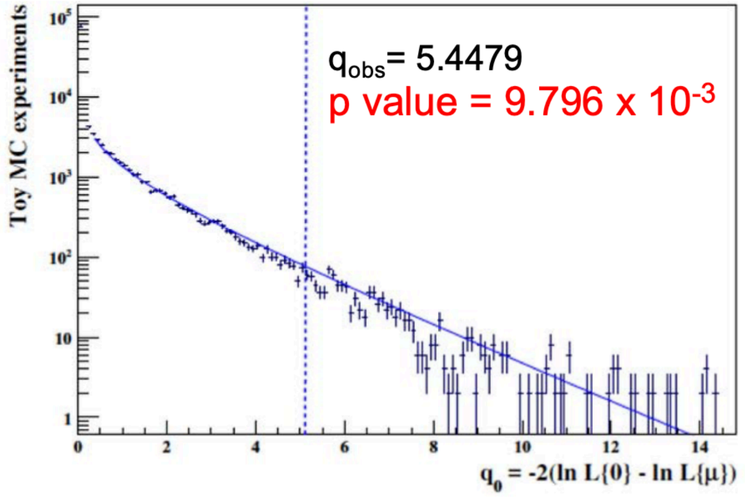


Prompt charge [photoelectrons]: 1 MeV ~500 photoelectrons

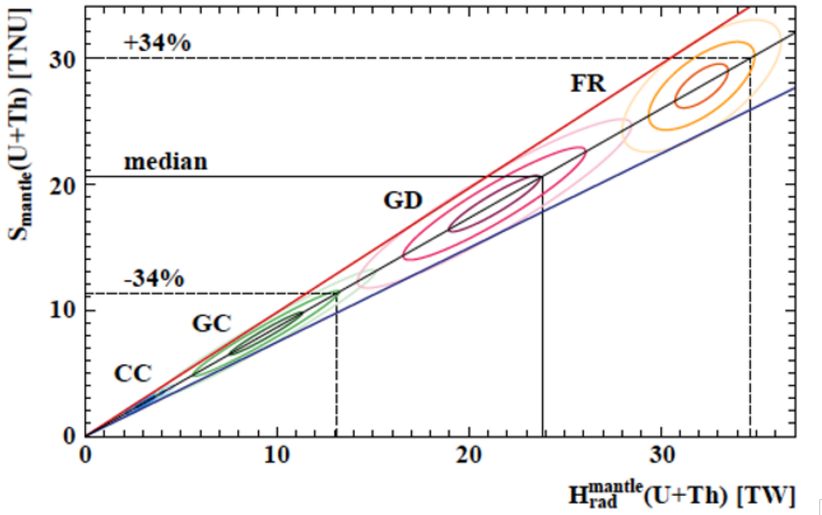


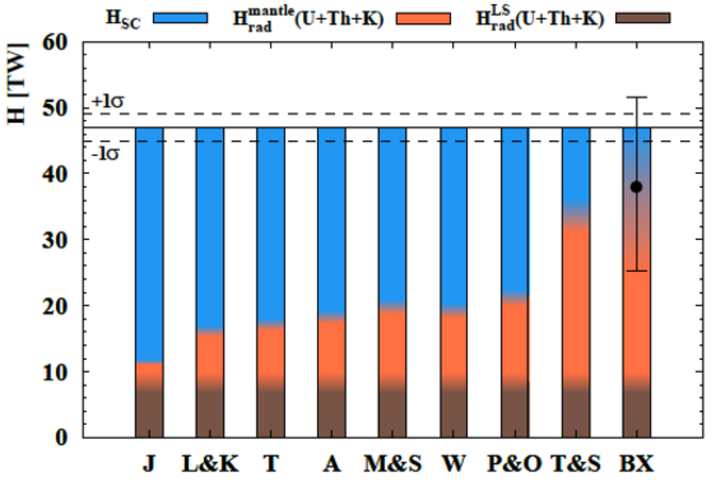
$21.2^{+9.6}_{-9.1} TNU$

Mantle events



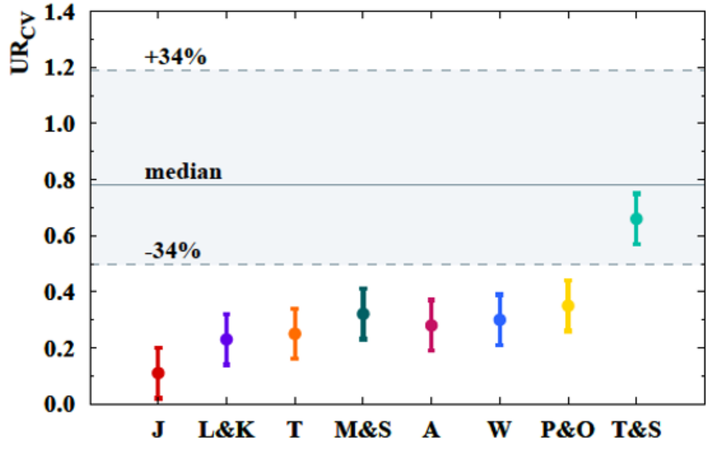
Borexino U+Th mantle signal





$$UR_{CV} = \frac{H_{rad} - H^{CC}_{rad}}{H_{tot} - H^{CC}_{rad}},$$

CC = continental crust



Mantle radiogenic heat from U+Th:

$$24.6^{+11.1}_{-10.4}\,TW$$

Compatible with predictions, but least (2.4σ) compatible with the CosmoChemical model (CC) predicting lowest U+Th mantle abundances

Earth radiogenic heat from U+Th+K:

$$38.2^{+13.6}_{-12.7}\,TW$$

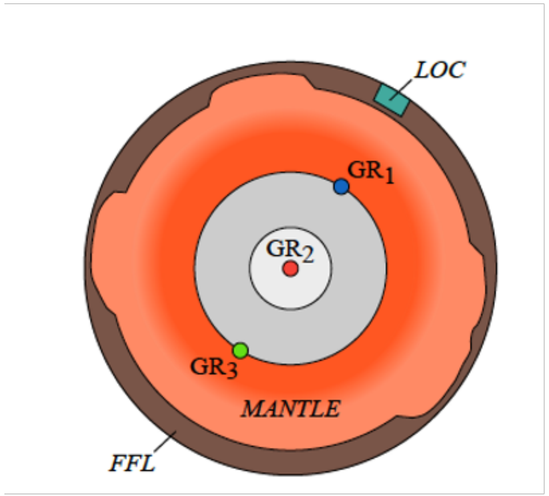
- Assuming 18% ^{40}K mantle contribution
- Lithospheric radiogenic heat U+Th+K $8.1^{+1.9}_{-1.4}$TW

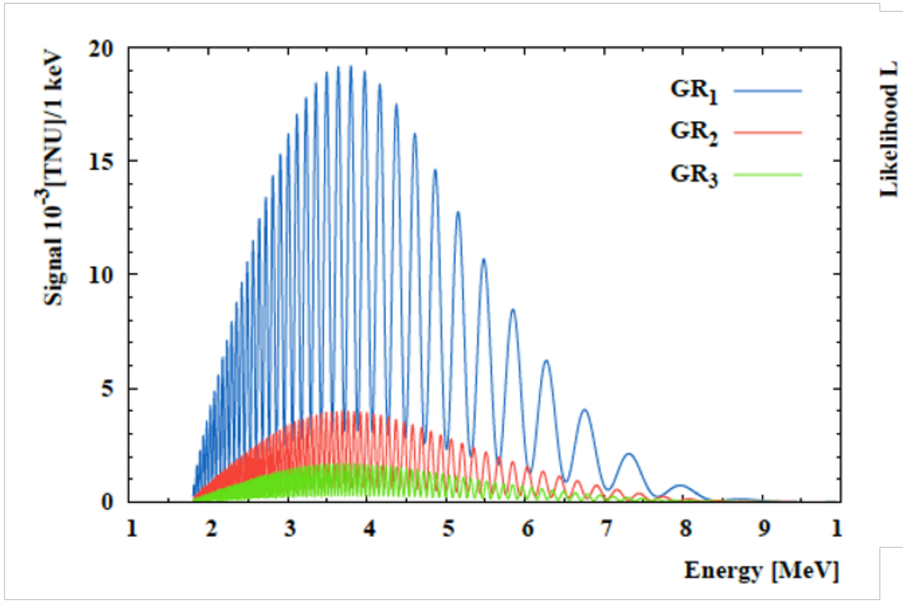
Convective Urey UR_{CV} ratio:

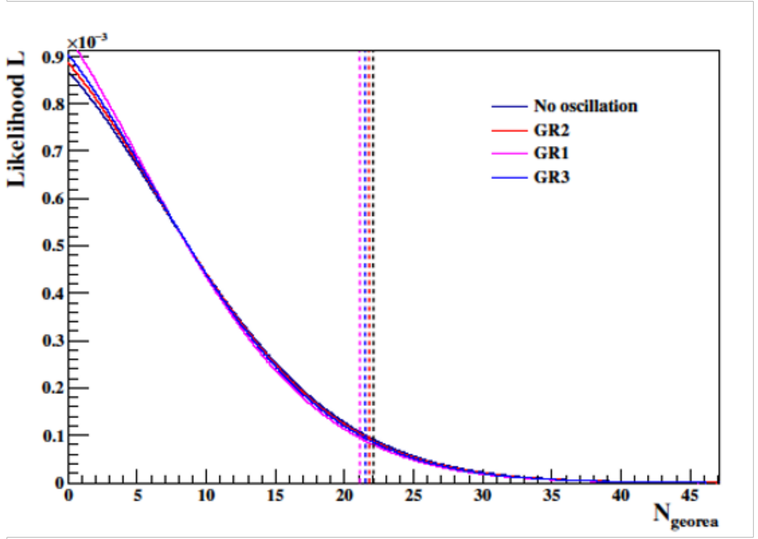
$$0.78^{+0.41}_{-0.28}$$

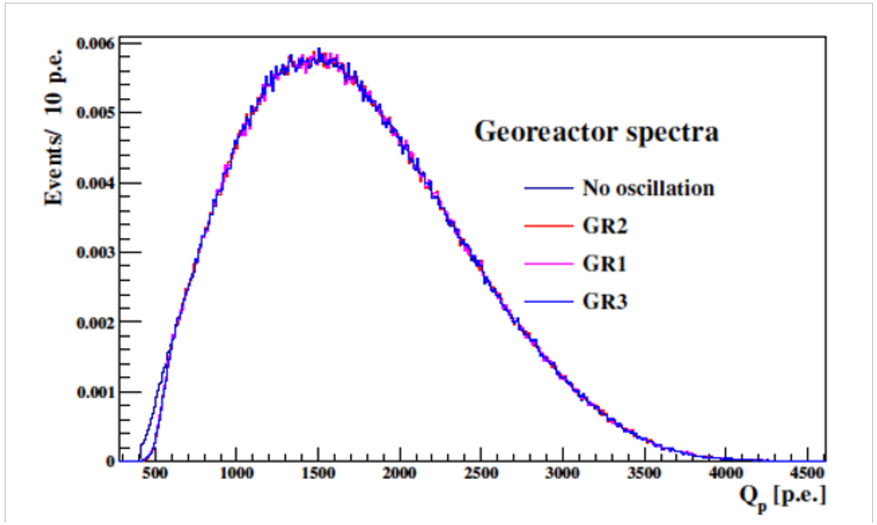
At 90% C.L., mantle characteristics:
a(Th) >48 ppb & a(U) >13ppb
UR_{CV} >0.13

Test of hypothetical geo-reactors









Upper limit (95% CL):

18.7 TNU

2.4 TW in the Earth's center
0.5 TW near CMB at 2900 km
5.7 TW far CMB at 9842 km

Conclusions

- $52.6^{+9.4}_{-8.6}$ (stat) $^{+2.7}_{-2.1}$ (sys) geo-neutrinos seen by Borexino in ~3300 days
- Total: $47.0^{+8.4}_{-7.7}$ (stat) $^{+2.4}_{-1.9}$ (sys) TNU
- Mantle: $21.2^{+9.5}_{-9.0}$ (stat) $^{+1.1}_{-0.9}$ (sys) TNU
- Null mantle signal excluded at 99.0% C.L

Summary fo BX results