The measurement of the geo-neutrino flux with the Borexino detector and its geophysical implications

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NEUTRINO 2020

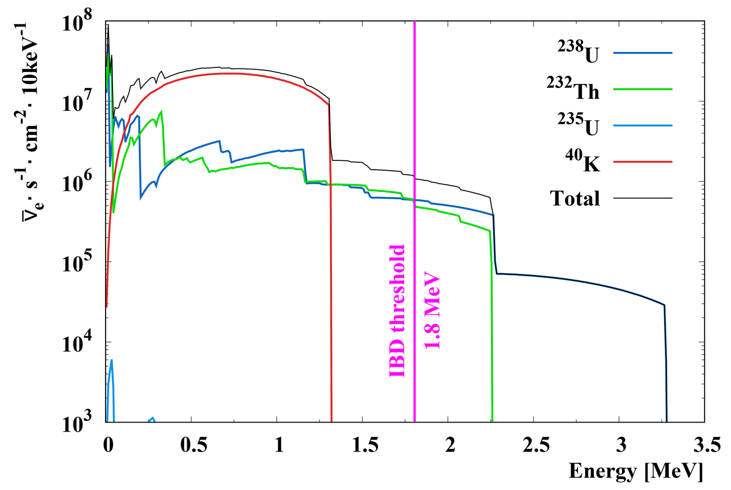
MINI-ABSTRACT

Borexino has measured geo-neutrinos with $\sim 18\%$ precision and confirmed the presence of the mantle signal at 99.0% C.L.

MOTIVATION: RESEARCH THE NATURE OF THE EARTH

- Radiogenic heat contribution to the Earth's heat budget
- Mantle homogeneity
- Our planet chemical composition
- Physical processes in the Earth's depth
- History of the Earth formation

The total Earth's surface heat flux: 47 ± 2 TW [1], the radiogenic heat H_{rad} = 10-35 TW



The main Heat Producing Elements (HPE's):

$$^{238}U \longrightarrow {}^{206}Pb + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.698\ \text{MeV}$$
$$^{232}Th \longrightarrow {}^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.562\ \text{MeV}$$
$$^{235}U \longrightarrow {}^{207}Pb + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.402\ \text{MeV}$$
$$^{40}K \longrightarrow {}^{40}Ca + e^- + \bar{\nu}_e + 1.311\ \text{MeV}\ (89.3\%)$$
$$^{40}K + e^- \longrightarrow {}^{40}Ar + \nu_e + 1.505\ \text{MeV}\ (10.7\%)$$

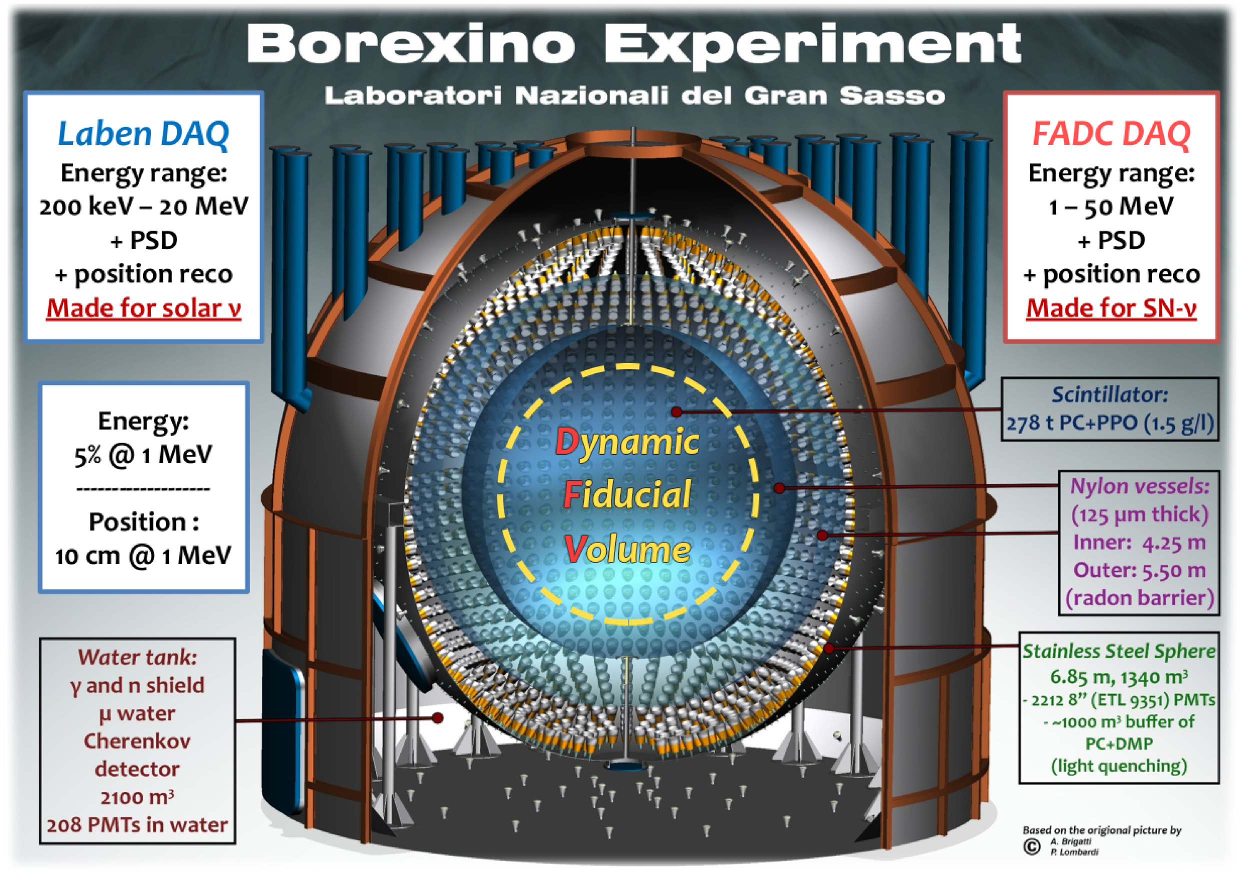
MODELS

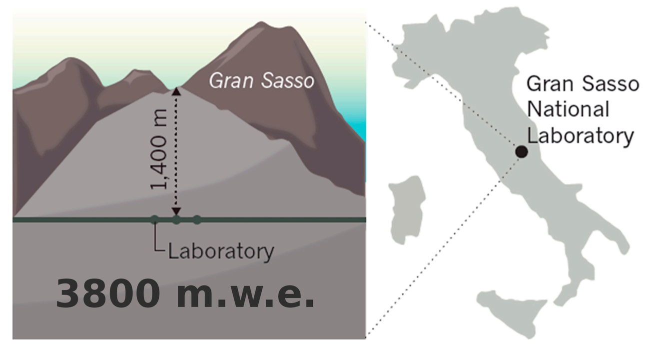
Max H_{rad} $\Longrightarrow$ Min H_{rad}

- Fully radiogenic (FR)
- Geodynamical (GD)
- Geochemical (GC)
- Cosmochemical (CC)

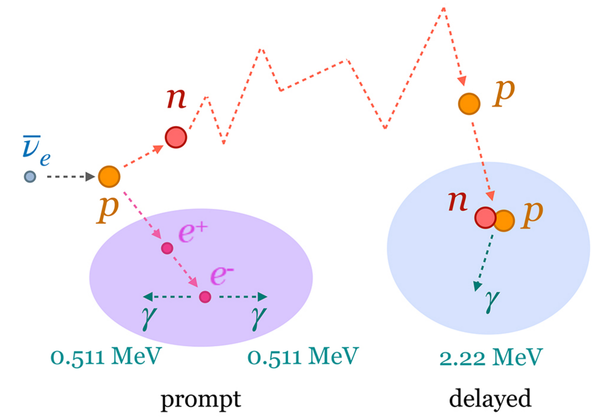
H_{rad}, TW: 47 ± 2 (FR), 33.5 ± 3.6 (GD), 20.2 ± 3.8 (GC), 11.3 ± 1.6 (CC)

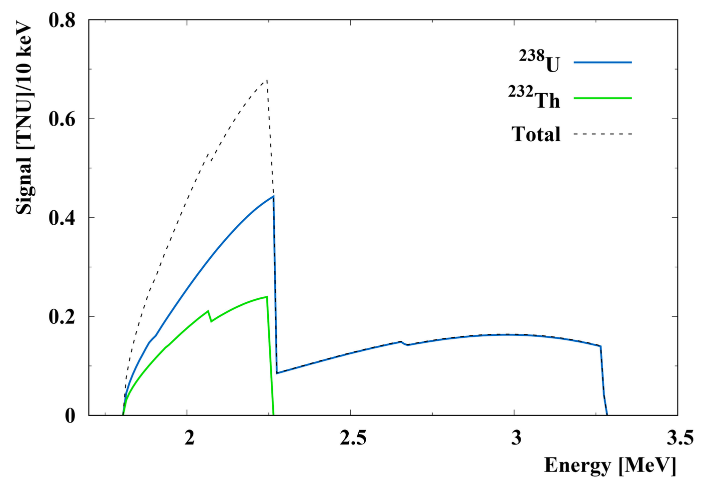
GEO-NEUTRINO DETECTION WITH BOREXINO





Inverse Beta Decay (IBD)



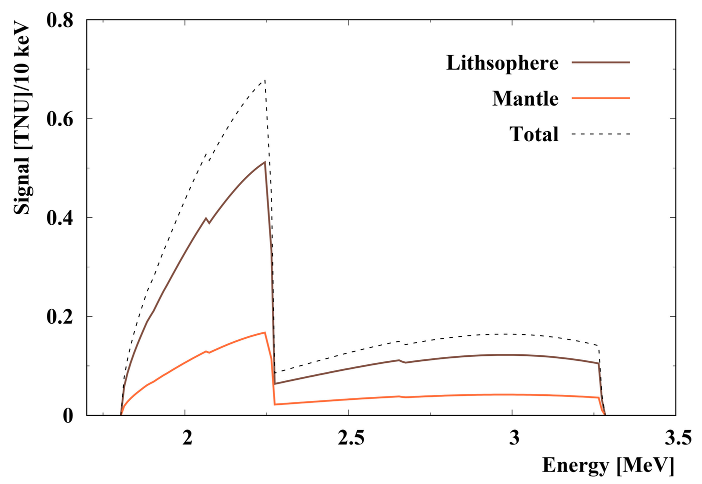


Geo-neutrino flux $\sim 10^6\ \text{cm}^{-2}\text{s}^{-1}$

$< P_{ee} > \approx 0.55$

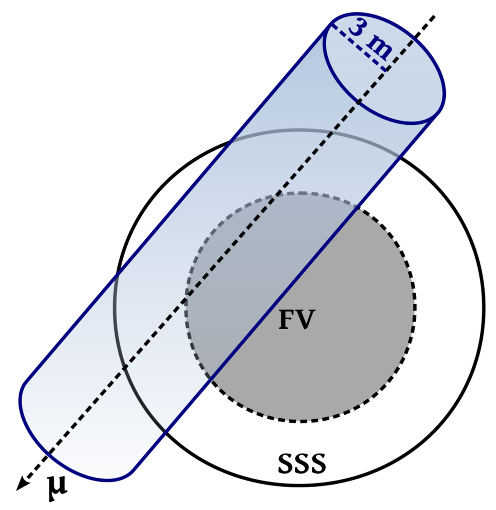
No reactors in Italy

Ultra-high purity construction materials



IMPROVED ANALYSIS – UPDATED SELECTION CUTS

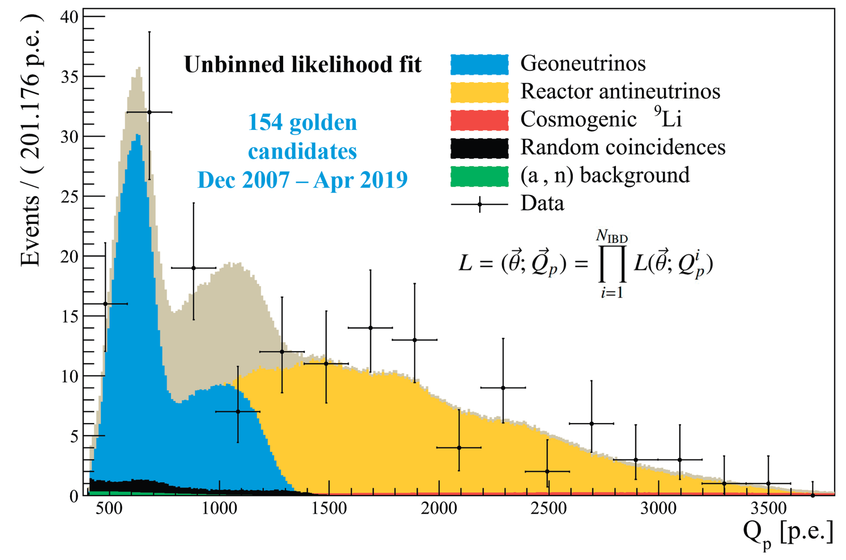
- Charge of the prompt event: e^+ kinetic energy and 2γ with E_γ = 511 keV, $E_{prompt} \geqslant$ 1022 keV: $\geqslant$ 408 p.e.
- Charge of the delayed event: n-capture on ^{1}H (2.22 MeV): 700–1300 p.e. **Enlarged!** on ^{12}C (4.95 MeV): 1300–3000 p.e. **New!**
- dt with the upper limit of 5τ, τ – n-capture time for single cluster events: 20–1280 μs for double cluster events: 2–12.5 μs **New!** 3.8% increase in efficiency
- dR between prompt and delayed: < 1.3 m **Enlarged!**
- Dynamic Fiducial Volume (DFV) cut: **Enlarged!** distance of the prompt event to the Inner Vessel > 10 cm Change: 30 cm $\longrightarrow$ 10 cm, 15.8% increase in exposure



- Cosmogenic vetoes: complex veto after internal muons: 2 s or 1.6 s or 2 ms **Improved!** applying 3 m cylindrical veto for one category of internal muons after external muons: 2 ms 10–11% exposure loss previously, only 2.2% exposure loss now
- Multiplicity cut: to reject neutrons the veto of 2 ms is applied before and after either the prompt event or the delayed one
- Pulse Shape Discrimination to reject α-like events: usage of neural network based on Multi-Layer Perceptron instead of the Gatti approach, MLP cut: > 0.8 **Better PSD!**

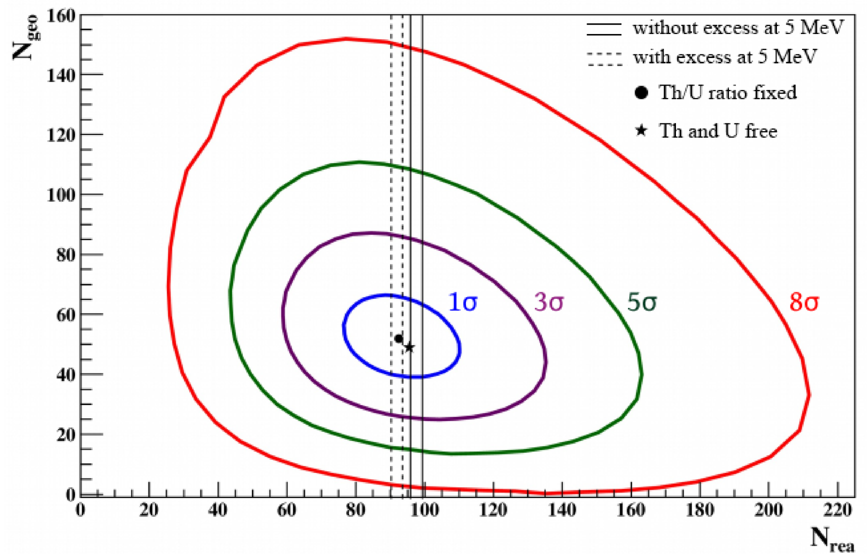
FINAL MEASUREMENT OF THE GEO-NEUTRINO FLUX

Background type	Signal, events
^{9}Li background	3.6 ± 1.0
Untagged muons	0.023 ± 0.007
Fast n's (μ in WT)	< 0.013
Fast n's (μ in rock)	< 1.43
Accidental coincidences	3.846 ± 0.017
(α,n) in scintillator	0.81 ± 0.13
(α,n) in buffer	< 2.6
(γ,n)	<0.34
Fission in PMTs	<0.057
^{214}Bi–^{214}Po	0.003 ± 0.001
Total	**8.28 ± 1.01**



$\mathcal{E}_p = (1.29 \pm 0.05) \times 10^{32}$ protons · year

Updated statistics and improved analysis techniques lead to $\sim 18\%$ precision in Borexino's geo-neutrino measurement



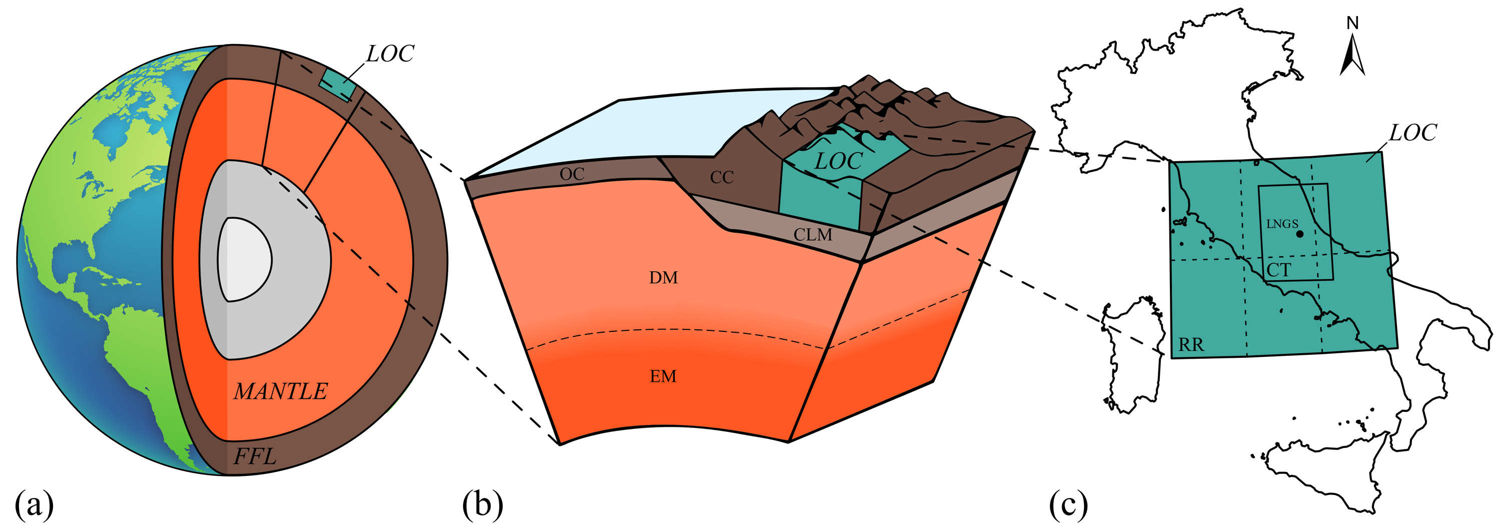
- $N_{rea} = 93.4^{+11.3}_{-10.8}(\text{stat})^{+4.8}_{-5.1}(\text{syst})$ ev.
  $S_{rea} = 80.5^{+9.8}_{-9.3}(\text{stat})^{+4.1}_{-4.4}(\text{syst})$ TNU

- $N_{geo} = 52.6^{+9.4}_{-8.6}(\text{stat})^{+2.7}_{-2.1}(\text{syst})$ ev.
  $S_{geo} = 47.0^{+8.4}_{-7.7}(\text{stat})^{+2.4}_{-1.9}(\text{syst})$ TNU
  1 TNU = 1 event / 10^{32} target protons / year
  with 100% detection efficiency, 10^{32} target protons $\simeq$ 1 kton LS
- Free parameters: geo- and reactor $\bar{\nu}$ signals (Th/U mass ratio is fixed to 3.9)
- Cosmogenic ^{9}Li, (α,n) and accidentals constrained using Gaussian pull terms
- Stable results with and without constraining reactor antineutrinos
- Consistent fit results when U and Th are fitted as free parameters
- The reactor signal is consistent with expectations

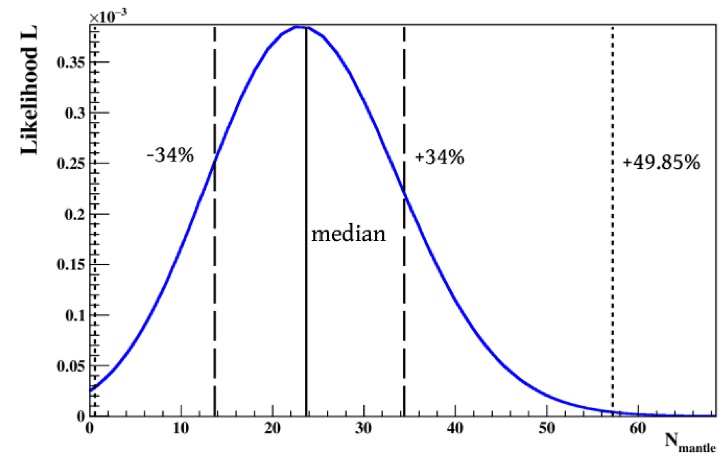
> 8σ evidence of geo-neutrinos

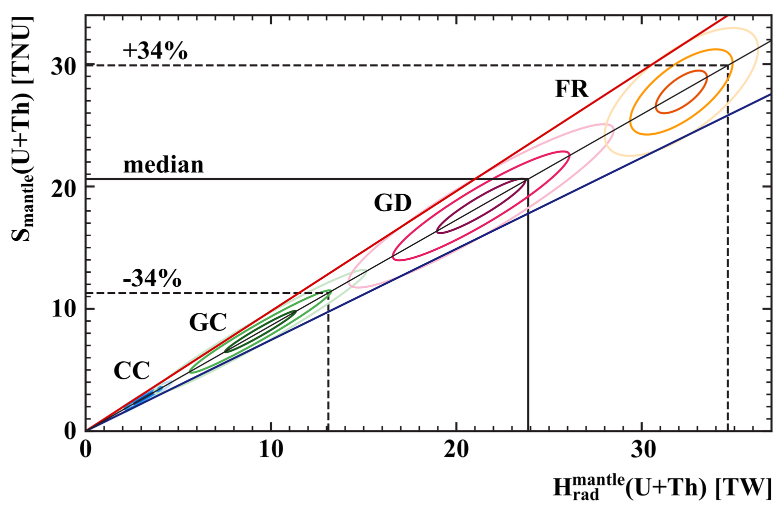
GEOPHYSICAL IMPLICATIONS — MANTLE AND RADIOGENIC HEAT

FFL – Far Field Lithosphere, LOC – Local Crust



- Relatively well-known lithosphere signal is constrained to 28.8 ± 5.6 events using knowledge of the local crust
- Th/U mass ratio (lithosphere) = 3.5
- Th/U mass ratio (mantle) = 3.7
- $N_{mantle} = 23.7^{+10.7}_{-10.0}(\text{stat})^{+1.2}_{-1.0}(\text{syst})$ ev.
- $S_{mantle} = 21.2^{+9.5}_{-9.0}(\text{stat})^{+1.1}_{-0.9}(\text{syst})$ TNU





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

Lithospheric constribution + measured mantle heat + expected 18% from ^{40}K in mantle

2.4σ tension with the Earth's models that predict the lowest amount of heat-producing elements inside mantle

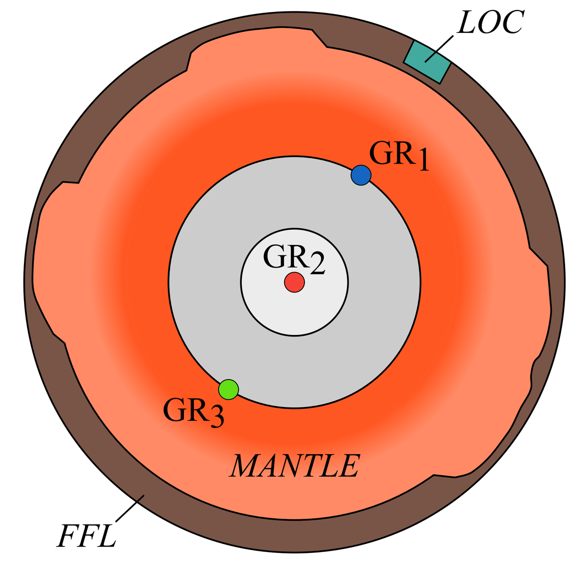
Convective Urey Ratio:

$$UR_{CV} = \frac{H_{rad} - H_{rad}^{CC}}{H_{tot} - H_{rad}^{CC}} = 0.78^{+0.41}_{-0.28}$$

GEOPHYSICAL IMPLICATIONS — GEOREACTOR

Upper limits on the hypothetical georeactor power (95% C.L.):

- Georeactor fuel: ^{235}U : ^{238}U $\approx$ 0.76 : 0.23
- Spectra similar to reactor antineutrinos which are constrained to the expected 97.6 ± 1.7(stat) ± 5.2(syst) events

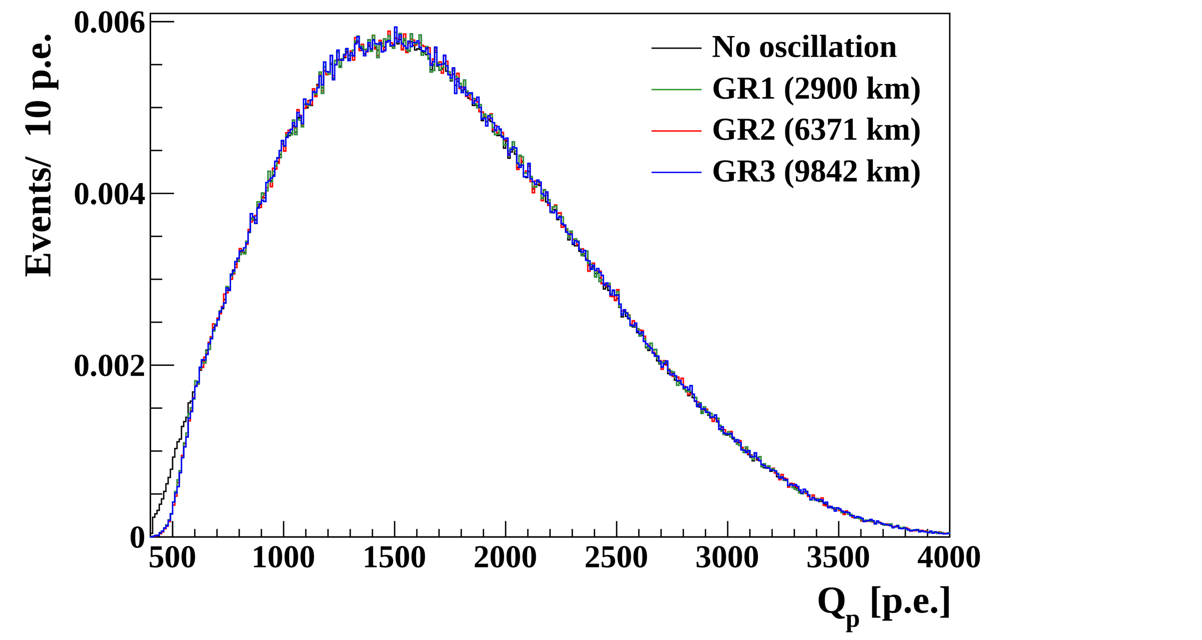


- Three characteristic locations:

GR1 Core-mantle boundary (d = 2900 km), Georeactor power P_{GR1} < 0.5 TW

GR2 In the Earth's center ($d = R_{Earth}$ = 6371 km), P_{GR2} < 2.4 TW

GR3 Core-mantle boundary (d = 9842 km), P_{GR3} < 5.7 TW



MC-based PDFs of prompts for a georeactor
No energy resolution to differentiate between the positions!

The article is available at https://doi.org/10.1103/PhysRevD.101.012009

[1] J. H. Davies and D. R. Davies, Solid Earth 1, 5 (2010).

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