Geoneutrinos spectroscopy with Borexino experiment

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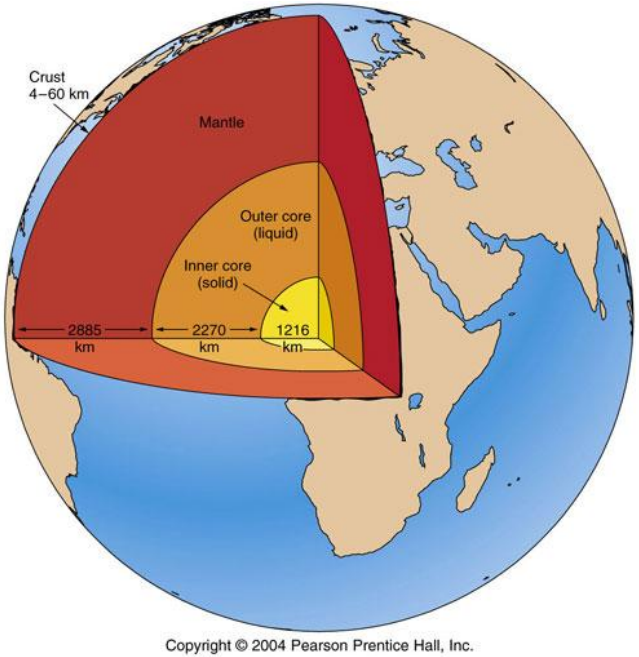
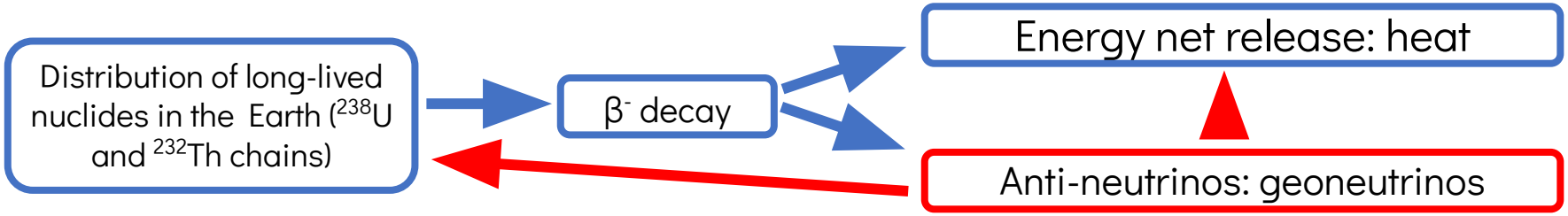
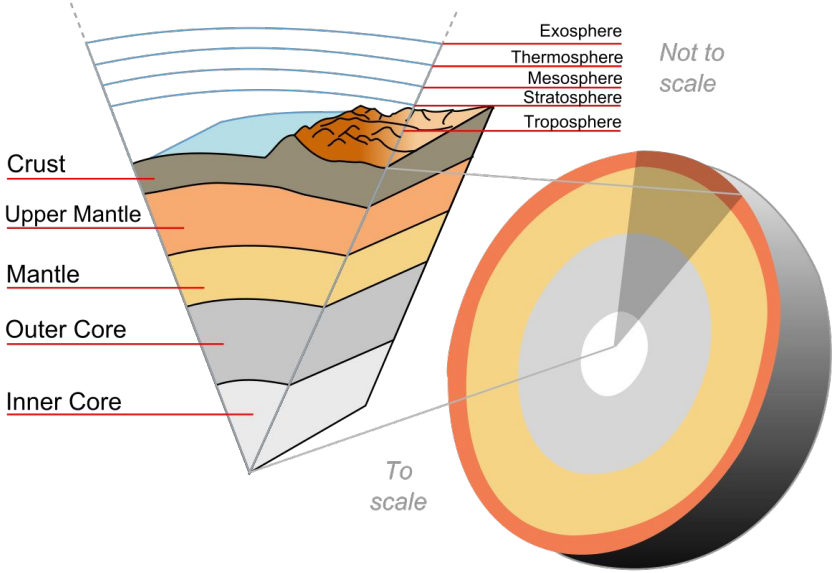
Outline

1. Geoneutrinos
2. Borexino
3. Analysis and results



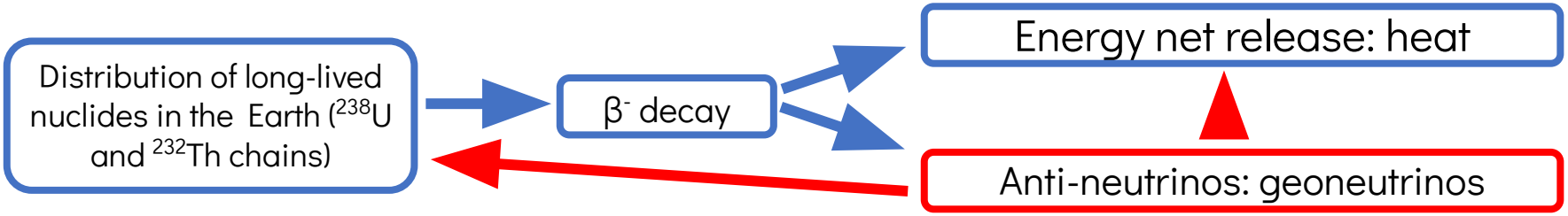
What are geoneutrinos?





- Direct messengers of the abundances of radioactive elements
- Measuring their flux and spectrum → understand the radiogenic contribution to the total heat balance of the Earth.
- Discriminate Earth models (cosmochemical, geochemical, geodynamical etc…)

What are geoneutrinos?



$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}$$
$$^{235}\mathrm{U} \rightarrow {}^{207}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.4\ \mathrm{MeV}$$
$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}$$
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.31\ \mathrm{MeV}\ (89.3\%)$$

Geoneutrino flux ~ 10^6 cm^{-2} s^{-1}
(Solar nu flux ~ 10^{10} cm^{-2} s^{-1})

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How to detect geoneutrinos?

Low interaction rates: $\sigma \sim 10^{-42}$ cm^2 @ MeV

Expected ~150 geoneutrino events for ~2000 ton × y exposure

What do we need? → experiments with **extremely low background**

- Large volume detectors
- Construction materials → high radiopurity

Borexino experiment in Gran Sasso, Italy

- **Extreme radiopurity** for solar neutrinos spectroscopy (main goal)
  → But also able to measure anti-neutrinos (IBD reaction)!
- **Underground lab** → shielding cosmic rays radiation
- **No nuclear power plant in Italy** → smaller background wrt KamLAND

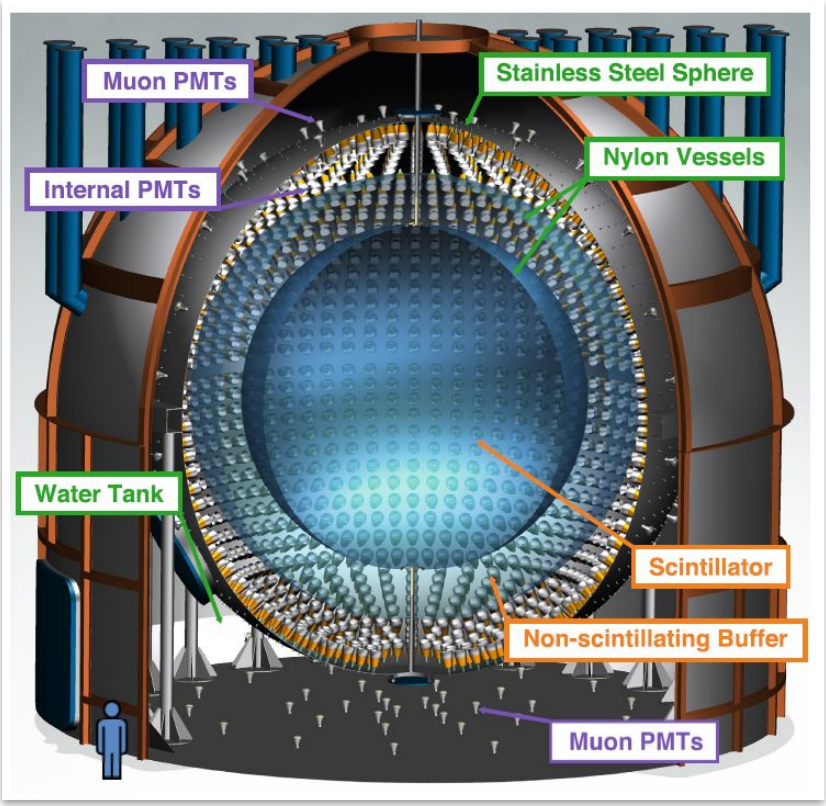
Gran Sasso National Laboratory (Italy)

Abruzzo

Hall C
(Borexino)

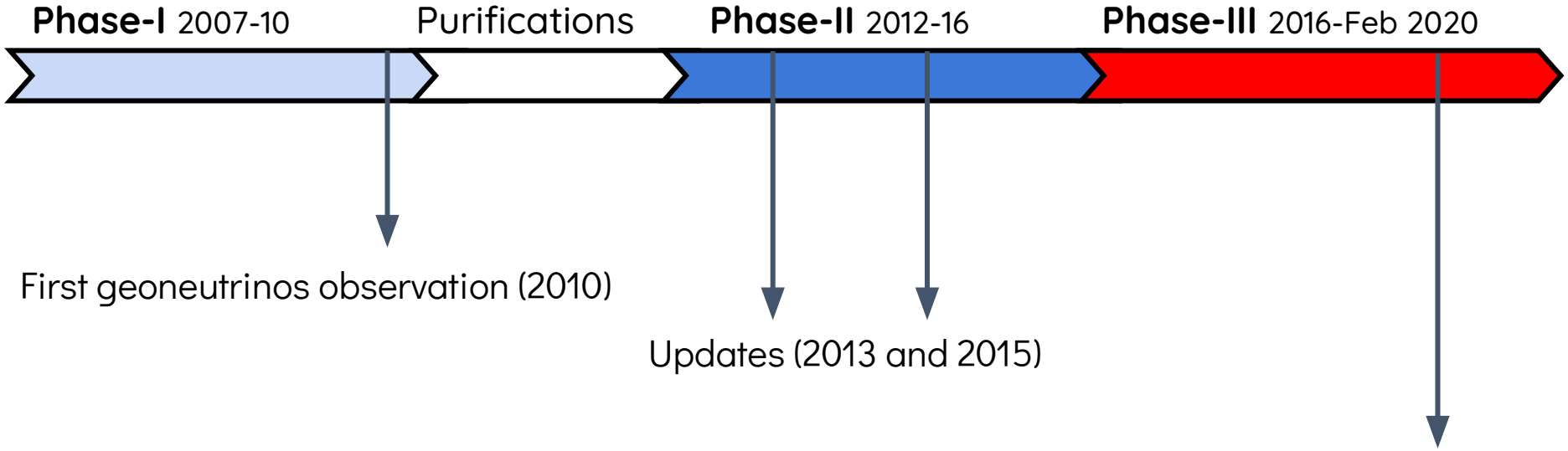
LNGS

Borexino detector



- DAQ started in 2007
- Main analysis: solar neutrinos spectroscopy (see X. Ding talk about CNO detection)
- 300 ton of ultra-pure liquid scintillator
- Graded shielding: buffer liquid and Gran Sasso → low radioactivity: 10^{-20} g/g ^{238}U, 10^{-19} g/g ^{232}Th
- 2000 PMTs to measure:
  - positions → photons time arrival
  - energy → number of photons detected

Borexino detector

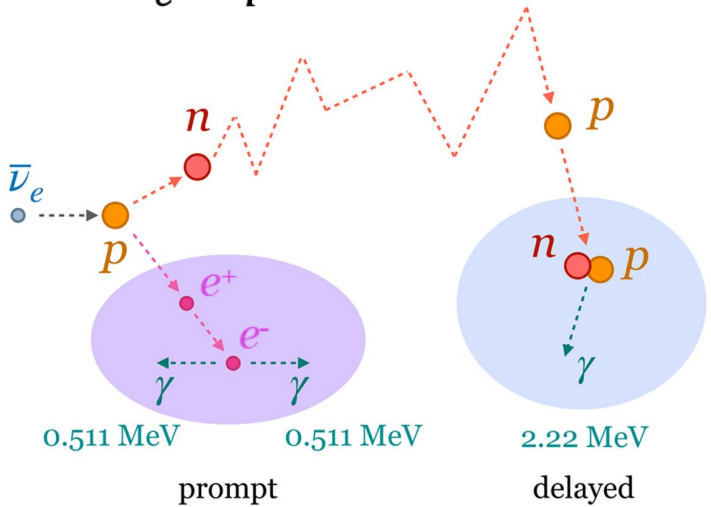


Comprehensive geoneutrino analysis with Borexino
Phys. Rev. D 101, 012009 (2020)
Extended data-taking: 3262 days (Dec 2007 - Apr 2019)
Improved analysis techniques

Anti-neutrinos detection

Inverse Beta Decay reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Prompt signal (e+):

- e^+ scintillation + annihilation (2γ)
- $E_{prompt} \approx E_{geoneutrino}$ - 0.782 MeV

Delayed signal (neutron capture on H):

- $E_{delayed} \approx 2.2$ MeV $\langle \Delta t \rangle \sim 254$ μs

Energy threshold: 1.8 MeV

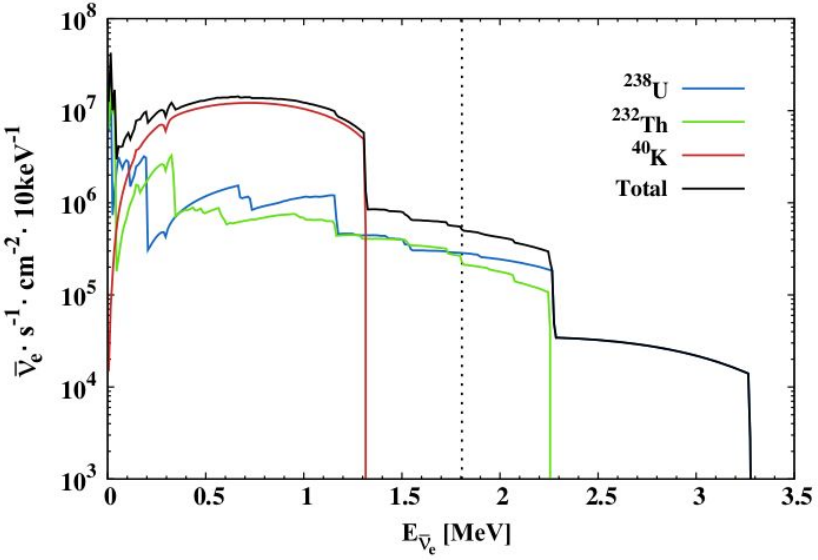
$\sigma \sim 10^{-42}$ cm^2 @MeV

(~100x more than scattering)

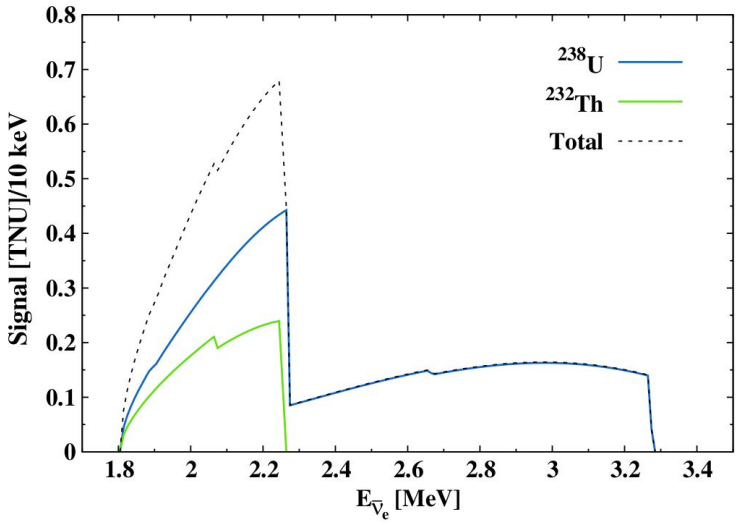
Coincidence in time / space / energy between prompt and delayed guarantees a **very high signal/background ratio**

Geoneutrinos energy spectrum

Geoneutrino energy spectra



Geoneutrino signal at LNGS



Local and global geological information
+ flavor oscillation (<Pee> ~ 0.55) + detection threshold

Reactor backgrounds

- Overlap between geoneutrino and reactor antineutrino signals (up to 10 MeV).
- 98% European ones
- Estimation of the exp. events from the spectral components of ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu

Power(r,m)

Component fraction

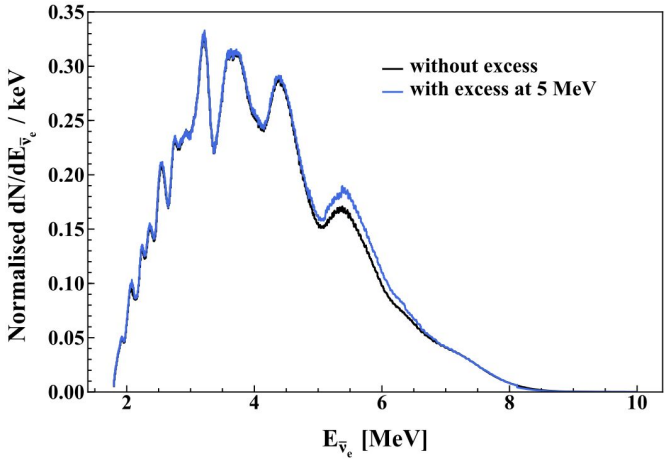
$$N_{react} = \sum_{r=1}^{R} \sum_{m=1}^{M} \frac{\eta_m}{4\pi L_r^2} P_{rm} \times \int dE_{\bar{\nu}_e} \sum_{i=1}^{4} \frac{f_i}{E_i} \phi_i(E_{\bar{\nu}_e}) \sigma(E_{\bar{\nu}_e}) P_{ee}(E_{\bar{\nu}_e}; \hat{\theta}, L_r)$$

Sum over reactors

distance

Sum over months

Expected reactor spectrum →



Non antineutrino backgrounds

1) **Cosmogenic-muon related:**
- ^{9}Li and ^{8}He: β^{-} + n pair;
- Fast neutrons (scattered protons as prompt signal)

2) **Accidental coincidences**

3) **Internal radioactivity:**
(α,n) and (γ,n) reactions
Scattered protons as prompt, ^{12}C(4.4 MeV) and ^{16}O (6.1 MeV)

Background type	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

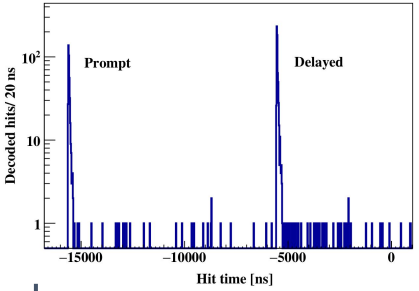
Selection cuts

Prompt and delayed charge

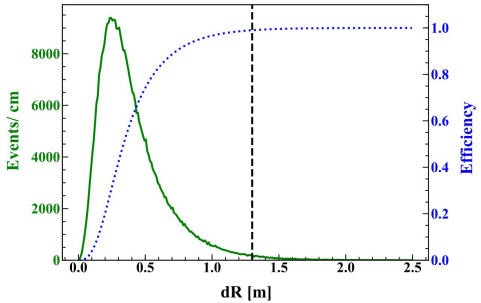
Q_prompt > 408 pe
700 pe < Q_delayed < 3000 pe
Neutron captures on proton (2.2 MeV) and in about 1% of cases on ^{12}C (4.95 MeV)

Time and space corr.

dt = (2.5 -12.5)μs + (20-1280) μs

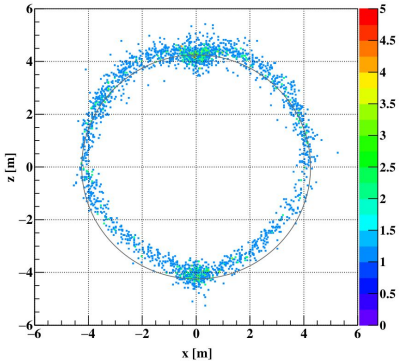


prompt-delayed dist. < 1.3 m



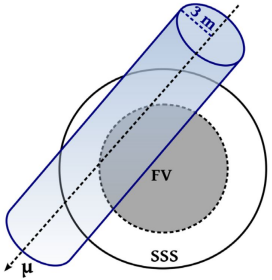
Dynamic Fiducial Volume

> 10 cm from IV (prompt)



Muon veto

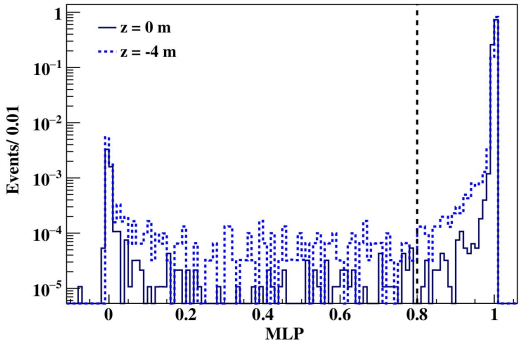
2s || 1.6 s : ^{9}Li(β + n)
2 ms: neutrons



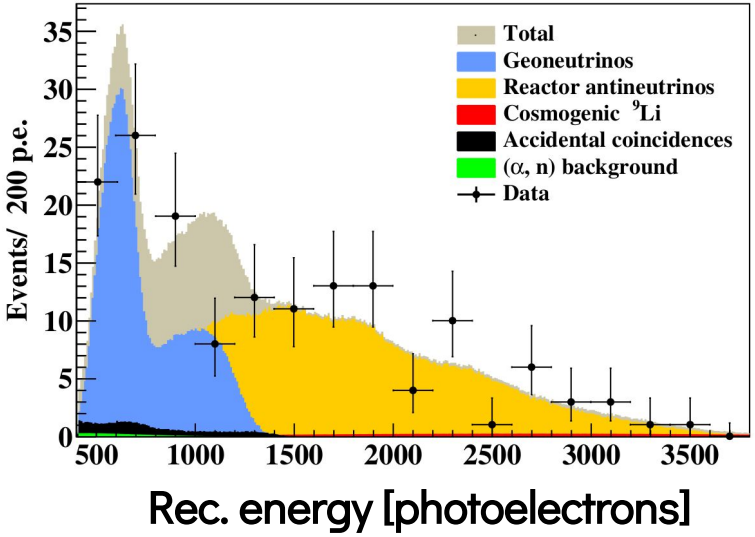
Multiplicity

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

α/β discrimination



Spectral fit, Th/U ratio constrained



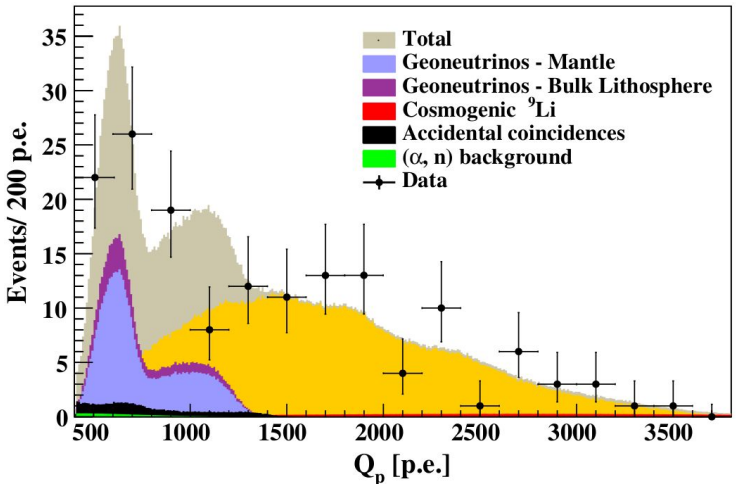
154 golden candidates Dec 2007 – Apr 2019
Unbinned likelihood fit

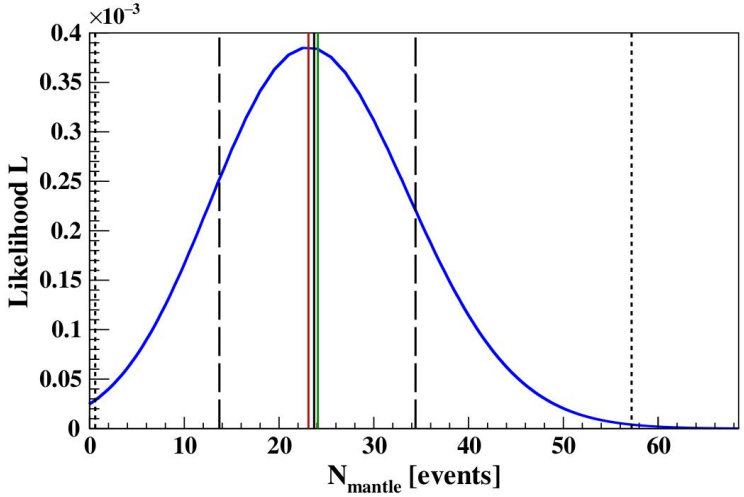
- S(Th)/S(U) = 0.27 → chondritic Th/U mass ratio of 3.9)

→ energy scale: 500 p.e. ~ 1 MeV

- **Resulting number of geoneutrinos $52.6_{-8.6}^{+9.4}(\text{stat})_{-2.1}^{+2.7}(\text{sys})$, precision −17.2+18.3%**
- Precision improved of a **factor 2** wrt Borexino 2015 analysis
- In agreement with the fit with Th/U fixed

Spectral fit, mantle signal





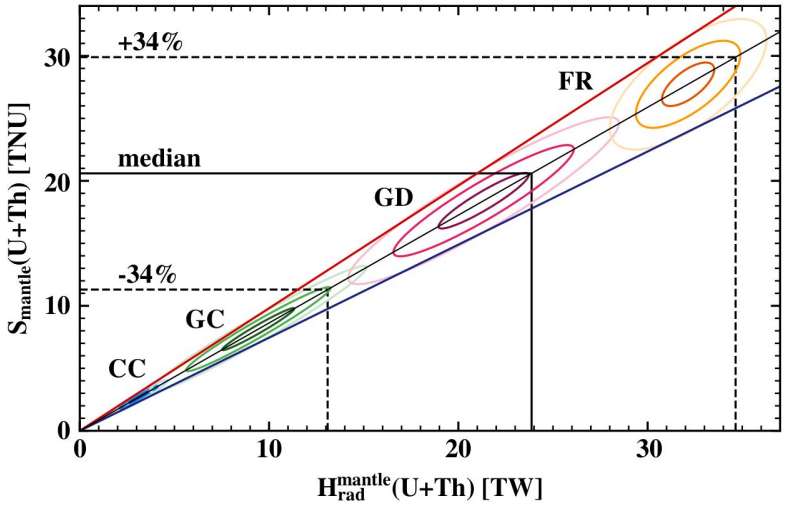
Local knowledge of litosphere → its contribution constrained in the spectral fit, (28.8 ± 5.6) events

No mantle signal hypothesis rejected at 99.0% C.L. , $S_{mantle} = 21.2^{+9.7}_{-9.0}$ TNU

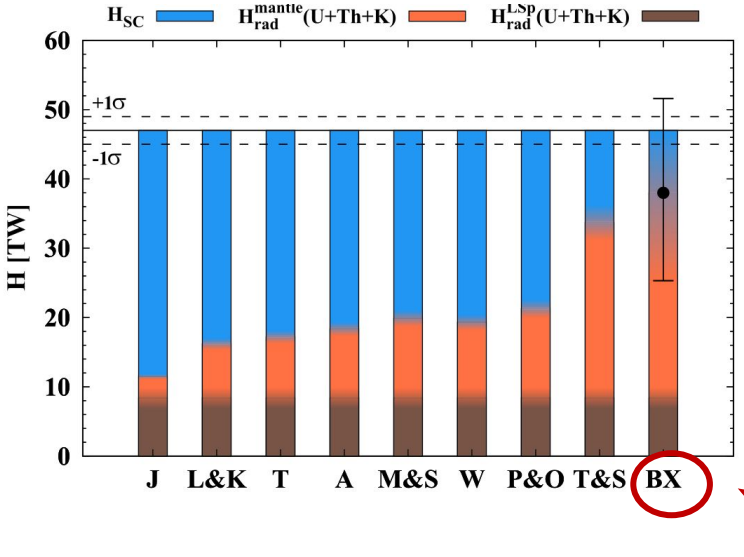
TNU (terrestrial neutrino unit): 1 antineutrino event detected via IBD over 1 y by a detector with 100% detection efficiency containing 10^{32} free target protons

Radiogenic heat

Mantle signal vs radiogenic heat



Heat budget



Mantle radiogenic heat: $24.6_{-10.4}^{+11.1}$ TW

Some Earth models (**CosmoChemical**) predict very low amount of Th and U inside mantle

→ **2.4σ tension**

Earth radiogenic heat (U+Th+K): $38.2_{-12.7}^{+13.6}$ TW

Assuming 18% ^{40}K contribution

Conclusions

Real-time spectroscopy of geoneutrinos by Borexino, 2007-2019 data

- Analysis techniques and data selection improved

Main results:

1. Precision improved of a factor 2 wrt Borexino 2015 analysis
2. Null mantle signal excluded at 99.0% C.L.
3. Agreement with geological prediction, tension against models predicting low U and Th abundances
4. Estimates of mantle radiogenic heat

Geoneutrinos are confirmed as a unique interdisciplinary tool to study the Earth interior layers.

Backup

Chondrited

- Chondrites are primitive, undifferentiated meteorites, a collection of the earliest formed material in the solar system.
- Studies of meteorites add much to our understanding of the age of the solar system and the nature of the building blocks that makes up the planets.
- Mixture of silicate and metal materials in proportions similar to that found in the terrestrial planet