# ANALYSIS STRATEGIES FOR THE UPDATED GEONEUTRINO MEASUREMENT WITH BOREXINO

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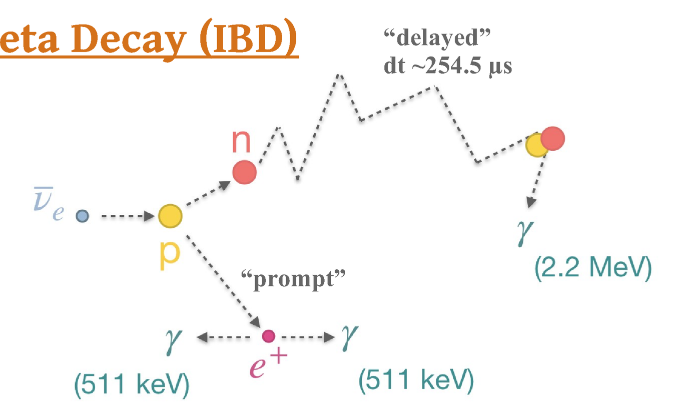
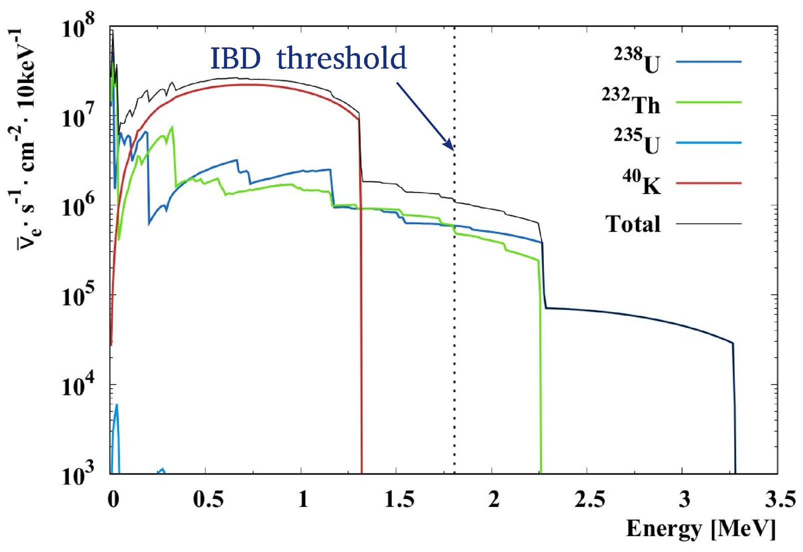
# Updated statistics and improved analysis techniques lead to ~18% precision in Borexino's geoneutrino measurement

## INTRODUCTION

**Inverse Beta Decay (IBD)**




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

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

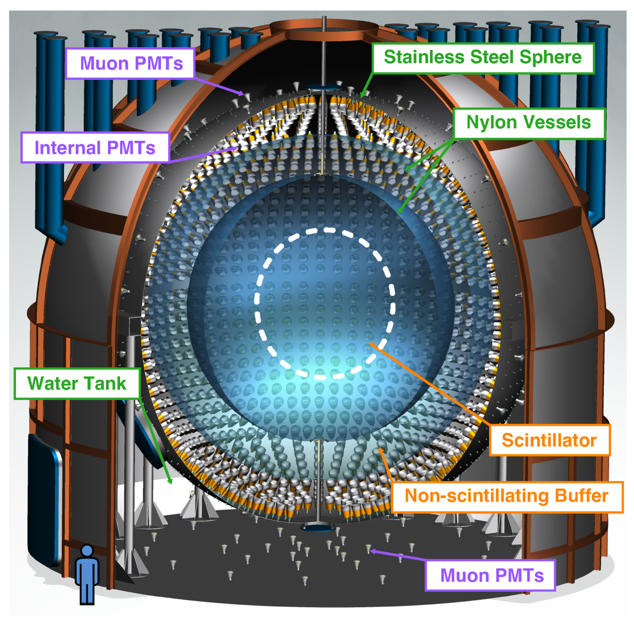
$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.7\ MeV$

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

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

**Borexino detector**

3800 m water equivalent depth



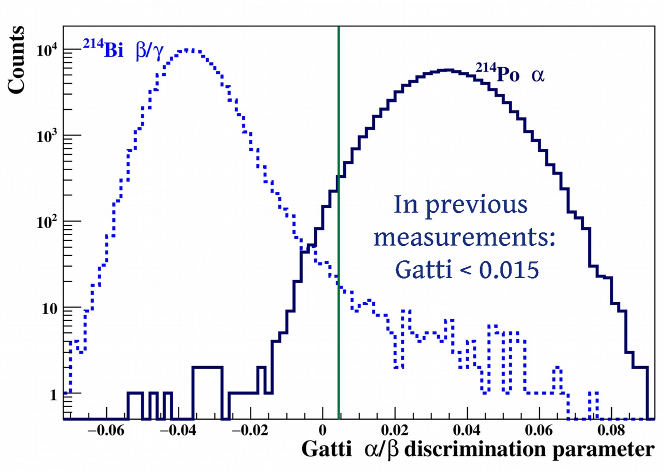

## ANALYSIS TECHNIQUES

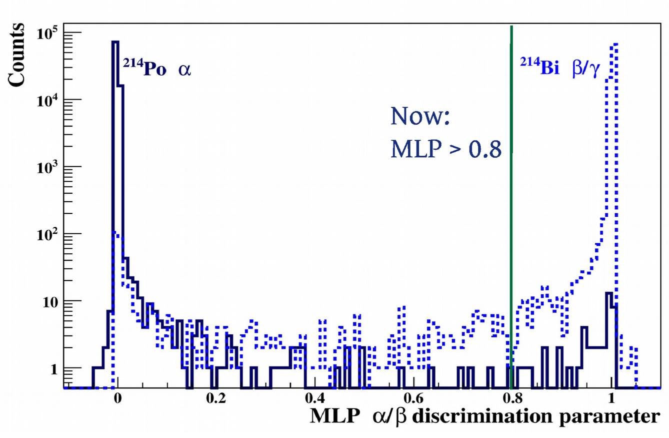
### Selection cuts

- **Charge of prompt**
  408 p.e. (2 x 511 keV γs)
- **Charge of delayed** *Enlarged!*
  n-capture on $^1H$ → 700 – 1300 p.e.
  n-capture on $^{12}C$ → 1300 – 3000 p.e. *New!*
- **dt:** 5 times n-capture time
  2 – 12.5 μs (double cluster events) *New!*
  20 – 1280 μs (single cluster events)
- **dR:** < 1.3 m between prompt and delayed *Enlarged!*

- **Cosmogenic vetoes** *Improved!*
  2 s, 1.6 s and 2 ms after internal muons
  2 ms after external muons
  3 m cylindrical veto for one category of internal muons *Enlarged!*
- **Dynamic Fiducial Volume (DFV) cut**
  distance of prompt to inner vessel > 10 cm
- **Pulse shape discrimination** *Better!*
  Multi-Layer Perceptron (MLP) > 0.8
  deep learning technique to reject α-like delayed
- **Multiplicity cut**
  to reject neutrons 2 ms before or after prompt or 2 ms after delayed

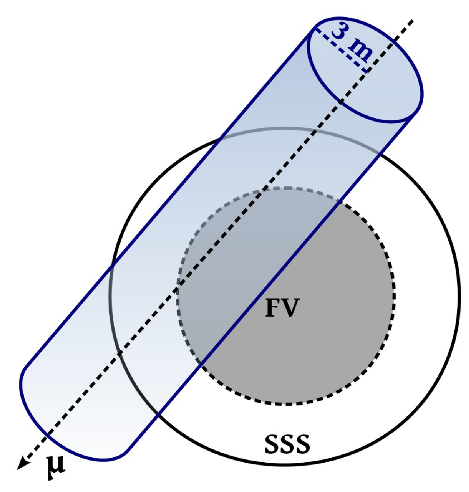
**Better pulse shape discrimination**



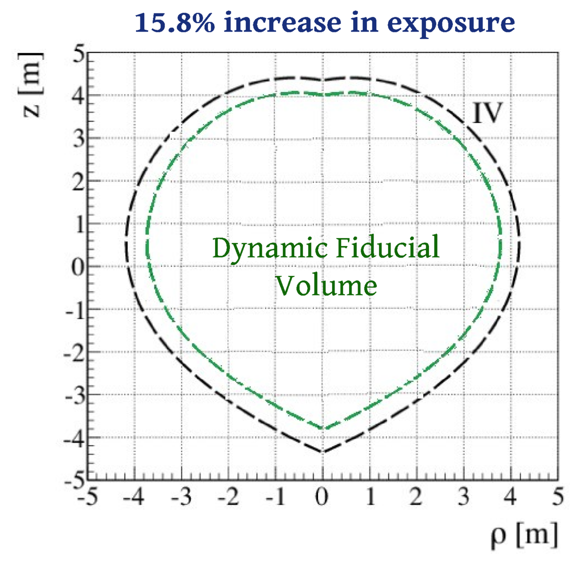

**Improved cosmogenic vetoes**

In previous measurements → 10-11% exposure loss
Now→ 2.2% exposure loss



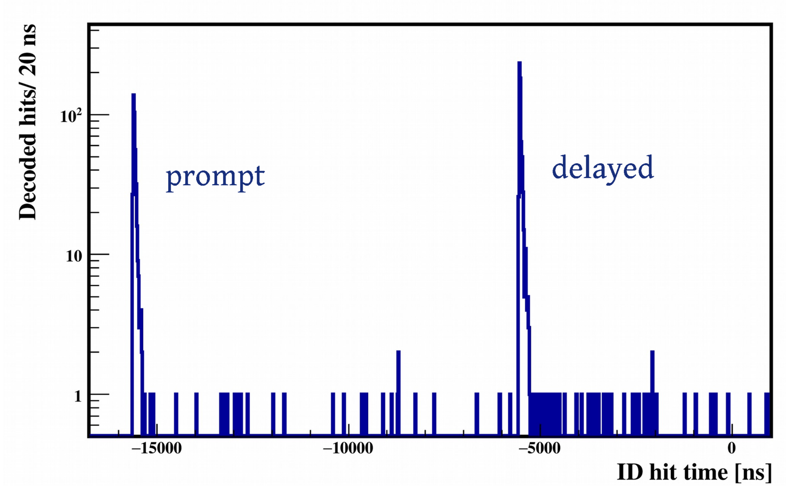

**Dynamic Fiducial Volume (DFV) cut**

30 cm → 10 cm
15.8% increase in exposure

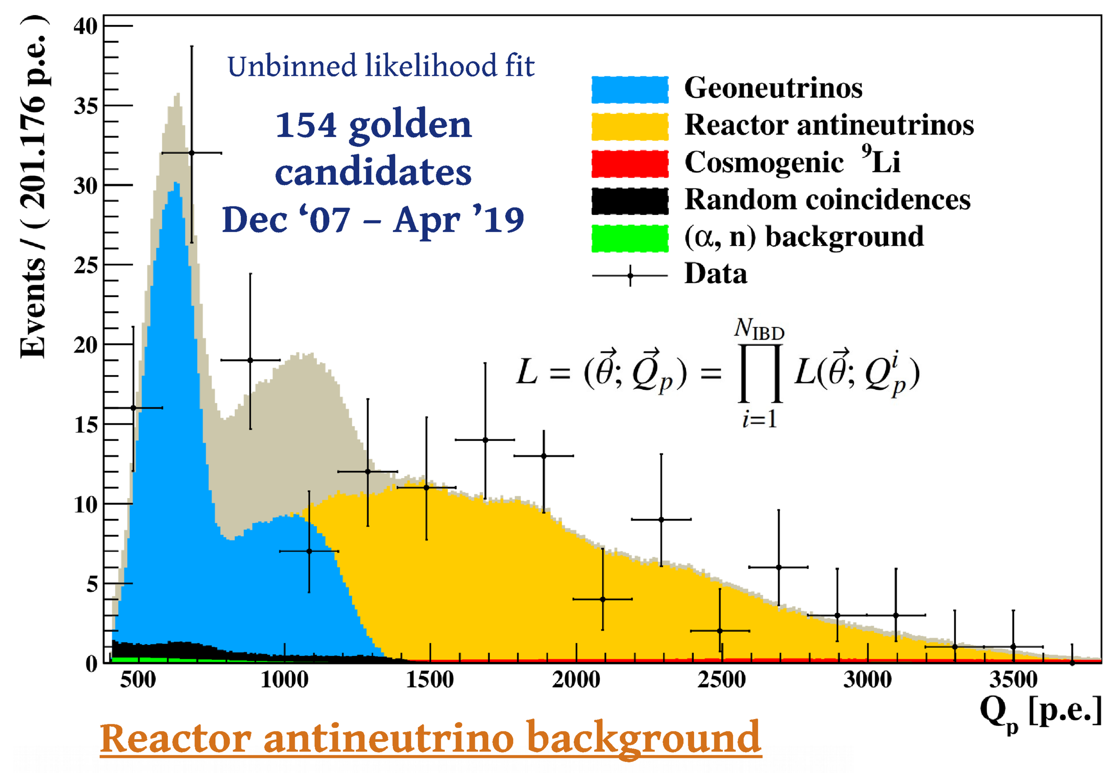



**Inclusion of double cluster events**

3.8% increase in efficiency




## RESULTS



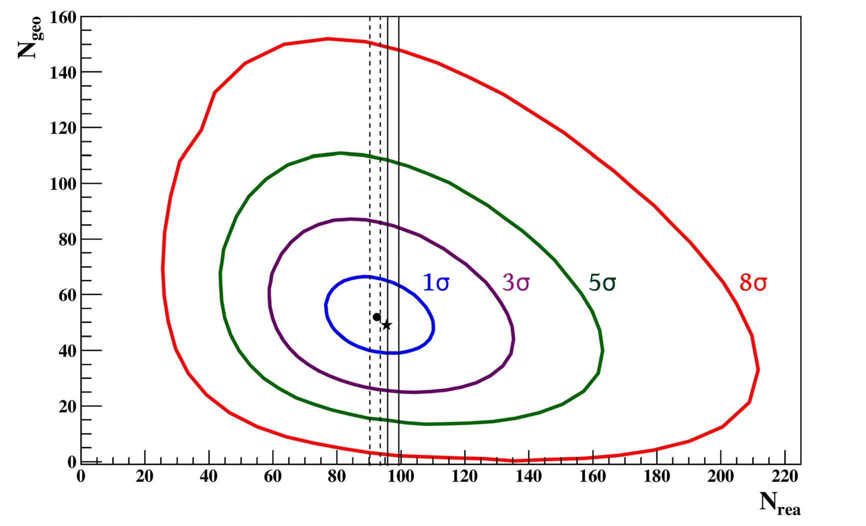

$$L = (\vec{\theta}; \vec{Q}_p) = \prod_{i=1}^{N_{IBD}} L(\vec{\theta}; Q_p^i)$$

**> 8σ evidence of geoneutrinos**

- $N_{geo} = 52.6^{+9.4}_{-8.6}$ events
  $S_{geo} = 47.0^{+8.4}_{-7.7}$ TNU
- Free parameters – Geoneutrinos (Th/U mass ratio = 3.9) and reactor antineutrinos.
- Stable results with and without constraining reactor antineutrinos
- Consistent fit results when U and Th are fit as free parameters

1 TNU = 1 event/ $10^{32}$ target protons (~1kton LS)/ year with 100% detection efficiency

**Reactor antineutrino background**




⋯ Reactor antineutrino expectation with excess at 5 MeV
— Reactor antineutrino expectation without excess at 5 MeV
• Measured reactor antineutrinos – Th/U ratio fixed
⋆ Measured reactor antineutrinos – Th & U as free parameters

**Other backgrounds**

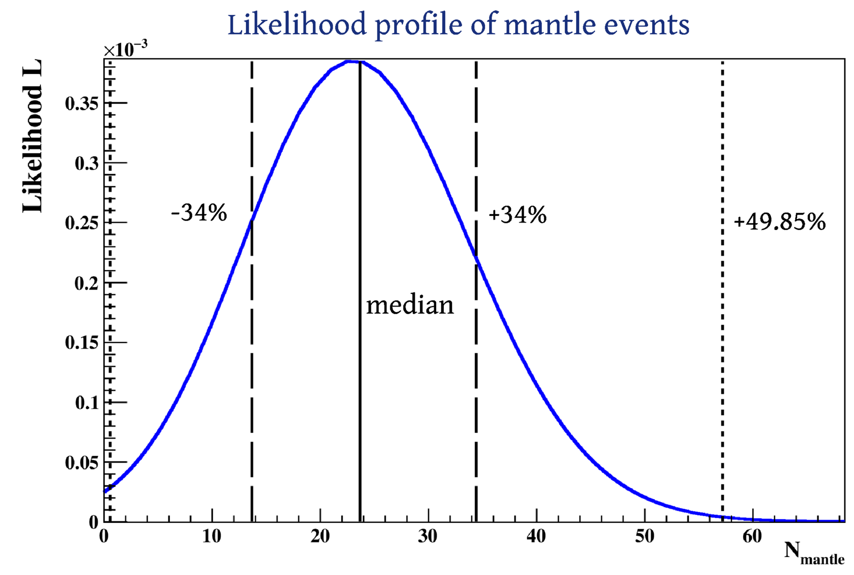
| Background type | No. of events |
|---|---|
| $^9$Li background | 3.6 ± 1.0 |
| Untagged muons | 0.023 ± 0.007 |
| Fast n's (from rock) | <0.013 |
| Fast n's (from WT) | <1.43 |
| Accidental coincidences | 3.846 ± 0.01 |
| (α, n) in scintillator | 0.81 ± 0.13 |
| (α, n) in buffer | <2.6 |
| (γ, n) | <0.34 |
| Fission in PMTs | <0.057 |
| $^{214}$Bi-$^{214}$Po | 0.003 ± 0.001 |
| TOTAL | 8.28 ± 1.01 |

## GEOLOGICAL INTERPRETATIONS

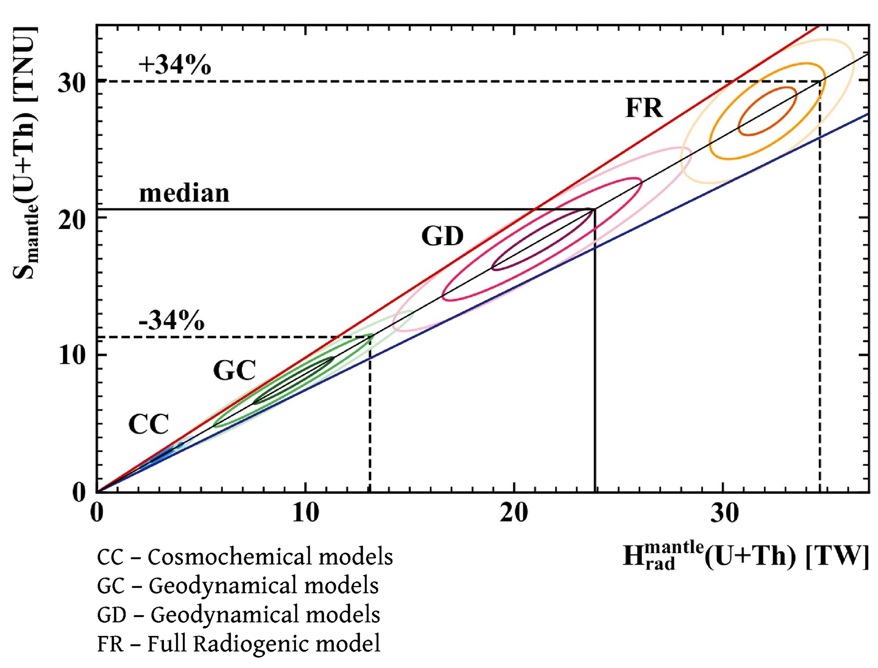
**99% C.L. exclusion of the null-hypothesis of the mantle signal**

- Relatively well-known lithosphere 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
- $S_{mantle} = 21.2^{+9.5}_{-9.0}$ TNU

Likelihood profile of mantle events




Mantle signal vs Radiogenic heat



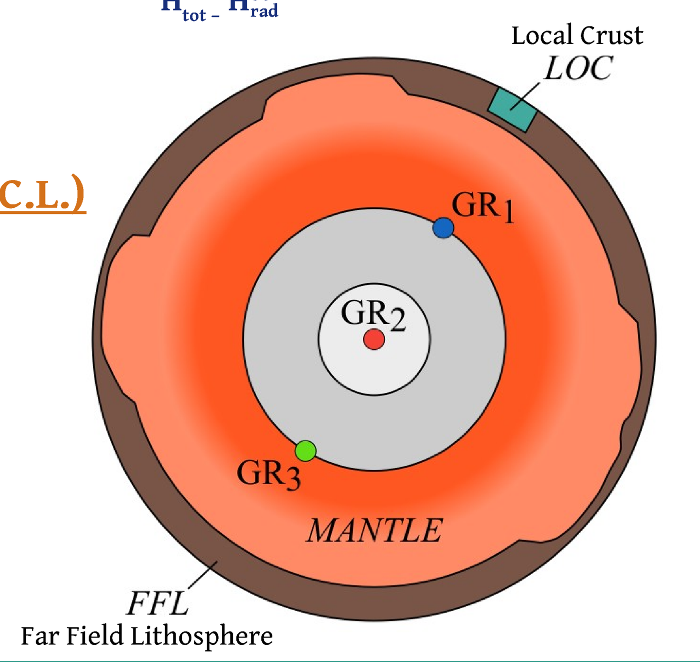

CC – Cosmochemical models
GC – Geodynamical models
GD – Geodynamical models
FR – Full Radiogenic model

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

- Radiogenic heat:
  $H(U+Th+K) = 38.2^{+13.6}_{-12.7}$ TW
  (Lithospheric contribution + measured mantle heat + expected 18% from $^{40}K$ in mantle)
- Convective Urey Ratio:
  $UR_{CV} = \frac{H_{rad} - H_{rad}^{CC}}{H_{tot} - H_{rad}^{CC}} = 0.78^{+0.41}_{-0.28}$

**Upper limits on hypothetical georeactor (95% C.L.)**

- Three different locations:
  < 0.5 TW – Core-mantle boundary (d = 2900 km) - GR1
  < 2.4 TW – Core (d = $R_{Earth}$) - GR2
  < 5.7 TW – Core-mantle boundary (d = 9842 km) - GR3
- Georeactor fuel → $^{235}U$ & $^{238}U$
- Spectra similar to reactor antineutrinos which are constrained to the expected 97.6 ± 5.5 events



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