Updated results of the geo-neutrino observation with the Borexino detector

LNGS Seminars
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on behalf of the Borexino Collaboration

MSU SINP
JINR

Motivation of geo-neutrinos search

Questions:

1) Surface heat flux puzzle ("main" problem)

2) Inner structure of the Earth

3) Chemical composition of our planet

4) Physical processes (including radioactive decays) in the depth of the Earth

5) History of the Earth formation

And

Geoneutrinos is a new tool to research the nature of the Earth

A few words about the surface heat flux puzzle

Comparison of different sources of the Earth heating

Source	Amount
Sun (Solar constant)	~ 1370 W/m^2
Earth itself	$\sim (0.06 - 0.09)$ W/m^2
Cosmic rays	$\sim 10^{-8}$ W/m^2

But the total heat from the depth of the Earth is **47 ± 2 TW**,
where **the radiogenic heat** portion is about **10-35 TW**
(according to geological BSE models)
Average geo-neutrino flux at the Earth's surface: $\Phi_{\tilde{\nu}} \sim 10^{-6}$ cm^{-2} s^{-1}

The main Heat Producing Elements (HPE's):

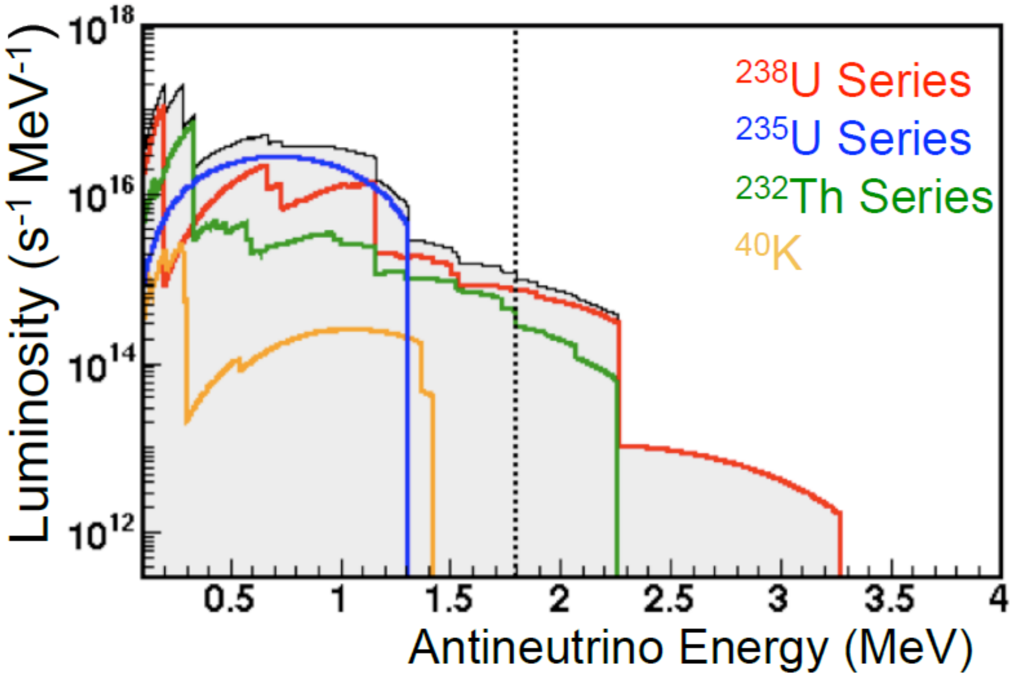
$$^{238}\text{U} \longrightarrow {}^{206}\text{Pb} + 8\alpha + 8e^- + 6\tilde{\nu}_e + 51.698 \text{ MeV}$$

$$^{232}\text{Th} \longrightarrow {}^{208}\text{Pb} + 6\alpha + 4e^- + 4\tilde{\nu}_e + 42.562 \text{ MeV}$$

$$^{235}\text{U} \longrightarrow {}^{207}\text{Pb} + 7\alpha + 4e^- + 4\tilde{\nu}_e + 46.402 \text{ MeV}$$

$$^{40}\text{K} \longrightarrow {}^{40}\text{Ca} + e^- + \tilde{\nu}_e + 1.311 \text{ MeV } (89.3\%)$$

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



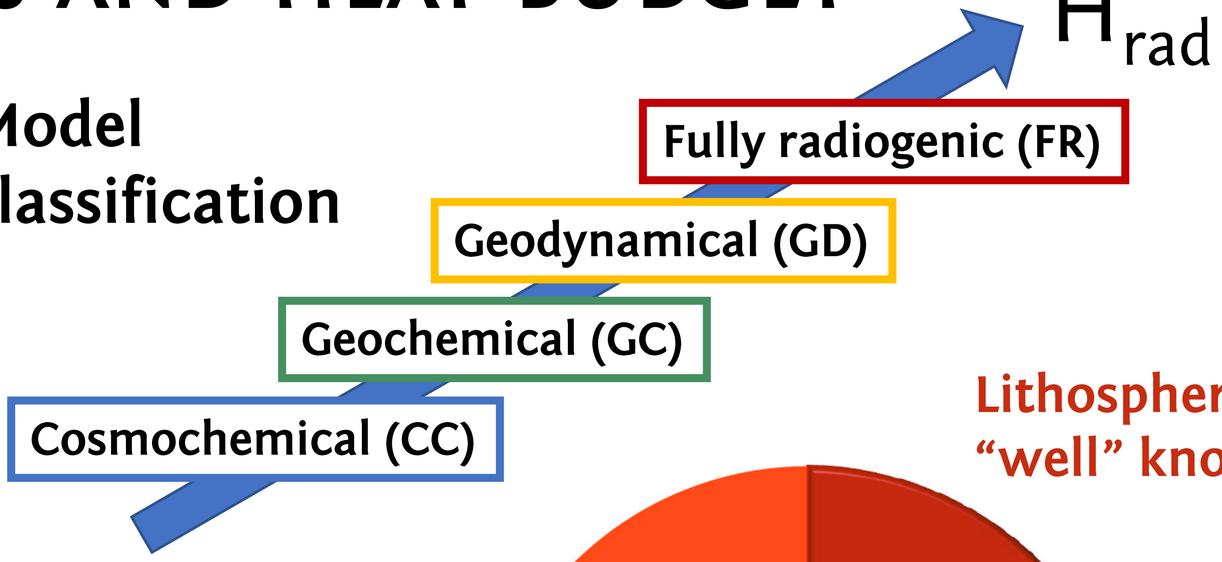
Earth's models and heat budget

BSE - Bulk Silicate Earth

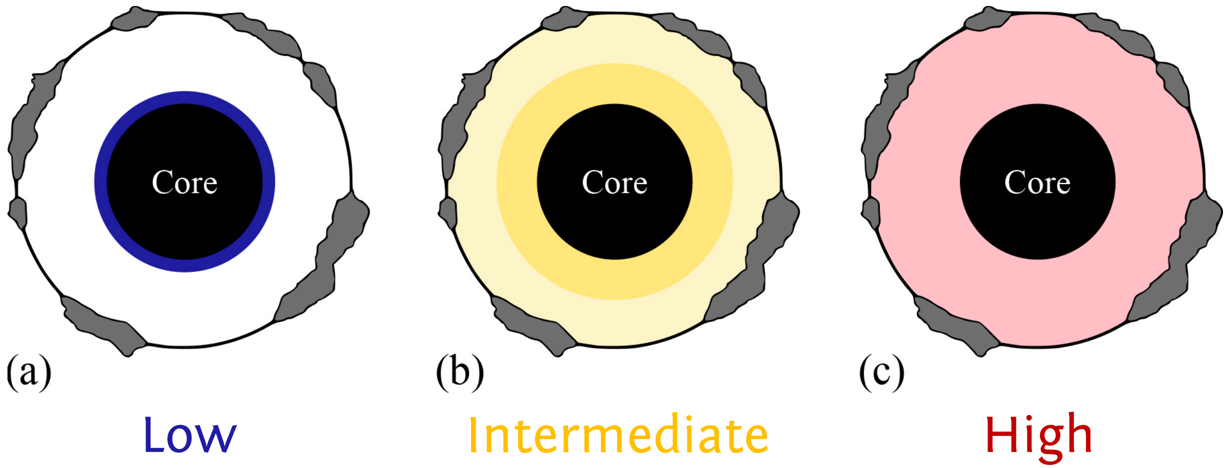
The BSE models define
the original chemical composition of
the primitive mantle

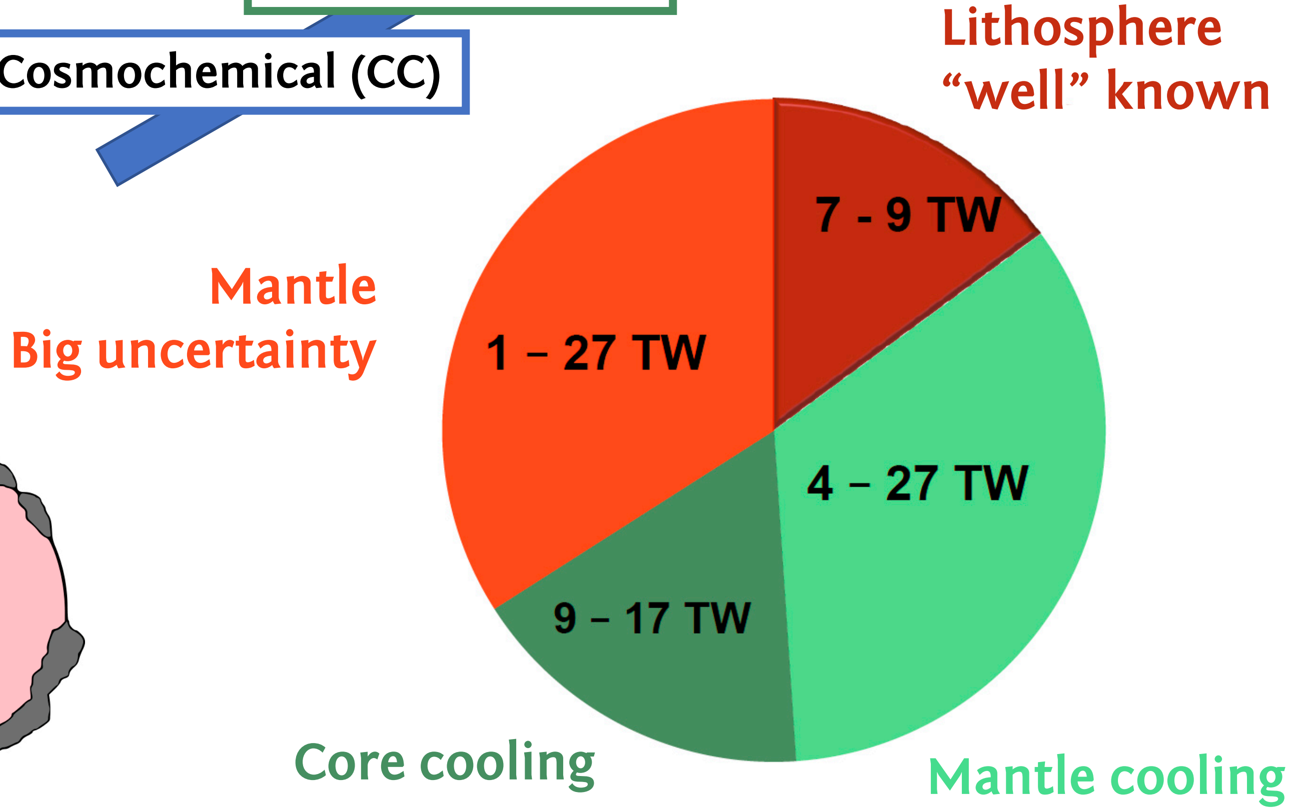
The elemental composition of BSE is obtained
assuming a common origin for celestial bodies
in the solar system

Model classification



Mantle Scenarios



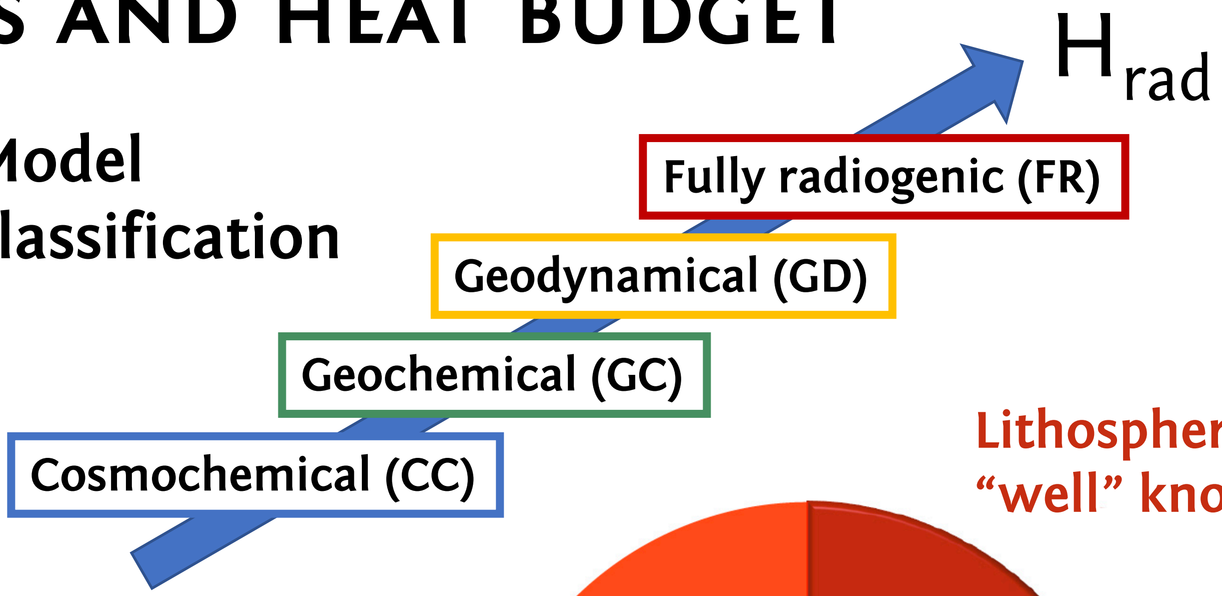


Heat budget

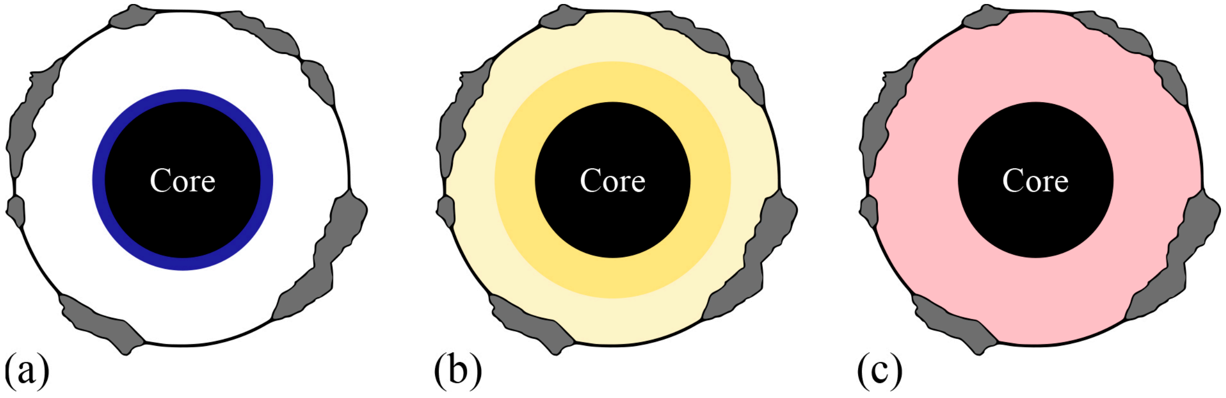
EARTH'S MODELS AND HEAT BUDGET

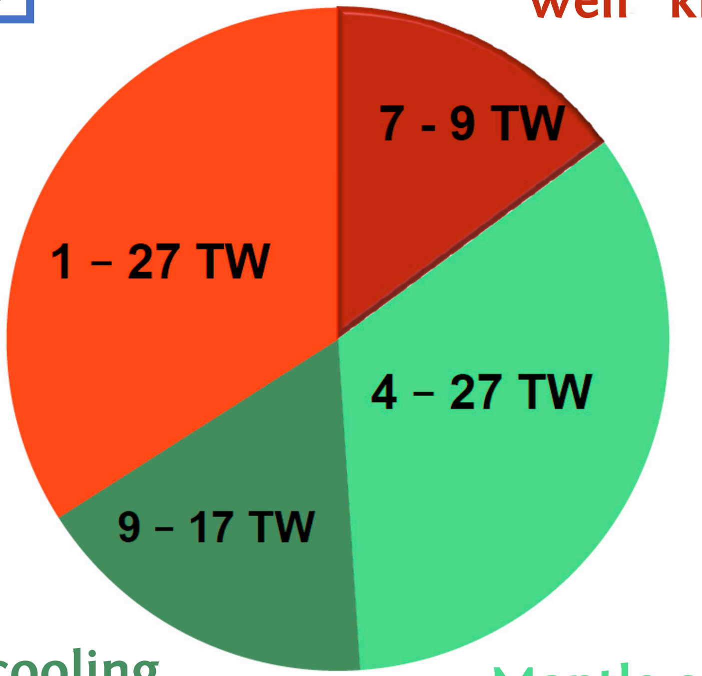
Geoneutrinos can help!

Model classification



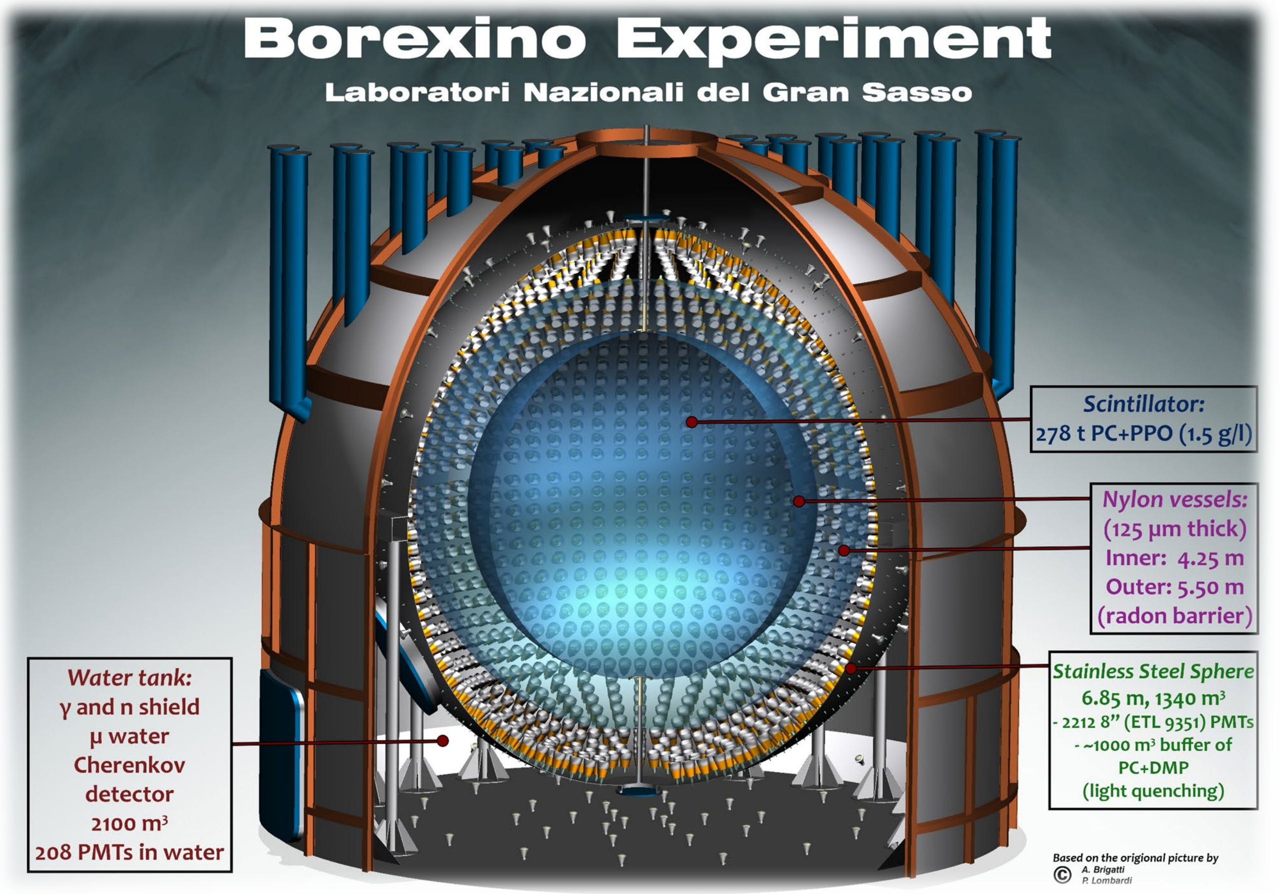
Mantle Scenarios

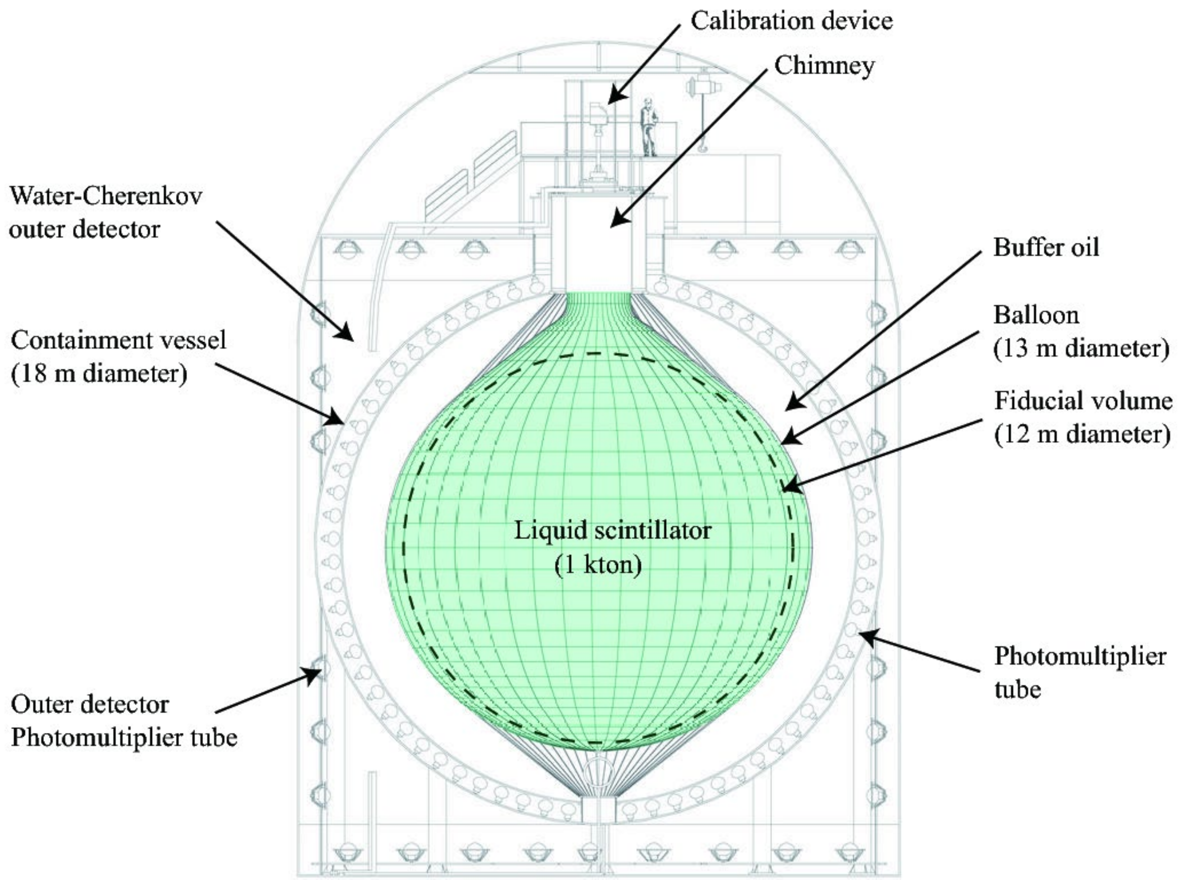




Heat budget

Detecting geoneutrinos





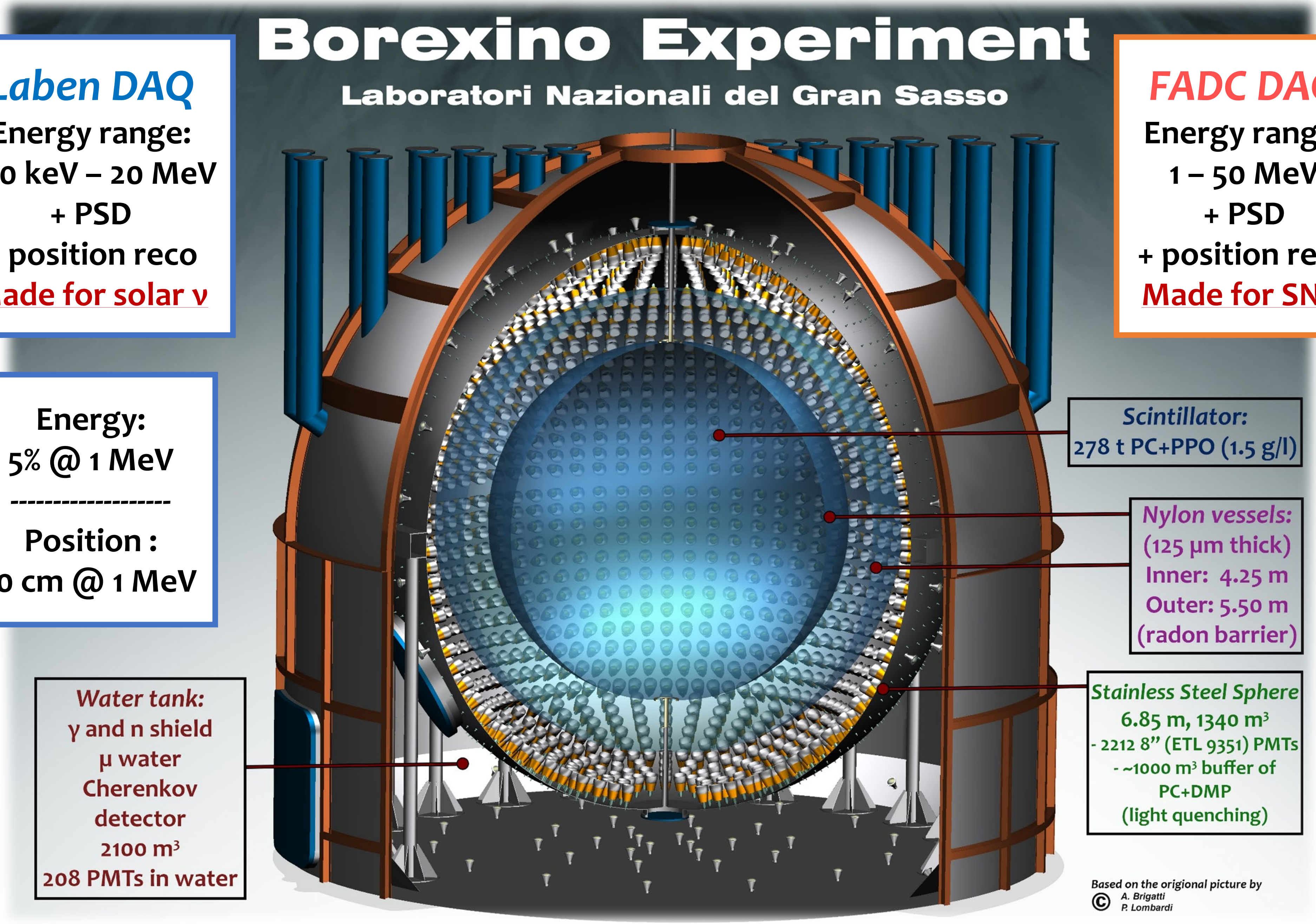
KamLAND

- only 2 experiments have measured geoneutrinos
- both are liquid scintillator detectors
- Inverse beta-decay reaction

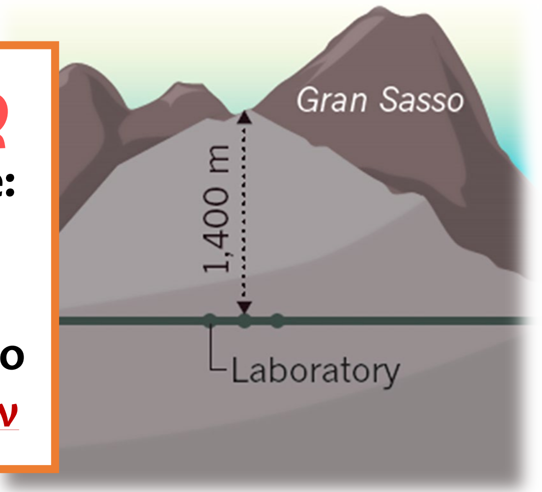
Laben DAQ
Energy range:
200 keV – 20 MeV
+ PSD
+ position reco
Made for solar ν

Energy:
5% @ 1 MeV

Position :
10 cm @ 1 MeV



FADC DAQ
Energy range:
1 – 50 MeV
+ PSD
+ position reco
Made for SN-ν



All nuclear reactors are far away from the detector

The mean weighted distance is about 1200 km, there are no reactors in Italy

Ultra-high purity construction materials

+ Set of cuts
+ Background studies

Antineutrino detection with liquid scintillators

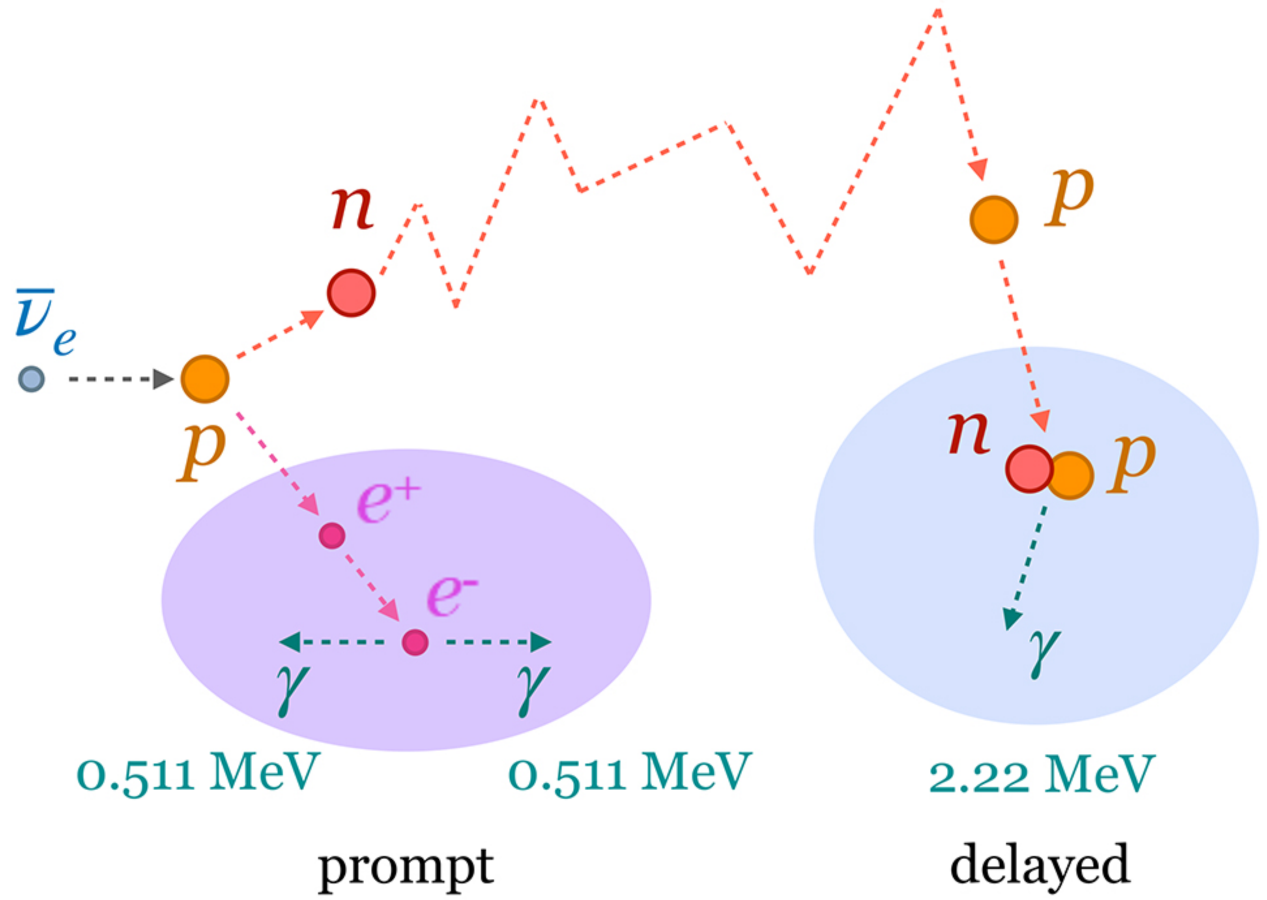
Electron antineutrino detection: delayed coincidence

- Inverse Beta Decay (IBD)
- Charge current, electron flavour only

Energy threshold = 1.8 MeV

σ @ few MeV: ~10^{-42} cm2

(~100x more than scattering)



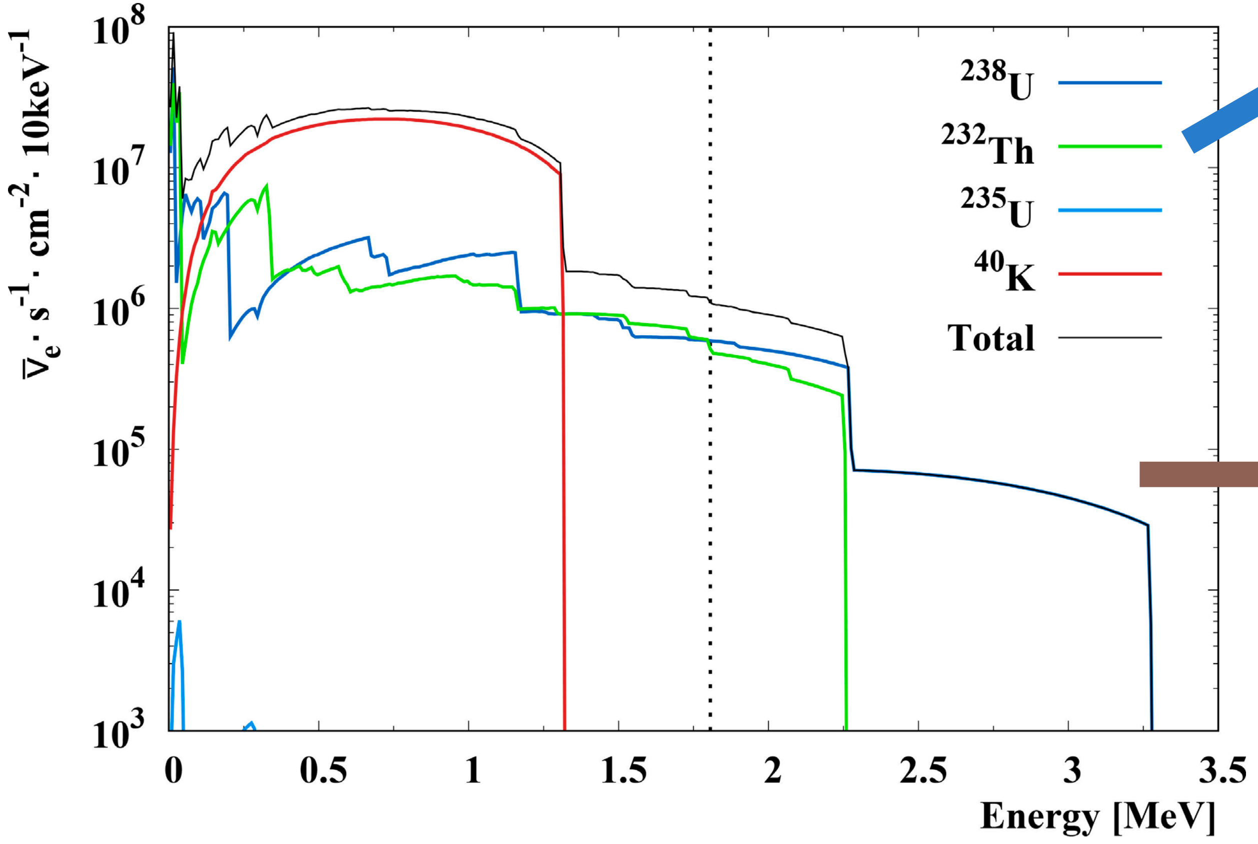
$$\overline{\nu}_e + p \longrightarrow n + e^+$$
$$e^+ + e^- \longrightarrow 2\gamma \text{ (prompt)}$$
$$n + p \longrightarrow d + \gamma \text{ (2.22 MeV) (delayed)}$$

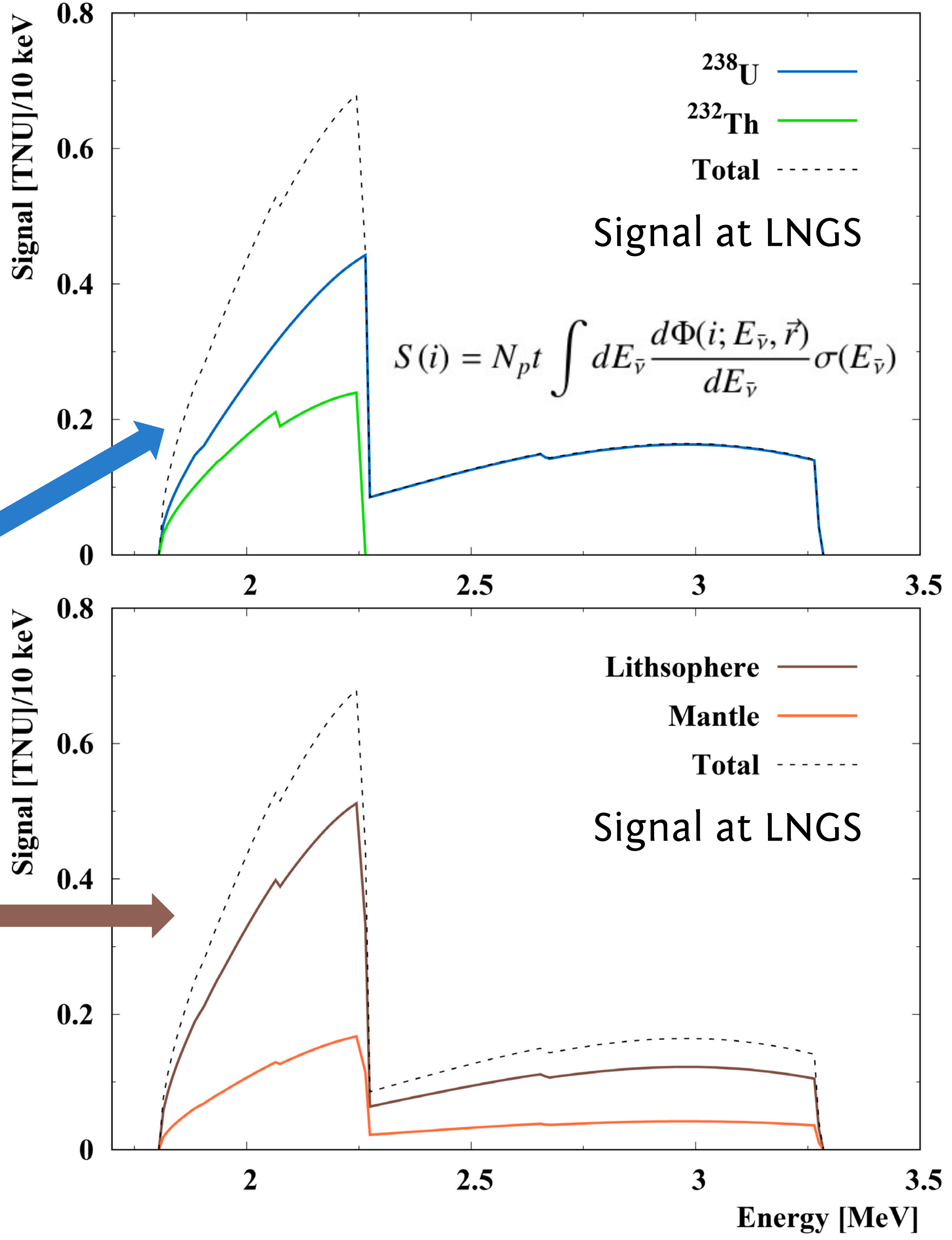
$$E_{prompt} = E_{visible}$$
$$= T_{e+} + 2 \times 511 \text{ keV}$$
$$\sim E_{antinu} - 0.784 \text{ MeV}$$

Detection of geoneutrinos

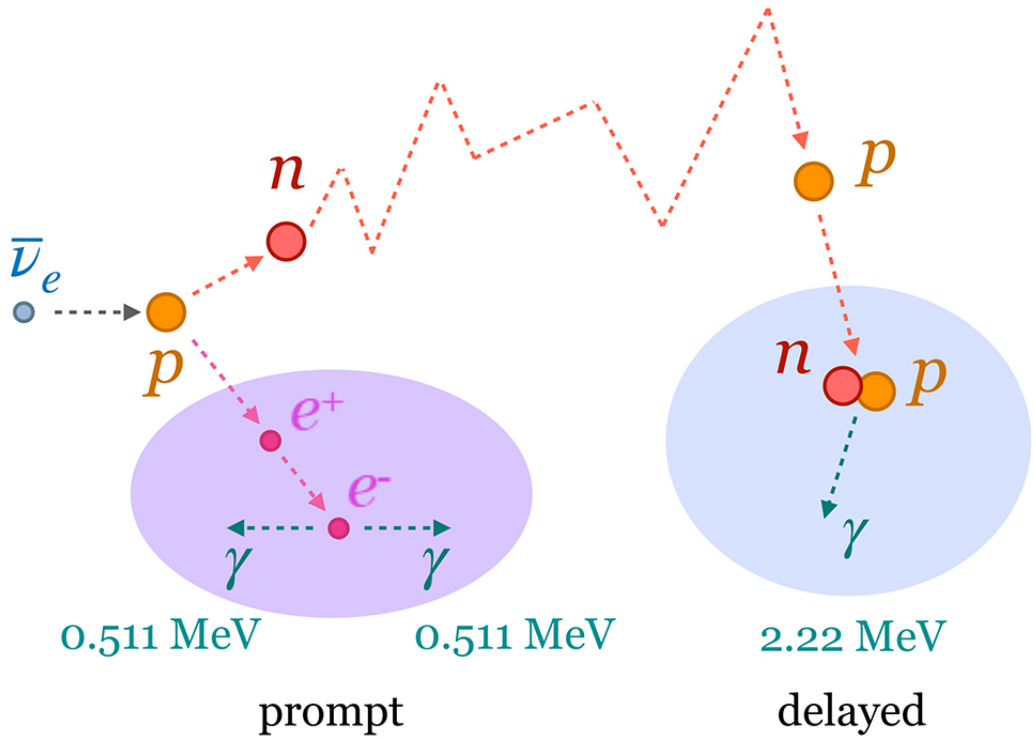
Geoneutrino flux ~ 10^6 cm^{-2}s^{-1}
$\langle P_{ee} \rangle$ ~ 0.55

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





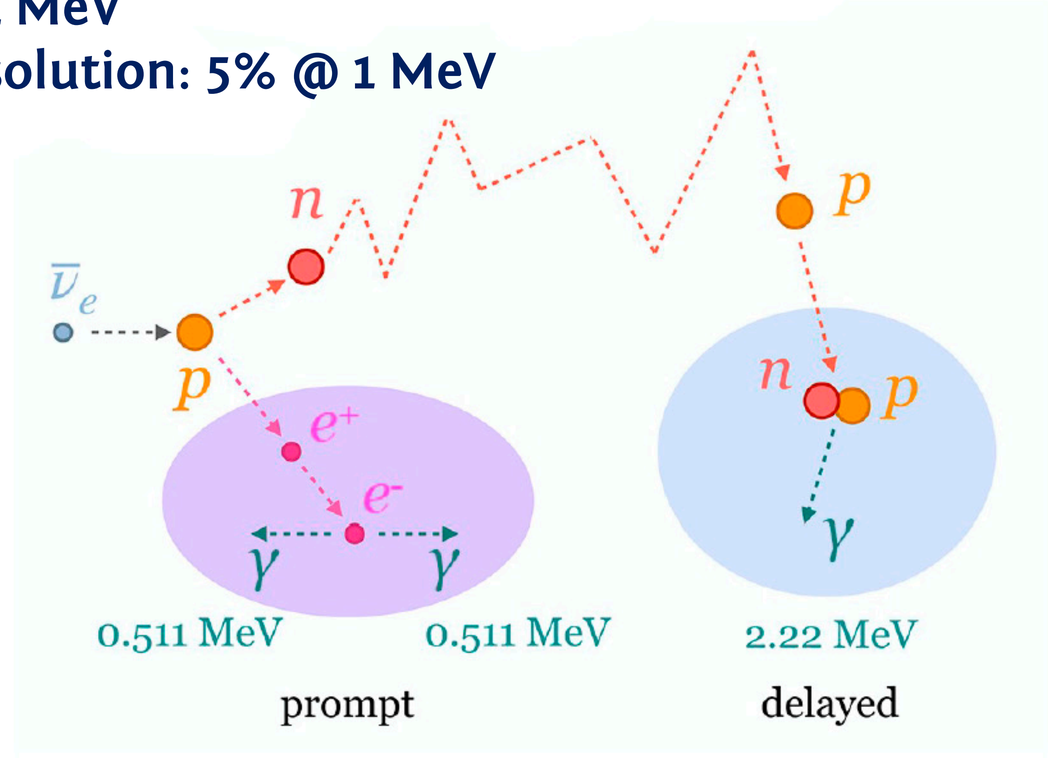
Overview of selection cuts



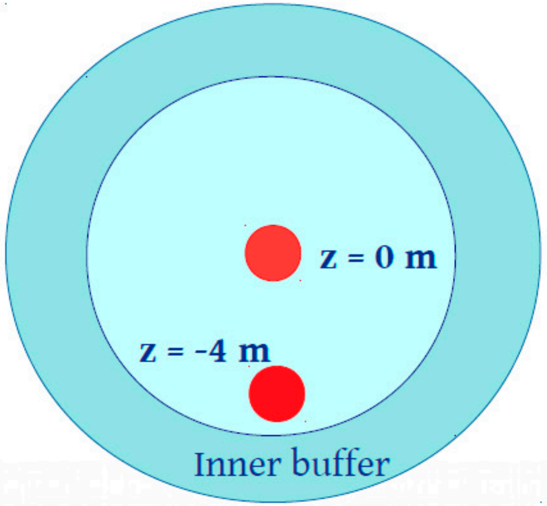
1) Energy cuts for prompt (Q_p)and delayed (Q_d)
2) Time between prompt and delayed (dt)
3) Distance between prompt and delayed (dR)
4) Muon Vetoes
5) Dynamic Fiducial Volume (DFV) cut
6) α/β discrimination

Selection cuts: energy cuts

500 p.e. / 1 MeV
Energy resolution: 5% @ 1 MeV



From ^{241}Am-^{9}Be calibration:
neutron source placed at different positions



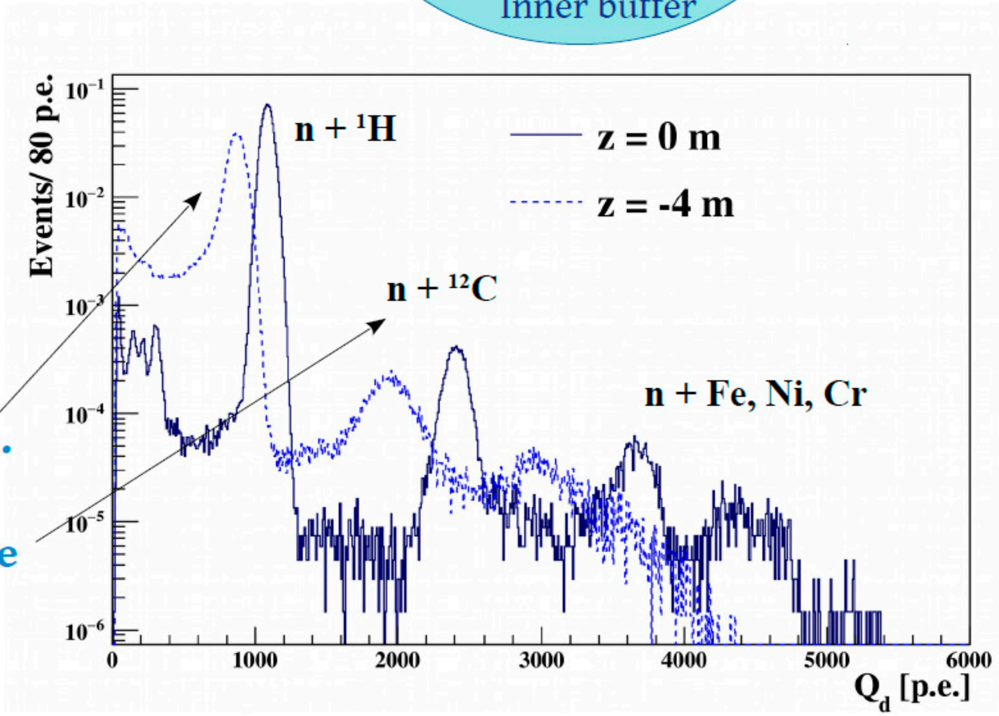
Energy of prompt
above IBD threshold

Q_p > 408 p.e. after considering energy resolution

Energy of delayed

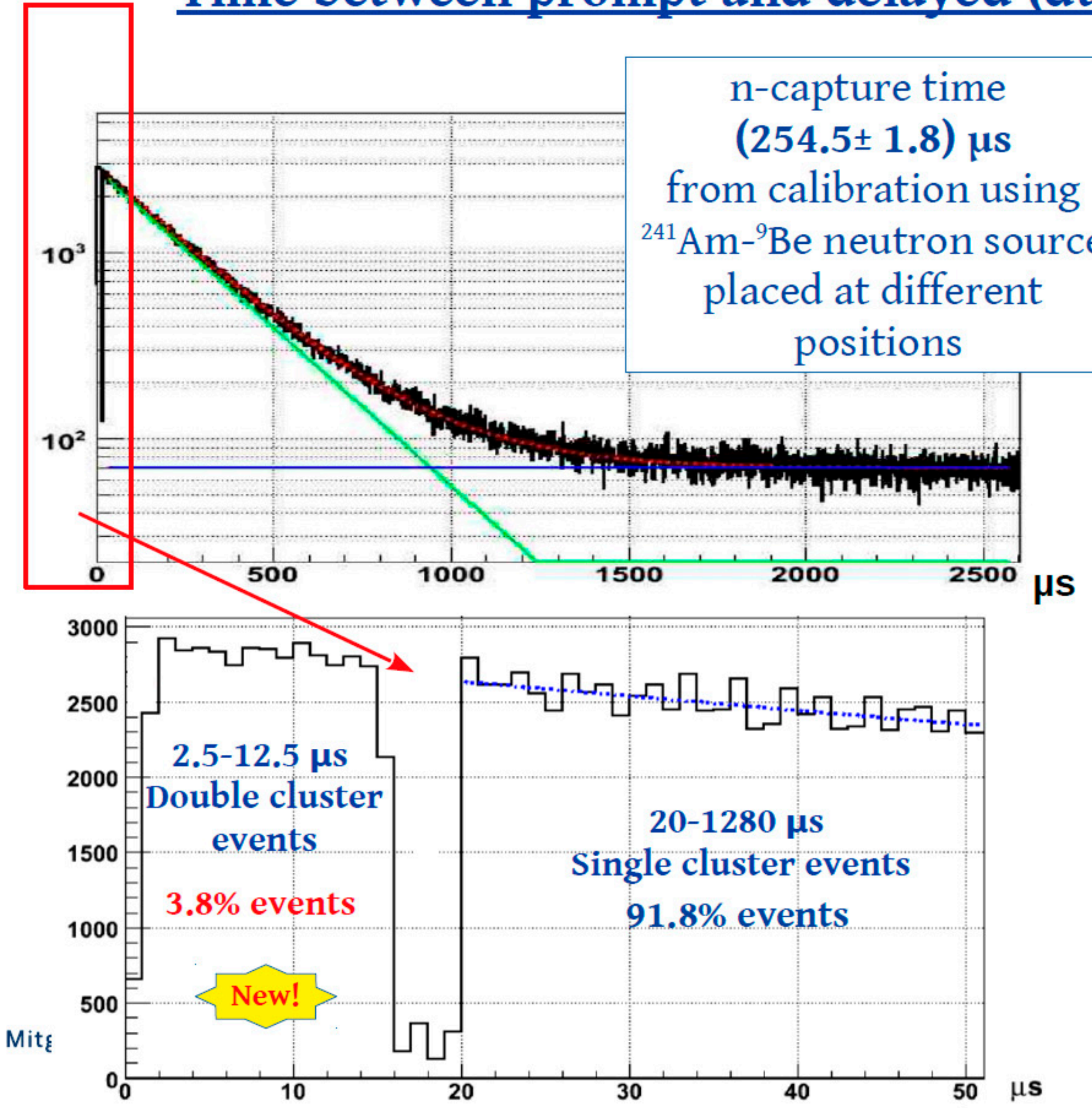
Enlarged! 700 < Q_d < 1300 p.e. (p-capture)

New! 1300 < Q_d < 3000 p.e (^{12}C-capture)



Selection cuts: time-space correlation

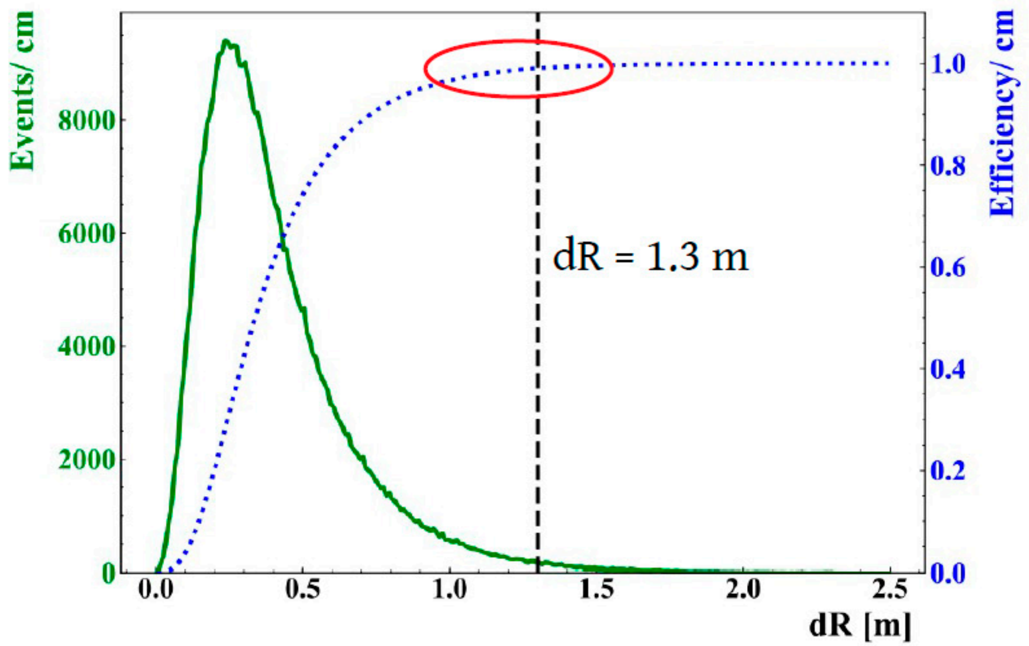
Time between prompt and delayed (dt)



Distance between prompt and delayed (dR)

Enlarged!

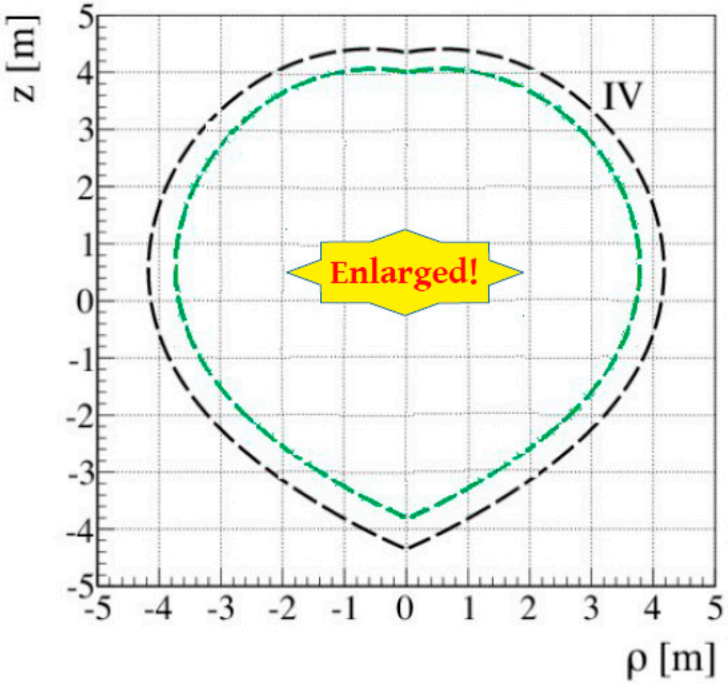
- Similar efficiency and precision for 1 to 1.5 m
- Accidental background under control



Position resolution: 10 cm at 1 MeV

Selection cuts

Dynamic Fiducial Volume



Drop in uncertainty for 30→10 cm
Safely removes background events without loss in precision
Increase in exposure

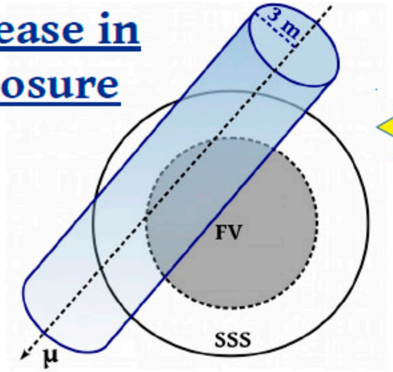
Improved Muon vetoes

- External muons: 2 ms dead time

Improved!

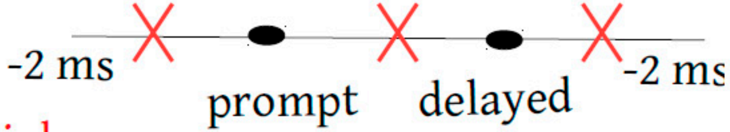
- Internal muons: 2 s, 1.6 s and 2 ms dead times depending on the muon's probability to form spallation products

Increase in exposure



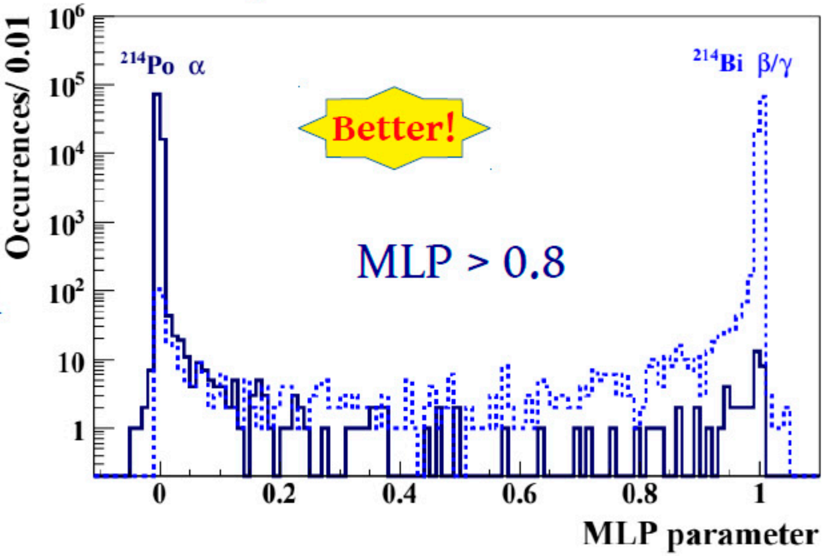
New!

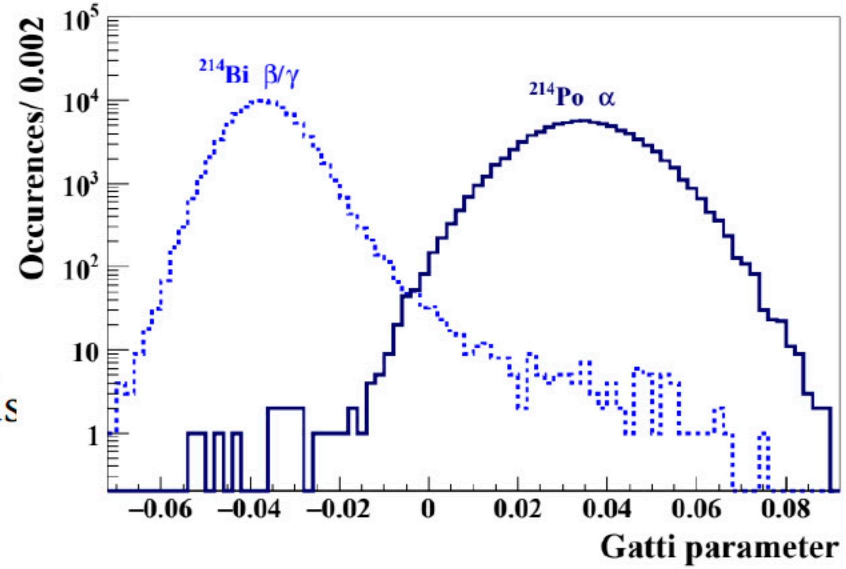
Multiplicity Cut



X No high energy event > 400 p.e.

α/β discrimination

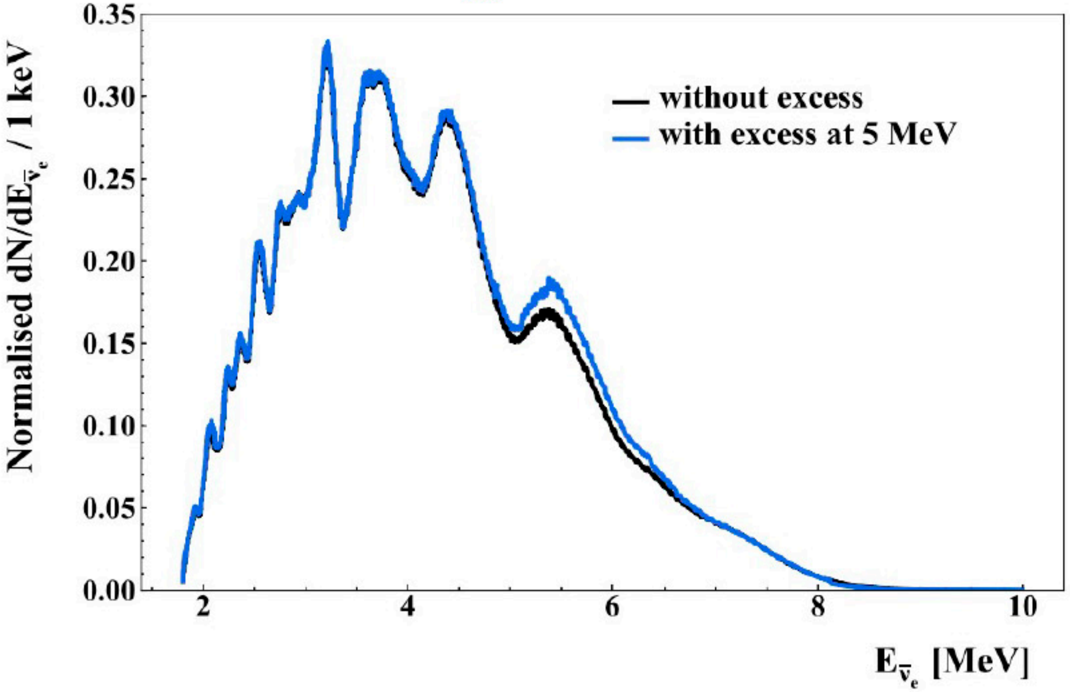




Antineutrino backgrounds

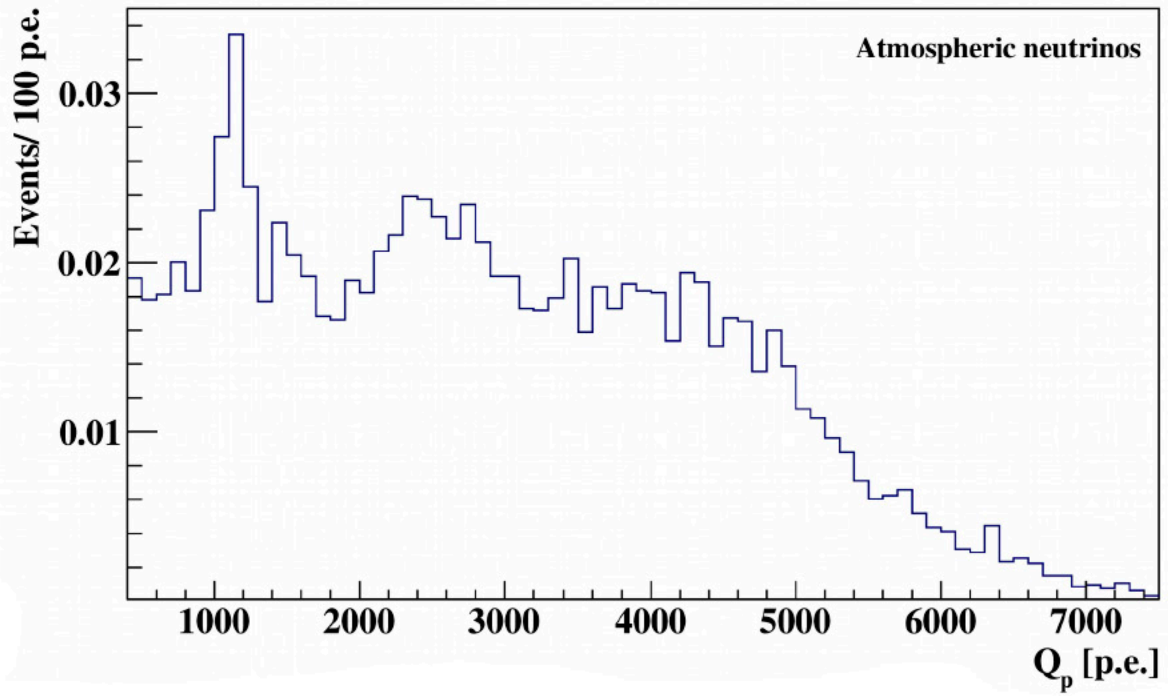
Reactor antineutrinos

- ~440 world reactors: nominal powers, monthly load factors → **PRIS database (IAEA)**
- ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu: power fractions, energy released per fission, energy spectra (Mueller et al. 2011, Daya Bay)
- **Detection efficiency = (89.55 ± 1.5) %**
- Expectation: $84.5^{+1.5}_{-1.4}$ TNU without excess,
  $79.6^{+1.4}_{-1.3}$ TNU with excess



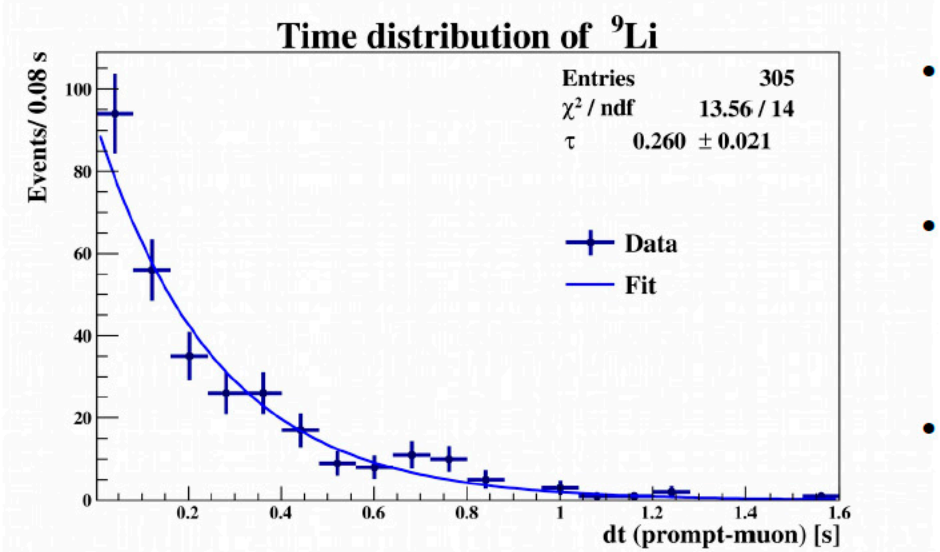
Atmospheric neutrinos

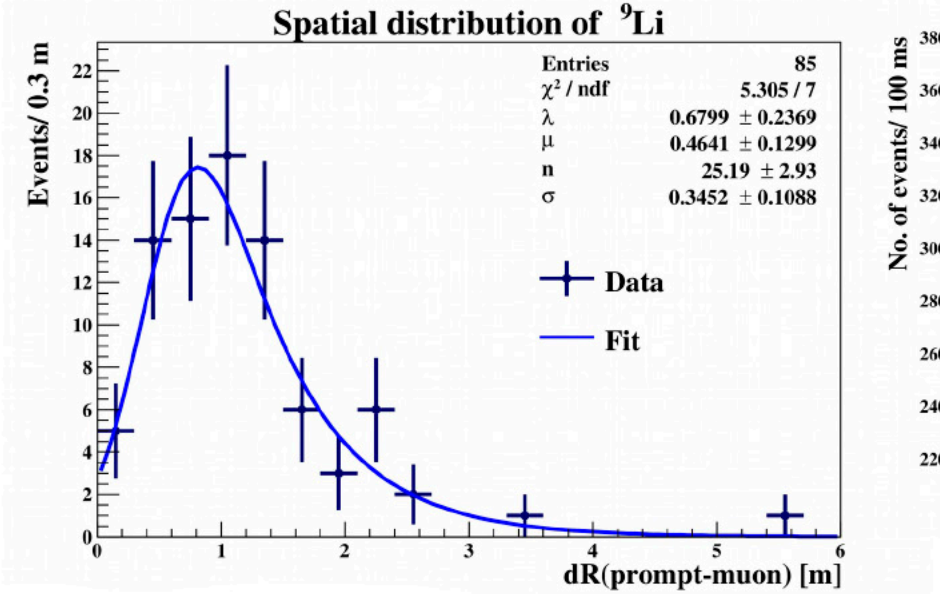
- Estimated **50% uncertainty** on the prediction
- Indications of overestimation
- Included in the **systematic error**
- Atmospheric neutrino fluxes from HKKM2014 (>100 MeV) and FLUKA (<100 MeV)
- **Matter effects** included



Non-antineutrino backgrounds

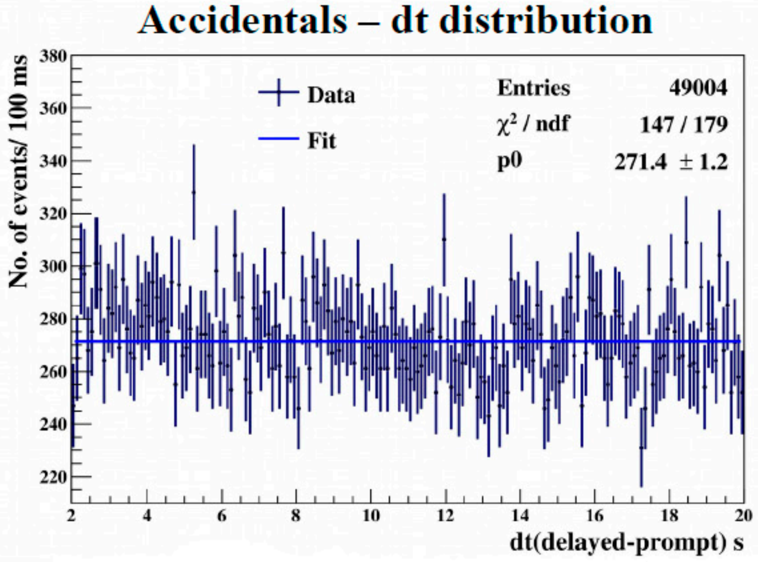
$$^{9}\mathrm{Li} \rightarrow e^{-} + \bar{\nu}_e + n + 2\alpha$$

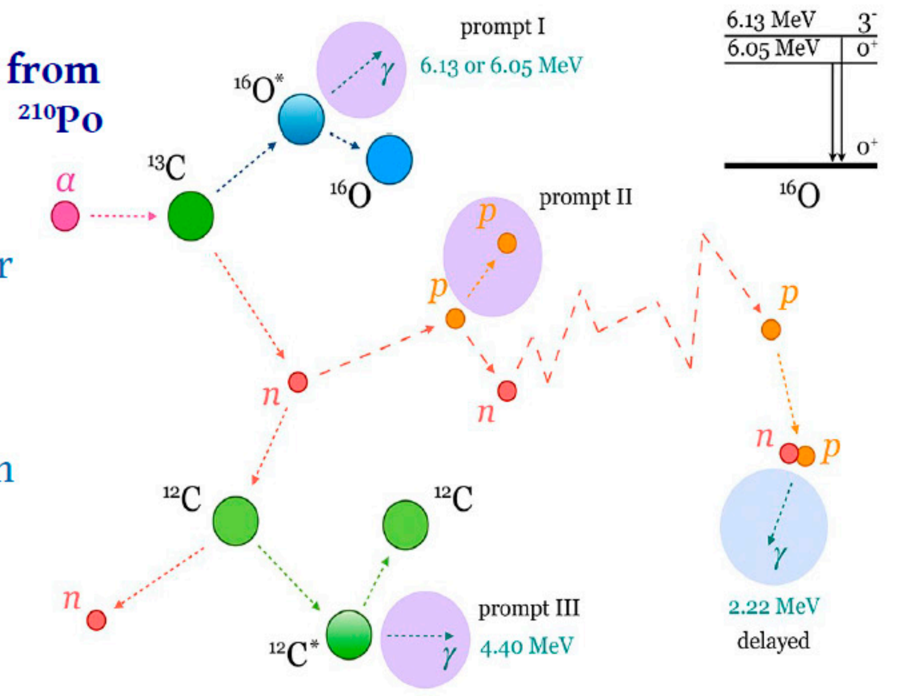


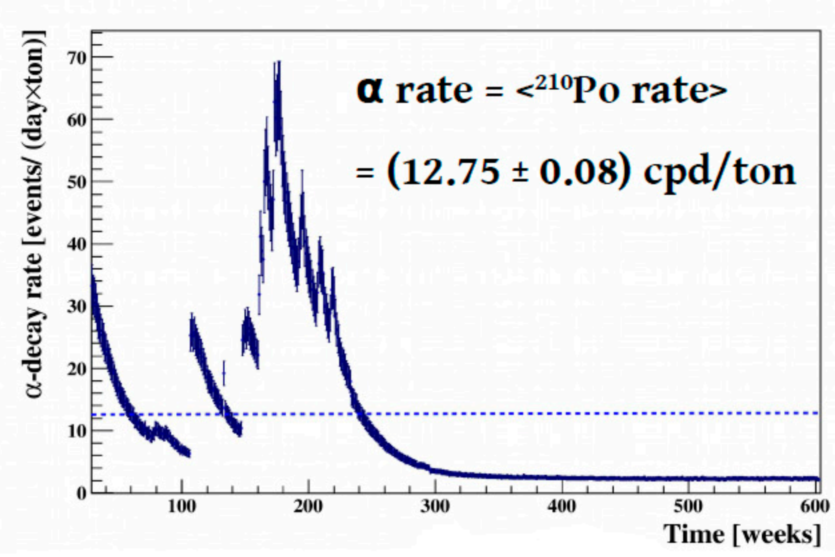


Important backgrounds for the final spectral fit:

- **Cosmogenic ^{9}Li:** expected events after the time and spatial veto
- **Accidentals:** random coincidences correlated in space and time. Events in 2-20 s window scaled back.
- **(α,n):** due to internal radioactivity







Non-antineutrino backgrounds: Summary

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

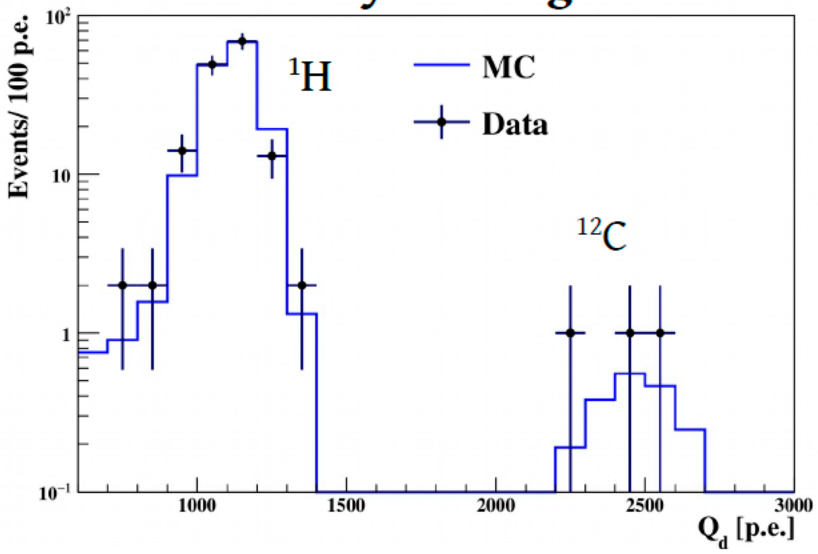
It was $0.78^{+0.13}_{-0.10}$

Fortunately, it is compensated by doubled statistics

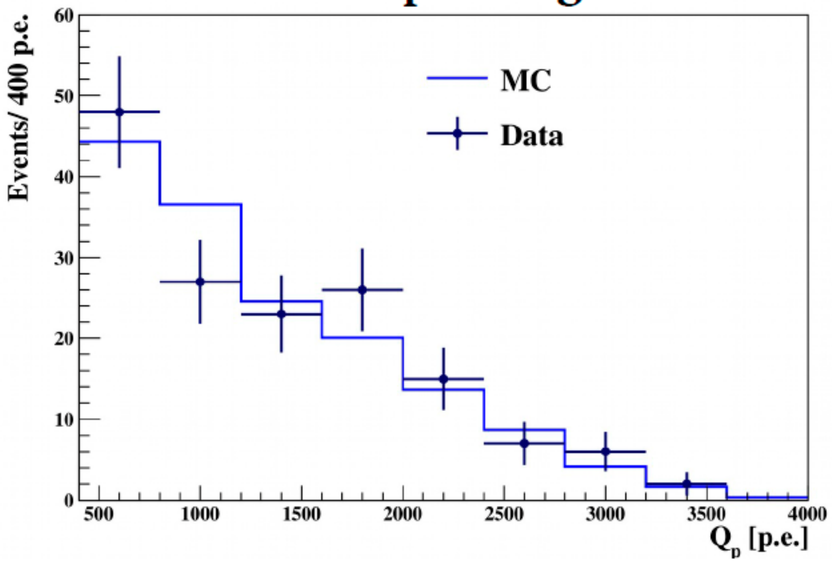
The price for relaxing the cuts is an increase of the background by an order of magnitude

Golden candidates

Delayed charge

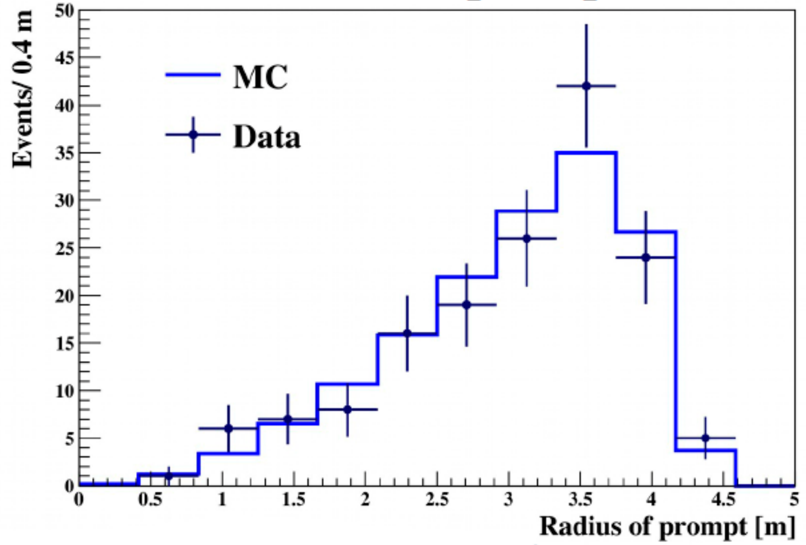


Prompt charge

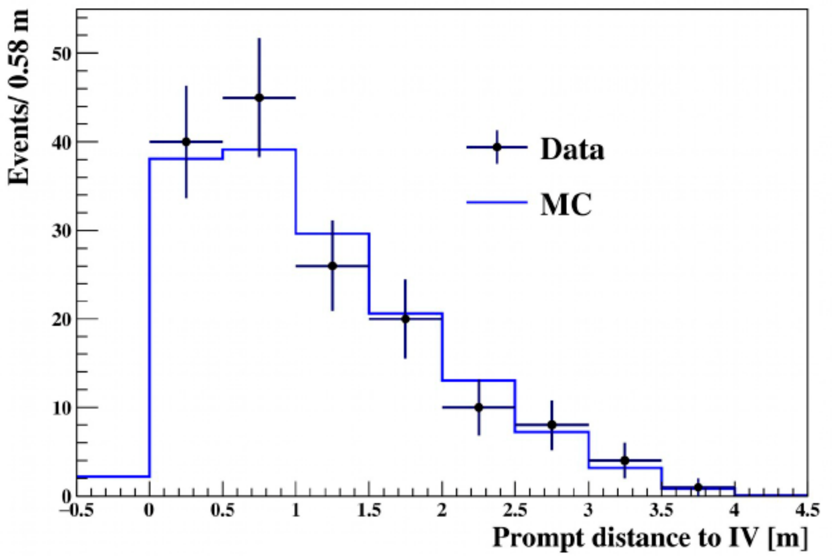


- 154 golden candidates
- 3263 days of data taking
- Average FV = (245.8 ± 8.7) ton
- Exposure = (1.29 ± 0.05) x 10^{32} proton x year (for 100% detection eff.)
- Detection Efficiency = (86.98 ± 1.5)%

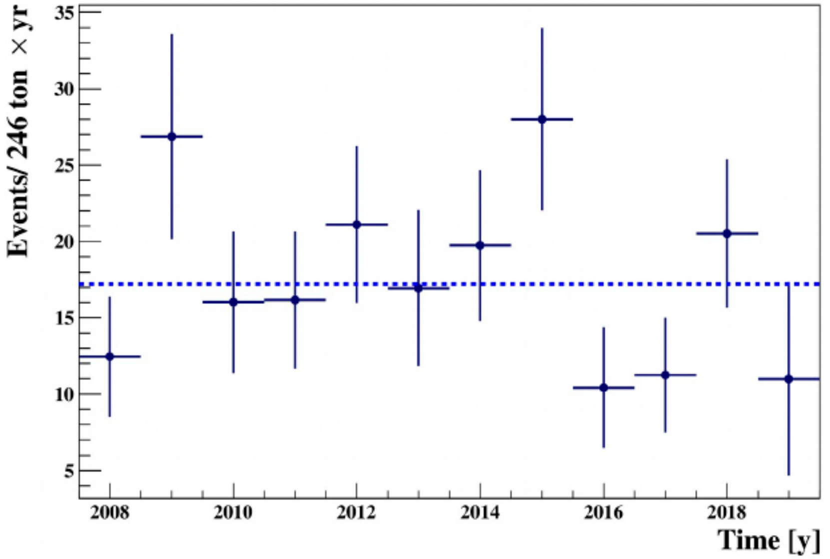
Radius of prompt



Distance to vessel of prompt



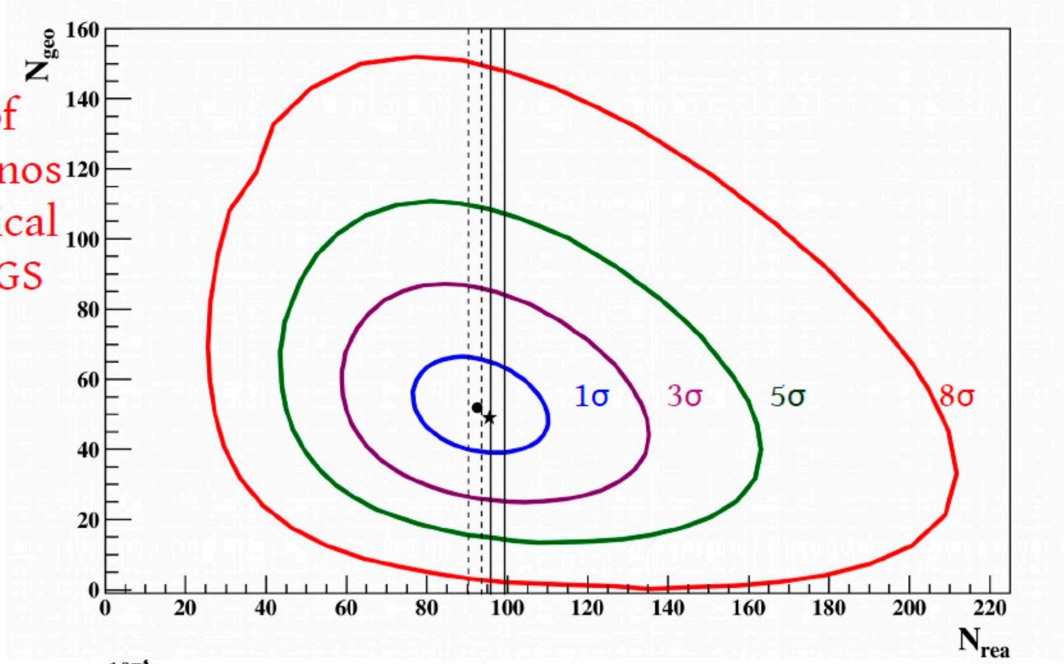
Yearly distribution

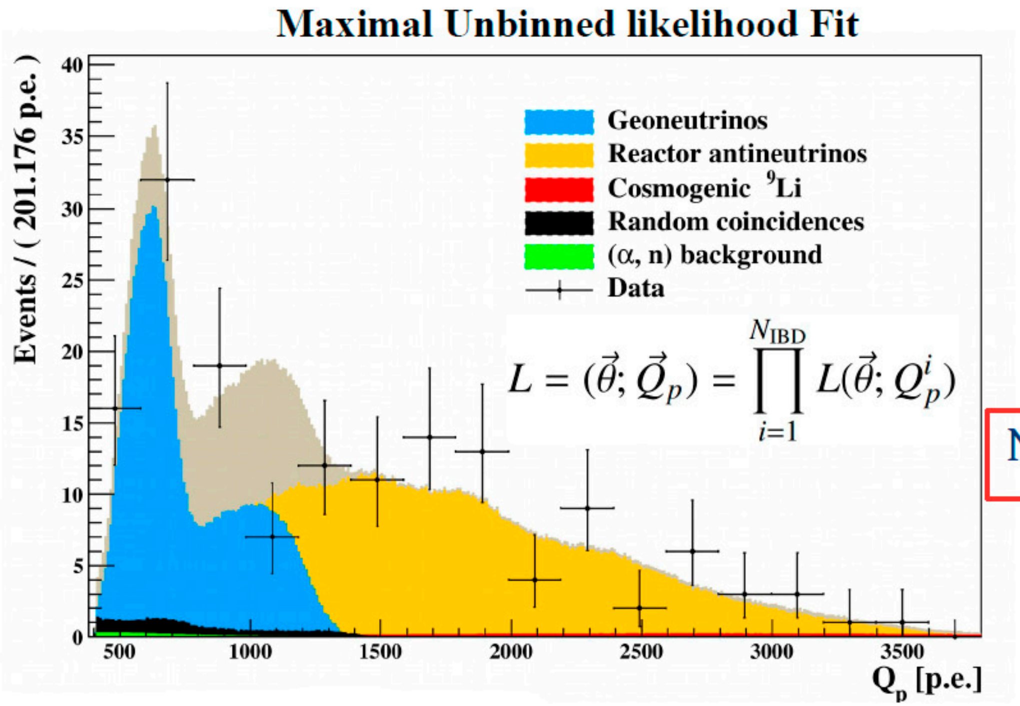


Spectral Fit:
Th/U mass ratio fixed to 3.9

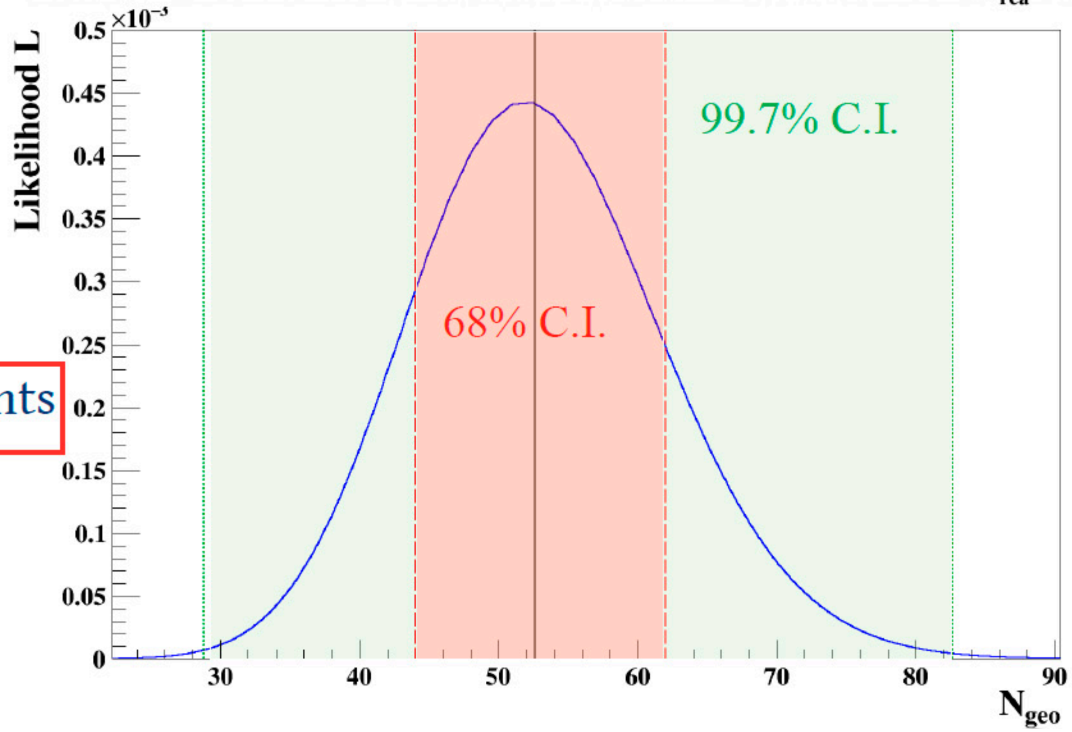
- Geoneutrinos and reactor antineutrinos **free**
- Cosmogenic ^{9}Li, (α,n) and accidentals **constrained** using Gaussian pull terms
- p.d.f – **Monte Carlo simulation**
- **Consistent results** after constraining reactor antineutrinos

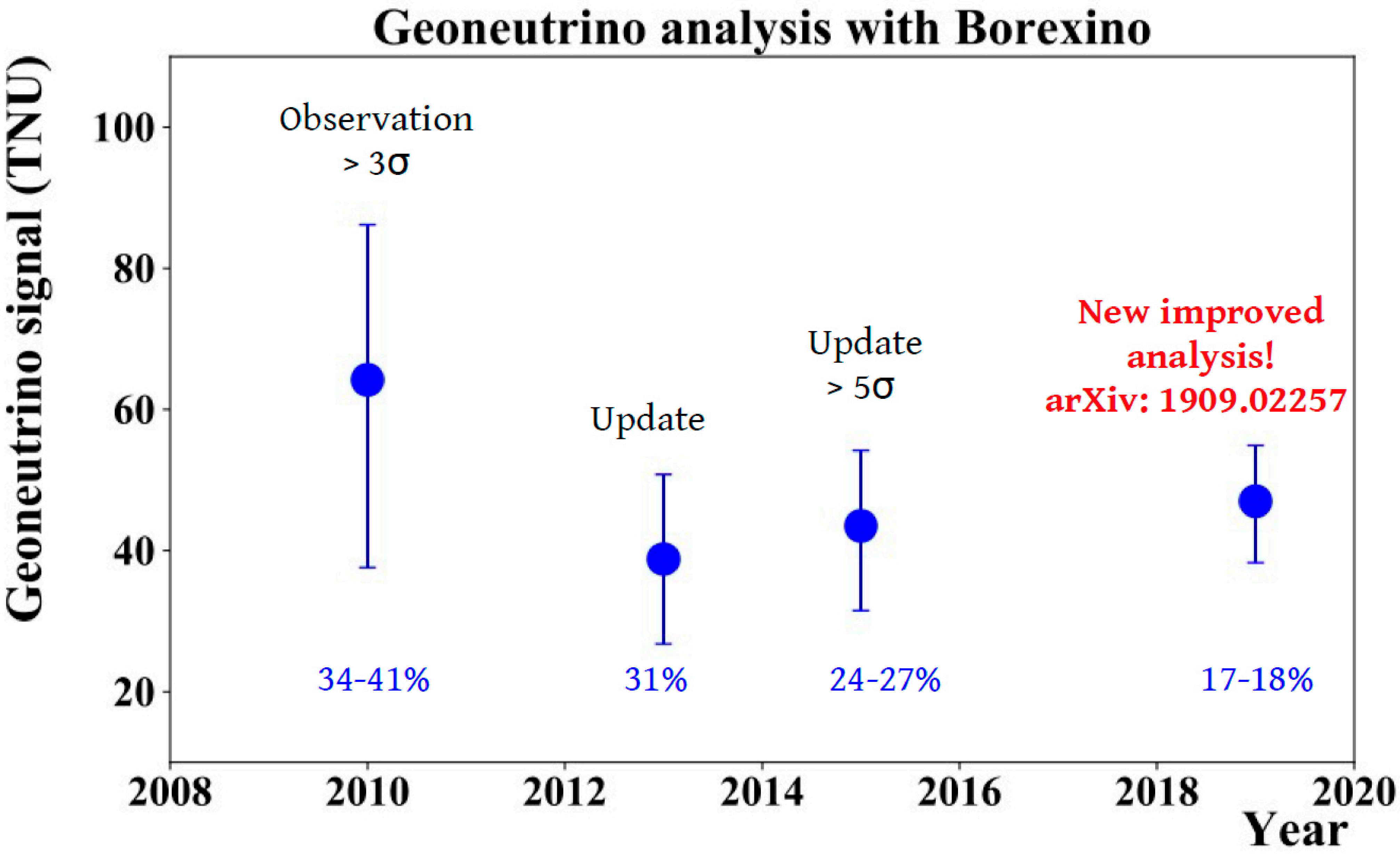
Best fit results of reactor antineutrinos within 1σ theoretical expectation at LNGS



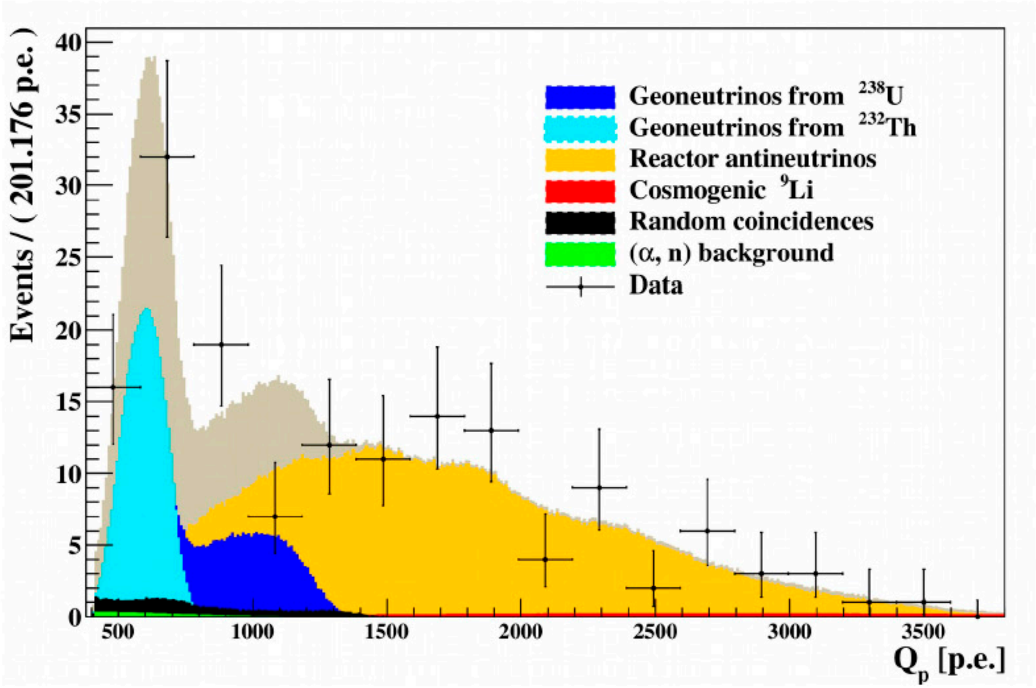


$N_{geo} = 52.6^{+9.4}_{-8.6}$ events

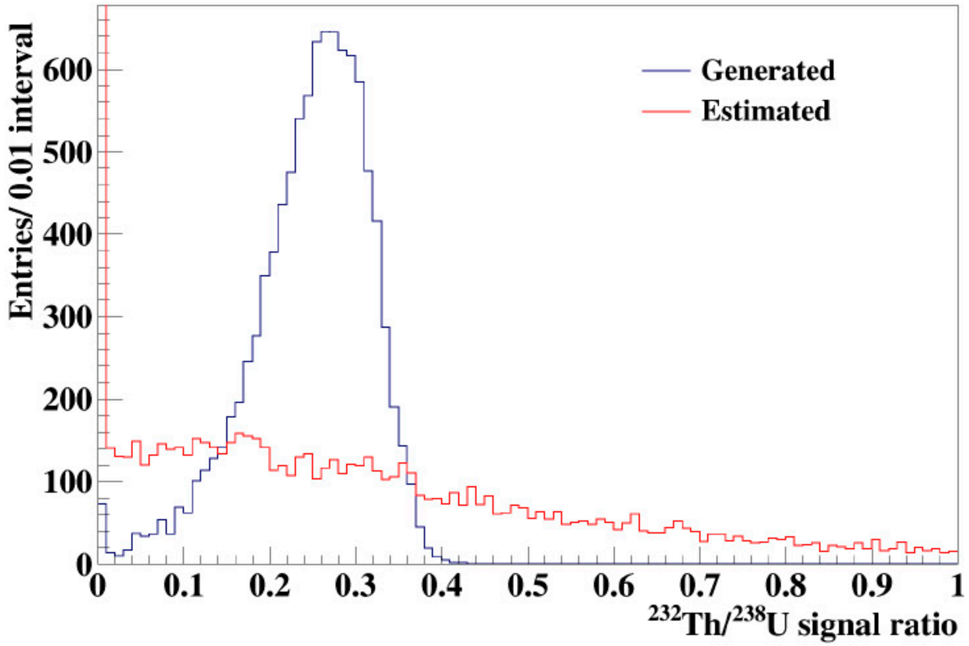



Geoneutrino analysis with Borexino
Geoneutrino signal (TNU)
Year
Observation
> 3σ
Update
Update
> 5σ
New improved
analysis!
arXiv: 1909.02257
34-41%
31%
24-27%
17-18%
100
80
60
40
20
2008
2010
2012
2014
2016
2018
2020

Spectral Fit: Th and U free



Not sensitive to Th/U ratio! Toy MC approach

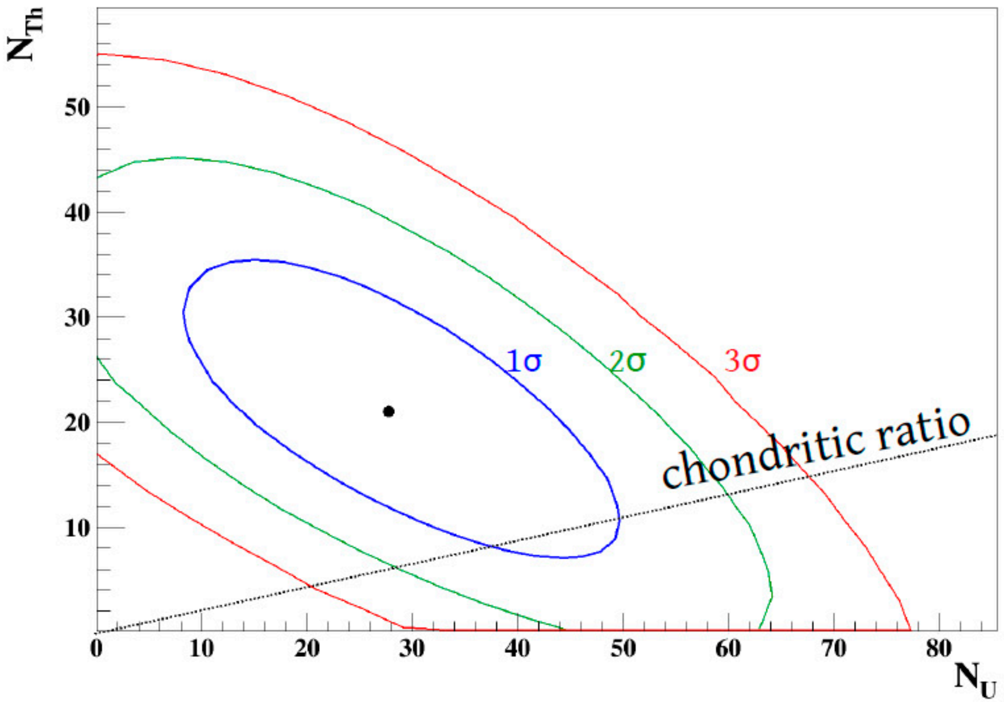


$N_U = 29.0^{+14.2}_{-13.0}$ events

$N_{Th} = 21.4^{+9.4}_{-9.2}$ events

$N_{geo} = 50.4^{+23.6}_{-22.2}$ events

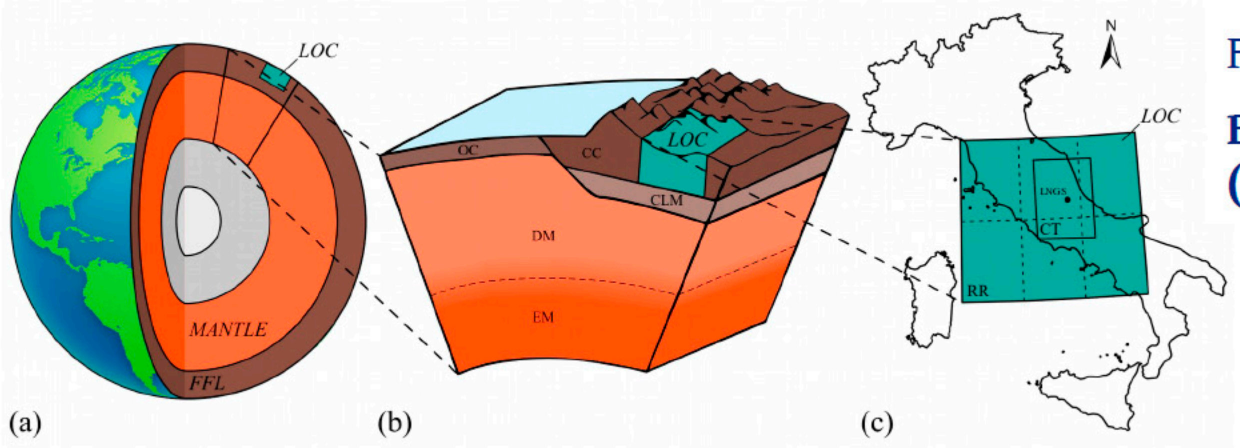
High uncertainty but in agreement with results of Th/U fixed



Systematic Uncertainties

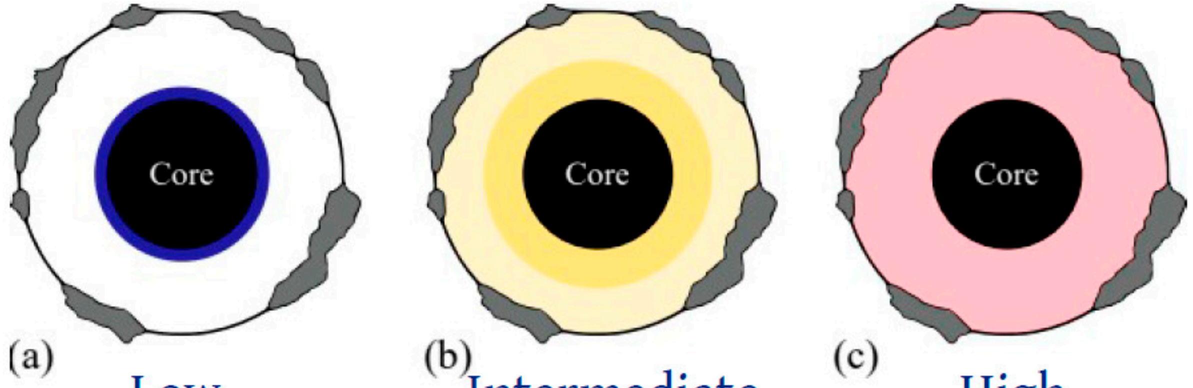
Source	Geo error (%)	Rea error (%)
Atmospheric neutrinos	+0.00 -0.38	+0.00 -3.90
Shape of reactor spectrum	+0.00 -0.57	+0.04 -0.00
Vessel shape	+3.46 -0.00	+3.25 -0.00
Efficiency	1.5	1.5
Position reconstruction	3.6	3.6
TOTAL	+5.2 -4.0	+5.1 -5.5

Geological inputs



- LOC – Local crust (492 x 444 km): carbonatic rocks & terrigenous sediments
- FFL – Far Field Lithosphere: Rest of the crust + CLM

Mantle Scenarios



	S (U +Th) [TNU]	R_s = S(Th)/S(U)
Local Crust (LOC)	9.2 ± 1.2	0.24
Far Field Lithosphere	$16.3^{+4.8}_{-3.7}$	0.33
Bulk Lithosphere (Bulk crust + CLM)	$\mathbf{25.9^{+4.9}_{-4.1}}$	**0.29**

Mantle R_s = S(Th)/S(U)= 0.26

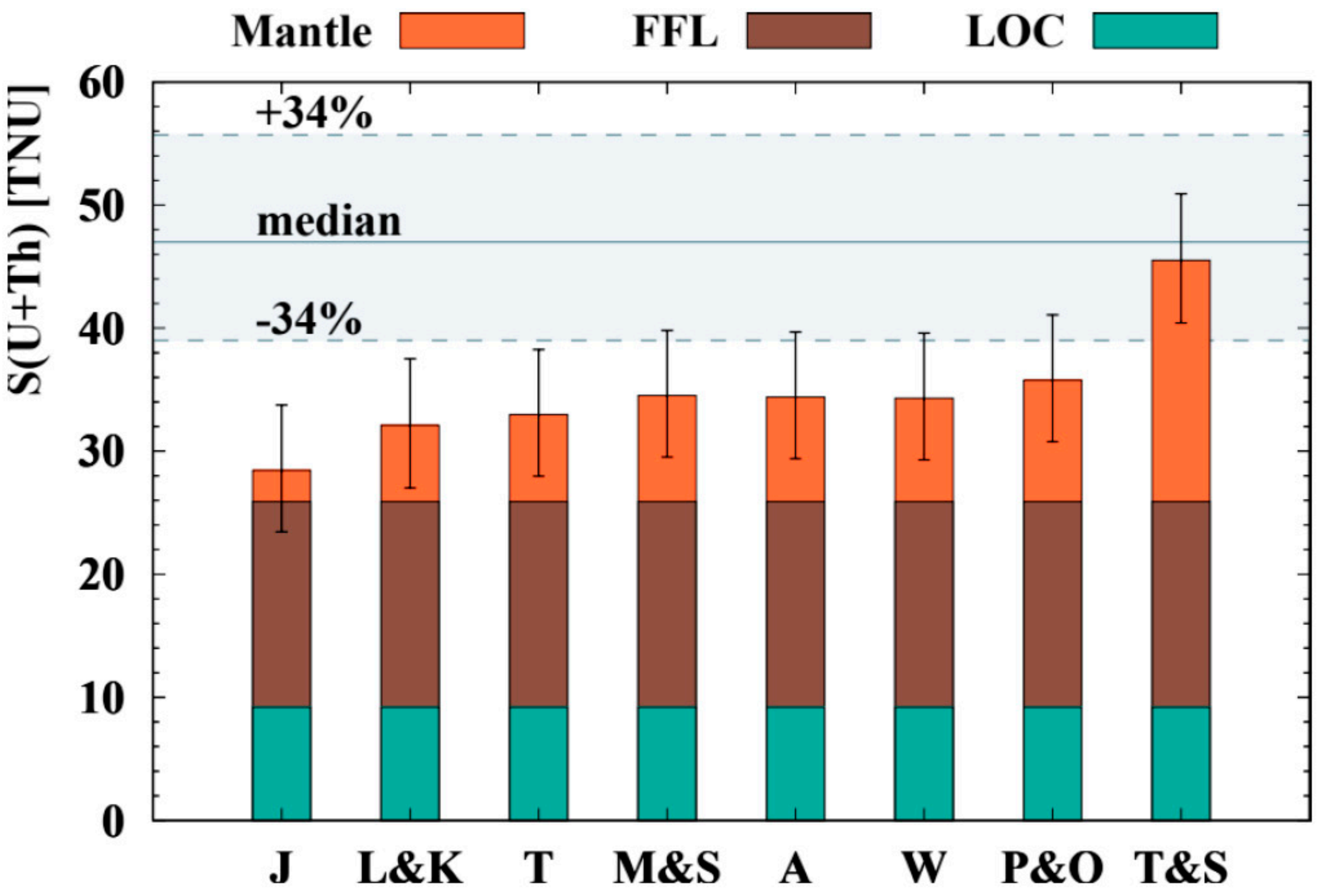
BSE models	S_{mantle}(U+Th) [TNU]
Cosmochemical (CC)	0.9-4.1
Geochemical (GC)	6.0-10.6
Geodynamical (GD)	15.7-22.4
Full Radiogenic (FR)	24.2-33.0

^{40}K contribution = 18%

Total expected signal at Borexino
S(U+Th+K) = 28.5-45.5 TNU

Geoneutrino Signal at LNGS

$$S_{geo}[\text{TNU}] = \frac{N_{geo}}{\varepsilon_{geo} \cdot \frac{\mathcal{E}_p}{10^{32}}} = \frac{N_{geo}}{\frac{\mathcal{E}'_p}{10^{32}}}$$



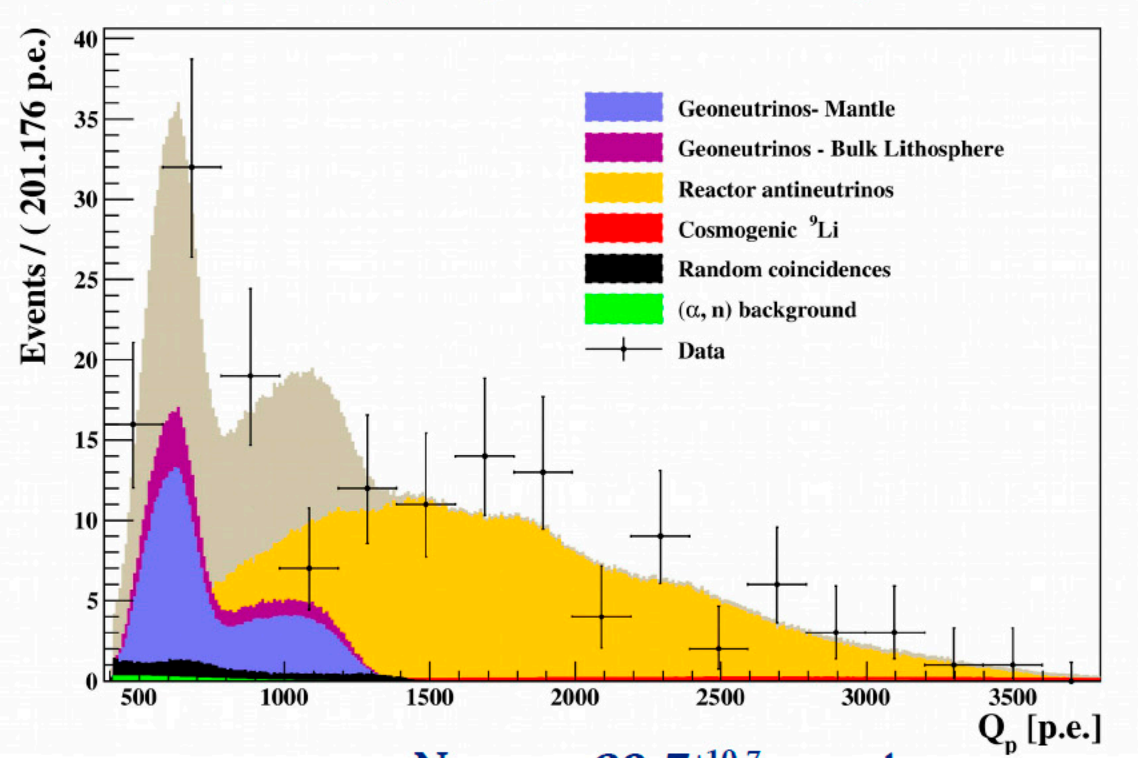
Compatible with all models. Preference for models with higher mantle signal

$$47.0^{+8.4}_{-7.7}\,(\text{stat})^{+2.4}_{-1.9}\,(\text{sys})\ \text{TNU}$$

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

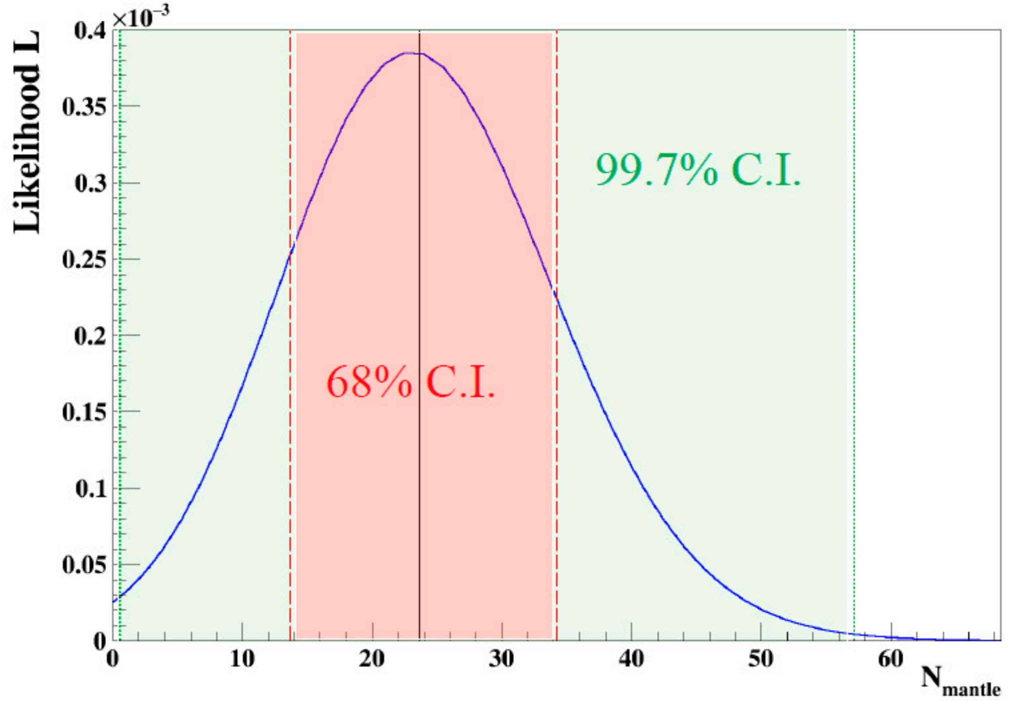
Mantle signal

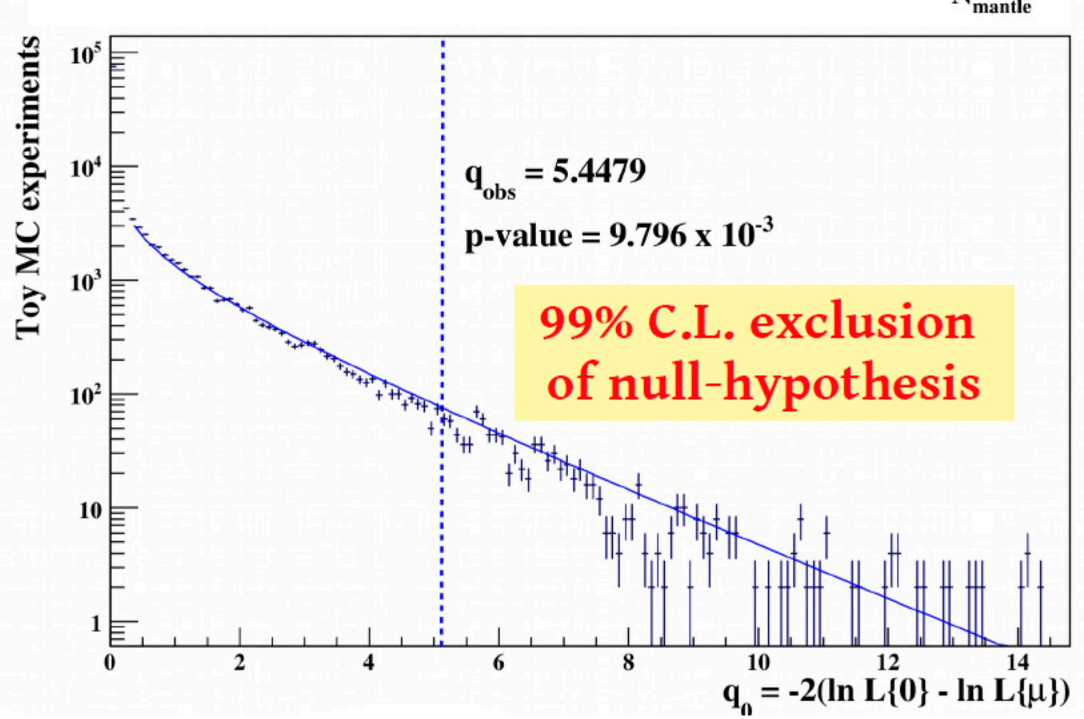
- Relatively **well-known lithosphere constrained** to 28.8 ± 5.6 events using knowledge of the local crust
- Th/U mass ratio (lithosphere) = 3.5 → measured
- Th/U mass ratio (mantle p.d.f.) = 3.7 → to be compatible with BSE



N_{mantle} = $23.7^{+10.7}_{-10.1}$ events

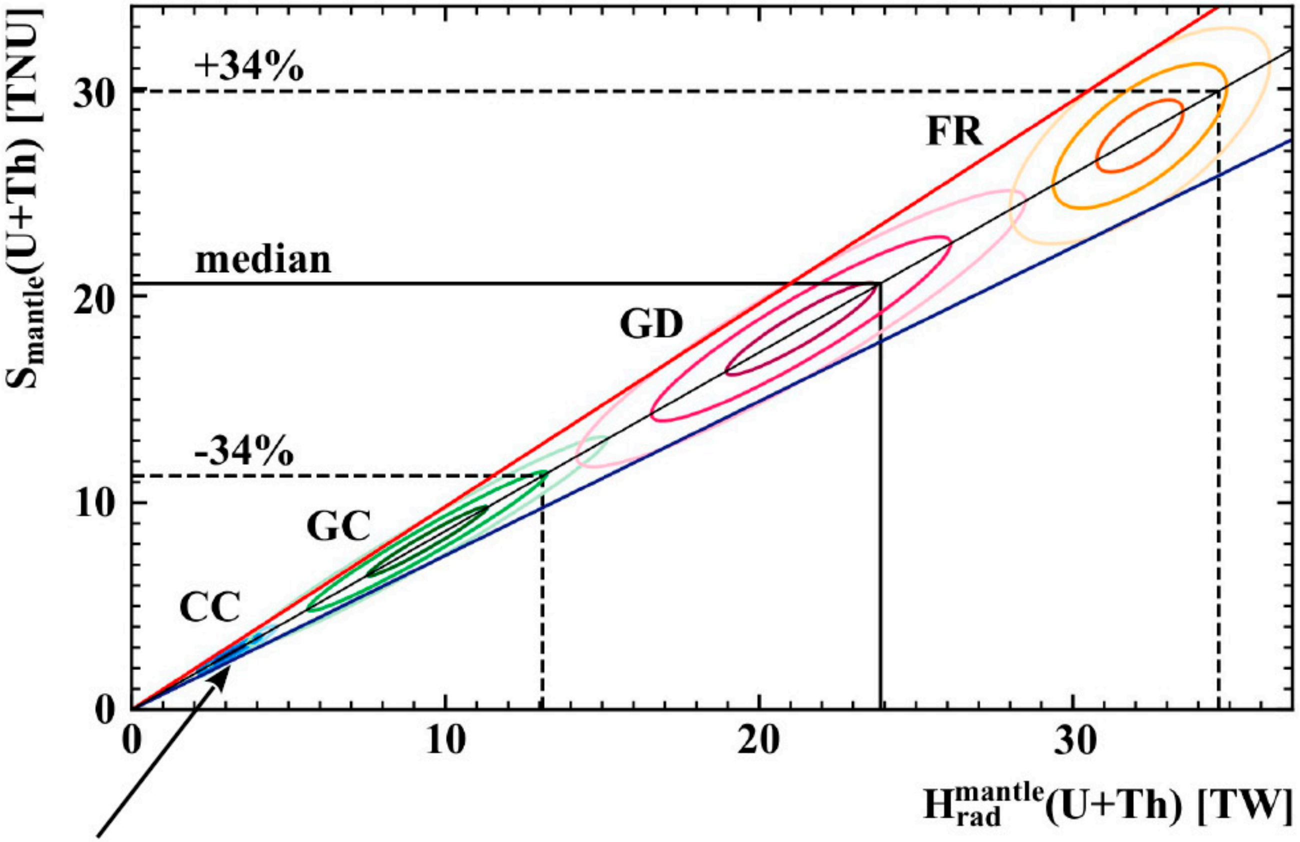
$$21.2^{+9.6}_{-9.0}\,(\text{stat})^{+1.1}_{-0.9}\,(\text{sys})\ \text{TNU}$$





Radiogenic heat

$$H^{rad}_{mantle}(U + Th) = h(U) \cdot M_{mantle}(U) + h(Th) \cdot M_{mantle}(Th)$$



2.4σ tension

Slope of the lines (TNU/TW)

$$S^{LS}_{mantle}(U + Th) = 0.75 \cdot [h(U) + 3.7 \cdot h(Th)] \cdot M_{mantle}(U)$$

$$S^{HS}_{mantle}(U + Th) = 0.98 \cdot [h(U) + 3.7 \cdot h(Th)] \cdot M_{mantle}(U)$$

$$S^{LS}_{mantle}(U + Th) = 0.75 \cdot H^{mantle}_{rad}(U + Th)$$

$$S^{HS}_{mantle}(U + Th) = 0.98 \cdot H^{mantle}_{rad}(U + Th)$$

β = 2/(0.75+0.98) Inverse of slope

$$H^{mantle}_{rad}(U + Th) = \beta \cdot S_{mantle}(U + Th) = 24.6 \text{ TW}$$

(18% K) $H^{mantle}_{rad}(U + Th + K) = 30.0^{+13.5}_{-12.7}$ TW

+

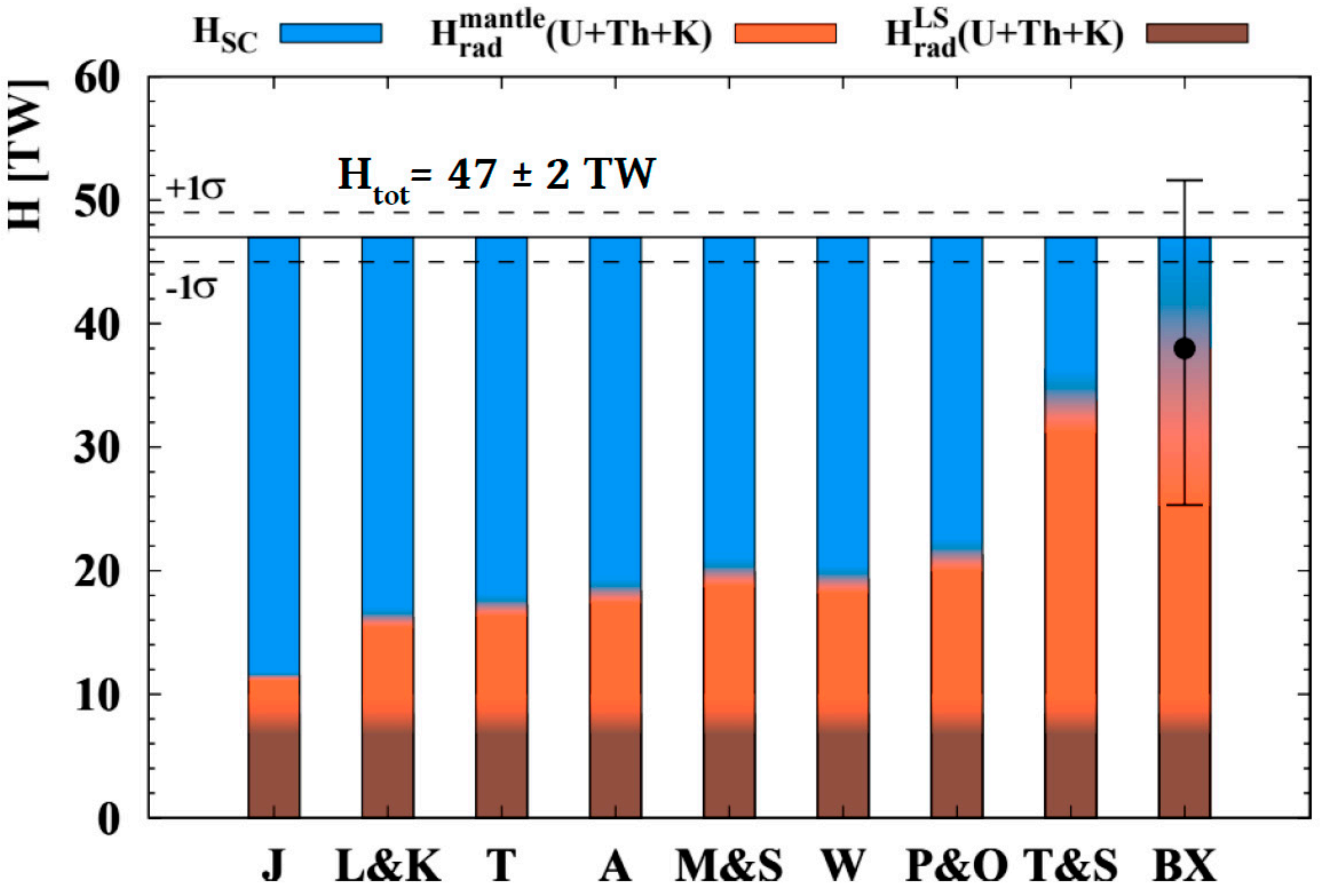
$$H^{LS}_{rad}(U+Th+K) = 8.1^{+1.9}_{-1.4} \text{ TW}$$

=

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

Radiogenic heat: comparison

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



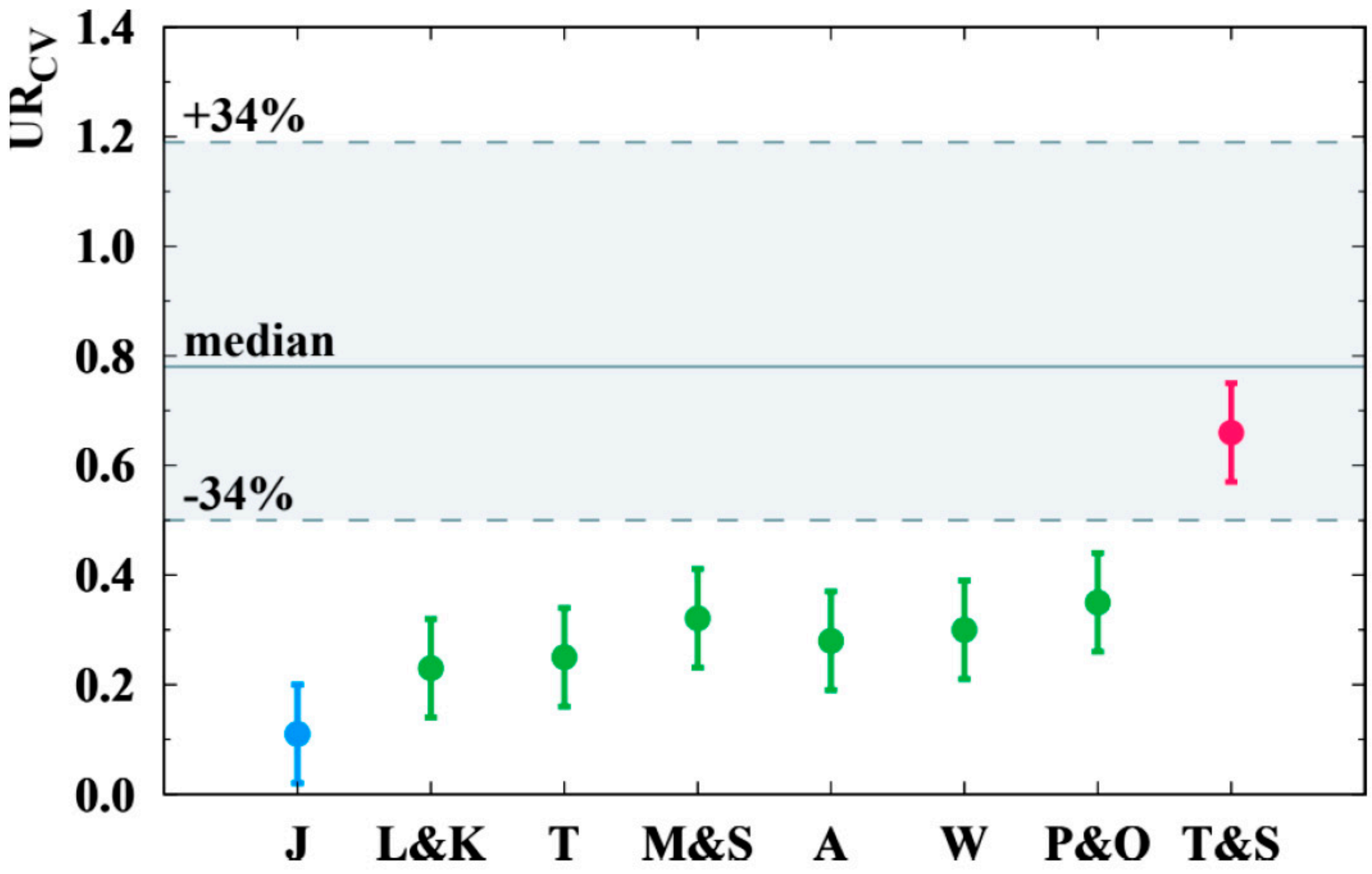
- J: Javoy at al., 2010
- L&K: Lyubetskaya and Korenaga, 2007
- T: Taylor, 1980
- A: Anderson, 2007
- M&S: Mc Donough and Sun, 1995
- W: Wang, 2018
- P&O: Palme and O'Neil, 2003
- T&S: Turcotte and Schubert, 2002
- BX: BOREXINO

Convective Urey Ratio

$H_{tot} = 47 \pm 2$ TW

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

$H^{CC}_{rad} = 6.8^{+1.4}_{-1.1}$ TW



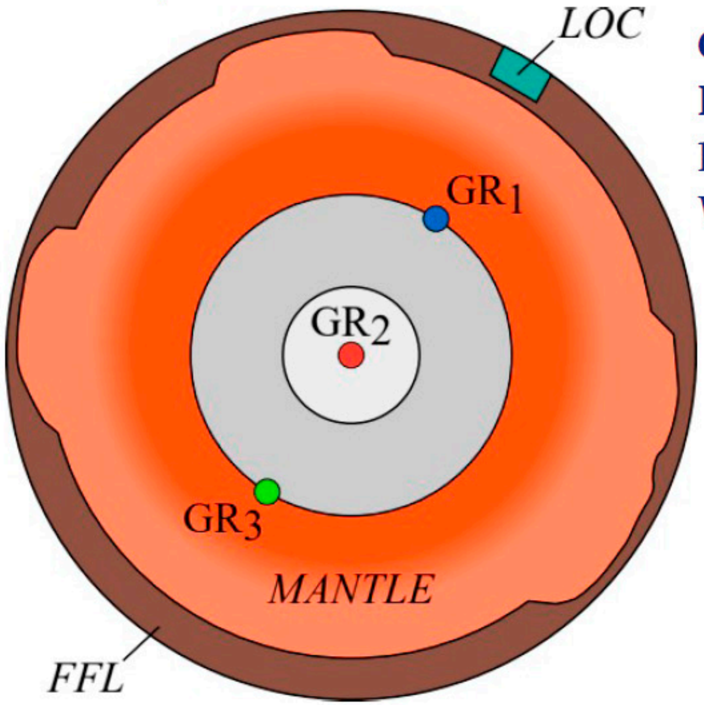
$$UR_{CV} = \frac{H_{rad} - H^{CC}_{rad}}{H_{tot} - H^{CC}_{rad}} = 0.78^{+0.41}_{-0.28}$$

Lower limits:

Parameter	90% C.L.	95% C.L.
$a_{mantle}(U)$	> 13 ppb	> 9 ppb
$a_{mantle}(Th)$	> 34 ppb	> 48 ppb
$H^{mantle}_{rad}(U+Th)$	> 12 TW	> 7 TW
$H^{mantle}_{rad}(U+Th+K)$	> 12.2 TW	> 8.6 TW
UR_{CV}	> 0.13	> 0.04

Georeactor

Georeactor fuel → ^{235}U:^{238}U = 0.76:0.23
(Herndon 2005)

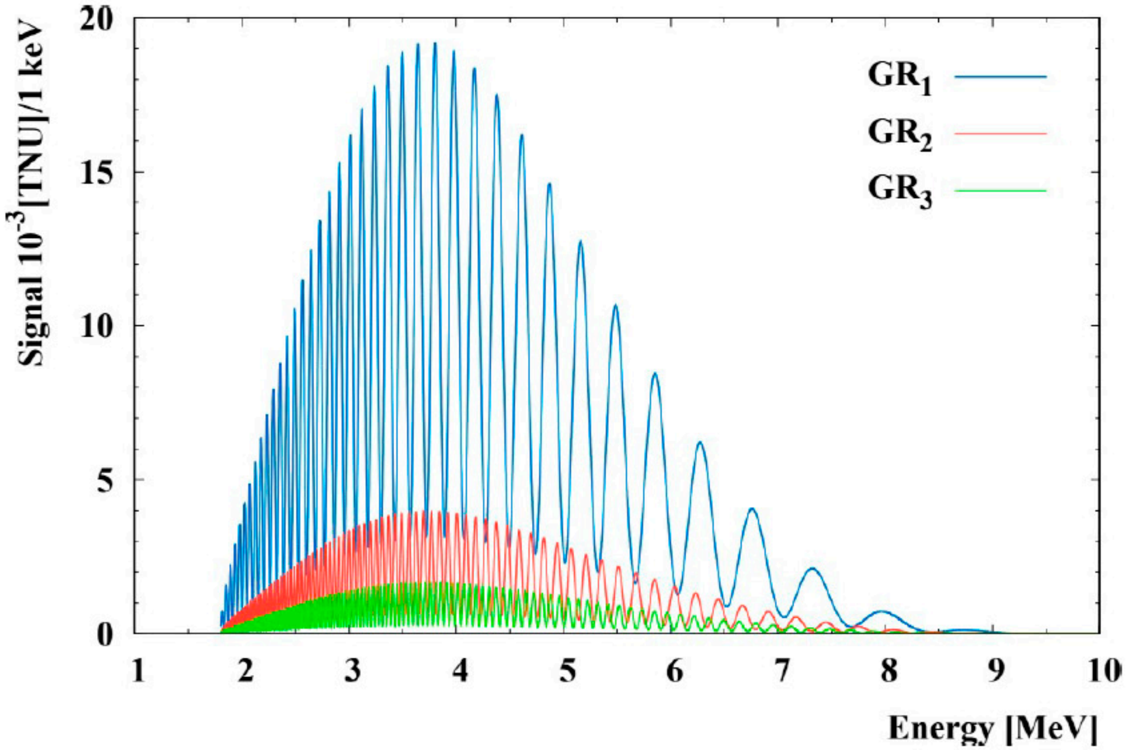


CMB: V. Rusov et al., 2007
Inner core boundary: R. d. de Meijer and W. Van Westrenen, 2008

- **GR1: CMB (d = 2900 km)**
- **GR2: TW – Core (d = R_{Earth})**
- **GR3: TW – CMB (d = 9842 km)**

1 TW georeactor

Position	TNU
GR2: Earth's center	7.73 ± 0.23
GR1: CMB at 2900 km	37.3 ± 1.12
GR3: CMB at 9842 km	3.24 ± 0.1



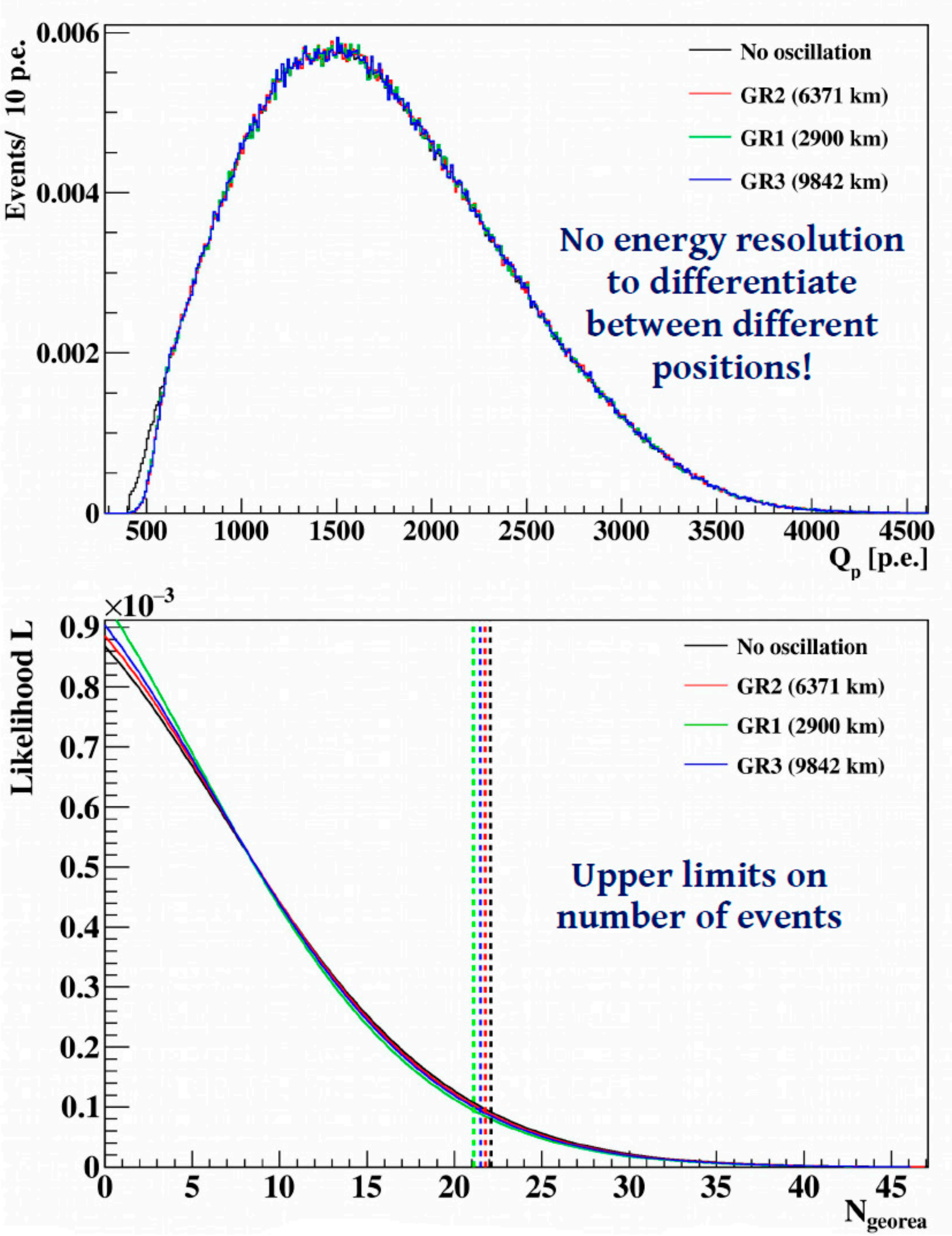
GEOREACTOR: RESULTS

Spectra similar to reactor antineutrinos which are constrained to the expected 97.6 ± 5.5 events in the spectral fit

Upper limits at 95% C.L.

Expected TNU for 1 TW/ TNU limit at 95% C.L.

< 0.5 TW – CMB (d = 2900 km) - GR1
< 2.4 TW – Core (d = R_{Earth}) - GR2
< 5.7 TW – CMB (d = 9842 km) - GR3



Conclusions

1) A total **uncertainty of ~18%** achieved in the geoneutrino signal using Borexino's data with improved analysis $47.0^{+8.4}_{-7.7}\,(\text{stat})^{+2.4}_{-1.9}\,(\text{sys})\,\text{TNU}$

2) Mantle signal extracted by using well-known knowledge of LOC
New statistical tools exploited to **reject the null-hypothesis of mantle signal at 99% C.L.** $21.2^{+9.6}_{-9.0}\,(\text{stat})^{+1.1}_{-0.9}\,(\text{sys})\,\text{TNU}$

3) Radiogenic heat calculated using the obtained mantle signal and assuming 18% contribution from ^{40}K in the mantle. **2.4σ tension with models predicting the lowest amount of mantle signal** $38.2^{+13.6}_{-12.7}\,\text{TW}$

4) Lower limits at 90% C.L. : $UR_{CV} > 0.3$; Mantle H_{rad} (U+Th+K) > 12.2 TW;
a_{mantle} (U) > 13 ppb; a_{mantle} (Th) > 48 ppb

5) Stringent georeactor upper limits at 95% C.L. for three different positions in the Earth
< 0.5 TW (2900 km) < 2.4 TW (center) < 5.7 TW (9842 km)

arXiv:1909.02257

THANK YOU FOR YOUR ATTENTION!

Backup: KamLAND summary

- The KamLAND experiment measures anti-neutrino from various sources over a wide energy range.

- **Preliminary results are presented.**
  - Low-reactor operation period :
    - ~4.8 years (40% of total livetime)
    - **clear energy spectrum of geo-neutrino** → **better understanding of U, Th each contribution**
  - geo-neutrino event measurement with **15.6 % uncertainty**
  - geoscience discussion
    - **Th/U mass ratio** : **$5.3^{+6.0}_{-3.6}$**, consistent with chondrite data and BSE models
    - **Radiogenic heat** : **$12.4^{+4.9}_{-4.9}$ TW** (Mantle+Crust, U+Th), consistent with Middle Q and Low Q models
    - **Separated test of ^{238}U and ^{232}Th geo-neutrinos** → **power to determine past radiogenic heat through the Earth's history**
    - **Mantle signal : $0.67^{+0.63}_{-0.64} \times 10^{6}$ cm^{-2}s^{-2}** → *** High Q is rejected with >2σ**
      *** depends on estimation of crust contribution**

More information - Neutrino Geoscience 2019:
https://indico.cern.ch/event/825708/contributions/3552210/

- **Future Prospects:**
  - KamLAND continues to measure geo-neutrinos with low-reactor backgrounds stably
  - Better understanding of crust contribution → **helps further estimation of mantel signals**
  - Multi-sight measurements
  - **Ocean Bottom Detector has strong power to measure mantle contribution directly.** Poster by H. Watanabe, K. Ueki et al