BOREXINO GEONEUTRINOS MEASUREMENT

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NOVEMBER 16, 2025 NEUTRINO GEOSCIENCE 2026,

ZHUHAI, CHINA



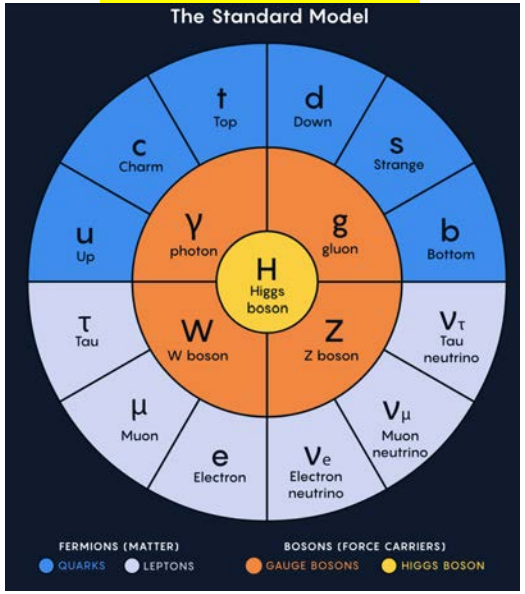


GSI

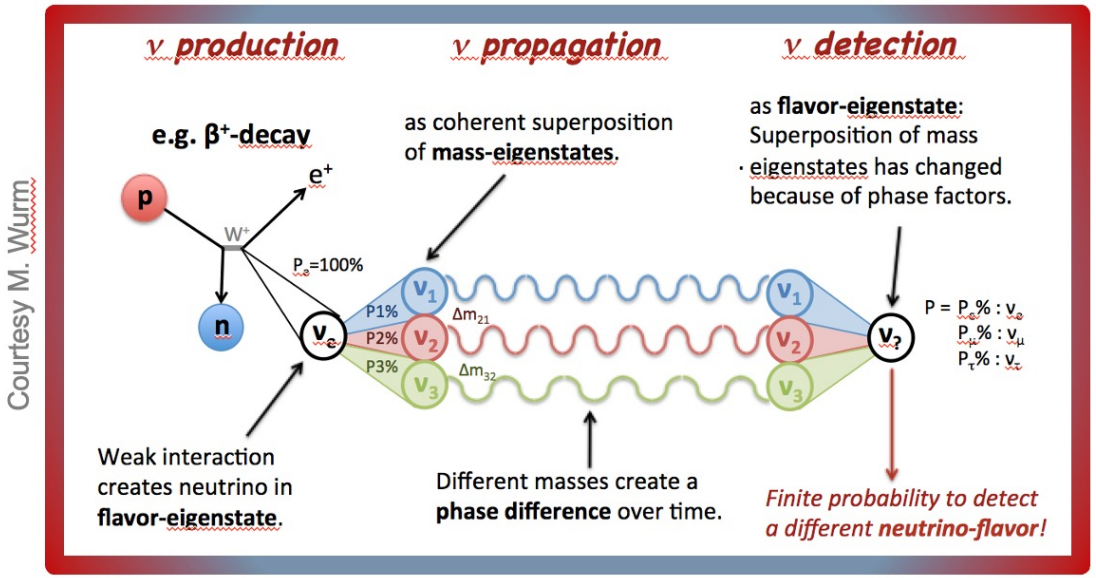
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

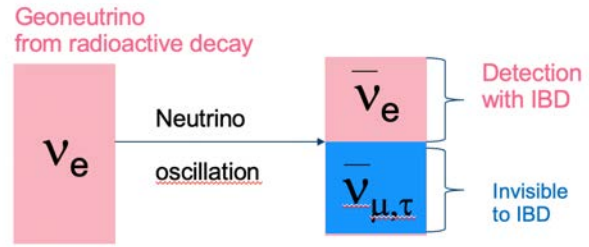
NEUTRINOS: SPECIAL AMONG ELEMENTARY PARTICLES

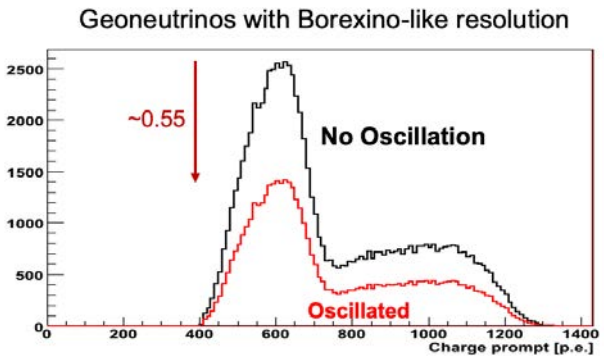
Standard Model



Neutrino Oscillations







Many Open Questions

- ✓ Neutrino mass ordering (normal vs inverted)
- ✓ CP-violating phase ?
- ✓ Octant of θ_{23} mixing angle
- ✓ Absolute mass-scale
- ✓ Origin of neutrino mass (Dirac vs Majorana)
- ✓ Existence of sterile neutrino

Weak Interactions: Detection Challenge

- Large detectors
- Underground laboratories
- Extreme radio-purity

Bring unperturbed information about the source: the Sun, SN, far-away galaxy…. **the Earth!**

NEUTRINO GEOSCIENCE

Abundances of radioactive elements

Nuclear physics

$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- +$ 6 anti-neutrinos + 51.7 MeV

$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- +$ 4 anti-neutrinos + 42.8 MeV

$^{40}K \rightarrow {}^{40}Ca + e^- +$ 1 anti-neutrino + 1.32 MeV

Main goal:
Mantle radiogenic heat

- U/Th ratio
- Mantle homogeneity
- Earth formation

Distribution of radioactive elements

Signal prediction

Geoneutrino signal

Measurement interpretation

Neutrino geoscience: a truly interdisciplinary field!

GEONEUTRINO DETECTION: INVERSE BETA DECAY

Why Inverse Beta Decay (IBD)?

✓ Clean delayed-coincidence signature

✓ Excellent background rejection

✓ Large (~10^{-42} $cm^{2)}$ & well known (~1%) cross section

✓ Antineutrino energy reconstruction

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

Threshold = 1.8 MeV

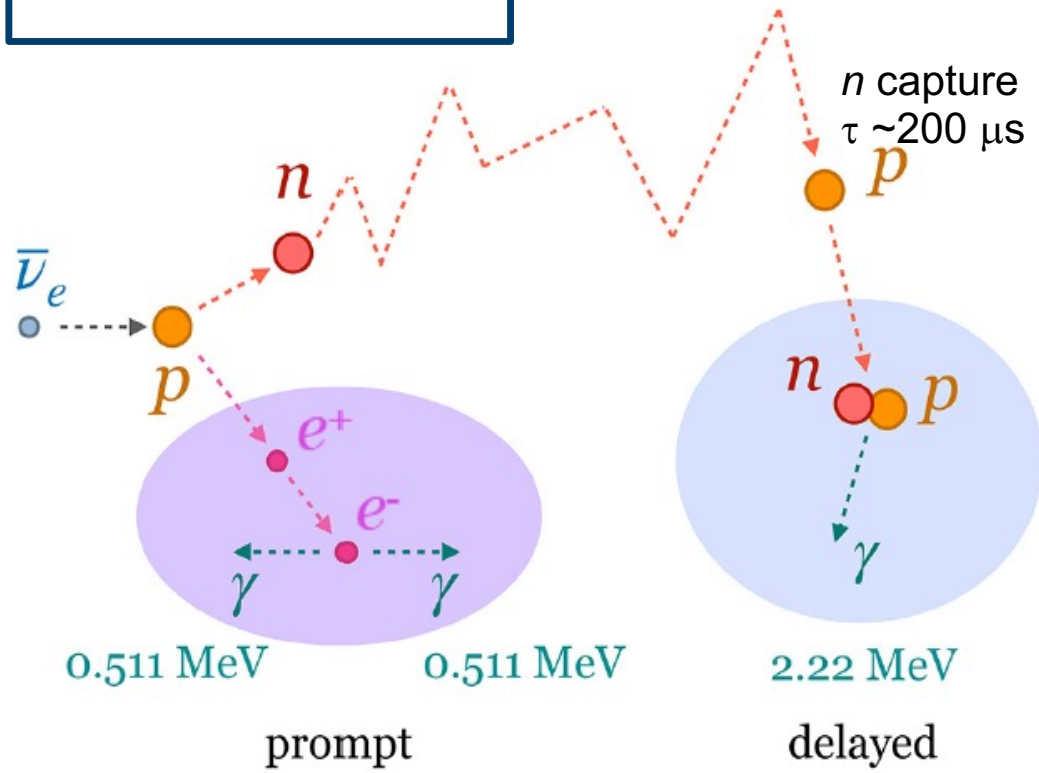
- ✓ ^{238}U & ^{232}Th geoneutrinos only
- ✓ No ^{40}K

Very limited directionality

- ✓ very limited statistical directional sensitivity.
- ✓ future concepts

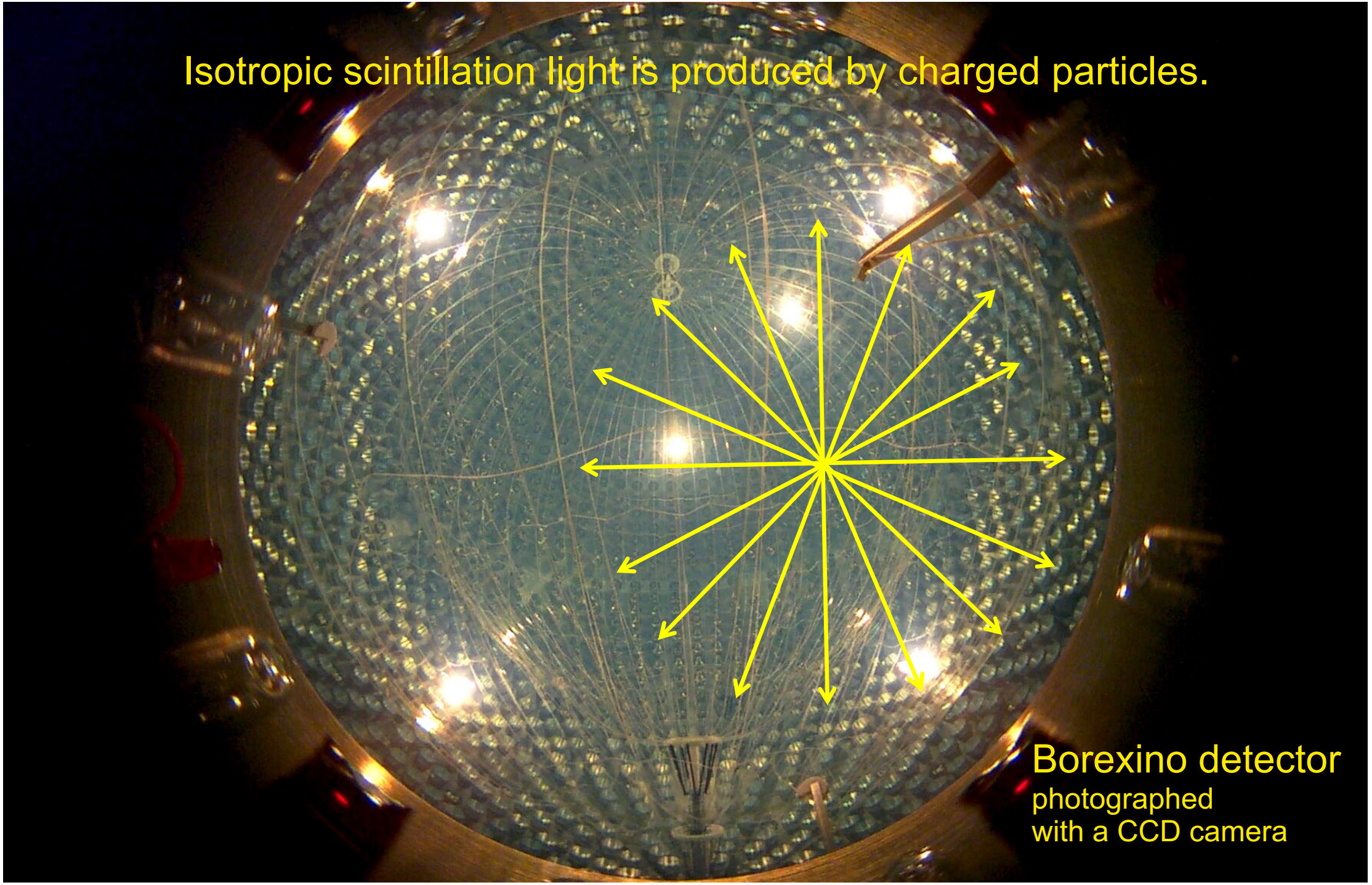
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

PHYS. REV. D 101, 012009 (2020)



The prompt and delayed event: detection in a liquid scintillator (LS) detector!

Isotropic scintillation light is produced by charged particles.



Borexino detector
photographed
with a CCD camera

SELECTING IBD CANDIDATES

IBD: antineutrino + proton → positron + neutron

E_{prompt} = E(antineutrino) – 0.784 MeV

$E_{delayed}$ = 2.2 MeV gamma

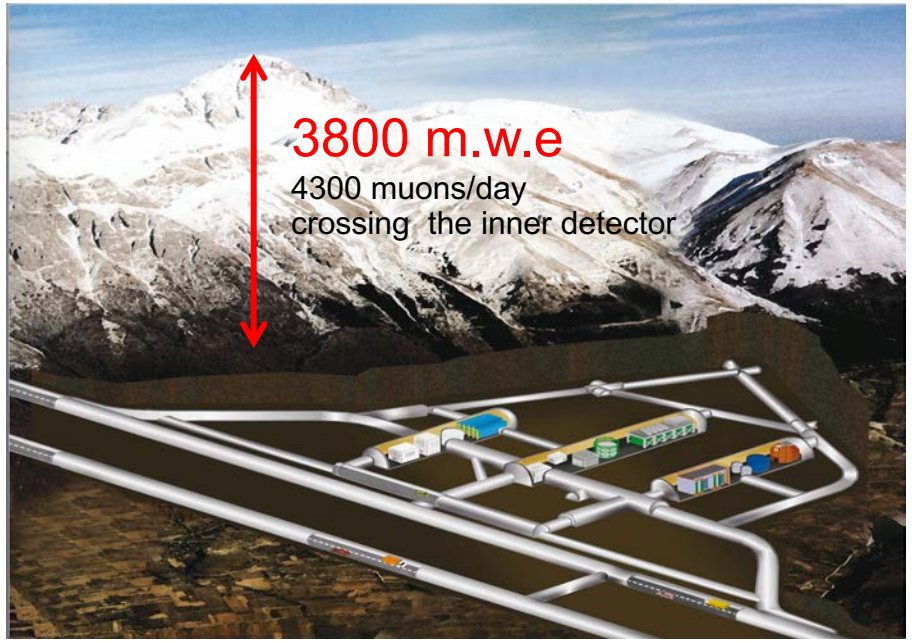
Δ time = time correlation

Δ R = space correlation

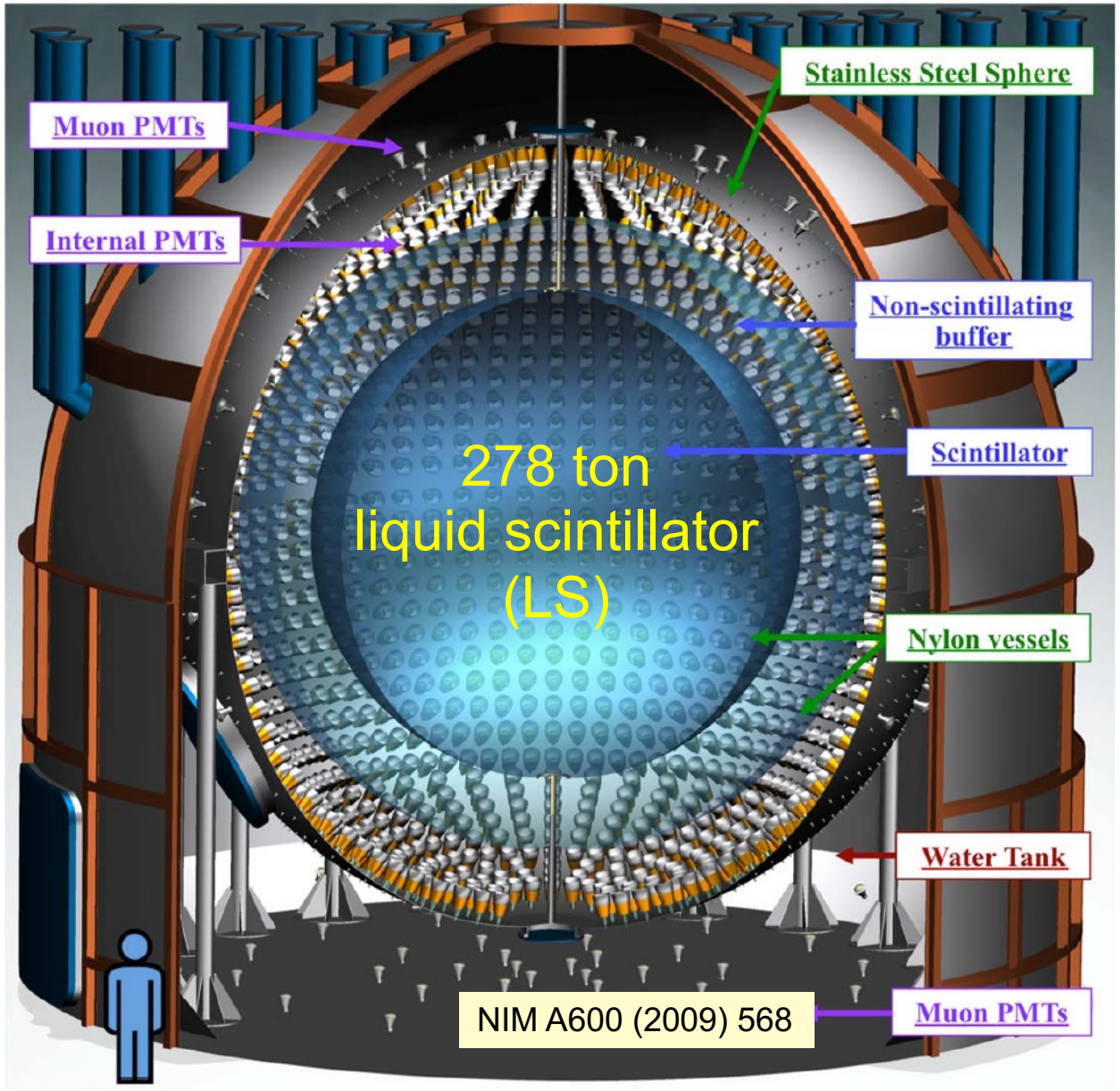
- Charged particles produce scintillation light;
- Gamma rays from the positron annihilation and from the neutron capture are neutral particles but in the scintillator they interact mostly via Compton scattering producing several electrons = charged particles;
- Scintillation light is detected by an array of phototubes (PMTs) converting photons to electrical signal (photoelectrons – pe);
- Number of photoelectrons = function of (energy deposit) -> E_{prompt}, $E_{delayed}$
- Hit PMTs time pattern = vertex reconstruction -> **ΔR** of events
- Each trigger has its GPS time -> **Δtime** of events

BOREXINO DETECTOR

Laboratori Nazionali del Gran Sasso, Italy



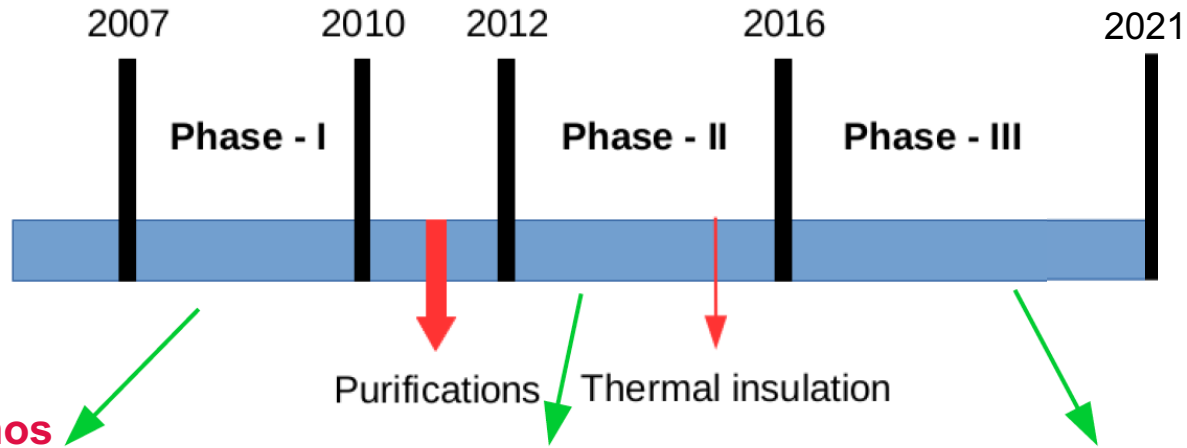
- **the world's radio-purest LS detector**
  $< 9 \times 10^{-19}$ g(Th)/g LS , $< 8 \times 10^{-20}$ g(U)/g LS
- **~500 hit PMTs / MeV**
- energy reconstruction: 5 keV (5%) @ 1 MeV
- position reconstruction: 10 cm @ 1 MeV
- pulse shape identification (α/β, e^+/e^-)



Development and construction from 1990 to 2007.
Data taking from May 2007 to October 2021.


To Gianpaolo
Gianpaolo Bellini
12 June 1935 · Milano
12 August 2026 · Foresto Sparso
With gratitude and affection.

TIMELINE OF BOREXINO RESULTS



Solar neutrinos

- First observation and precise measurement of ^{7}Be ν
- First observation of *pep* ν, ^{8}B ν with low threshold
- Give the best limit of CNO ν

- Precise measurement of *pp* ν
- First complete study of all components of the pp-chain

Nature 562 (2018) 496

CNO observation
Nature 587 (2020) 577

CNO & Implications for the Sun *Phys. Rev. Lett.* 129 (2022) 252701

Final CNO results with Directionality *Phys. Rev. D* 108 (2023) 102005.

Geo neutrinos

- First observation in 2010

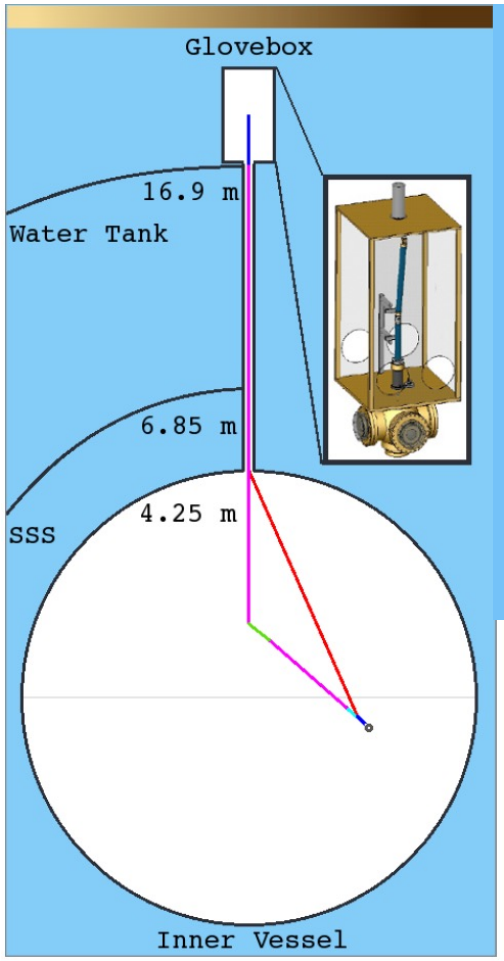
Updates in 2013 and 2015

"Geoneutrino long paper" PRD 21/01/2020

Other topics

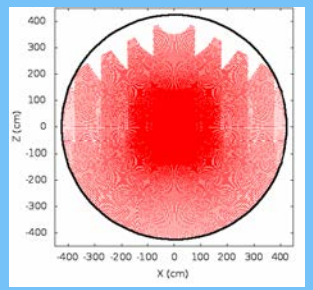
- Search for solar, astro anti-ν (2011)
- Test of electric charge conservation (2015)
- Limit on ν-magnetic moment (2017)
- Search for solar axions (2008, 2012)
- Search for coincidence with GRB's (2016 / 2017)

BOREXINO CALIBRATION



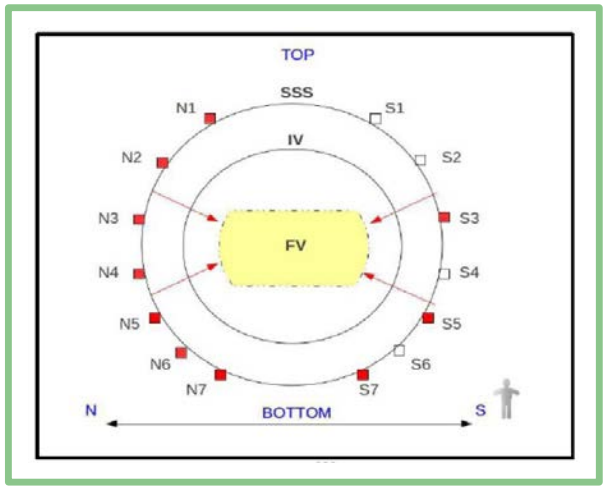
Internal calibration

- ~300 points in the whole scintillator volume
- LED-based source positioning system





Source	Type	E [MeV]	Position	Motivations
^{57}Co	γ	0.122	in IV volume	Energy scale
^{139}Ce	γ	0.165	in IV volume	Energy scale
^{203}Hg	γ	0.279	in IV volume	Energy scale
^{85}Sr	γ	0.514	z-axis + sphere R=3 m	Energy scale + FV
^{54}Mn	γ	0.834	along z-axis	Energy scale
^{65}Zn	γ	1.115	along z-axis	Energy scale
^{60}Co	γ	1.173, 1.332	along z-axis	Energy scale
^{40}K	γ	1.460	along z-axis	Energy scale
^{222}Rn+^{14}C	β,γ	0-3.20	in IV volume	FV+uniformity
	α	5.5, 6.0, 7.4	in IV volume	FV+uniformity
^{241}Am^{9}Be	n	0-9	sphere R=4 m	Energy scale + FV

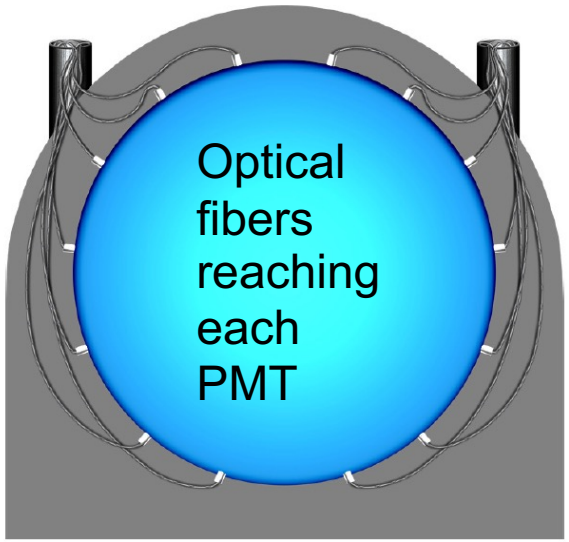


External calibration

9 positions with ^{228}Th source (γ 2.615 MeV)

Laser calibration

- PMT time equalisation
- PMT charge calibration (charge calib. also using ^{14}C)



JINST 7 (2012) P10018

BOREXINO MONTE CARLO

Better than 1% precision
for all relevant quantities in the solar analysis <2 MeV

Astrop. Phys. 97 (2018) 136

Geant-4 based

Tracking code

- Full detector geometry
- Energy loss
- Photon production & propagation

C++ Borexino custom

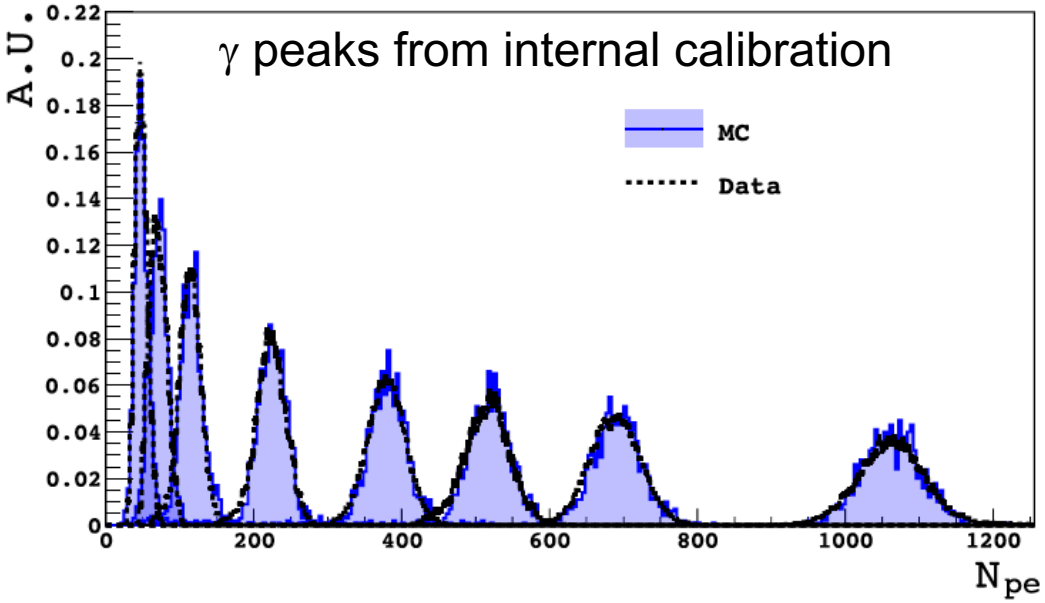
Electronics simulation

Follows real DAQ conditions
- PMT quality and calibration
- Dark noise
- Trigger condition
- Number of working channels on an event-by-event basis

Echidna: C++ Borexino custom

Reconstruction

- Several energy estimators
- Position reconstruction
- Pulse-shape variables
- Output in the same format as reconstructed data files



- **Tuning on calibration data.**
- **Independently measured input parameters**: emission spectra, attenuation length, PMT after-pulse, refractive index, effective quantum efficiencies.

The spectral shape of signal (geoneutrinos) and most of the background components (see later) was produced with this tuned Monte Carlo.

MAIN BACKGROUND SOURCES

1) Cosmogenic background

- **^{9}Li and ^{8}He** ($\tau_{1/2}$ = 119/178 ms)
  - ✓ decay: β(prompt) + neutron (delayed);
- **fast neutrons**
  - ✓ scattered protons (prompt)

Estimated by studying IBD-like coincidences detected AFTER muons.

- Muons from the rock – negligible via MC.

2) Accidental coincidences;

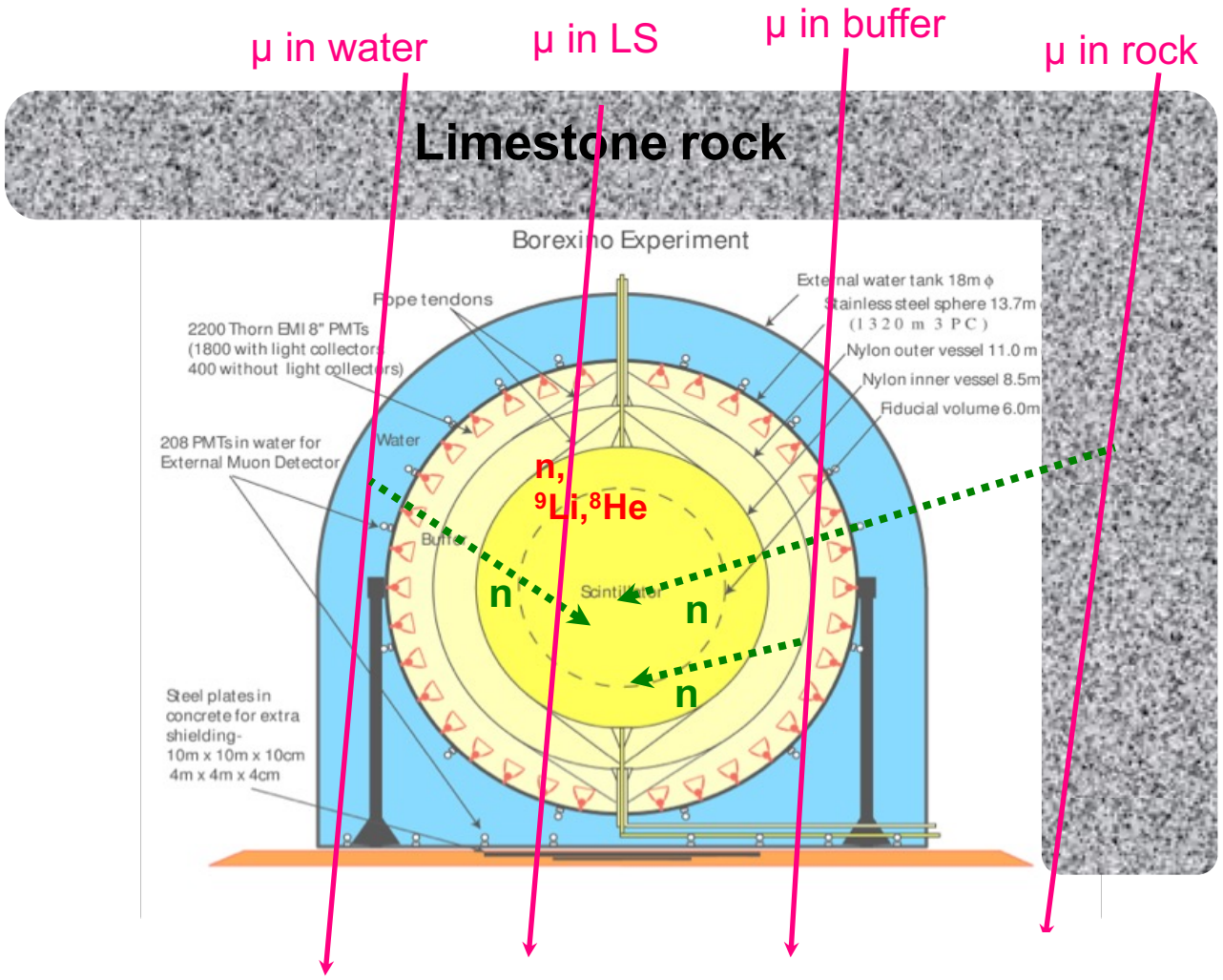
Estimated from OFF-time IBD-like coincidences.

3) Due to the internal radioactivity:

(α, n) reactions: ^{13}C(α, n)^{16}O

Prompt: scattered proton, ^{12}C(4.4 MeV) & ^{16}O (6.1 MeV)

Estimated via MC using ^{210}Po(α) and ^{13}C contamination levels & (α, n) cross section.



OPTIMIZED IBD SELECTION CUTS

Geoneutrino detection efficiency: (86.98 ± 1.50)%

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

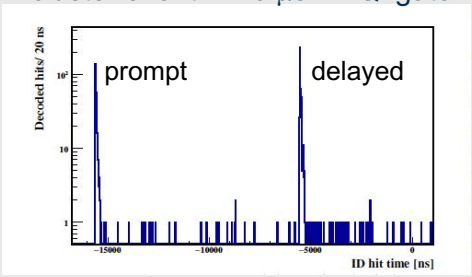
- Neutron captures on **proton (2.2 MeV)** and in about 1% of cases on **^{12}C (4.95 MeV)**
- Spill out effect at the nylon inner vessel border
- Radon correlated ^{214}Po($\alpha + \gamma$) decays from ^{214}Bi and ^{214}Po fast coincidences

Time correlation

dt = (2.5-12.5) μs + (20-1280) μs

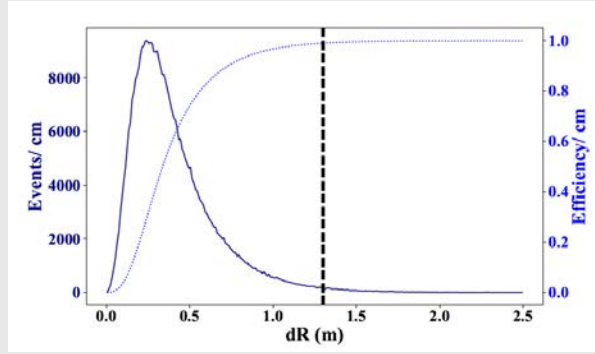
Neutron capture $\tau = (254.5 \pm 1.8)$ μs

2 cluster event in 16 μs DAQ gate



Space correlation

dR < 1.3 m

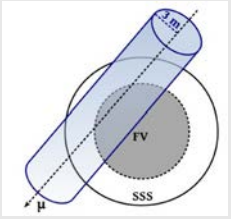


Muon veto

2s || 1.6 s : ^{9}Li(β + n)

2 ms: neutrons

- Several veto categories
- Strict and special muon tags



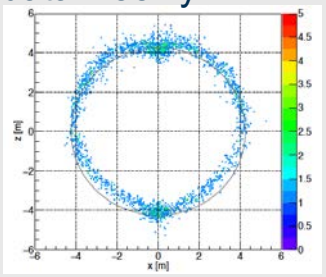
- Whole detector
- **Cylinder**

Only 2.2% exposure loss

Dynamic Fiducial Volume

> 10 cm from IV (prompt)

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



Multiplicity

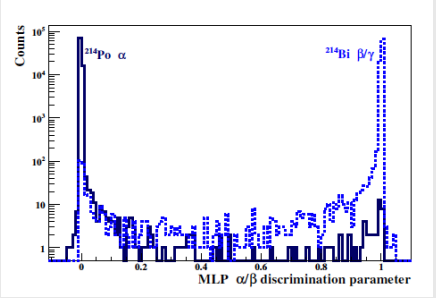
No event with Q >400 pe ±2 ms around prompt/delayed

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

α/β discrimination

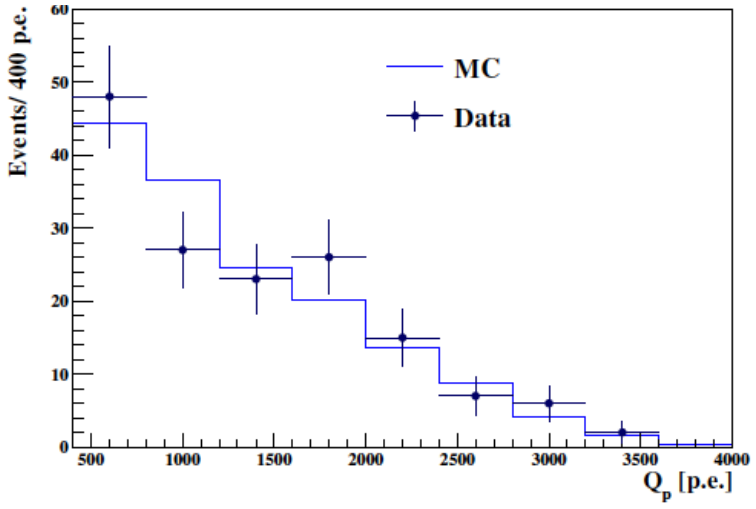
$MLP_{delayed}$ > 0.8

- Radon correlated ^{214}Po(α+γ)

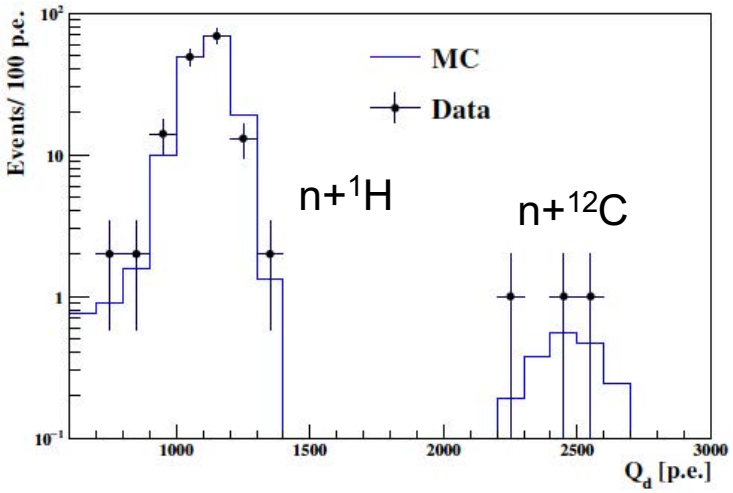


GOLDEN CANDIDATES: 154

Prompt charge spectrum

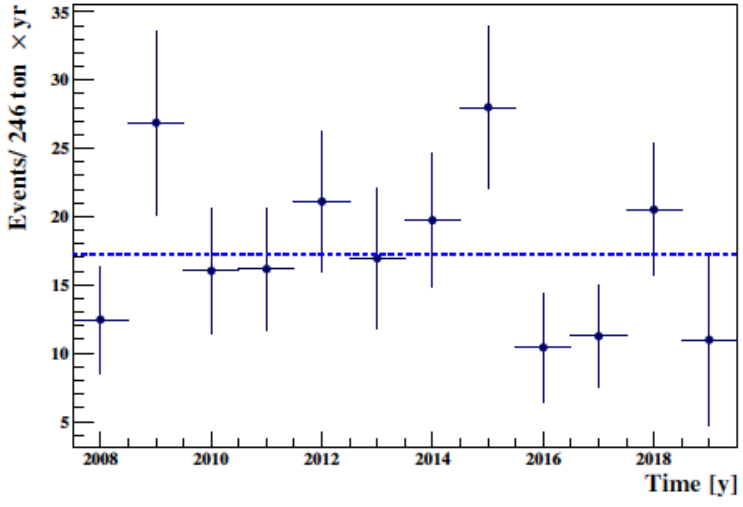


Delayed charge spectrum

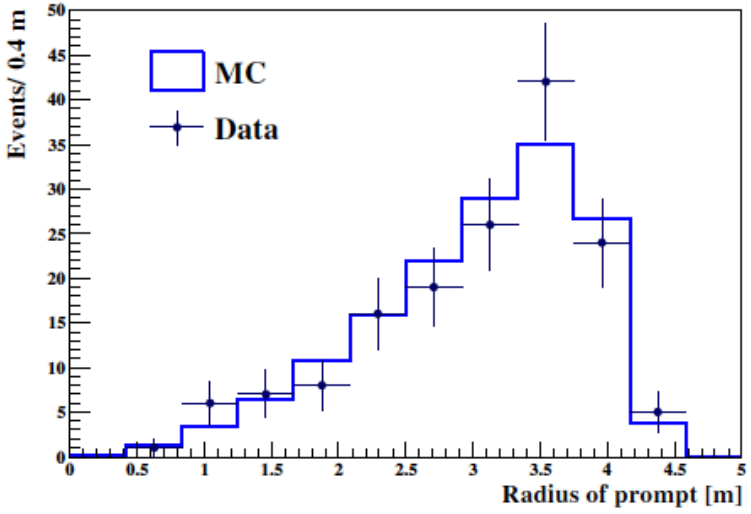


- December 9, 2007 to April 28, 2019
- 3262.74 days of data taking
- Average FV = (245.8 ± 8.7) ton
- **Exposure = (1.29 ± 0.05) x 10^{32} proton x year**
- Including systematics on position reconstruction and muon veto loss, for 100% detection eff.

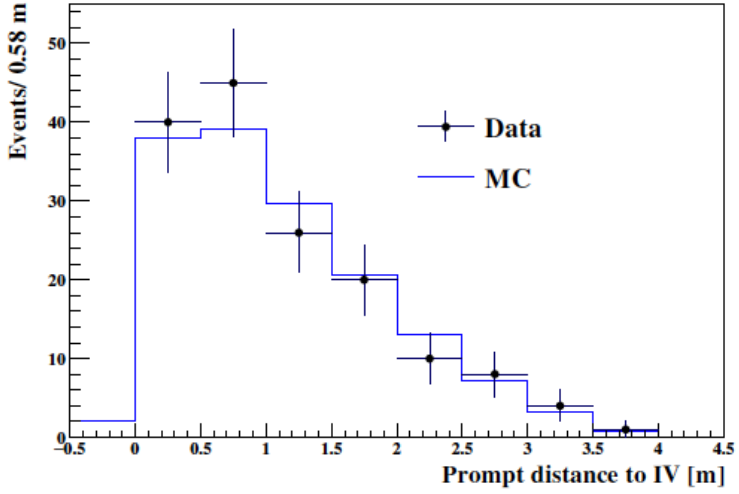
Distribution in time



Radial distribution



Distance to the Inner Vessel



We have then golden candidates found as time and spatial coincidences:

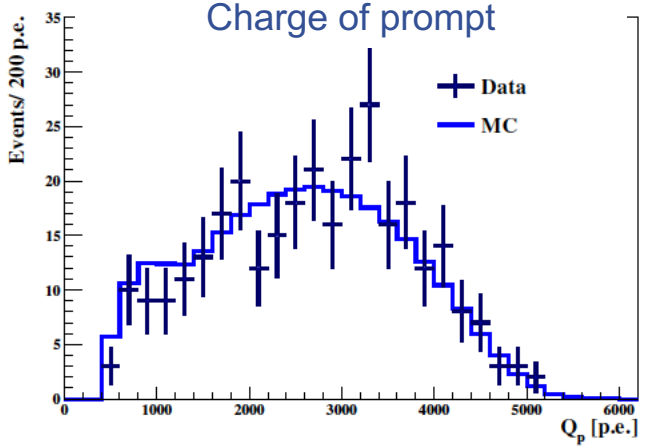
- They can be due to:
  - ✓**Geo-neutrinos;**
  - ✓**Reactor antineutrinos;**
  - ✓**Non-antineutrino backgrounds;**
- We need to estimate different contributions and then to extract the number of measured geo-neutrinos by fitting the E_{prompt} energy spectrum;

NON-ANTINEUTRINO BACKGROUNDS

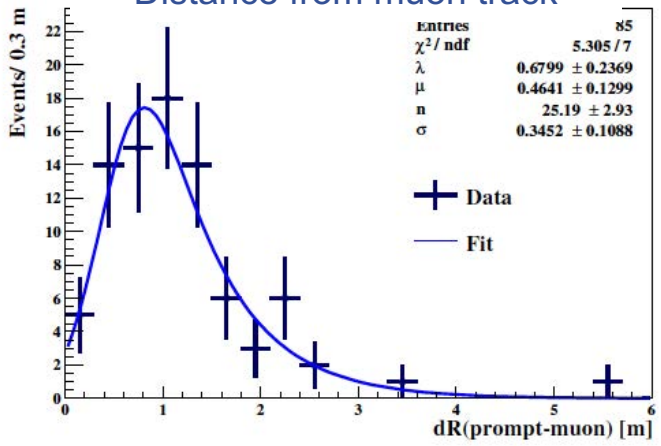
^{9}Li (β+n) events < 2s after muons

$\tau_{measured}$ = (0.260 ± 0.021) s

Charge of prompt



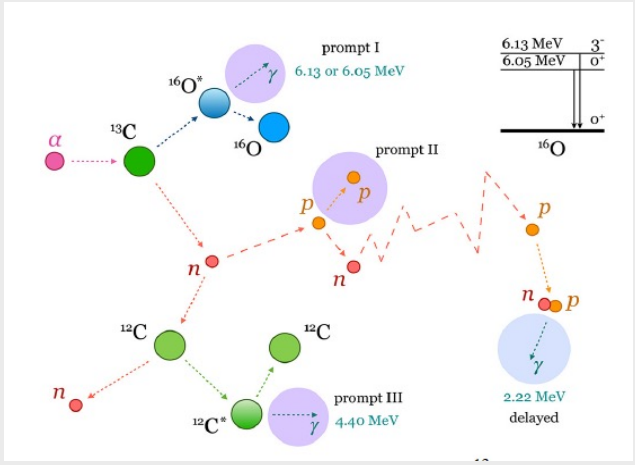
Distance from muon track

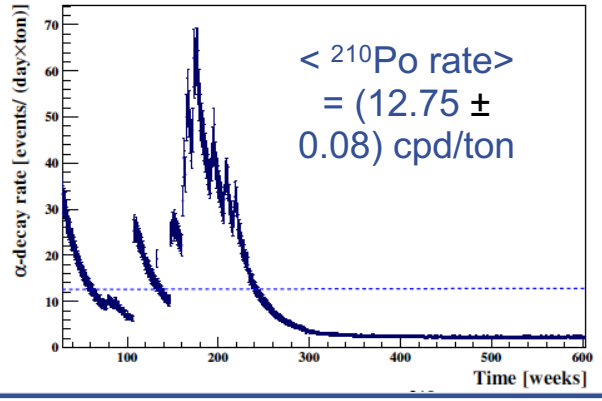


^{13}C(^{210}Po(α), n) ^{16}O

Y_n = (1.45 ± 0.22) x 10^{-7}

$\varepsilon_{IBD\text{-}like}$ = 0.56 for ^{210}Po in LS





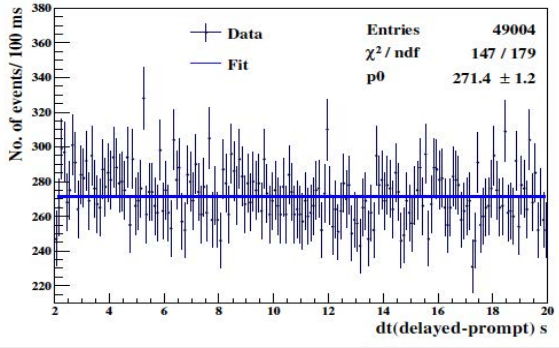
< ^{210}Po rate> = (12.75 ± 0.08) cpd/ton

Accidentals

R_{acc} = (3029.0 ± 12.7) s^{-1}

including scaling factor
exp(-R_{muon} x 2s) = 0.896
due to the 2 s muon veto before delayed

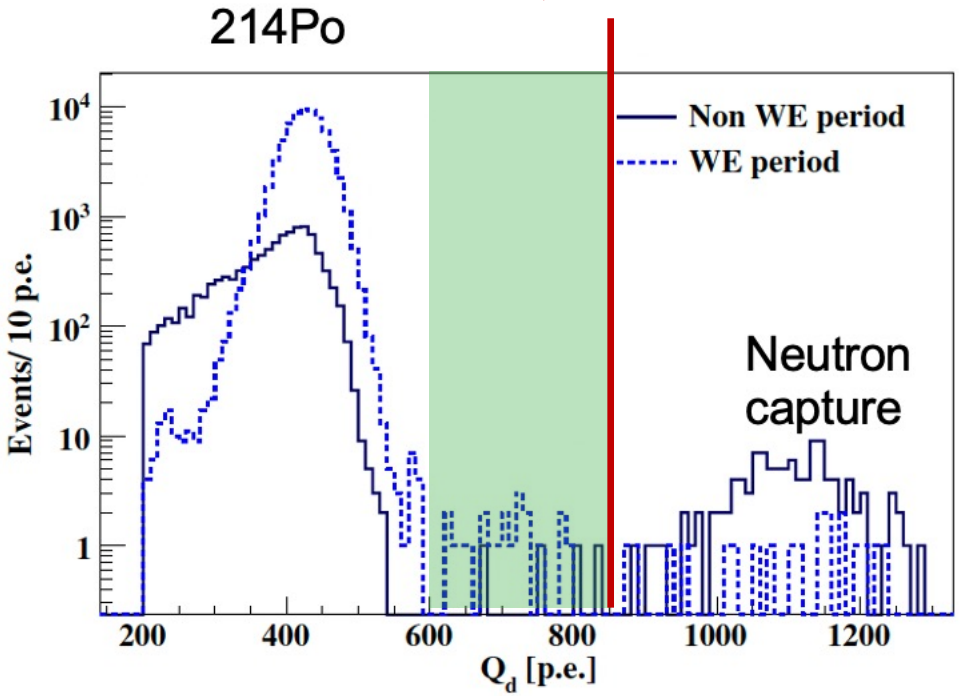
Off-time window dt = 2 -20 s



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 ± 0.0010
Total	8.28 ± 1.01

^{214}Bi – ^{214}Po correlated background

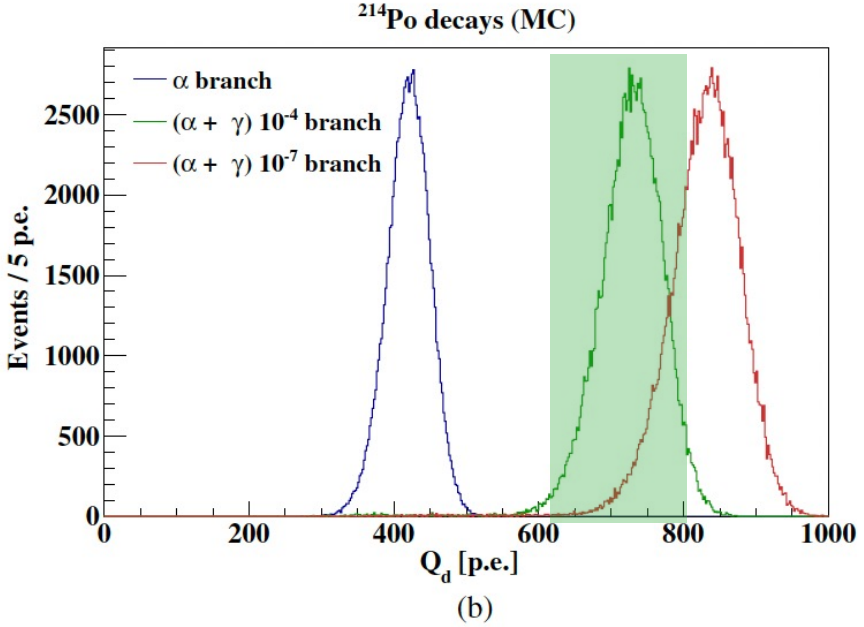
$Q_{d,min}$= 860 pe (WE period)



- WE… water extraction period, with increased ^{222}Rn background – about 100,000 ^{214}Bi – ^{214}Po events
- During this period, the minimum delayed-energy threshold was raised to 860 p.e.
- Pulse-shape discrimination requiring β-like delayed signals.

TABLE XI. Decay modes of ^{214}Po.

Decay mode	Branching ratio [%]	Energy [keV]
α	99.99	$E_\alpha = 7833.46$
$\alpha + \gamma$	1.04×10^{-4}	$E_\alpha = 7033.66$ $E_\gamma = 799.7$
$\alpha + \gamma$	6.0×10^{-7}	$E_\alpha = 6735.76$ $E_\gamma = 1097.7$

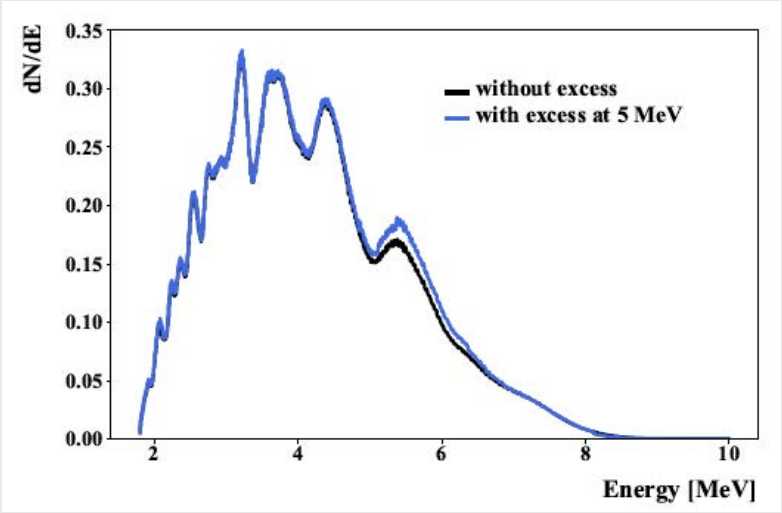


NEUTRINO BACKGROUNDS

Reactor antineutrinos

	Mueller et al 2011	With "5 MeV bump"
Signal [TNU]	$84.5^{+1.5}_{-1.4}$	$79.6^{+1.4}_{-1.3}$
# Events	$97.6^{+1.7}_{-1.6}$	$91.9^{+1.6}_{-1.5}$

- For all ~440 world reactors (1.2 TW total power)
  - ✓ their nominal thermal powers (PRIS database of IAEA)
  - ✓ monthly load factors (PRIS database)
  - ✓ distance to LNGS (no reactors in Italy)
- ^{235}U, ^{238}U, ^{239}Pu , and ^{241}Pu fuel
  - ✓ power fractions for different reactor types
  - ✓ energy released per fission
  - ✓ energy spectra (Mueller et al. 2011 and Daya Bay)
- P_{ee} electron neutrino survival probability
- IBD cross section
- Detection efficiency = 0.8955 ± 0.0150

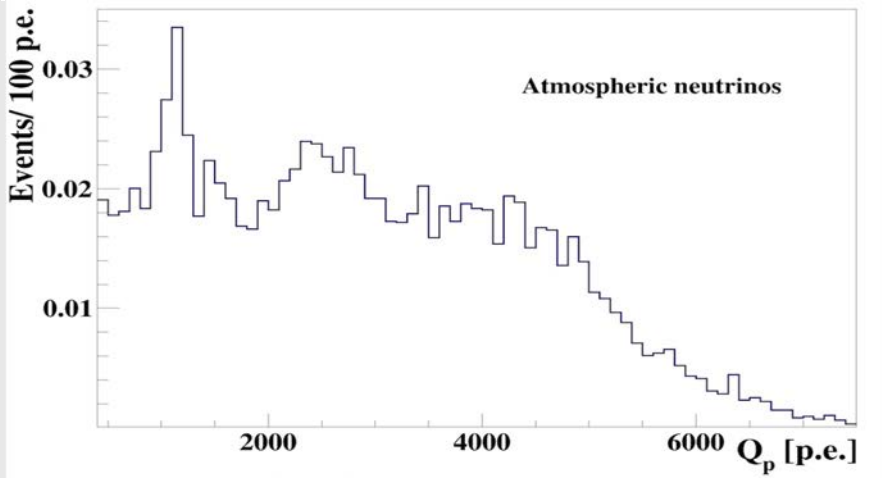


Atmospheric neutrinos

Energy window	Geoneutrino	Reactor antineutrino	> 1 MeV
Events	2.2 ± 1.1	6.7 ± 3.4	9.2 ± 4.6

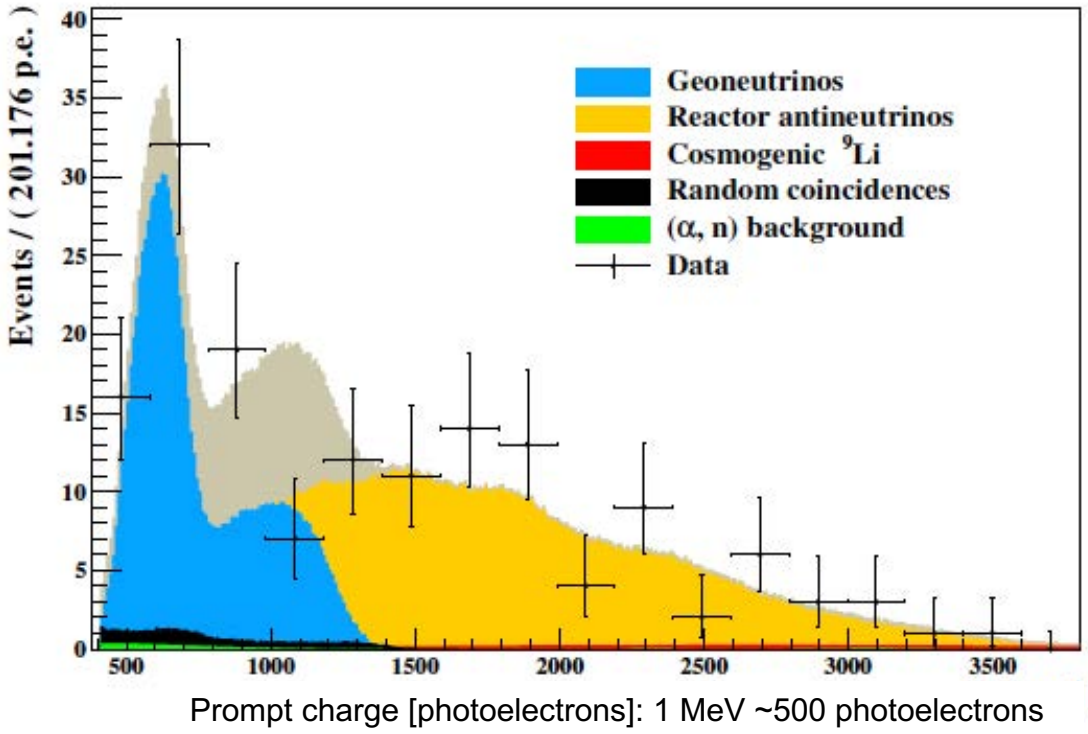
- Estimated 50% uncertainty on the prediction
- Indications of overestimation
- Included in the systematic error
- Atmospheric neutrino fluxes from HKKM2014 (>100 MeV) and FLUKA (<100 MeV)
- Matter effects included

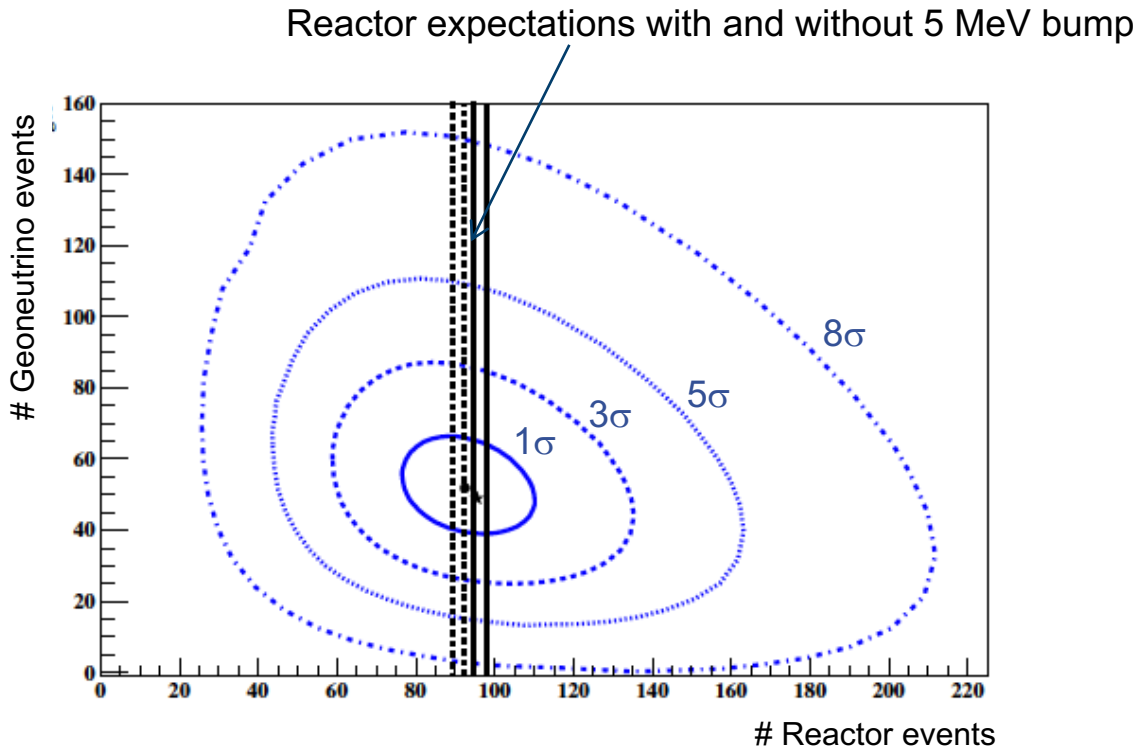
Charge spectrum after IBD selection cuts



1 MeV ~ 500 p.e.

SPECTRAL FIT with fixed chondritic Th/U ratio





- Unbinned likelihood fit of charge spectrum of 154 prompts
- S(Th)/S(U) = 2.7 (corresponds to chondritic Th/U mass ratio of 3.9)
- **Reactor signal unconstrained** and result compatible with expectations
- ^{9}Li, accidentals, and (α, n) background constrained to expectations
- **Systematics** includes atmospheric neutrinos, shape of reactor spectrum, vessel shape and position reconstructions, detection efficiency
- Compatible results with U and Th ratio free on total signal, but no sensitivity to U/Th ratio due to the low exposure

Resulting number of geoneutrinos (median value)

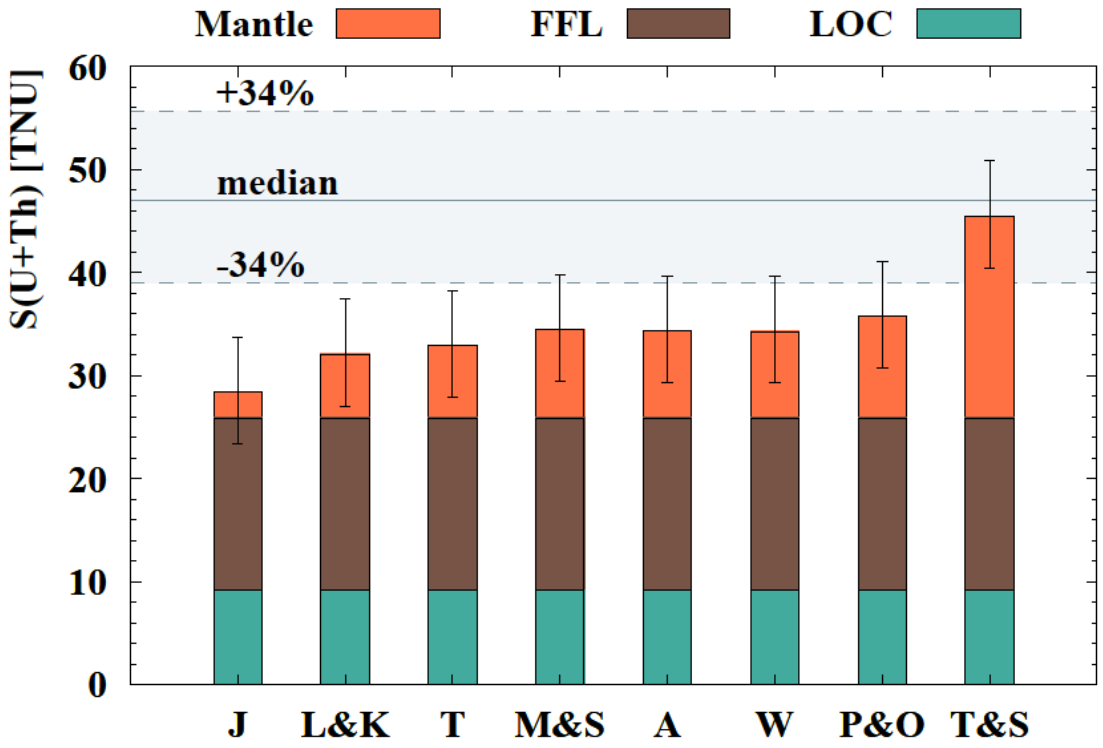
$$52.6^{+9.4}_{-8.6}(stat)^{+2.7}_{-2.1}(sys)events$$

$^{+18.3}_{-17.2}\%$ total precision

GEONEUTRINO SIGNAL AT LNGS

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

See talk of Fabio Mantovani on Thursday morning



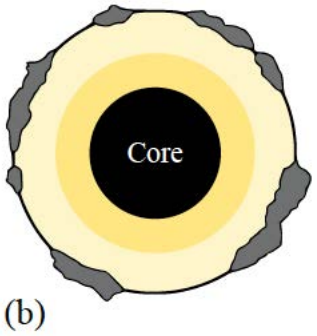
Overall agreement with expectations

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

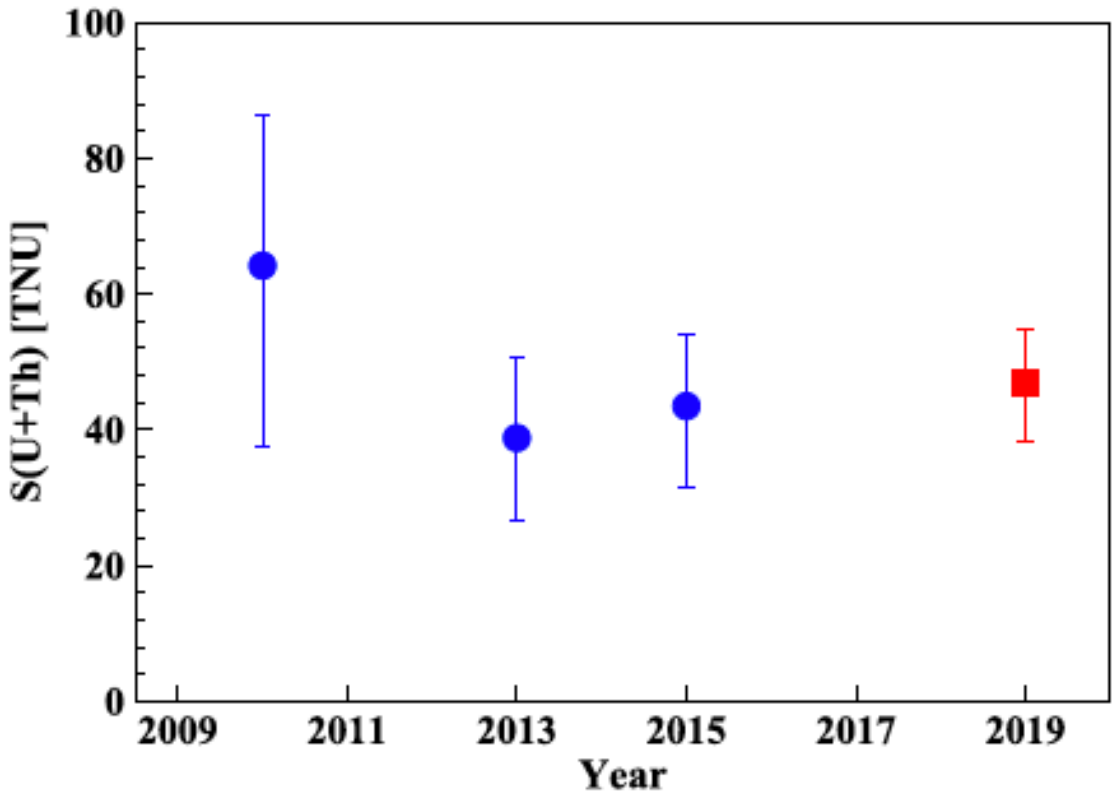
J : Javoy et al., 2010
L&K : Lyubetskaya and Korenaga, 2007
T : Taylor, 1980
M&S : McDonough and Sun, 1995
A : Anderson, 2007
W : Wang, 2018
P&O : Palme and O'Neil, 2003
T&S : Turcotte and Schubert, 2002



Intermediate scenario
2 layer distribution
of U and Th in the mantle

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

Comparison with previous Borexino measurements



- **2010: 99.997 CL observation** (PLB 687 (2010) 299)

  $9.9^{+4.1}_{-3.4}$ geonu's (December 2007 – December 2009)

  small exposure but very low background level

  1.5 x 10^{31} target-proton year

- **Update in 2013** (PLB 722 (2013) 295–300)

  14.3 ± 4.4 geonu's (December 2007 – August 2012)

  3.69 x 10^{31} target-proton year

  0-hypothesis @ 6 x 10^{-6}

- **Update in 2015: 5.9σ CL** (PRD 92 (2015) 031101 (R))

  $23.7^{+6.5}$ (stat) $^{+0.9}$ (sys) geonu's (December 2007 – March 2015)

  5.5 x 10^{31} target-proton year

  0-hypothesis @ 3.6 x 10^{-9}

- **Latest result in 2020** (Phys. Rev. D 101 (2020) 012009)

  $52.6^{+9.4}$ (stat) $^{+2.7}$ (sys) geonu's (December 2007 - April 2019)

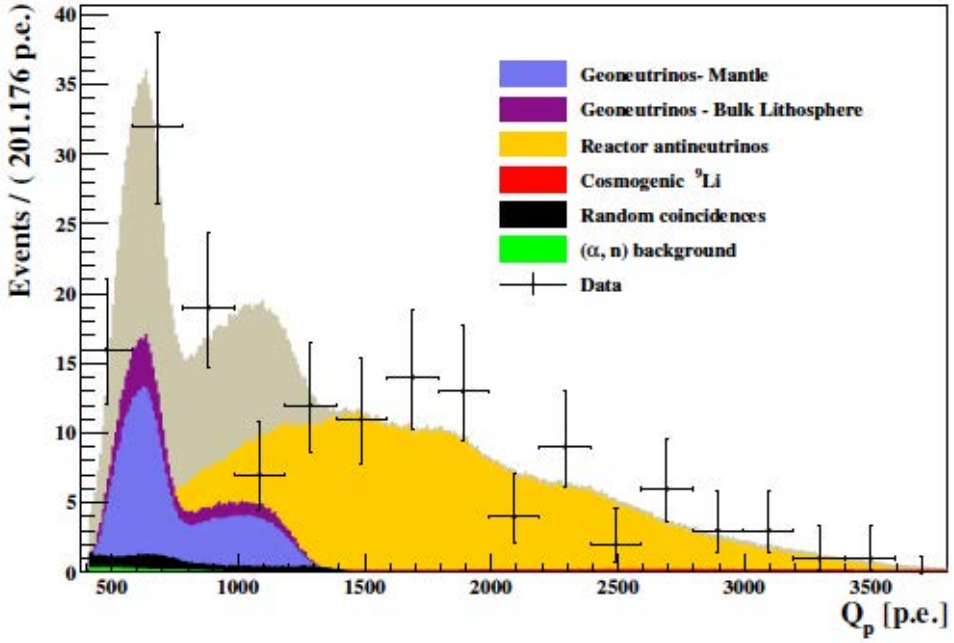
  1.29 x 10^{32} target-proton year,

FIT TO EXTRACT MANTLE SIGNAL

1) **Lithospheric signal:** (28.8 ± 5.6) events with S(Th)/S(U) = 0.29

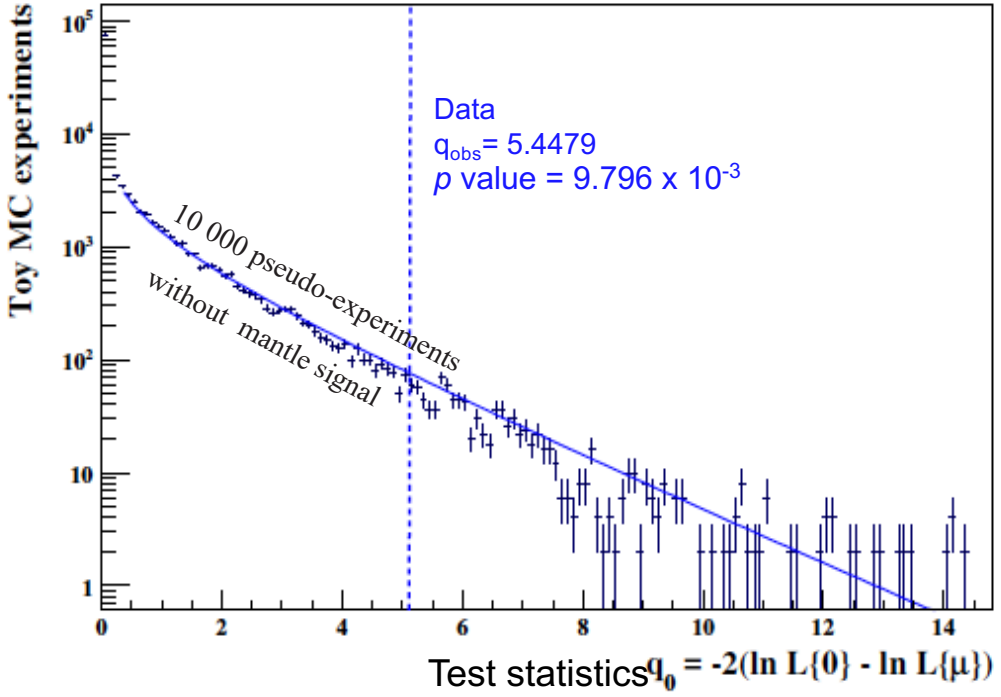
- LOC: Coltorti et al. Geochim. Cosmoch. Acta 75 (2011) 2271.
- FFL: Y. Huang et al., Geoch. Geoph. Geos. 14 (2013) 2003

2) **Mantle signal ratio**: S(Th)/S(U) = 0.26, maintaining the bulk Earth with chondritic Th/U



Mantle events	$23.7^{+10.7}_{-10.1}$
Mantle signal U + Th [TNU]	$21.2^{+9.6}_{-9.1}$

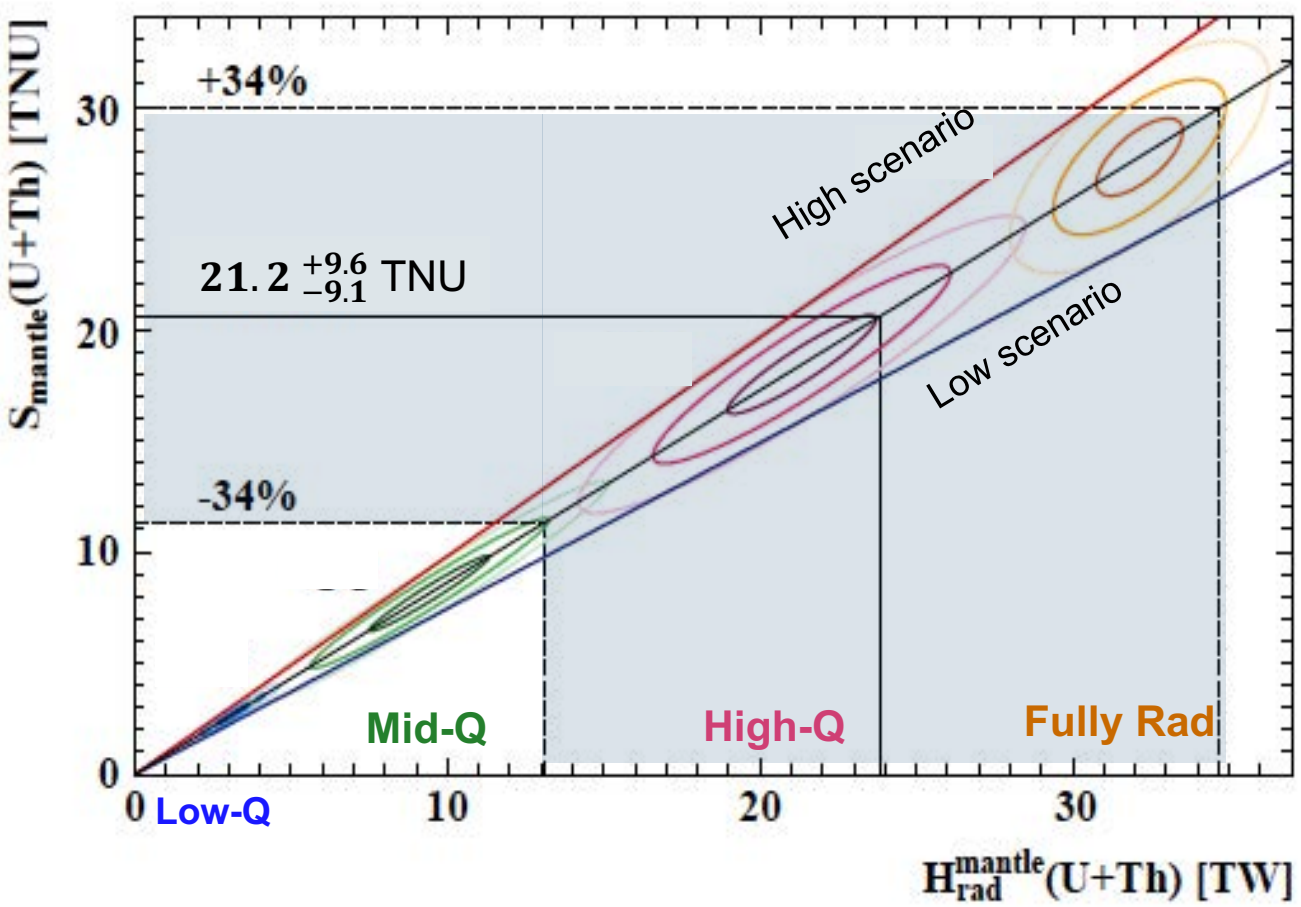
Statistical significance of the mantle signal via log-likelihood ratio method:



Mantle null hypothesis rejected at 99.0% C.L.

MANTLE RADIOGENIC HEAT from U and Th

From mantle signal to mantle radiogenic heat

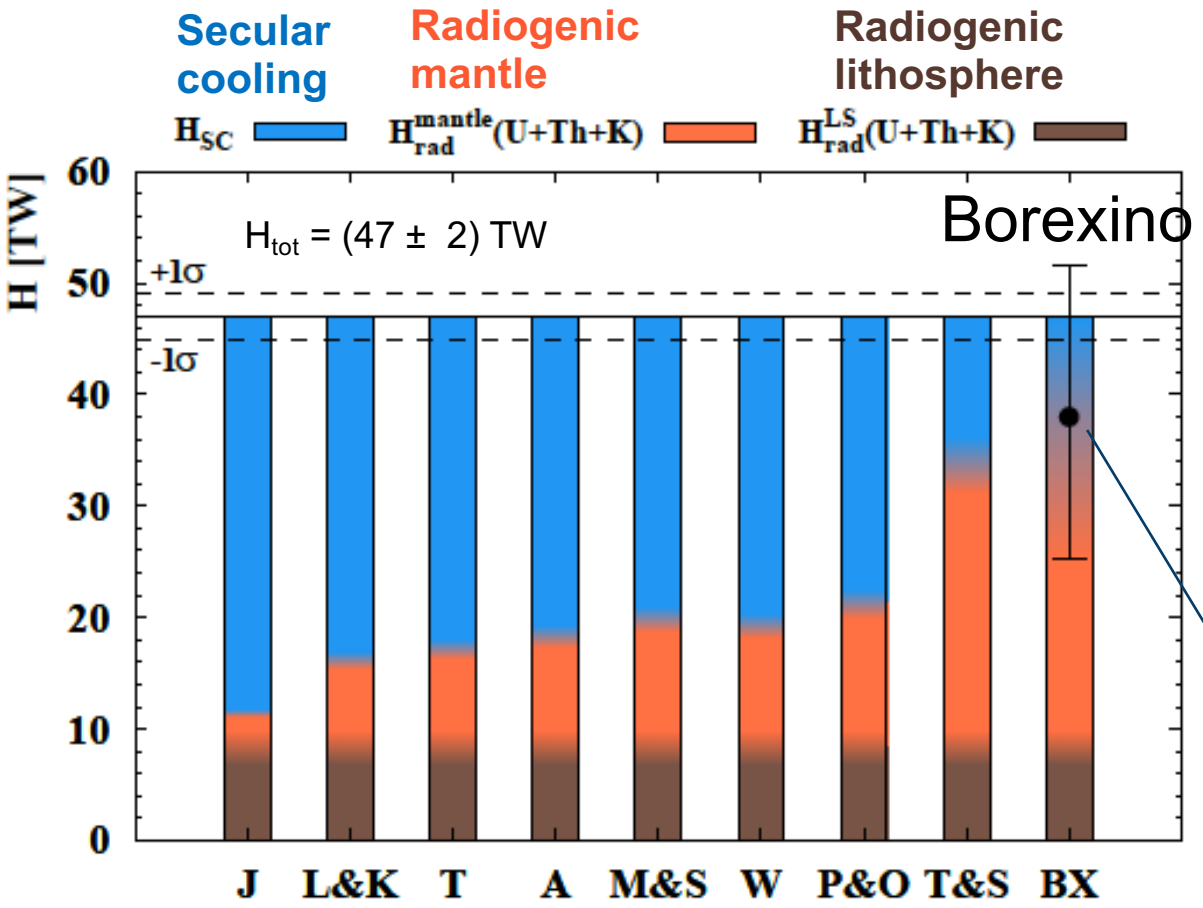


Mantle events	$23.7\ ^{+10.7}_{-10.1}$
Mantle signal U + Th [TNU]	$21.2\ ^{+9.6}_{-9.1}$
Mantle heat U + Th [TW]	$24.6\ ^{+11.1}_{-10.4}$

Borexino mantle measurement is compatible with geological predictions:

- central value in High–Q BSE
- least compatible (2.4σ) with Low-Q BSE

TOTAL EARTH RADIOGENIC HEAT



J : Javoy et al., 2010
L&K : Lyubetskaya and Korenaga, 2007
T : Taylor, 1980
M&S : McDonough and Sun, 1995

A : Anderson, 2007
W : Wang, 2018
P&O : Palme and O'Neil, 2003
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Mantle events	$23.7\ ^{+10.7}_{-10.1}$
Mantle signal U + Th [TNU]	$21.2\ ^{+9.6}_{-9.1}$
Mantle heat U + Th [TW]	$24.6\ ^{+11.1.}_{-10.4}$

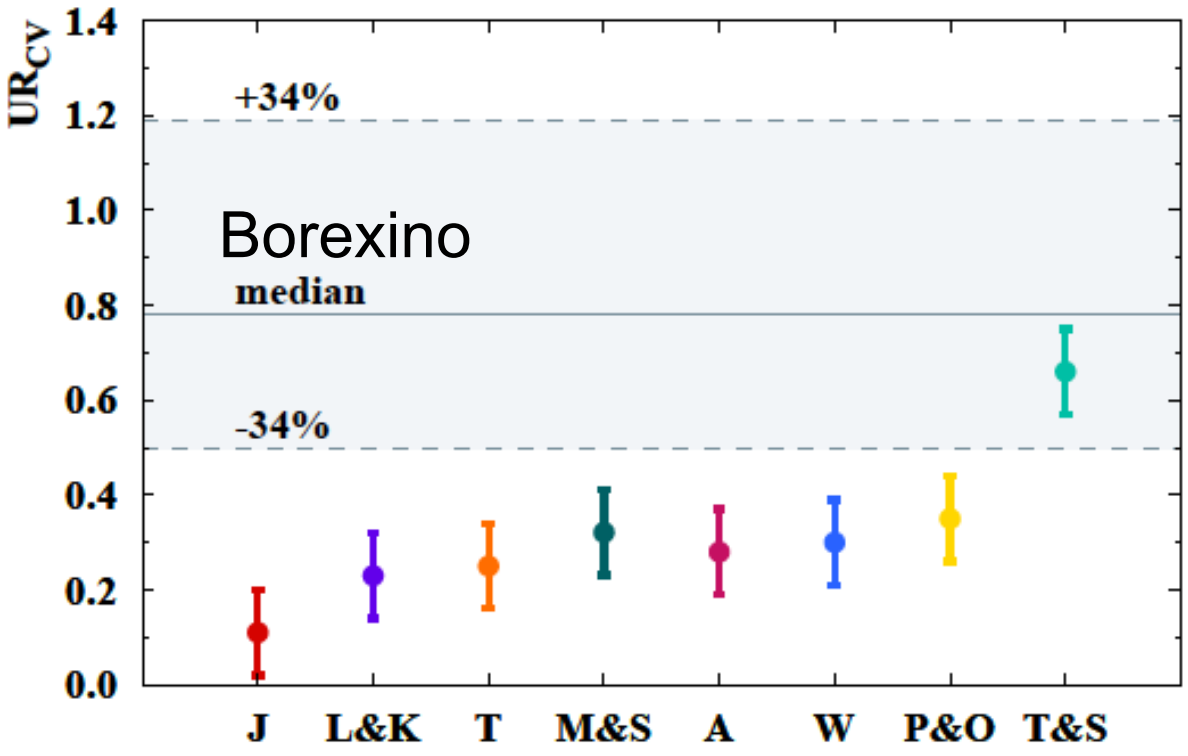
↓

+ 18% contribution of ^{40}K in the mantle (average across different BSE models)
+ $8.1\ ^{+1.9.}_{-1.4}$ TW from lithosphere (U + Th + K)

↓

Total Earth U + Th + K [TW]	$38.2\ ^{+13.6.}_{-12.7}$

Convective Urey ratio



J : Javoy et al., 2010
L&K : Lyubetskaya and Korenaga, 2007
T : Taylor, 1980
M&S : McDonough and Sun, 1995

A : Anderson, 2007
W : Wang, 2018
P&O : Palme and O'Neil, 2003
T&S : Turcotte and Schubert, 2002

CC = continental crust

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

Convective Urey UR_{CV} ratio:

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

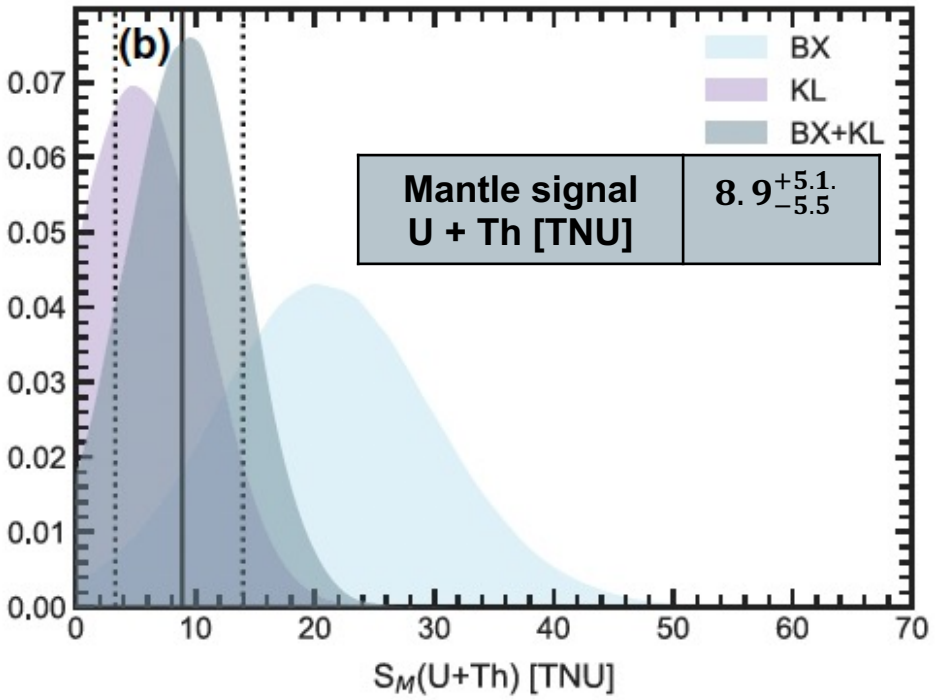
At 90% C.L., mantle characteristics:

- a(Th) > 48 ppb
- a(U) > 13ppb
- $UR_{CV} > 0.13$

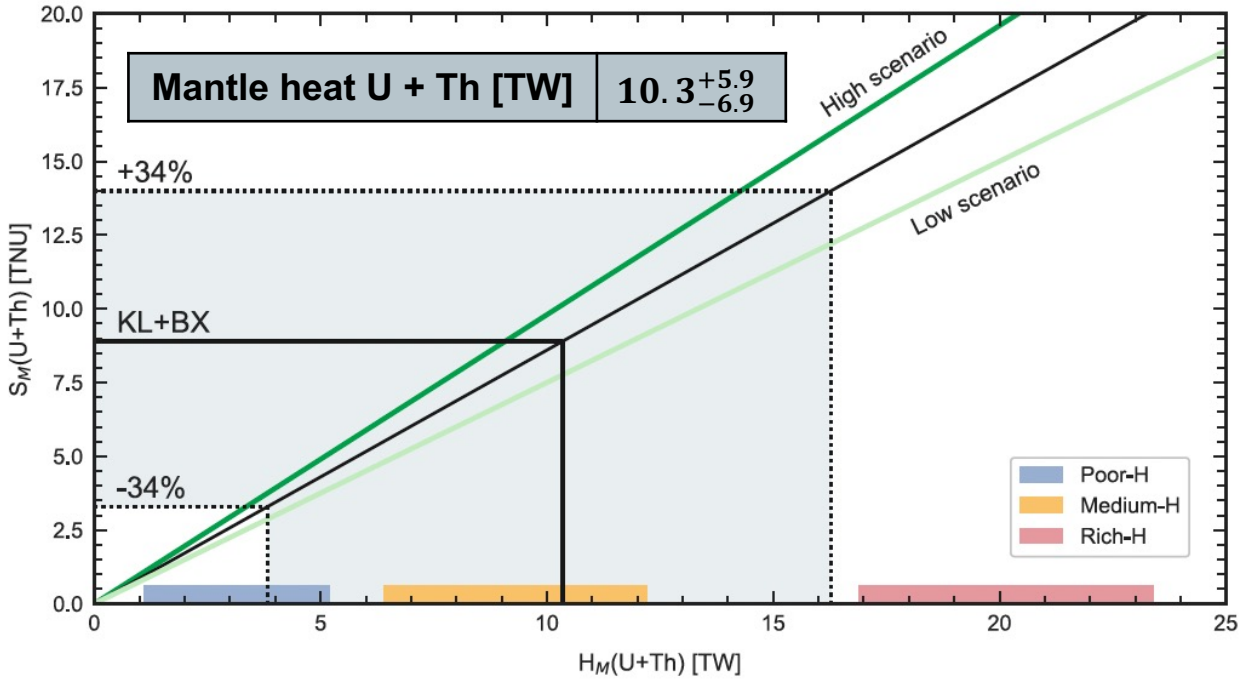
BOREXINO + KAMLAND COMBINED

Bellini et al.: La rivista del Nuovo Cimento 45 (2022) 1

Mantle U + Th signal

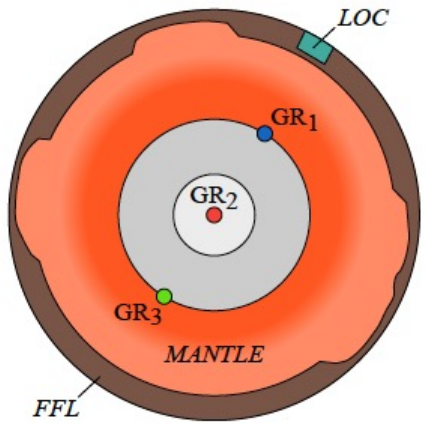


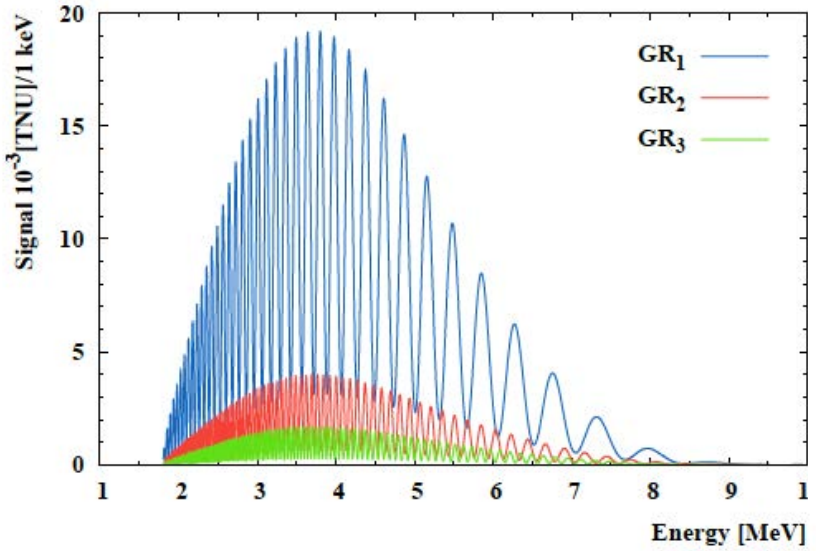
Mantle radiogenic heat vs BSE

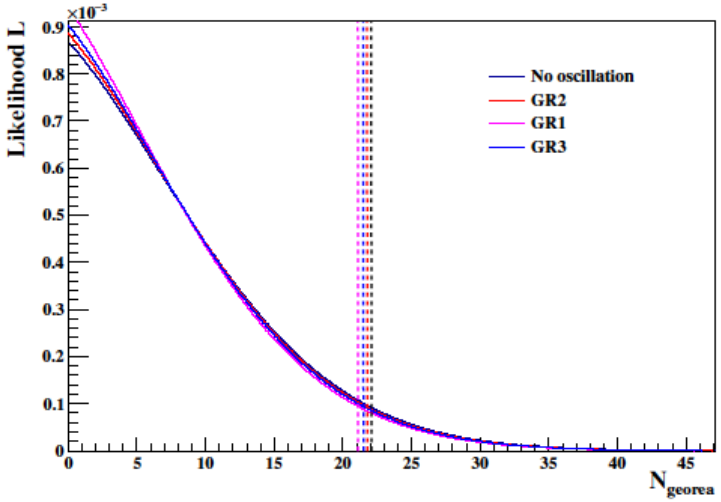


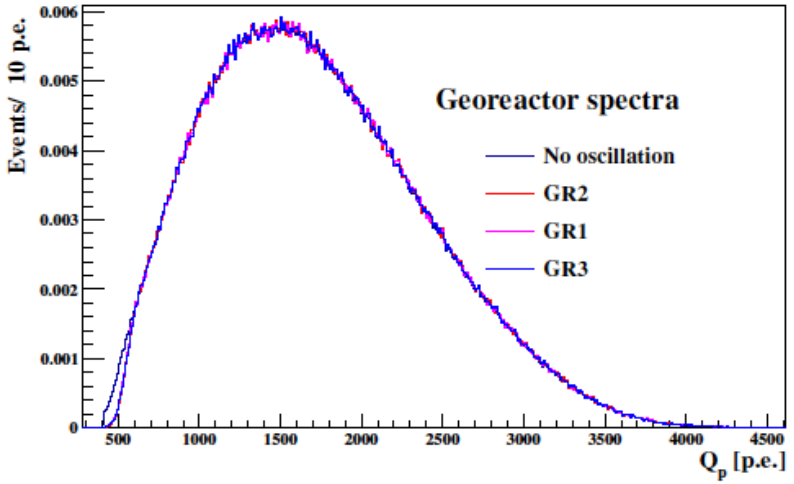
- Analysis assumes laterally homogeneous mantle.
- Some level of disagreement between the two experiments.
- **Combined analysis perfectly compatible with Mid-Q / Medium-H BSE Models.**

TESTING GEOREACTOR HYPOTHESIS









- Hypothetical fission of Uranium deep in the Earth
- Three locations considered
- ^{235}U : ^{238}U = 0.76 : 0.23 (Herndon)
- Fit with reactor spectrum constrained
- No sensitivity to oscillation pattern

Upper limit (95% CL): 18.7 TNU

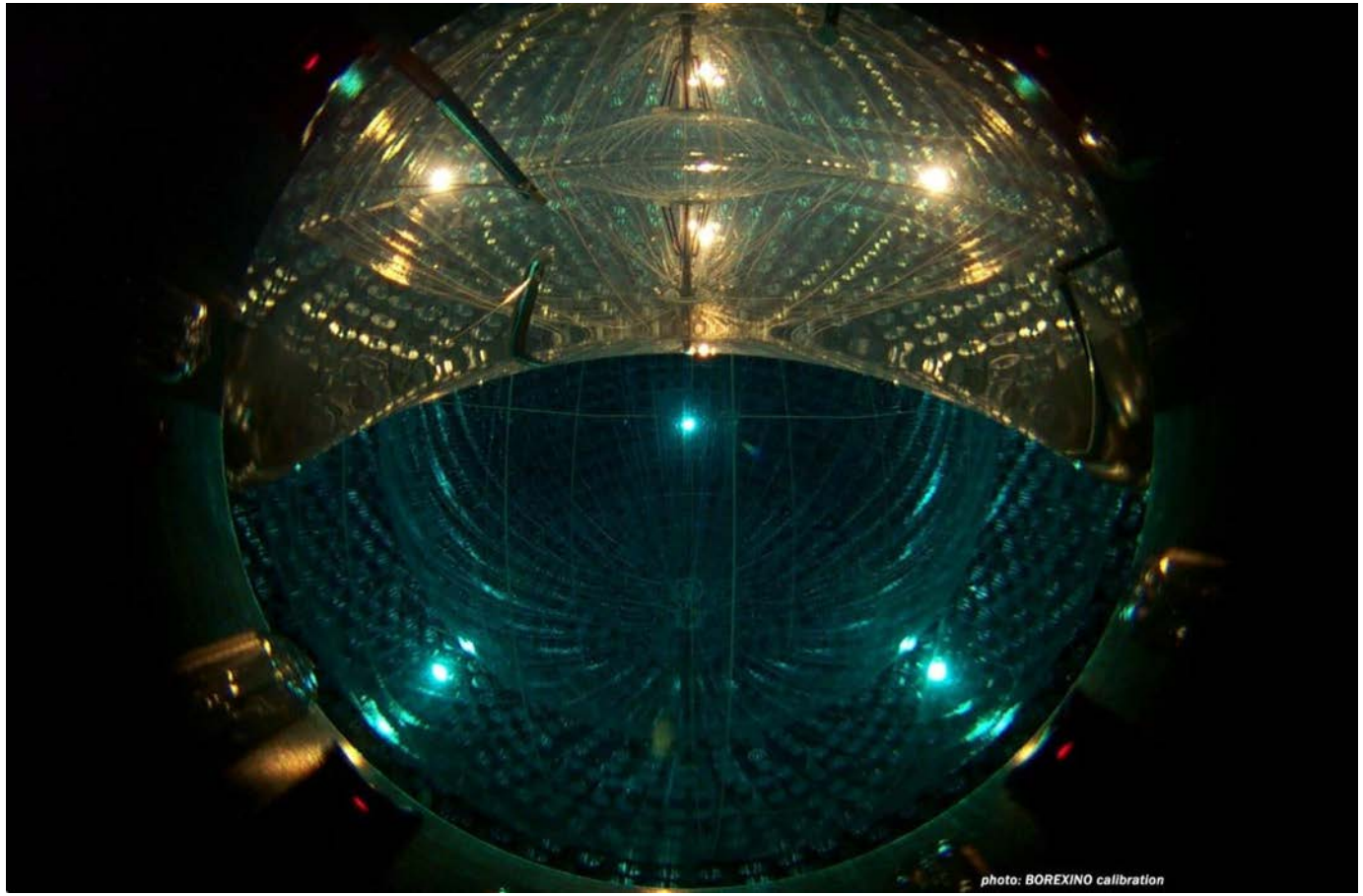
Limit (95% CL)
on the power of georeactor:

2.4 TW in the Earth's center

0.5 TW near CMB at 2900 km

5.7 TW far CMB at 9842 km

SUMMARY



<u>Borexino was taking data for nearly 15 years, until October 2021</u>

- ✓ Unprecedented radiopurity and thermal stability achieved, after 17 years of development and construction.
- ✓ Geoneutrino measurement
  - **with ~17 -18% precision**
  - in agreement with expectations, preference for High-Q BSE models
  - **Mantle geoneutrino signal detected at 99.0% C.L.**
  - no sensitivity to U/Th ratio
  - stringent limits on the power of hypothetical georeactor

Thank you!!













Back up slides

^{214}Bi – ^{214}Po correlated background

214Po

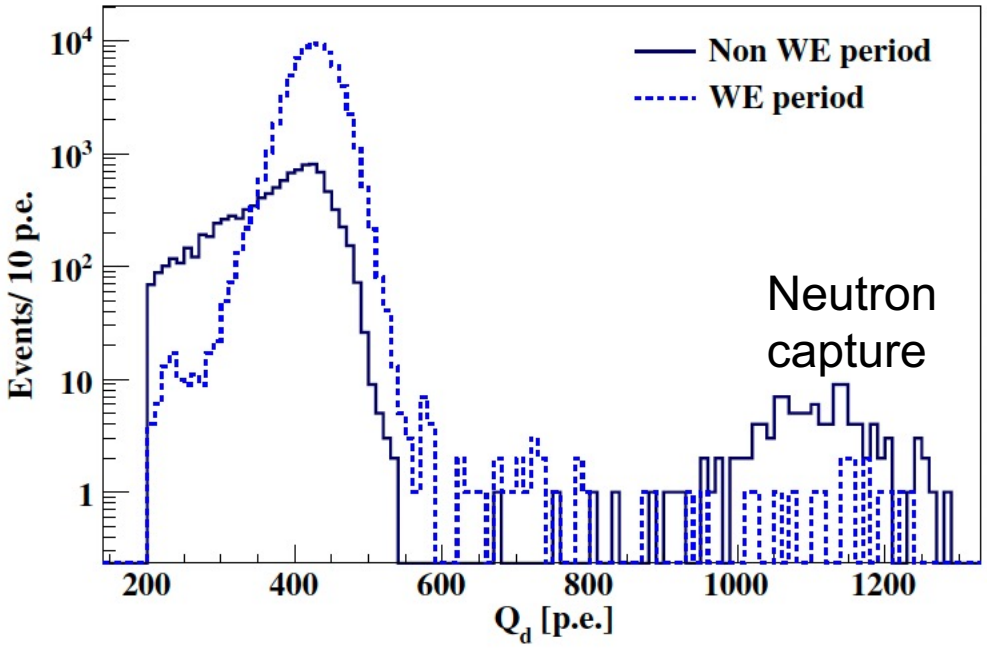
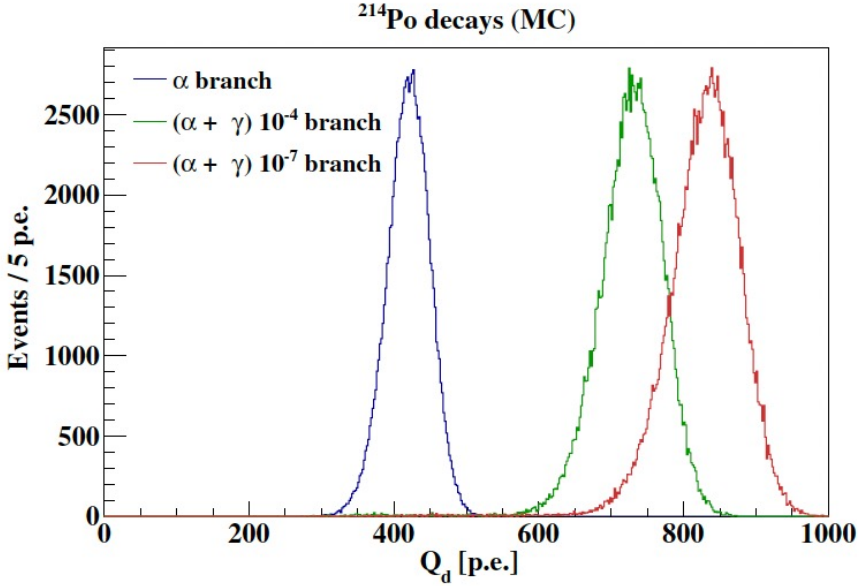


FIG. 40. Charge distribution of delayed signals selected with the low-energy threshold of 200 p.e. and without any MLP cut for the WE period (dotted blue) and the rest of the data-taking (solid blue). The neutron capture peak of the IBDs can be seen at around 1100 p.e. The peak at 400 p.e. is the main α decay of ^{214}Po due to the radon events. The handful of events in between 600 and 860 p.e. are due to the $(\alpha + \gamma)$ decay branch of ^{214}Po, as shown in Table XI.

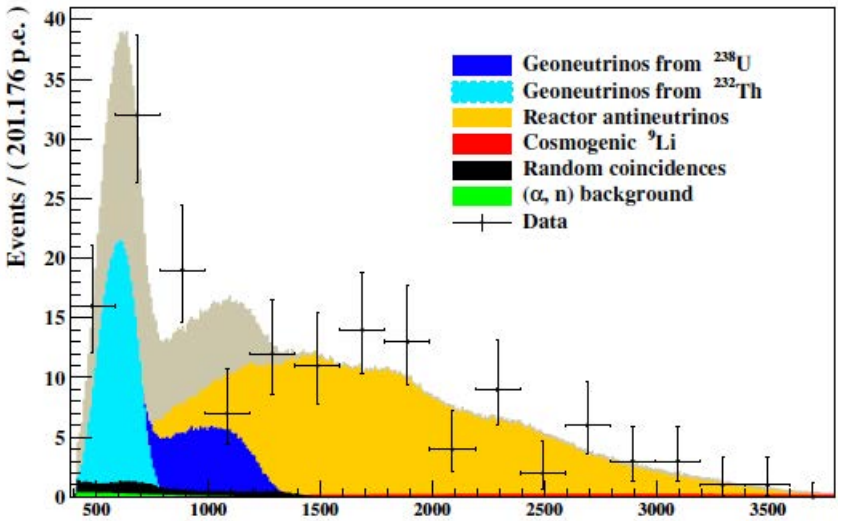
TABLE XI. Decay modes of ^{214}Po.

Decay mode	Branching ratio [%]	Energy [keV]
α	99.99	$E_\alpha = 7833.46$
$\alpha + \gamma$	1.04×10^{-4}	$E_\alpha = 7033.66$ $E_\gamma = 799.7$
$\alpha + \gamma$	6.0×10^{-7}	$E_\alpha = 6735.76$ $E_\gamma = 1097.7$

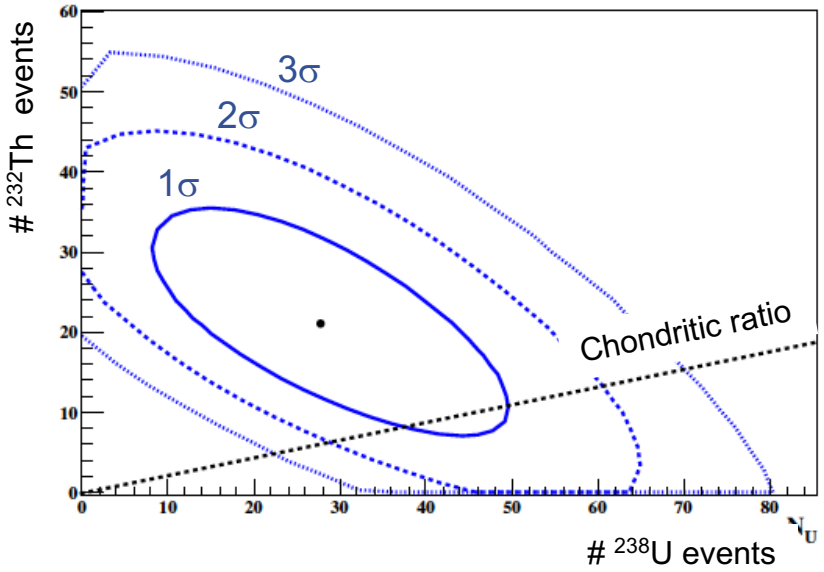


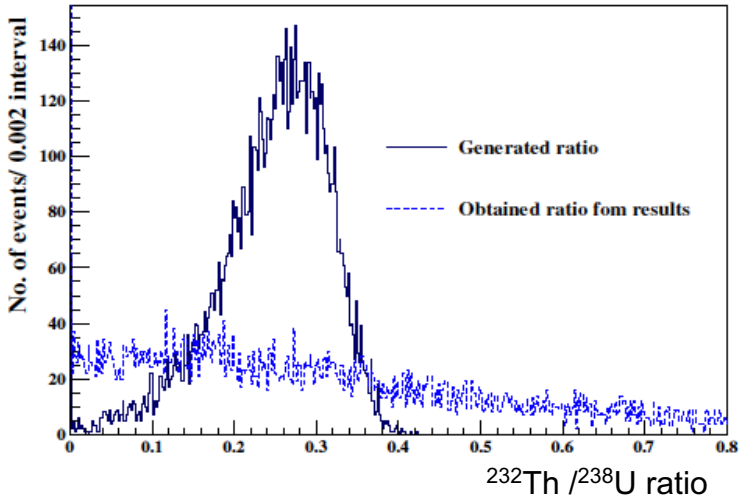
(b)

SPECTRAL FIT with Th and U fit independently



Prompt charge [photoelectrons]: 1 MeV ~500 photoelectrons

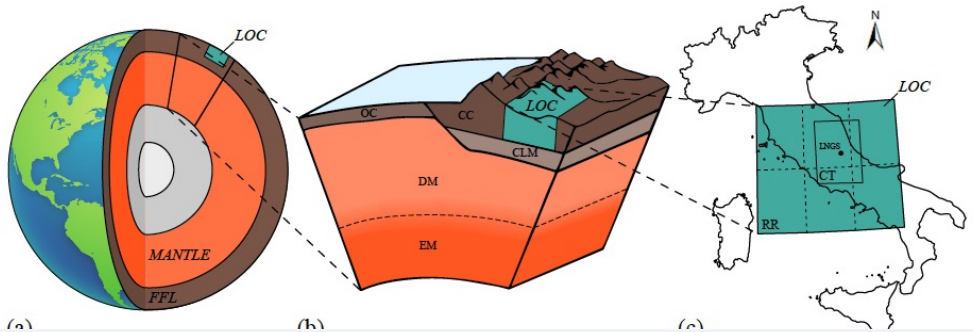




no sensitivity to measure Th/U ratio

EXPECTED GEONEUTRINO SIGNAL AT GRAN SASSO

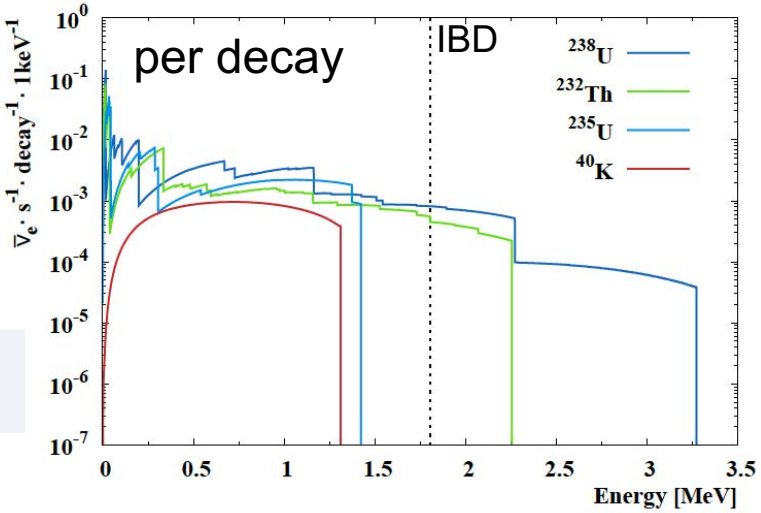
LOCAL AND GLOBAL GEOLOGICAL INFORMATION



U, Th abundances & distribution + density profiles

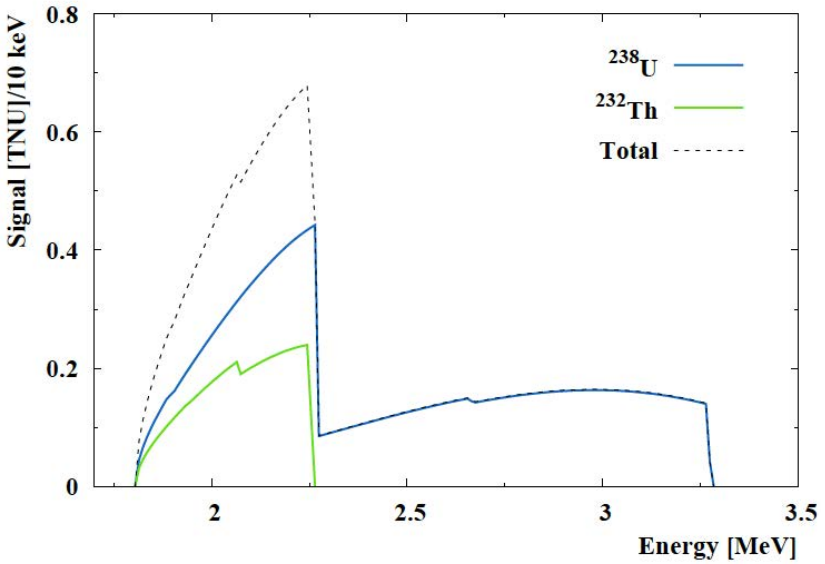
~50% of the signal comes from the area of few 100 km radius

GEONEUTRINO ENERGY SPECTRA



- $\sigma_{IBD}(E_\nu) \sim 10^{-42}$ cm^2
- $\langle P_{ee} \rangle \sim 0.55$

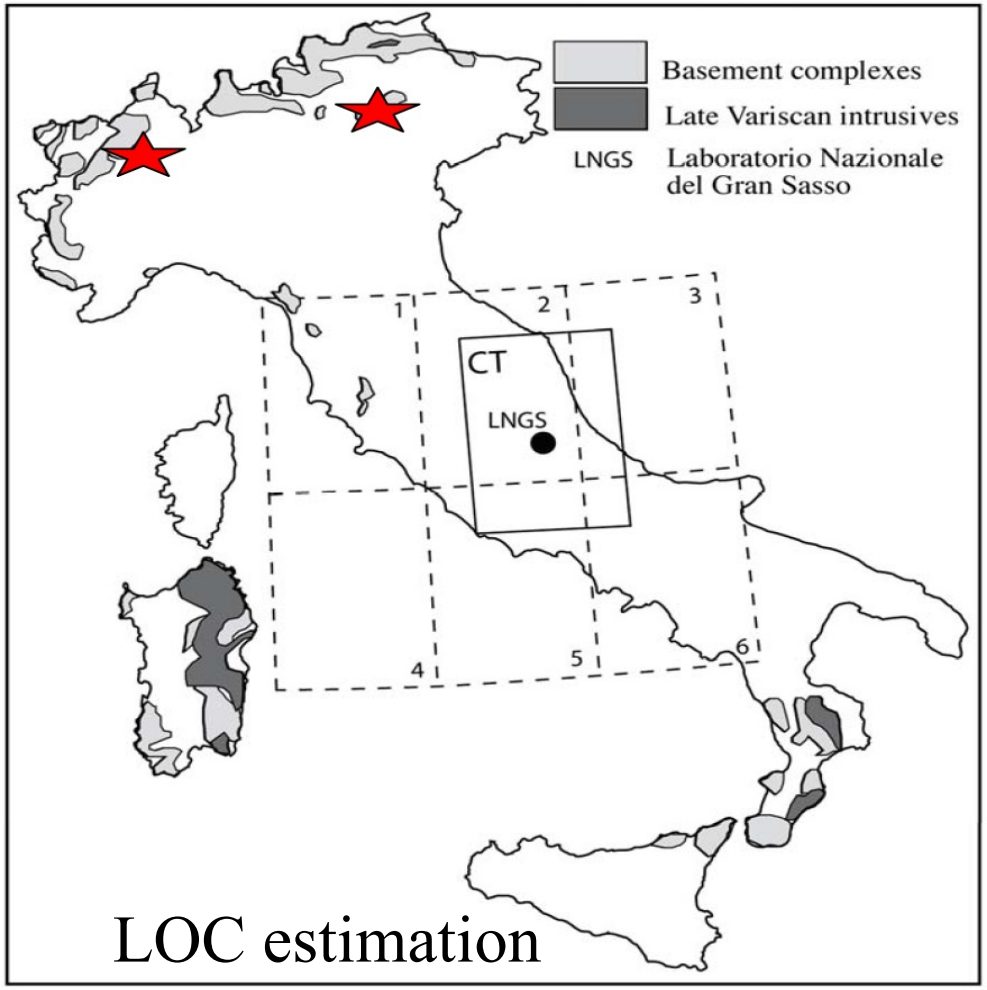
GEONEUTRINO SIGNAL AT LNGS



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

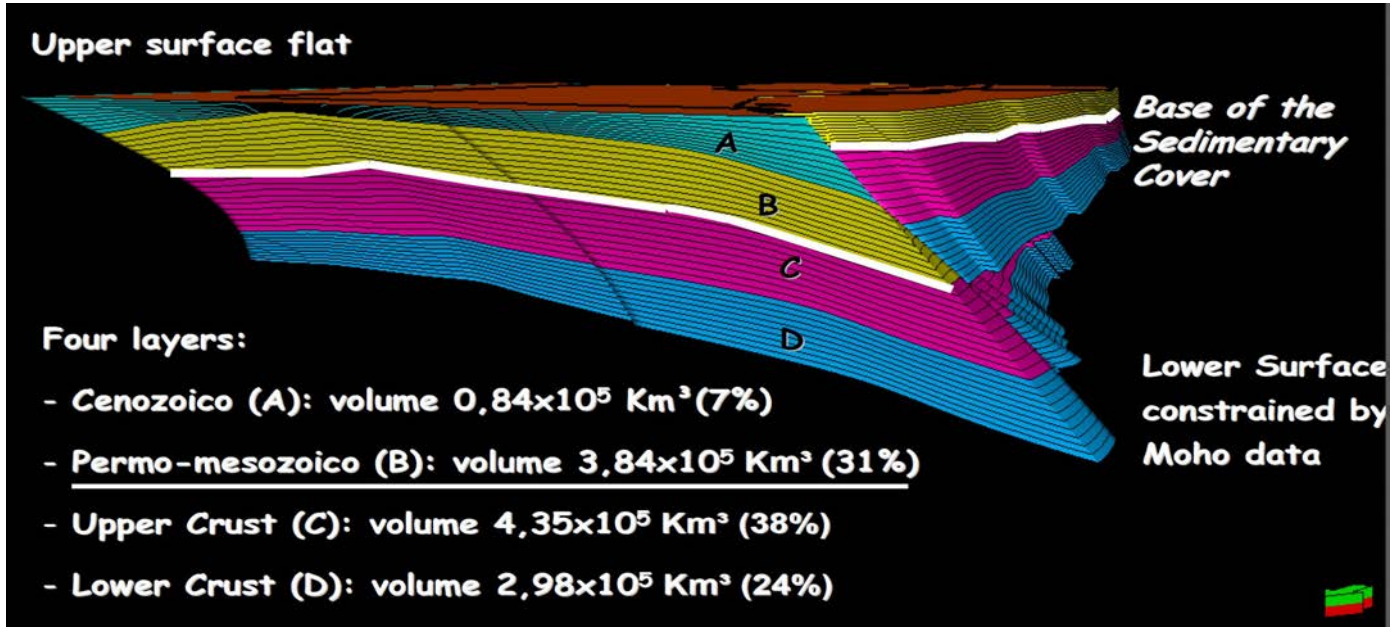
	S (U + Th) [TNU]	S(Th)/S(U)	H (U + Th +K) [TW]
Local Crust (LOC) (~500 km radius)	9.2 ± 1.2	0.24	-
Bulk Lithosphere (including LOC)	$25.9^{+4.9}_{-4.1}$	0.29	$8.1^{+1.9}_{-1.4}$
Mantle = Bulk Silicate Earth model – lithosphere	2.5 – 19.6	0.26 (assuming for BSE chondritic value of 0.27)	3.2 – 25.4
Total	**28.5 – 45.5**	0.27 (chondritic)	11.3 – 33.5

3D GEOLOGICAL MODEL AROUND LNGS



LOC estimation

Coltorti at al. 2011



CALCULATION OF THE EXPECTED REACTOR ANTI-N FLUX

$$\Phi\left(E_{\bar{\nu}_e}\right) = \sum_{r=1}^{N_{react}} \sum_{m=1}^{N_{month}} \frac{T_m}{4\pi L_r^2} P_{rm} \sum_{i=1}^{4} \frac{f_{ri}}{E_i} \Phi_i\left(E_{\bar{\nu}_e}\right) P_{ee}\left(E_{\bar{\nu}_e}; \hat{\vartheta}, L_r\right)$$

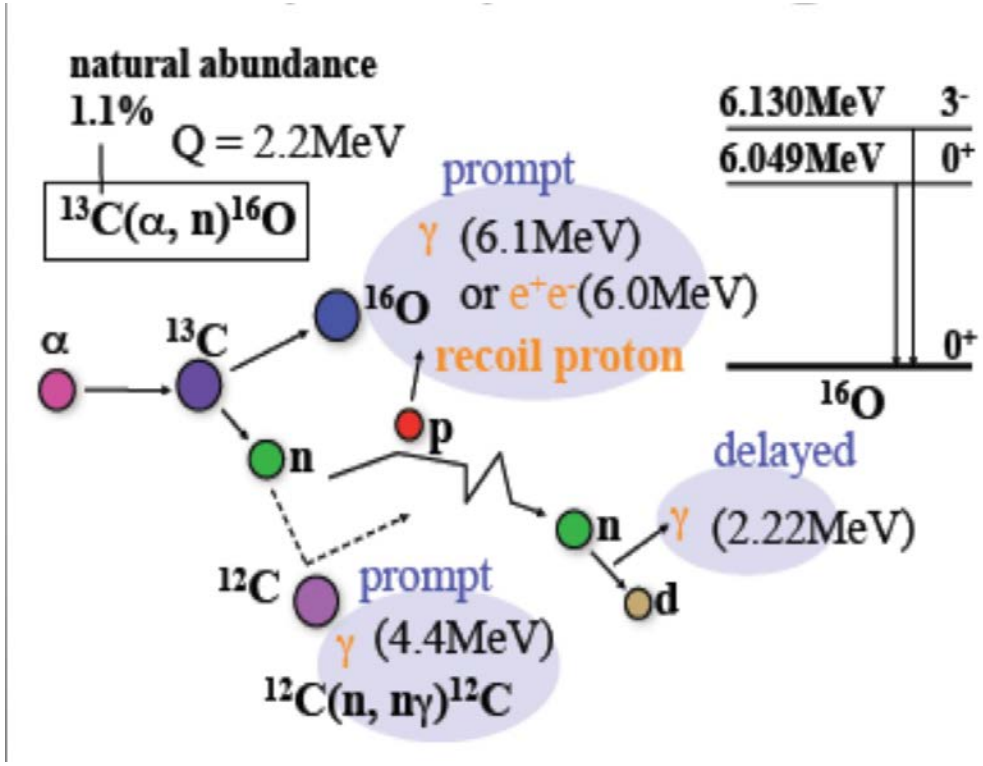
- **Nuclear and neutrino physics:**
  - E_i : energy release per fission of isotope i (Huber-Schwetz 2004);
  - Φ_i: antineutrino flux per fission of isotope i (polynomial parameterization, Mueller et al.2011, Huber-Schwetz 2004);
  - P_{ee}: oscillation survival probability;
- **Experiment-related:**
  - T_m: live time during the month m;
  - L_r: reactor r – detector distance;
- **Data from nuclear agencies:**
  - P_{rm}: thermal power of reactor r in month m (IAEA , EDF, and UN data base);
  - f_{ri}: power fraction of isotope i in reactor r;

^{235}U
^{239}Pu
^{238}U
^{241}Pu

+ consider energy-dependent IBD cross section → expected reactor-antinu rate for 100 detection eff.

$^{13}C(\alpha, neutron)^{16}O$ background

- Isotopic abundance of ^{13}C: 1.1%
- $^{210}Po(\alpha)$ = 14.1 cpd / ton (average value)



MC-based spectrum of E_{prompt}

