GEONEUTRINOS: A NEW TOOL TO STUDY THE EARTH

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GERMANY

Photo credit: Tom Pfeifer, Krakatau volcano, Indonesia

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XXXI INTERNATIONAL CONFERENCE
ON NEUTRINO PHYSICS AND ASTROPHYSICS

MILANO, ITALY

RWTH AACHEN UNIVERSITY

JÜLICH Forschungszentrum

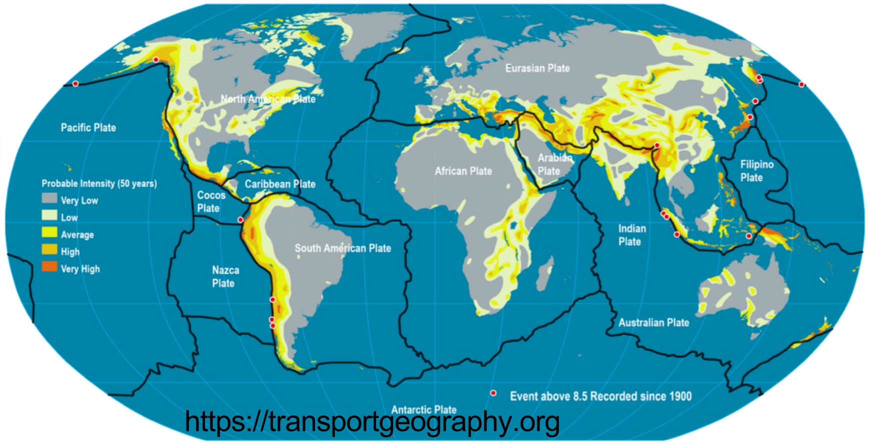
Mitglied der Helmholtz-Gemeinschaft

Vulcanism

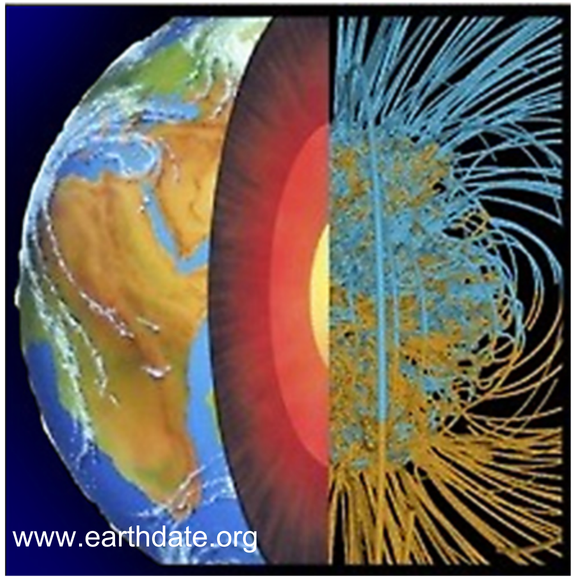
From where is coming the energy driving these processes?

How can neutrino physics help us to understand?

Plate tectonics & mantle convection



Geo-dynamo



Earthquakes

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Vulcanism

From where is coming the energy driving these processes?

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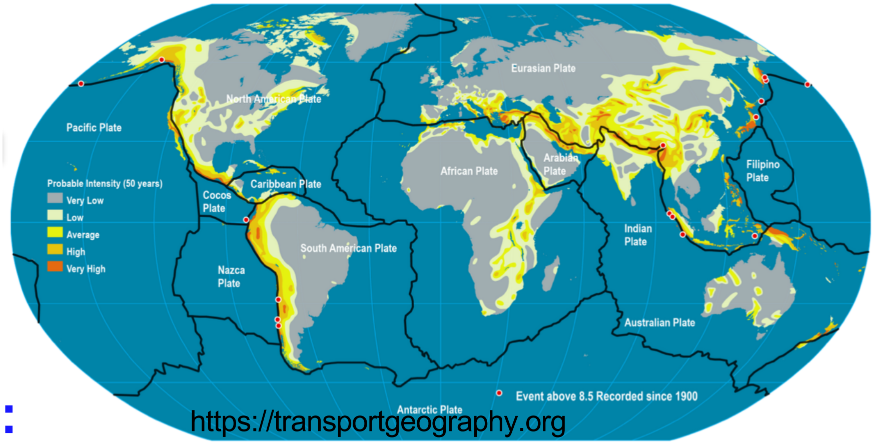
Geoneutrinos

Earth shines in geoneutrinos:
flux ~ 10^6 cm^{-2} s^{-1}

Plate tectonics & mantle convection



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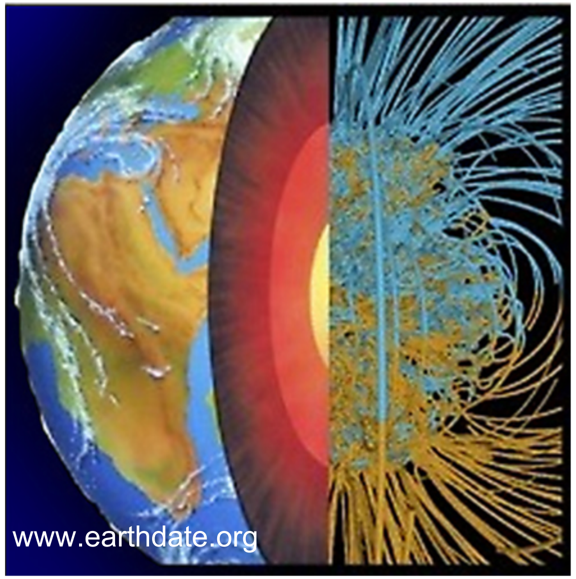

Earthquakes

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GEONEUTRINOS AND GEOSCIENCE

Abundances (mass) of radioactive elements

Nuclear physics →

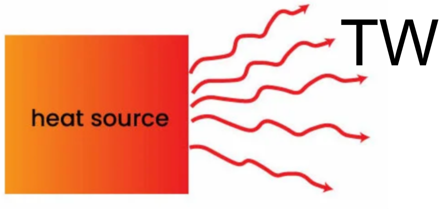
$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^{-}$ + 6 anti-neutrinos + 51.7 MeV

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

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

Main goal:
Mantle radiogenic heat

- Mantle homogeneity
- U/Th ratio
- Earth formation



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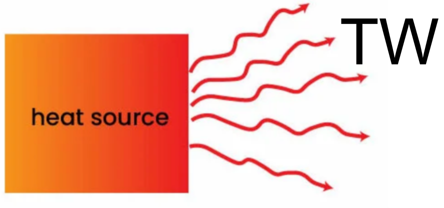

Geoneutrino flux
(signal)

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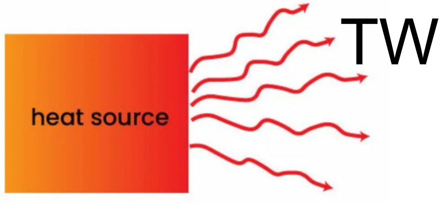

Distribution of radioactive elements

Signal prediction

Geoneutrino flux (signal)

GEONEUTRINOS AND GEOSCIENCE

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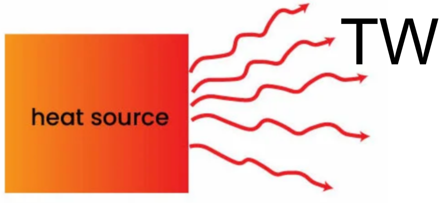

Distribution of radioactive elements

Signal prediction

Geoneutrino flux
(signal)

Signal interpretation

Neutrino geoscience: a truly inter-disciplinary field!

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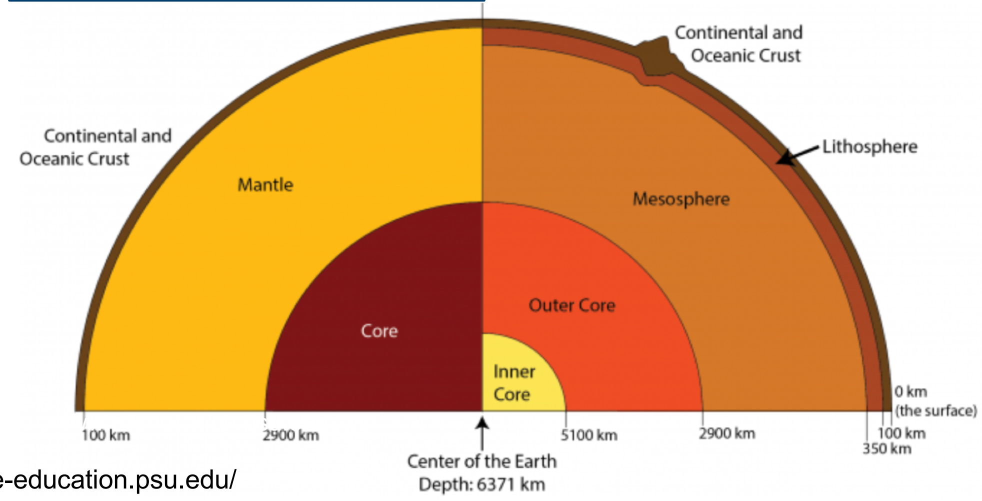
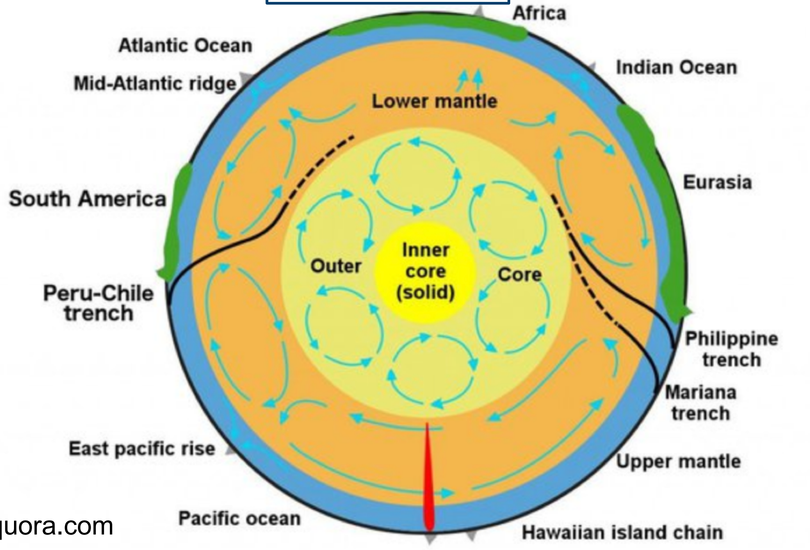
THE EARTH TODAY

Compositional layers | **Mechanical layers**



www.e-education.psu.edu/

Dynamics



www.quora.com

U and Th distribution

Refractory (high condensation T) & **Lithophile** (silicate loving)

Typical concentration for ^{238}U
(Mantovani *et al.* 2004)

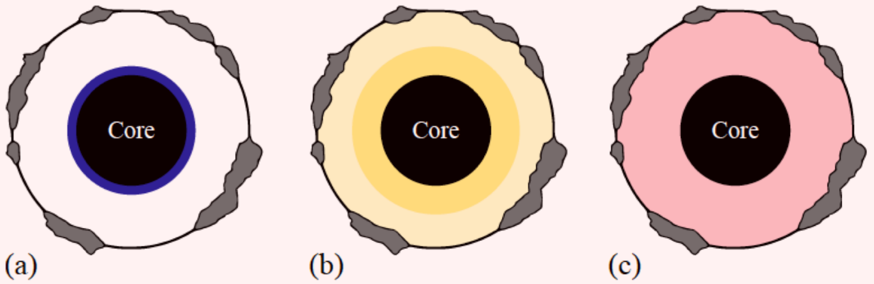
SILICATES	upper continental crust:	2.5 ppm
SILICATES	middle continental crust:	1.6 ppm
SILICATES	lower continental crust:	0.63 ppm
SILICATES	oceanic crust:	0.1 ppm
SILICATES	upper mantle:	6.5 ppb
	core (**metallic**)	**NOTHING**

Decreases with depth

U/Th distribution in the mantle (3 scenario)

Geoneutrino flux from the mantle

Low — Intermediate — High



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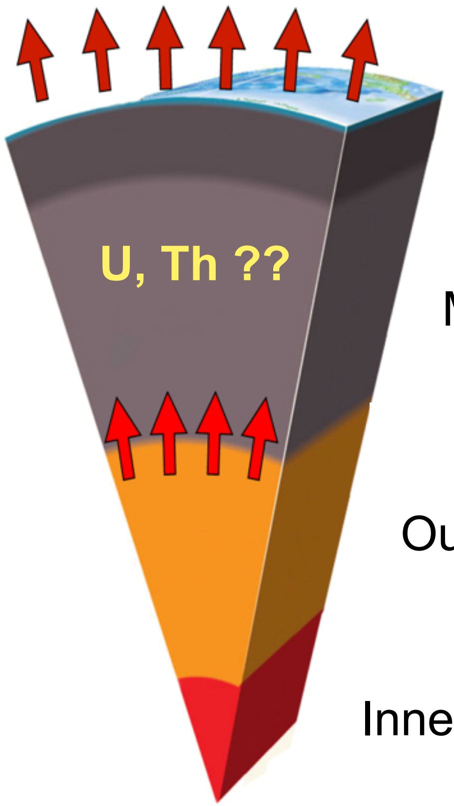
THE EARTH'S HEAT BUDGET

Integrated surface heat flux:

From measured T-gradients along bore-holes

H_{tot} = 47 ± 2 TW



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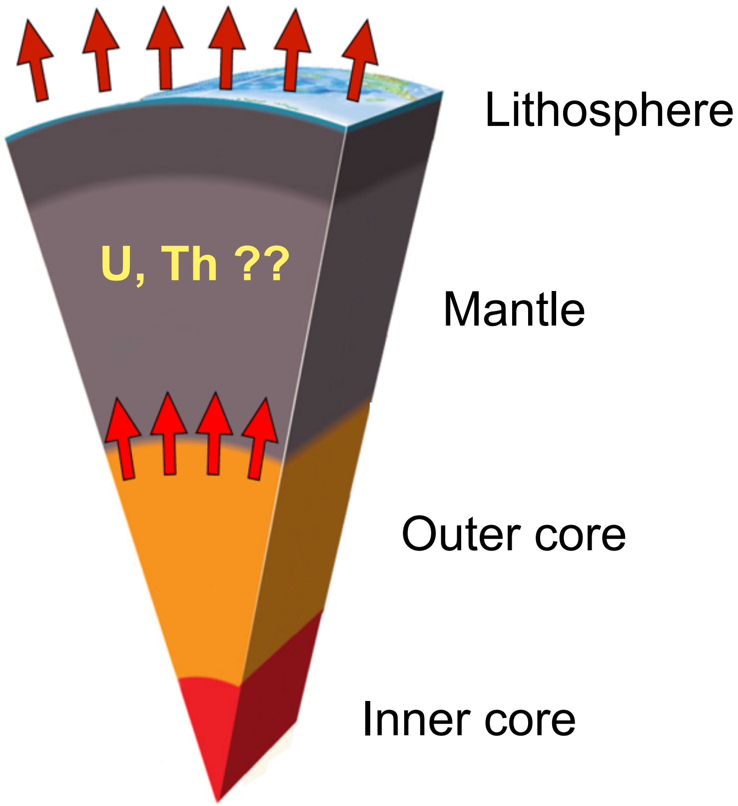
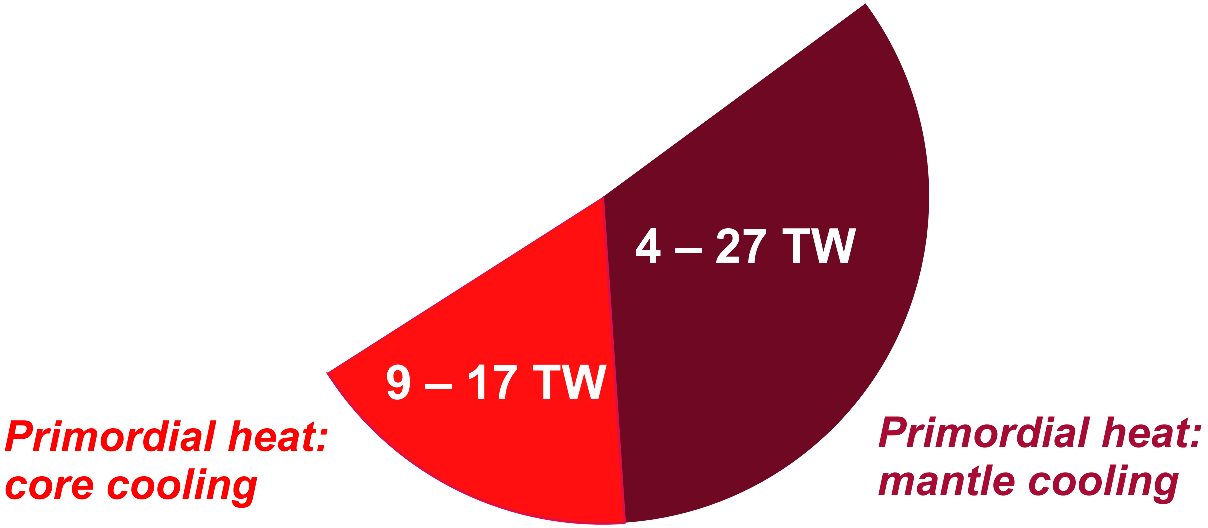
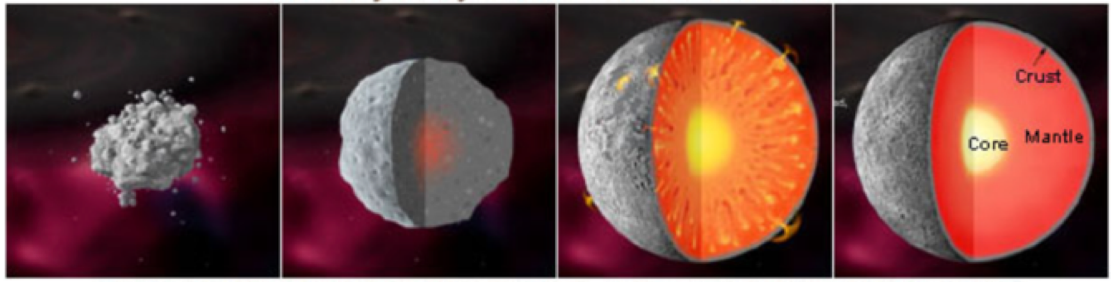




A Rocky Body Forms and Differentiates



(From Smithsonian National Museum of Natural History - http://www.mnh.si.edu/earth/text/5_1_4_0.html)

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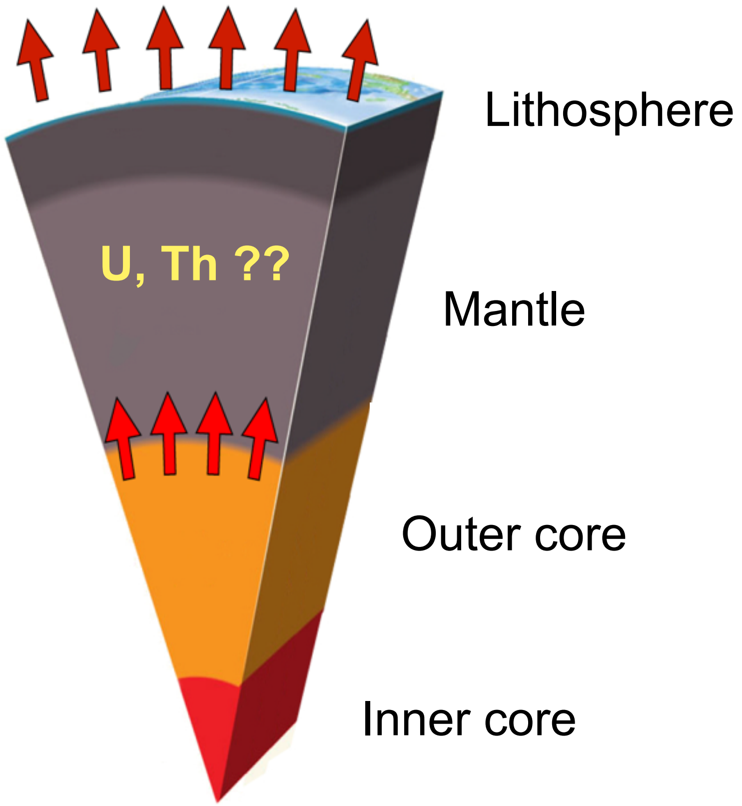

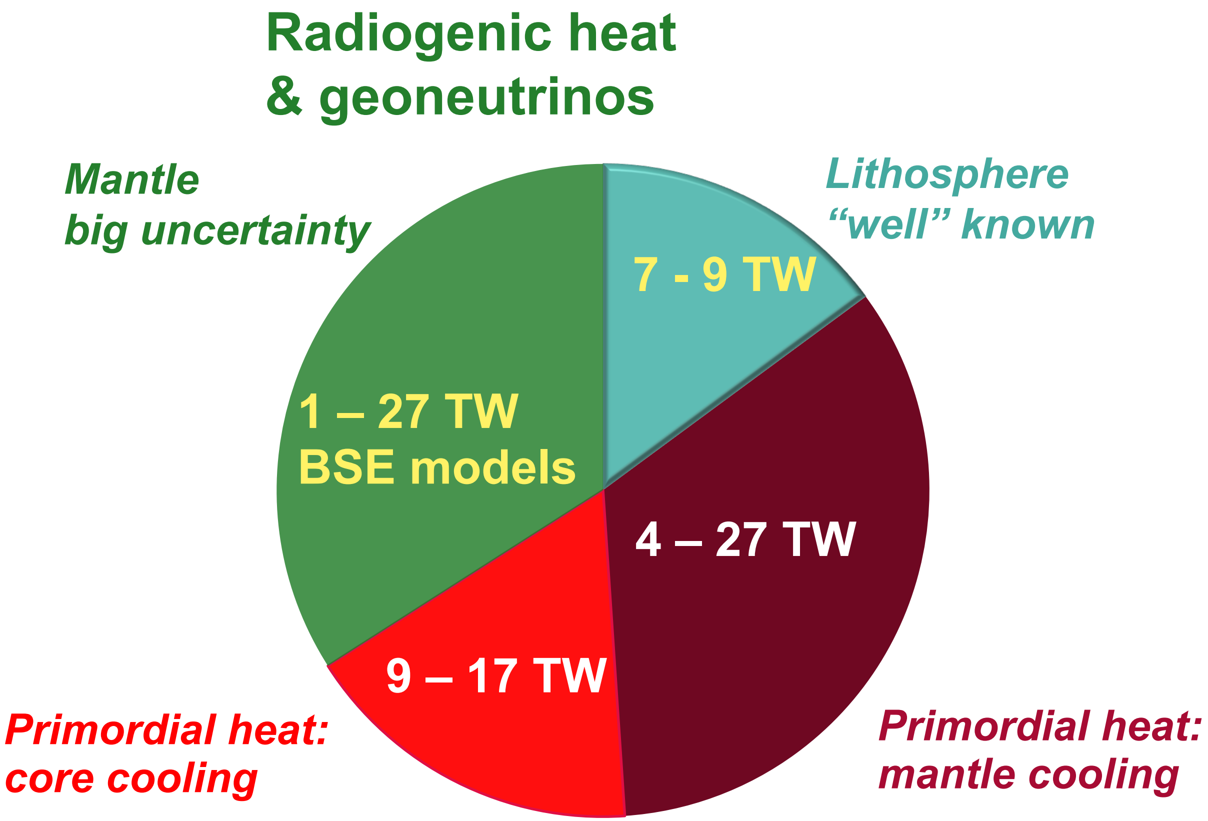

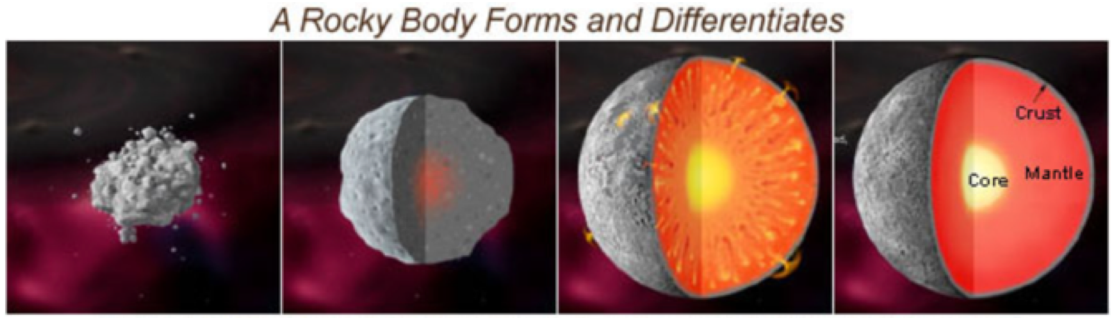

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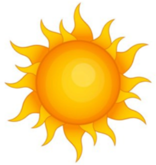
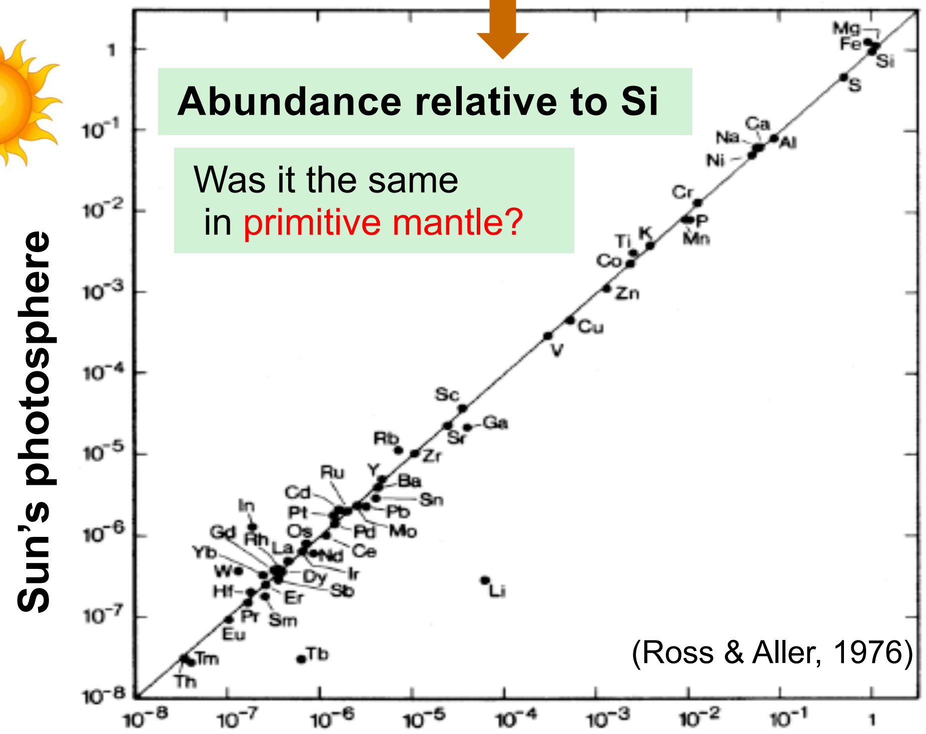
BULK SILICATE EARTH (BSE) MODELS

Modeling the composition of the Earth primitive mantle
Various inputs: *composition of rock samples from the crust and upper mantle, energy needed to run the mantle and core convections,* ***composition of chondritic meteorites and its correlations with the composition of the solar photosphere…***

silicate primitive mantle = present-day **crust + mantle**





Abundance relative to Si

Was it the same in primitive mantle?

(Ross & Aller, 1976)

C1 carbonaceous chondritic meteorites

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BSE model	M (U) [10^{16} kg]	M (Th) [10^{16} kg]	M (K) [10^{19} kg]	H_{rad} (U + Th + K) [TW]	
Cosmochemical (CC)	5 ± 1	17 ± 2	59 ± 12	**11.3 ± 1.6**	**Low-Q**
Geochemical (CC)	8 ± 2	32 ± 5	113 ± 24	**20.2 ± 3.8**	**Mid-Q**
Geodynamical (GD)	14 ± 2	57 ± 6	142 ± 14	**33.5 ± 3.6**	**High-Q**
„Fully radiogenic“ (FR)	20 ± 1	77 ± 3	224 ± 10	47 ± 2	

- Mantle composition is inferred from the BSE models by subtracting the relatively well-known crustal composition.
- Ratios of different elements, including U and Th, are much better known than their absolute abundances:
mass ratio of Th/U = 3.9 (chondrites)

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GEONEUTRINO DETECTION

- Inverse Beta Decay on proton (IBD): **delayed coincidence.**
- Charge current interaction mediated by W bosons.
- Sensitive only to **electron flavour antineutrinos.**
- Cross section well known.
- Coincidence = powerful **background suppression** tool.
- **Reactor neutrinos – irreducible background,** with ~10 MeV end-point, geoneutrinos ~3.3 MeV.

Energy threshold = 1.8 MeV

σ @ few MeV: ~10^{-42} cm^2

(~100 x more than elastic scattering on electron)

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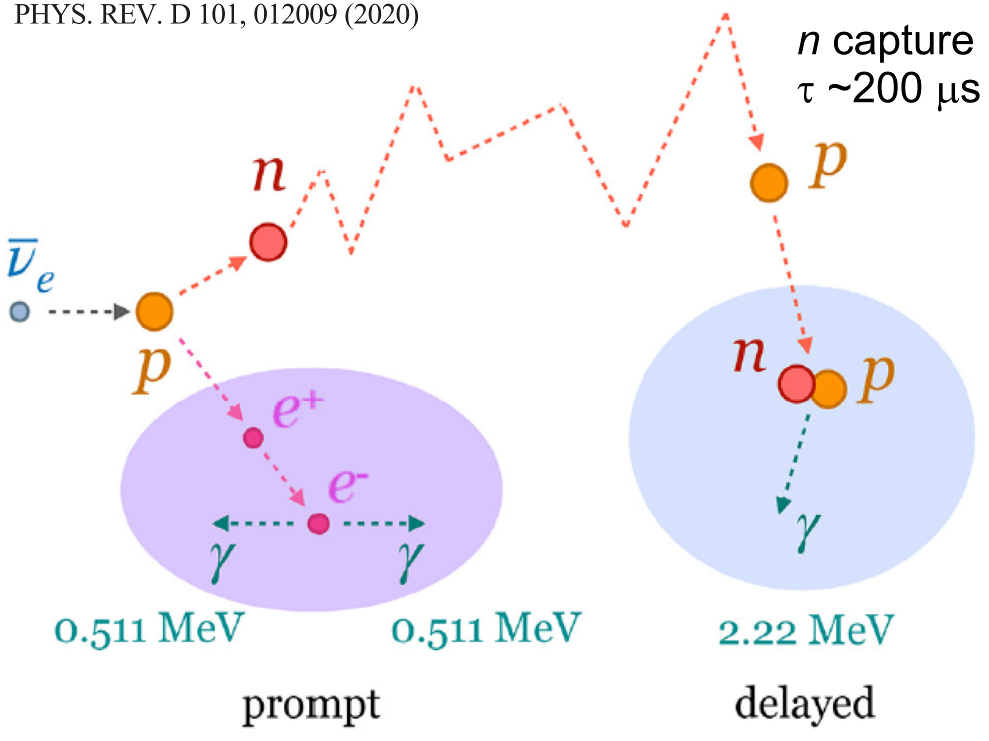


Geoneutrino from radioactive decay

$\bar{\nu}_e$

Neutrino oscillation

average P_{ee} ~ **0.55**

$\bar{\nu}_e$ — Detection with IBD

$\bar{\nu}_{\mu,\tau}$ — Invisible to IBD

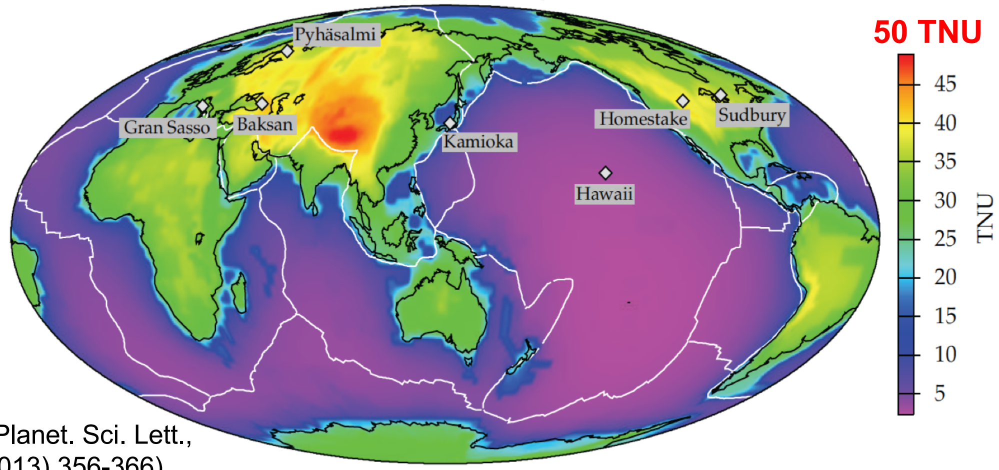
$E_{prompt} = E_{visible}$

$= T_{e+} + 2 \times 511$ keV

$\sim E_{antinu} - 0.784$ MeV

GEONEUTRINO SIGNAL WORLDWIDE: from $\phi \sim 10^6$ cm^{-2} s^{-1} to a handful of events

Expected crustal signal: "known" and "large".



Earth Planet. Sci. Lett., 361 (2013) 356-366)

The signal is small, we need big detectors!

Terrestrial Neutrino Unit

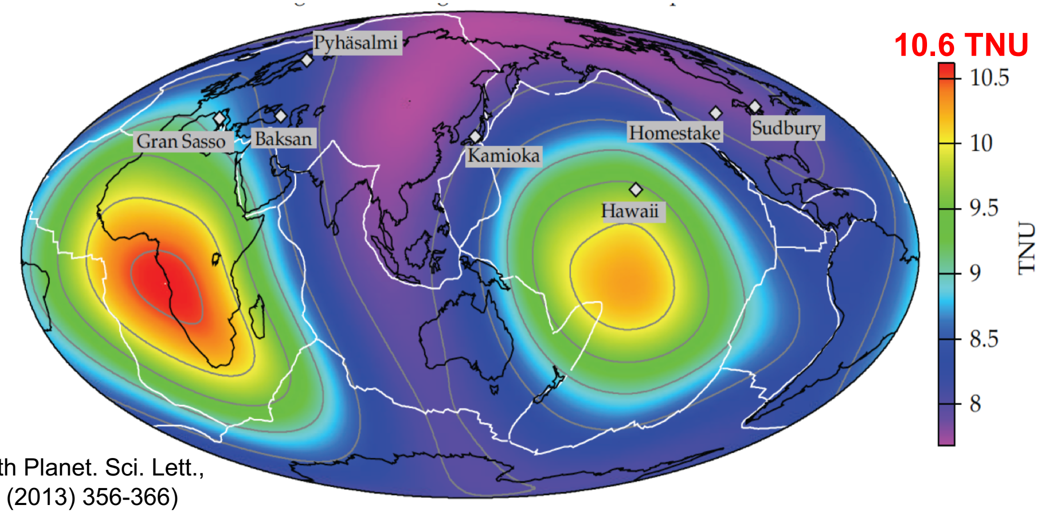
1 TNU = 1 IBD event / 10^{32} target protons / year

(cca 1 IBD event /1 kton /1 year)

with 100% detection efficiency

Expected mantle signal: super-tiny and unknown.

Hypothesis of heterogeneous mantle composition motivated by the observed **Large Shear Velocity Provinces** at the mantle base.



Earth Planet. Sci. Lett., 361 (2013) 356-366)

Mantle signal is even more challenging!

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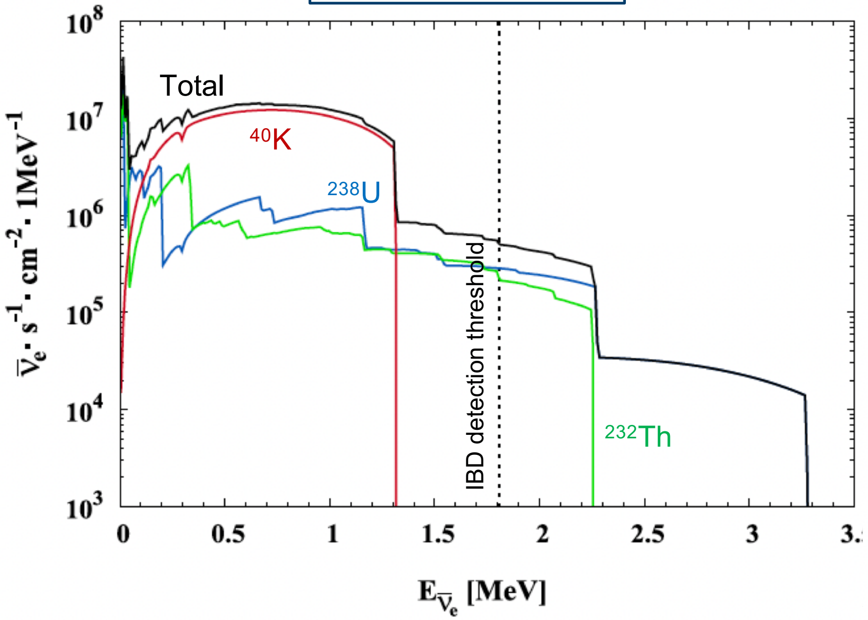
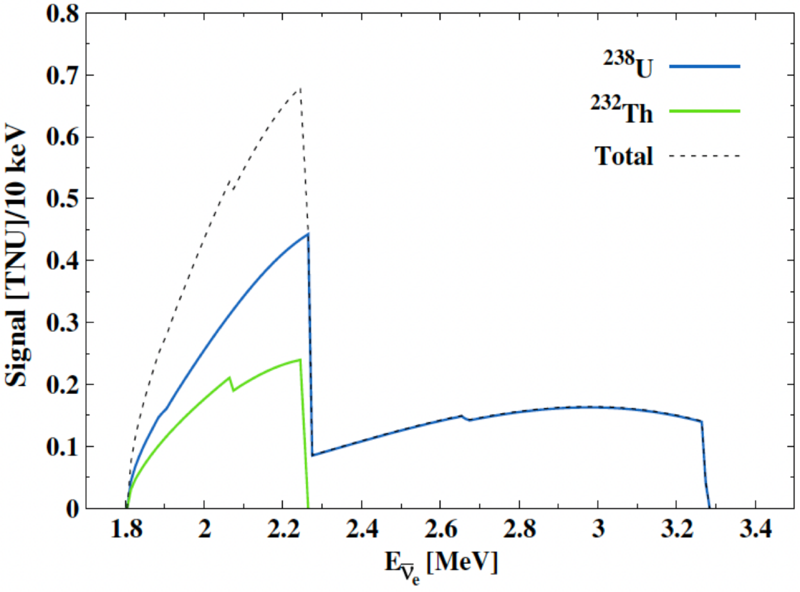
GEONEUTRINO SPECTRAL SHAPE @ LNGS

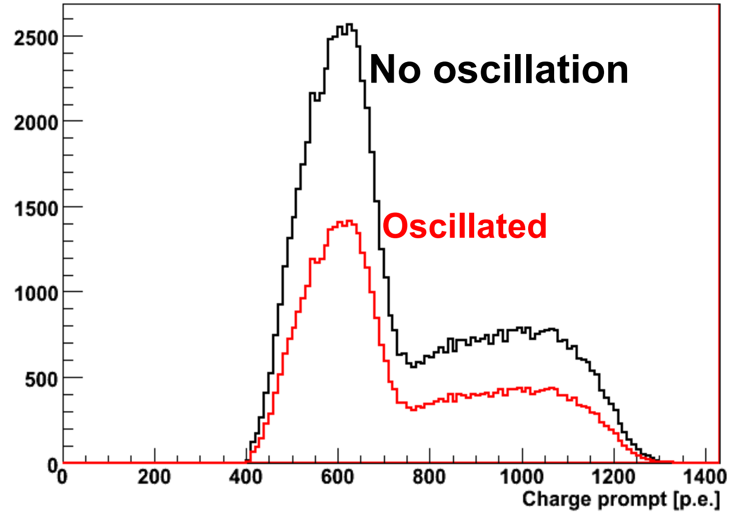
Geoneutrino flux



Geoneutrinos detected via IBD



Effect of neutrino oscillations



500 p.e. ~ 1 MeV

- We are able to **detect geoneutrinos only from the decay chains of ^{238}U and ^{232}Th** above 1.8 MeV.
- ^{238}U and ^{232}Th have different end points: **the key how to spectrally distinguish them**.
- **^{40}K** geoneutrinos cannot be detected.
- **Effect of neutrino oscillations**: for 3 MeV antineutrino, the oscillation length is ~100 km; considering the Earth's dimensions and continuous distribution of U and Th: for the precision of current experiments – suppression of the visible signal without spectral deformation.

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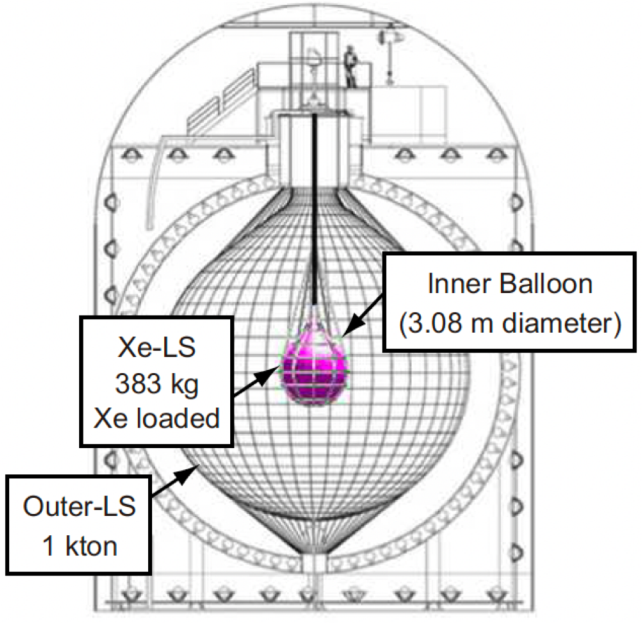
EXPERIMENTS THAT MEASURED GEONEUTRINOS

KamLAND(- Zen), Kamioka, Japan

Border between OCEANIC / CONTINENTAL CRUST



- Main goal: reactor neutrinos (+ since 2011 $0\nu\beta\beta$)
- Data taking: since 2002
- LS: ~1000 tons
- Depth: 2700 m.w.e.
- S(reactors) / S(geo) ~ 6.7 (up to 2010)
  ~ 0.4 (from 2011 after Fukushima)

Liquid scintillator detectors

Large target volume

Placed underground

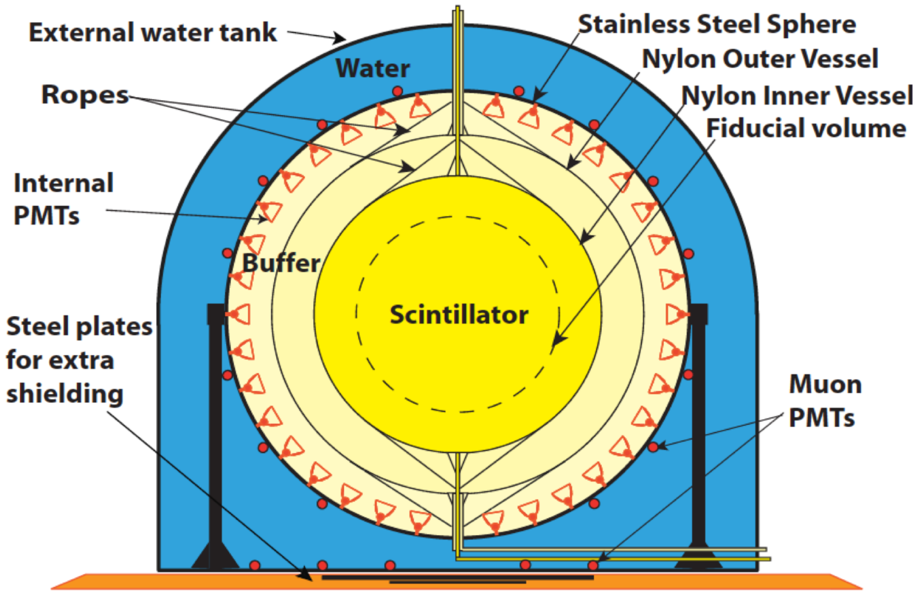
PMT arrays to detect scintillation light

Water Cherenkov veto

Radiopurity

Borexino, LNGS, Italy

CONTINENTAL CRUST



- Main goal: solar neutrinos:
  extreme radio-purity needed and achieved
- Data taking: 2007 – 2021
- LS: 280 tons
- Depth: 3800 m.w.e.
- S(reactors) / S(geo) ~ 0.3 (2010)

HISTORY OF GEONEUTRINO MEASUREMENTS

KamLAND, Kamioka, Japan

The first investigation 2005: Nature 436 (2005) 499

4.5 – 54.2 geonu's @ 90% CL, non-0 hypothesis **CL < 2σ**

7.09×10^{31} proton x year

Update 2008: PRL 100 (2008) 221803

73 ± 27 geonu's — 37%

2.44×10^{32} proton x year

99.997 CL in 2011: Nature Geoscience 4 (2011) 647

106^{+29}_{-28} geonu's — 26%

3.49×10^{32} proton x year (Mar 2002 – Apr 2009)

Results from 2013: PRD 88 (2013) 033001

116^{+28}_{-27} geonu's — 24%

4.9×10^{32} proton x year (Mar 2002 – Nov 2012)

Latest result in 2022 (Geophys. Res. Lett. 49 e2022GL099566)

183^{+29}_{-28} geonu's — 15-16%

6.39×10^{32} proton x year (Mar 2002 – Dec 2020)

Borexino, LNGS, Italy

99.997 CL observation: PLB 687 (2010) 299

$9.9^{+4.1}_{-3.4}$ geonu's — 34-41%

1.5×10^{31} target-proton year (Dec 2007 – Dec 2009)

Update in 2013: PLB 722 (2013) 295–300

14.3 ± 4.4 geonu's — 31%

3.69×10^{31} target-proton year (Dec 2007 – Aug 2012)

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

$23.7^{+6.5}_{-5.7}$ (stat) $^{+0.9}_{-0.6}$ (sys) geonu's — 24-27%

5.5×10^{31} target-proton year (Dec 2007 – Mar 2015)

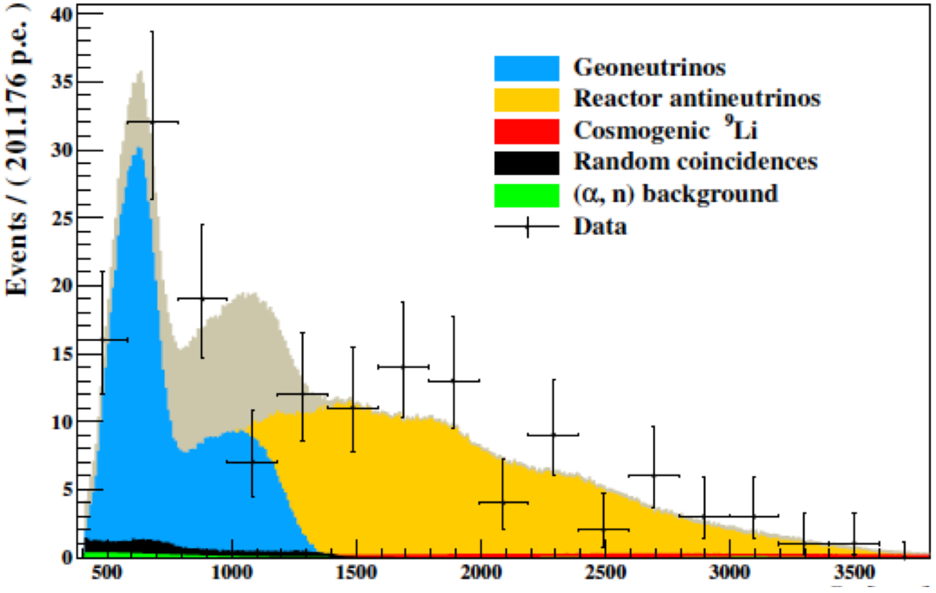
Latest result in 2020 (Phys. Rev. D 101 (2020) 012009)

$52.6^{+9.4}_{-8.6}$ (stat) $^{+2.7}_{-2.1}$ (sys) geonu's — 17-18%

1.29×10^{32} proton x year, (Dec 2007 - Apr 2019)

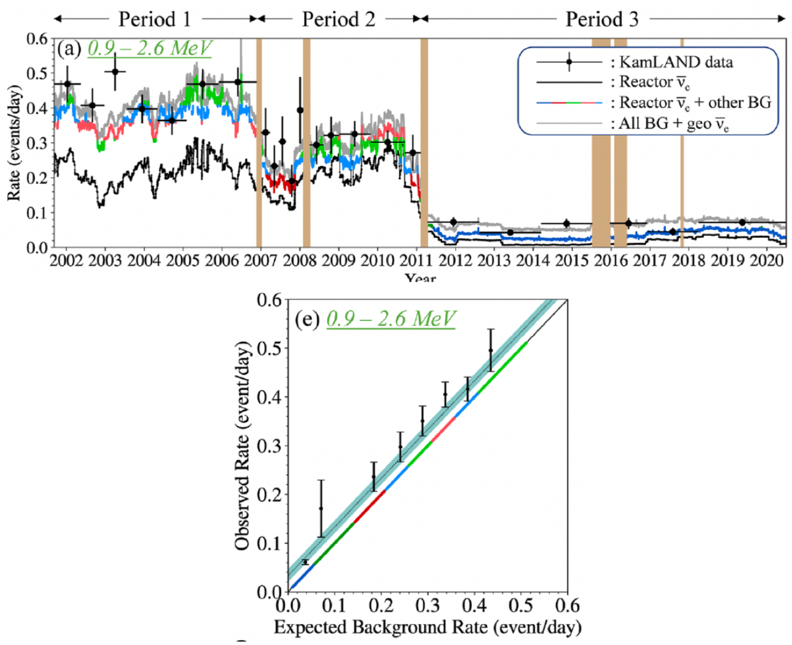
LATES RESULTS: SPECTRAL FIT with chondritic Th/U ratio

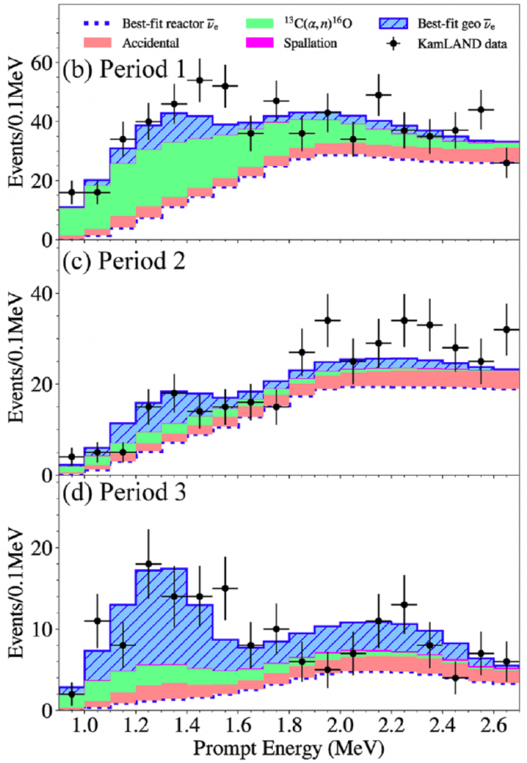
Borexino (PRD101 (2020) 012009)



Prompt charge [photoelectrons]: 1 MeV ~500 photoelectrons

KamLAND (Geophys. Res. Lett. 49 e2022GL099566)

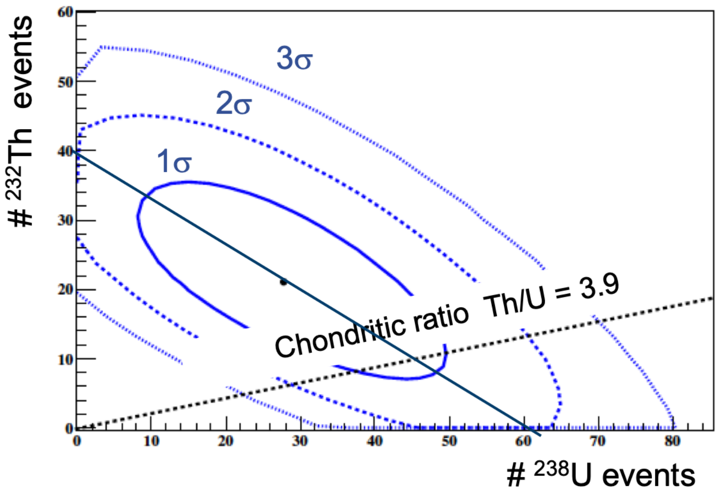




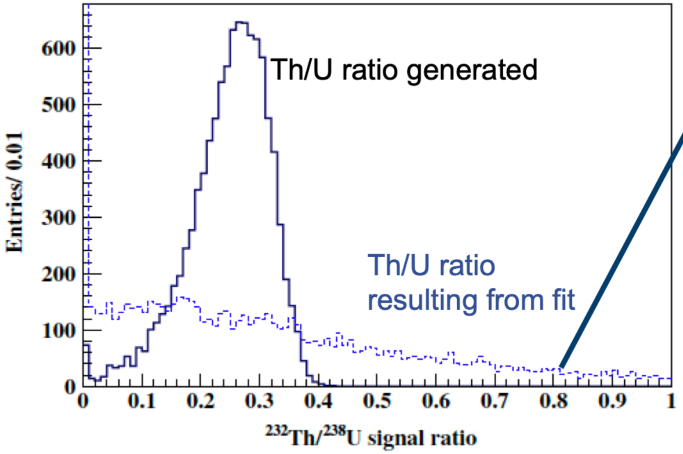
1.29 x 10^{32} proton x years (3262 days, 280 m^3 of FV)	**Exposure [proton x year]**	**6.39 x 10^{32} proton x years** (5227 days, 905 m^3)
154 in total (~90 in the geonu energy window)	**IBD candidates**	**1178** in the geoneutrino energy window
$52.6^{+9.4}_{-8.6}$ *(stat)* $^{+2.7}_{-2.1}(sys)$ $^{+18.3}_{-17.2}\%$	**Geoneutrinos** (mass Th/U fixed to 3.9)	183^{+29}_{-28} *(stat + sys)*: $^{+15.8}_{-15.3}\%$
$47.0^{+8.4}_{-7.7}$ *(stat)* $^{+2.4}_{-1.9}(sys)$	**Signal [TNU]**	Not provided
Shape only, reactor-ν free – results compatible with prediction	**Analysis with** S(Th)/S(U) = 2.7 (corresponds to chondritic Th/U mass ratio of 3.9)	Rate + shape + time

LATES RESULTS: SPECTRAL FIT with Th and U free

Borexino (PRD101 (2020) 012009)



Th/U ratio: 10,000 pseudo-experiments



U: $29.0^{+14.1}_{-12.9}$ events

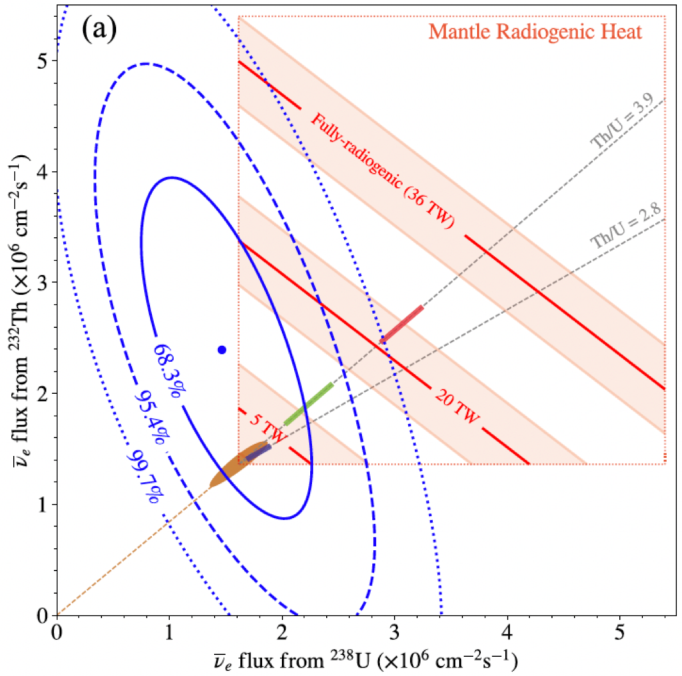
Th: $21.4^{+9.4}_{-9.1}$ events

U + Th: $50.4^{+10.1}_{-9.2}$ events

The resulting Th/U ratio is compatible with the chondritic value,

but with the achieved exposure **1.29 x 10^{32} proton x years,** Borexino has no sensitivity to measure the Th/U ratio.

KamLAND (Geophys. Res. Lett. 49 e2022GL099566)

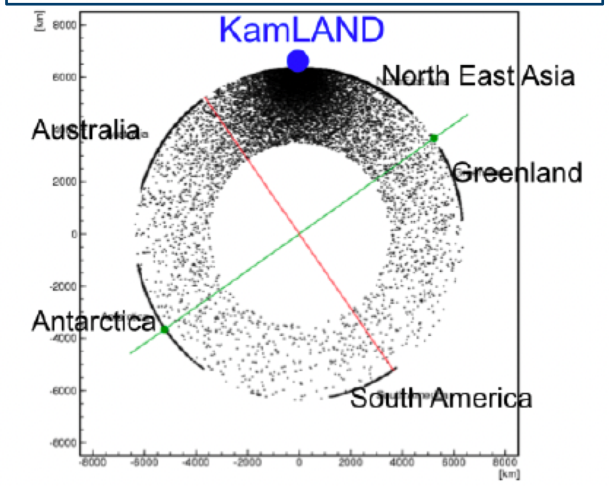


6.39 x 10^{32} proton x year

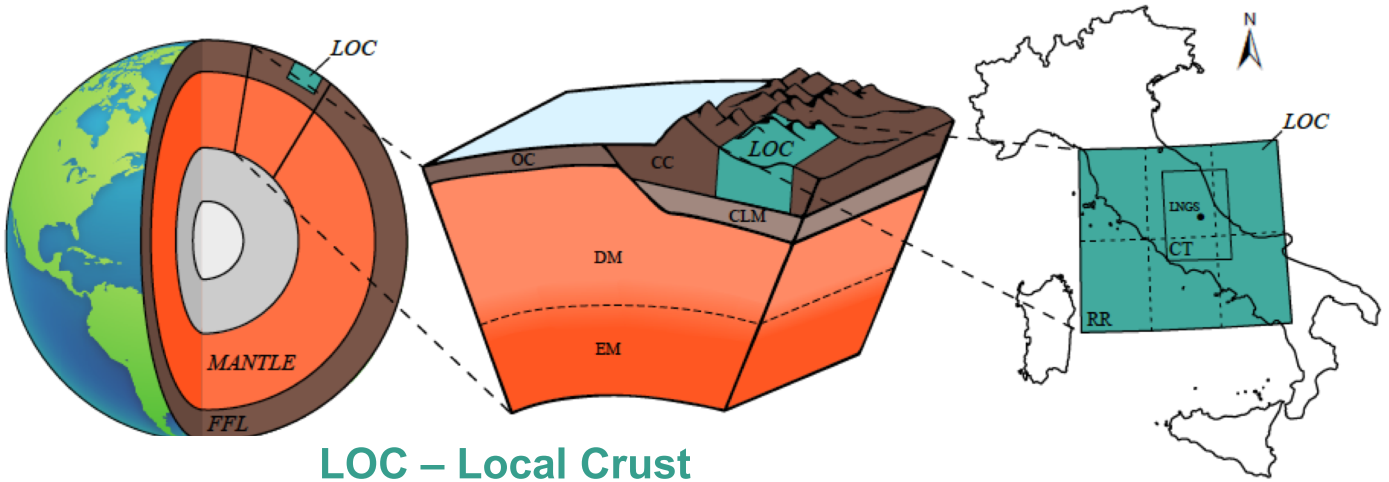
	N of event	0signal rejection
U	117^{+41}_{-39}	3.3σ
Th	58^{+25}_{-24}	2.4σ
U+Th	174^{+31}_{-29}	8.3σ

MANTLE SIGNAL: IMPORTANCE OF LOCAL GEOLOGY

Contribution of different Earth's regions to total KamLAND's signal

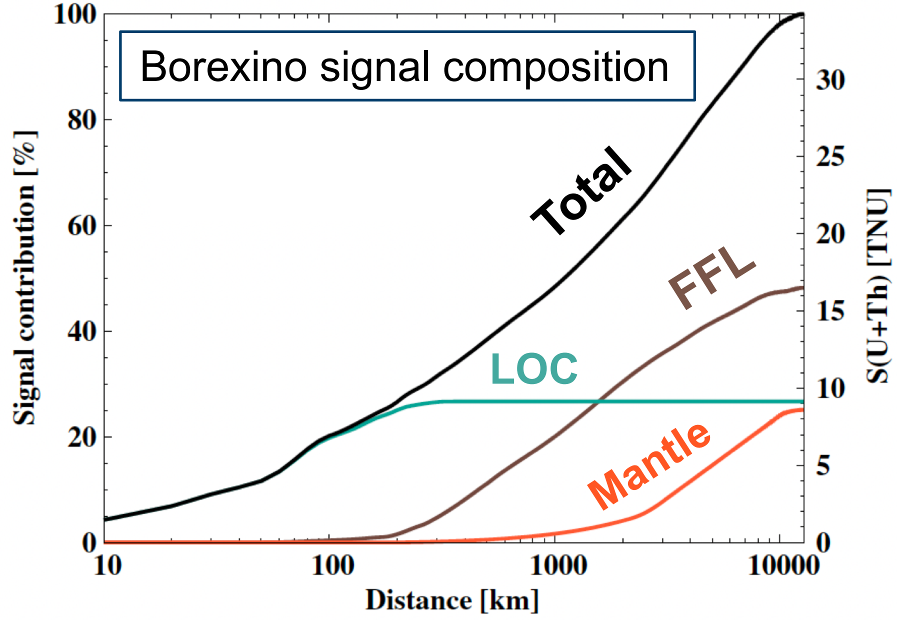


Courtesy: H. Watanabe



LOC – Local Crust
FFL – Far Field Lithosphere
Mantle

PRD101 (2020) 012009

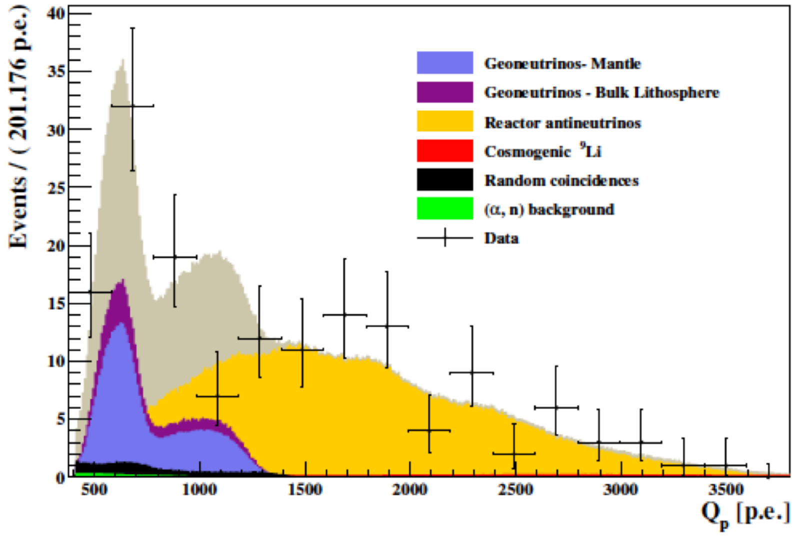


- In order to measure the **Mantle** signal, lithospheric signal must be subtracted.
- **Local Crust (LOC) -** the area of a few hundreds km around the experiment contributes up to 40-50% of the total geoneutrino signal and must be known rather precisely.
- **Far Field Lithosphere (FFL)** – complementary part of the crust to LOC + the continental lithospheric mantle, more approximations are allowed.

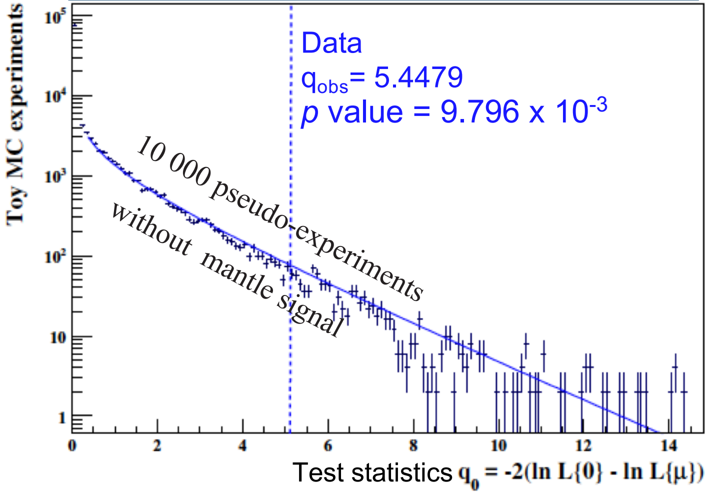
BOREXINO: MANTLE SIGNAL & RADIOGENIC HEAT

PRD101 (2020) 012009

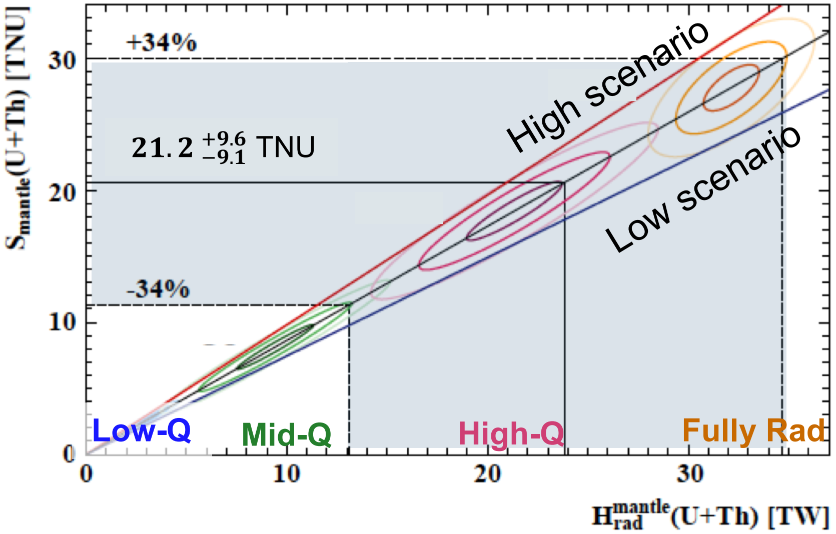
Lithospheric signal: (28.8 ± 5.6) events with S(Th)/S(U) = 0.29
Mantle: S(Th)/S(U) = 0.26
Maintaining for the bulk Earth chondritic Th/U



Sensitivity study
with log-likelihood ratio method



From mantle signal to mantle radiogenic heat



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

Mantle null hypothesis rejected at 99.0% C.L.

Mantle events	$23.7^{+10.7}_{-10.1}$
Mantle signal U + Th [TNU]	$21.2^{+9.6}_{-9.1}$
Mantle heat U + Th [TW]	$24.6^{+11.1}_{-10.4}$
Total Earth U + Th + K [TW]	$38.2^{+13.6}_{-12.7}$

Borexino is compatible with geological predictions:
central value in High–Q BSE & **least compatible (2.4σ) Low-Q BSE**.

+ 18% contribution of ^{40}K in the mantle
+ $8.1^{+1.9}_{-1.4}$ TW from lithosphere (U+Th+K)

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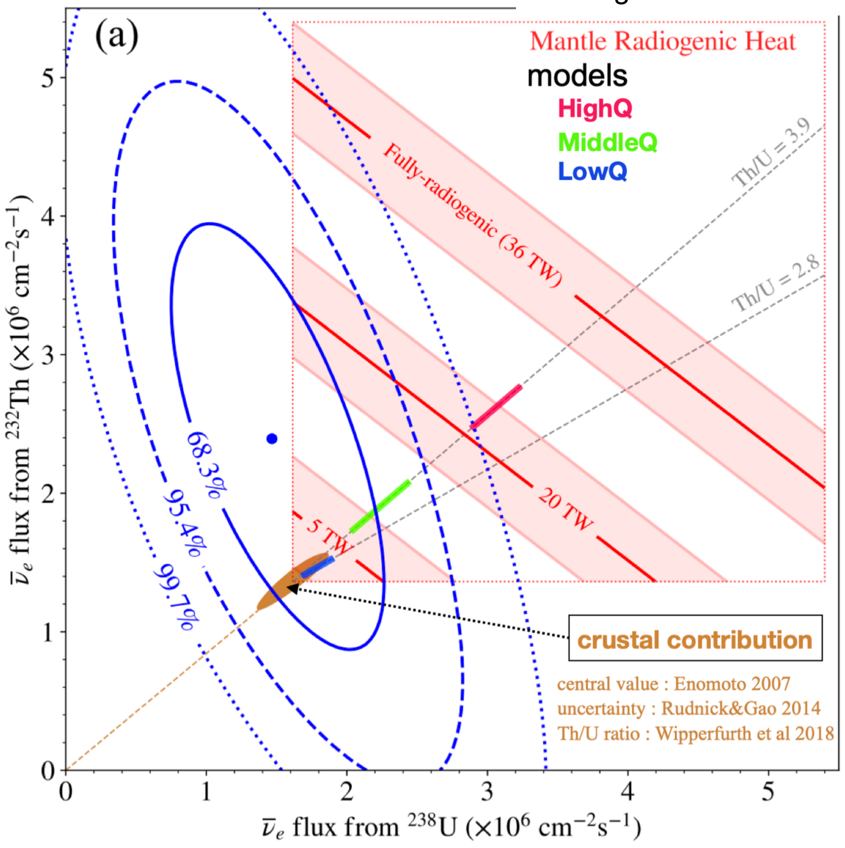
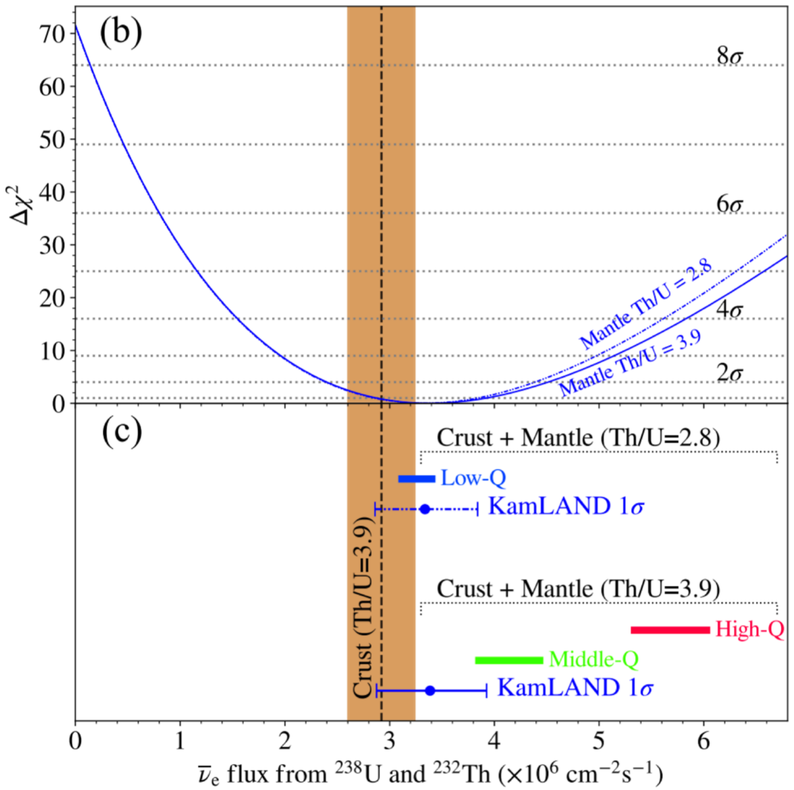
KAMLAND: RADIOGENIC HEAT

Geophys. Res. Lett. 49 e2022GL099566 & courtesy H. Watanabe

Homogeneous mantle





High-Q BSE model is rejected at

99.76 % C.L. (homogeneous mantle)

97.9% C.L. (concentrated at CMB)

Radiogenic Heat

Th/U free

Adding heat estimate from crust, ^{238}U : 3.4 TW, ^{232}Th : 3.6 TW

Crust + mantle

$$Q^{\mathrm{U}} = 3.3^{+3.2}_{-0.8}\ \mathrm{TW}$$

$$Q^{\mathrm{Th}} = 12.1^{+8.3}_{-8.6}\ \mathrm{TW}$$

$$Q^{\mathrm{U}} + Q^{\mathrm{Th}} = 15.4^{+8.3}_{-7.9}\ \mathrm{TW}$$

1σ lower limit allows unphysical Q_{mantle} < 0

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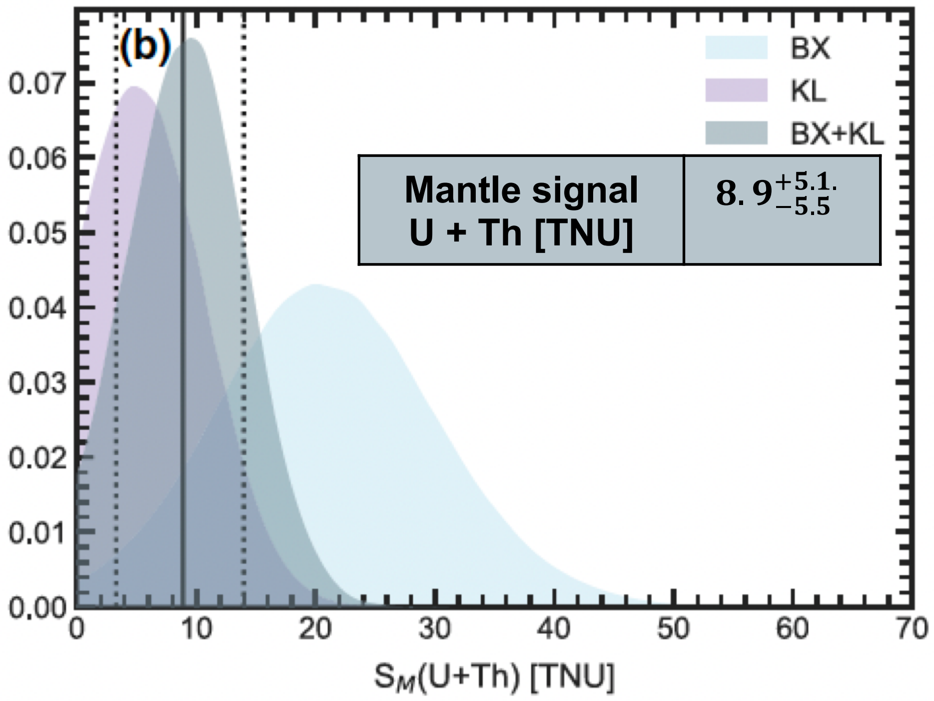
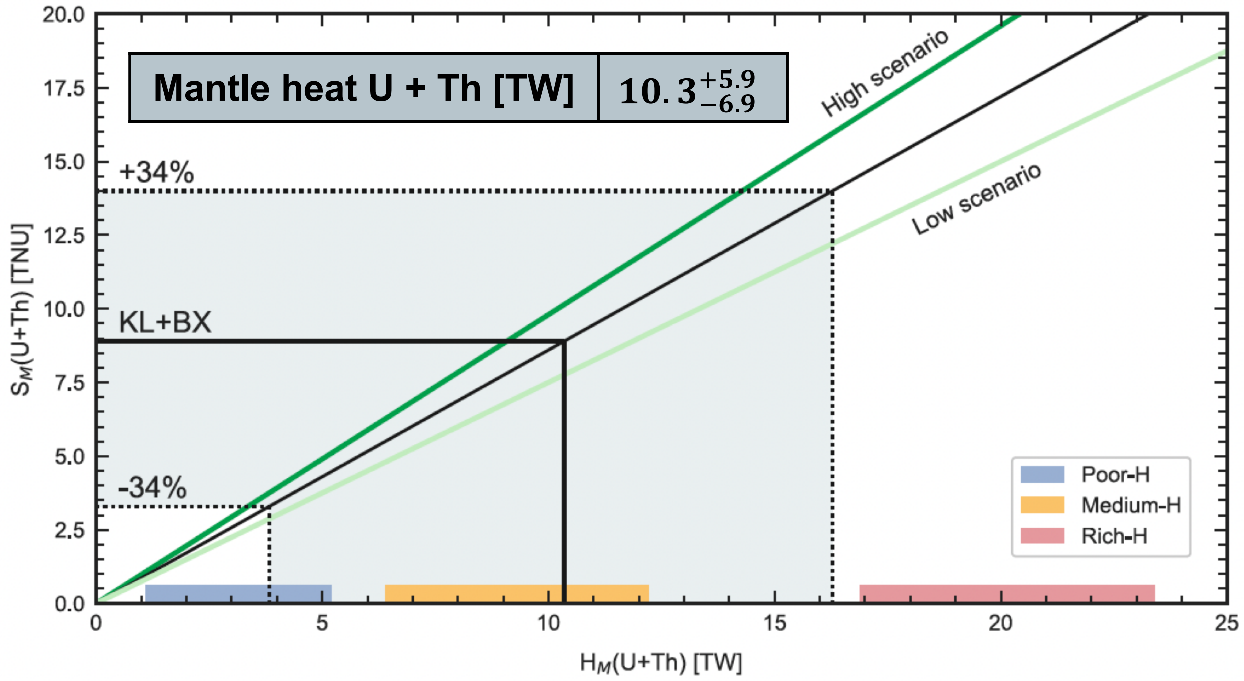
BOREXINO + KAMLAND COMBINED

Bellini at 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.**

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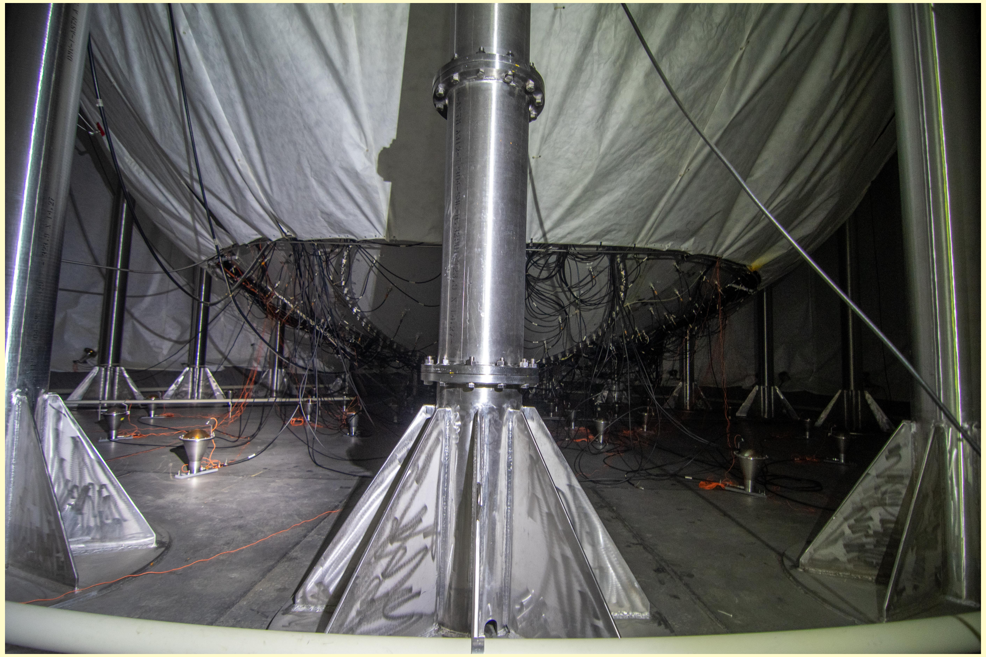
Where to navigate next?
© Livia Ludhova Photography
Photocredit: LL, Bark Europa @ Weddell Sea, Antarctica

Borexino, LNGS, Italy

Stopped data taking in October 2021.

Last update with data till April 2019.

Further updates not planned.



Fotocredit: LL., Borexino water pool during dismantling.

KamLAND, Kamioka, Japan

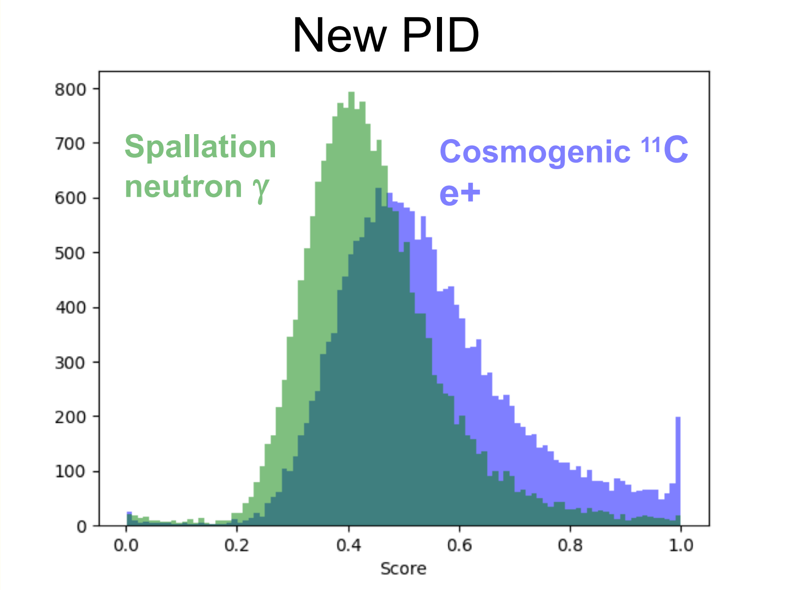
Data taking ongoing.

Last update with data till December 2020.

Analysis improvements ongoing.

Poster #64 on Friday by T. Sakai

Advanced new tool for background rejection in KamLAND geo-neutrino analysis using machine learning methods

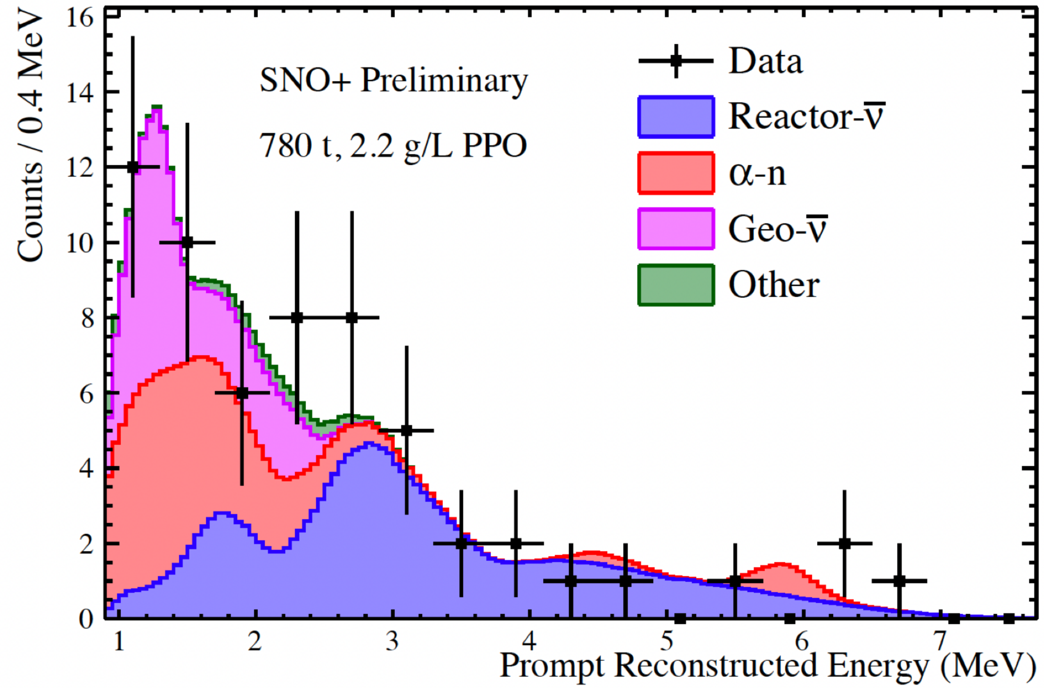


SNO+ COMING ON THE SCENE!

SNO+ is presenting their first full-scintillator antineutrino spectrum at Neutrino 2024.

Plenary talk J. Maneira

Poster #525 on Friday
by S. Andringa



There is an evidence for the geoneutrino detection!

Preliminary fit: 64 $\pm$ 44 TNU

- Their new result is a measurement of reactor neutrino oscillation parameter Δm^2_{21}.
- Will be updated **soon to report their first geoneutrino flux** measurement including (α,n) background rejection.

- ~6000 m.w.e. in 2 km depth
- ~780 ton of LS
- 3rd geographical location on old continental crust

Congratulations!

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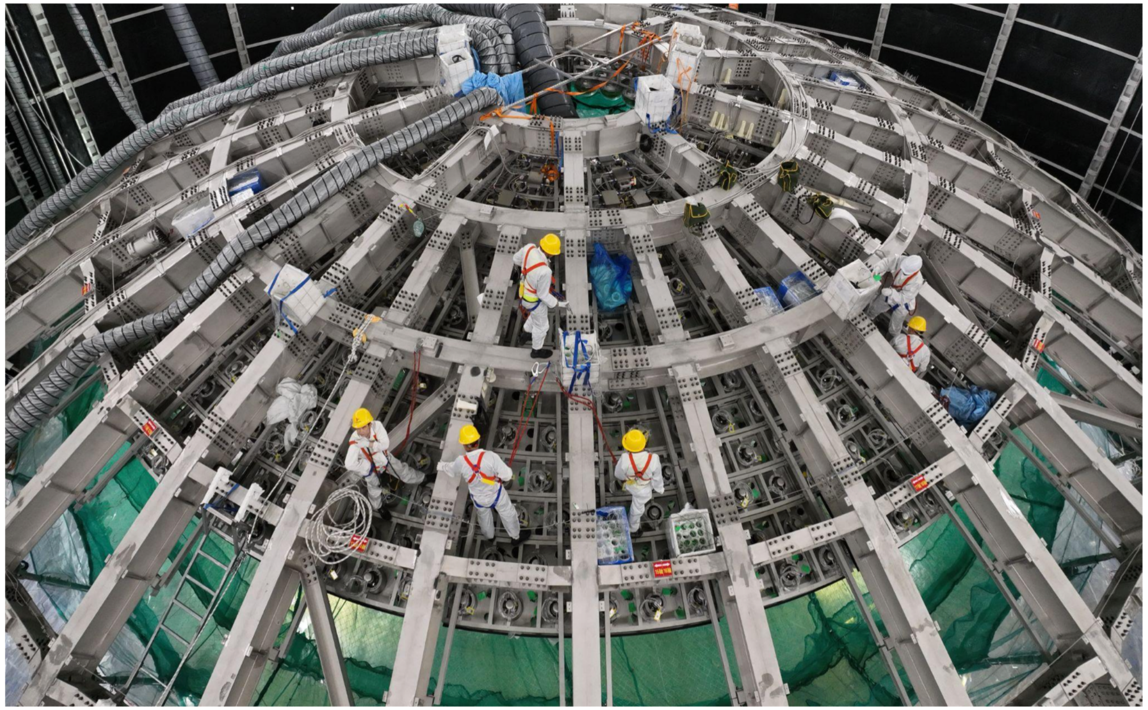
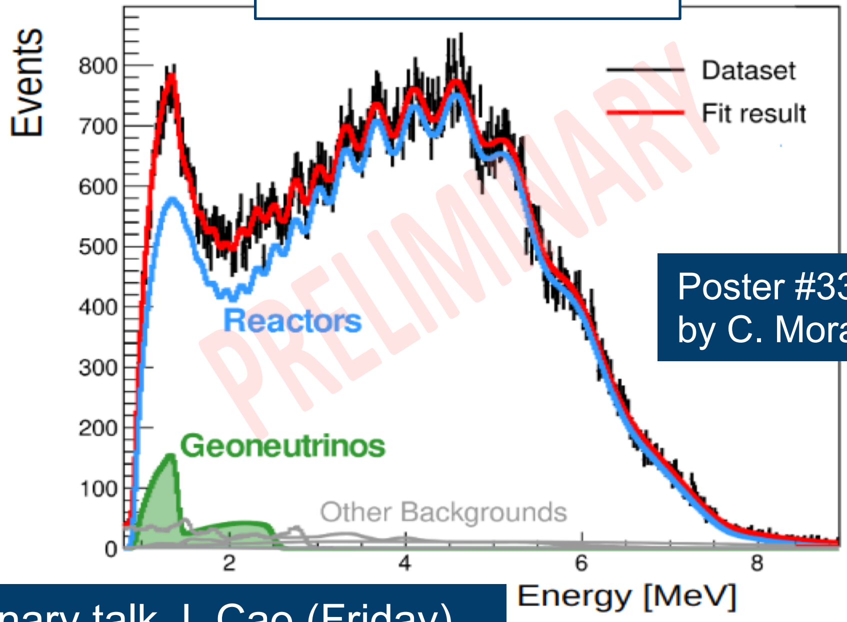
JUNO – 20 kTON DETECTOR UNDER COMPLETION



JUNO will collect the world‘s largest dataset :
~400 geoneutrinos / year

10 years expectation



Poster #333 on Friday
by C. Morales

Plenary talk J. Cao (Friday)

JUNO's main goal: NMO with reactor neutrinos, that represent an irreducible background to geoneutrinos.

Nevertheless, the large collected statistics will allow to reach so far unprecedented precision.

Preliminary expected sensitivity [%]

Th/U ratio fixed	
Time	**U+ Th**
1 year	~22
6 years	~10
10 years	~8

Th and U free				
Time	**U**	**Th**	**U+Th**	**U/Th**
6 years	~35	~40	~18	~70
10 years	~30	~35	~15	~55

Jinping Neutrino Experiment (JNE), China

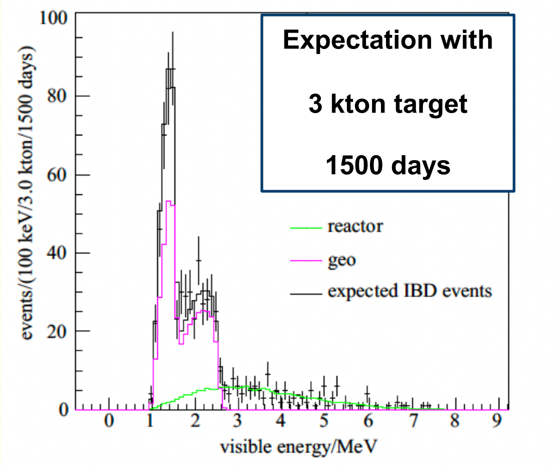
Chinese Phys. C 41 (2017) 023002.

In China Jinping Underground Laboratory – deepest in the world.

Almost no background from reactors.

Very thick continental crust.

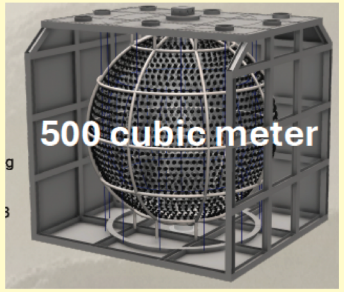
Slow scintillator to enable separation of the fast Cherenkov light.



Expectation with

3 kton target

1500 days



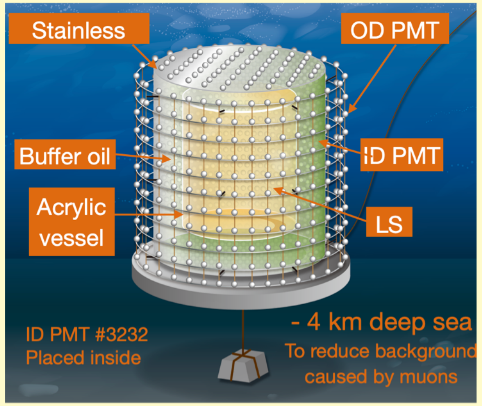
Prototype to be constructed by 2026

Poster #66 on Tuesday by W. Luo

Research and Development of Jinping Neutrino Experiment

Ocean Bottom Detector inspired by HanoHano

Japan Agency for Marine-Earth Science and Technology & Tohoku University, Japan



Direct access to mantle signal.

Oceanic crust is thin, simple, and depleted in U and Th.

Target mass 10 - 50 kton.

Many technological challenges.

The ultimate geoneutrino detector!

- Detection of ^{40}K
- Directionality
- More statistics
- Multi-site experiments
- Experiments at geologically particular locations

More on future developments in talk of C. Rott

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Photo credit L.L., Shiveluch volcano, Kamchatka, Russia

Thank you!

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Forschungszentrum

Back up slides

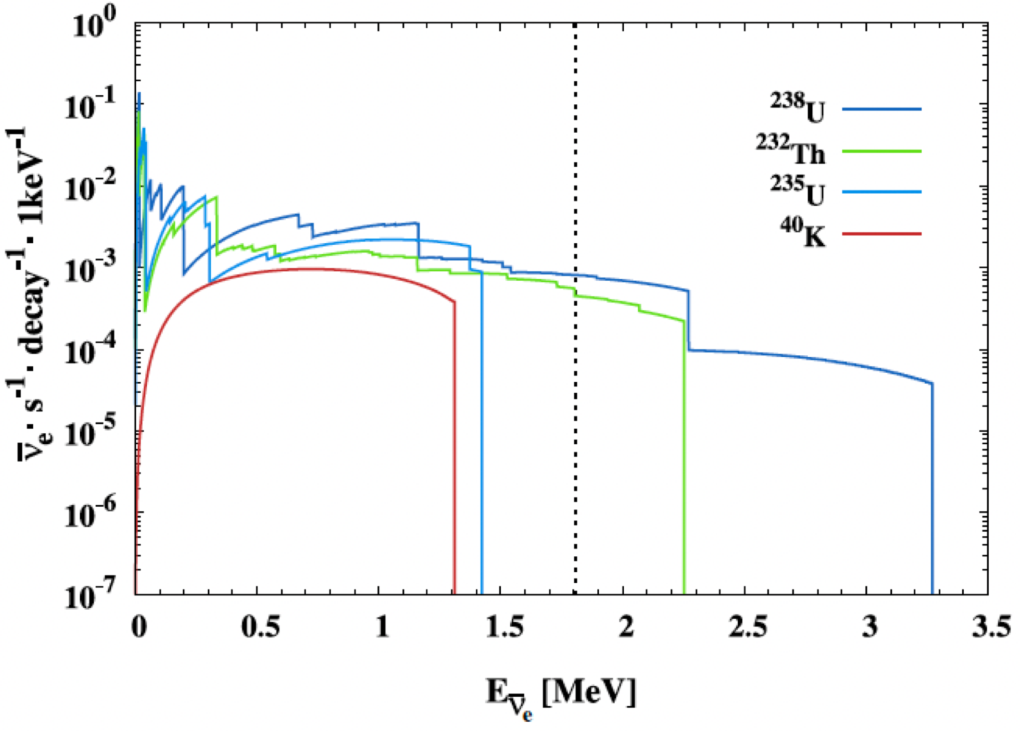
$$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.7\ \text{MeV}$$

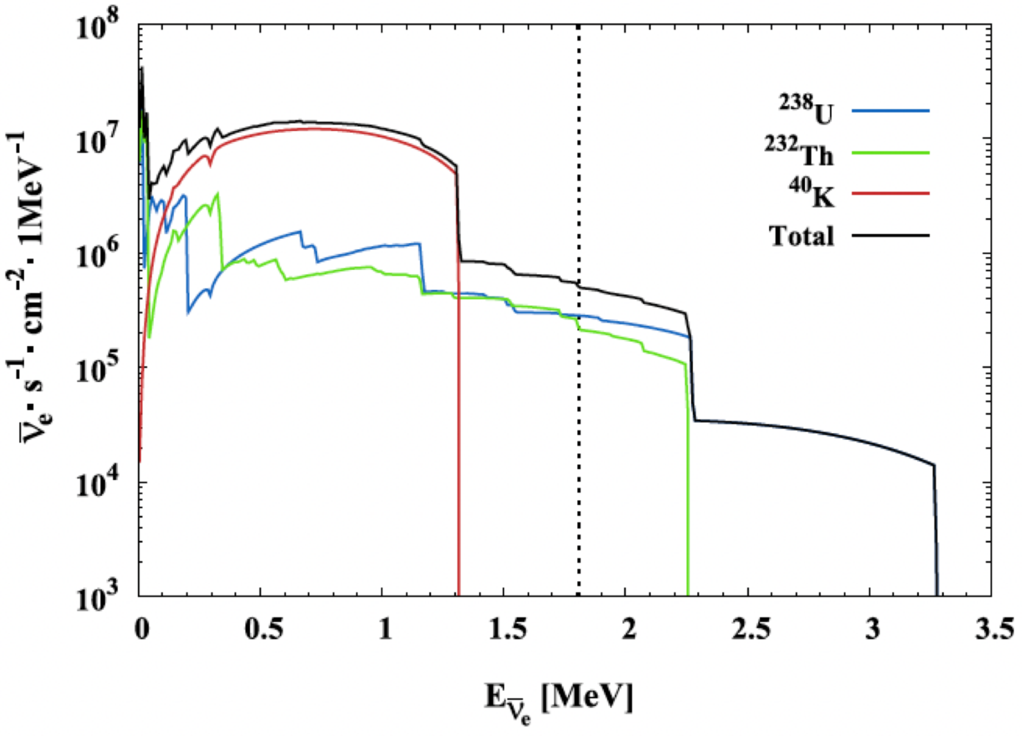
$$^{235}U \rightarrow {}^{207}Pb + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.4\ \text{MeV}$$

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

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

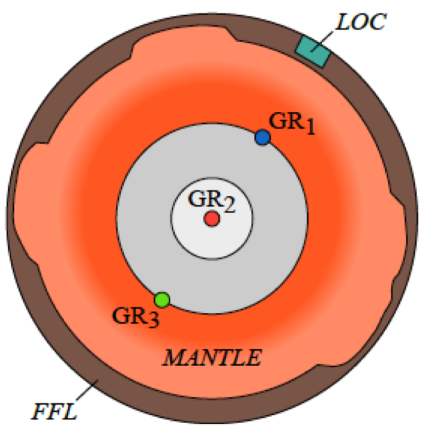
$$^{40}K + e^- \rightarrow {}^{40}Ar + \nu_e + 1.505\ \text{MeV}\ (10.7\%)$$

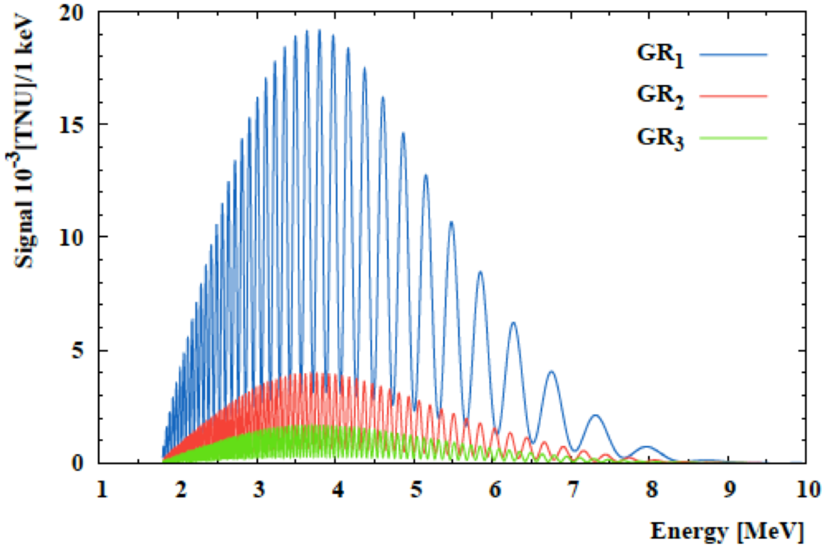


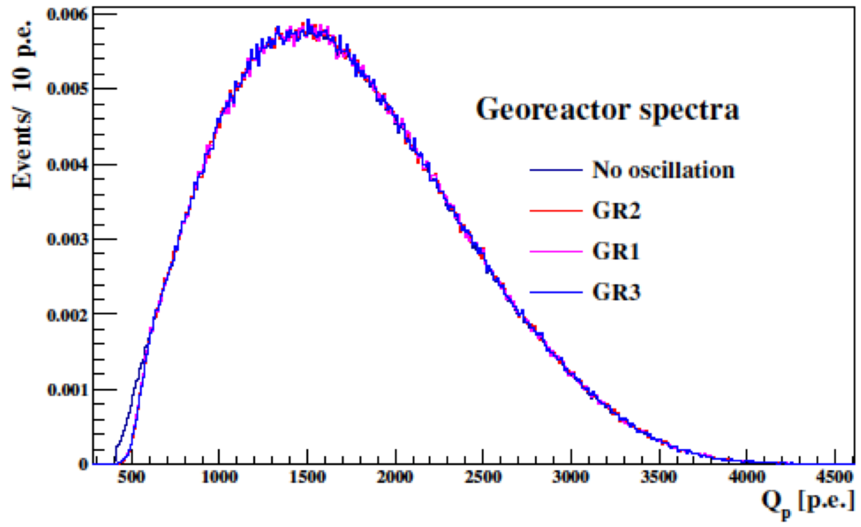


Limits on the existence of a GEOREACTOR

Fast oscillation pattern → cannot be resolved experimentally







Borexino

- 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

Borexino

Upper limit (95% CL): 18.7 TNU – conversion to TW depends on the location of the 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

KamLAND

fission ration from commercial reactors assumed
averaged oscillation probability
U and Th left free in fit

KamLAND

1.26 TW at 90% CL (center?)

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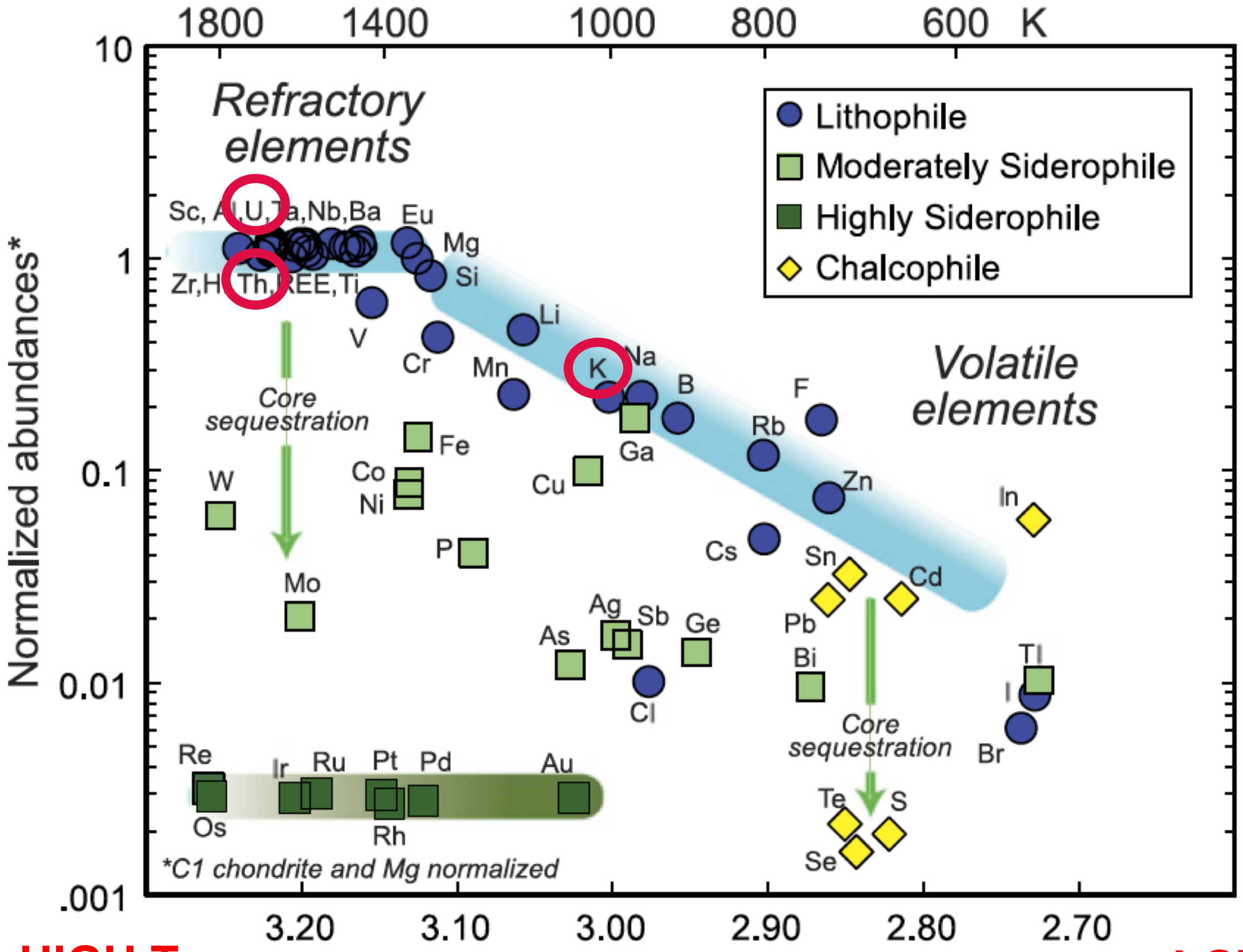
Composition of the primitive mantle



HIGH T refractory

LOW T volatile

Progress in Particle and Nuclear Physics 73 (2013) 1–34

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NON-ANTINEUTRINO BACKGROUNDS

1) <u>Cosmogenic background</u>

- **^{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.

2) <u>Accidental coincidences</u>;

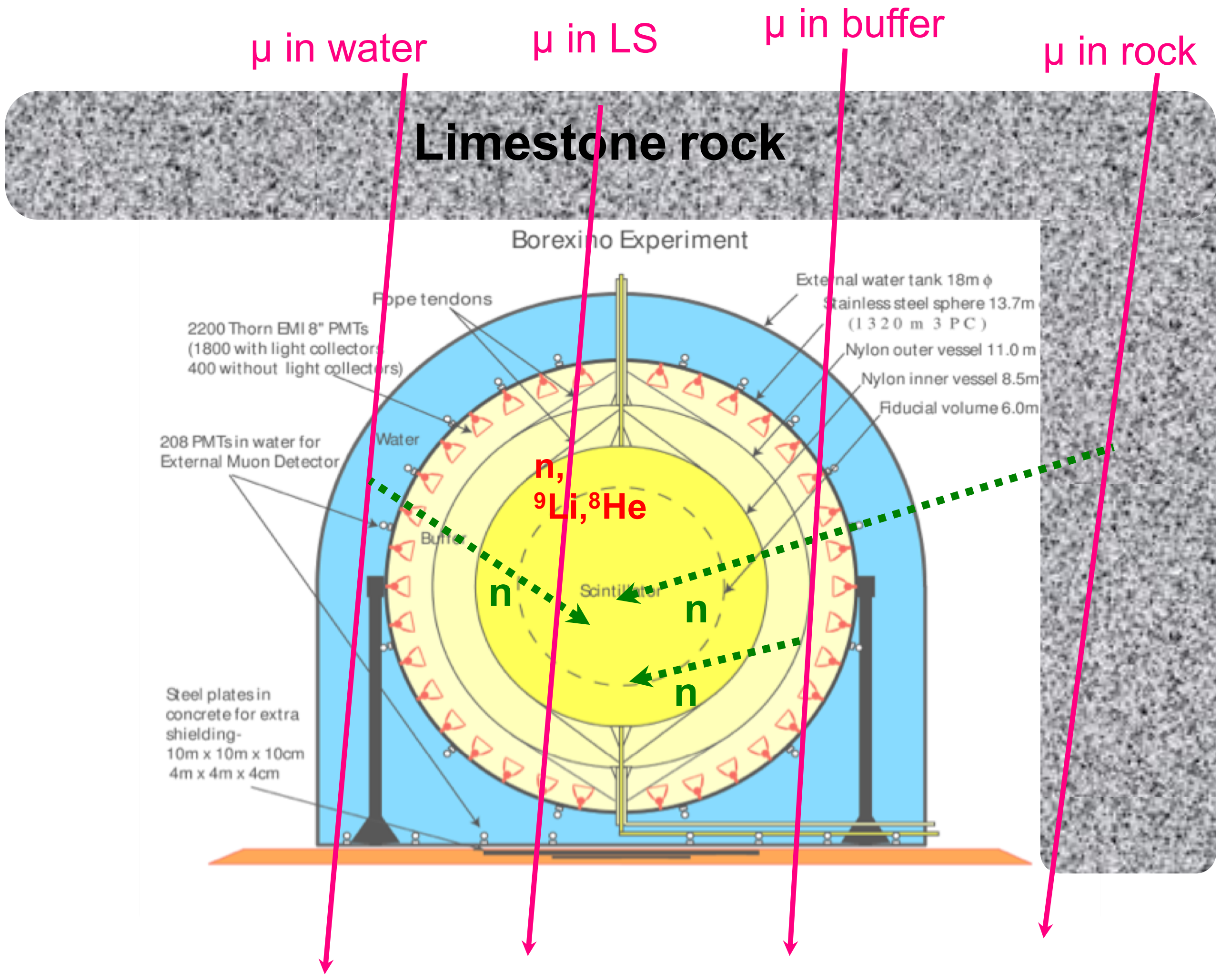
Estimated from OFF-time IBD-like coincidences.

3) <u>Due to the internal radioactivity</u>:

(α, n) reactions: ^{13}C(α, n)^{16}O

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

Estimated from ^{210}Po(α) and ^{13}C contaminations, (α, n) cross section.

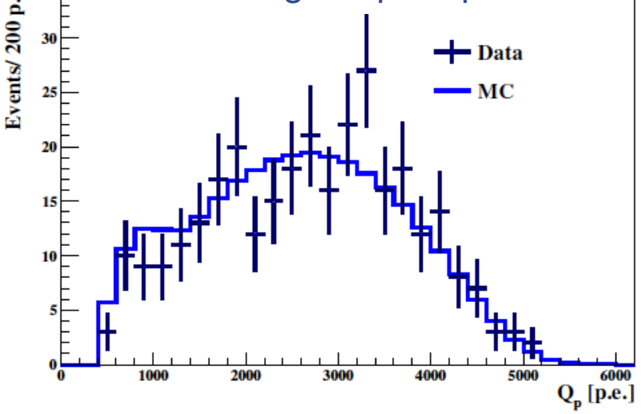


NON-ANTINEUTRINO BACKGROUNDS in Borexino

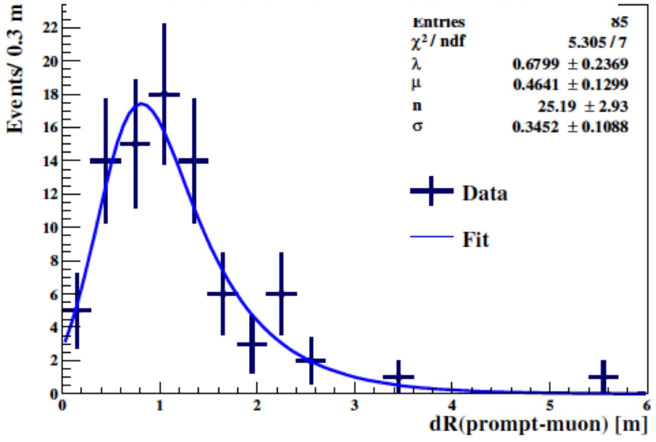
^{9}Li (β+n) events < 2s after muons

$\tau_{measured}$ = (0.260 ± 0.021) s

Charge of prompt



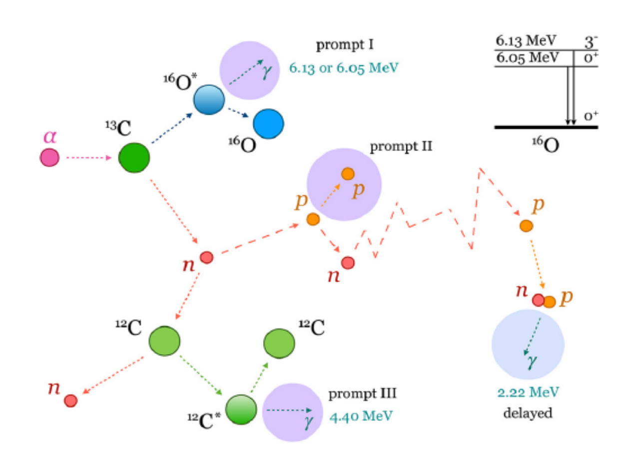
Distance from muon track

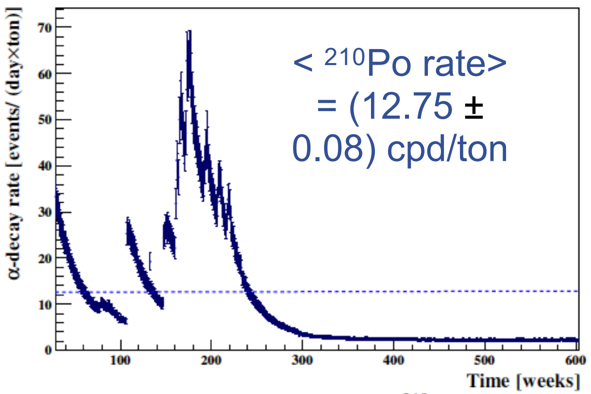


^{13}C(^{210}Po(α), n) ^{16}O

Y_n = (1.45 ± 0.22) x 10^{-7}

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



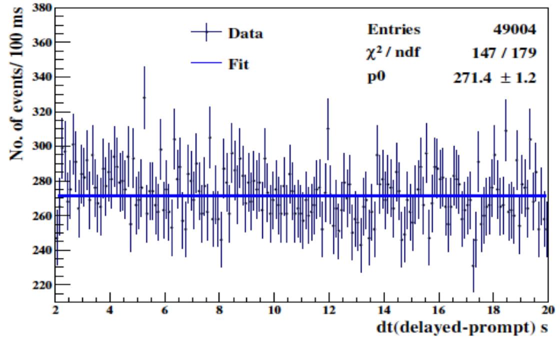


Accidentals

R_{acc} = (3029.0 ± 12.7) s^{-1}

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

IBD-like events in dt = 2 -20 s



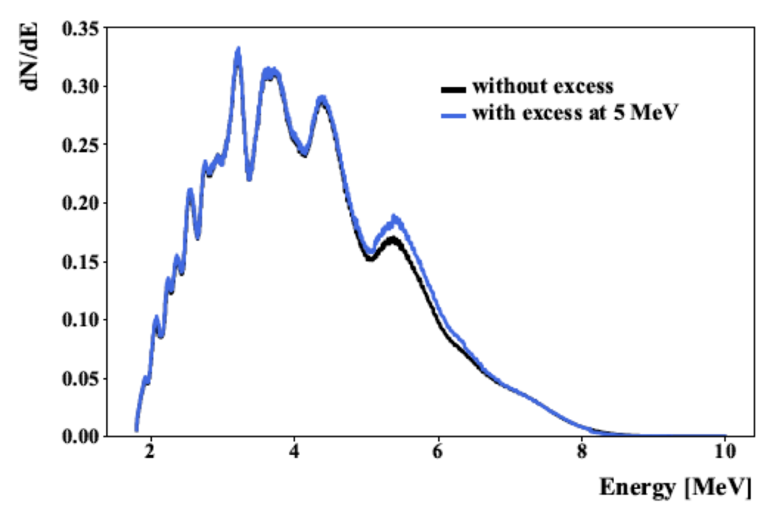
Background Type	Events
^{9}Li background	3.6 ± 1.0
Untagged Muons	0.023 ± 0.007
Fast n's (μ in WT)	<0.013
Fast n's (μ in rock)	<1.43
Accidental coincidences	3.846 ± 0.017
(α, n) in scintillator	0.81 ± 0.13
(α, n) in buffer	<2.6
(γ, n)	<0.34
Fission in PMTs	<0.057
^{214}Bi-^{214}Po	0.003 ± 0.0010
Total	8.28 ± 1.01

NEUTRINO BACKGROUNDS IN Borexino

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 at al. 2011 and Daya Bay)
- P_{ee} electron neutrino survival probability
- IBD cross section
- Detection efficiency = 0.8955 ± 0.0150

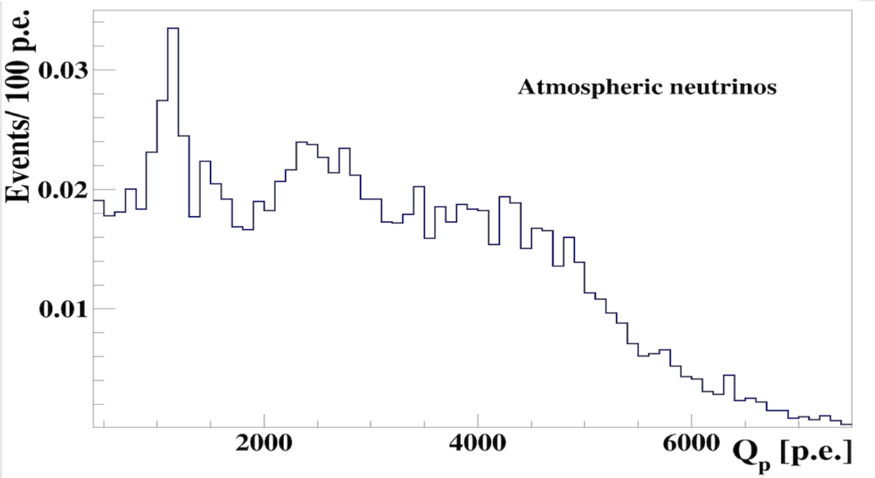


Atmospheric neutrinos

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.

OPTIMIZED IBD SELECTION CUTS in Borexino

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

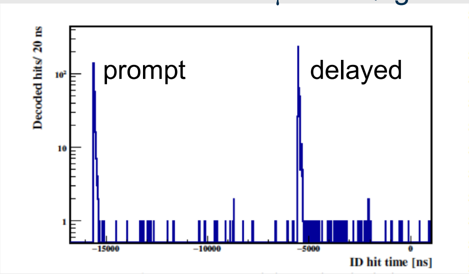
- Neutron captures on proton (2.2 MeV) and in about 1% of cases on ^{12}C (4.95 MeV)
- Spill out effect at the nylon inner vessel border
- Radon correlated $^{214}Po(\alpha + \gamma)$ decays from ^{214}Bi and ^{214}Po fast coincidences

Time correlation

dt = (2.5-12.5) μs + (20-1280) μs

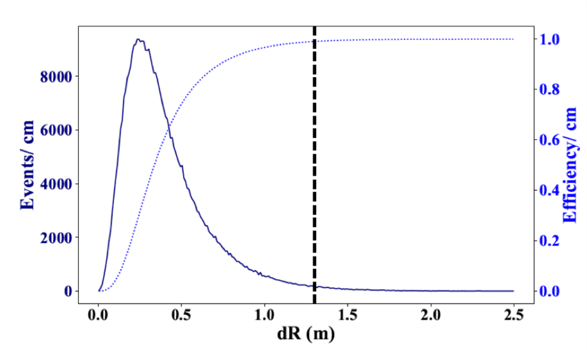
Neutron capture $\tau = (254.5 \pm 1.8)$ μs

2 cluster event in 16 μs DAQ gate



Space correlation

dR < 1.3 m

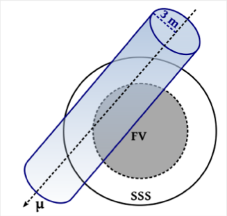


Muon veto

2s || 1.6 s : $^9Li(\beta + n)$

2 ms: neutrons

- Several veto categories
- Strict and special muon tags



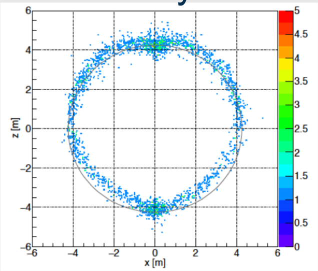
- Whole detector
- **Cylinder**

Only 2.2% exposure loss

Dynamic Fiducial Volume

> 10 cm from IV (prompt)

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



Multiplicity

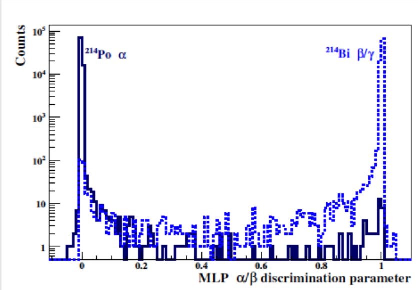
No event with Q >400 pe ±2 ms around promt/delayed

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

α/β discrimination

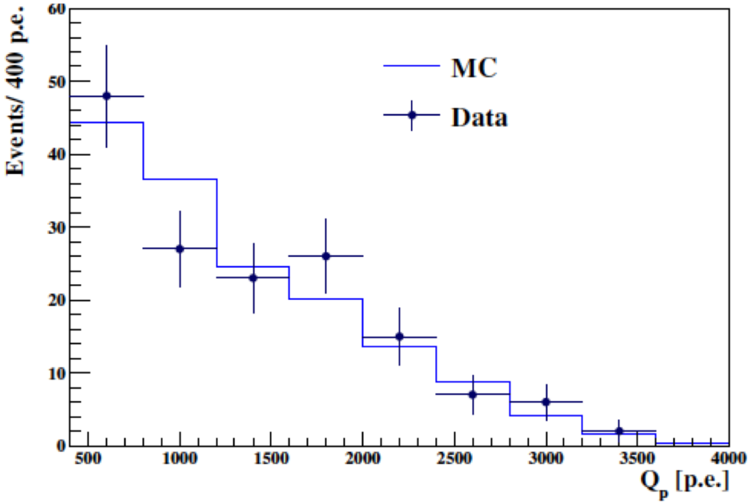
$MLP_{delayed}$ > 0.8

- Radon correlated $^{214}Po(\alpha+\gamma)$

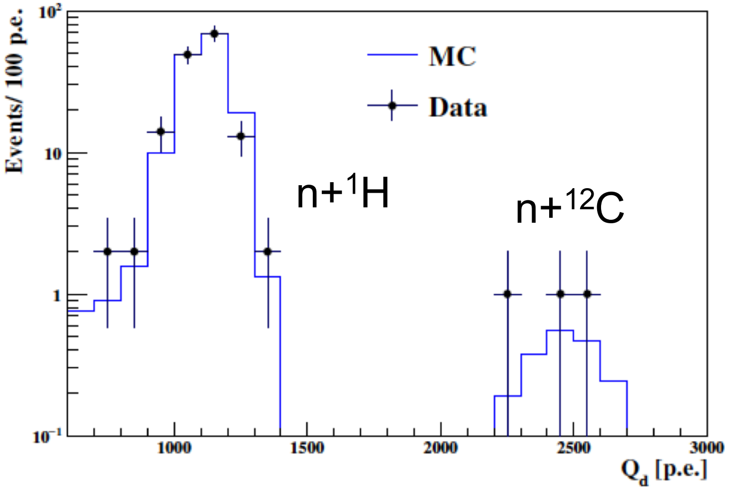


GOLDEN CANDIDATES: 154

Prompt charge spectrum

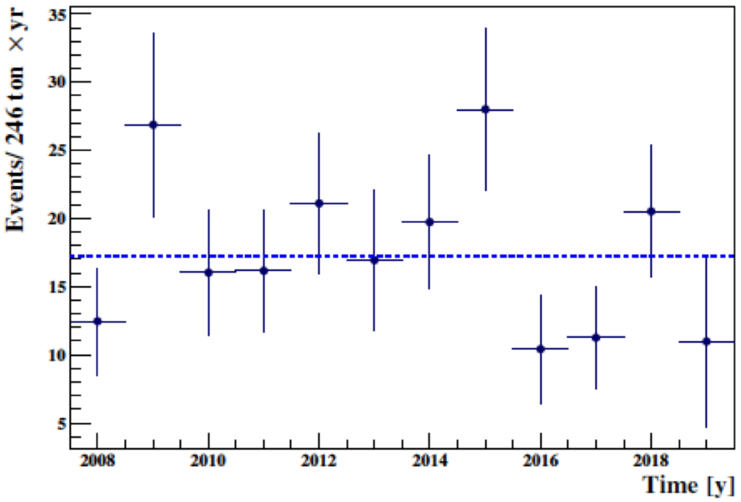


Delayed charge spectrum

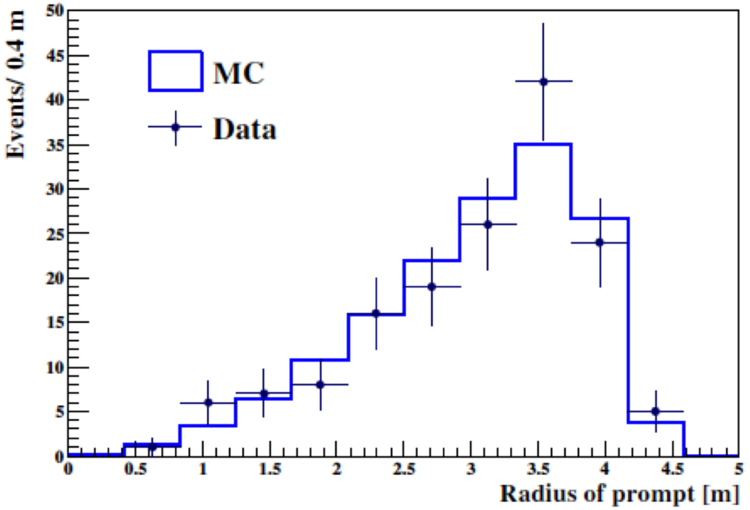


- December 9, 2007 to April 28, 2019
- 3262.74 days of data taking
- Average FV = (245.8 ± 8.7) ton
- **Exposure = (1.29 ± 0.05) x 10^{32} proton x year**
- Including systematics on position reconstruction and muon veto loss, for 100% detection eff.

Distribution in time



Radial distribution



Distance to the Inner Vessel