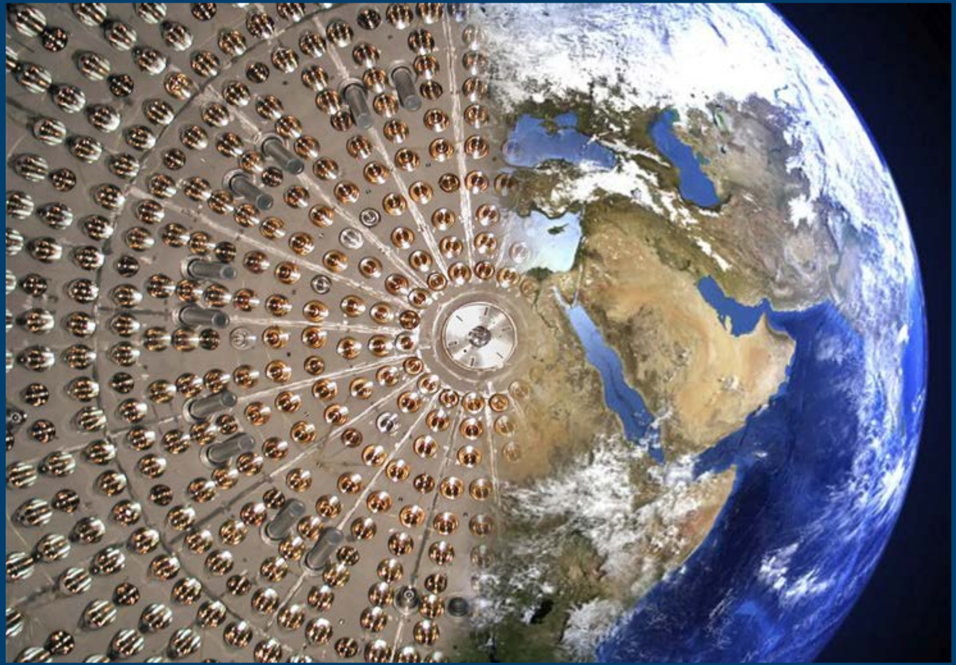
OVERVIEW OF EXPERIMENTAL RESULTS ON GEONEUTRINOS

LIVIA LUDHOVA

IKP-2, FORSCHUNGSZENTRUM JÜLICH
AND RWTH AACHEN UNIVERSITY,
GERMANY



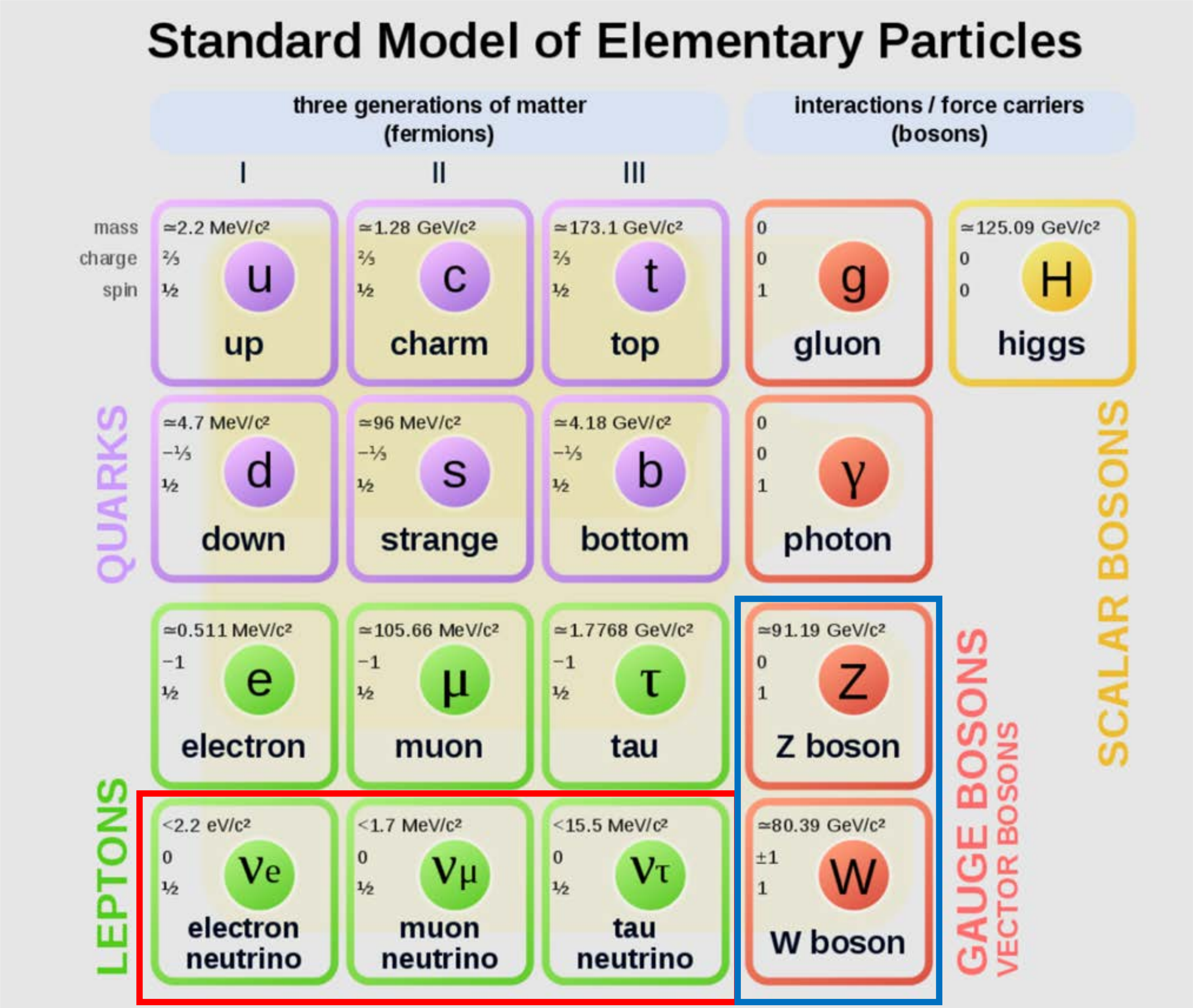
JULY 6TH, 2023

INTERNATIONAL WORKSHOP ON MULTI-MESSENGER TOMOGRAPHY OF THE EARTH

WELCOME TO THIS JOURNEY
...... TO THE CENTER OF THE EARTH.........

- Basic neutrino properties
- Geoneutrino detection
- Borexino and KamLAND
  - detectors
  - analysis strategy
  - geoneutrino latest results

NEUTRINOS AMONG OTHER ELEMENTARY PARTICLES



Neutrinos of 3 flavours

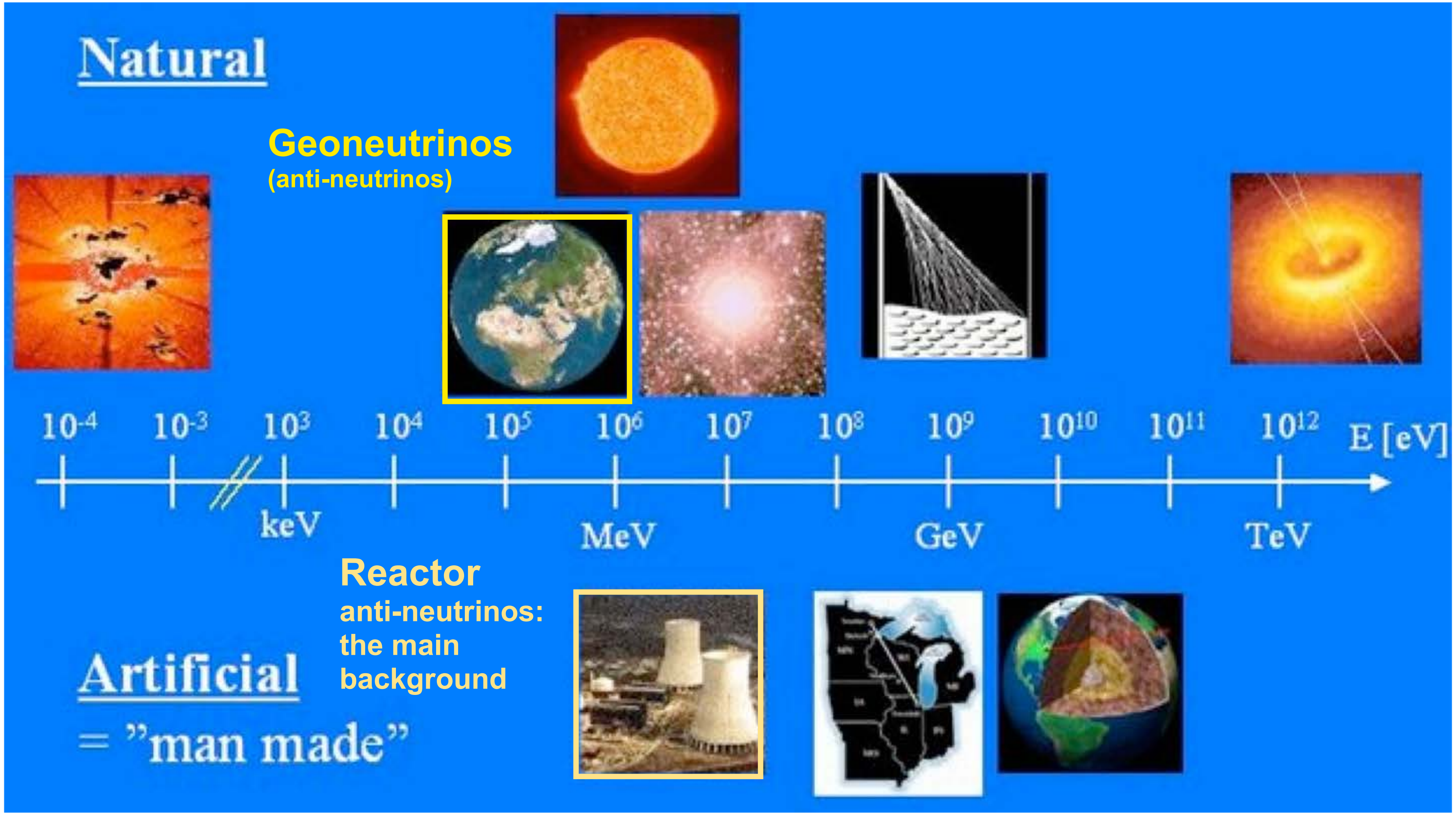
Weak interaction mediators

Leptons - antileptons

particles lepton number +1		-	**antiparticles** lepton number -1	
e^-	ν_e	3 flavors	e^+	$\bar{\nu}_e$
μ^-	ν_μ		μ^+	$\bar{\nu}_\mu$
τ^-	ν_τ		τ^+	$\bar{\nu}_\tau$

JÜLICH Forschungszentrum

NEUTRINO SOURCES



NEUTRINOS ARE SPECIAL

Only weak interactions

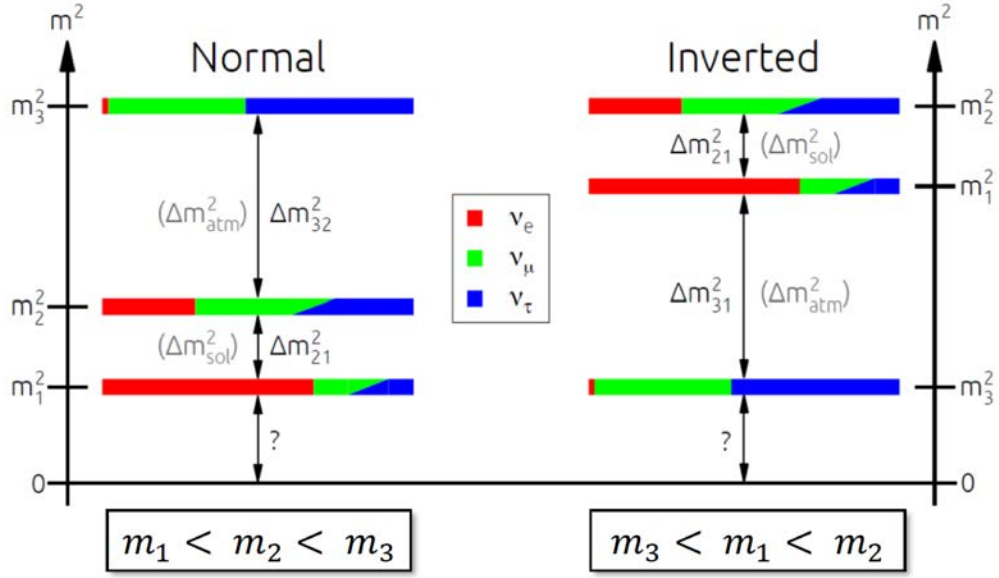
- ✓ **Difficult to detect**
  - Large detectors
  - Underground laboratories
  - Extreme radio-purity
- ✓ **Bring unperturbed information about the source** (**Sun, Earth**, SN)

Open questions in neutrino physics

- ✓ Mass Hierarchy (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

linked

Two possible scenarios of neutrino mass hierarchy



In spite of many open questions about neutrino properties,
we are able to use neutrinos to learn about the place of their origin – the Earth included!

Geoneutrinos: antineutrinos/neutrinos from the decays of long-lived radioactive isotopes naturally present in the Earth

^{238}U (99.2739% of natural U) → ^{206}Pb + 8 α + 8 e^- + 6 anti-neutrons of electron flavour + **51.7 MeV**	
^{232}Th → ^{208}Pb + 6 α + 4 e^- + 4 anti-neutrinos of electron flavour + **42.8 MeV**	
^{235}U (0.7205% of natural U) → ^{207}Pb + 7 α + 4 e^- + 4 anti-neutrinos of electron flavour + **46.4 MeV**	
^{40}K (0.012% of natural K) → ^{40}Ca + e^- + 1 anti-neutrino of electron flavour + **1.32 MeV** (BR=89.3 %)	
^{40}K + e^- → ^{40}Ar + 1 neutrino + **1.505 MeV** (BR = 10.7 %)	

- **direct probe of the deep Earth**
- **released heat and geoneutrino flux in a well fixed ratio**
- to measure geoneutrino flux = (in principle) = to get radiogenic heat
- in practice (as always) more complicated….. (see talk of Virginia)

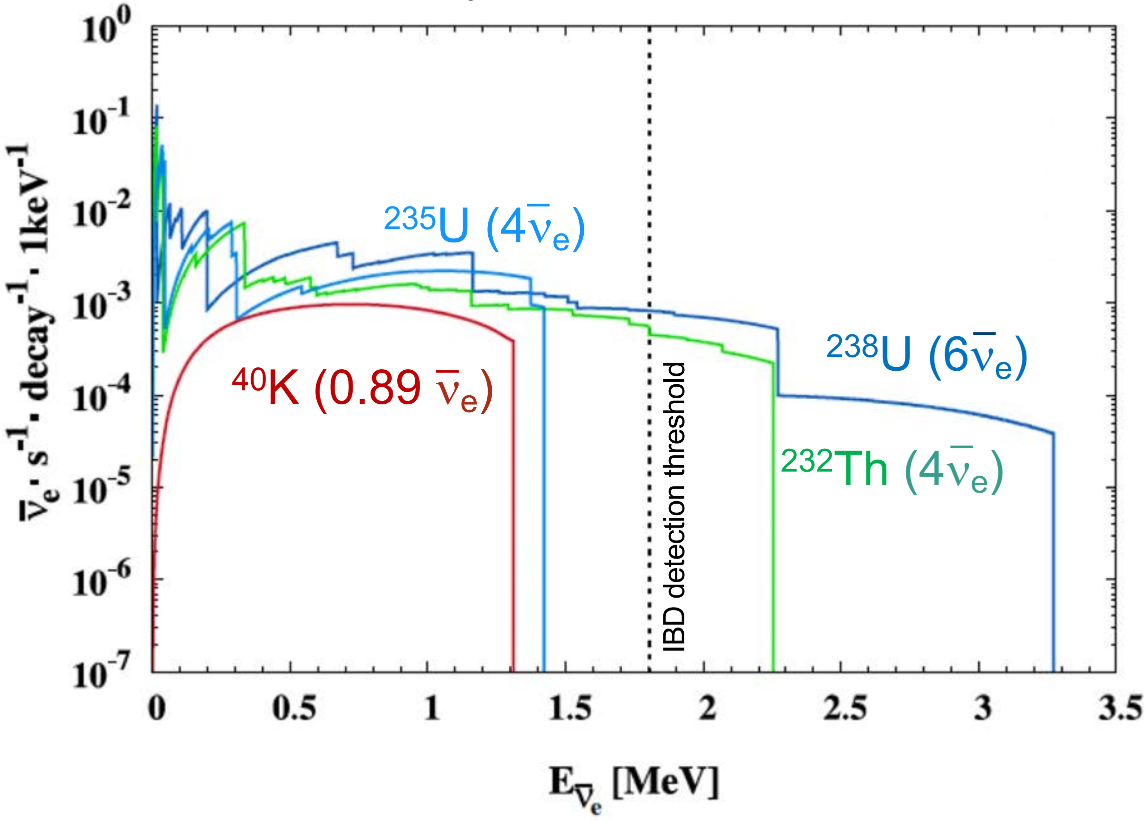
Earth shines in geoneutrinos: flux ~10^6 cm^{-2} s^{-1}

leaving freely and instantaneously the Earth interior

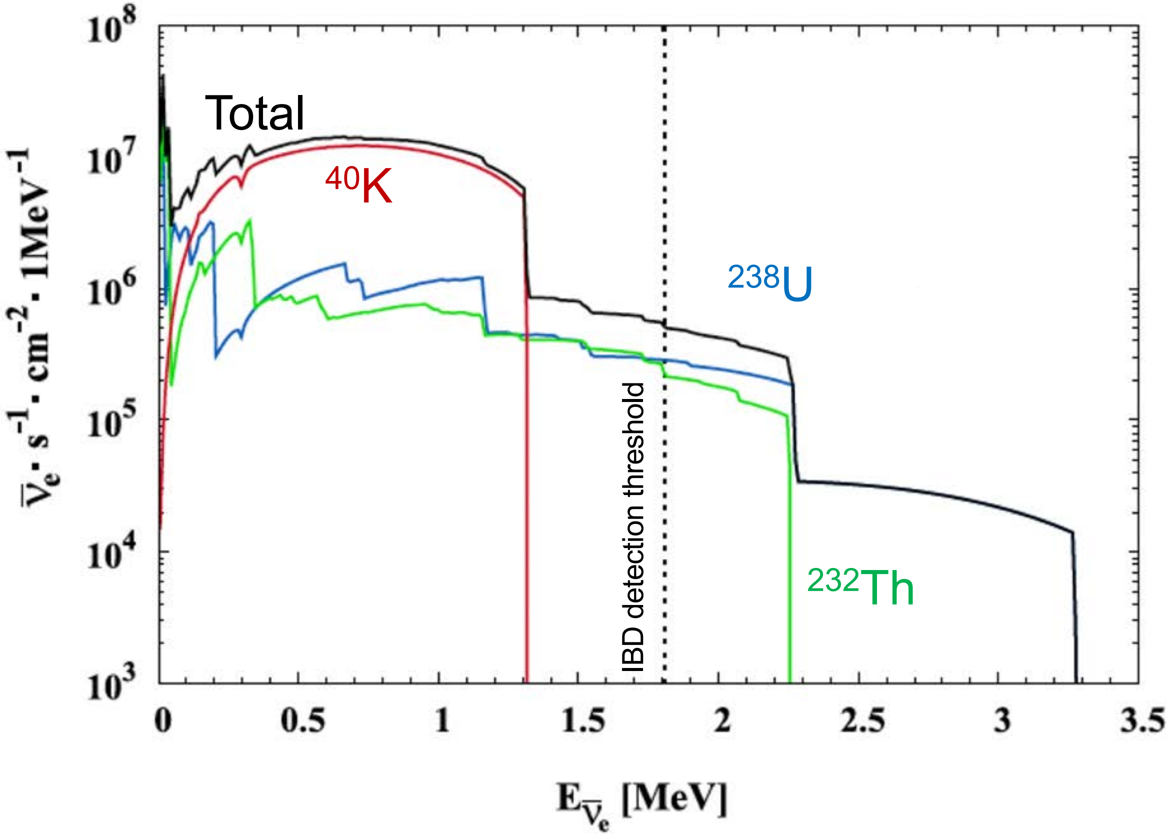
(to compare: solar neutrinos (NOT antineutrinos!) flux ~10^{10} cm^{-2} s^{-1})

GEONEUTRINO ENERGY SPECTRA

Per decay of the head element



Scaled to expected flux at Gran Sasso, Italy



With the existing detection techniques, we can detect geoneutrinos only from the decay chains of ^{238}U and ^{232}Th above 1.8 MeV energy.

^{238}U and ^{232}Th have different end points of their spectra: the key how to distinguish them!

JÜLICH Forschungszentrum

ANTINEUTRINO DETECTION INTERACTION: IBD

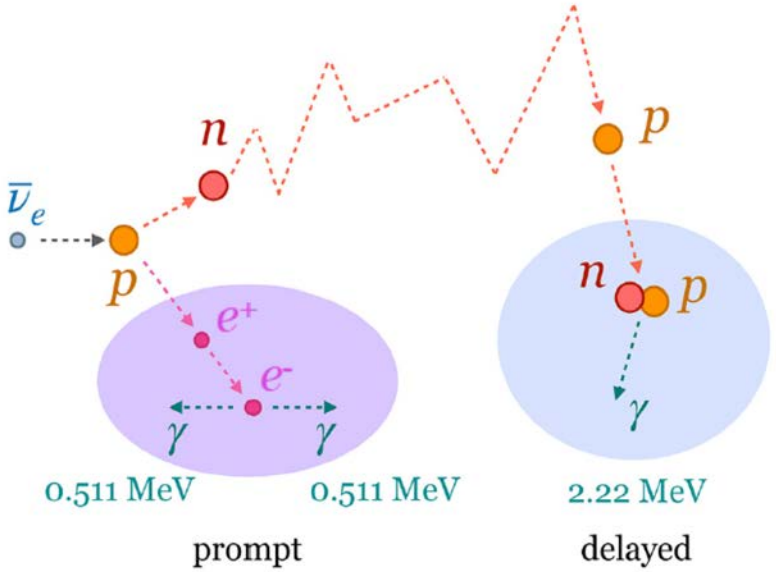
Electron antineutrino detection: delayed coincidence

- Inverse Beta Decay on proton (IBD)
- Charge current interaction mediated by W
- Sensitive only to **electron flavour antineutrinos**

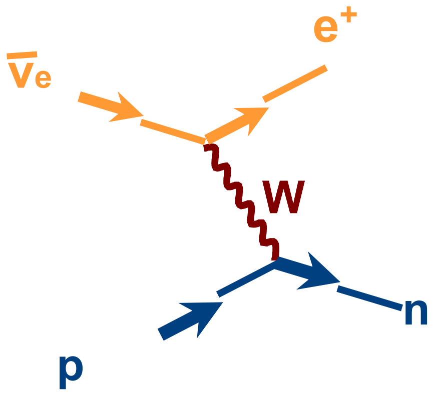
Energy threshold = 1.8 MeV

σ @ few MeV: ~10^{-42} cm^2

(~100 x more than elastic scattering on e^-)



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



Prompt-delayed space and time coincidence:

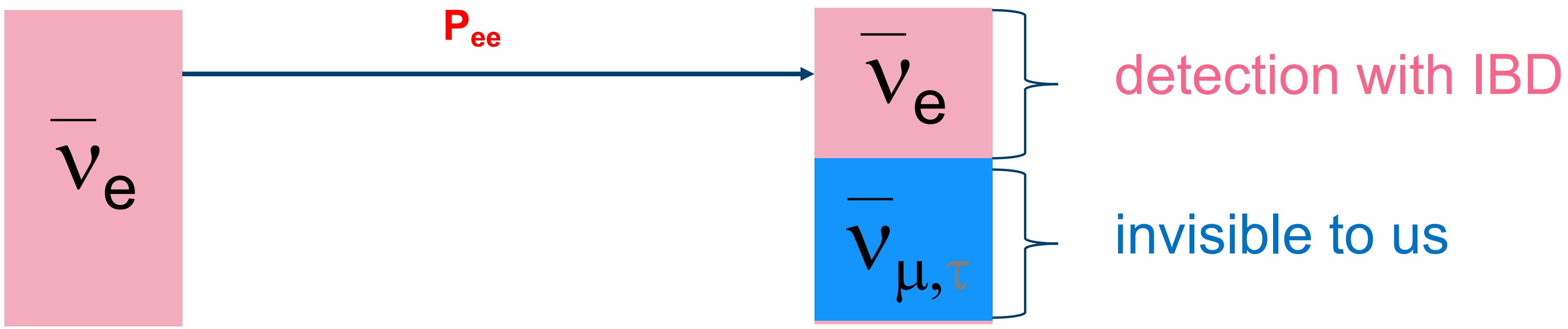
- golden channel for rare signal detection
- powerful **background suppression**
- energy of the prompt is related to the energy of incident neutrino

JÜLICH Forschungszentrum

NEUTRINO MIXING AND OSCILLATIONS

- A process that can change neutrino flavour & does NOT change the number of (anti)neutrinos

- For geoneutrinos, for which we can detect only the electron flavour (IBD interaction),
we need to know
P_{ee} – electron flavour survival probability



NEUTRINO MIXING AND OSCILLATIONS

α = e, μ, τ
Flavour eigenstates
INTERACTIONS

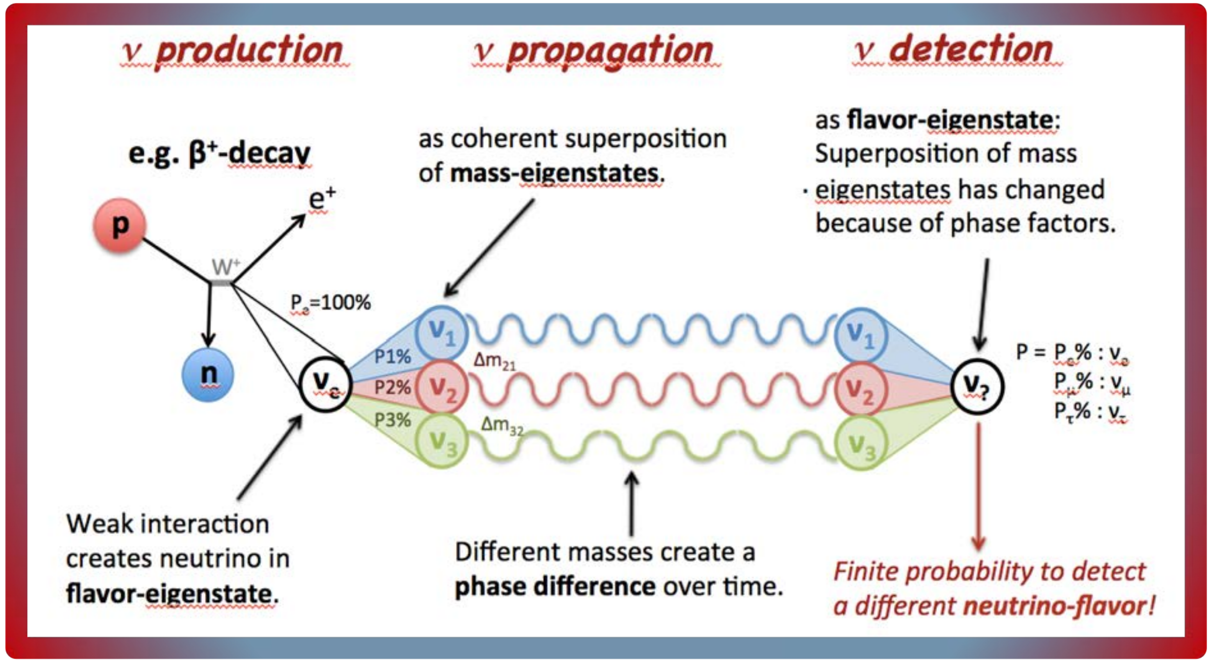
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}\,|\nu_i\rangle$$

i = 1, 2, 3
Mass eigenstates
PROPAGATION

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric	Reactor	Solar	Majorana

Courtesy M. Wurm

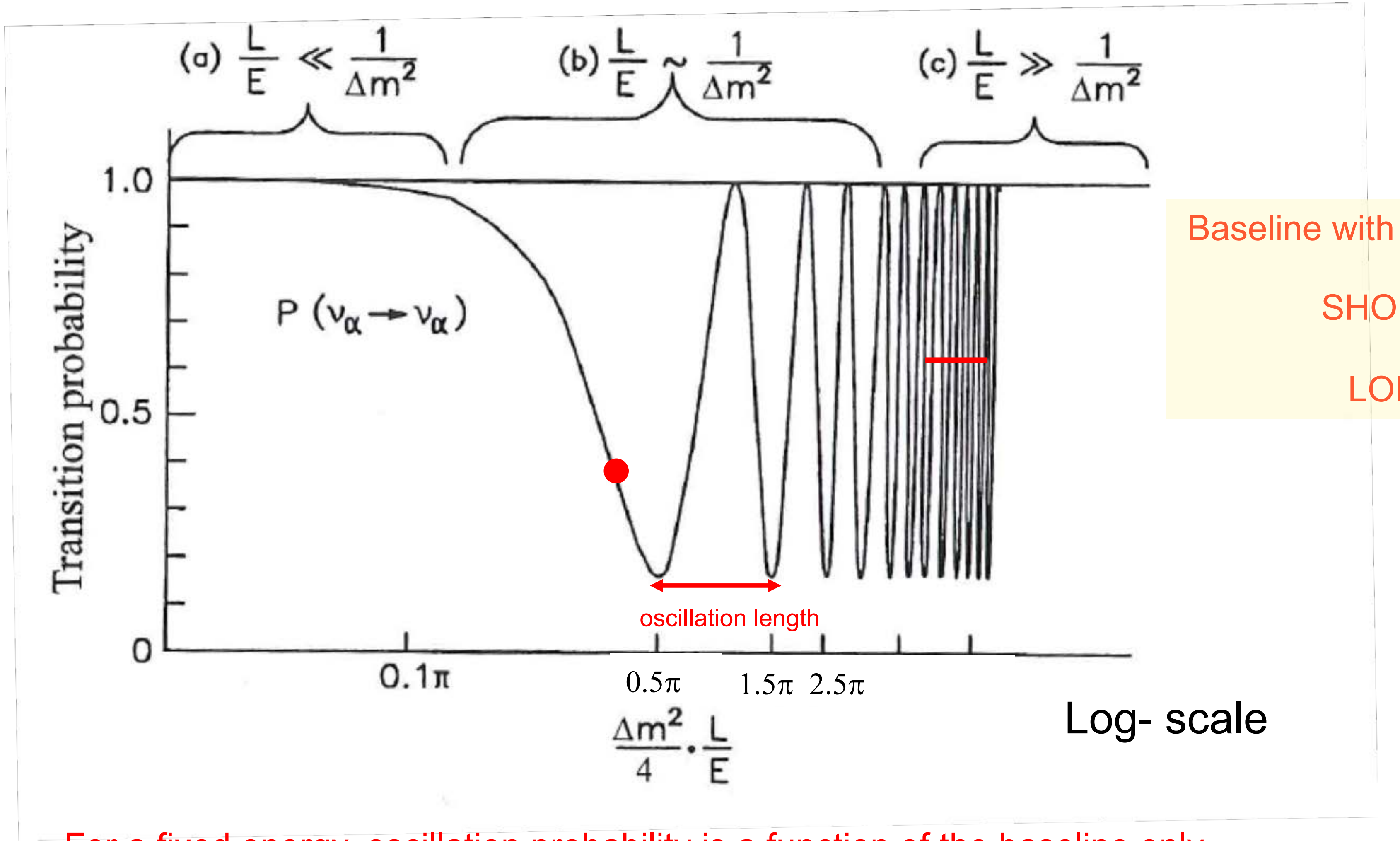


- **3 mixing angles θ_{ij}:**
  - $\theta_{23} \approx 45°$
  - $\theta_{13} \approx 9°$
  - $\theta_{12} \approx 33°$
- **Majorana phases $\alpha 1$, $\alpha 2$** and **CP-violating phase δ** unknown

- **Neutrino oscillations**
  - Non-0 rest mass (Nobel prize 2015)
  - Survival probability of certain flavour = f(baseline L, neutrino energy E_ν)
  - Different combination (L, E_ν) => sensitivity to different (θ_{ij}, Δm_{ij}^2)
  - Appearance/disappearance experiments
  - Oscillations in matter -> effective (θ_{ij}, Δm_{ij}^2) parameters = f(e^- density N_e, E_ν)

JÜLICH Forschungszentrum

OSCILLATIONS AT DIFFERENT BASELINES



Baseline with respect to the oscillation length:

SHORT: a distinct value of P ●

LONG: an average value —

For a fixed energy, oscillation probability is a function of the baseline only.

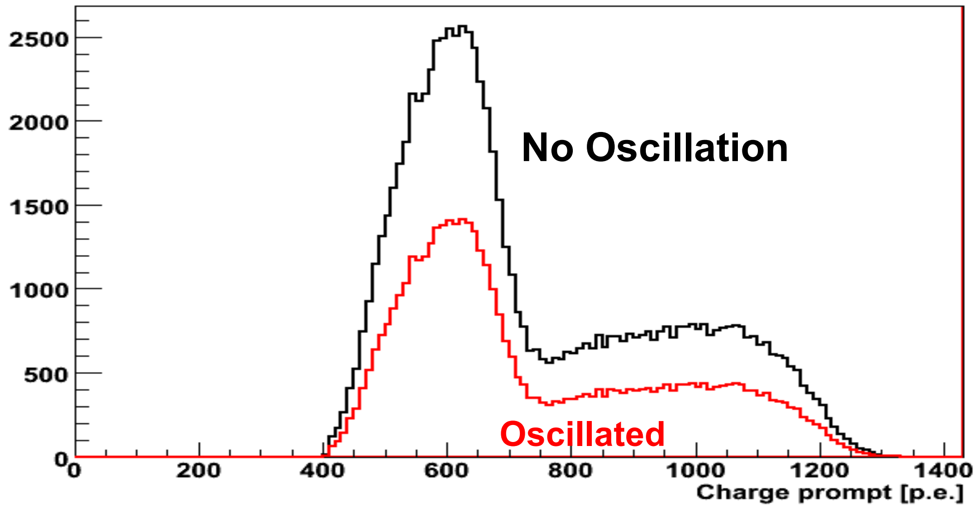
JÜLICH Forschungszentrum

EFFECT OF NEUTRINO OSCILLATIONS

For 3 MeV antineutrino: oscillation length of ~100 km

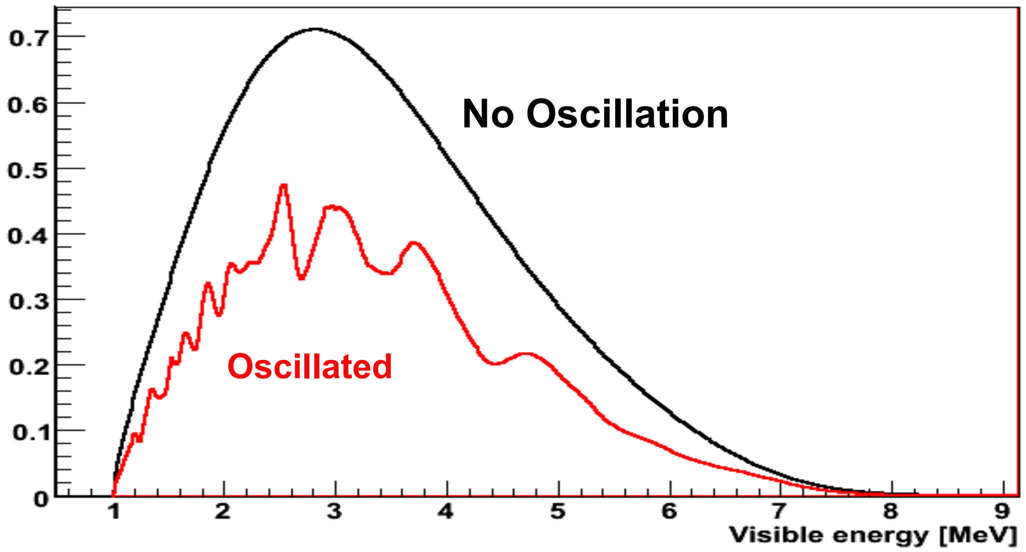
For the precision of the current experiments: for geoneutrinos we can use an average survival probability of about 0.551 but for reactor antineutrinos we must sum over all world reactors individually!

Geoneutrinos



“No” shape change – only suppresion of the visible signal

Reactor antineutrinos at LNGS

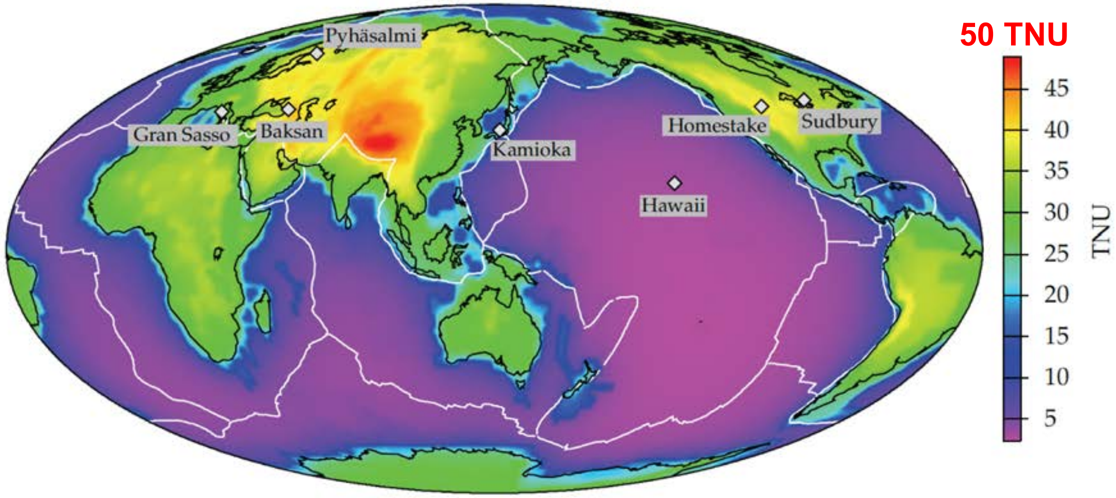


Significant change of the spectral shape

JÜLICH Forschungszentrum

EXPECTED GEONEUTRINO SIGNAL: from ϕ ~10^6 cm^{-2} s^{-1} to a handful of events

Expected "known and big" crustal signal

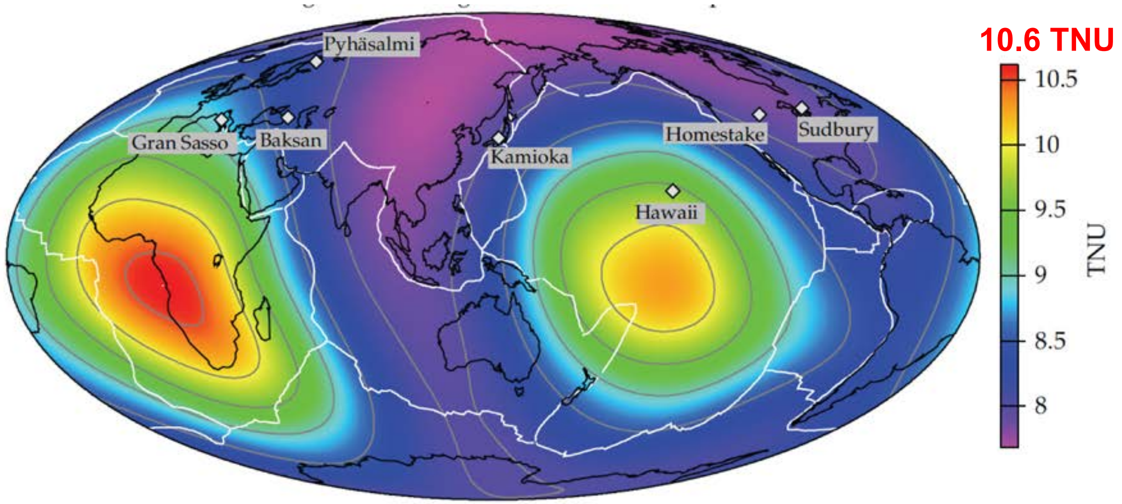


The signal is small, we need big detectors!

1 TNU = 1 event / 10^{32} target protons / year
cca 1 IBD event /1 kton /1 year, 100% detection efficiency

Expected mantle signal: hypothesis of heterogeneous composition

Motivated by the observed Large Shear Velocity Provinces at the mantle base



Mantle signal is even more challenging!

O. Šrámek et al. "Geophysical and geochemical constraints on geoneutrino fluxes from Earths mantle", Earth Planet. Sci. Lett., 361 (2013) 356-366)

JÜLICH Forschungszentrum

DETECTING GEONEUTRINOS (IBD with LS-detectors)

- **only 2 experiments have measured geoneutrinos;**
- **liquid scintillator detectors**;
- (Anti-)neutrinos have low interaction rates, therefore:
    - **Large volume detectors needed;**
    - **High radio-purity of construction materials;**
    - **Underground labs to shield cosmic radiations;**

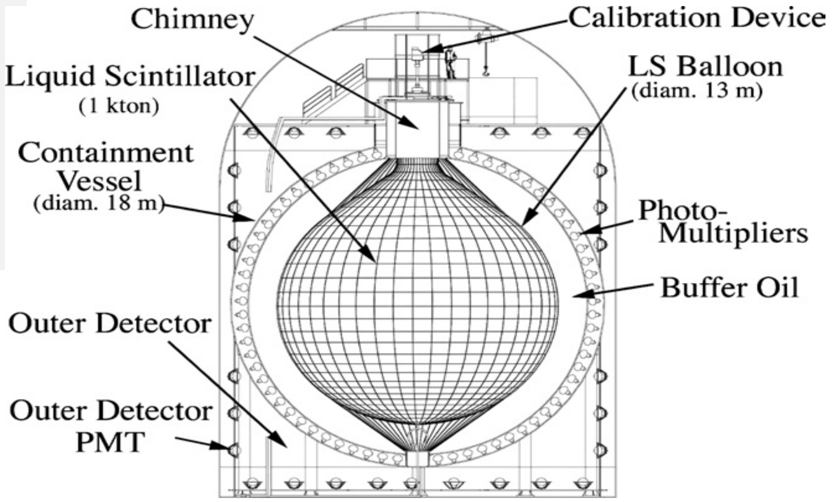
KamLAND in Kamioka, Japan
Border between OCEANIC / CONTINENTAL CRUST

- built to detect reactor anti-ν;
- ~1000 tons;
- S(reactors)/S(geo) ~ 6.7 (2010)
- **After the Fukushima** disaster (03/2011) many reactors OFF and **S(reactors)/S(geo) ~ 1!**
- Data since 2002;
- 2700 m.w.e. shielding;

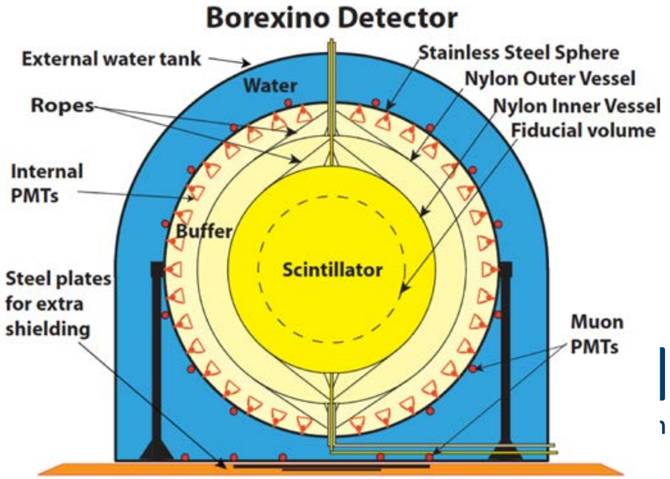
Borexino in Gran Sasso, Italy
CONTINENTAL CRUST

- originally built to measure neutrinos from the Sun – extreme radio-purity needed and achieved;
- 280 tons;
- S(reactors)/S(geo) ~ 0.3 (2010)
- DAQ 2007 - 2021;
- 3800 m.w.e. shielding;

KamLAND



Borexino



HISTORY OF GEONEUTRINO MEASUREMENTS

KamLAND (Japan)

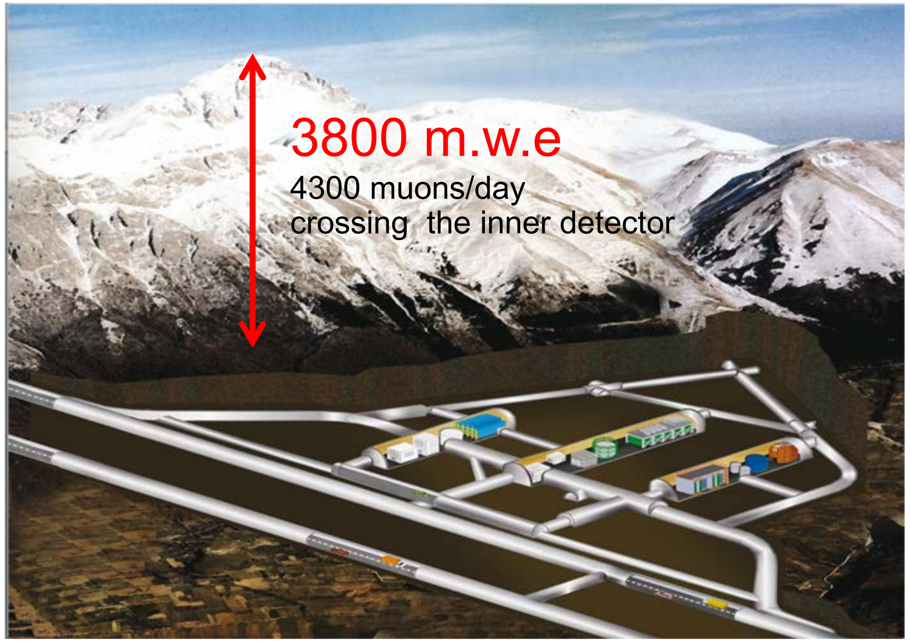
- **The first investigation in 2005**
  CL < 2σ **Nature 436 (2005) 499**
  7.09 x 10^{31} target-proton year
- **Update in 2008** PRL 100 (2008) 221803
  73 ± 27 geonu's
  2.44 x 10^{32} target-proton year
  37%
- **99.997 CL observation in 2011**
  106^{+29}_{-28} geonu's
  (March 2002 – April 2009)
  3.49 x 10^{32} target-proton year
  Nature Geoscience 4 (2011) 647
  26%
- **Results from 2013**
  116^{+28}_{-27} geonu's
  (March 2002 – November 2012)
  4.9 x 10^{32} target-proton year
  PRD 88 (2013) 033001
  24%
- **Latest result in 2022** (Geophys. Res. Lett. 49 e2022GL099566)
  183^{+29}_{-28} geonu's
  (March 2002 – December 2020)
  6.39 x 10^{32} target-proton year
  15-16%

Borexino (Italy)

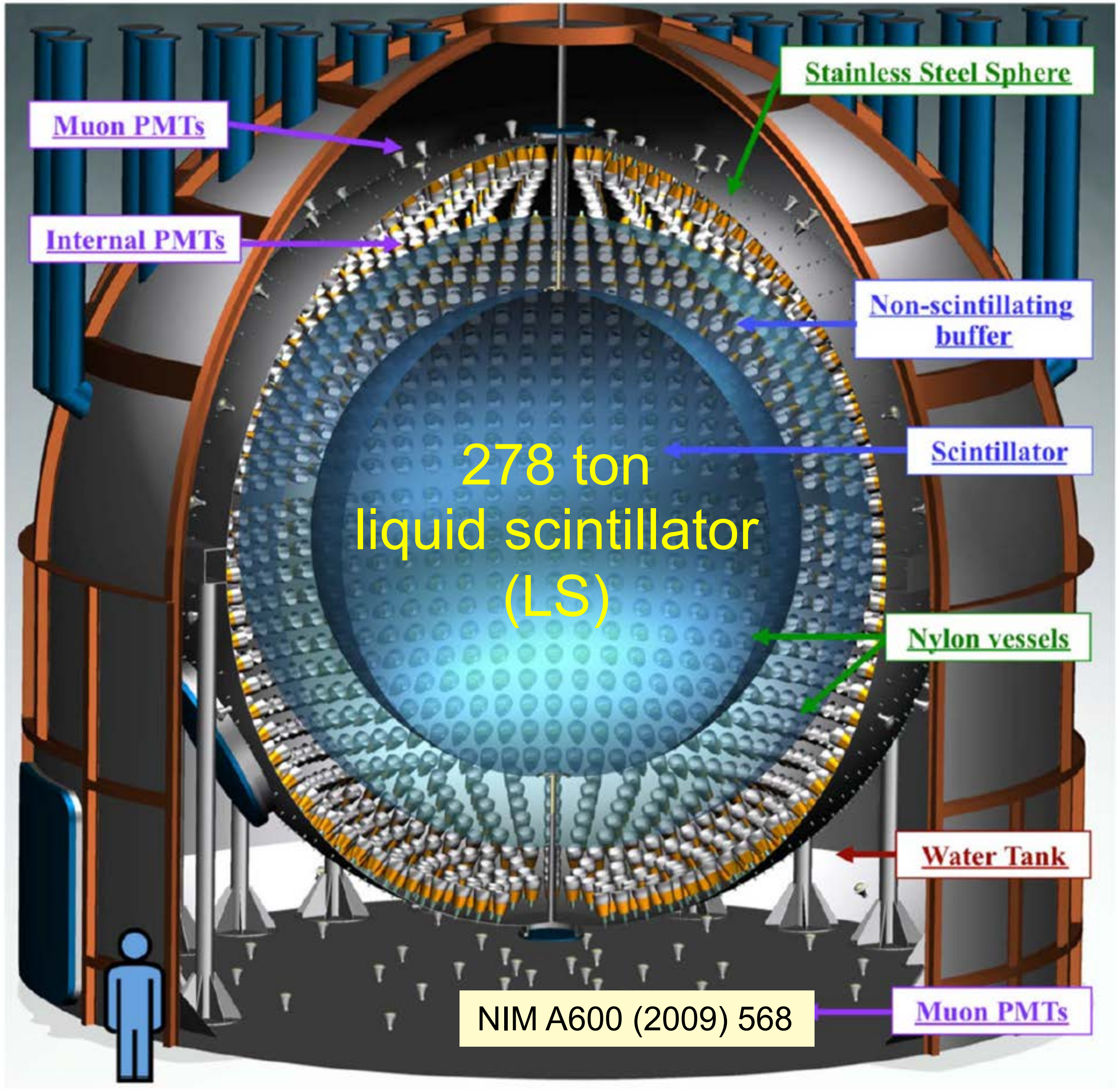
- **99.997 CL observation in 2010**
  $9.9^{+4.1}_{-3.4}$ geonu's
  small exposure but low background level
  (December 2007 – December 2009)
  1.5 x 10^{31} target-proton year
  PLB 687 (2010) 299
  34-41%
- **Update in 2013**
  14.3 ± 4.4 geonu's
  (December 2007 – August 2012)
  3.69 x 10^{31} target-proton year
  0-hypothesis @ 6 x 10^{-6}
  PLB 722 (2013) 295–300
  31%
- **June 2015: 5.9σ CL** PRD 92 (2015) 031101 (R))
  $23.7^{+6.5}_{-5.7}$ (stat) $^{+0.9}_{-0.6}$ (sys) geonu's
  (December 2007 – March 2015)
  5.5 x 10^{31} target-proton year
  0-hypothesis @ 3.6 x 10^{-9}
  24-27%
- **Latest result in 2020** (Phys. Rev. D 101 (2020) 012009)
  $52.6^{+9.4}_{-8.6}$ (stat) $^{+2.7}_{-2.1}$ (sys) geonu's
  (December 2007 - April 2019)
  1.29 x 10^{32} target-proton year,
  17-18%

BOREXINO DETECTOR

Laboratori Nazionali del Gran Sasso, Italy

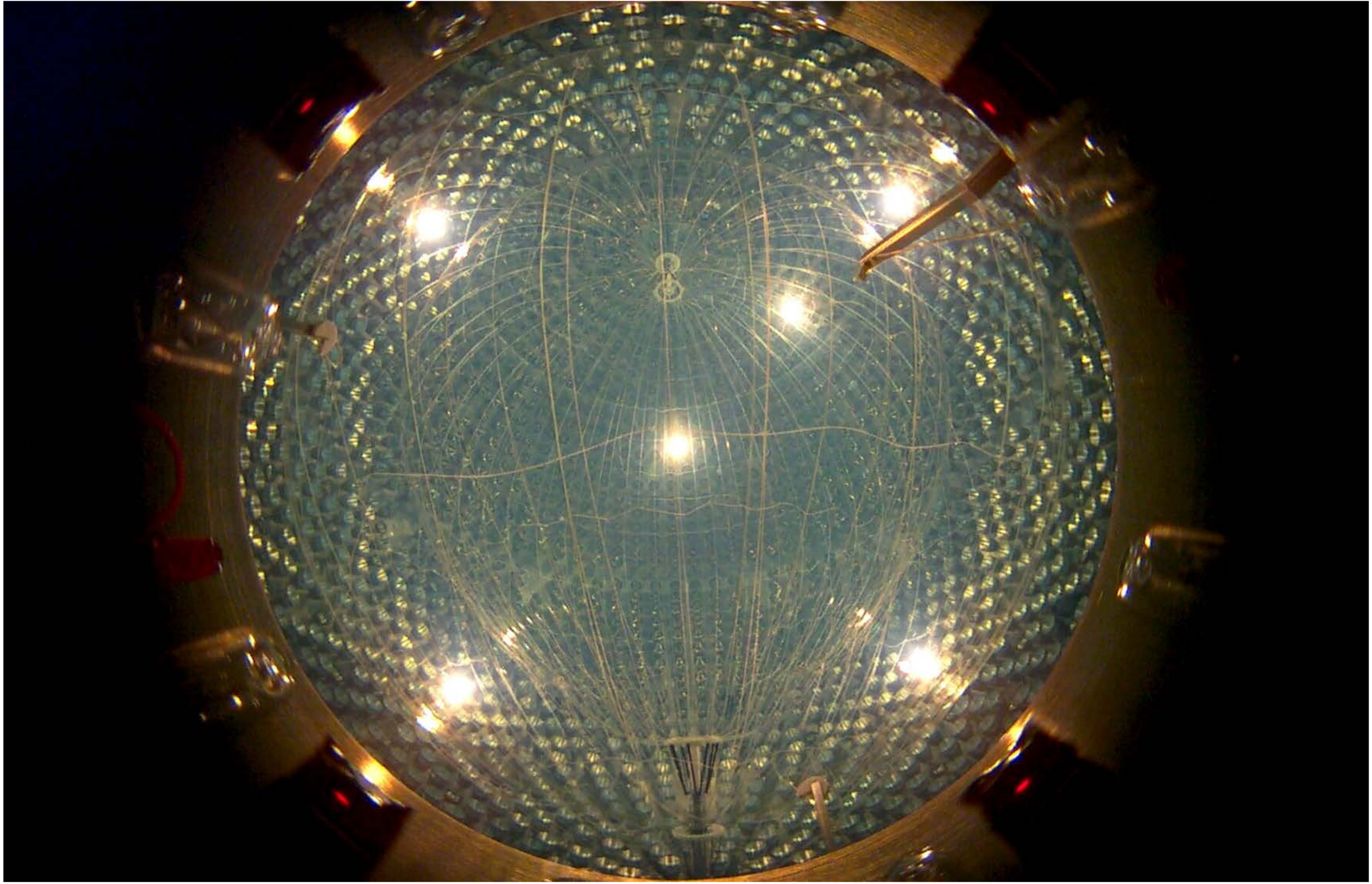


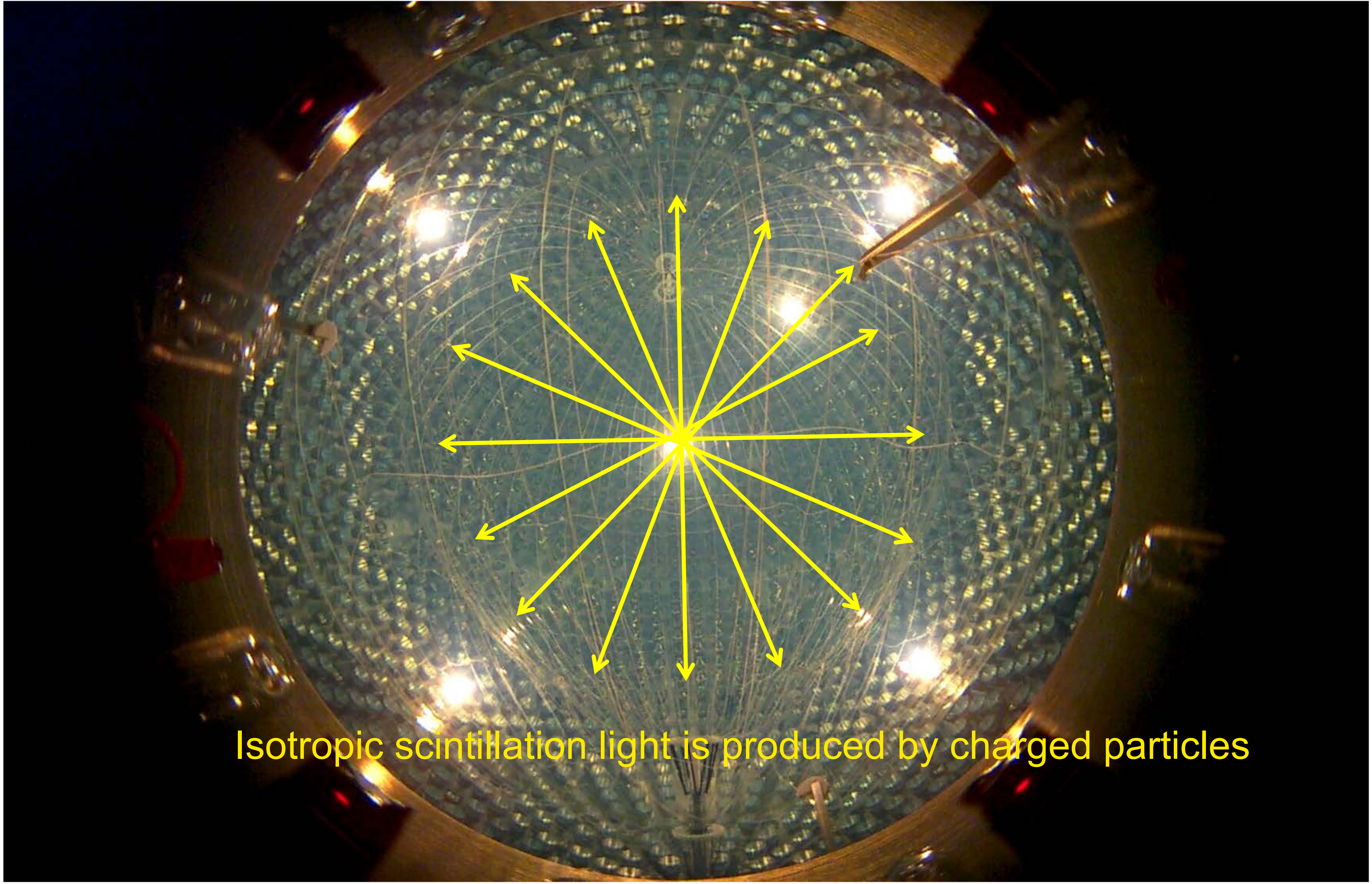
- **the world's radio-purest LS detector**
  $< 9 \times 10^{-19}$ g(Th)/g LS , $< 8 \times 10^{-20}$ g(U)/g LS
- **~500 hit PMTs / MeV**
- energy reconstruction: 5 keV (5%) @ 1 MeV
- position reconstruction: 10 cm @ 1 MeV
- pulse shape identification (α/β, e^+/e^-)



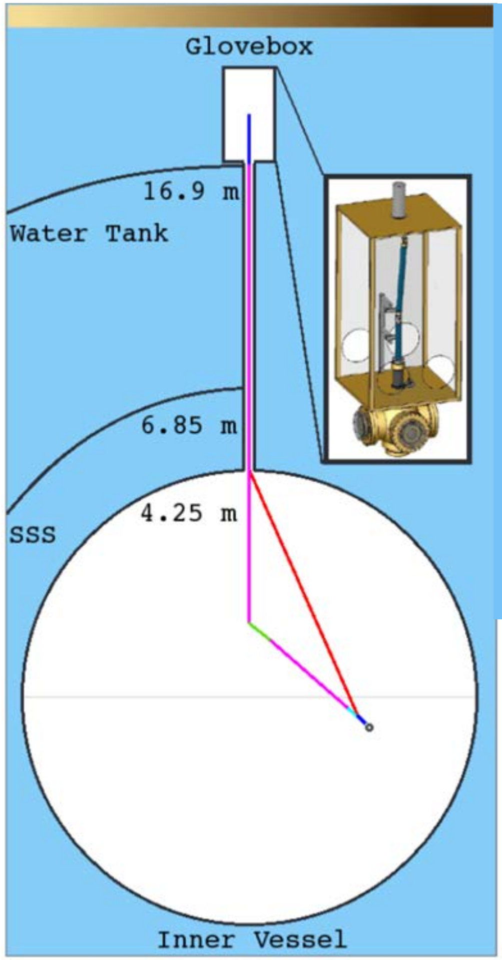
Operated from 05/2007 to 10/2021

Forschungszentrum JÜLICH




Isotropic scintillation light is produced by charged particles

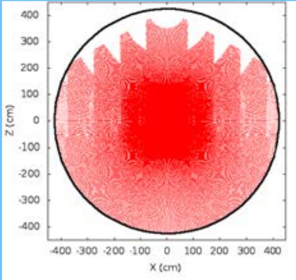
BOREXINO CALIBRATION



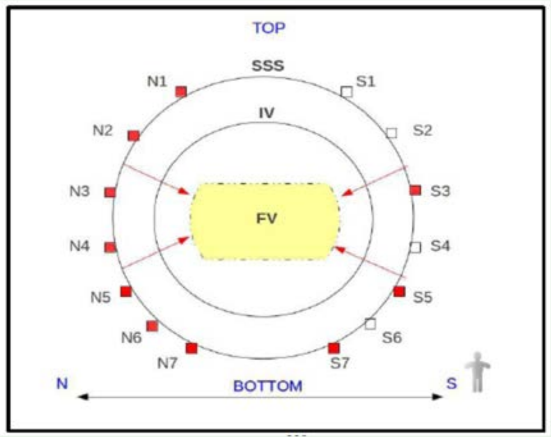
JINST 7 (2012) P10018

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

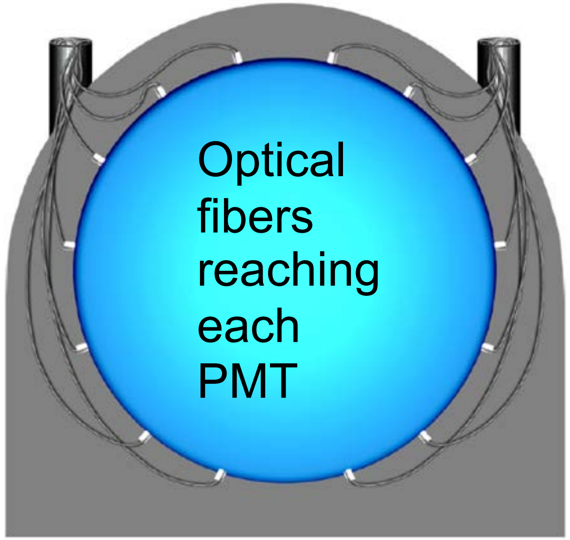


External calibration

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

Laser calibration

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



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

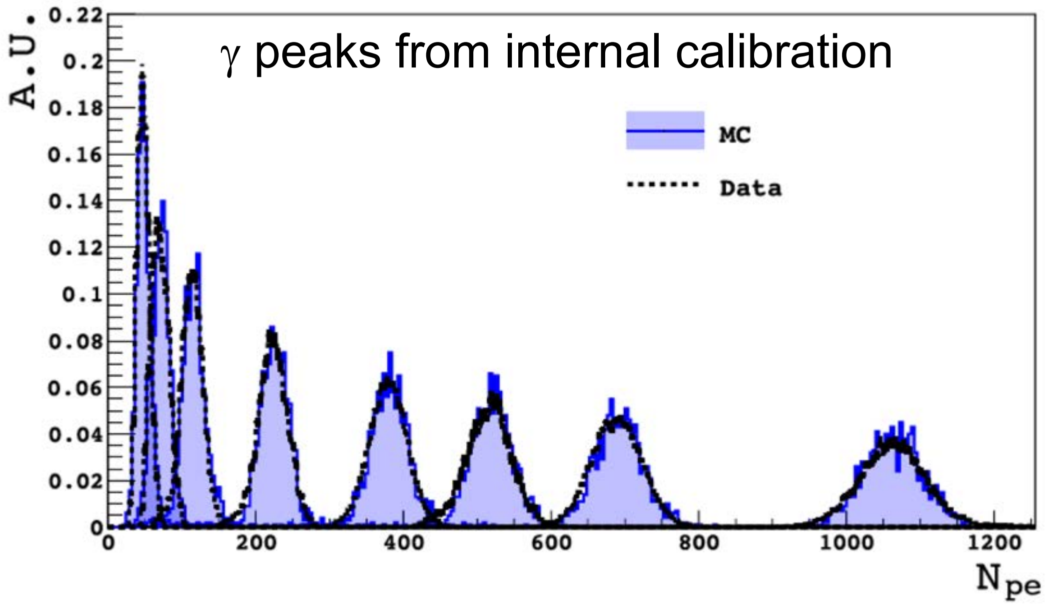
Electronics simulation

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



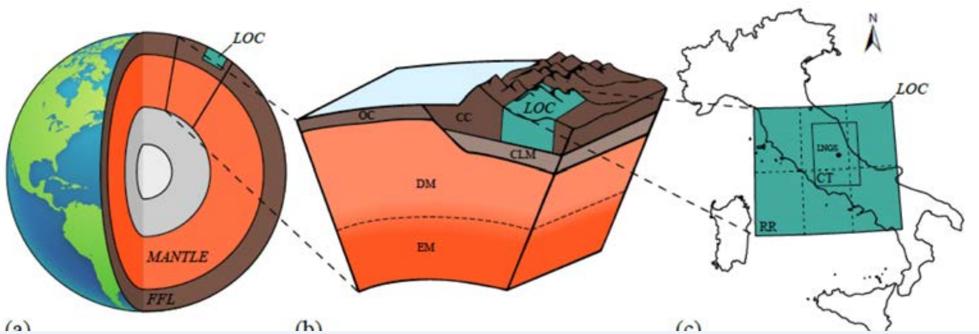
- **Tuning on calibration data.**
- **Independently measured input parameters**: emission spectra, attenuation length, PMT after-pulse, refractive index, effective quantum efficiencies.

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

JÜLICH Forschungszentrum

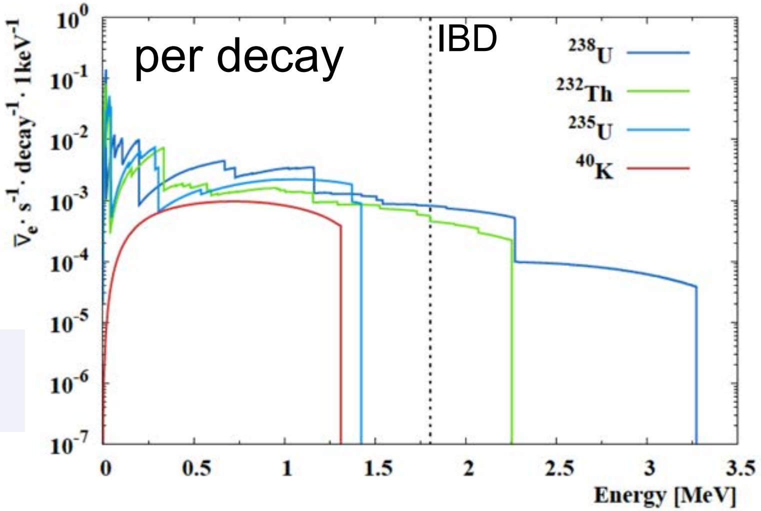
EXPECTED GEONEUTRINO SIGNAL AT GRAN SASSO

LOCAL AND GLOBAL GEOLOGICAL INFORMATION



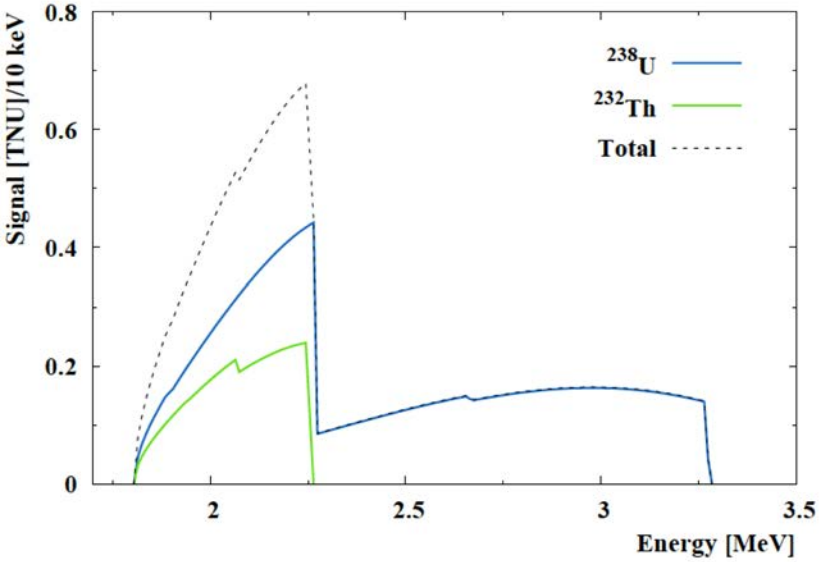
U, Th abundances & distribution + density profiles
~50% of the signal comes from the area of few 100 km radius

GEONEUTRINO ENERGY SPECTRA



- σ(IBD) ~10^{-42} cm^2
- <P_{ee}> ~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

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) -> Eprompt, Edelayed
- Hit PMTs time pattern = position reconstruction of the event -> **ΔR** of events
- Each trigger has its GPS time -> **Δtime** of events

JÜLICH Forschungszentrum

OPTIMIZED IBD SELECTION CUTS

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

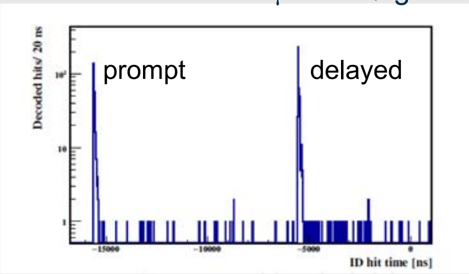
- Neutron captures on proton (2.2 MeV) and in about 1% of cases on **^{12}C (4.95 MeV)**
- Spill out effect at the nylon inner vessel border
- Radon correlated $^{214}Po(\alpha+\gamma)$ decays from ^{214}Bi and ^{214}Po fast coincidences

Time correlation

dt = (2.5-12.5) μs + (20-1280) μs

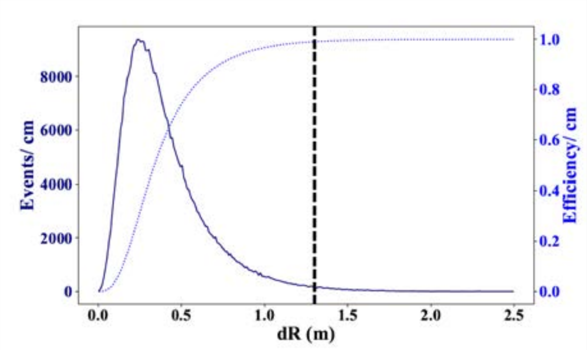
Neutron capture τ = (254.5 ± 1.8) μs

2 cluster event in 16 μs DAQ gate



Space correlation

dR < 1.3 m

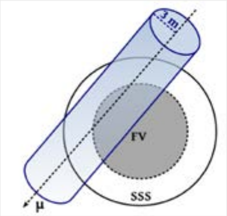


Muon veto

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

2 ms: neutrons

- Several veto categories
- Strict and special muon tags



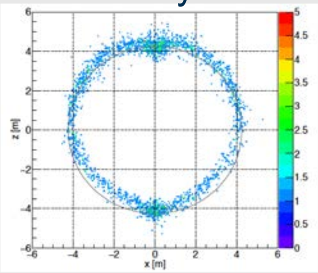
- Whole detector
- **Cylinder**

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

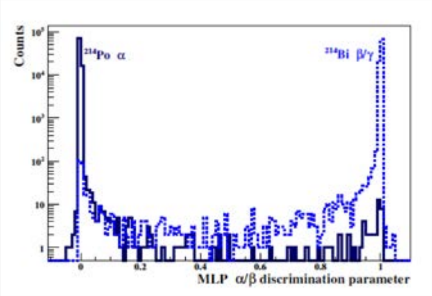
No event with Q >400 pe ±2 ms around promt/delayed

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

α/β discrimination

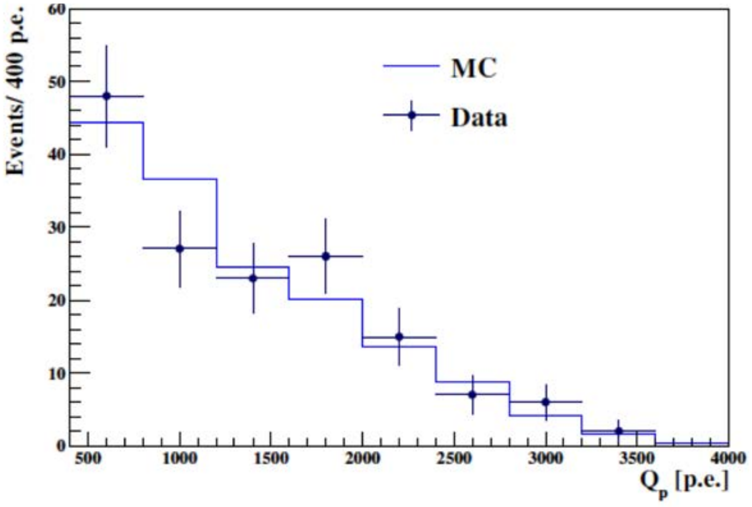
$MLP_{delayed}$ > 0.8

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

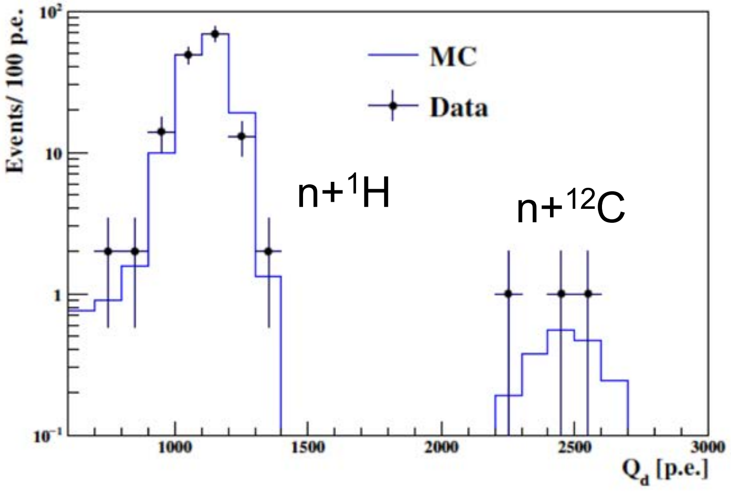


GOLDEN CANDIDATES: 154

Prompt charge spectrum

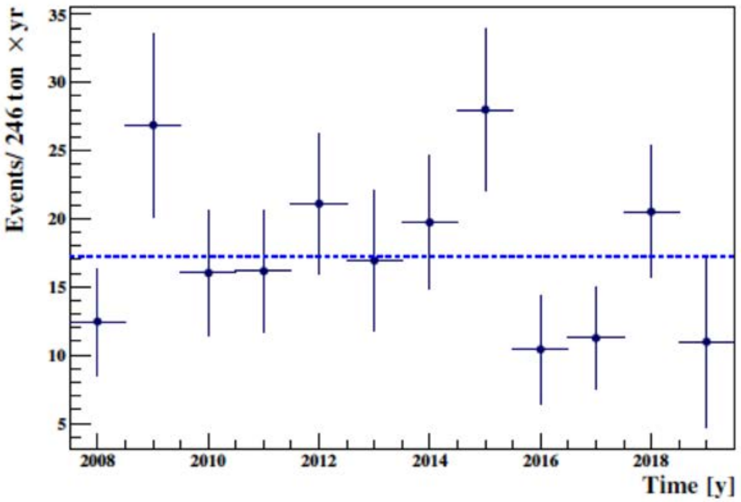


Delayed charge spectrum

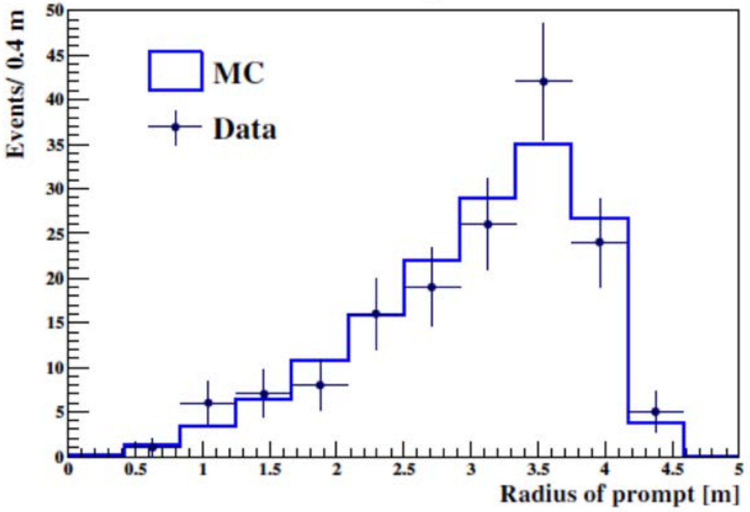


- December 9, 2007 to April 28, 2019
- 3262.74 days of data taking
- Average FV = (245.8 ± 8.7) ton
- **Exposure = (1.29 ± 0.05) x 10^{32} proton x year**
- Including systematics on position reconstruction and muon veto loss, for 100% detection eff.

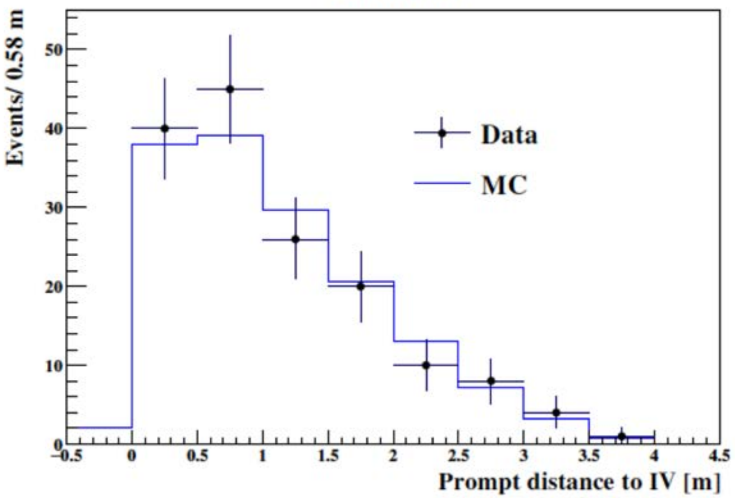
Distribution in time



Radial distribution



Distance to the Inner Vessel



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

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.

2) Accidental coincidences;

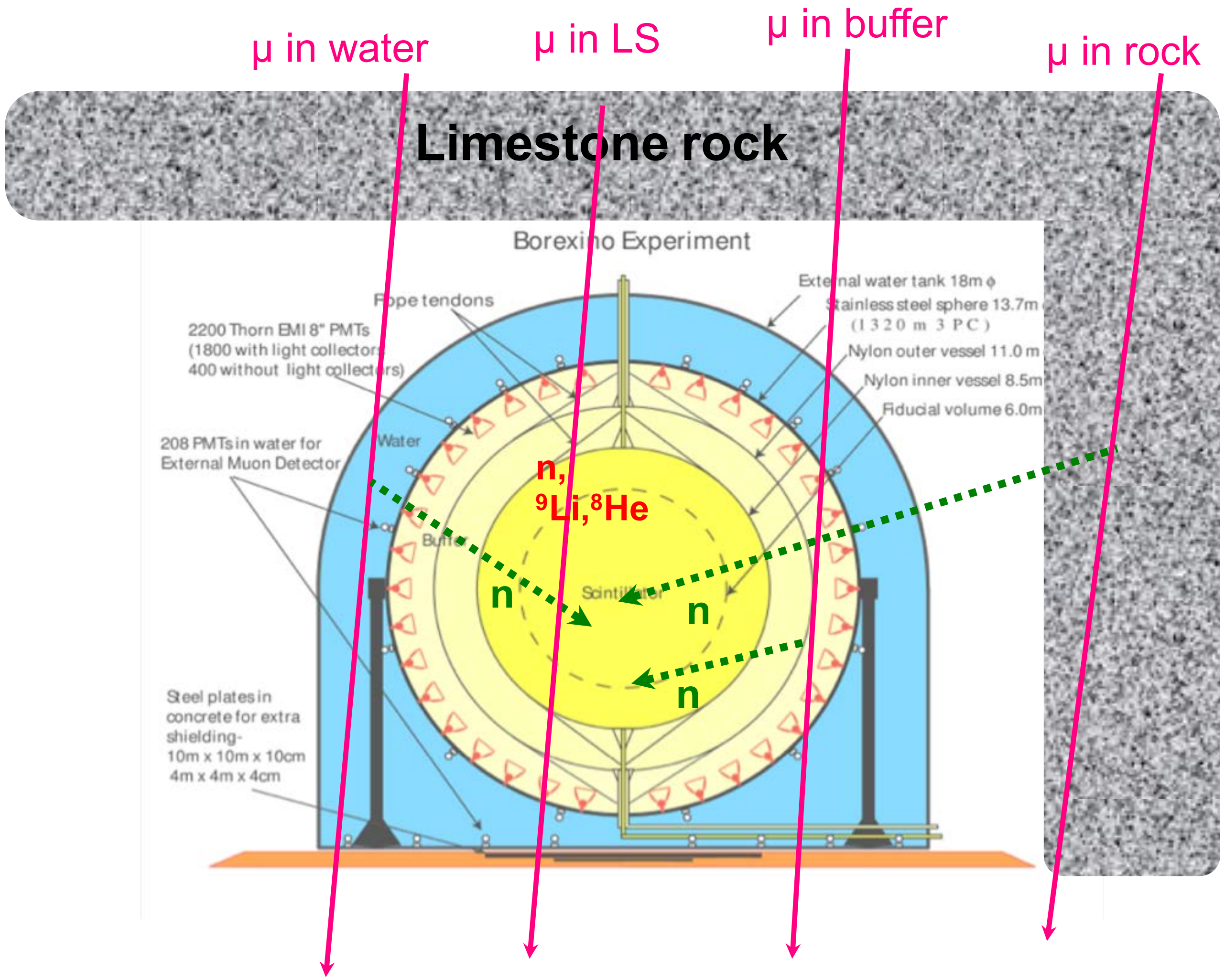
Estimated from OFF-time IBD-like coincidences.

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)

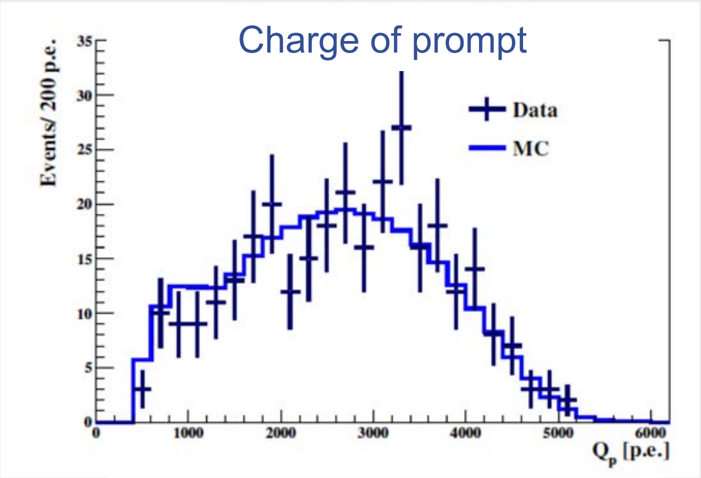
Estimated from ^{210}Po(α) and ^{13}C contaminations, (α, n) cross section.

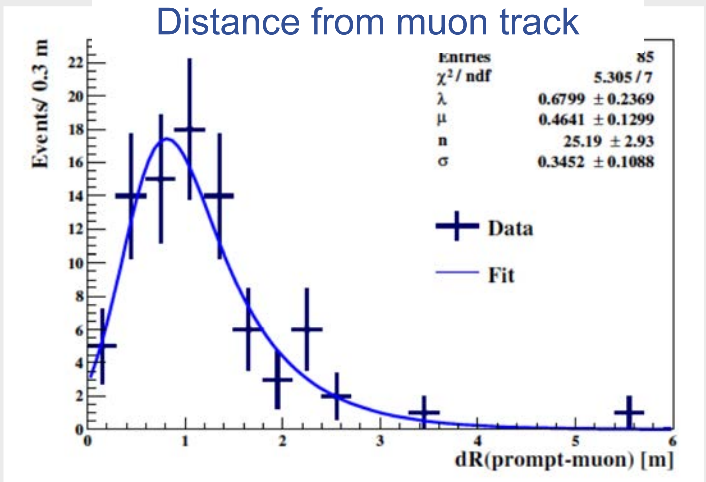


NON-ANTINEUTRINO BACKGROUNDS

^{9}Li (β+n) events < 2s after muons

$\tau_{measured}$ = (0.260 ± 0.021) s

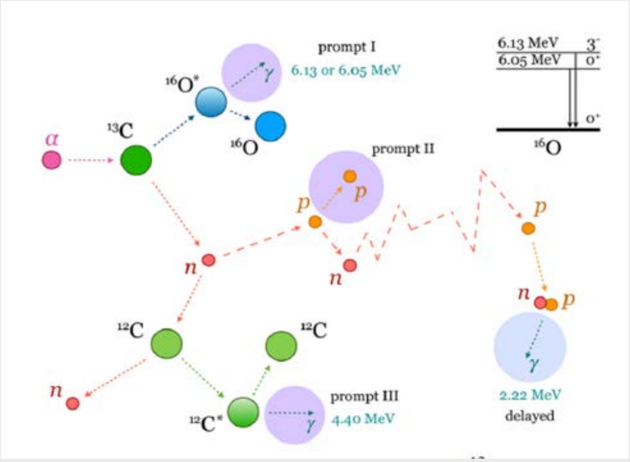


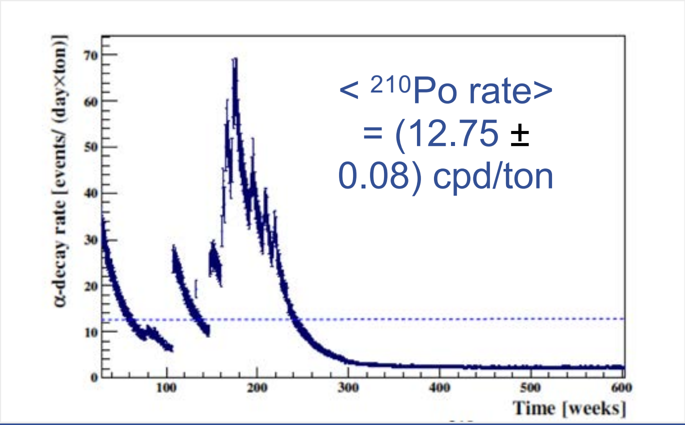


^{13}C(^{210}Po(α), n) ^{16}O

Y_n = (1.45 ± 0.22) x 10^{-7}

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

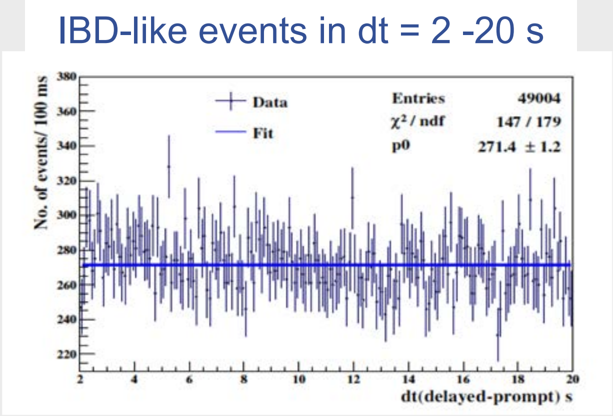




Accidentals

R_{acc} = (3029.0 ± 12.7) s^{-1}

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



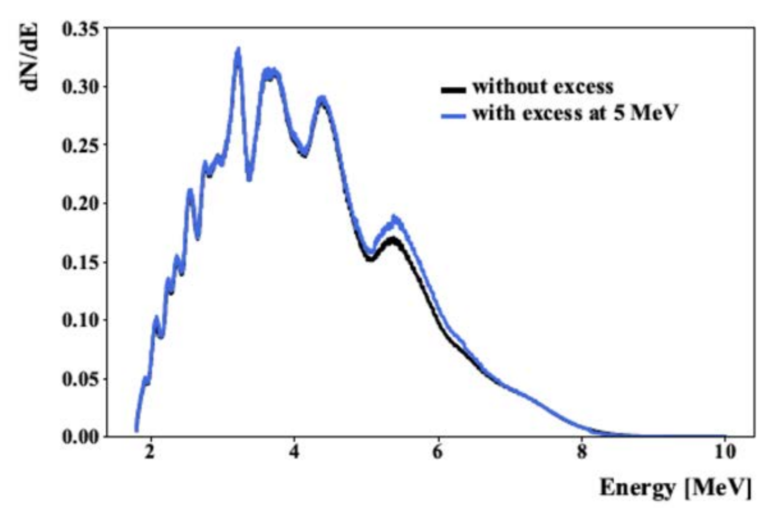
Background Type	Events
^{9}Li background	3.6 ± 1.0
Untagged Muons	0.023 ± 0.007
Fast n's (μ in WT)	<0.013
Fast n's (μ in rock)	<1.43
Accidental coincidences	3.846 ± 0.017
(α, n) in scintillator	0.81 ± 0.13
(α, n) in buffer	<2.6
(γ, n)	<0.34
Fission in PMTs	<0.057
^{214}Bi-^{214}Po	0.003 ± 0.0010
Total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

NEUTRINO BACKGROUNDS

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

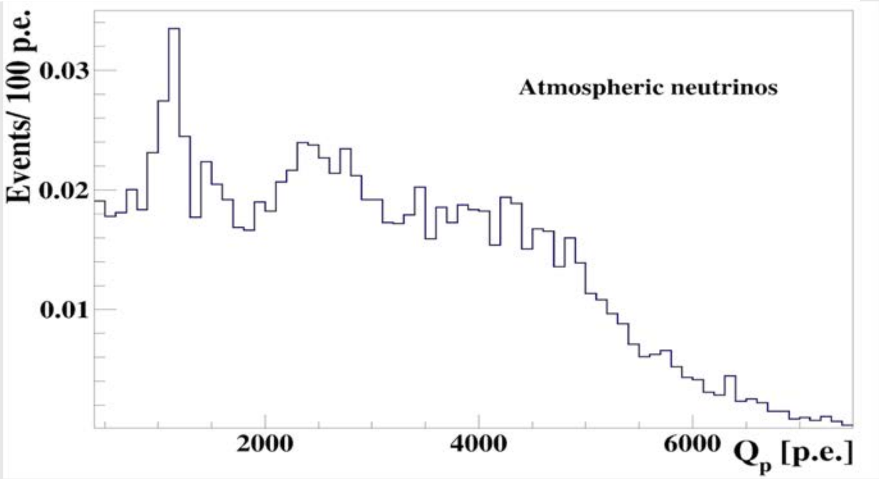


Atmospheric neutrinos

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

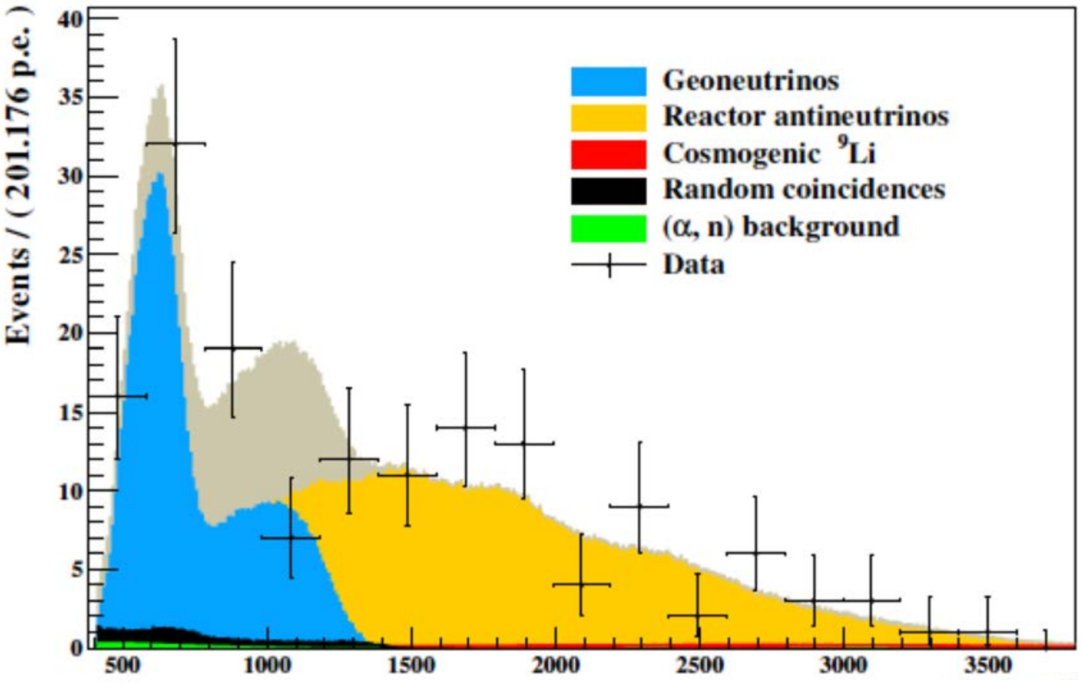
- Estimated 50% uncertainty on the prediction
- Indications of overestimation
- Included in the systematic error
- Atmospheric neutrino fluxes from HKKM2014 (>100 MeV) and FLUKA (<100 MeV)
- Matter effects included

Charge spectrum after IBD selection cuts



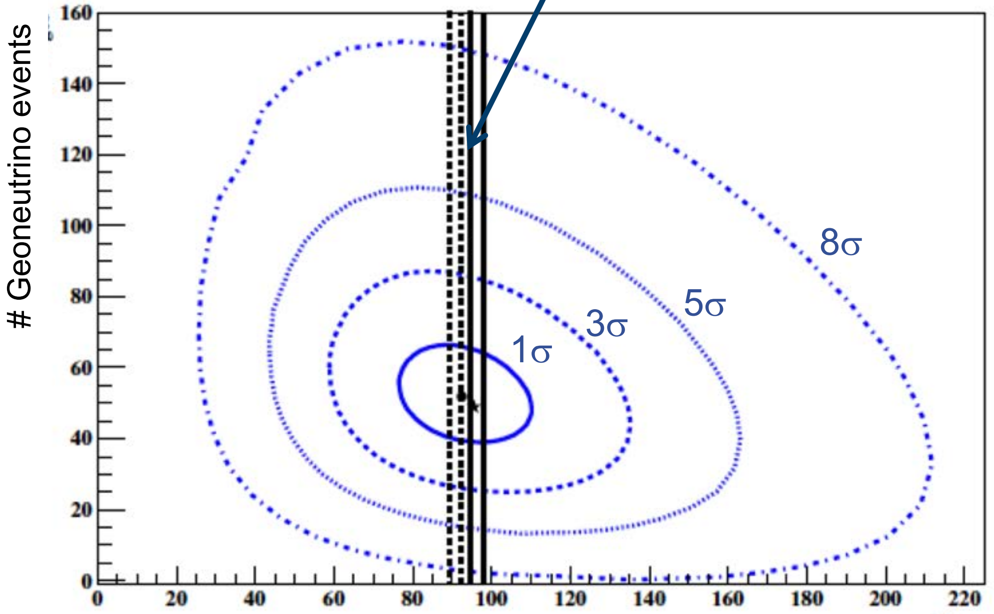
1 MeV ~ 500 p.e.

SPECTRAL FIT with fixed chondritic Th/U ratio



Prompt charge [photoelectrons]: 1 MeV ~500 photoelectrons

Reactor expectations with and without 5 MeV bump



- 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

Resulting number of geoneutrinos (median value)

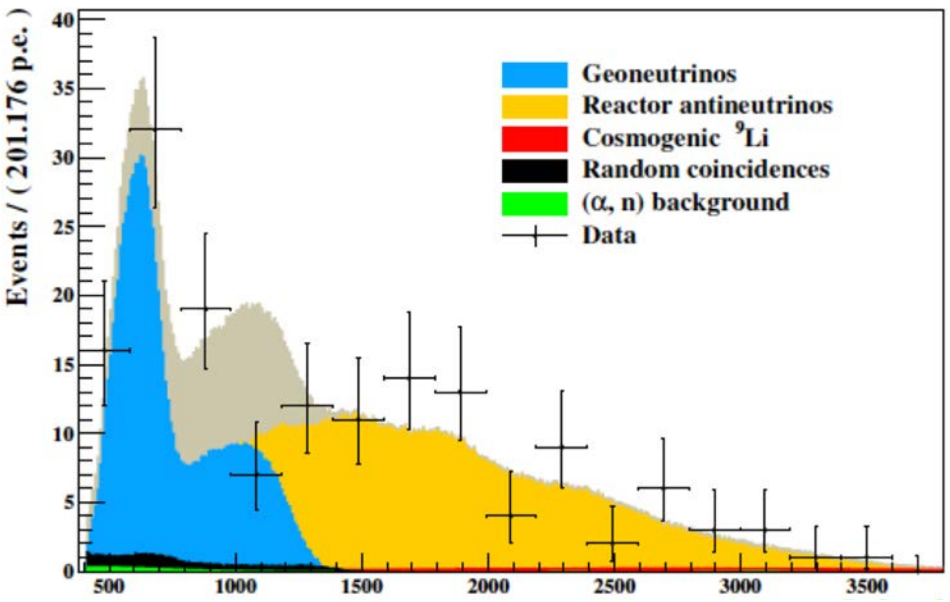
$$52.6^{+9.4}_{-8.6}(stat)^{+2.7}_{-2.1}(sys)events$$

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

JÜLICH Forschungszentrum

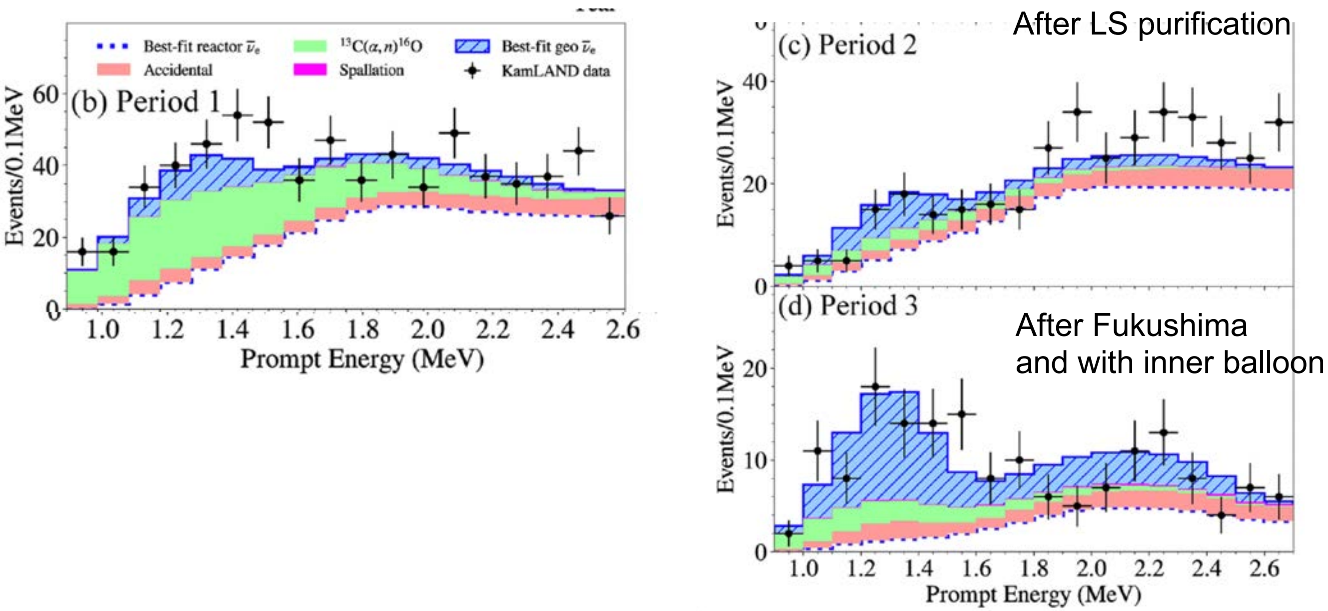
Comparison with KamLAND (SPECTRAL FIT with fixed chondritic Th/U ratio)

Borexino (PRD101 (2020) 012009)



Prompt charge [photoelectrons]: 1 MeV ~500 photoelectrons

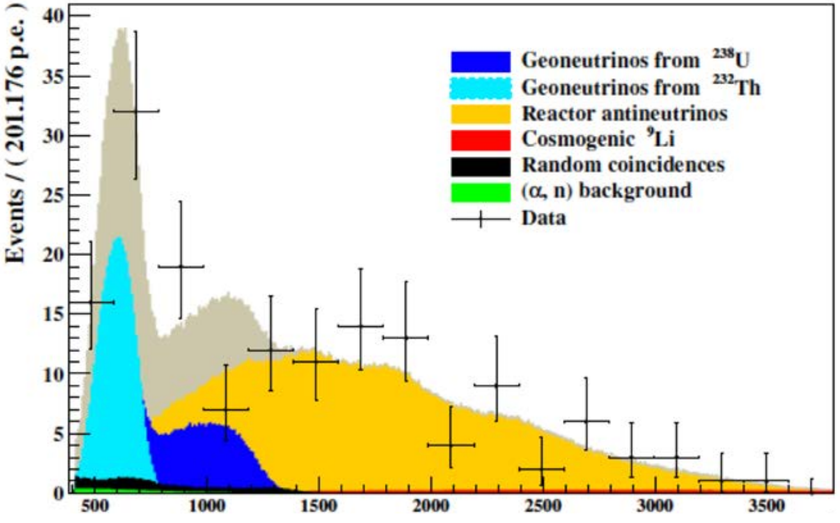
KamLAND (Geophys. Res. Lett. 49 e2022GL099566)



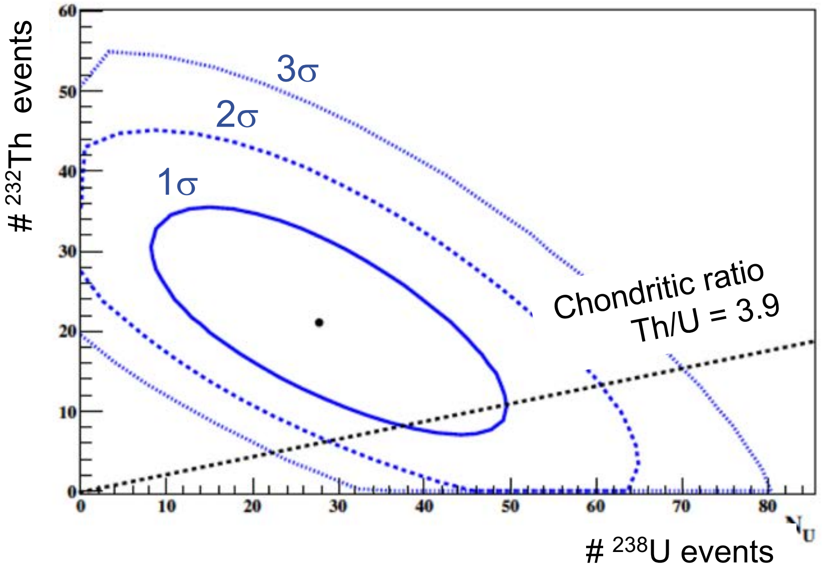
1.29 x 10^{32} (3262 days, 280 m^3 of FV)	**Exposure [proton x year]**	**6.39 x 10^{32}** (5227 days, 905 m^3)
154 in total (~90 in the geonu energy window)	**IBD candidates**	**1178** in the geoneutrino energy window
$52.6\ ^{+9.4}_{-8.6}$ *(stat)* $^{+2.7}_{-2.1}(sys)$ $^{+18.3}_{-17.2}\%$	**Geoneutrinos** (mass Th/U fixed to 3.9)	$183\ ^{+29}_{-28}$ *(stat + sys)*: $^{+15.8}_{-15.3}\%$
$47.0\ ^{+8.4}_{-7.7}$ *(stat)* $^{+2.4}_{-1.9}(sys)$ / (39.3 - 55.4)	**Signal [TNU]** / (68% CL interval)	Not provided
Shape only, reactor-ν free	**Analysis**	Rate + shape + time

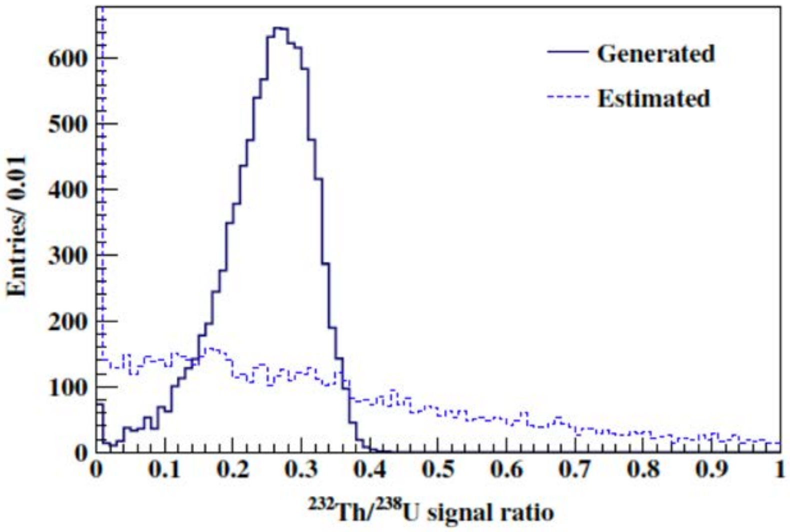
SPECTRAL FIT with Th and U fit independently

Borexino (PRD101 (2020) 012009)



Prompt charge [photoelectrons]: 1 MeV ~500 photoelectrons





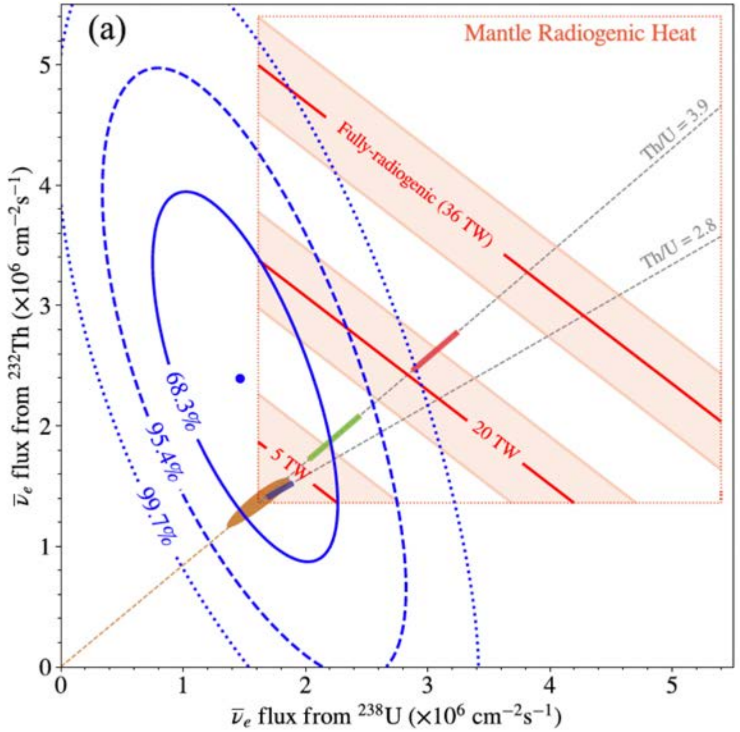
Borexino has no sensitivity
to measure the Th/U ratio

$^{238}\mathrm{U}: 29.0^{+14.1}_{-12.9}\ events$

$^{232}\mathrm{Th}: 21.4^{+9.4}_{-9.1}\ events$

KamLAND

(Geophys. Res. Lett. 49 e2022GL099566)



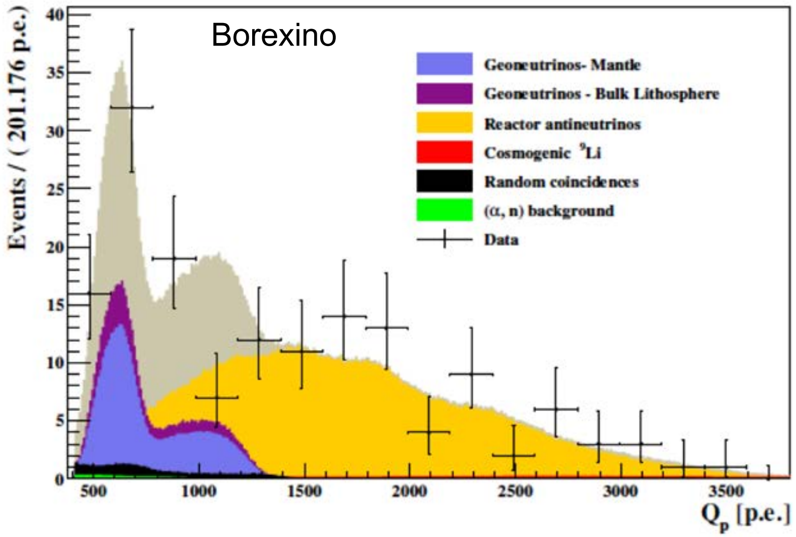
$^{238}\mathrm{U}: 117^{+41}_{-39}$ events (> 0 @ 3.3σ CL)

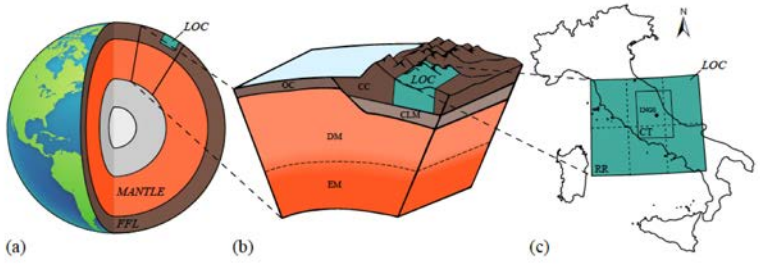
$^{232}\mathrm{Th}: 58\ ^{+25}_{-24}$ events

JÜLICH Forschungszentrum

MANTLE SIGNAL: IMPORTANCE OF LOCAL GEOLOGY

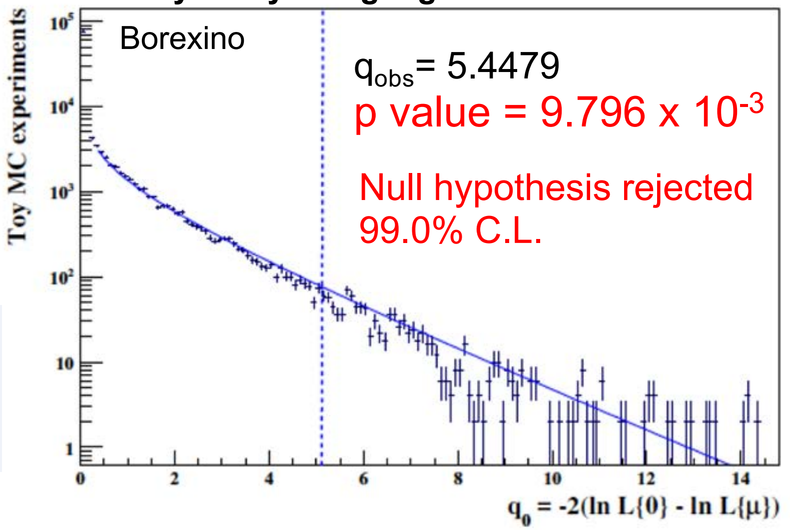
Borexino dedicated fit: lithospheric signal constrained to (28.8 ± 5.6) events with S(Th)/S(U) = 0.29 and Mantle PDF constructed with S(Th)/S(U) = 0.26, maintaining the bulk Earth chondritic Th/U





LOC – local crust: Coltorti et al. Geochim. Cosmoch. Acta 75 (2011) 2271.
Far Field Lithosphere:
Y. Huang et al., Geoch. Geoph. Geos. 14 (2013) 2003.

Sensitivity study using log-likelihood ratio method

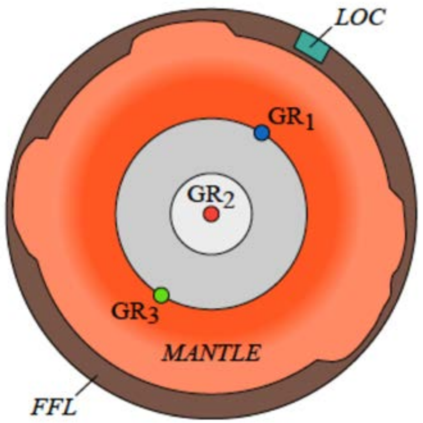


Borexino		KamLAND
Fit with lithospheric contribution constrained	**Analysis**	**Direct subtraction of crustal contribution**
$23.7^{+10.7}_{-10.1}$	**Mantle events**	-
$21.2^{+9.6}_{-9.1}$	**Mantle signal U + Th [TNU]**	$6.0^{+5.6}_{-5.7}$ (crust S. Enomoto et al. EPSL 258 (2007) 147)
$24.6^{+11.1}_{-10.4}$ / (14.2 – 35.7) 68%CL interval)	**Mantle heat U + Th [TW]**	~ 5.4 (= $12.4^{+4.9}_{-4.9}$ - 7)

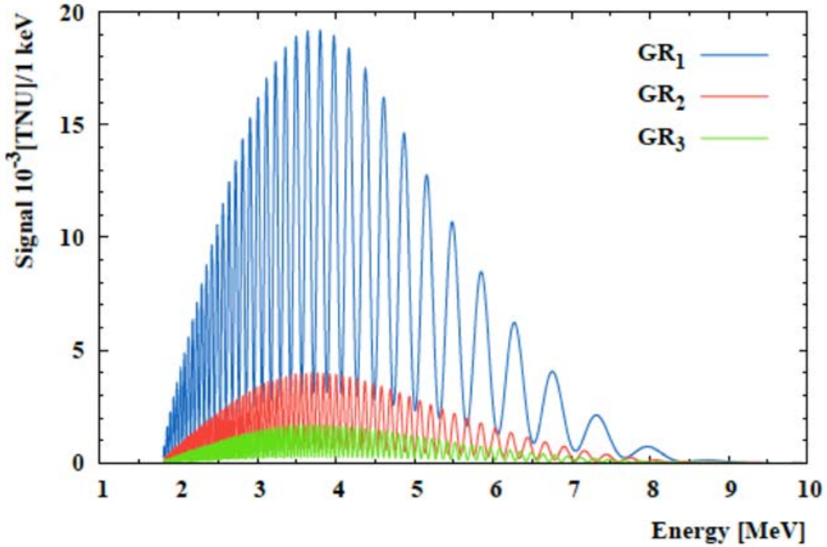
Borexino excludes null mantle signal at 99% CL

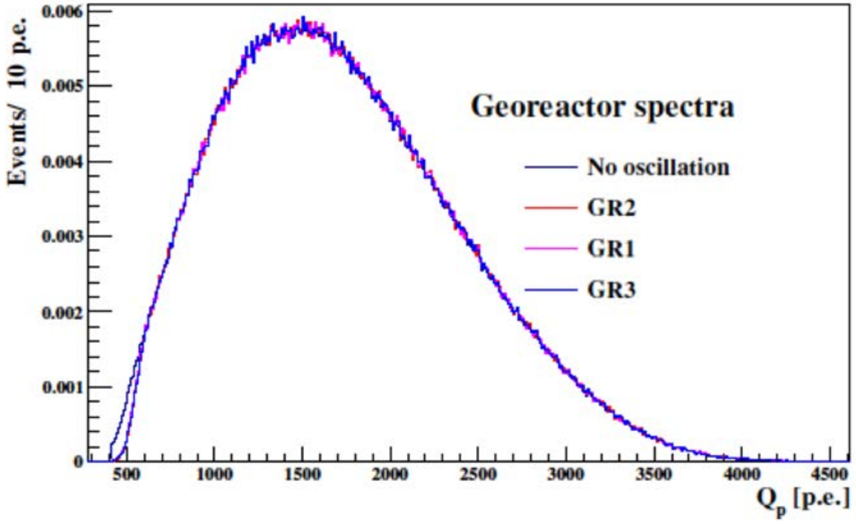
JÜLICH Forschungszentrum

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?)

JÜLICH Forschungszentrum

Geoneutrino summary

- Geo-neutrinos has been observed with high statistical significance by Borexino and KamLAND.
- These results are compatible with the range of geological models – big success! (see talk of V. Strati).
- Some tension between Borexino and KamLAND results when assuming laterally homogeneous mantle.
- The new interdisciplinary field is born **(Neutrino Geoscience conference series** since 2005 & last time in 2019 in Prague, **ISAPP Summer School** Using Particle Physics to Understand and Image the Earth in 2016 and 2018).
- New generation experiments are needed for geologically highly significant results.

Mt. Everest group, flight from Kathmandu (Nepal) to Paro (Bhutan), March 2018

Back up slides

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;

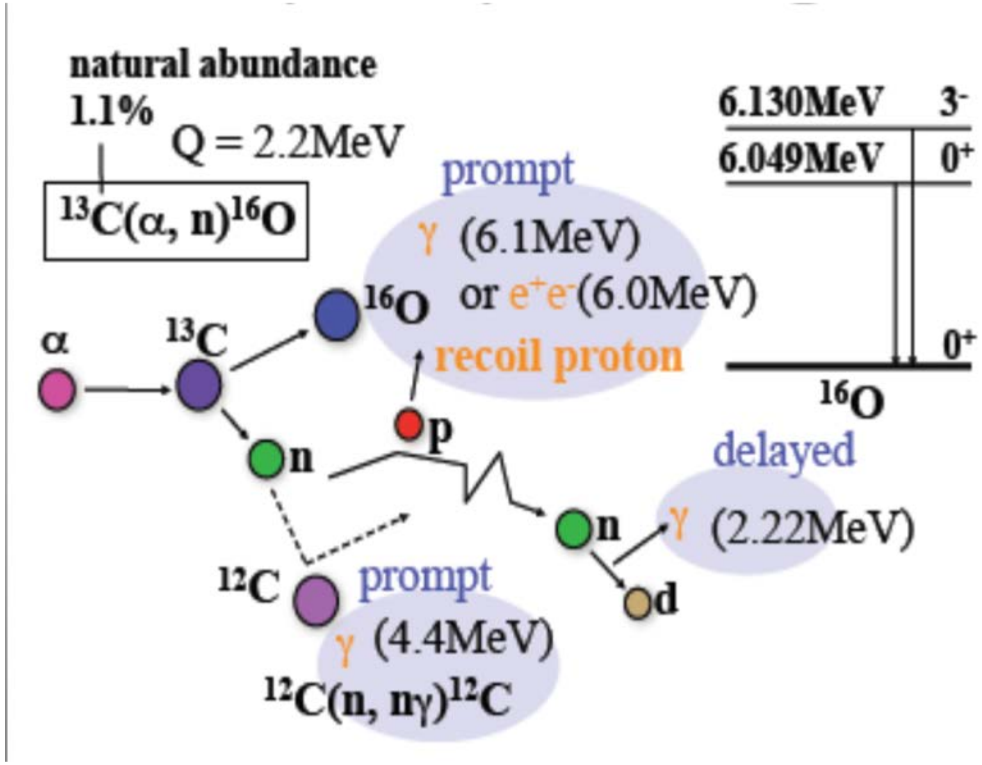
^{235}U
^{239}Pu
^{238}U
^{241}Pu

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

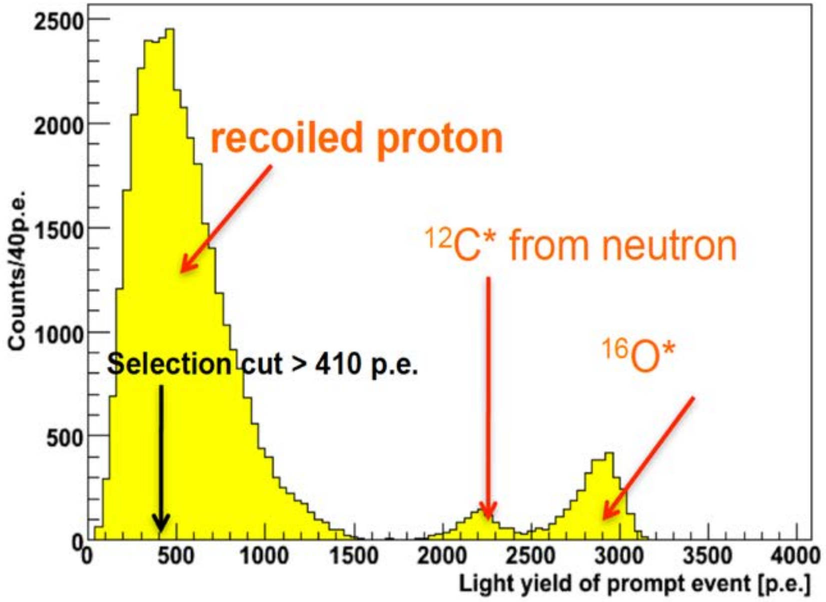
JÜLICH Forschungszentrum

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

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



MC-based spectrum of E_{prompt}



JÜLICH Forschungszentrum