

Гео-нейтрино и исследования строения Земли

Семинар ОЭПВАЯ
14.10.2021

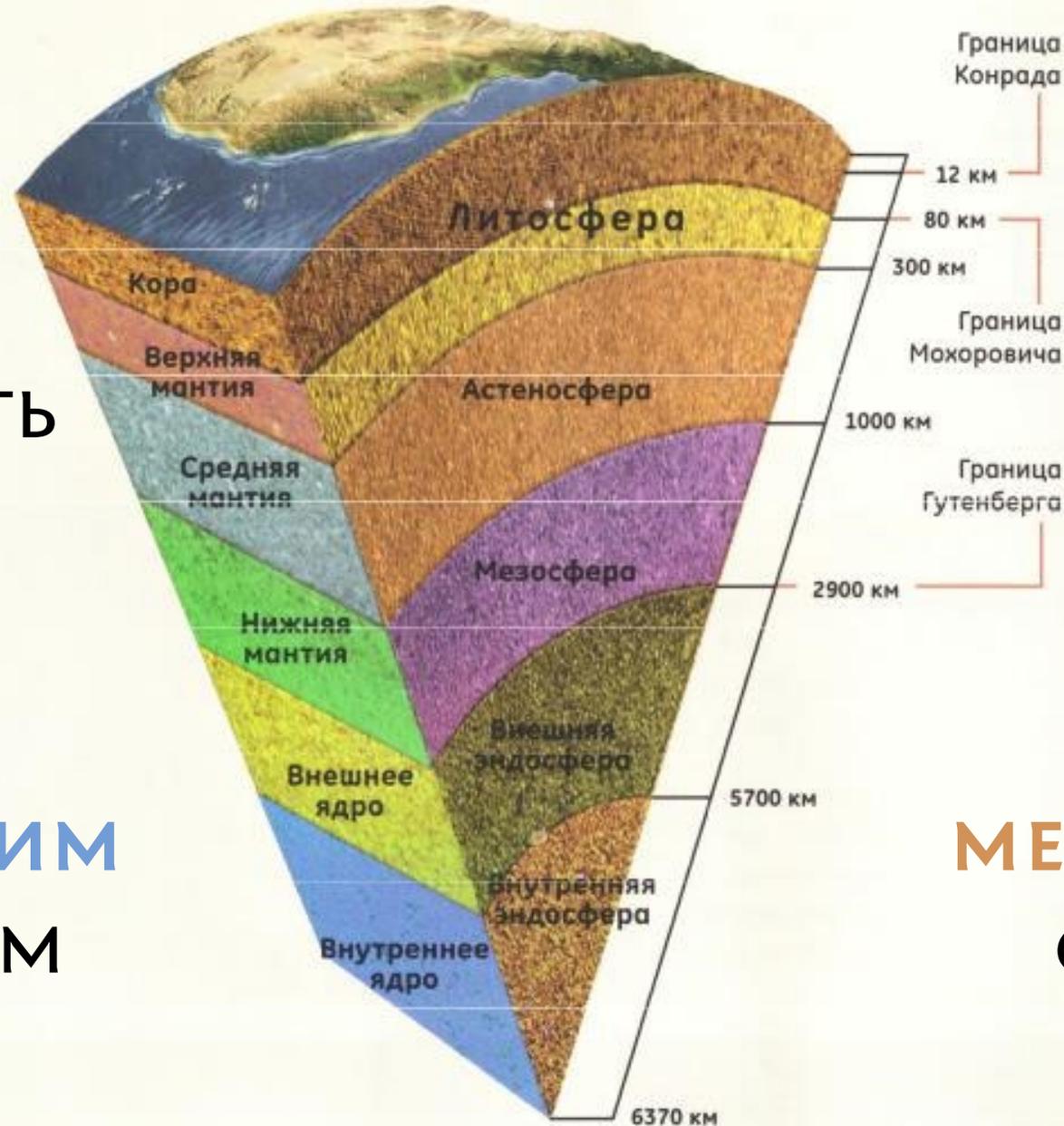
Громов М.Б.

НИИЯФ МГУ
ОИЯИ

ЧТО МЫ ЗНАЕМ О СТРОЕНИИ ЗЕМЛИ?

НЕДРА ЗЕМЛИ
МОЖНО ДЕЛИТЬ
НА СЛОИ

ПО ИХ
ХИМИЧЕСКИМ
СВОЙСТВАМ



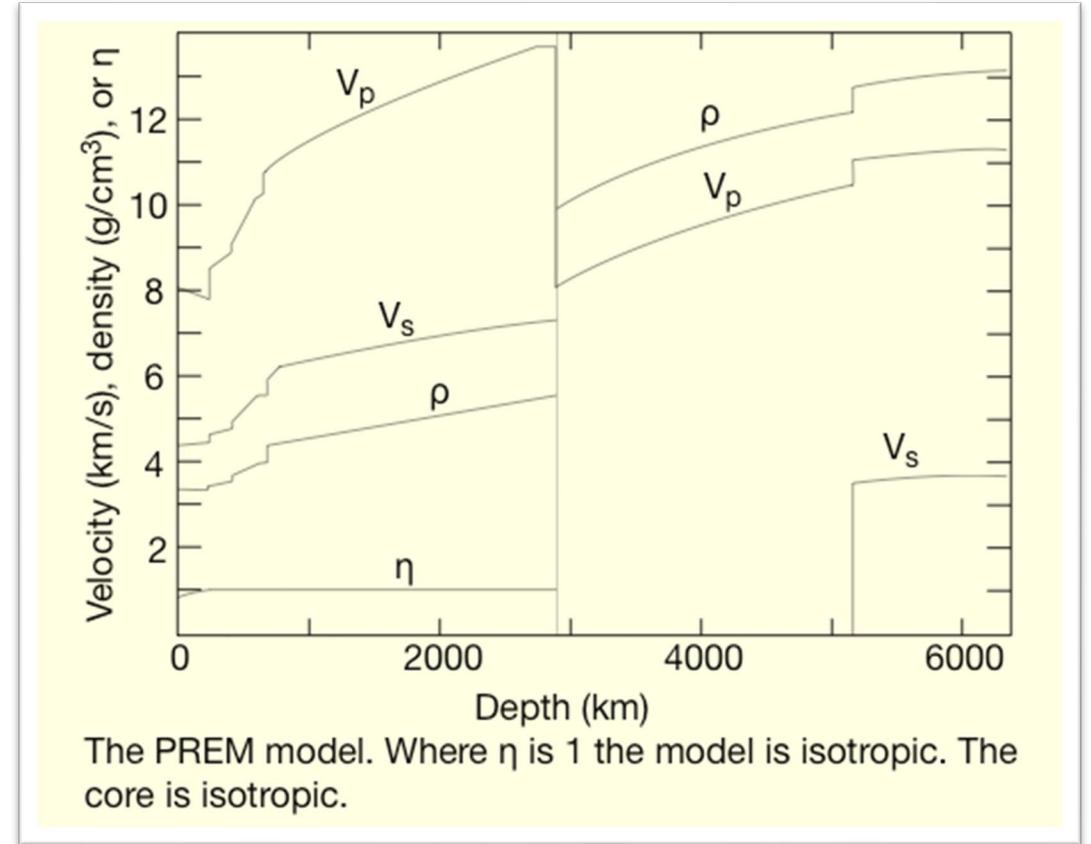
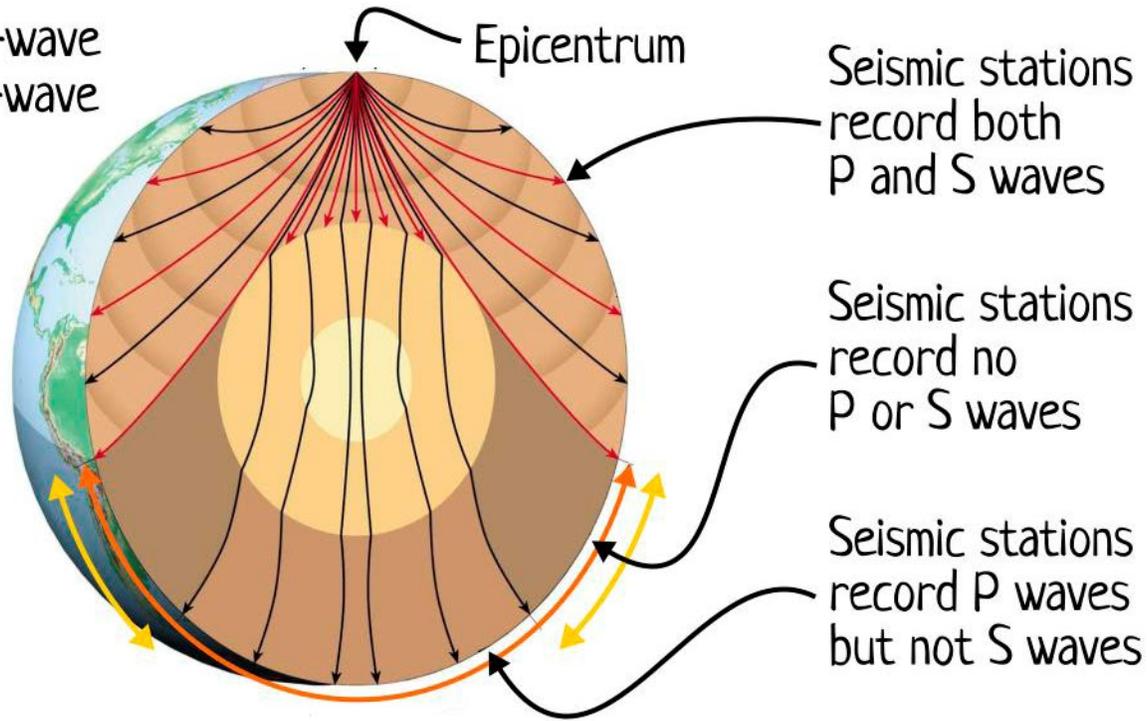
ПО ИХ
МЕХАНИЧЕСКИМ
СВОЙСТВАМ

ОТКУДА МЫ ЗНАЕМ О СТРОЕНИИ ЗЕМЛИ?

Преломление объёмных волн на границе двух упругих сред

Землетрясение

↗ P-wave
↘ S-wave



Объёмные волны (упругие)

P-волна – продольная волна или волна сжатия

S-волна – поперечная волна или волна сдвига

Жидкости (и газы) не пропускают S-волны

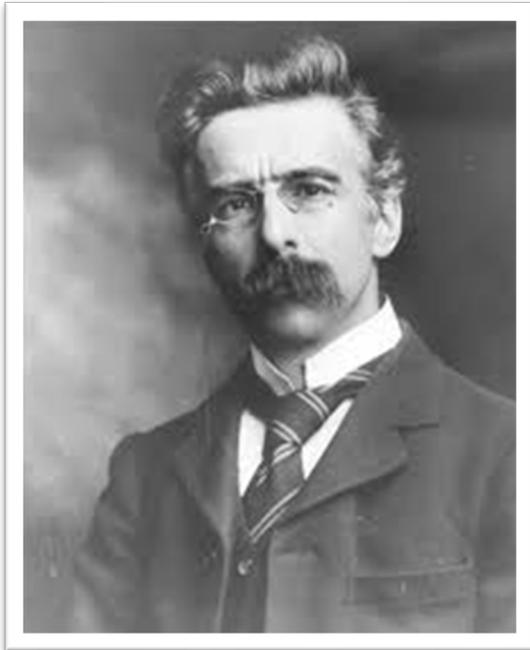
Preliminary reference Earth model (PREM, 1D model)

Предварительная эталонная модель Земли

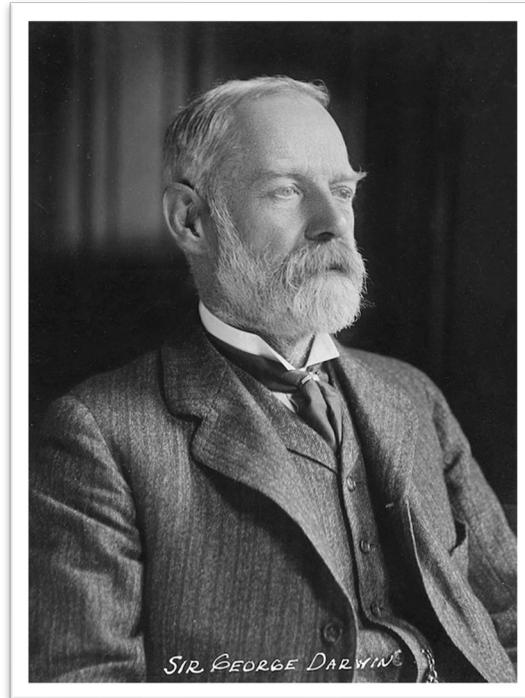
РАДИОАКТИВНОСТЬ И ПОТОК ТЕПЛА ОТ ЗЕМЛИ

1903 г.

Ирландский геолог и физик Джон Джоли (John Joly) и английский астроном и математик Джордж Дарвин (George Darwin) впервые обратили внимание на радиоактивность пород, как источник геотермальной энергии.



Джон Джоли

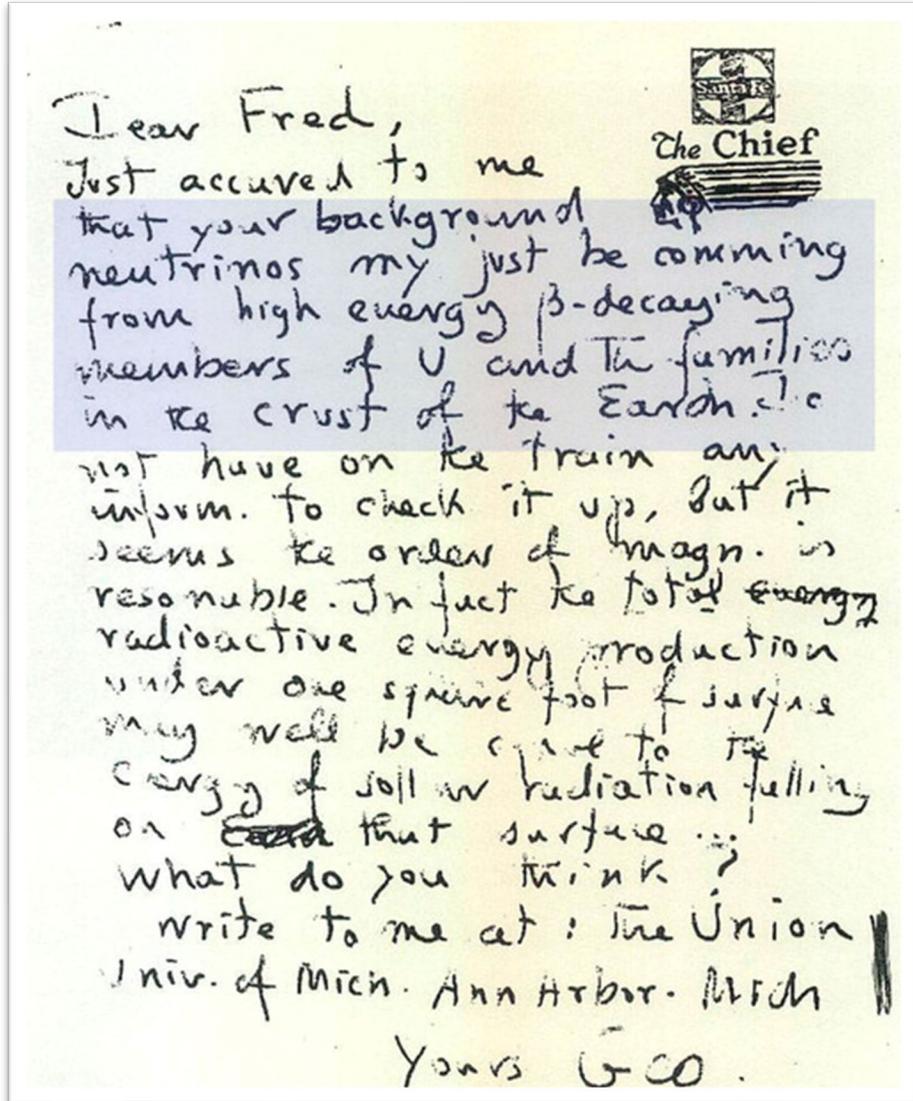


Джордж Дарвин

Расчеты показывали, что концентрация радиоактивных изотопов во всей Земле не может соответствовать их концентрации в земной коре, в противном случае радиогенное тепло превышало бы известный поток тепла от Земли. Другими словами, концентрация радиоактивных изотопов в мантии и ядре ниже, чем в земной коре.

В 1970-х концентрация U и Th была измерена в образцах из мантии, собранных со дна океана, и она, действительно, оказалась очень низкой ($\sim 10^{-8}$ г/г).

ПЕРВОЕ ЗАДОКУМЕНТИРОВАННОЕ УПОМИНАНИЕ О ГЕО-НЕЙТРИНО



Прошло полвека... 1953 г.

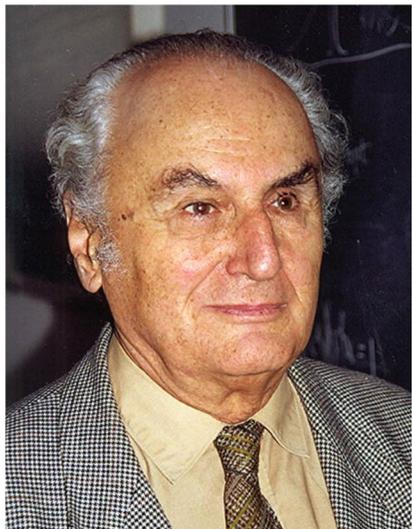
В письме Гамова к Райнису:

«Дорогой Фред,
...ваши фоновые нейтрино
могут просто испускаться
высокоэнергетическими
 β -распадными членами
семейств урана и тория
в коре Земли.»

Георгий Гамов



ИДЕИ 60-х



Георгий Маркс

G. Marx, N. Menyhard Mitteilungen der Sternwarte, Budapest, 48 (1960)

Первая реалистичная оценка потоков гео-нейтрино от U, Th и K.

М.А. Марков в книге «Нейтрино», 1964

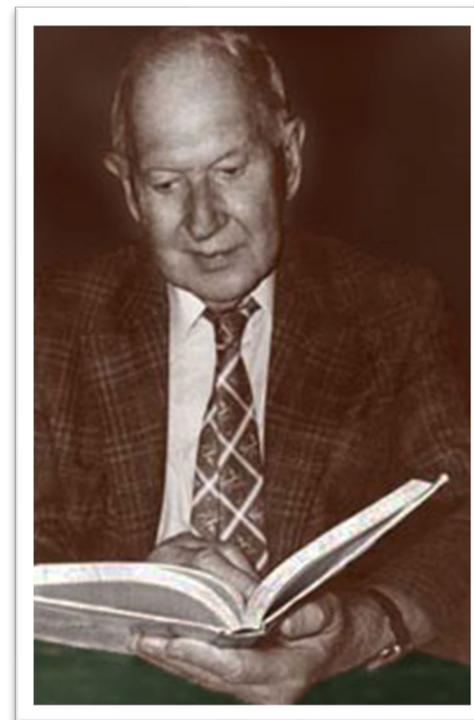
Важное освещение и обсуждение вопроса

Gernot Eder Terrestrial neutrinos, Nucl Phys 78 (1966)

Указал на важность регистрации и изучения гео-нейтрино для объяснения наблюдаемого теплового излучения Земли. Также указал на возможность определения распространённости (количества) долгоживущих радиоактивных элементов в Земле путём измерения потока гео-нейтрино.

G. Marx Geophysics by neutrinos, Czechoslovak Journal of Physics B 19 (1969)

Обсуждение возможных геофизических исследований с помощью нейтрино

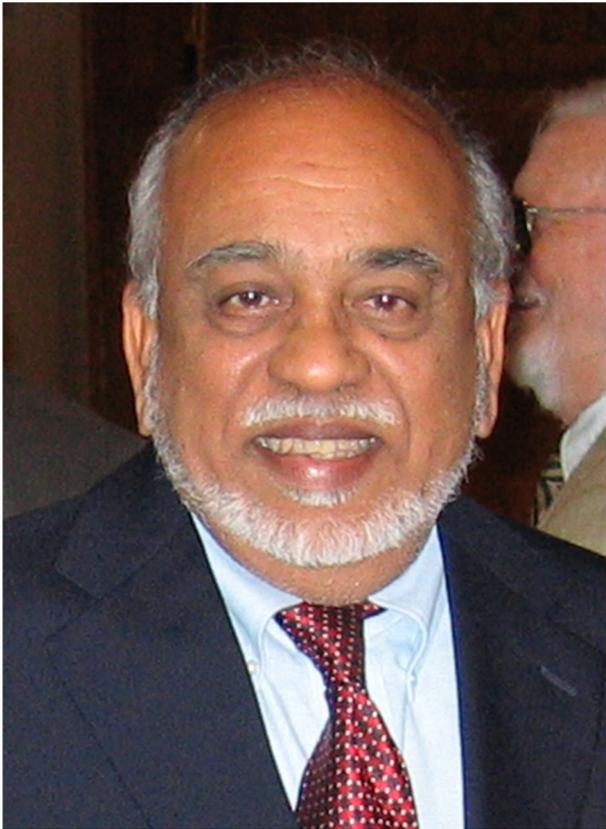


Моисей Марков



Гернот Эдер

ОТ СЛОВ ИДЕЙ К ДЕЛУ ЭКСПЕРИМЕНТУ



Рамасвами (Раджу)
Рагхаван

R. Raghavan et al. *Measuring the global radioactivity in the Earth by multi-detector antineutrino spectroscopy*, *Phys. Rev. Lett.* 80 (1998) and
C.G. Rothschild, M. Chen, F.P. Calaprice,
Geophys. Res. Lett. 25 (1998)

Предложение об использовании проектируемых на тот момент нейтринных детекторов Borexino и KamLAND для регистрации гео-нейтрино и проведения соответствующих исследований, в том числе совместных

MOTIVATION OF GEO-NEUTRINOS SEARCH

Questions:

- 1) Surface heat flux puzzle ("main" problem)
- 2) Inner structure of the Earth
- 3) Chemical composition of our planet
- 4) Physical processes (including radioactive decays) in the depth of the Earth
- 5) History of the Earth formation

And

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

THE PUZZLE OF THE SURFACE HEAT FLUX

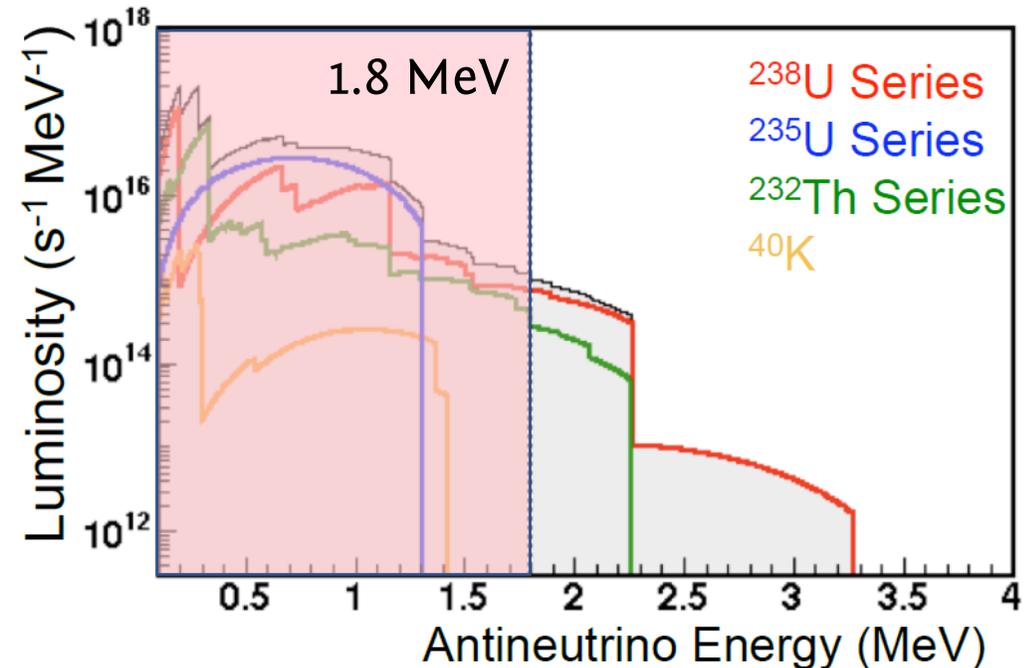
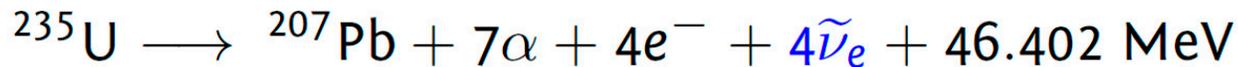
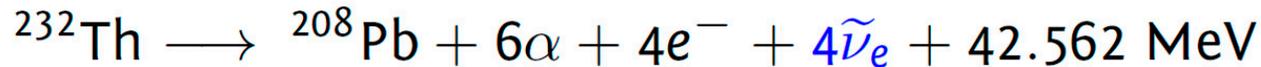
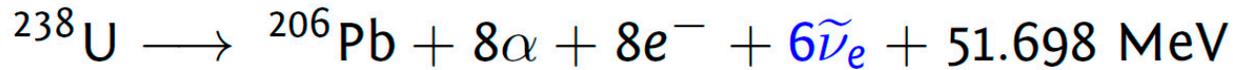
Comparison of different sources of the Earth heating

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

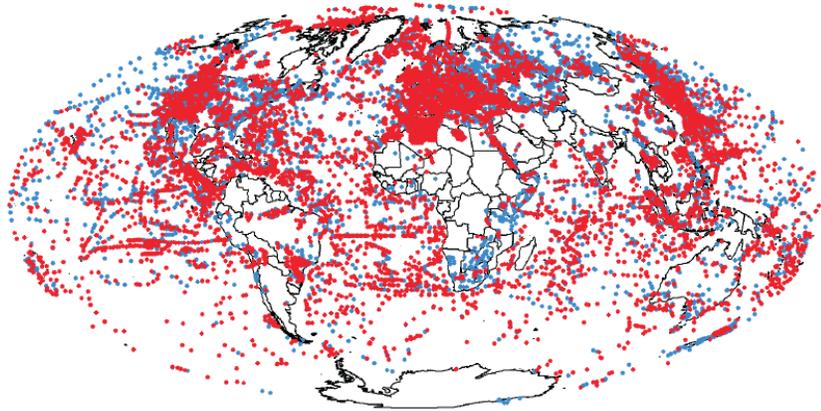
But the total heat from the depth of the Earth is $47 \pm 2 \text{ TW}$,
 where **the radiogenic heat** portion is about **10-35 TW**
 (according to geological BSE models)

Average geo-neutrino flux at the Earth's surface: $\Phi_{\tilde{\nu}} \sim 10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$

The main **H**eat **P**roducing **E**lements (**HPE**'s):



ПОТОК ТЕПЛА У ПОВЕРХНОСТИ ЗЕМЛИ



“Earth’s surface heat flux”, J. H. Davies and D. R. Davies

47 ± 2 ТВт

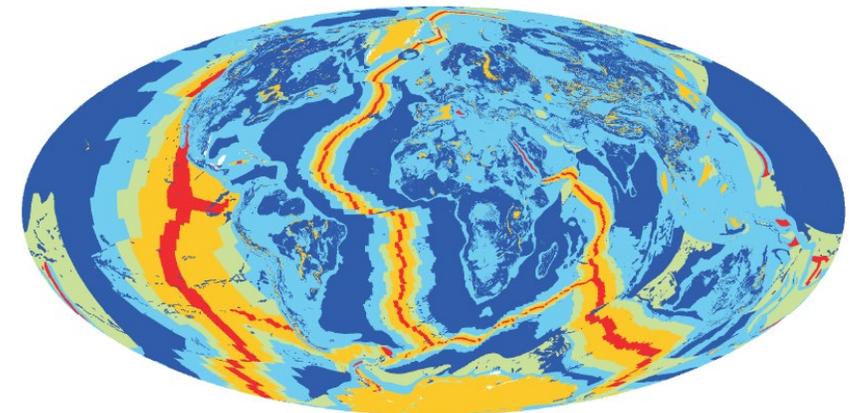
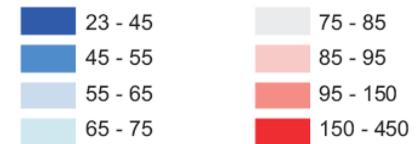
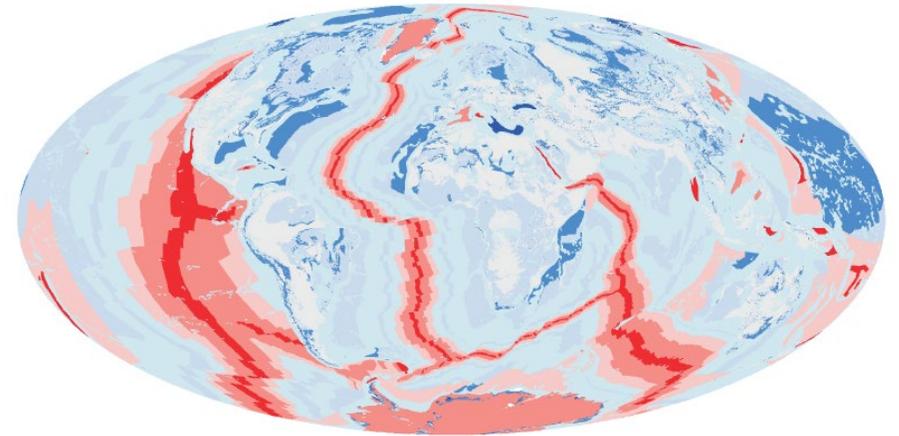
Использовались **38 347** измерений теплового потока

В согласии с предыдущими оценками:

46 ± 3 ТВт [Jaupart et al., 2007] и

44 ± 1 ТВт [Pollack et al., 1993],

где использовался неполный набор тех же данных.



КАМЕННЫЕ МЕТЕОРИТЫ И СОСТАВ ПРОТОПЛАНЕТНОГО ДИСКА

подавляющее большинство каменных метеоритов (92,3 % каменных, 85,7 % общего числа падений) — **хондриты**.

Хондры — сферические или эллиптические образования преимущественно силикатного состава (от 1 мм до нескольких мм в диаметре).

Состав хондритов практически полностью повторяет химический состав Солнца, за исключением лёгких газов, таких как водород и гелий. Поэтому считается, что хондриты образовались непосредственно из протопланетного облака, окружавшего и окружающего Солнце, путём конденсации вещества и аккреции пыли с промежуточным нагреванием. В хондритах нет следов плавления.

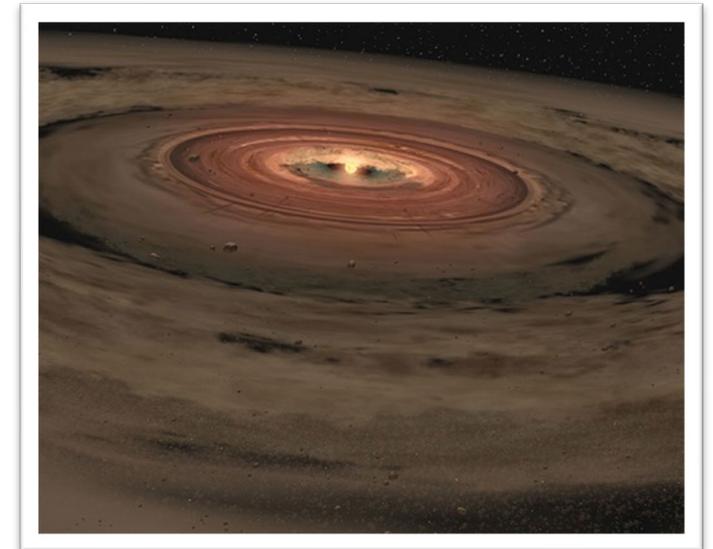


BULK SILICATE EARTH (BSE, СИЛИКАТНЫЕ МОДЕЛИ ЗЕМЛИ)



Состав Хондритов -
состав примитивной
(первичной) мантии

- Описание современной системы кора+мантия обеспечивается моделью BSE: реконструкции примитивной (первичной, изначальной) мантии Земли сразу после отделения ядра, но до дифференциации коры, на основании геохимических аргументов.
- Примитивный резервуар - любая область мантии, которая сохранила этот состав.
- Массовые или хондритовые отношения:
 $M(\text{Th})/M(\text{U}) = 3.9,$
 $M(\text{K})/M(\text{U}) = 10^4,$
распространенность U $\sim 2 \cdot 10^{-8}$ г/г.



МОДЕЛИ КОМПОНЕНТНОГО СОСТАВА ЗЕМЛИ

- **Космохимические**, в которых в качестве опорного берётся состав энстатитных хондритов и принимается во внимание процесс столкновительной эрозии
- **Геохимические**, в которых в качестве опорного берётся состав углеродистых хондритов и учитывается распространённость разных химических элементов в образцах земной коры и мантии
- **Геодинамические**, базирующиеся на измерениях потока тепла от Земли и на учёте конвекции мантии
- **Радиогенная**. Специальная модель, в которой искусственно повышены распространённости радиоактивных элементов, чтобы полностью описать наблюдаемый тепловой поток энергосвыделением в цепочках распадов этих элементов

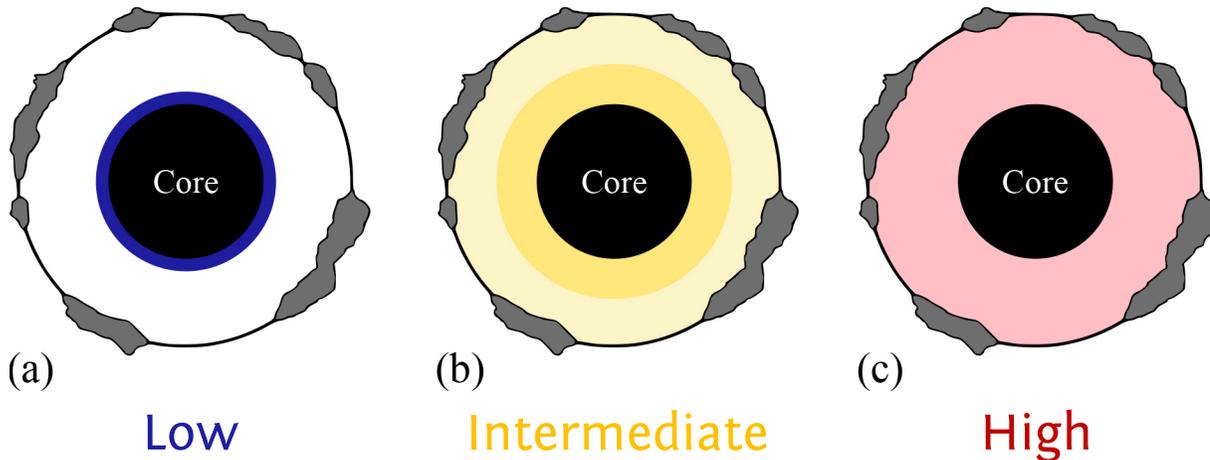
EARTH'S MODELS AND HEAT BUDGET

BSE - Bulk Silicate Earth

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

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

Mantle Scenarios



Model classification

Cosmochemical (CC)

Geochemical (GC)

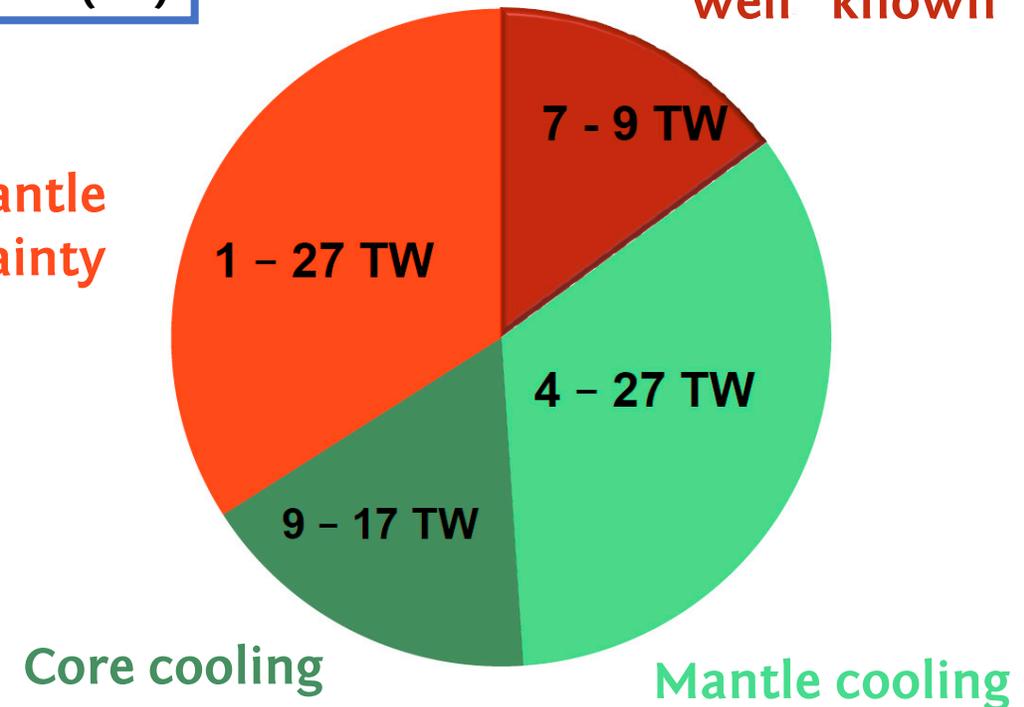
Geodynamical (GD)

Fully radiogenic (FR)

H_{rad}

Mantle
Big uncertainty

Lithosphere
"well" known



Heat budget

EARTH'S MODELS AND HEAT BUDGET

**Geoneutrinos
can help!**

Model
classification

Cosmochemical (CC)

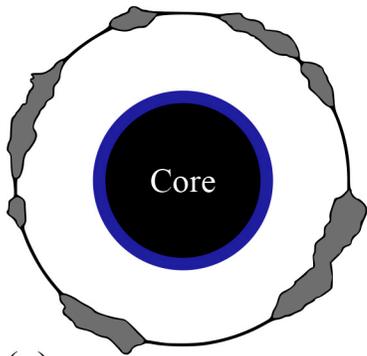
Geochemical (GC)

Geodynamical (GD)

Fully radiogenic (FR)

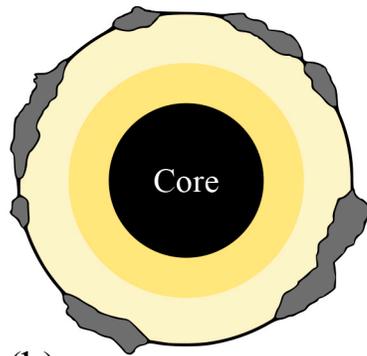
H_{rad}

Mantle Scenarios



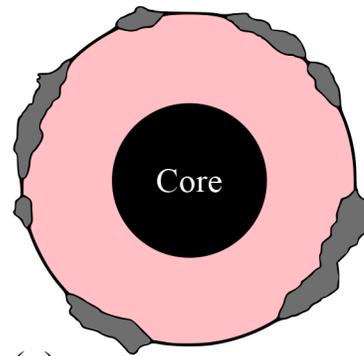
(a)

Low



(b)

Intermediate

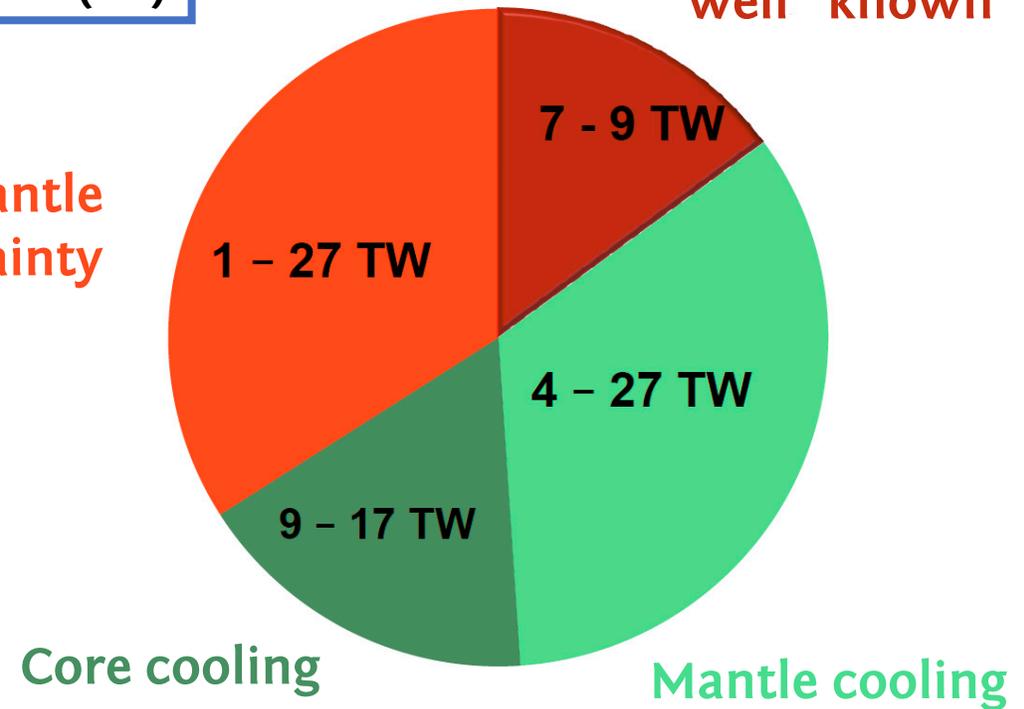


(c)

High

Mantle
Big uncertainty

Lithosphere
"well" known

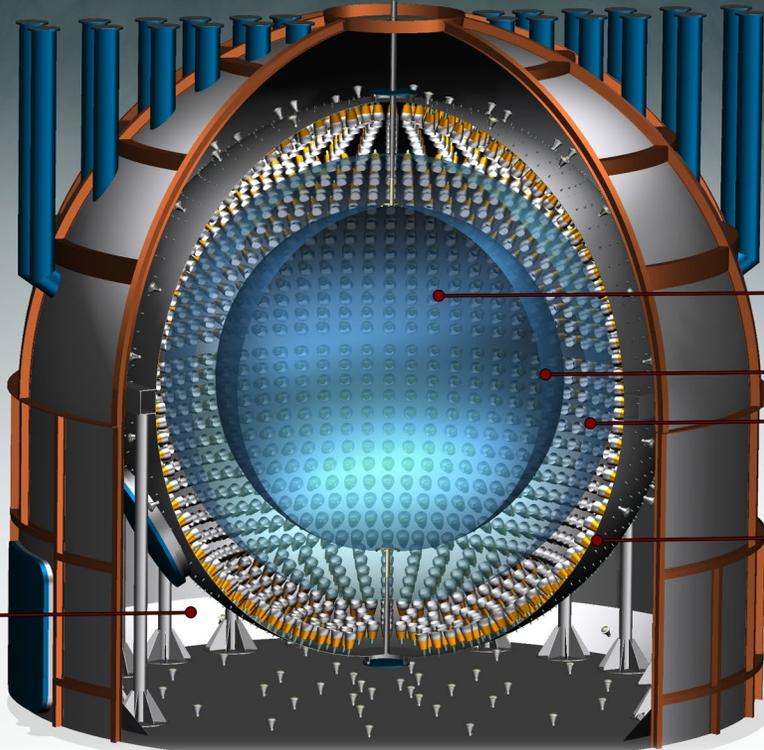


Heat budget

DETECTING GEONEUTRINOS

Borexino Experiment

Laboratori Nazionali del Gran Sasso



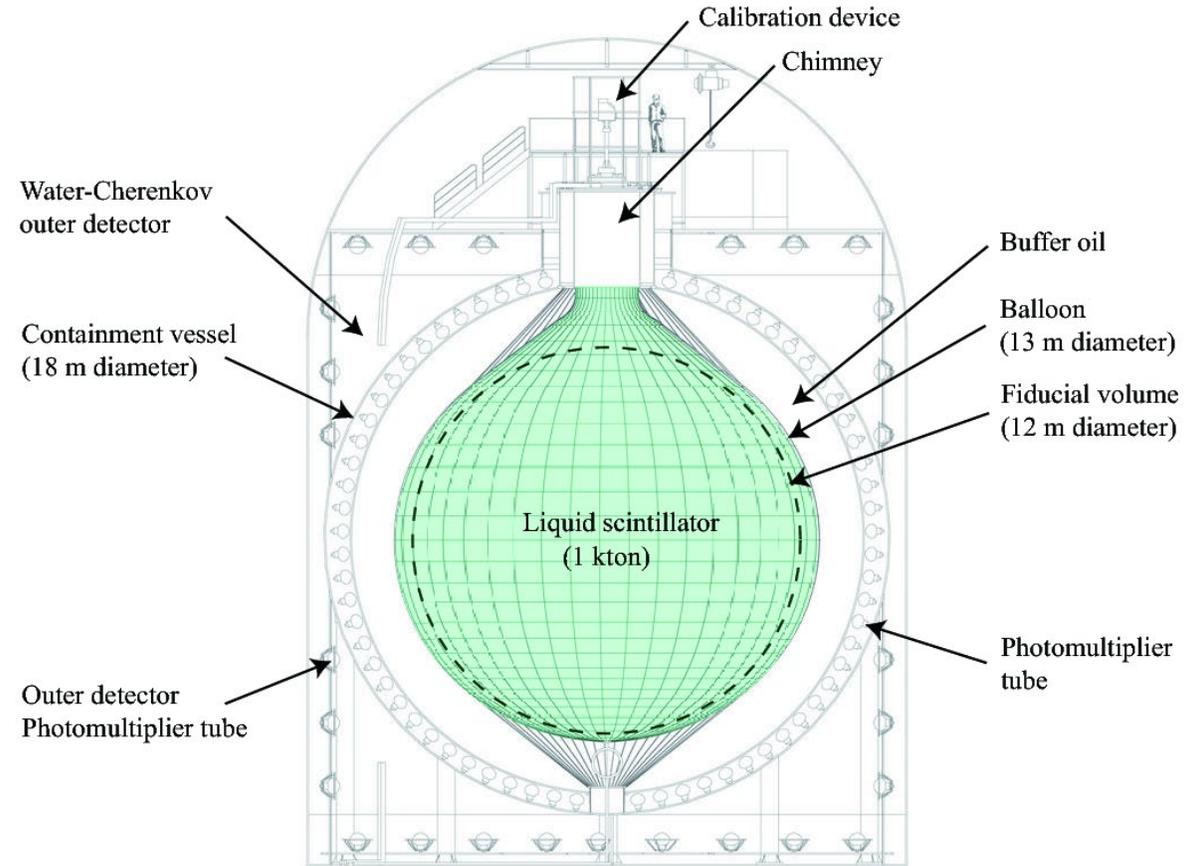
Water tank:
γ and n shield
μ water
Cherenkov
detector
2100 m³
208 PMTs in water

Scintillator:
278 t PC+PPO (1.5 g/l)

Nylon vessels:
(125 μm thick)
Inner: 4.25 m
Outer: 5.50 m
(radon barrier)

Stainless Steel Sphere
6.85 m, 1340 m³
- 2212 8" (ETL 9351) PMTs
- ~1000 m³ buffer of
PC+DMP
(light quenching)

Based on the original picture by
A. Brigatti
P. Lombardi



Water-Cherenkov
outer detector

Containment vessel
(18 m diameter)

Outer detector
Photomultiplier tube

Calibration device

Chimney

Buffer oil

Balloon
(13 m diameter)

Fiducial volume
(12 m diameter)

Liquid scintillator
(1 kton)

Photomultiplier
tube

KamLAND

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

BOREXINO

Borexino Experiment

Laboratori Nazionali del Gran Sasso

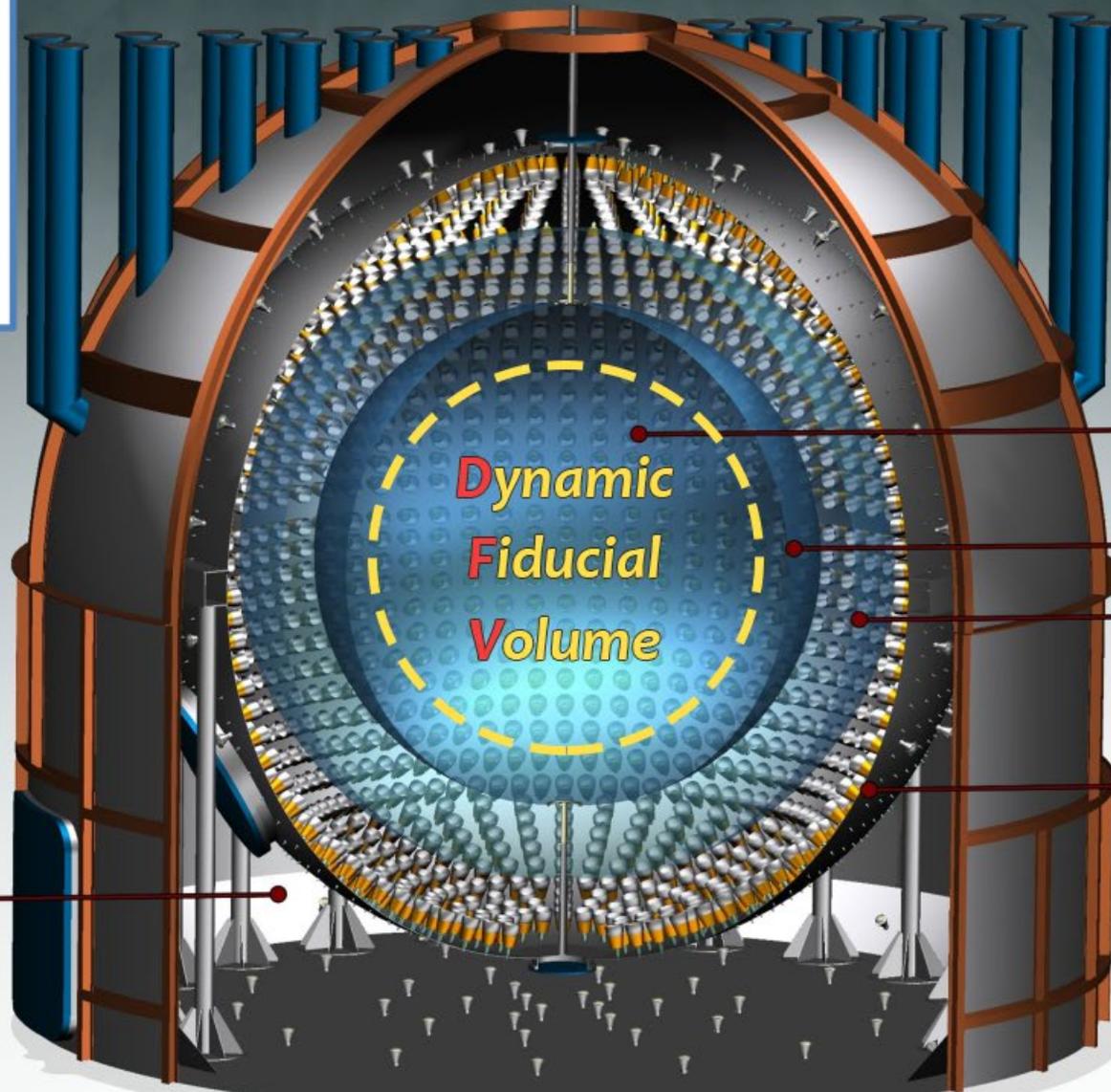
Laben DAQ

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

Energy:
5% @ 1 MeV

Position :
10 cm @ 1 MeV

Water tank:
 γ and n shield
 μ water
Cherenkov
detector
2100 m³
208 PMTs in water



FADC DAQ

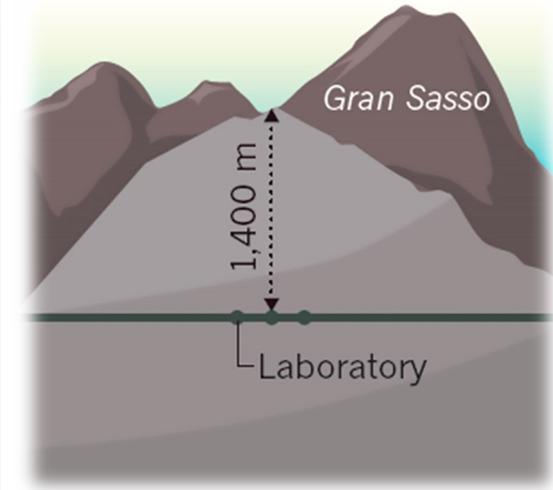
Energy range:
1 – 50 MeV
+ PSD
+ position reco
Made for SN- ν

Scintillator:
278 t PC+PPO (1.5 g/l)

Nylon vessels:
(125 μ m thick)
Inner: 4.25 m
Outer: 5.50 m
(radon barrier)

Stainless Steel Sphere
6.85 m, 1340 m³
- 2212 8" (ETL 9351) PMTs
- ~1000 m³ buffer of
PC+DMP
(light quenching)

Based on the original picture by
A. Brigatti
P. Lombardi



All nuclear reactors are
far away from
the detector

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

Ultra-high purity
construction materials

+ Set of cuts
+ Background studies

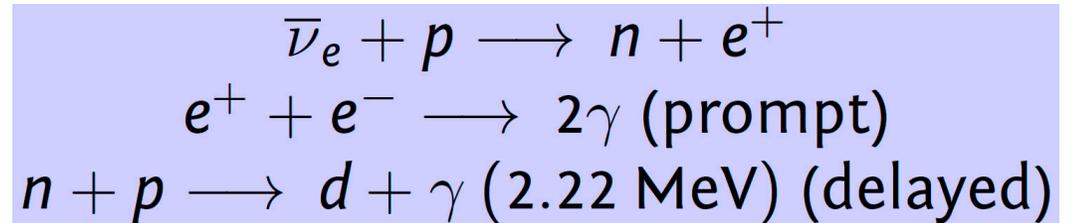
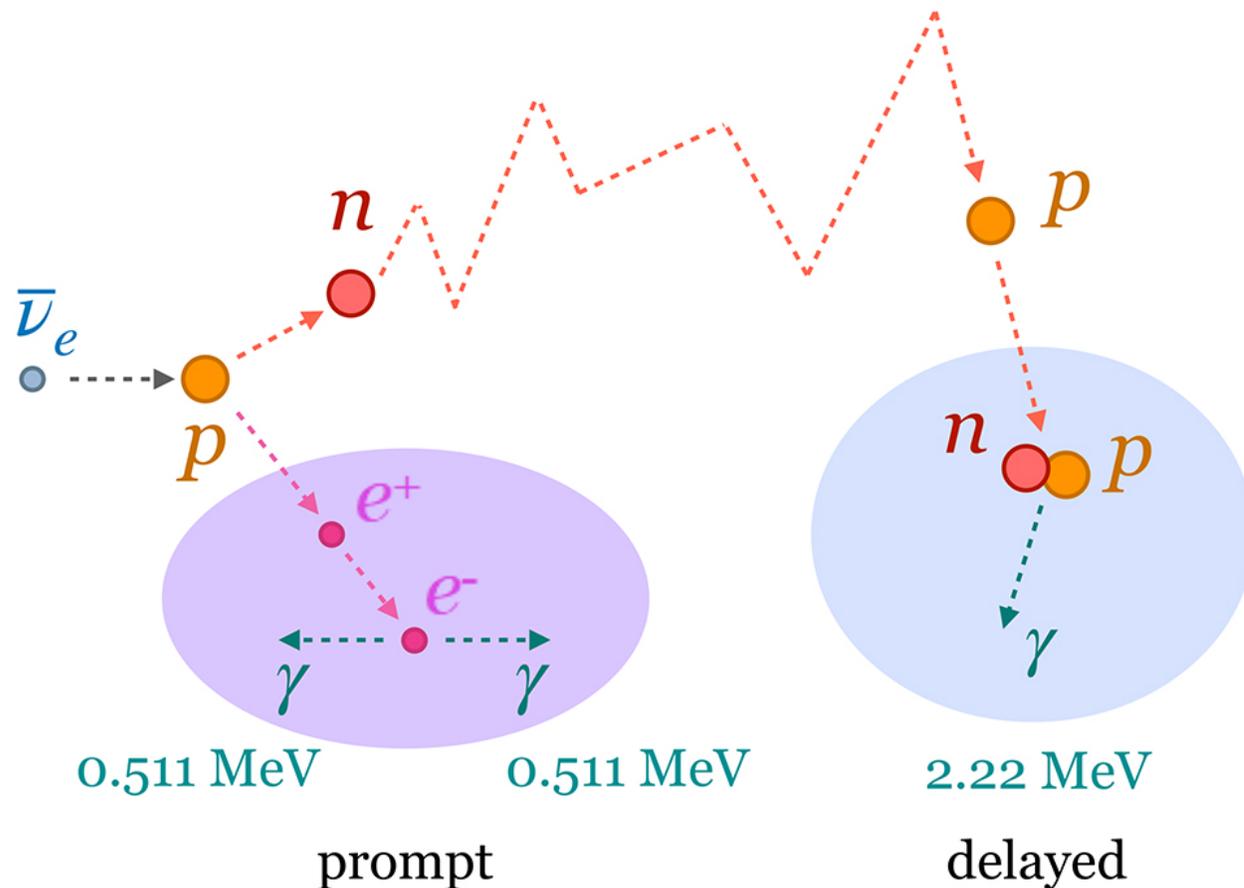
ANTINEUTRINO DETECTION WITH LIQUID SCINTILLATORS

Electron antineutrino detection: delayed coincidence

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

Energy threshold = 1.8 MeV

σ @ few MeV: $\sim 10^{-42}$ cm²
(~ 100 x more than scattering)



$$E_{\text{prompt}} = E_{\text{visible}}$$

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

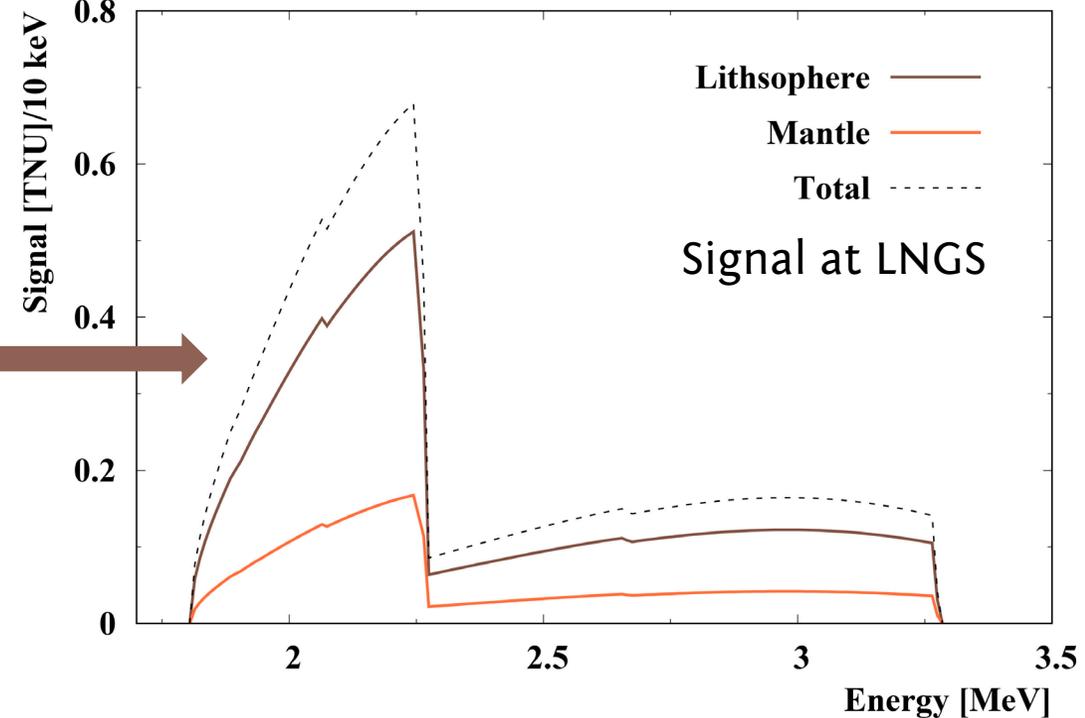
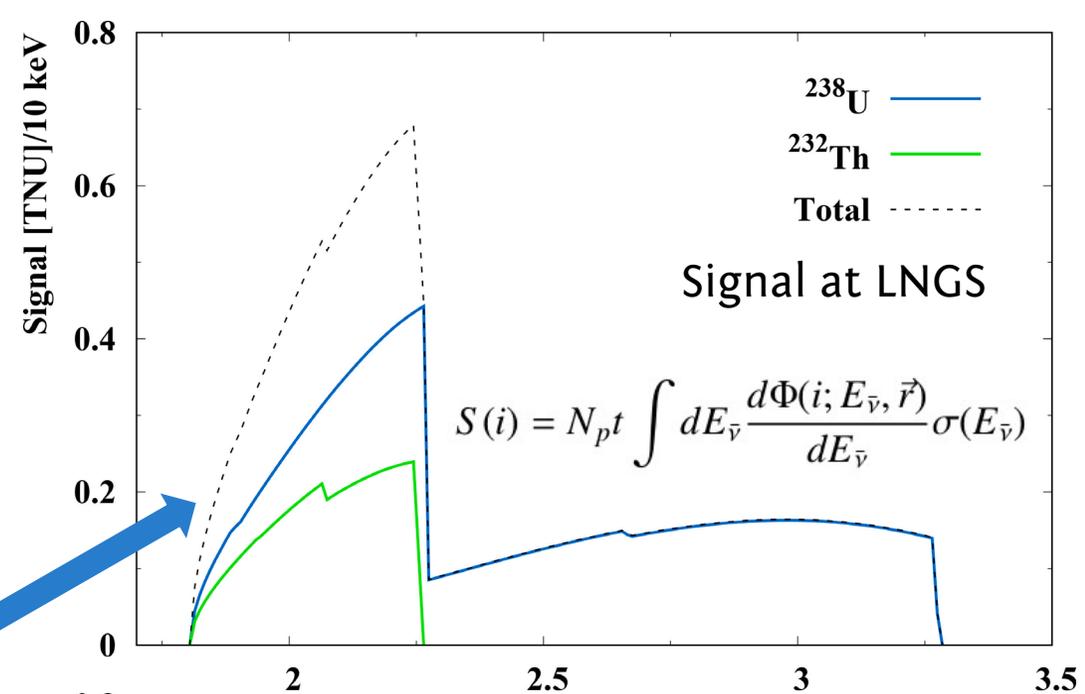
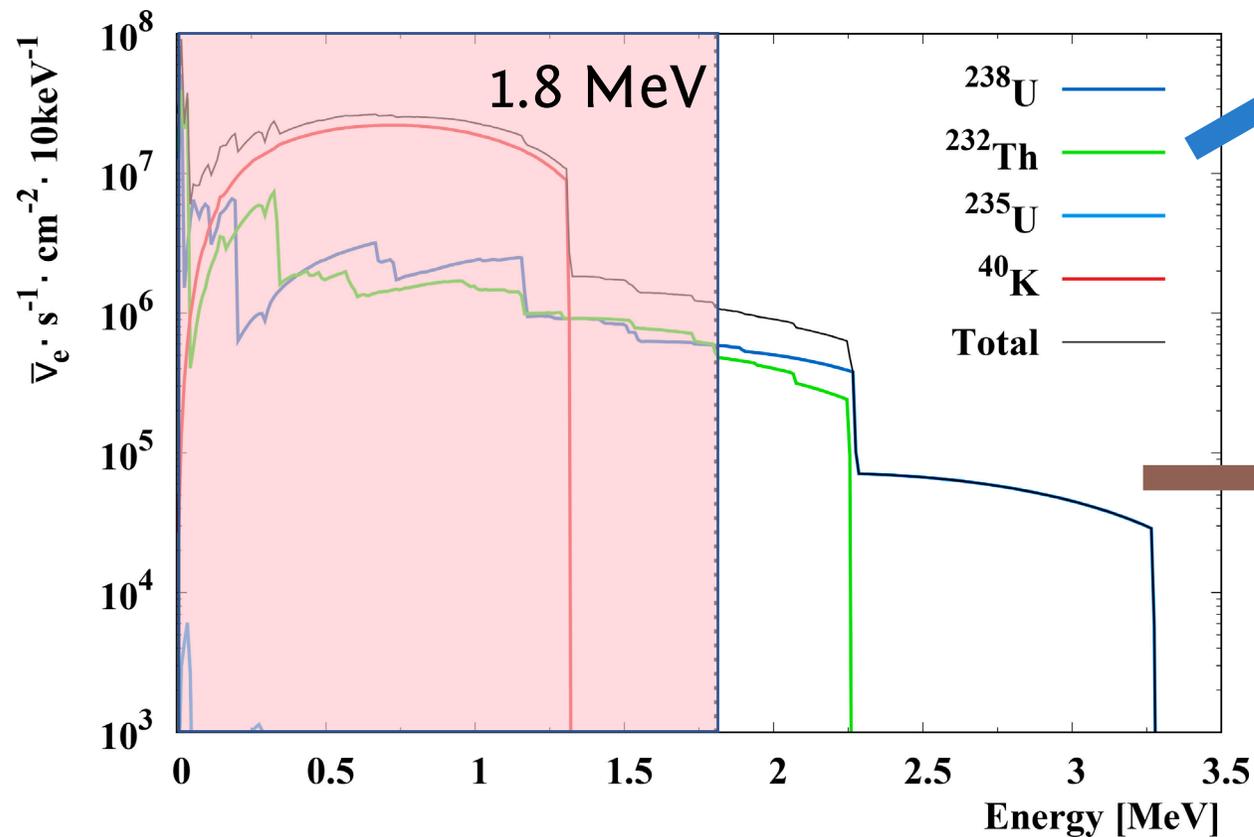
$$\sim E_{\text{antinu}} - 0.784 \text{ MeV}$$

DETECTION OF GEONEUTRINOS

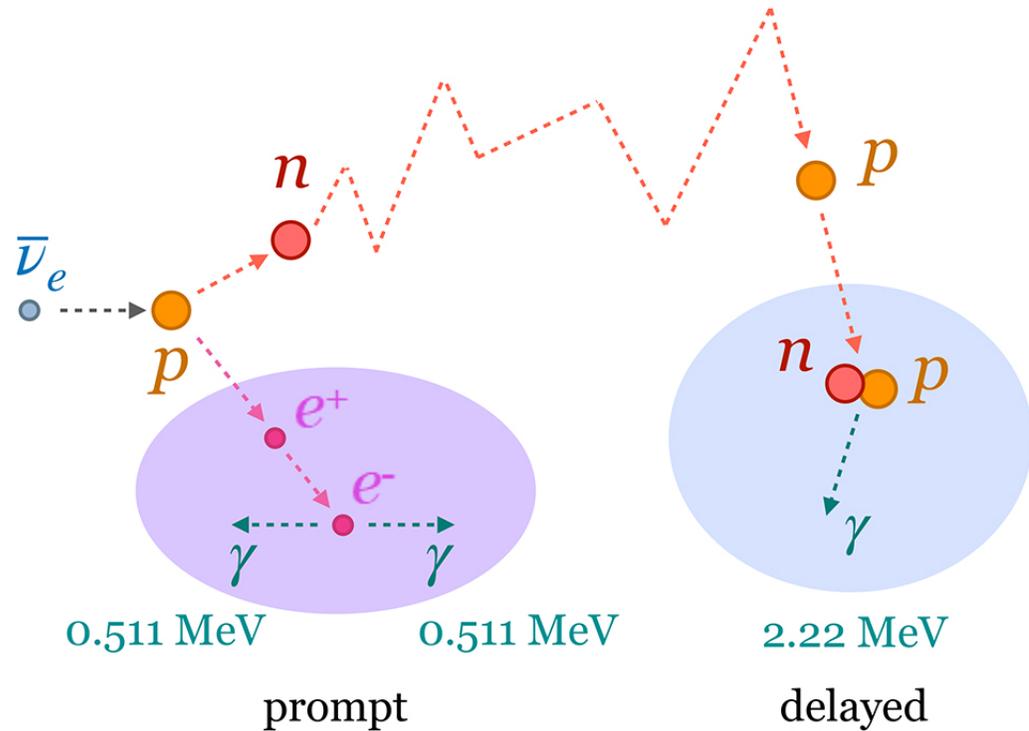
Geoneutrino flux $\sim 10^6 \text{ cm}^{-2}\text{s}^{-1}$

$\langle P_{ee} \rangle \sim 0.55$

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



OVERVIEW OF SELECTION CUTS

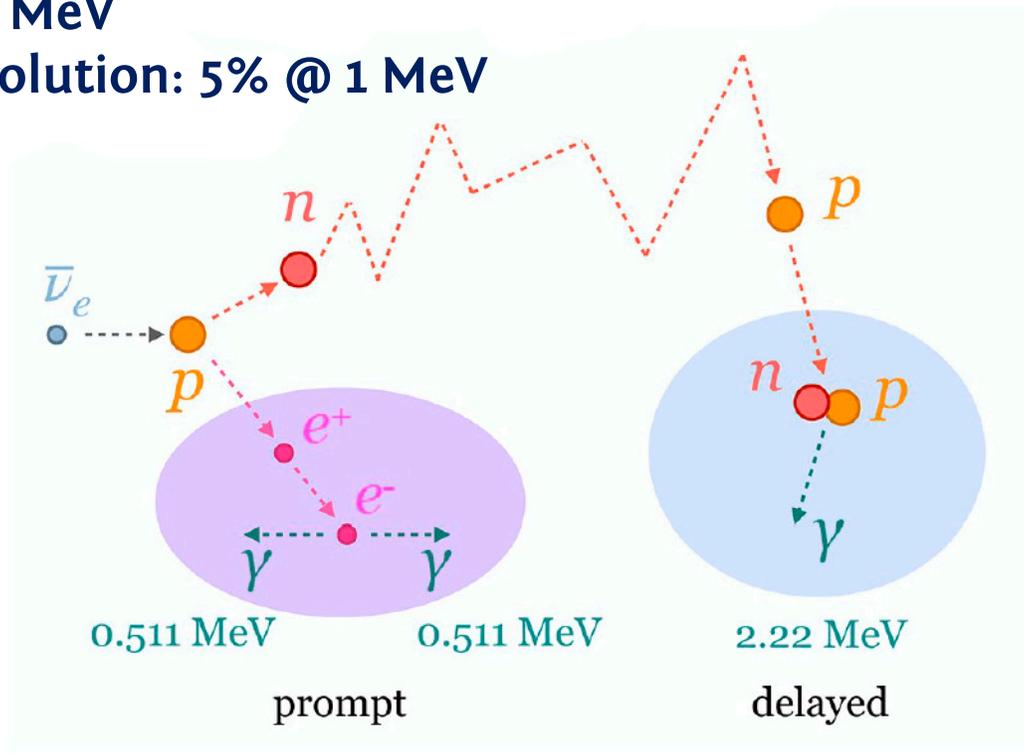


- 1) Energy cuts for prompt (Q_p) and delayed (Q_d)
- 2) Time between prompt and delayed (dt)
- 3) Distance between prompt and delayed (dR)
- 4) Muon Vetoes
- 5) Dynamic Fiducial Volume (DFV) cut
- 6) α/β discrimination

SELECTION CUTS: ENERGY CUTS

500 p.e. / 1 MeV

Energy resolution: 5% @ 1 MeV



Energy of prompt
above IBD threshold

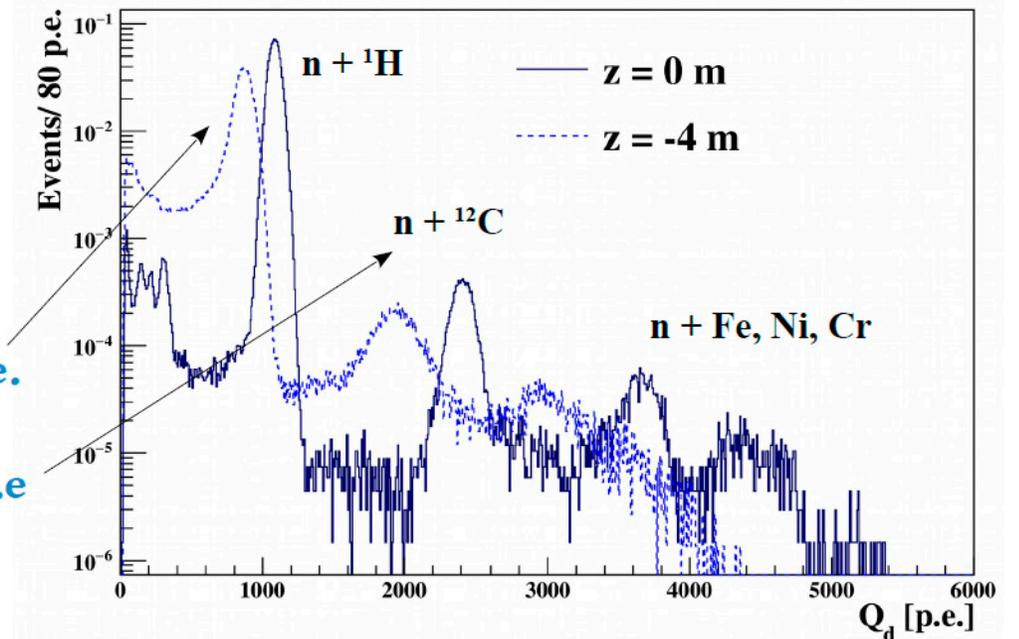
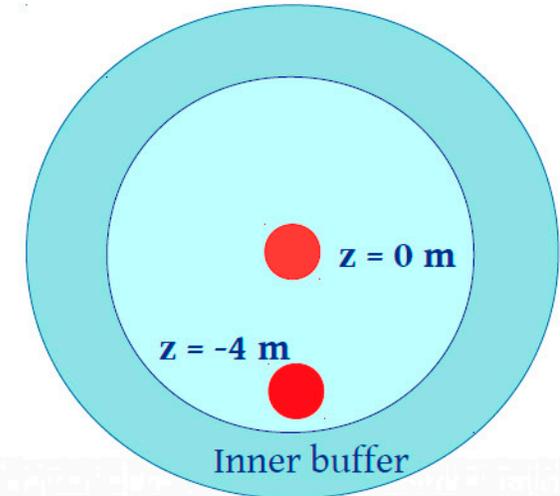
$Q_p > 408$ p.e. after
considering energy
resolution

Enlarged!

Energy of delayed

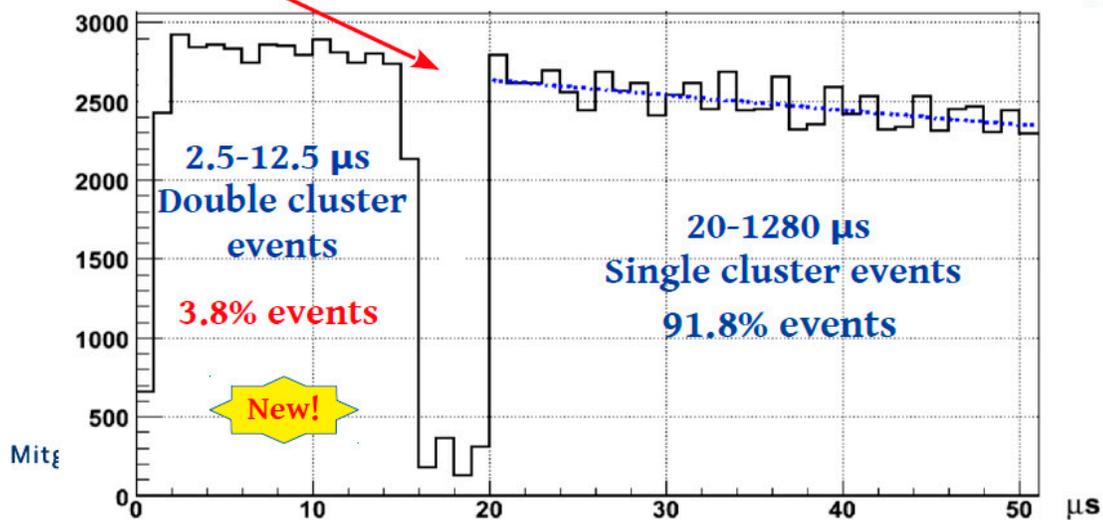
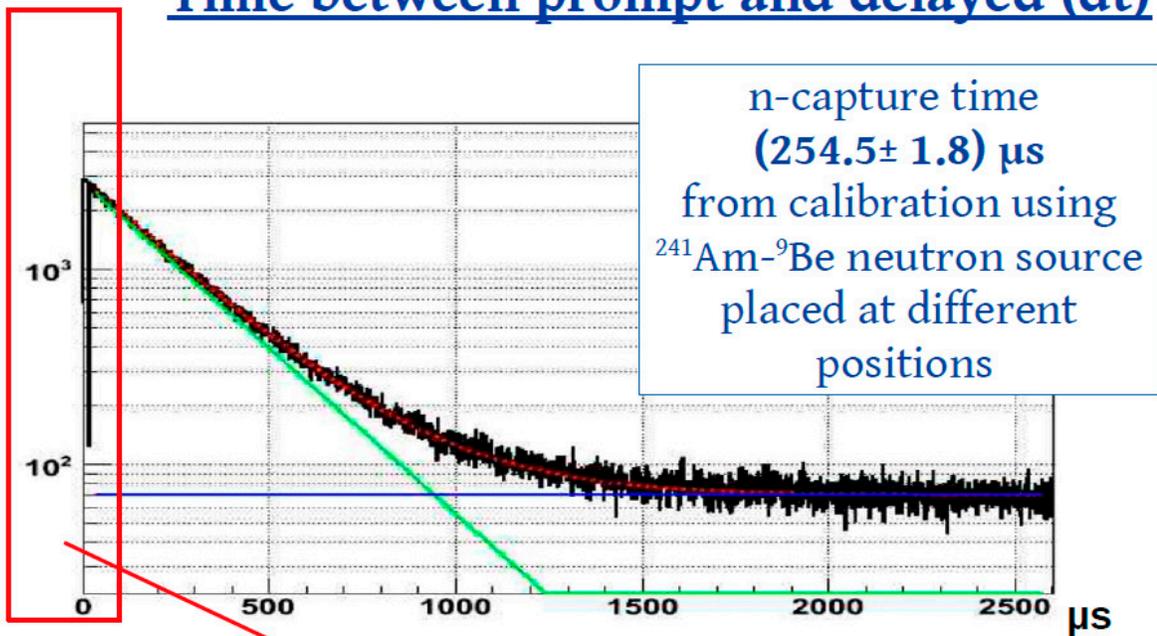
$700 < Q_d < 1300$ p.e.
(p-capture)
New! $1300 < Q_d < 3000$ p.e.
(^{12}C -capture)

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



SELECTION CUTS: TIME-SPACE CORRELATION

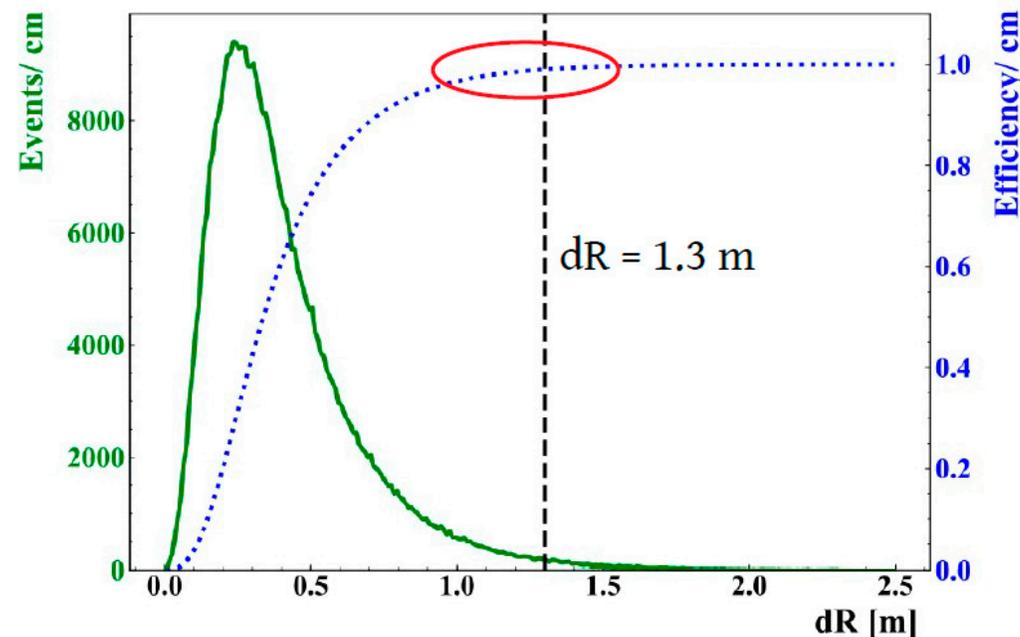
Time between prompt and delayed (dt)



Distance between prompt and delayed (dR)

Enlarged!

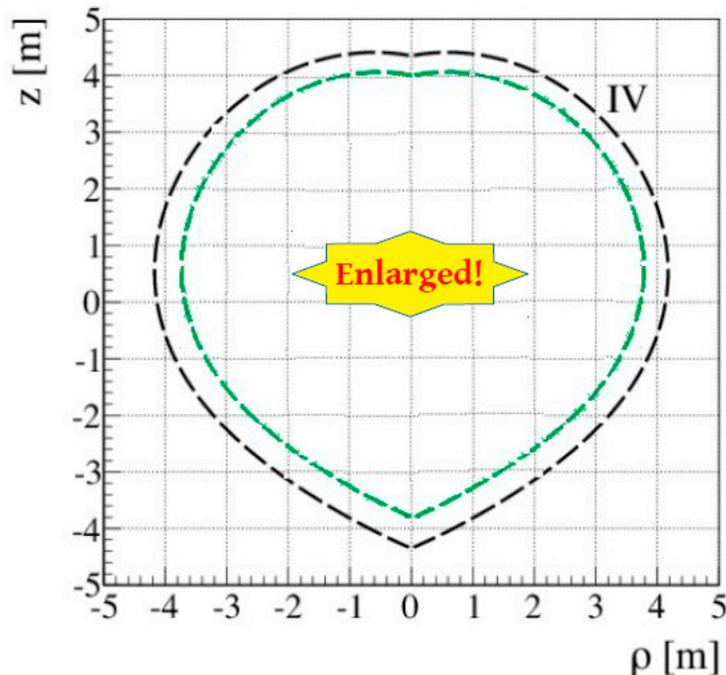
- Similar efficiency and precision for 1 to 1.5 m
- Accidental background under control



Position resolution: 10 cm at 1 MeV

SELECTION CUTS

Dynamic Fiducial Volume



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

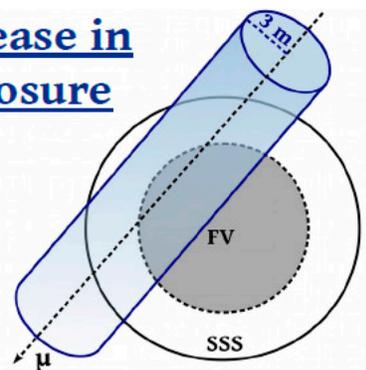
Increase in exposure

Improved Muon vetoes

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

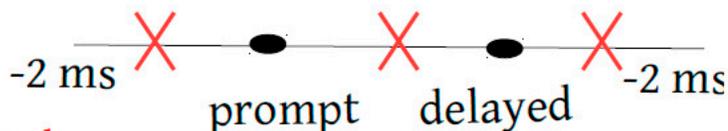
Improved!

Increase in exposure



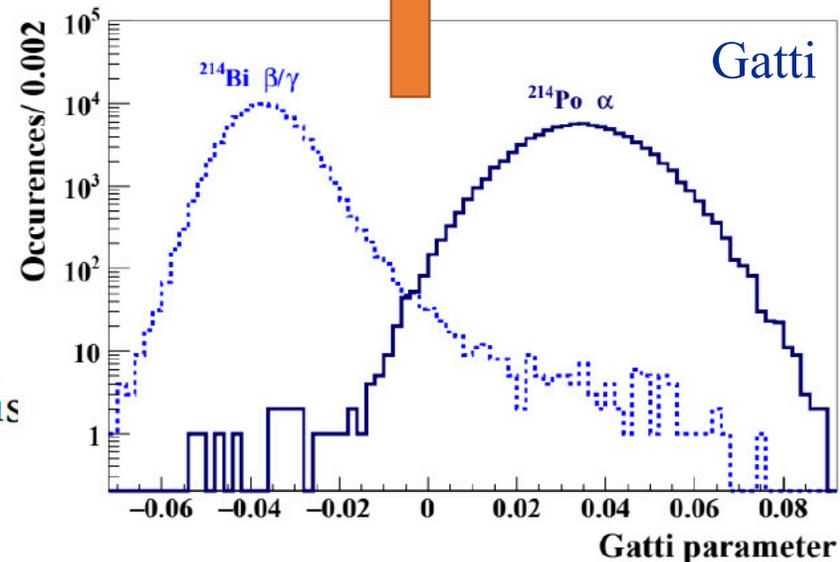
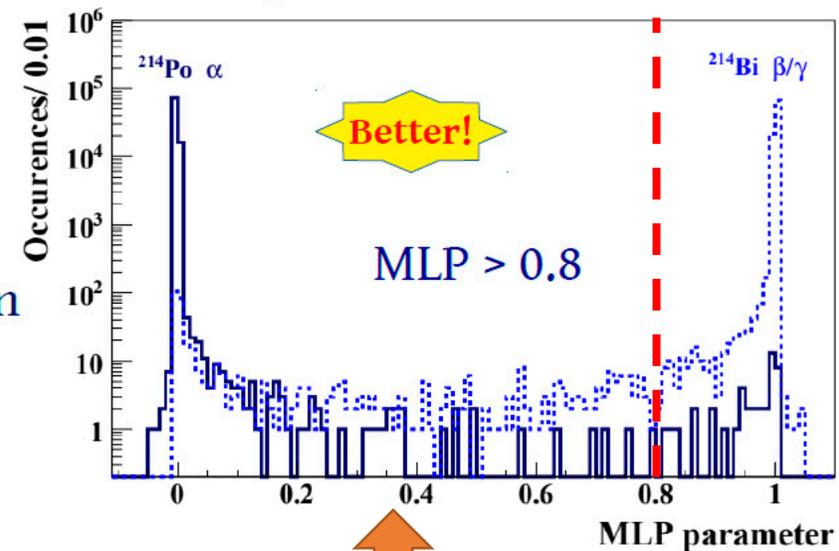
New!

Multiplicity Cut



X No high energy event > 400 p.e.

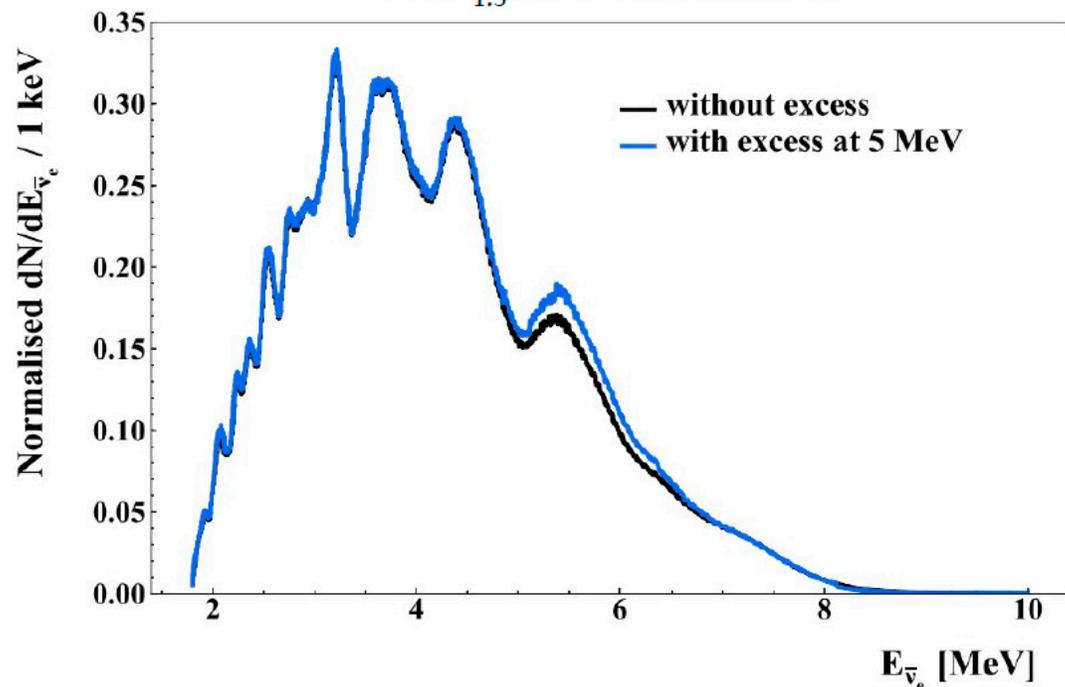
α/β discrimination



ANTINEUTRINO BACKGROUNDS

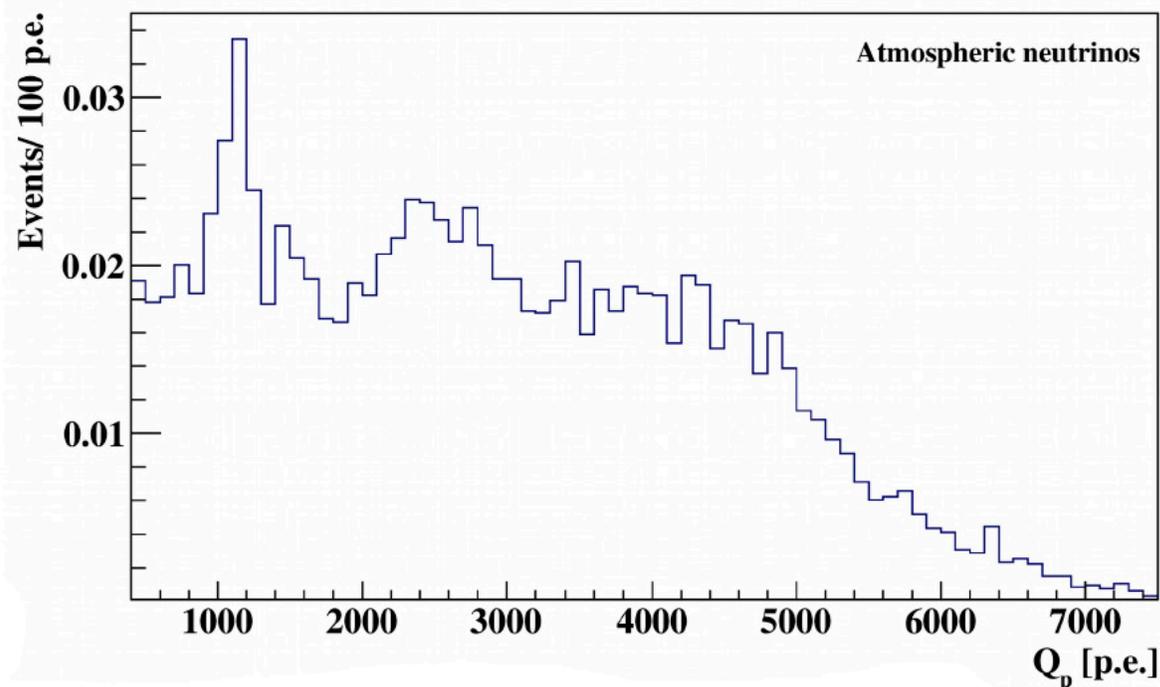
Reactor antineutrinos

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



Atmospheric neutrinos

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

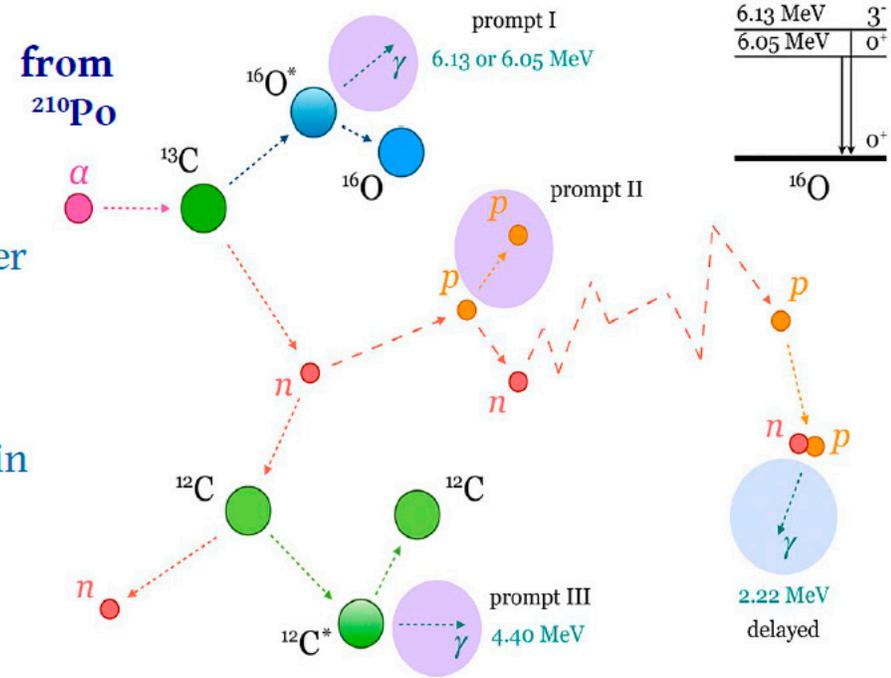


NON-ANTINEUTRINO BACKGROUNDS

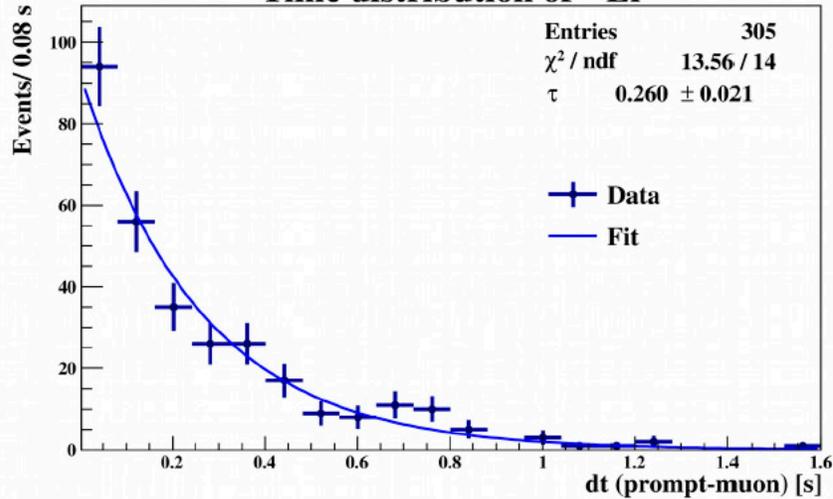


Important backgrounds for the final spectral fit:

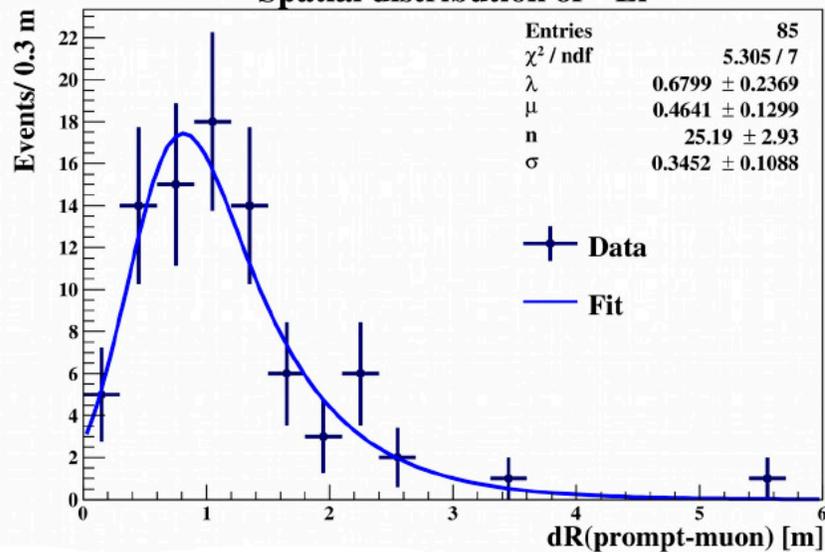
- **Cosmogenic ${}^9\text{Li}$:** expected events after the time and spatial veto
- **Accidentals:** random coincidences correlated in space and time. Events in 2-20 s window scaled back.
- **(α, n) :** due to internal radioactivity



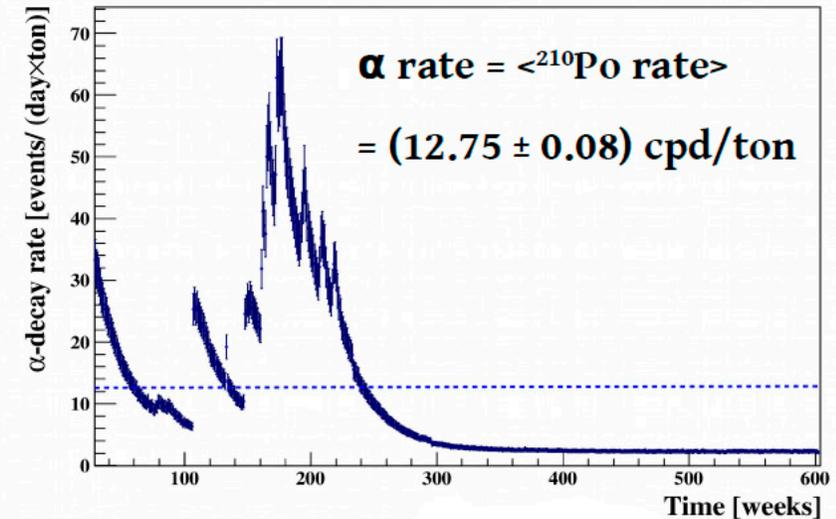
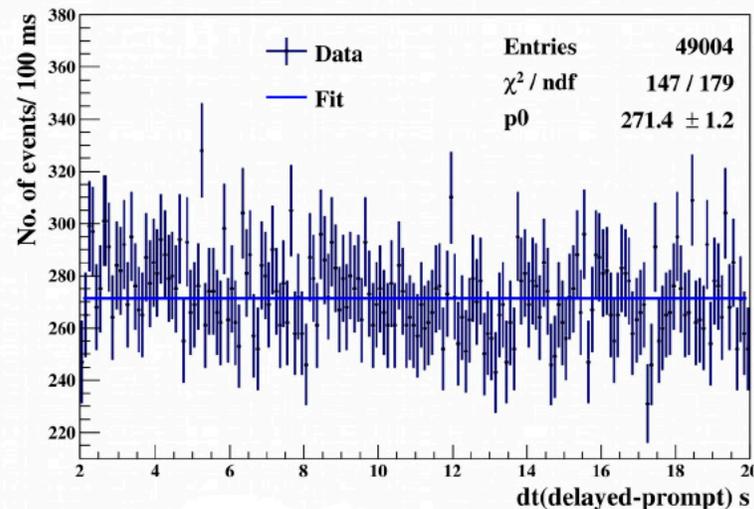
Time distribution of ${}^9\text{Li}$



Spatial distribution of ${}^9\text{Li}$



Accidentals – dt distribution



NON-ANTINEUTRINO BACKGROUNDS: SUMMARY

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

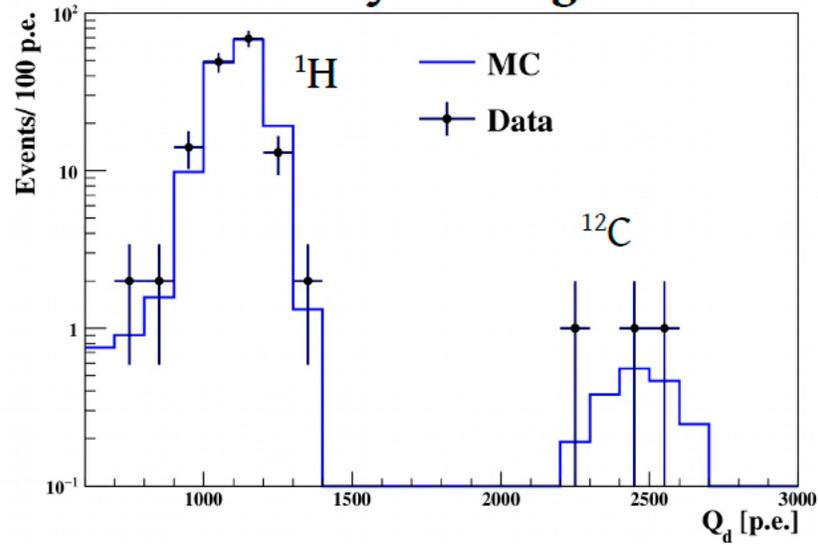
Fortunately,
it is compensated
by doubled statistics

It was $0.78^{+0.13}_{-0.10}$
(2015)

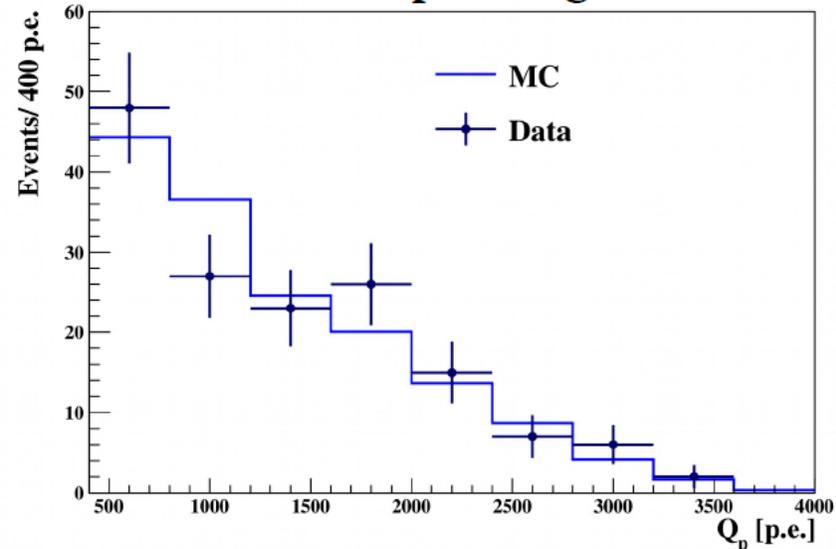
The price for relaxing the cuts is
an increase of the background by an order of magnitude

GOLDEN CANDIDATES

Delayed charge

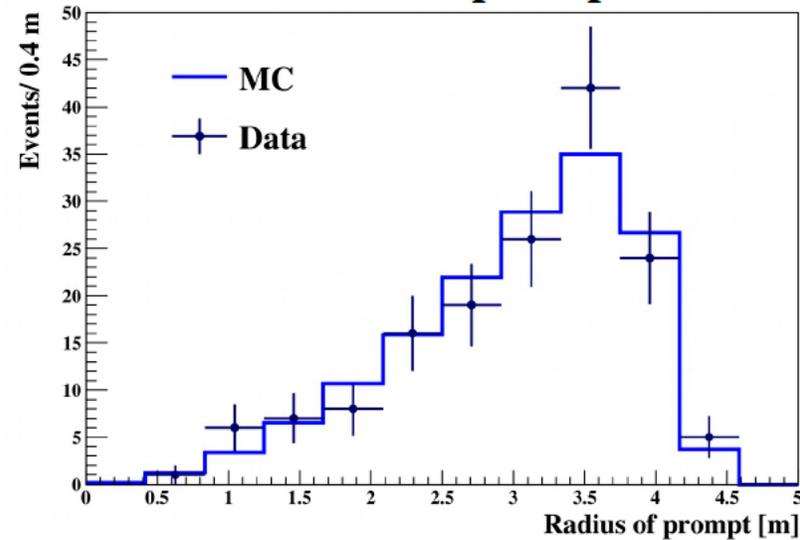


Prompt charge

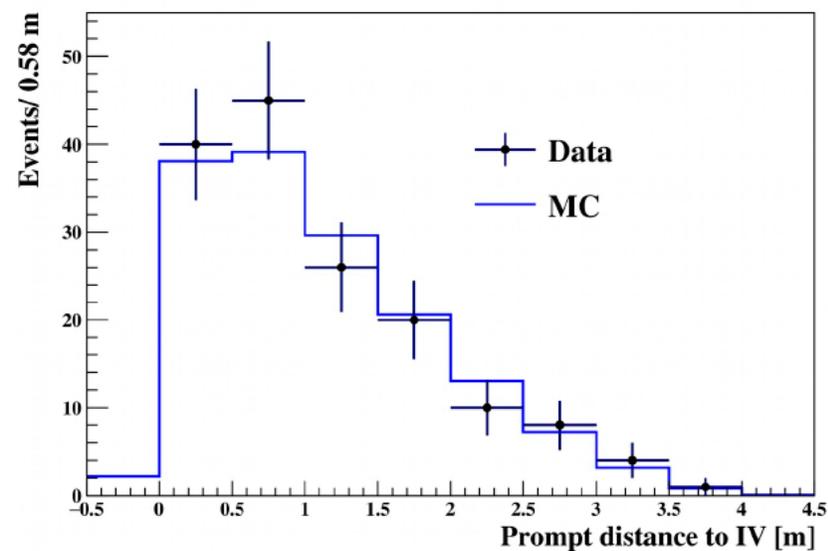


- ✓ 154 golden candidates
- ✓ 3263 days of data taking
- ✓ Average FV = (245.8 ± 8.7) ton
- ✓ Exposure = $(1.29 \pm 0.05) \times 10^{32}$ proton x year (for 100% detection eff.)
- ✓ Detection Efficiency = $(86.98 \pm 1.5)\%$

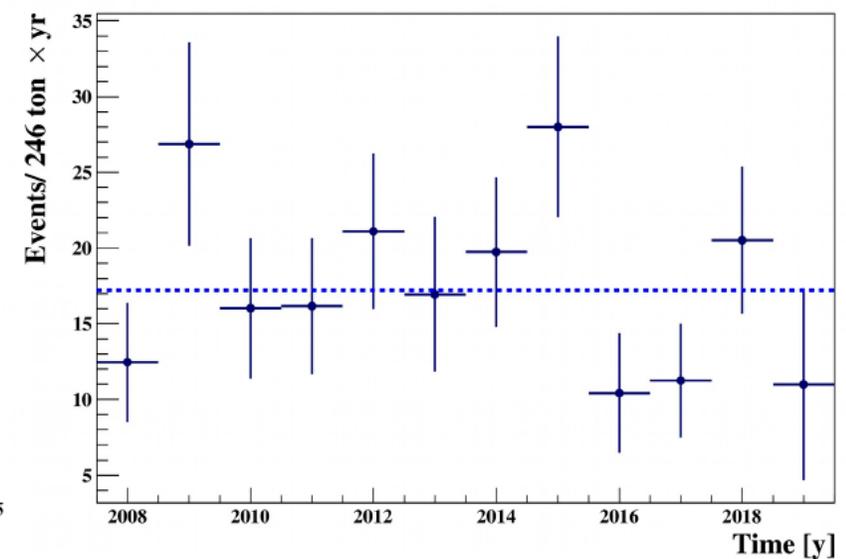
Radius of prompt



Distance to vessel of prompt



Yearly distribution

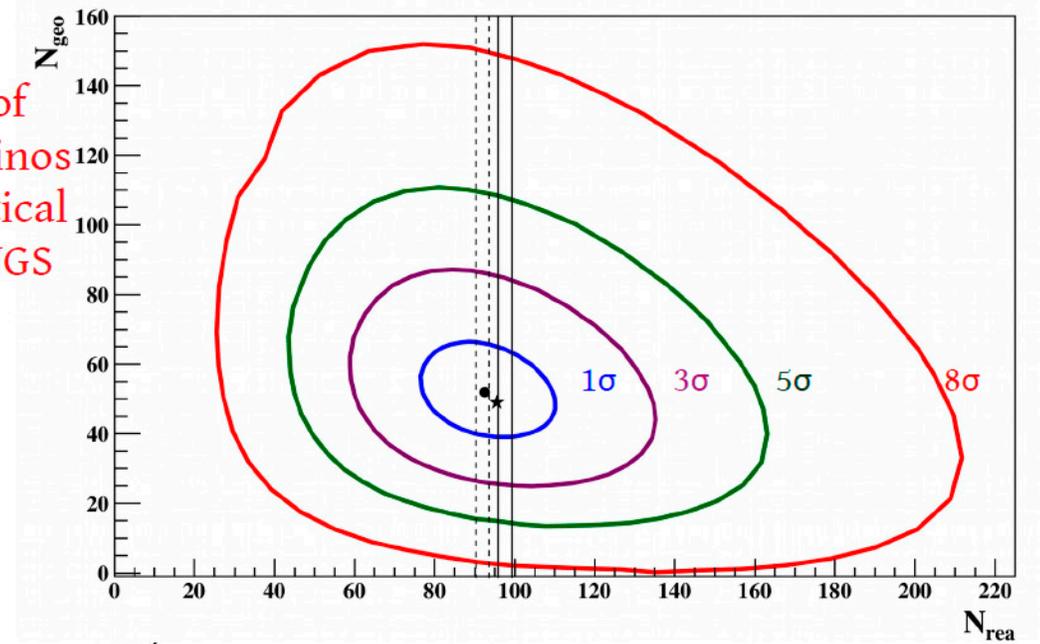


SPECTRAL FIT:

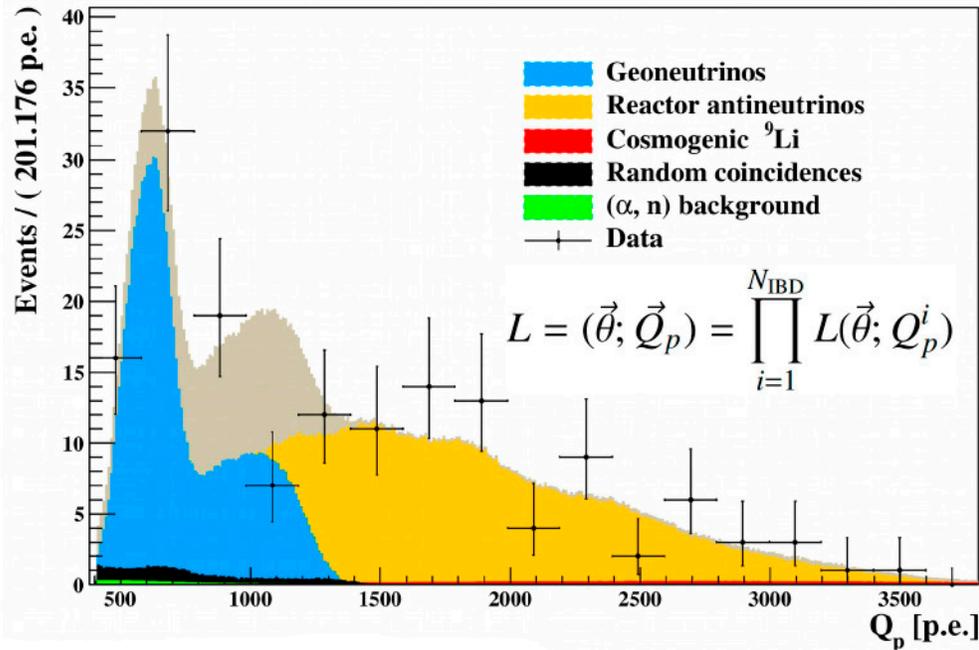
TH/U MASS RATIO FIXED TO 3.9

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

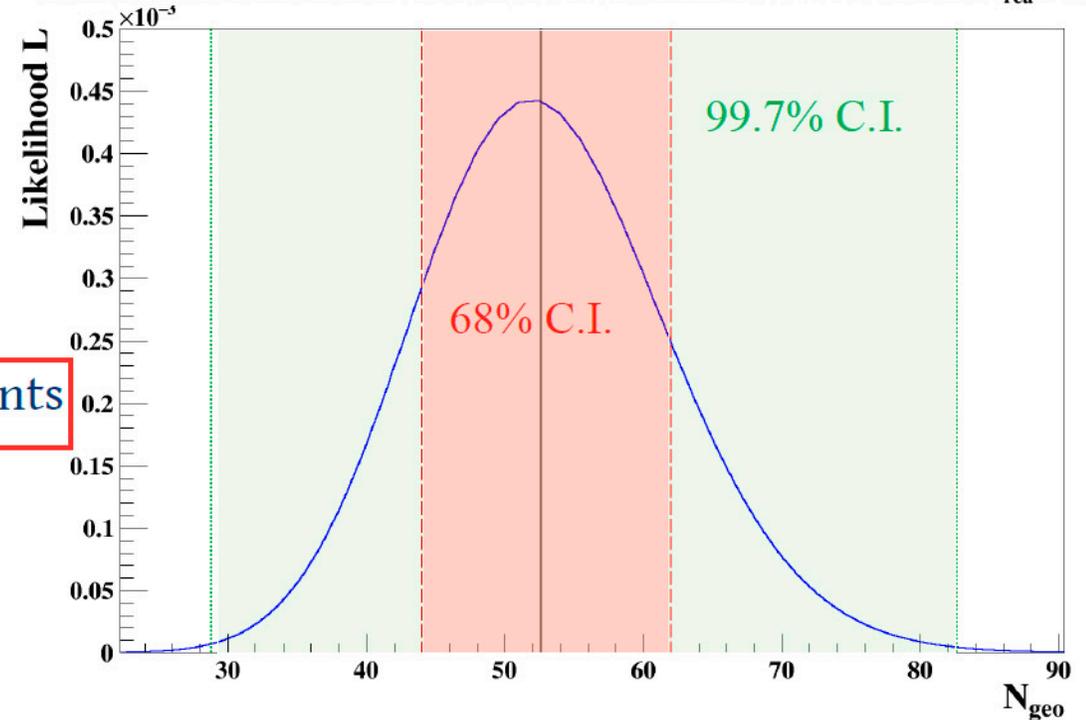
Best fit results of reactor antineutrinos within 1σ theoretical expectation at LNGS



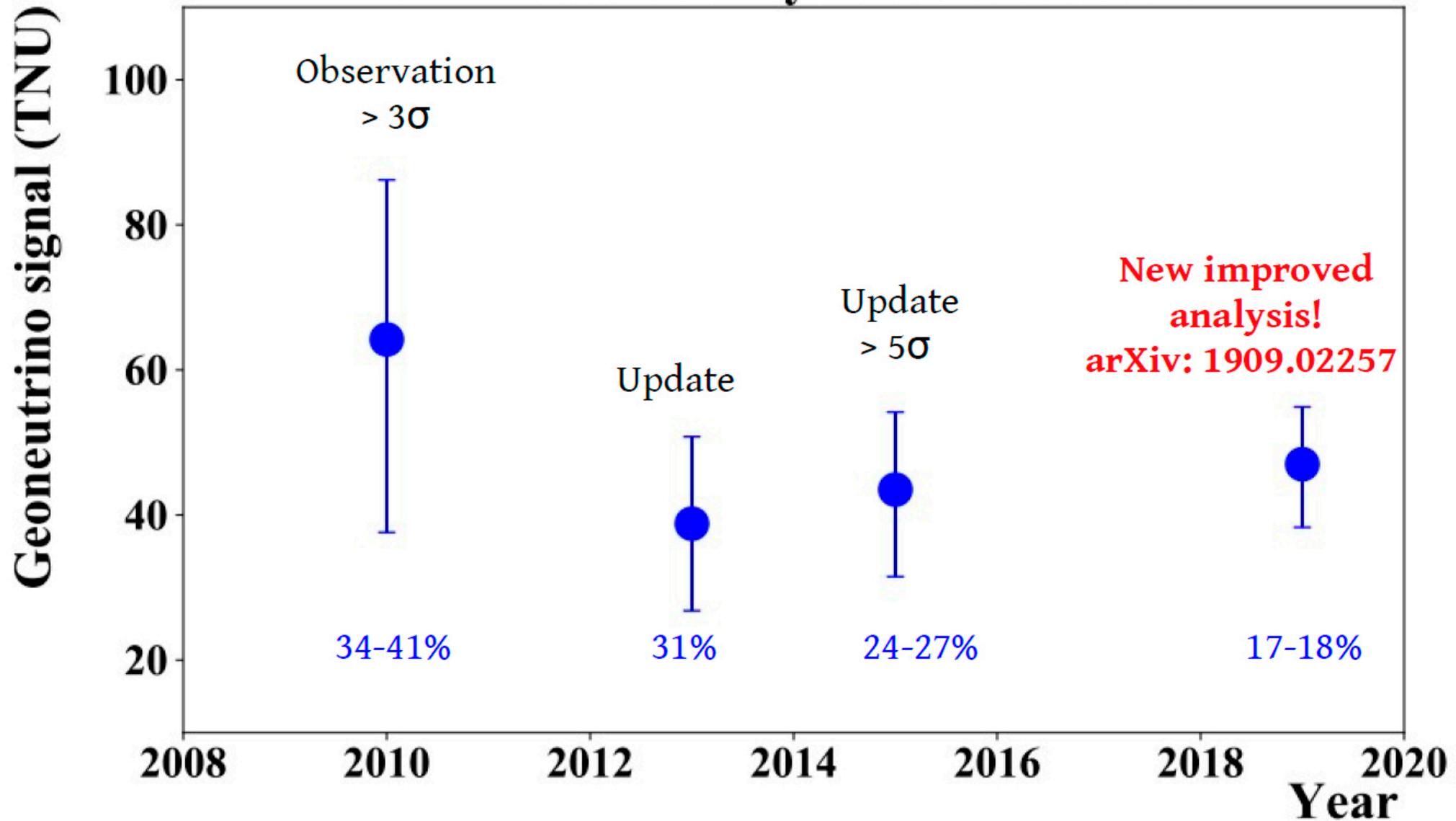
Maximal Unbinned likelihood Fit



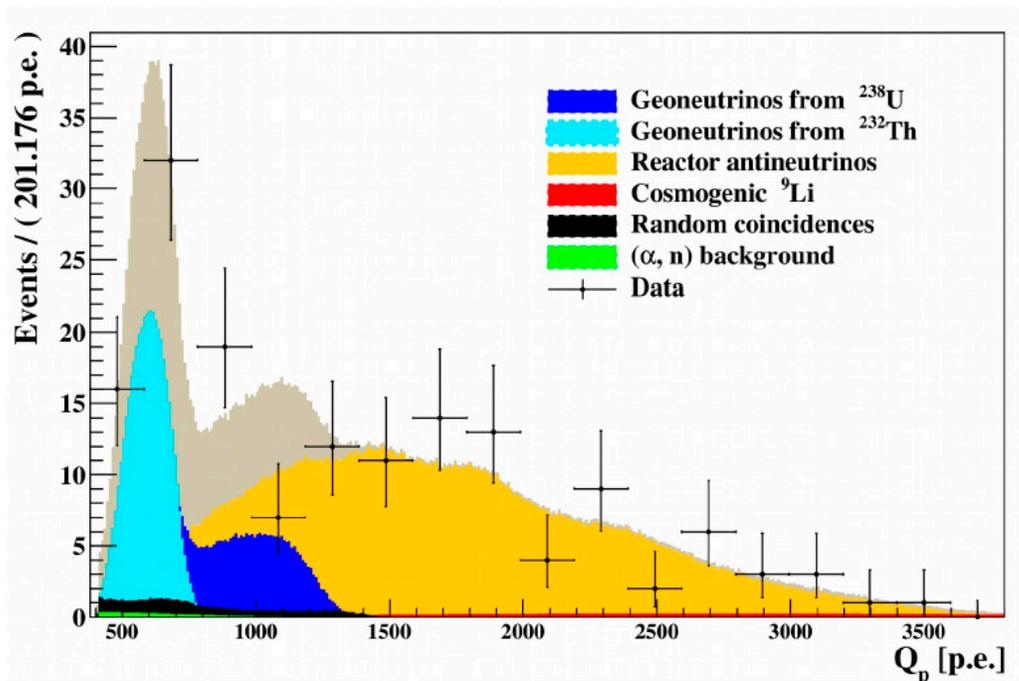
$$N_{\text{geo}} = 52.6^{+9.4}_{-8.6} \text{ events}$$



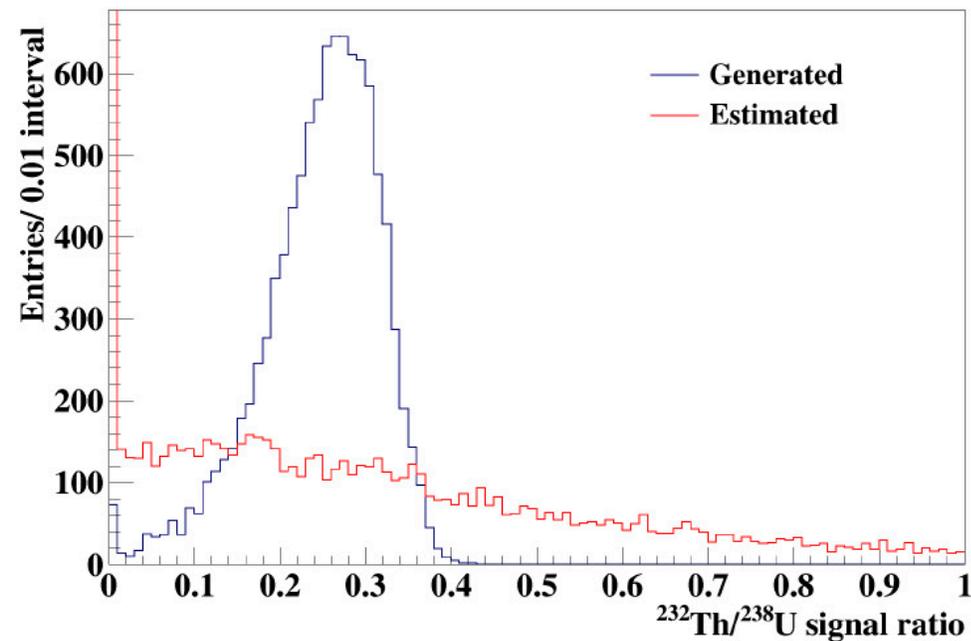
Geoneutrino analysis with Borexino



SPECTRAL FIT: TH AND U FREE



Not
 sensitive to
 Th/U ratio!
 Toy MC
 approach

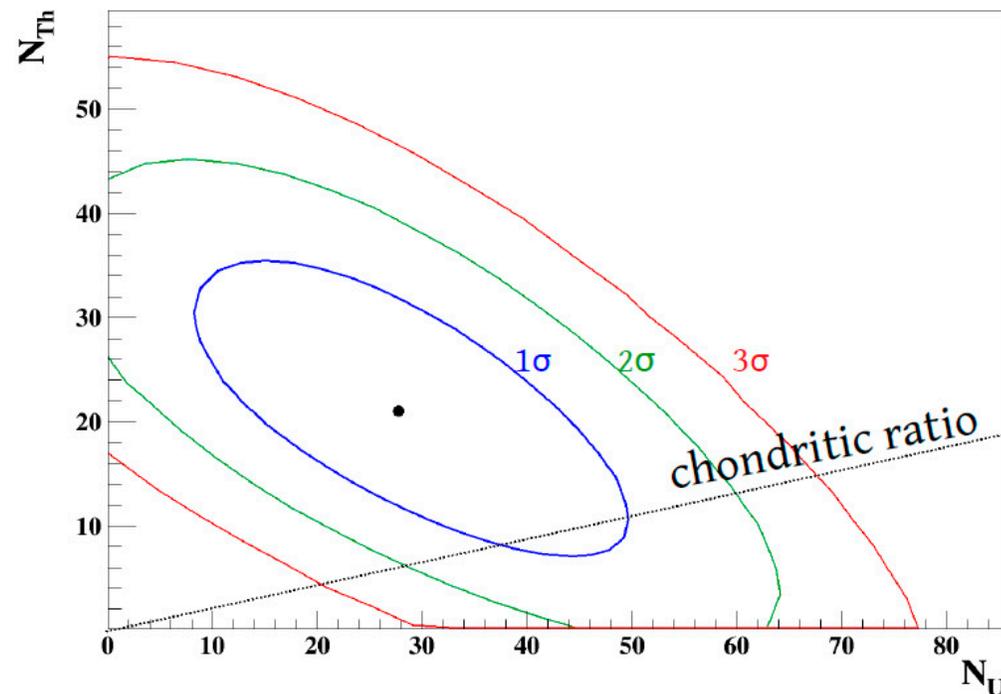


$$N_U = 29.0^{+14.2}_{-13.0} \text{ events}$$

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

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

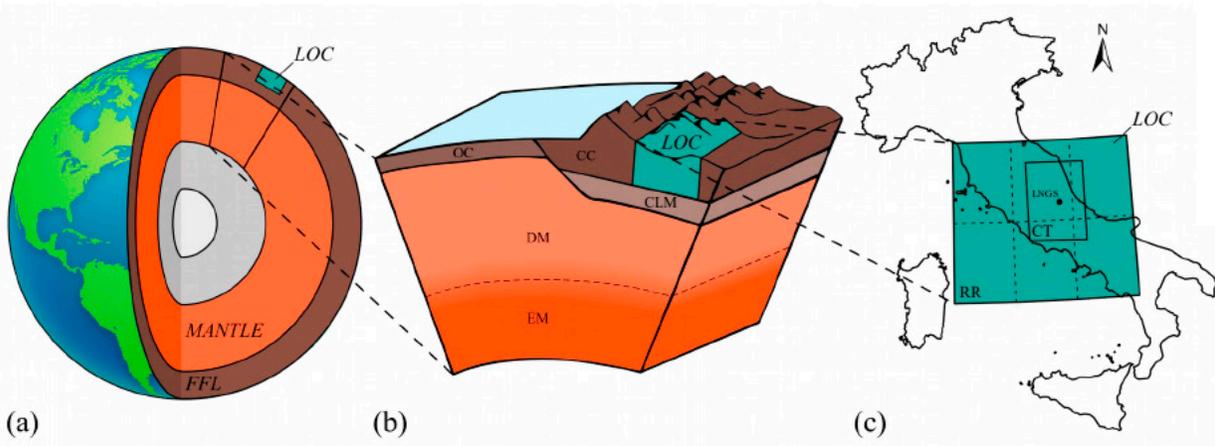
High uncertainty
 but in agreement
 with results of
 Th/U fixed



SYSTEMATIC UNCERTAINTIES

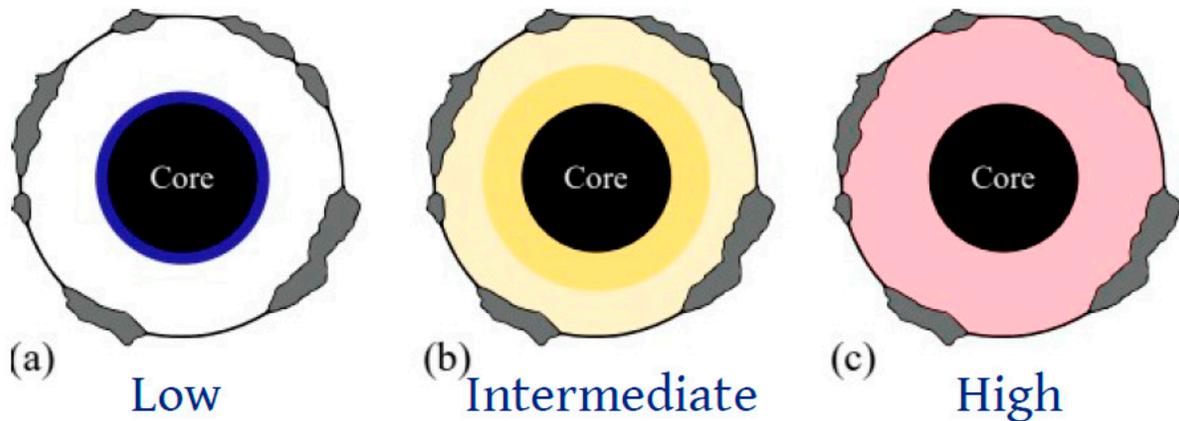
Source	Geo error (%)	Rea error (%)
Atmospheric neutrinos	+0.00 -0.38	+0.00 -3.90
Shape of reactor spectrum	+0.00 -0.57	+0.04 -0.00
Vessel shape	+3.46 -0.00	+3.25 -0.00
Efficiency	1.5	1.5
Position reconstruction	3.6	3.6
TOTAL	+5.2 -4.0	+5.1 -5.5

GEOLOGICAL INPUTS



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

Mantle Scenarios



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

Mantle $R_s = S(\text{Th})/S(\text{U}) = 0.26$

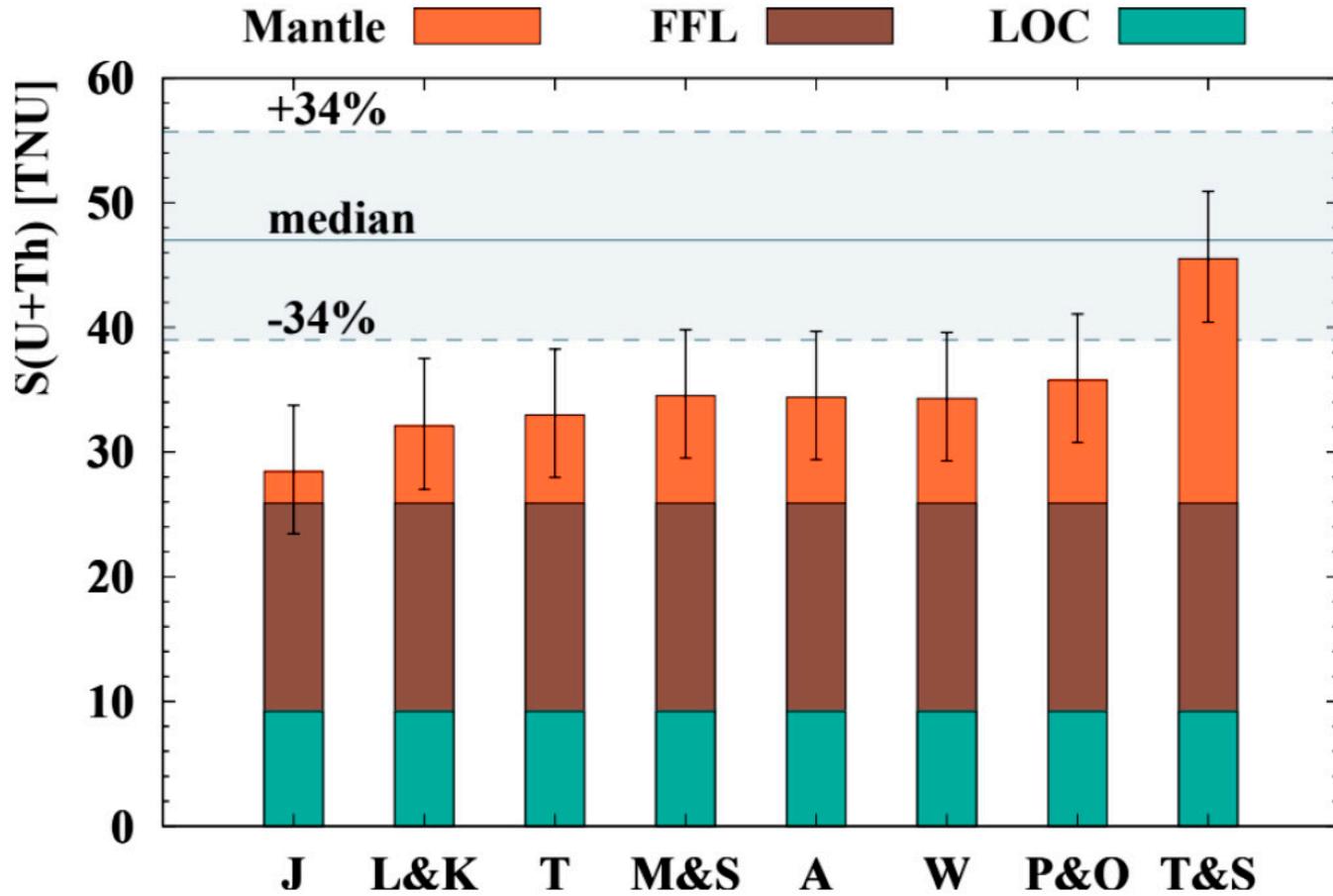
BSE models	$S_{\text{mantle}}(\text{U+Th})$ [TNU]
Cosmochemical (CC)	0.9-4.1
Geochemical (GC)	6.0-10.6
Geodynamical (GD)	15.7-22.4
Full Radiogenic (FR)	24.2-33.0

^{40}K contribution = 18%

Total expected signal at Borexino
 $S(\text{U+Th+K}) = 28.5-45.5$ TNU

GEONEUTRINO SIGNAL AT LNGS

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



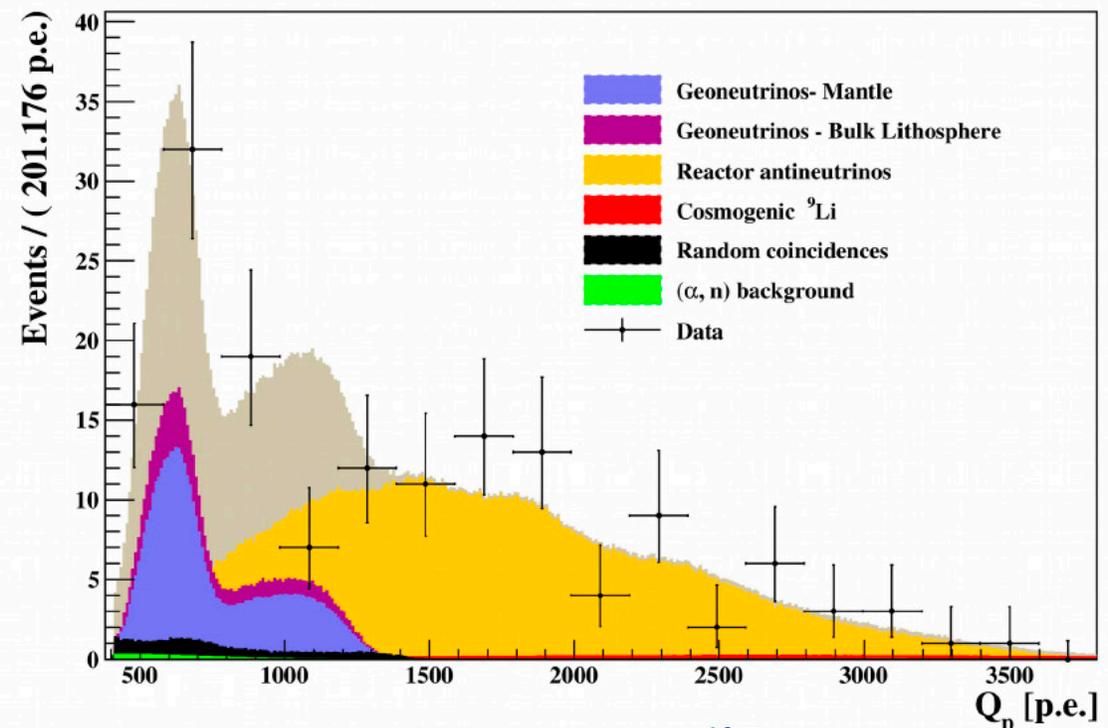
Compatible with all models. Preference for models with higher mantle signal

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

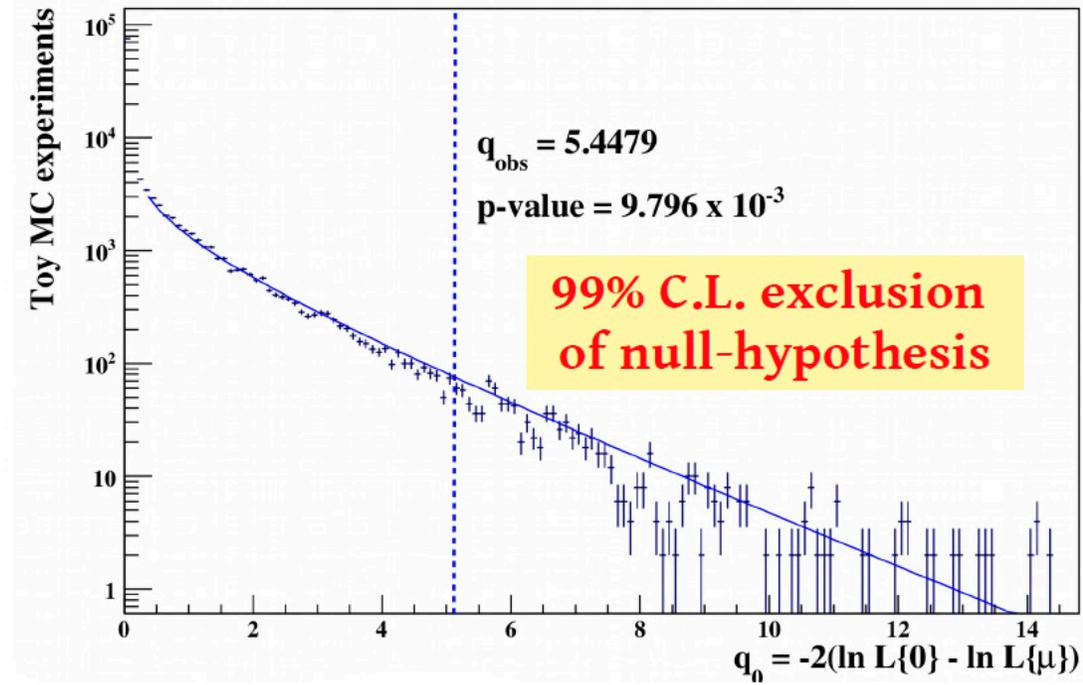
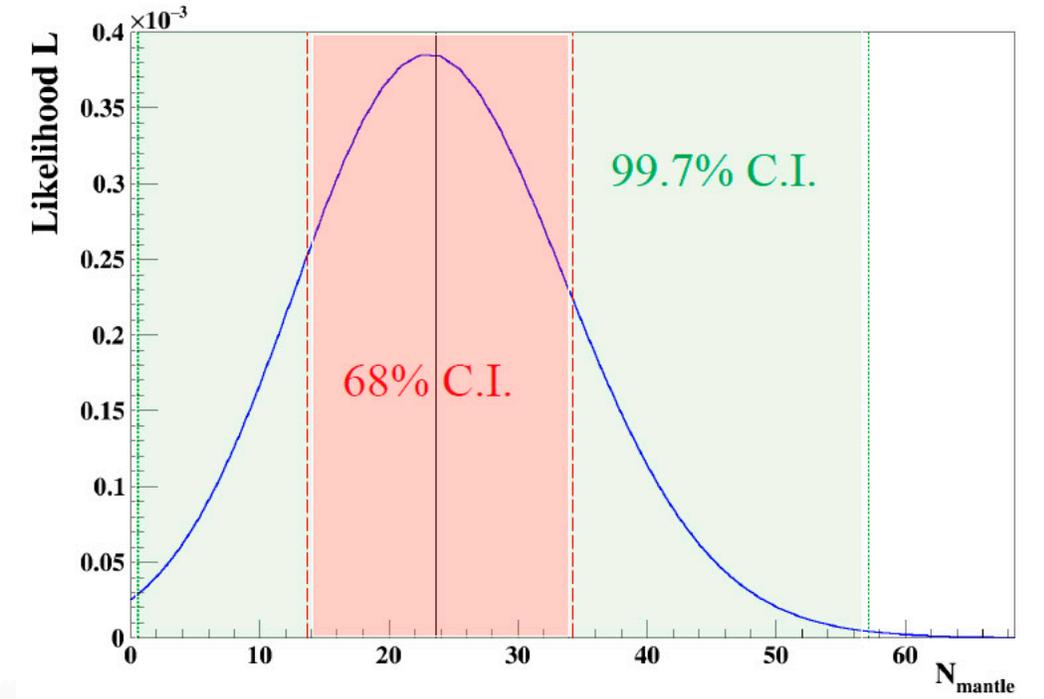
- J: Javoy et al., 2010
- L&K: Lyubetskaya and Korenaga, 2007
- T: Taylor, 1980
- A: Anderson, 2007
- M&S: Mc Donough and Sun, 1995
- W: Wang, 2018
- P&O: Palme and O'Neil, 2003
- T&S: Turcotte and Schubert, 2002

MANTLE SIGNAL

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



$N_{\text{mantle}} = 23.7^{+10.7}_{-10.1}$ events
 $21.2^{+9.6}_{-9.0} \text{ (stat)}^{+1.1}_{-0.9} \text{ (sys) TNU}$



RADIOGENIC HEAT

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

Slope of the lines (TNU/TW)

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

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

$$S_{\text{mantle}}^{\text{LS}}(U + \text{Th}) = 0.75 \cdot H_{\text{rad}}^{\text{mantle}}(U + \text{Th})$$

$$S_{\text{mantle}}^{\text{HS}}(U + \text{Th}) = 0.98 \cdot H_{\text{rad}}^{\text{mantle}}(U + \text{Th})$$

$\beta = 2/(0.75+0.98)$ Inverse of slope

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

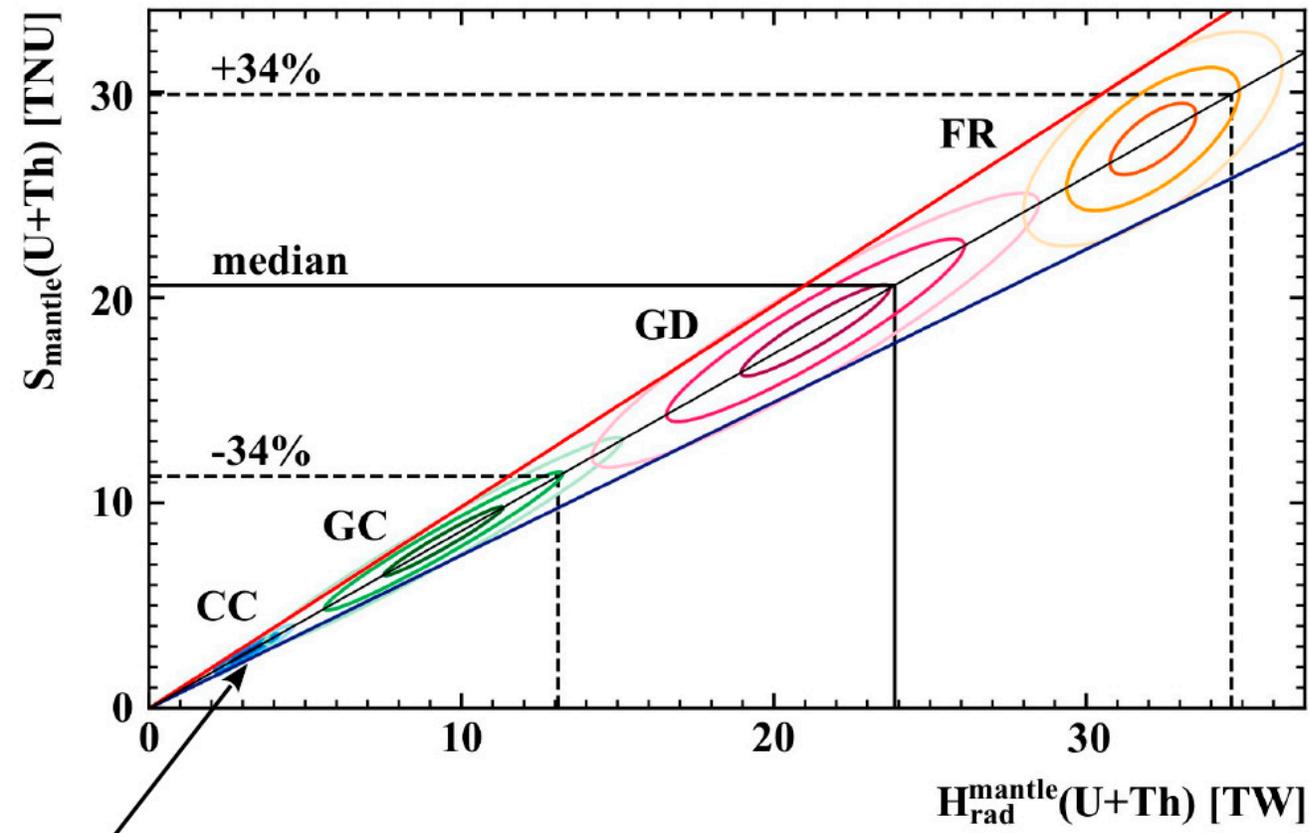
$$(18\% \text{ K}) \quad H_{\text{rad}}^{\text{mantle}}(U + \text{Th} + \text{K}) = 30.0^{+13.5}_{-12.7} \text{ TW}$$

+

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

=

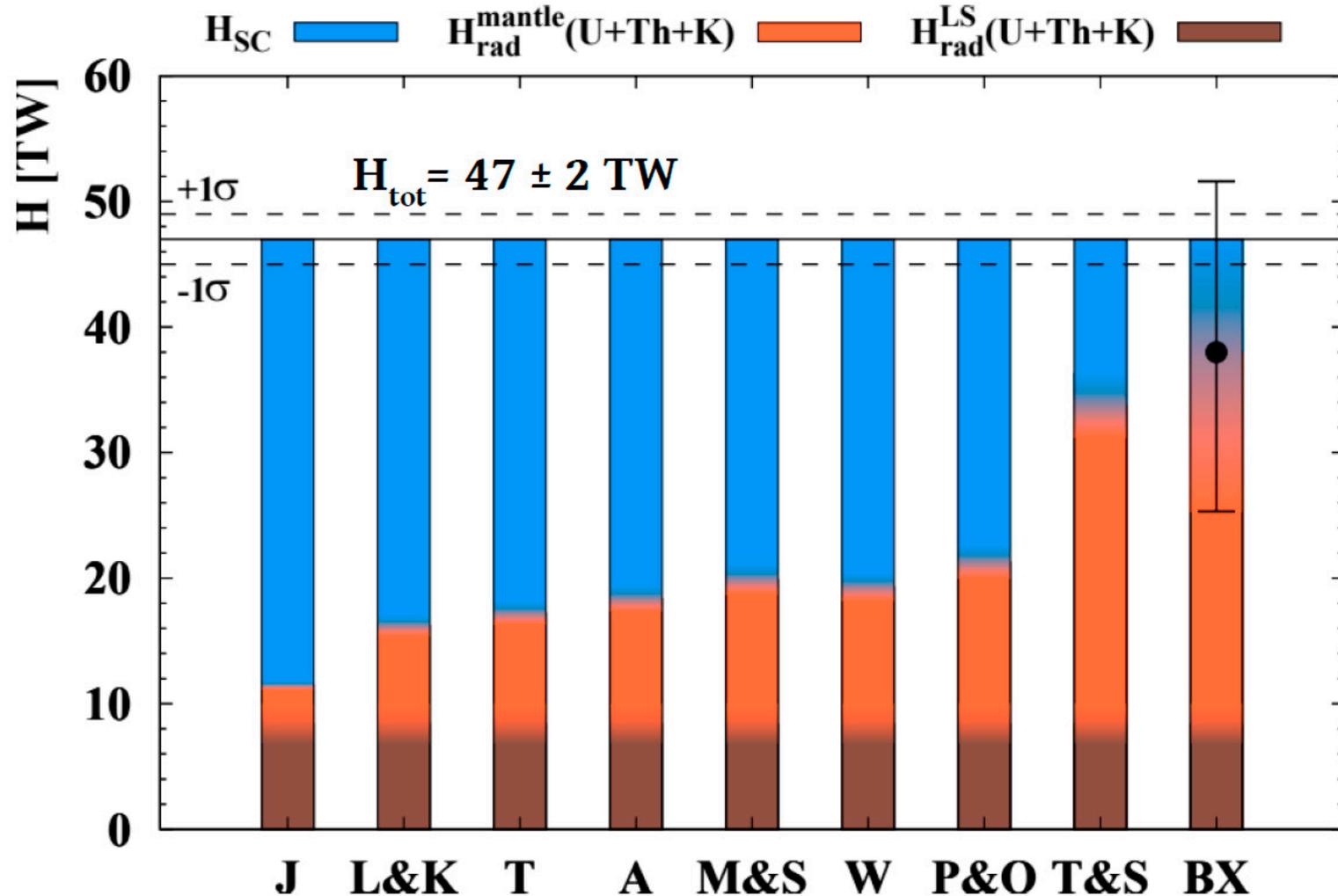
$$H_{\text{rad}}(U + \text{Th} + \text{K}) = 38.2^{+13.6}_{-12.7} \text{ TW}$$



2.40 tension

RADIOGENIC HEAT: COMPARISON

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



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

CONVECTIVE UREY RATIO

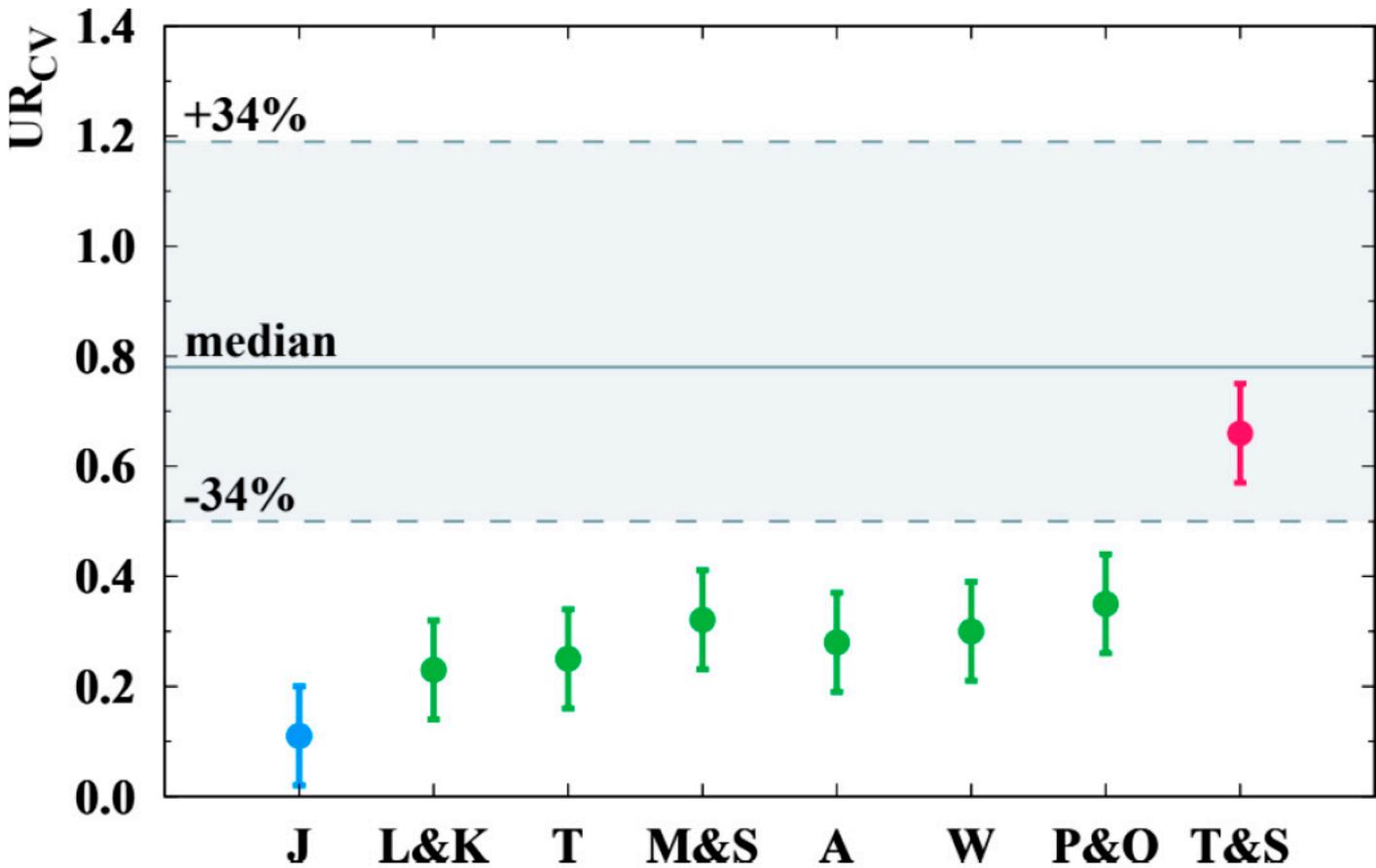
$$H_{\text{tot}} = 47 \pm 2 \text{ TW}$$

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

$$H_{\text{rad}}^{\text{CC}} = 6.8^{+1.4}_{-1.1} \text{ TW}$$

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

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



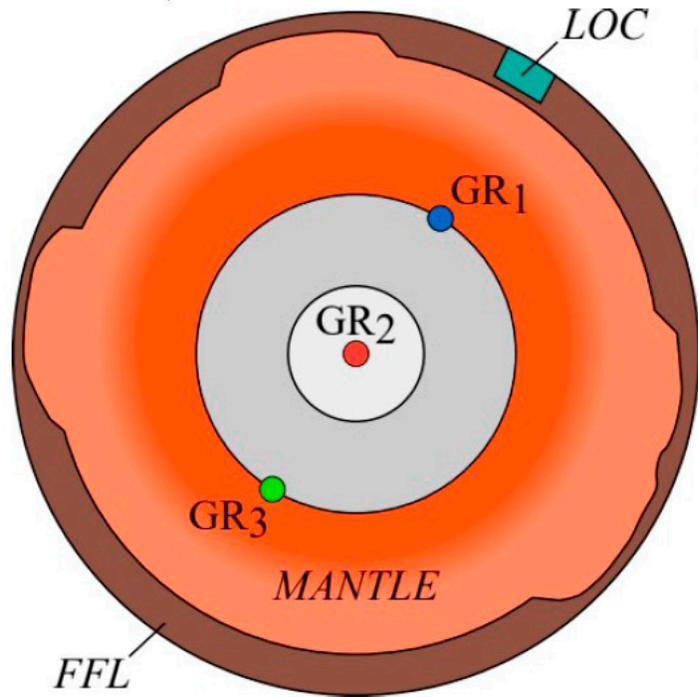
Lower limits:

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

GEOREACTOR

Georeactor fuel \rightarrow $^{235}\text{U}:\text{}^{238}\text{U} = 0.76:0.23$

(Herndon 2005)



CMB: V. Rusov et al., 2007

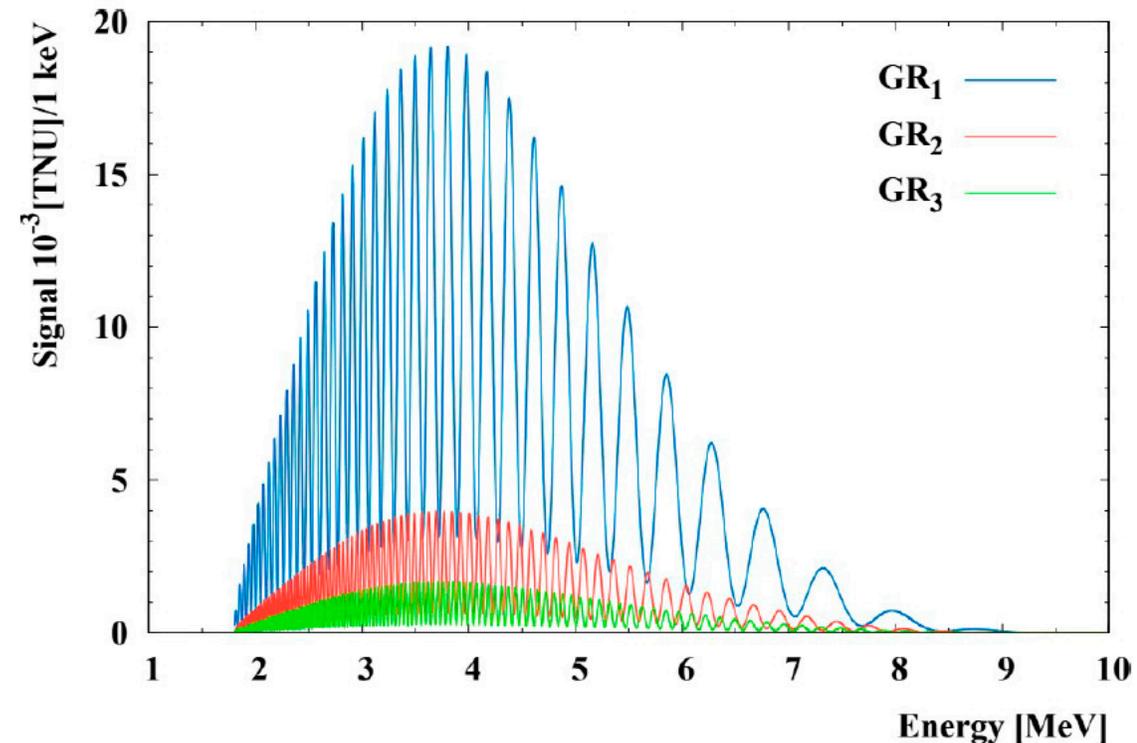
Inner core boundary:

R. d. de Meijer and W. Van Westrenen, 2008

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

1 TW georeactor

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



GEOREACTOR: RESULTS

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

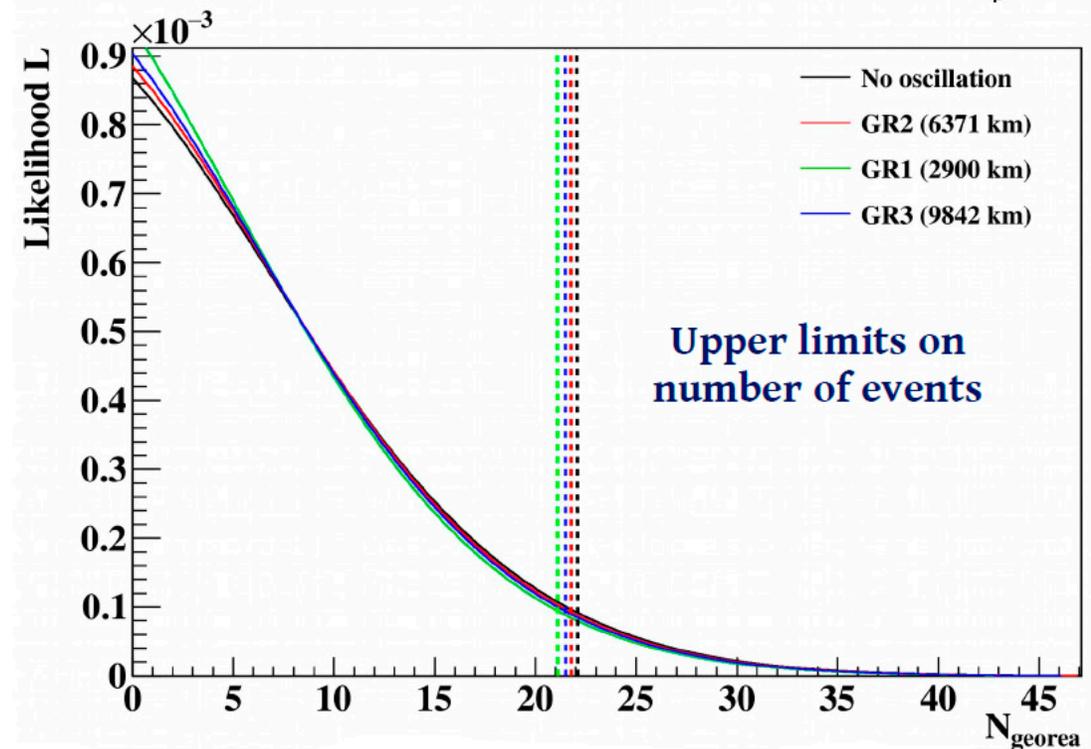
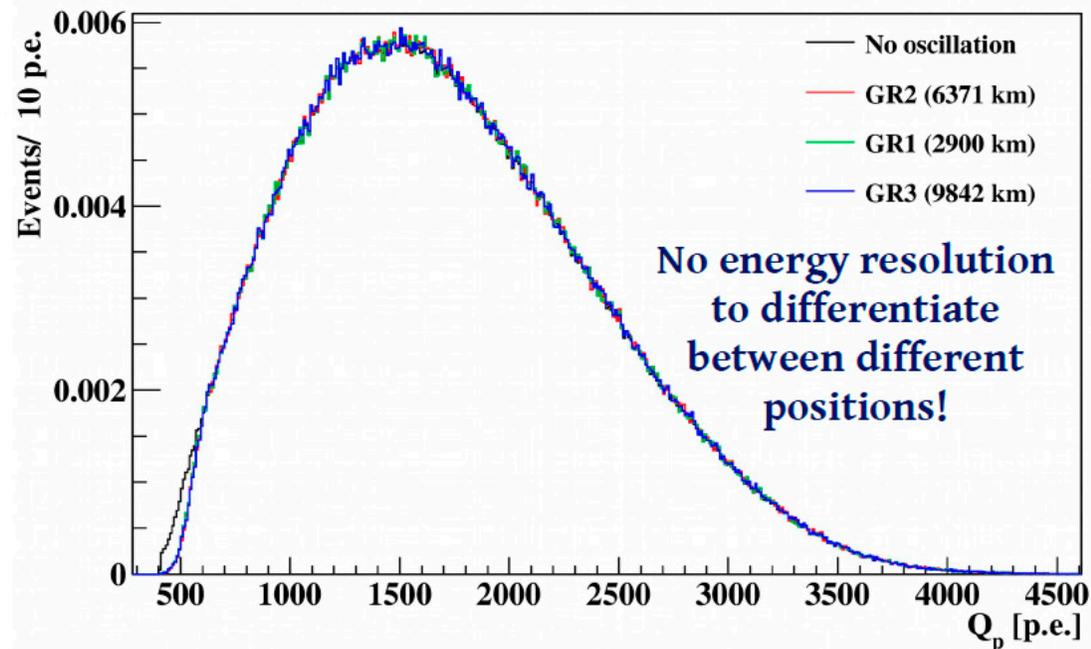
Upper limits at 95% C.L.

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

< 0.5 TW – CMB ($d = 2900$ km) - GR1

< 2.4 TW – Core ($d = R_{\text{Earth}}$) - GR2

< 5.7 TW – CMB ($d = 9842$ km) - GR3



MAIN BOREXINO RESULTS

1) A total **uncertainty of ~18%** achieved in the geoneutrino signal using Borexino's data with improved analysis

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

2) Mantle signal extracted by using well-known knowledge of LOC
New statistical tools exploited to **reject the null-hypothesis of mantle signal at 99% C.L.**

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

3) Radiogenic heat calculated using the obtained mantle signal and assuming 18% contribution from ^{40}K in the mantle. **2.4 σ tension with models predicting the lowest amount of mantle signal**

$$38.2_{-12.7}^{+13.6} \text{ TW}$$

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

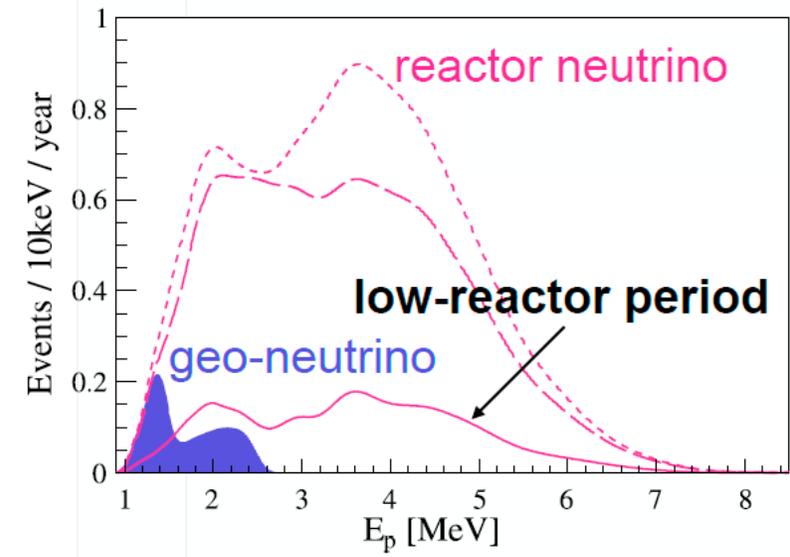
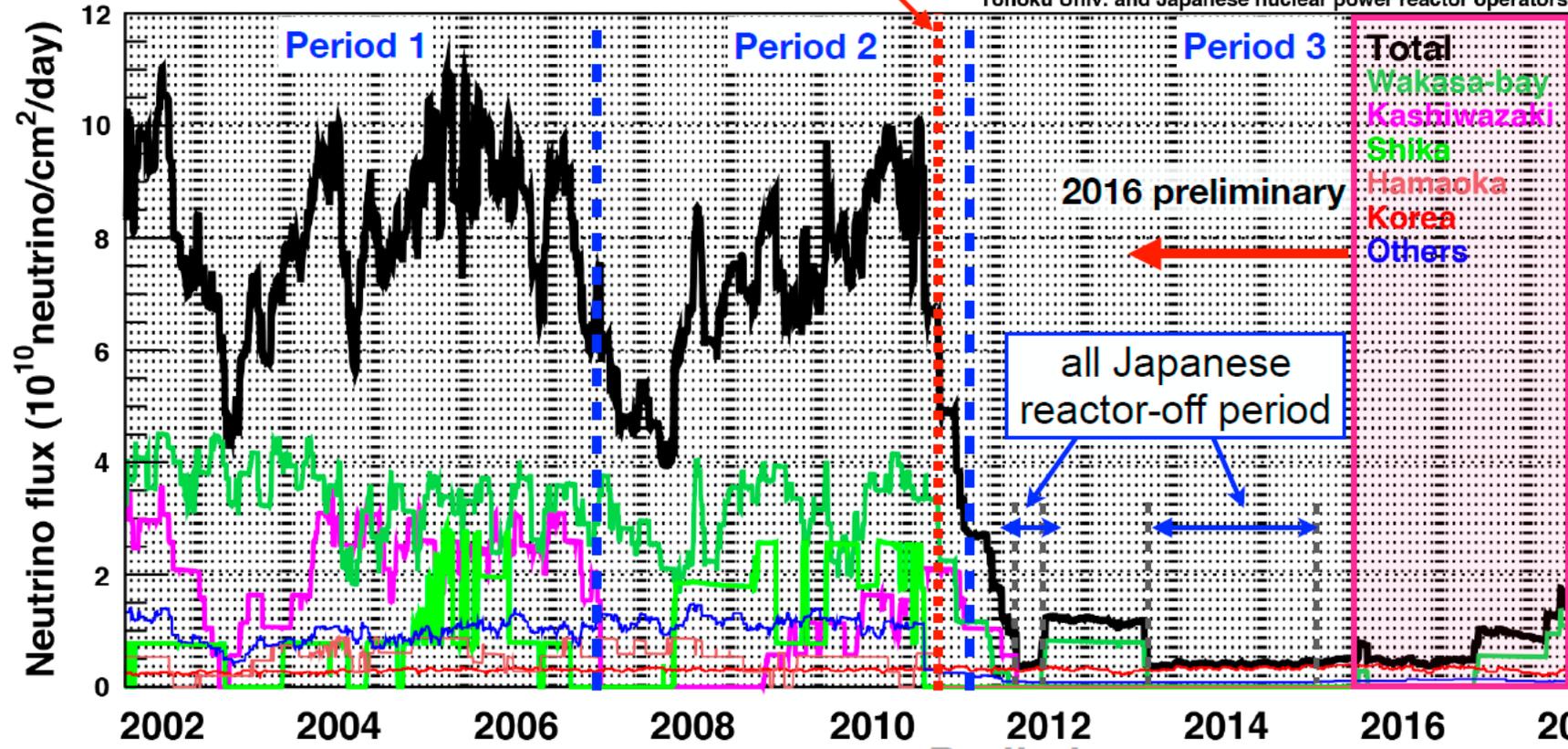
5) Stringent georeactor upper limits at 95% C.L. for three different positions in the Earth
< 0.5 TW (2900 km) < 2.4 TW (center) < 5.7 TW (9842 km)

KAMLAND

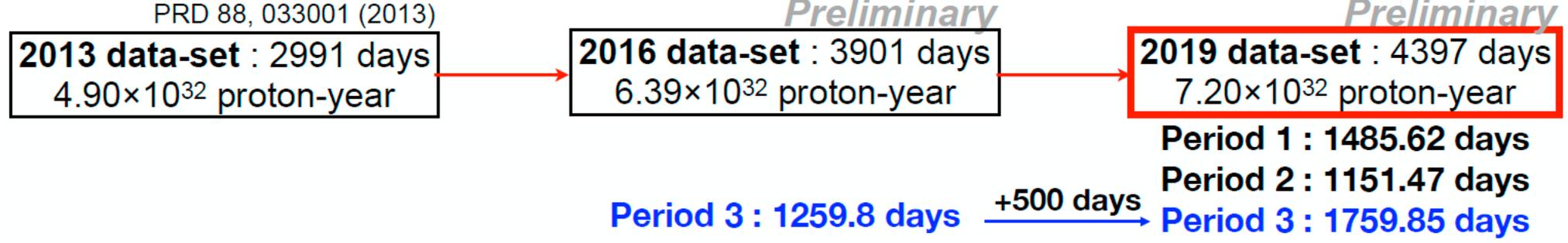
KAMLAND: ОСОБЕННОСТИ НАБОРОВ ДАННЫХ

Reactor Neutrino Flux @Kamioka March 2011 Earthquake ~Apr. 15, 2018

Data provided according to the special agreements between Tohoku Univ. and Japanese nuclear power reactor operators.

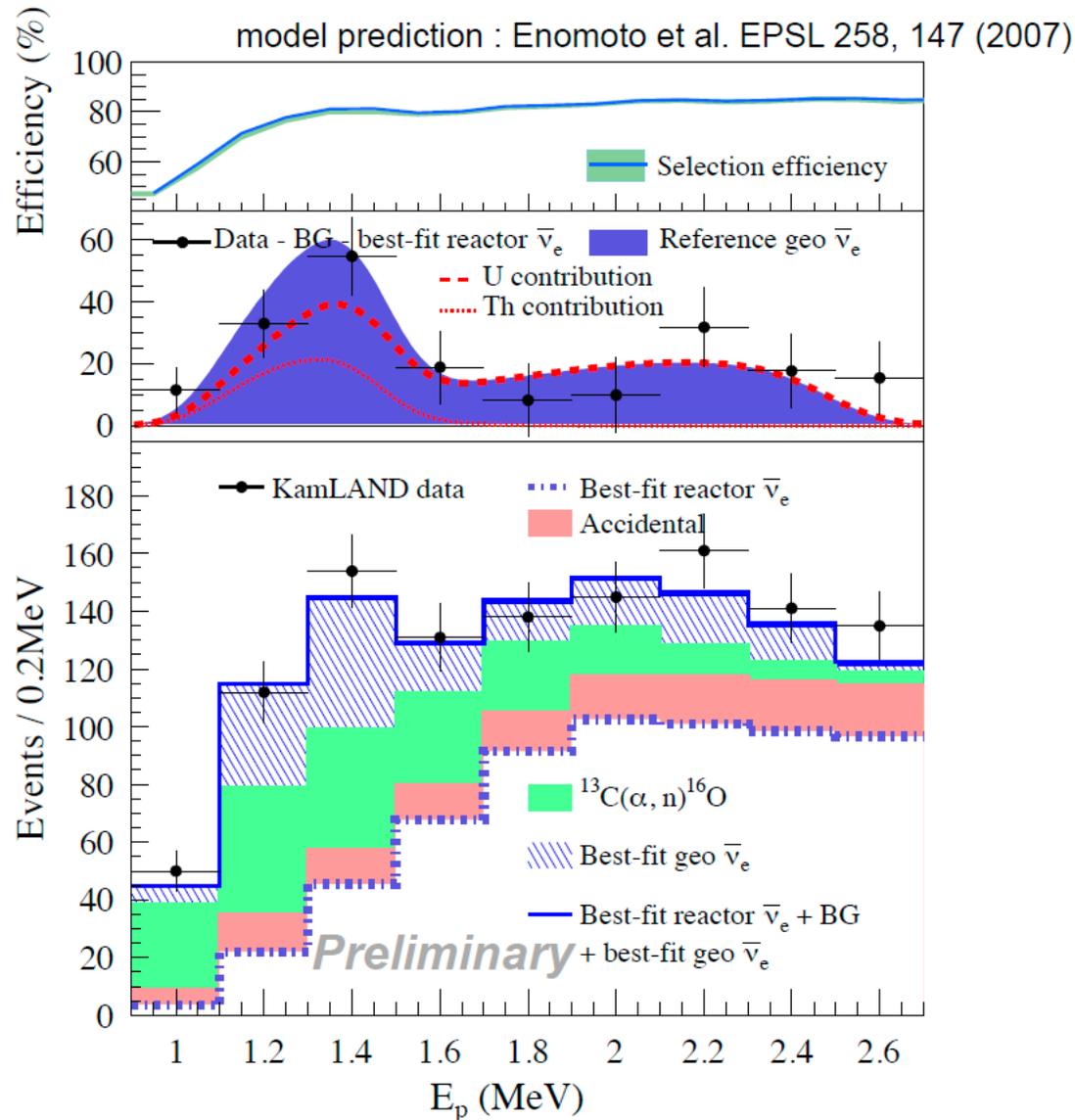


+500 days of low-reactor phase from 2016 data-set



СПЕКТР ОТОБРАННЫХ СОБЫТИЙ ДЛЯ ПОЛНОГО НАБОРА ДАННЫХ

2019 Preliminary Result



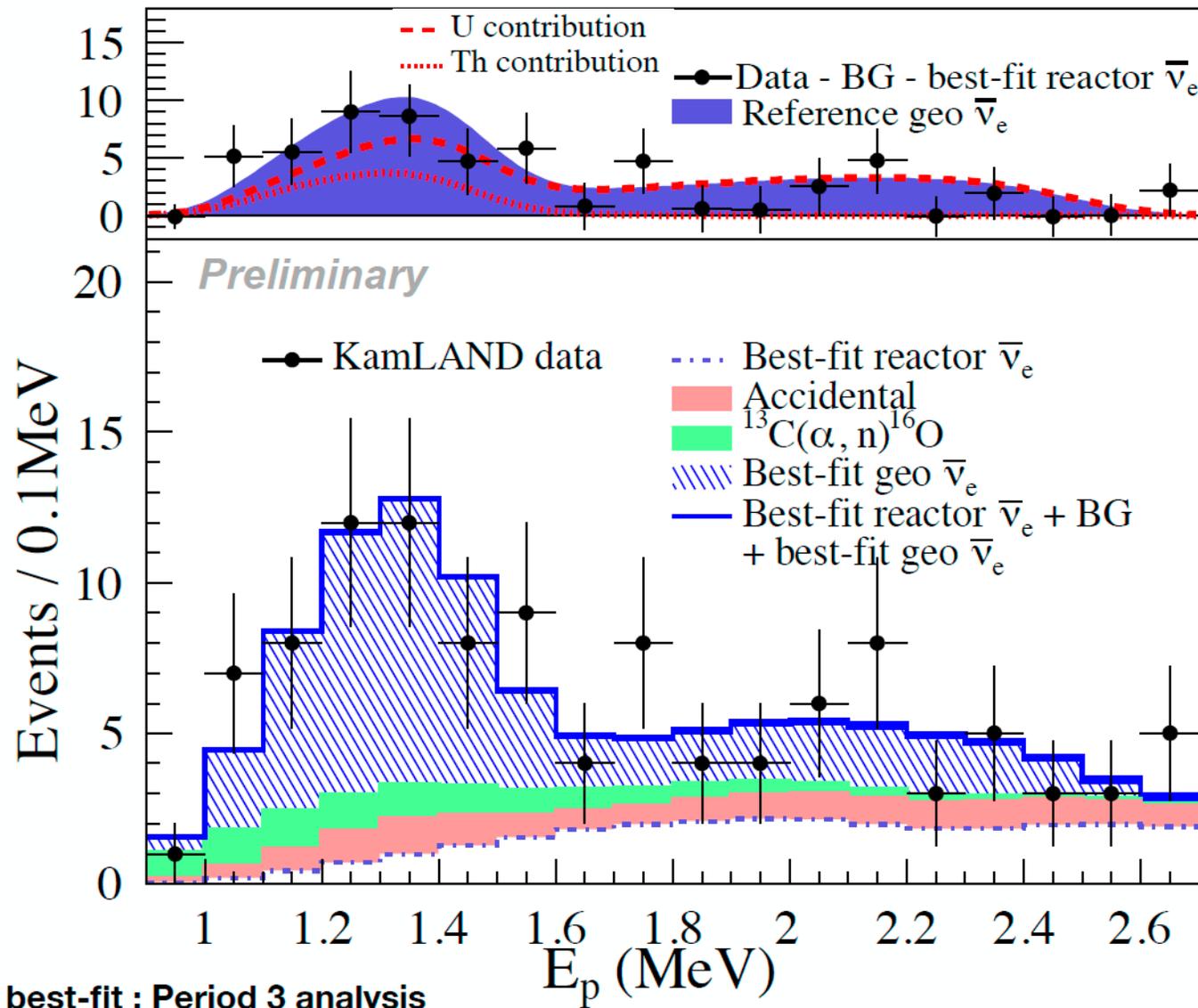
Livetime : 4397 days

Candidate : 1167 ev

Background Summary

^9Li	4.4 ± 0.1
Accidental	121.9 ± 0.1
Fast neutron	< 4.1
$^{13}\text{C}(\alpha, n)^{16}\text{O}$	211.6 ± 23.3
Reactor $\bar{\nu}_e$	629.0 ± 34.4
Total	966.9 ± 41.8

СПЕКТР ОТОБРАННЫХ СОБЫТИЙ ДЛЯ ПЕРИОДА 3 (МИНИМАЛЬНОЕ ЧИСЛО РАБОТАЮЩИХ АЭС)



best-fit : Period 3 analysis

Livetime : 1760 days

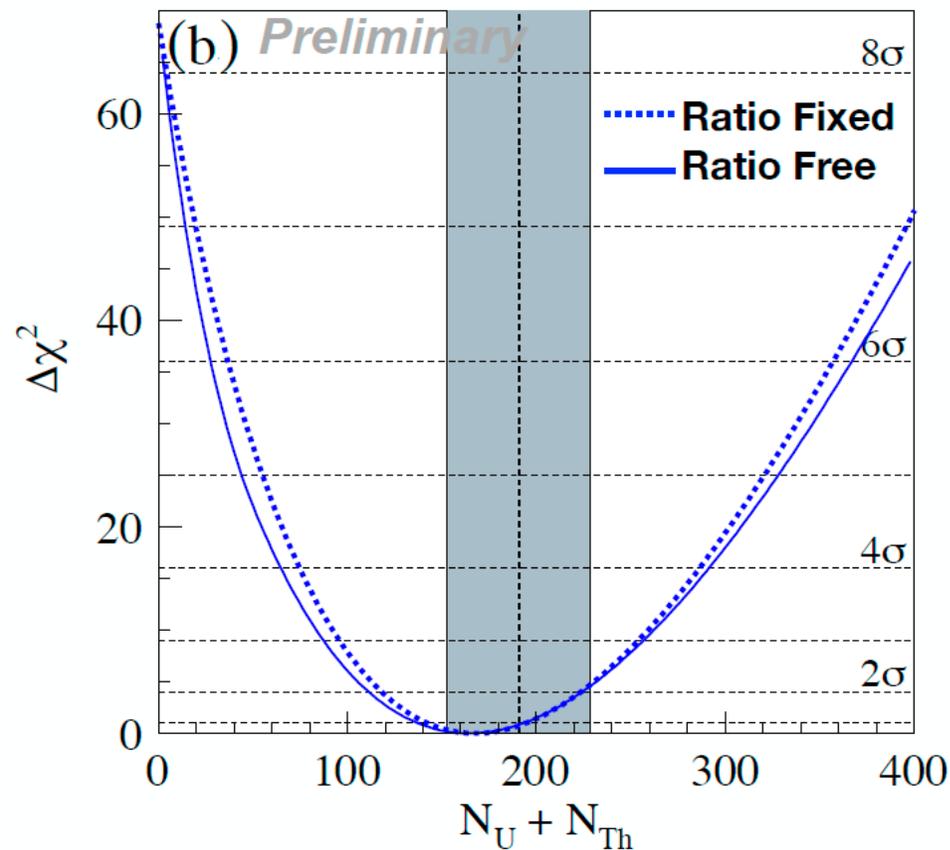
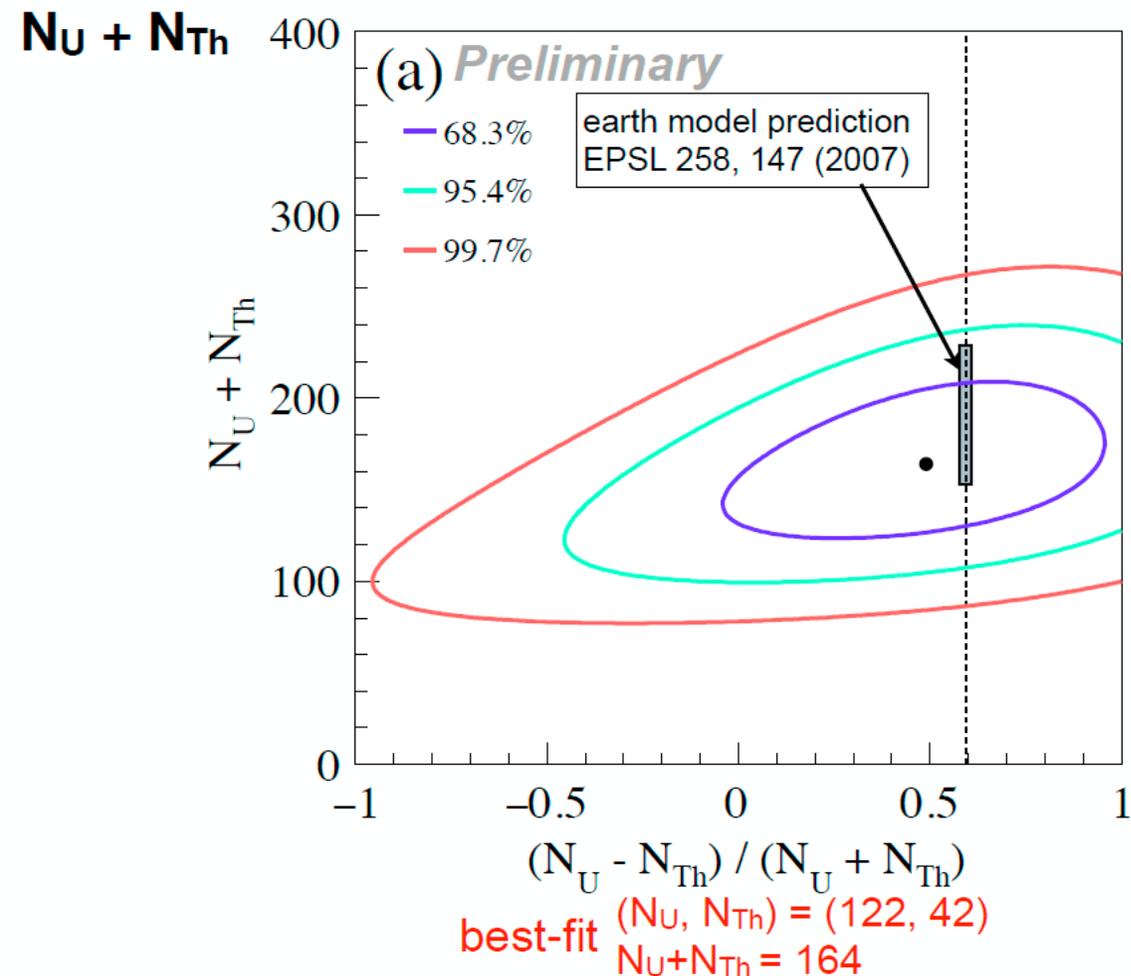
Candidate : 110 ev

Geo-neutrino / Background
= 66.3 ev / 50.3 ev ~1.3

We clearly measured geo-neutrino spectrum.

→ better understanding of U, Th each contribution

ПОТОК ГЕО-НЕЙТРИНО

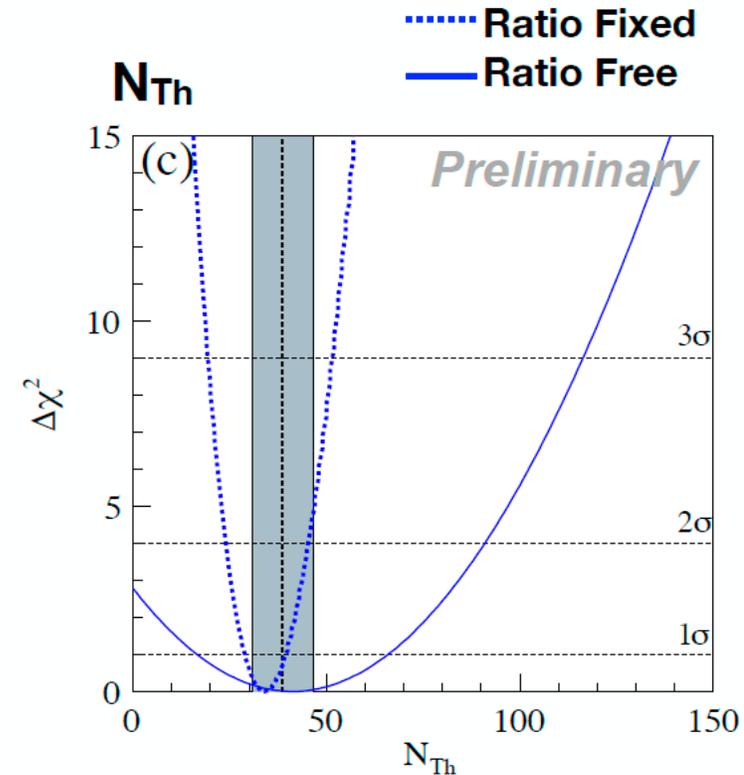
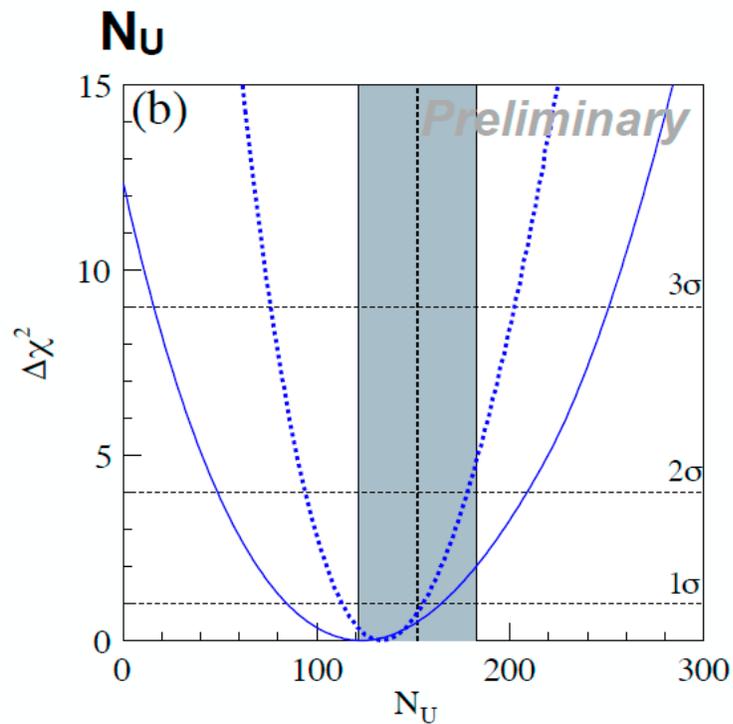
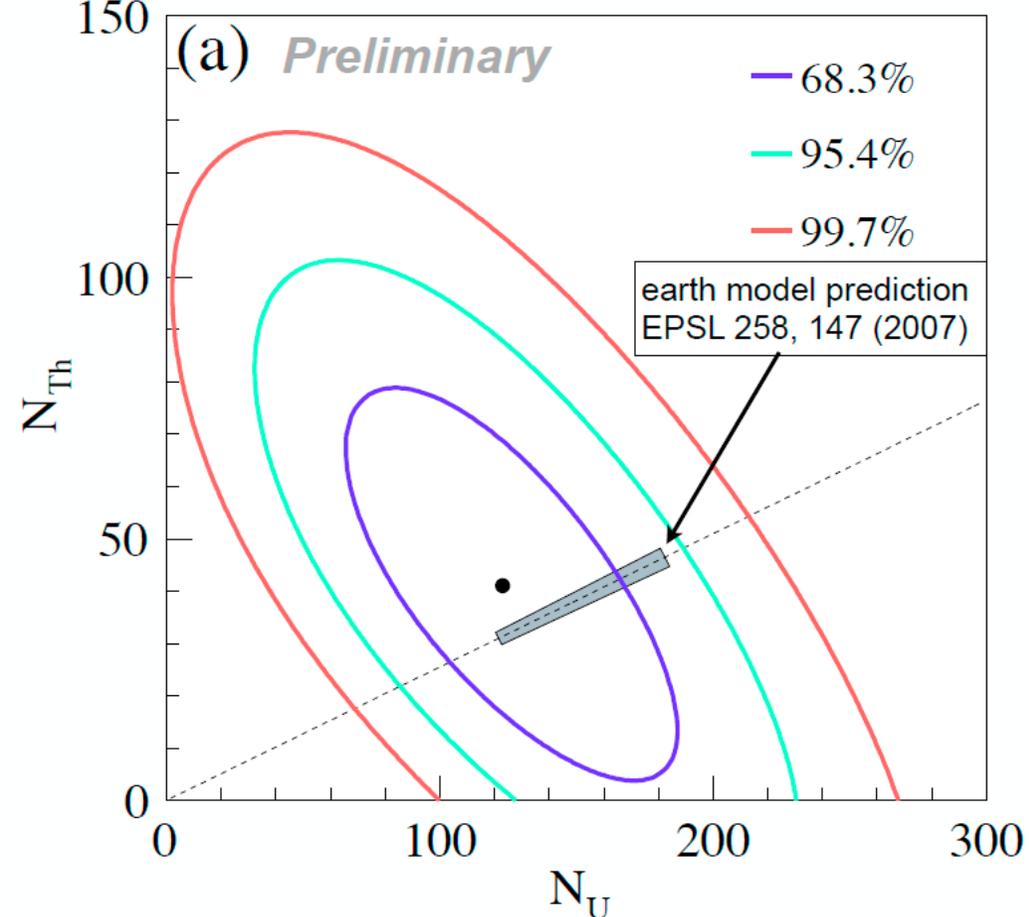


ratio fixed

	[event]	[TNU]	Flux [$\times 10^6 \text{ cm}^{-2}\text{s}^{-1}$]		0 signal rejection
			best-fit	model	
U+Th	168.8 +26.3/-26.5 (15.6%)	32.1 +5.0/-5.0	3.6 +0.6/-0.6	4.1	8.14 σ

ПОТОКИ ГЕО-НЕЙТРИНО ОТ U И Th

N_U vs N_{Th}

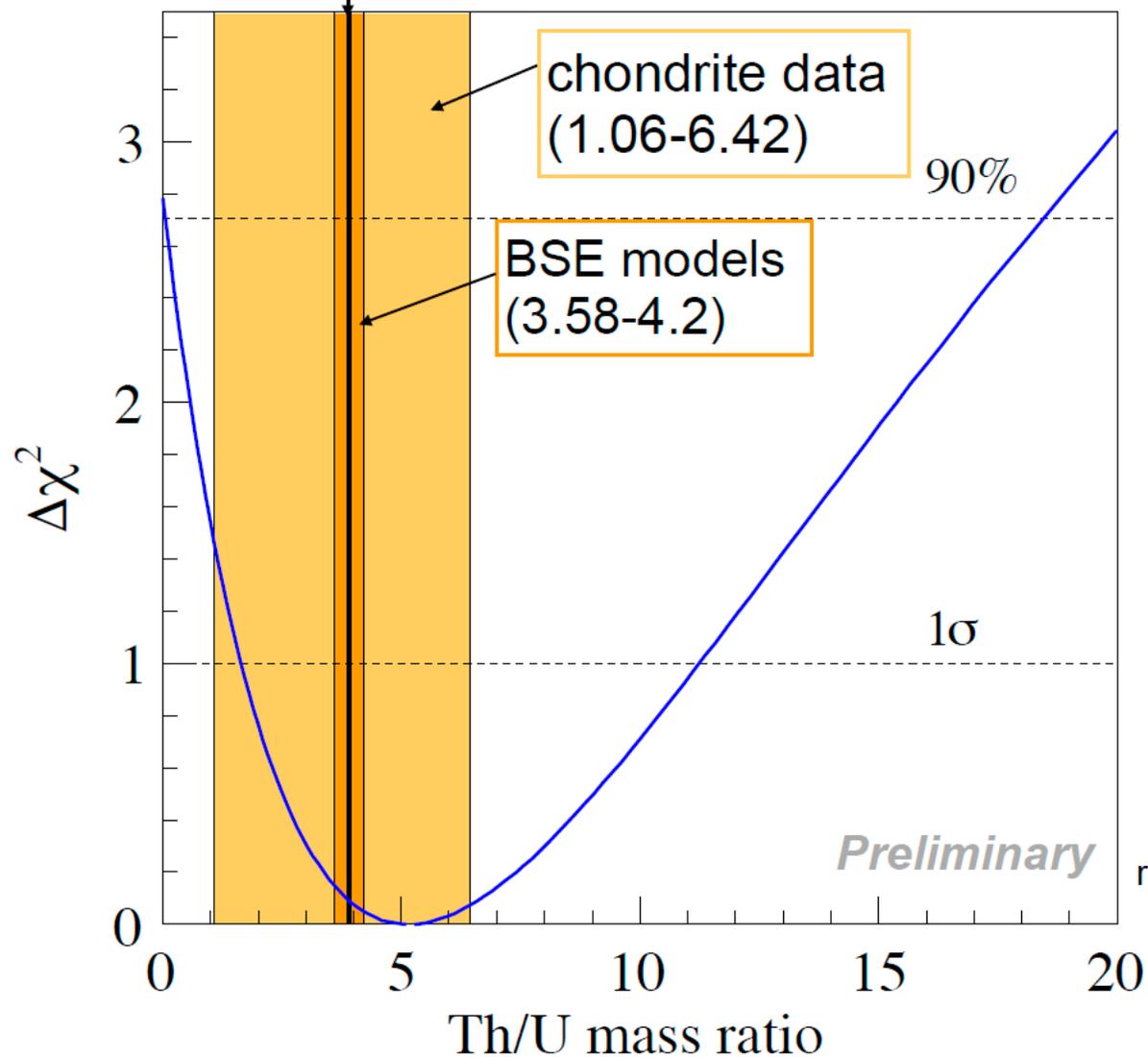


ratio free

	[event]	[TNU]	Flux [$\times 10^5 \text{ cm}^{-2}\text{s}^{-1}$]		0 signal rejection
			best-fit	model	
U	123.3 +41.2/-39.1	23.3 +7.8/-7.4	17.9 +6.0/-5.7	22.0	3.51σ
Th	41.6 +24.6/-24.7	8.1 +4.8/-4.8	20.0 +11.9/-11.9	18.6	1.68σ

МАССОВОЕ ОТНОШЕНИЕ Th и U

Th/U mass ratio = 3.9



Best fit

$$\text{Th/U} = 5.3^{+6.0}_{-3.6}$$

$$\text{Th/U} < 18.5 \text{ (90\% C.L.)}$$

ref) 2016 preliminary

$$\text{Th/U} = 4.1^{+5.5}_{-3.3}, < 17.0 \text{ (90\% C.L.)}$$

KamLAND best-fit is consistent with chondrite data and BSE models.

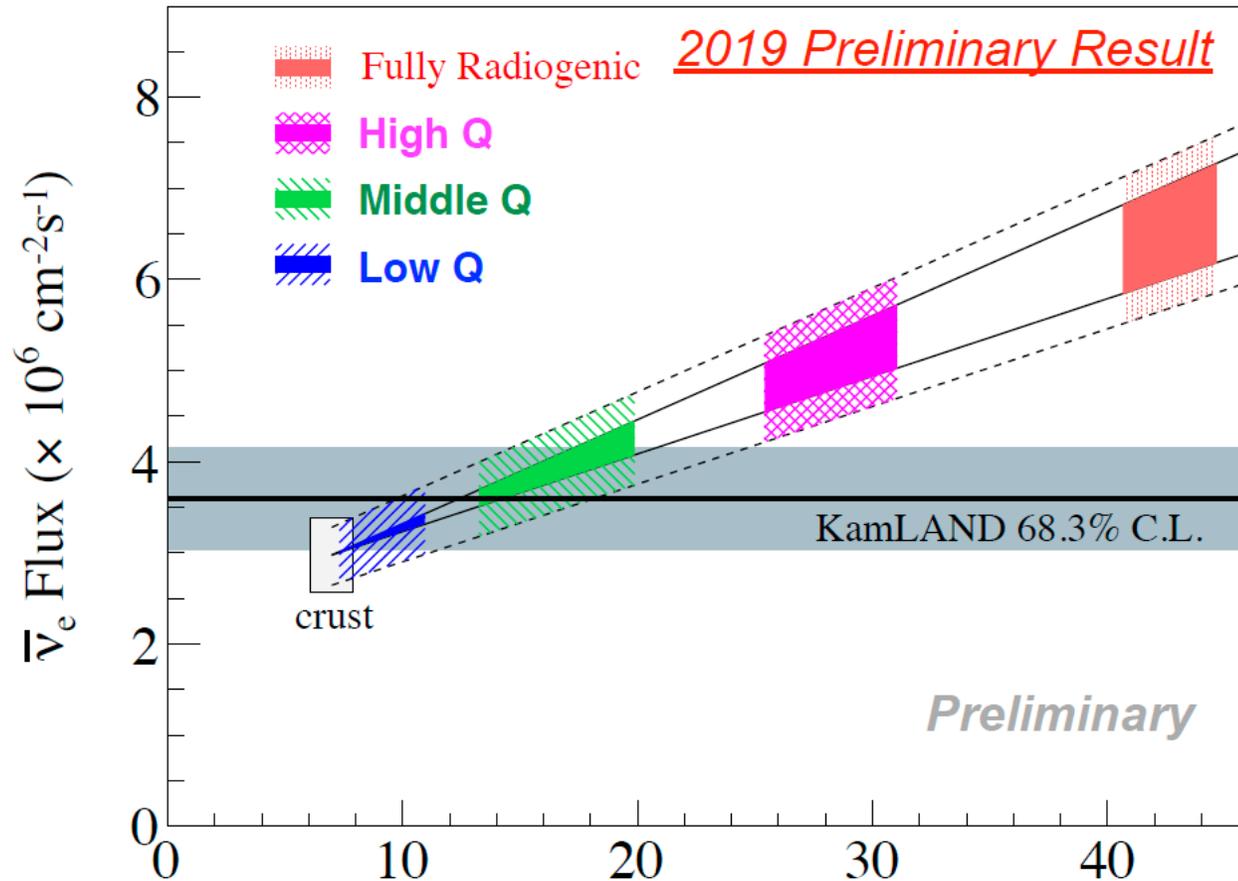
ref) chondrite data

Ordinary Chondrites : J. S. Goreva & D. S. Burnett, Meteoritics & Planetary Science 36, 63-74 (2001)

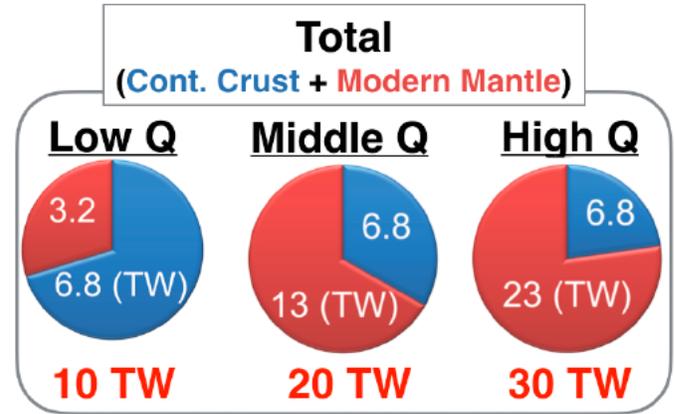
Carbonaceous Chondrites : A. Rocholl & K. P. Jochum, EPSL 117, 265-278 (1993)

Enstatite Chondrites : M. Javoy & E. Kaminski, EPSL 407, 1-8 (2014)

РАДИОГЕННОЕ ТЕПЛО



Radiogenic Heat from $^{238}\text{U} + ^{232}\text{Th}$ (TW)
 Radiogenic Heat : **12.4** $^{+4.9}_{-4.9}$ TW
 (Mantle+Crust, U+Th)



[BSE models]

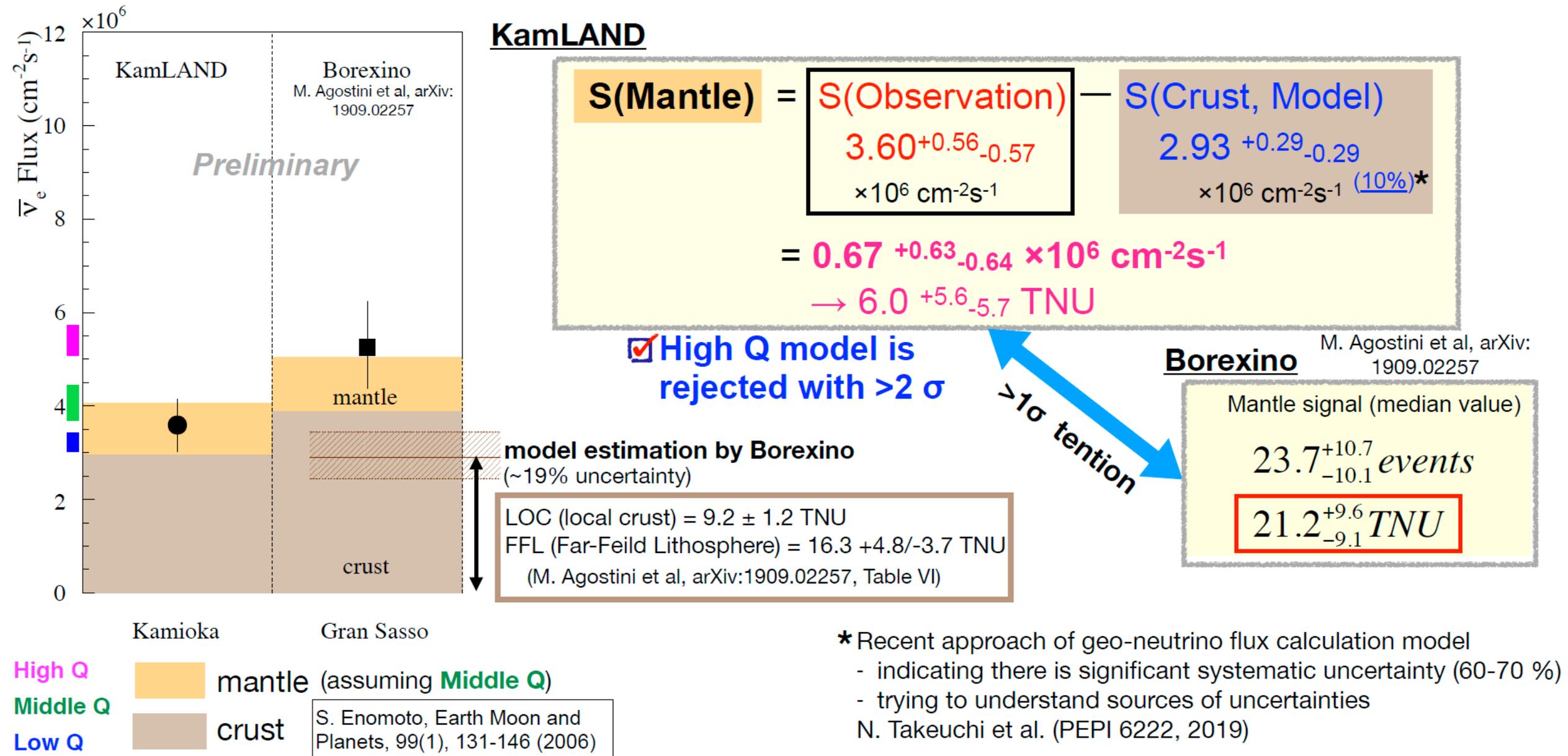
High Q
 based on balancing mantle viscosity and heat dissipation

Middle Q
 based on mantle samples compared with chondrites

Low Q
 based on isotope constraints and chondritic models

ref) Crust (U+Th) ~7 TW Enomoto et al. EPSL 258, 147 (2007) → Mantle (U+Th) ~5.4 TW

ГЕО-НЕЙТРИННЫЙ СИГНАЛ ИЗ МАНТИИ



KAMLAND: РЕЗУЛЬТАТЫ И ПЕРСПЕКТИВЫ

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

▶ **Preliminary results are presented.**

MORE INFORMATION - [NEUTRINO GEOSCIENCE 2019:](https://indico.cern.ch/event/825708/contributions/3552210/)

[HTTPS://INDICO.CERN.CH/EVENT/825708/CONTRIBUTIONS/3552210/](https://indico.cern.ch/event/825708/contributions/3552210/)

- Low-reactor operation period :

- ~4.8 years (40% of total livetime)

- **clear energy spectrum of geo-neutrino** → **better understanding of U, Th each contribution**

- geo-neutrino event measurement with **15.6 % uncertainty**

- geoscience discussion

- **Th/U mass ratio** : $5.3^{+6.0}_{-3.6}$, consistent with chondrite data and BSE models

- **Radiogenic heat** : $12.4^{+4.9}_{-4.9}$ TW (Mantle+Crust, U+Th), consistent with Middle Q and Low Q models

- **Separated test of ^{238}U and ^{232}Th geo-neutrinos** → **power to determine past radiogenic heat through the Earth's history**

- **Mantle signal** : $0.67^{+0.63}_{-0.64} \times 10^6 \text{ cm}^{-2}\text{s}^{-2}$ → * High Q is rejected with $>2\sigma$

* depends on estimation of crust contribution

▶ **Future Prospects:**

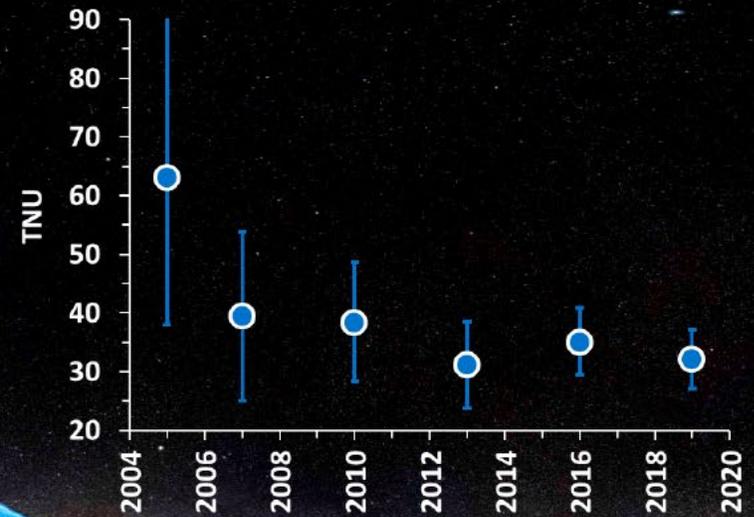
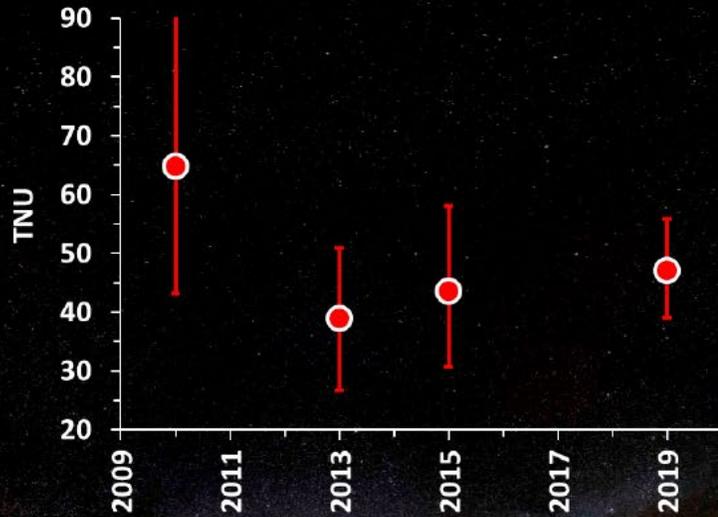
- KamLAND continues to measure geo-neutrinos with low-reactor backgrounds stably

- Better understanding of crust contribution → **helps further estimation of mantle signals**

- Multi-sight measurements

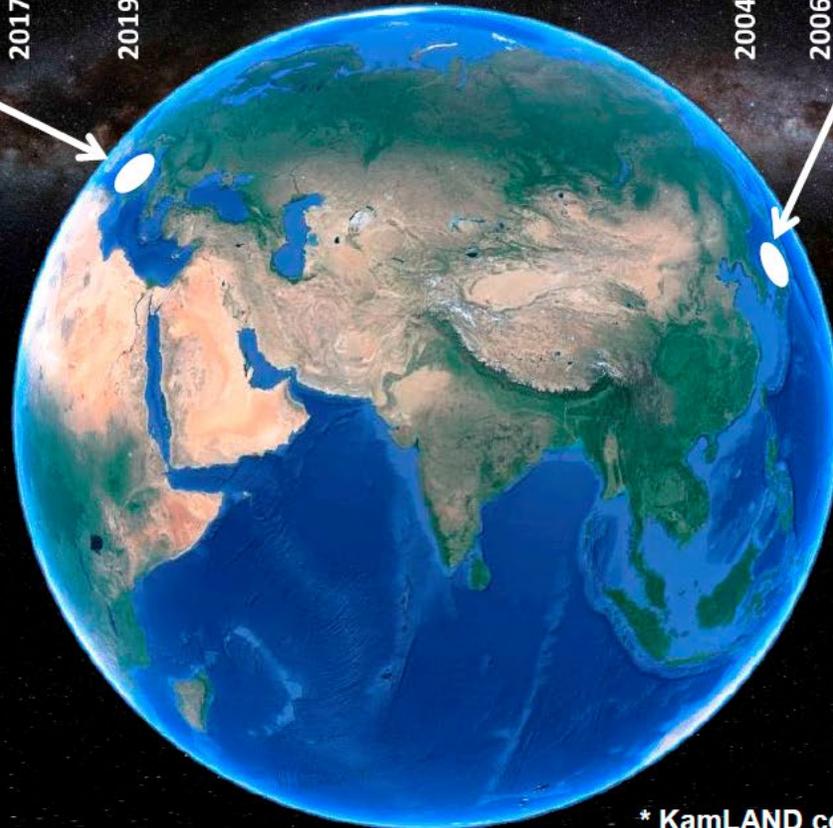
- **Ocean Bottom Detector has strong power to measure mantle contribution directly.** Poster by H. Watanabe, K. Ueki et al

Borexino and KamLAND results 2019



Borexino

- Period:
2007 – 2019
- Geo- ν events:
 $52.6^{+7.4}_{-6.3}$
- Signal:
 $47.0^{+8.7}_{-7.9}$ TNU
- Expected Signal with
Geochemical BSE:
 $34.6^{+5.5}_{-5.0}$ TNU



KamLAND*

- Period:
2002 – 2019
- Geo- ν events:
 $168.8^{+26.3}_{-26.5}$
- Signal: 32 ± 5 TNU
- Expected Signal
with Geochemical
BSE: 35.3 ± 2.7 TNU

* KamLAND collaboration, 2019 – NGS Prague 2019

ТЕКУЩИЕ И БУДУЩИЕ ЭКСПЕРИМЕНТЫ

SNO+

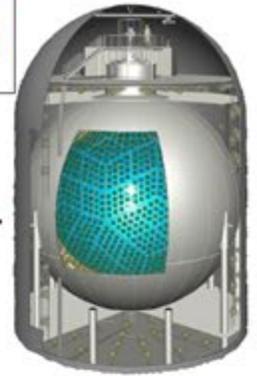
1 kt, LS+, 5.4 km.w.e.
running since April 2021
 (up to mid-late 2022)

Baksan

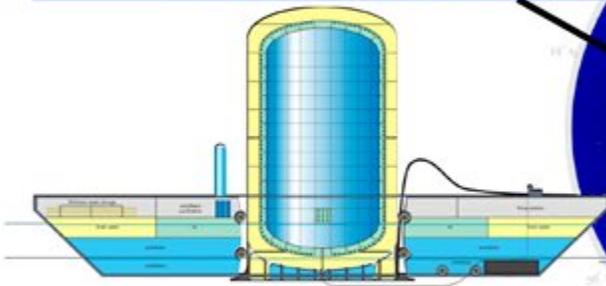
~10 kt, LS
 4.8 km.w.e.
 R&D

KamLAND

1 kt, LS
 2.7 km.w.e.
running



Ocean Bottom Detector

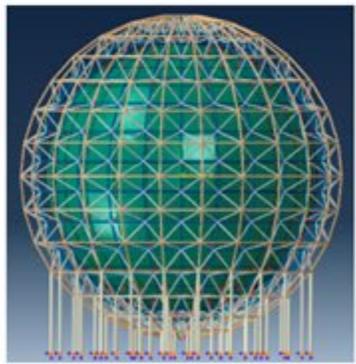


10-50 kt, LS, ~5 km.w.e.
movable, R&D ~20 kg (2022)



U and Th geo-neutrino flux

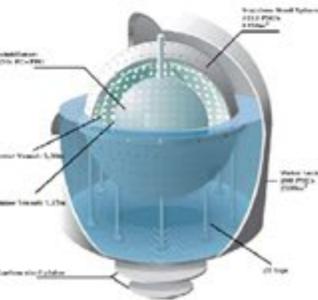
JUNO



20 kt, LS
 1.5 km.w.e.
undue construction
 (~2023)

Borexino

0.3 kt, LS
 3.8 km.w.e.
finished
 (07.10.21)



ANDES

~3 kt, LS
 4.5 km.w.e.
 R&D

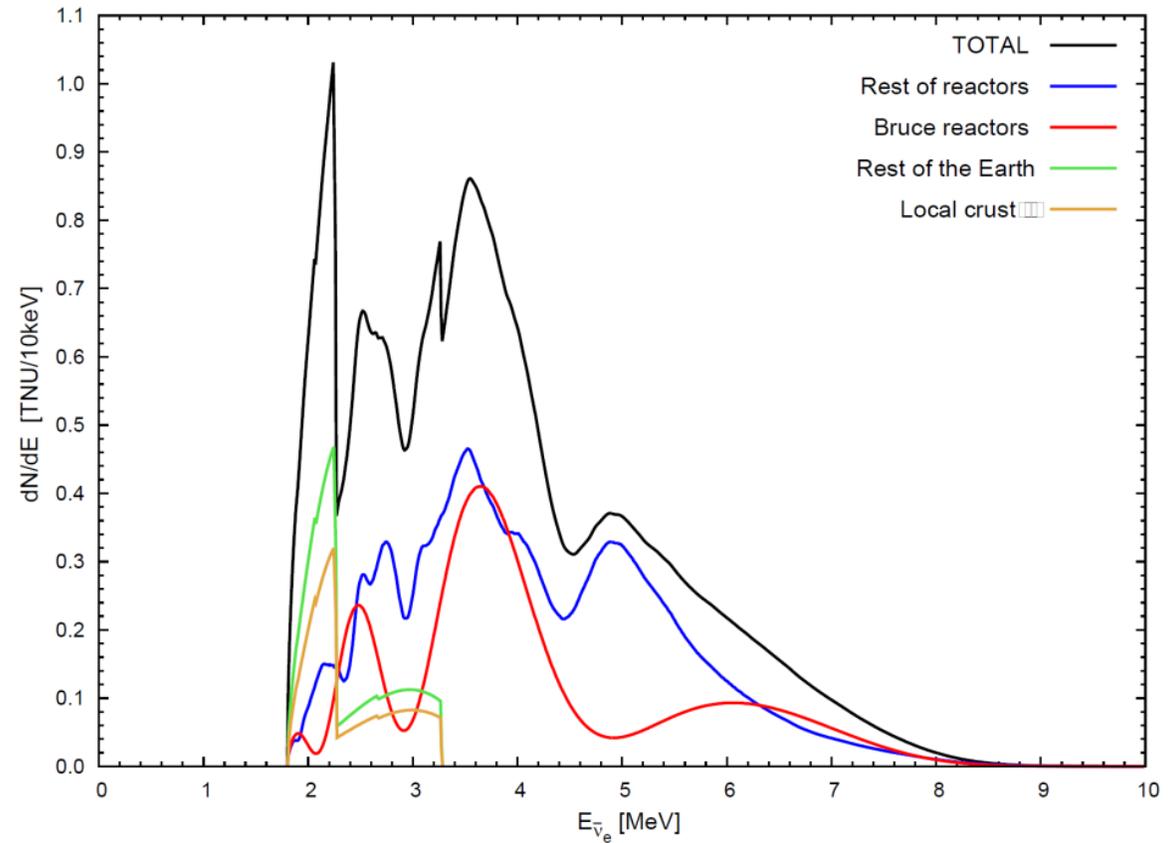
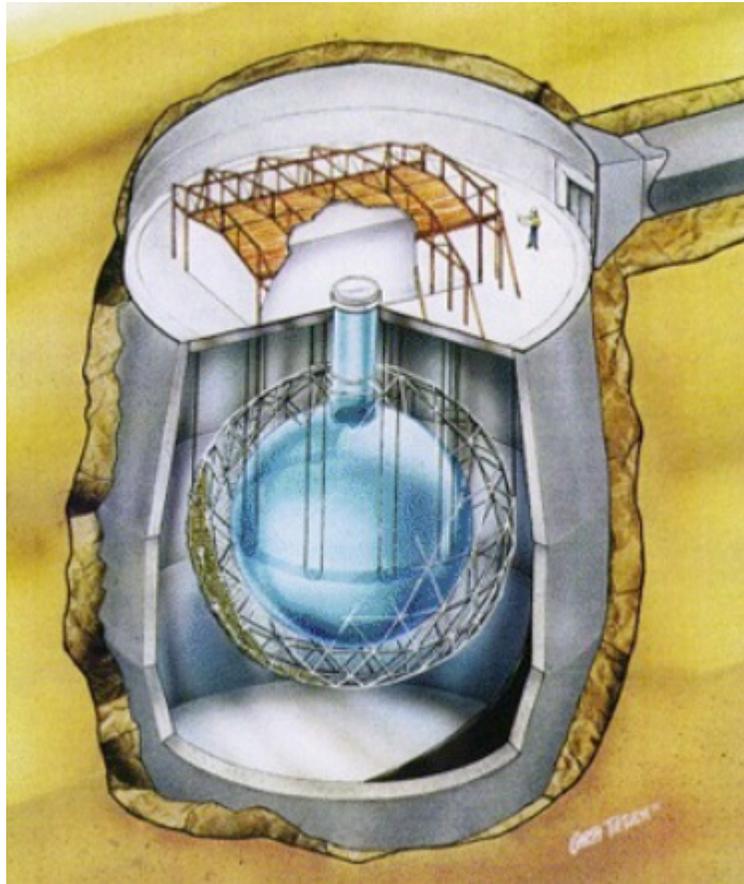


Jinping

1 kt, LS
7.5 km.w.e.
 Scheduled

JUNO

SNO+ (ШАХТА КРЕЙГТОН, САДБЕРИ, КАНАДА)

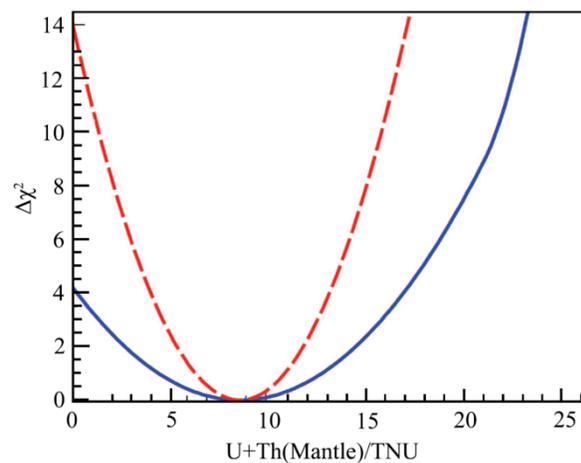
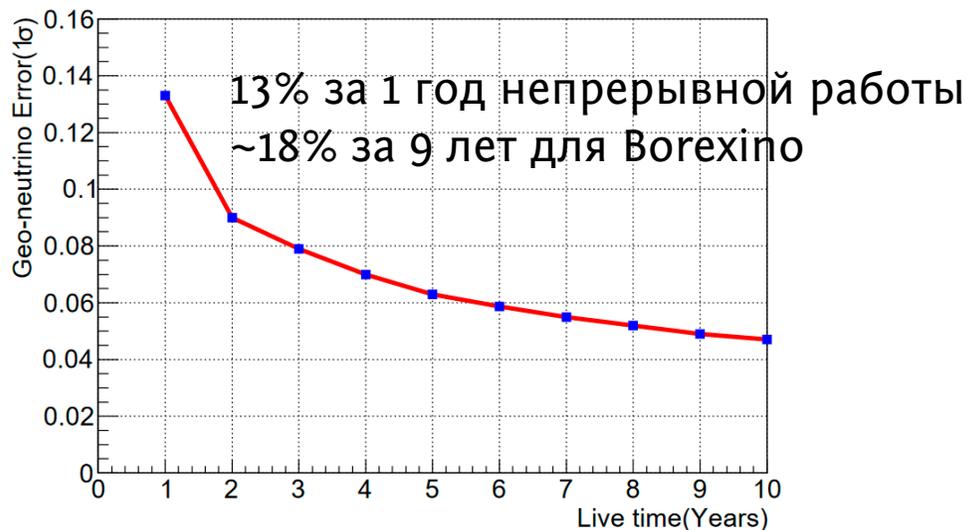
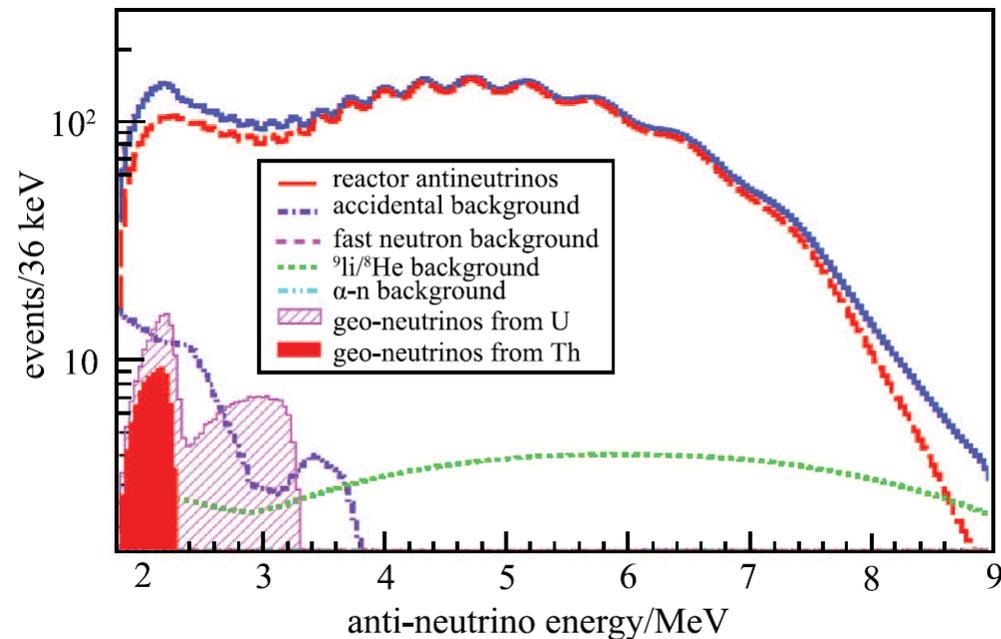
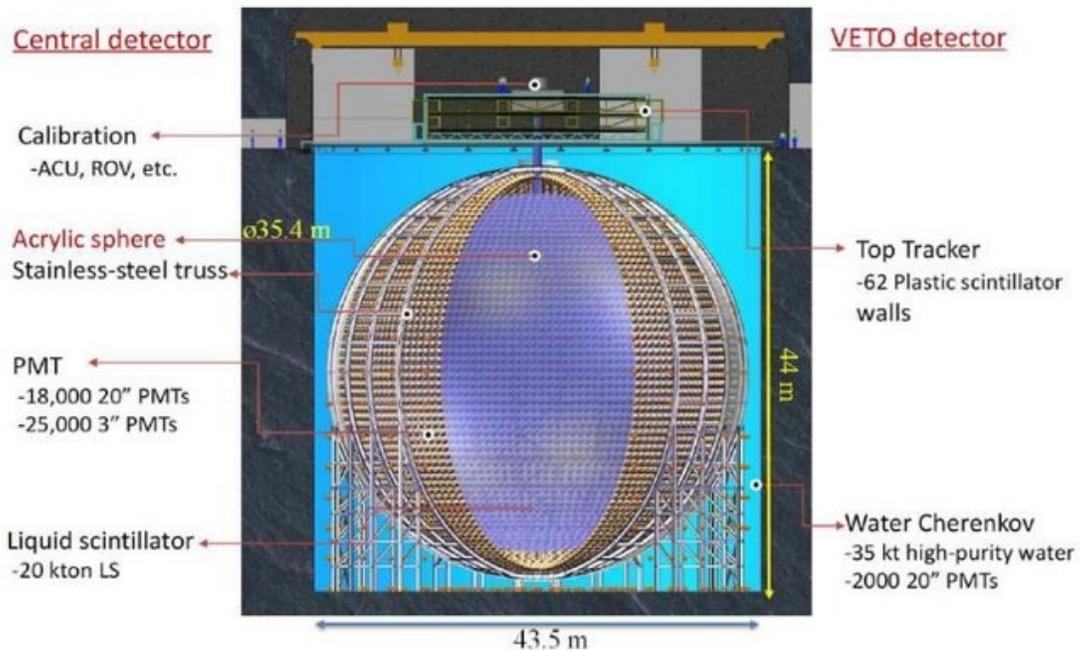


Ожидаемый сигнал - 29 геонейтринных событий в год (в 780 тонн LAB) и 26 соб. от реакторных антинейтрино в той же области энергий

Геология местности, возможно, наиболее изученная в сравнении с другими областями

JUNO (провинция Гуандун, Китай)

Ожидаемый антинейтринный спектр



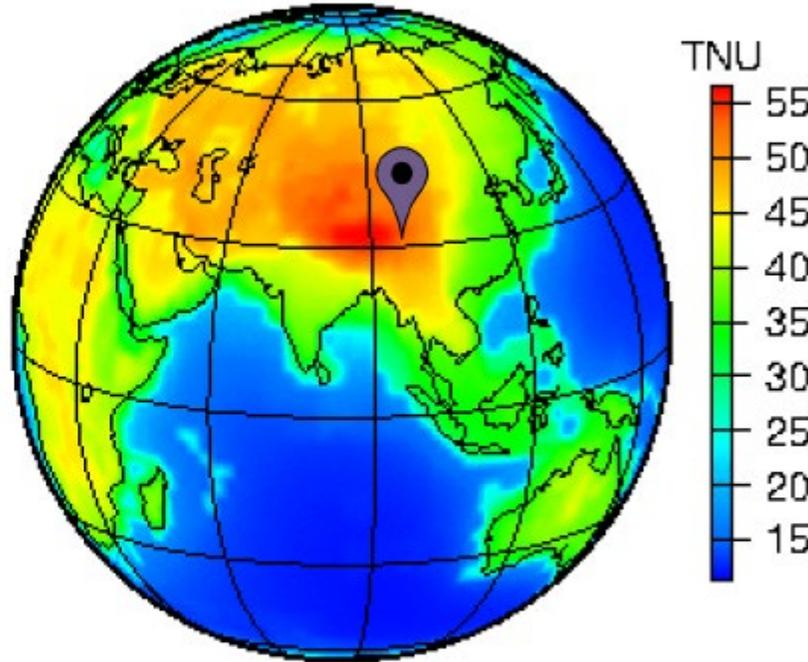
Выделение сигнала из мантии зависит от точности оценки сигнала гео-нейтрино из коры

8%
18%

JINPING NEUTRINO EXPERIMENT (СЫЧУАНЬ, КИТАЙ)

CJPL: Location

CJPL: China JinPing Laboratory



☐ Near Himalaya mountains.

☐ Located in Sichuan, China. 2 hours drive from Xichang airport.

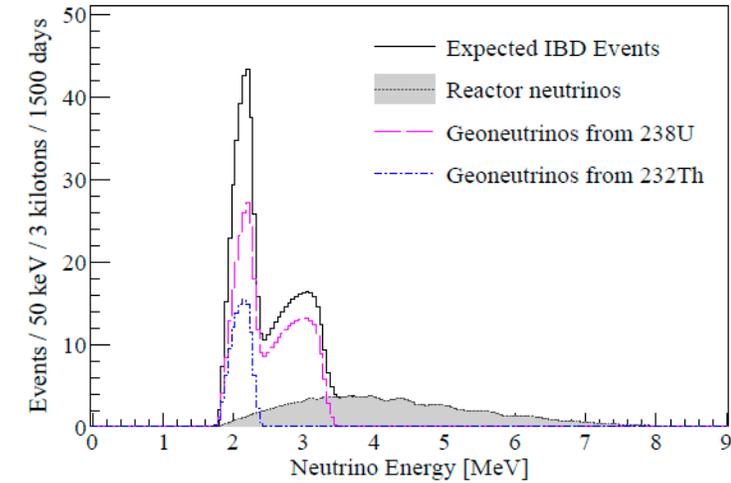


FIG. 5. Predicted IBD events at the Jinping site. $\bar{\nu}_e$ sources include ^{238}U decay (magenta dashed), ^{232}Th decay (blue dotted-dashed), and man-made reactor background (gray filled). The black solid line sums up all.

Geo $\bar{\nu}_e$ (TNU)	Crust	Mantle	BSE
Th	10.6 ± 0.8	2.1 ± 0.5	12.7 ± 1.0
U	38.4 ± 6.6	8.3 ± 2.3	46.7 ± 6.7
Th+U	49.0 ± 7.3	10.4 ± 2.7	59.4 ± 7.6

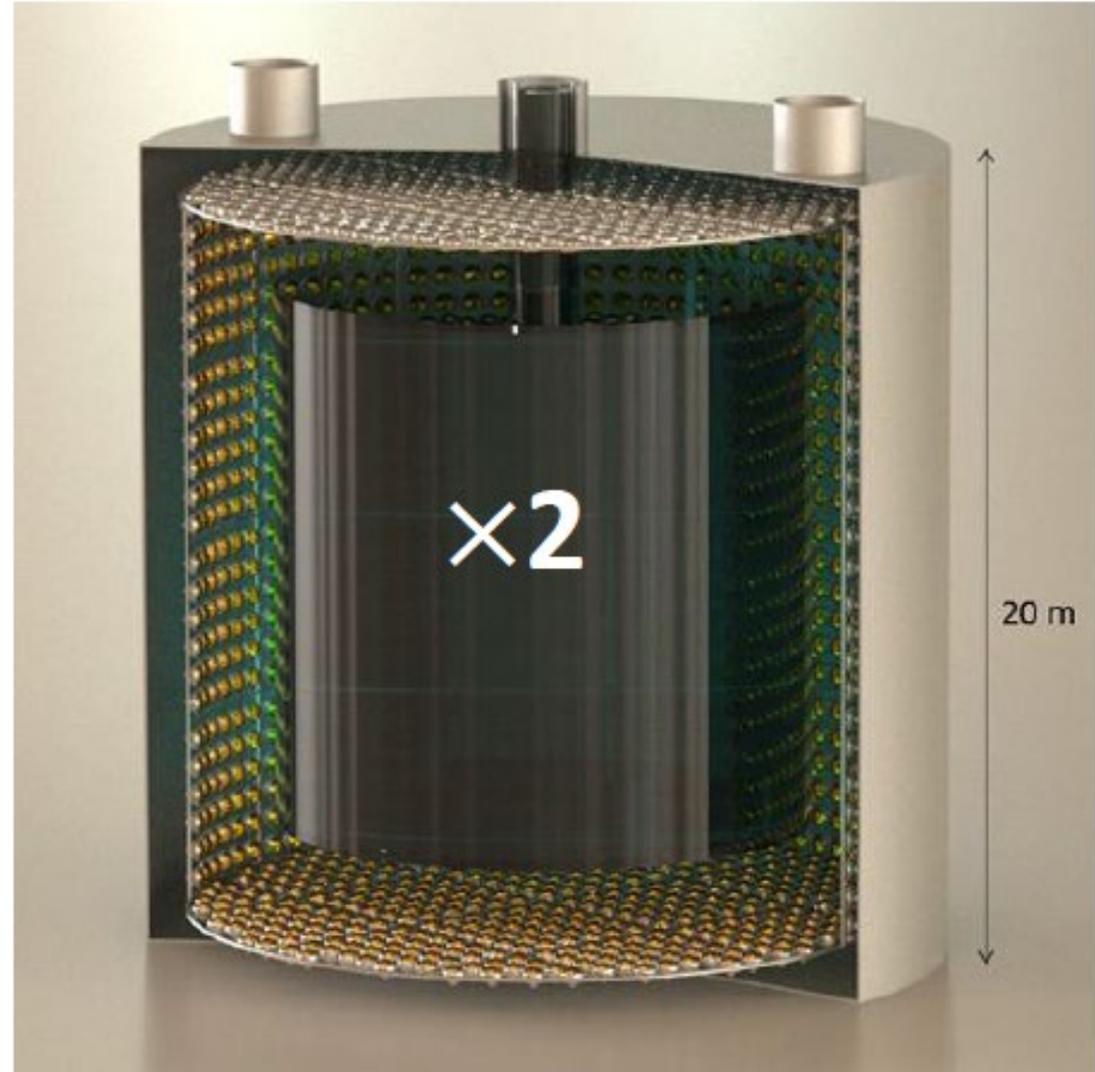
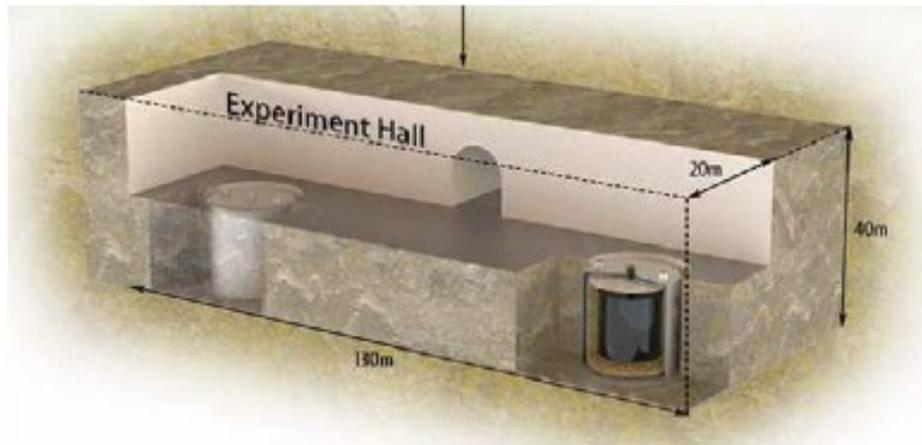
TABLE V. Summary of predicted geoneutrino event rates in TNU at Jinping.

Event Rate (TNU)	Geoneutrino			Reactor	
	^{238}U	^{232}Th	Total	FER	SER
Total Events	414.5	113.6	527.3	246.8	60.4

TABLE VI. Geoneutrino and reactor neutrino event rates and total events with an exposure of 3 kilotons \times 1,500 days at Jinping.

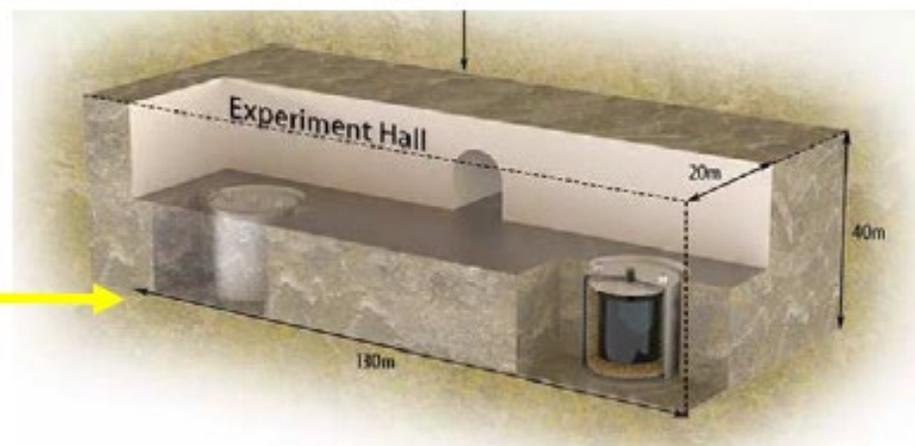
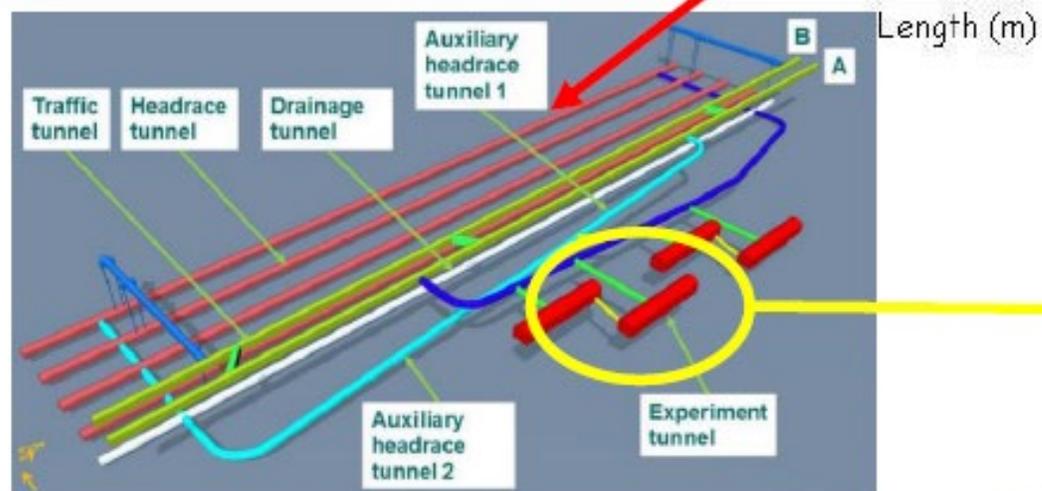
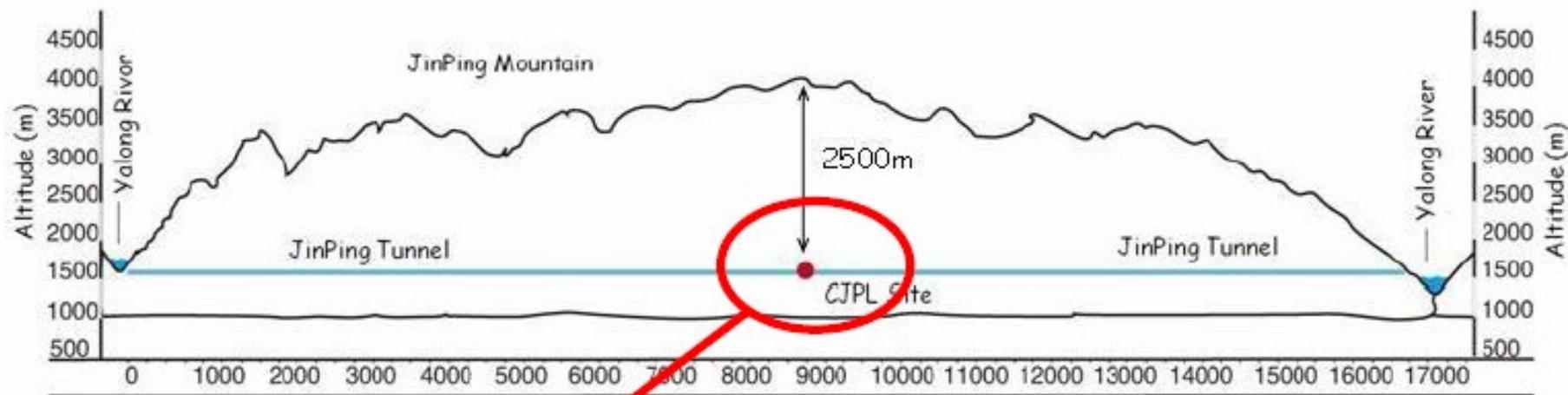
Detector Concept

- ❑ 1.5 kton×2 Fiducial for IBD
- ❑ PMT coverage >70%
with self-designed light concentrator
- ❑ Energy Resolution: 500 p.e.



JINPING NEUTRINO EXPERIMENT

CJPL: Tunnel View



□ Tunnel construction nearly finished.

[岩土工程学报, Vol. 38 Supp. 2, 67](#)

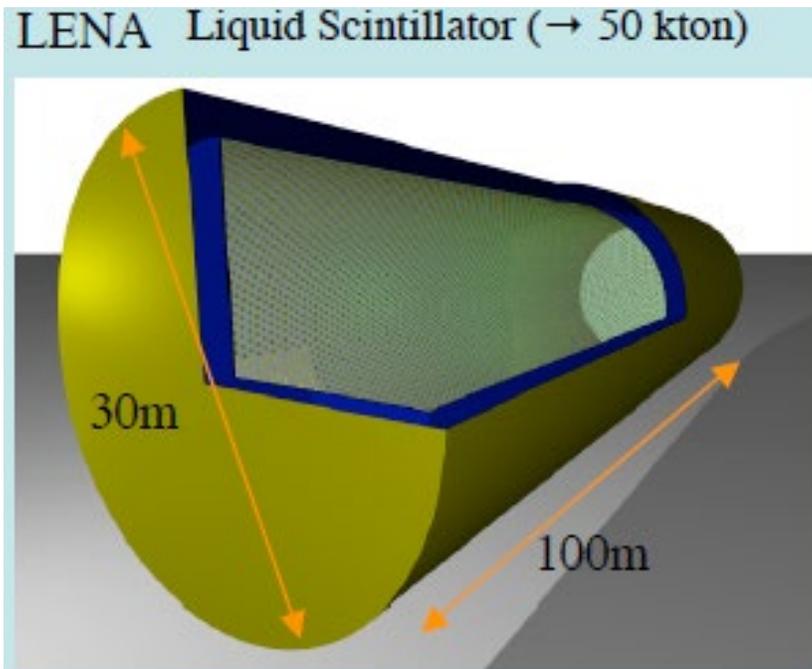
□ On average **2,400 m** rock shielding;

□ 20 m * 100 m experiment hall;

НЕУТВЕРЖДЕННЫЕ ПРОЕКТЫ

LENA: 50 кт

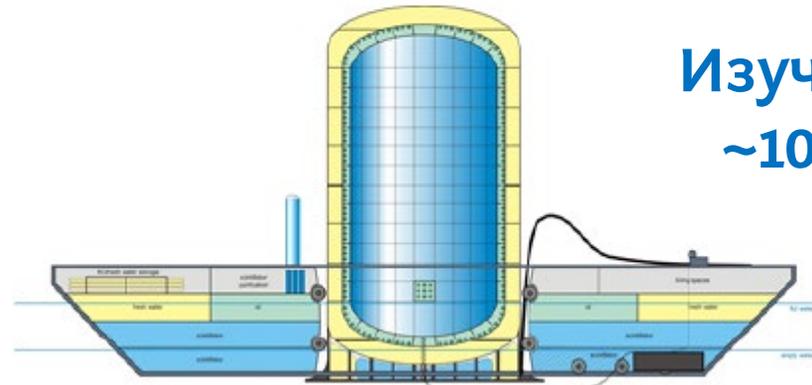
Многоцелевой детектор
~1500 гео-нейтрино/год



См: <http://geoscience.lngs.infn.it/>

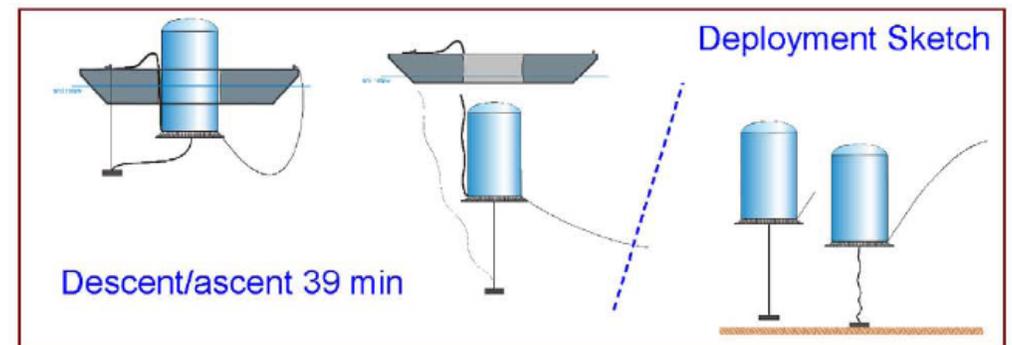
Hanohano: 10 кт

Подводный,
Изучение вклада мантии
~100 гео-нейтрино/год

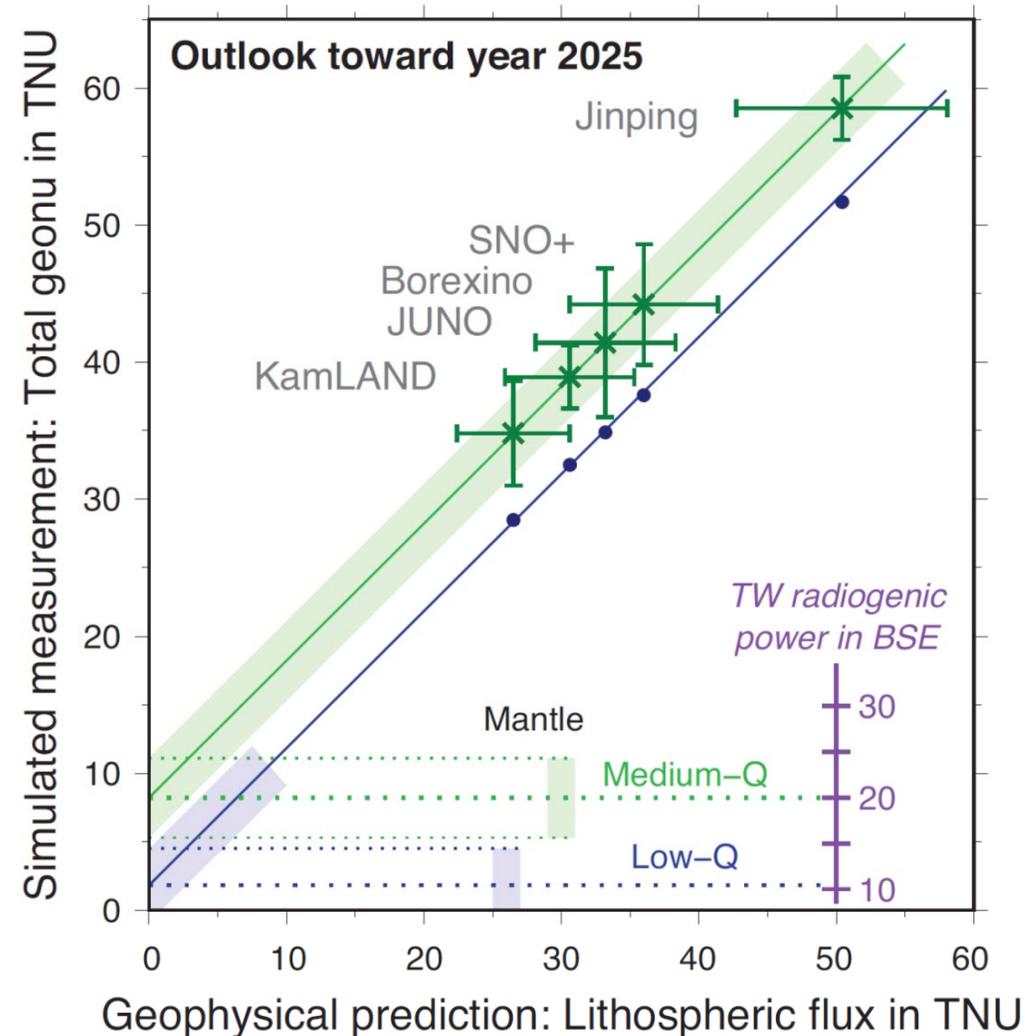
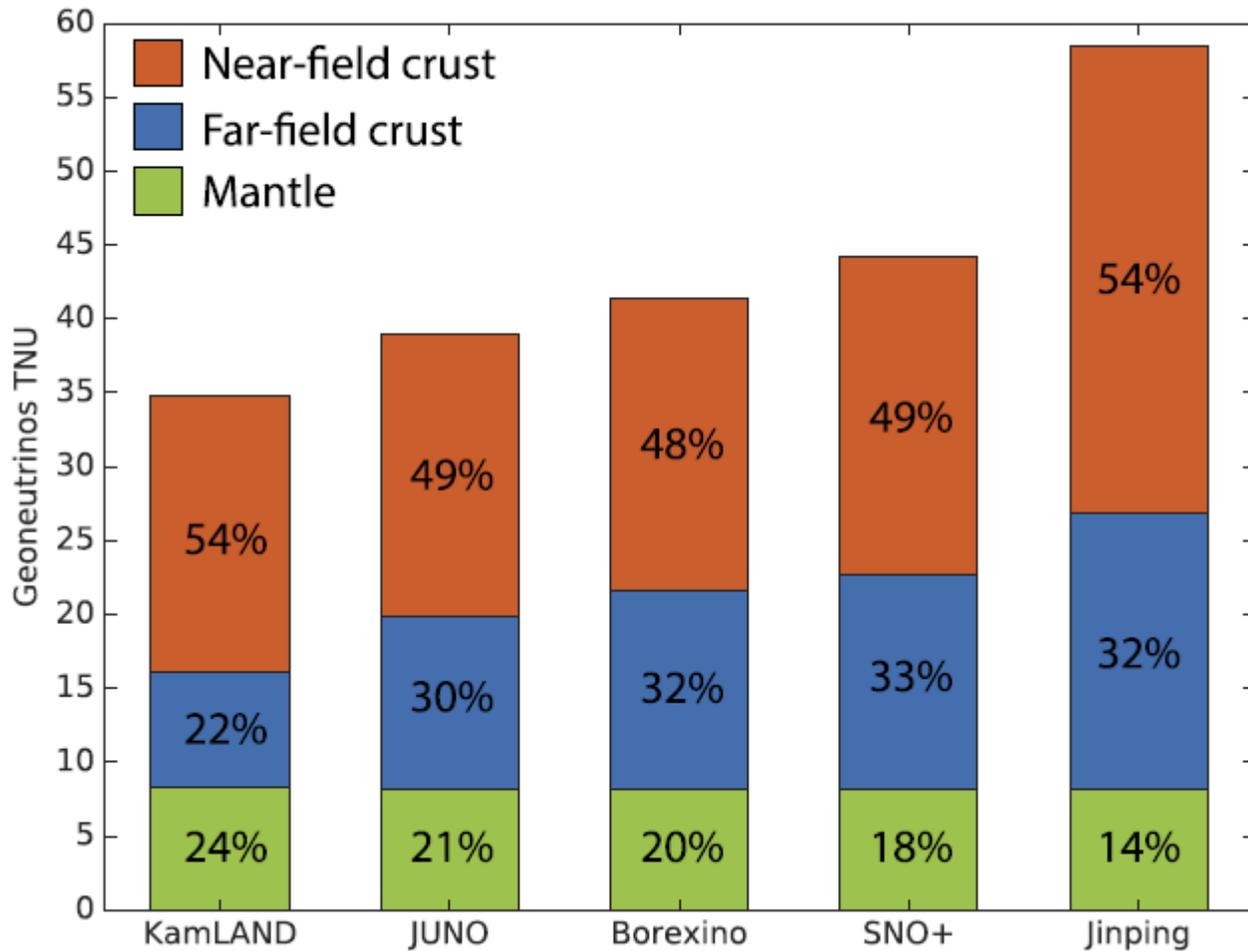


Hanohano

(~10 kt deep ocean detector)

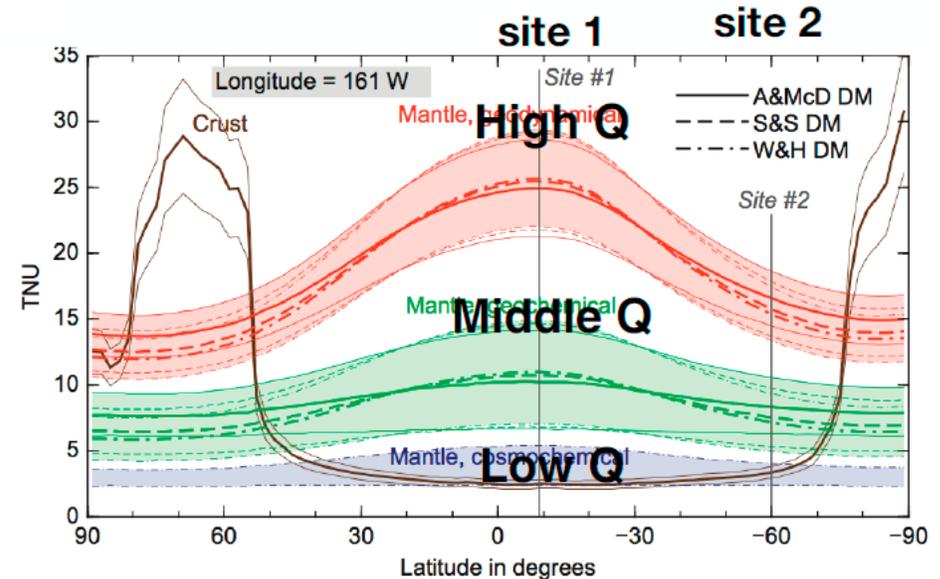
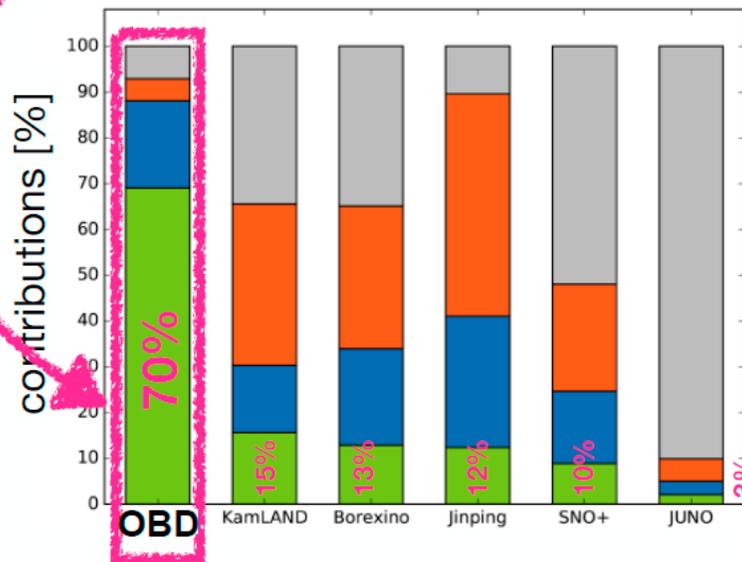
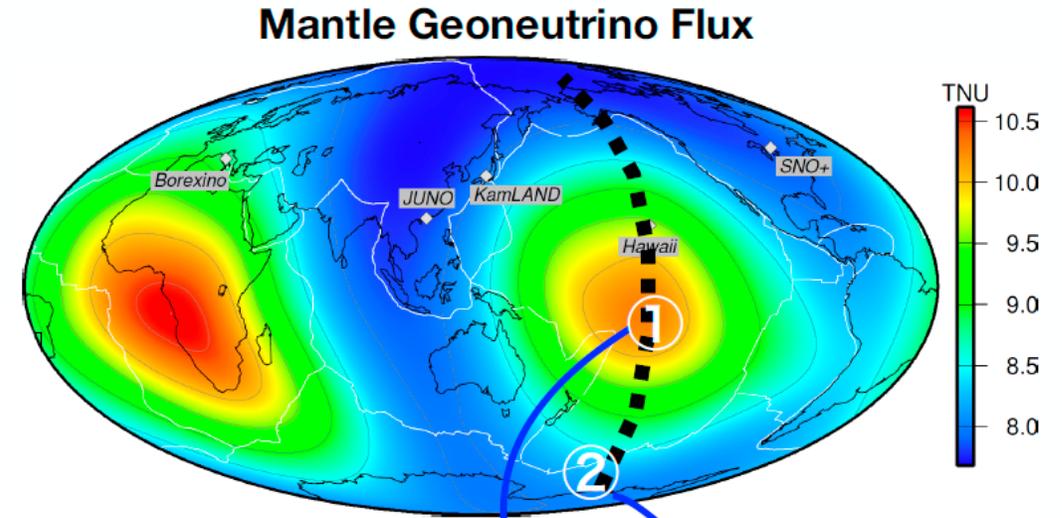
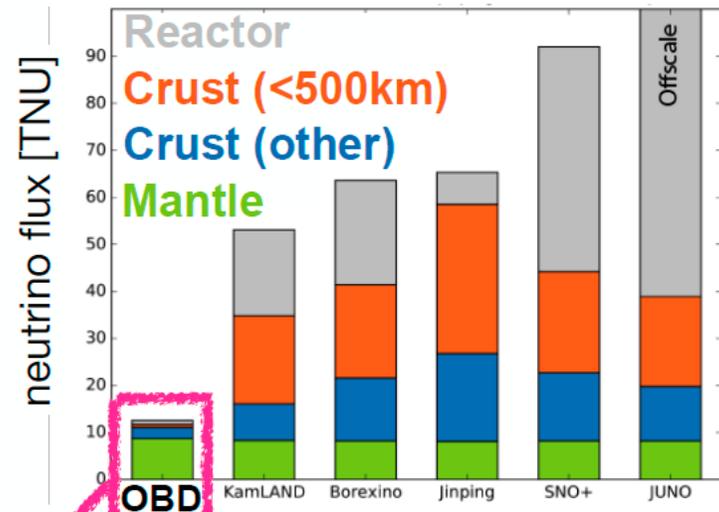


ОПРЕДЕЛЕНИЕ СИГНАЛА ОТ МАНТИИ ПО ДАННЫМ РАЗНЫХ ЭКСПЕРИМЕНТОВ



OCEAN BOTTOM DETECTOR

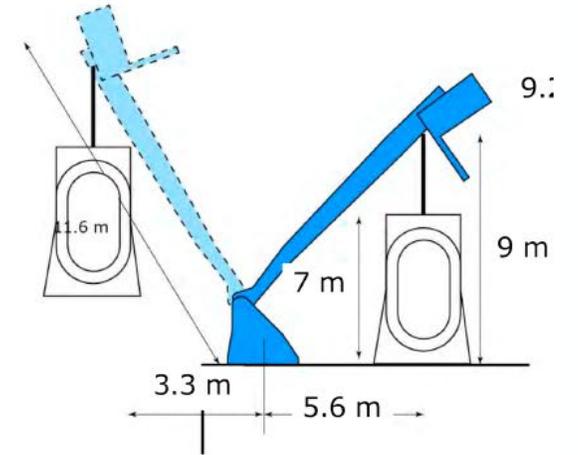
Šrámek et al (2013) EPS, 10.1016/j.epsl.2012.11.001



ТЕКУЩИЙ СТАТУС ПРОЕКТА OBD

OBD project has just started with Tohoku U and JAMSTEC.
(Japan Agency for Marine-Earth Science)

Chikyu



* JAMSTEC

- * Leading ocean engineering
- * Own scientific vessels (e.g. Chikyu)

- * Started to discuss design of prototype detector (~10 t) assuming applying engineering developments for larger detectors (~1.5 kt, 10-50 kt) Over 1 year / 1 place

More info. [Joint workshop on OBD with Ocean Engineering, Earth Science and Neutrino Physics](#)

- 12m x 22m
- cart : < 400t

ЗАКЛЮЧЕНИЕ

- 1) Существование геонейтрино независимо подтверждено данными Borexino и KamLAND
- 2) Точность измерений сигнала U+Th пока что невысока: ~16-18%, и для свободного отношения U/Th точность измерения R(U) и R(Th) еще хуже, но существующие эксперименты подтвердили возможность регистрации геонейтрино. Рождается новая область науки
- 3) По существующим данным разные геологические модели пока что неразличимы, требуются более точные измерения
- 4) Для уточнения моделей необходима региональная геология
- 5) Необходимы независимое измерение в разных местах для проверки вклада от коры и мантии
- 6) Ждем данные от новых детекторов

~~Талмуд т1~~

ЗАМЕЧАТЕЛЬНАЯ СТАТЬЯ:
ВСЁ ОБ ИССЛЕДОВАНИЯХ ГЕО-НЕЙТРИНО
В ЭКСПЕРИМЕНТЕ BOREXINO



[ARXIV:1909.02257](https://arxiv.org/abs/1909.02257)

~~Талмуд т2~~

ЗАМЕЧАТЕЛЬНЫЙ ОБЗОР:
ВСЁ О ГЕО-НЕЙТРИНО



[ARXIV:1910.09321](https://arxiv.org/abs/1910.09321)

СПАСИБО ЗА ВНИМАНИЕ!