Geo-neutrino : experimental status and perspectives

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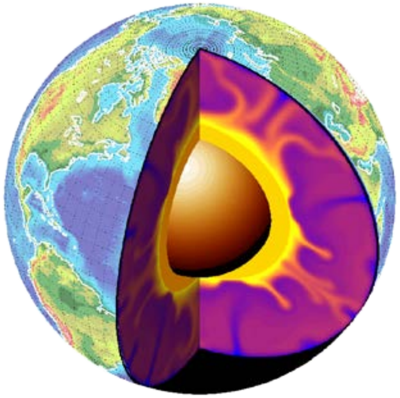
Geoneutrino

- Introduction
- Measurements with Borexino and KamLAND : review of main results
- Prospects for future experiments (JUNO and other future projects)
- Nuclear physics inputs needed for geoneutrino analysis

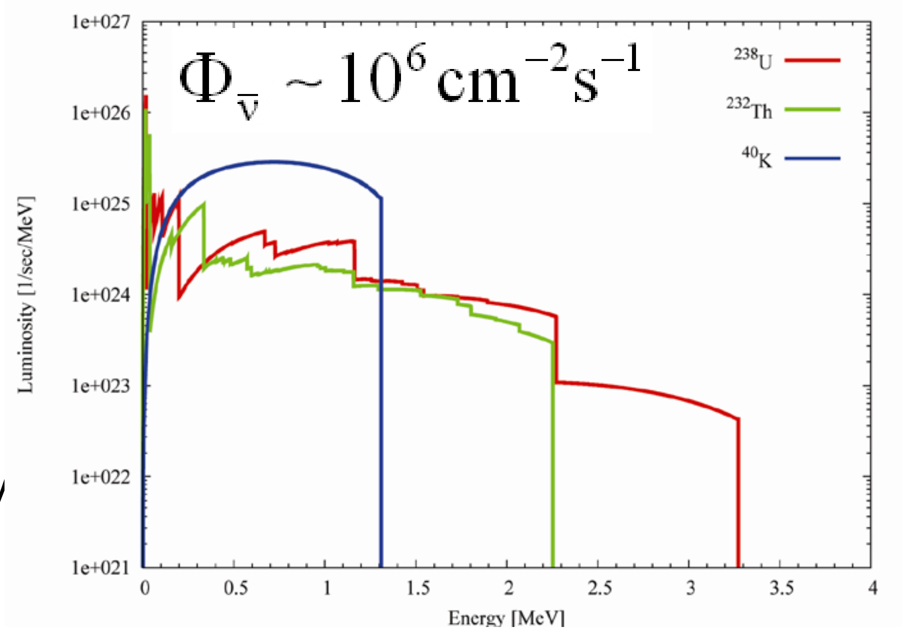
Geo-neutrinos: anti-neutrinos from β-decays of radioactive elements in the Earth



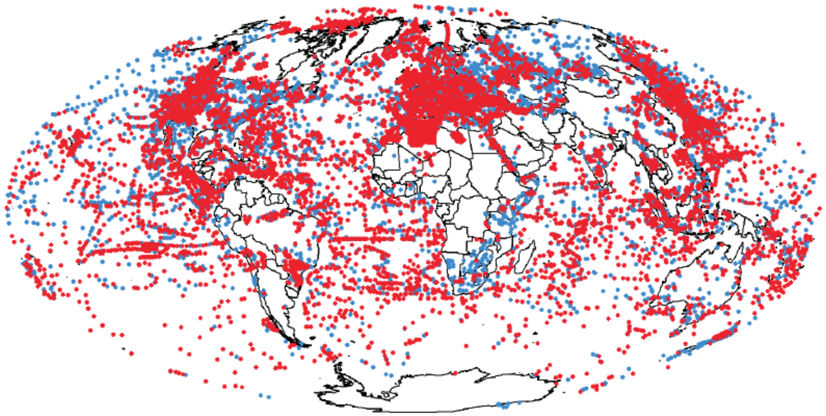
^{238}U, ^{232}Th and ^{40}K (^{87}Rb,^{235}U) release heat together with antineutrinos

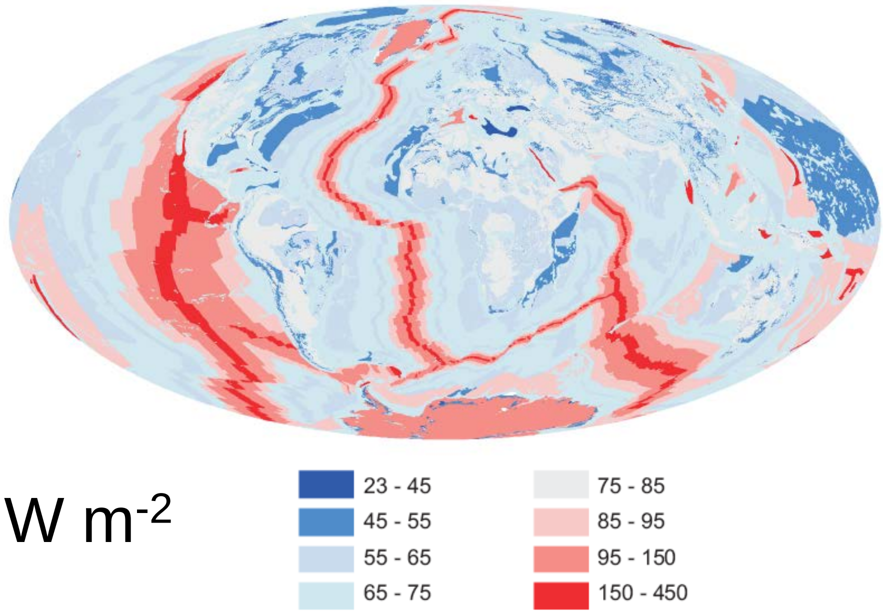
Decay	$T_{1/2}$ [10^9 yr]	$E_{\max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$kg^{-1}s^{-1}$]	ε_H [W/kg]
$^{238}U \to {}^{206}Pb + 8\,{}^4He + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}Th \to {}^{208}Pb + 6\,{}^4He + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}K \to {}^{40}Ca + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}

- Earth emits (mainly) antineutrinos whereas Sun shines in neutrinos.
- A fraction of geo-neutrinos from U and Th are above threshold for inverse β on protons: 1.8 MeV
- Different components can be distinguished due to different energy spectra: e. g. anti-ν with highest energy are from Uranium.



Heat flow through the surface of the Earth





mW m^{-2}

"Earth's surface heat flux", J. H. Davies and D. R. Davies (2010)

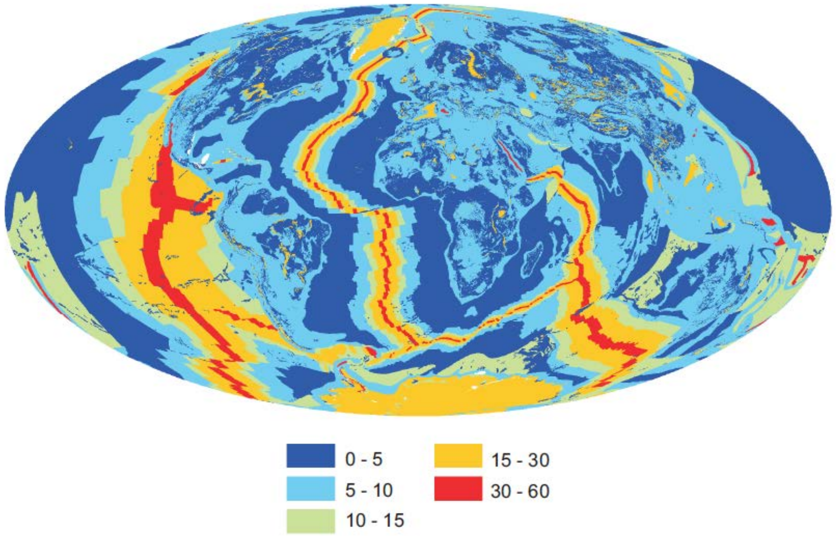
47±2 TW

38 347 measurements of the thermal flux

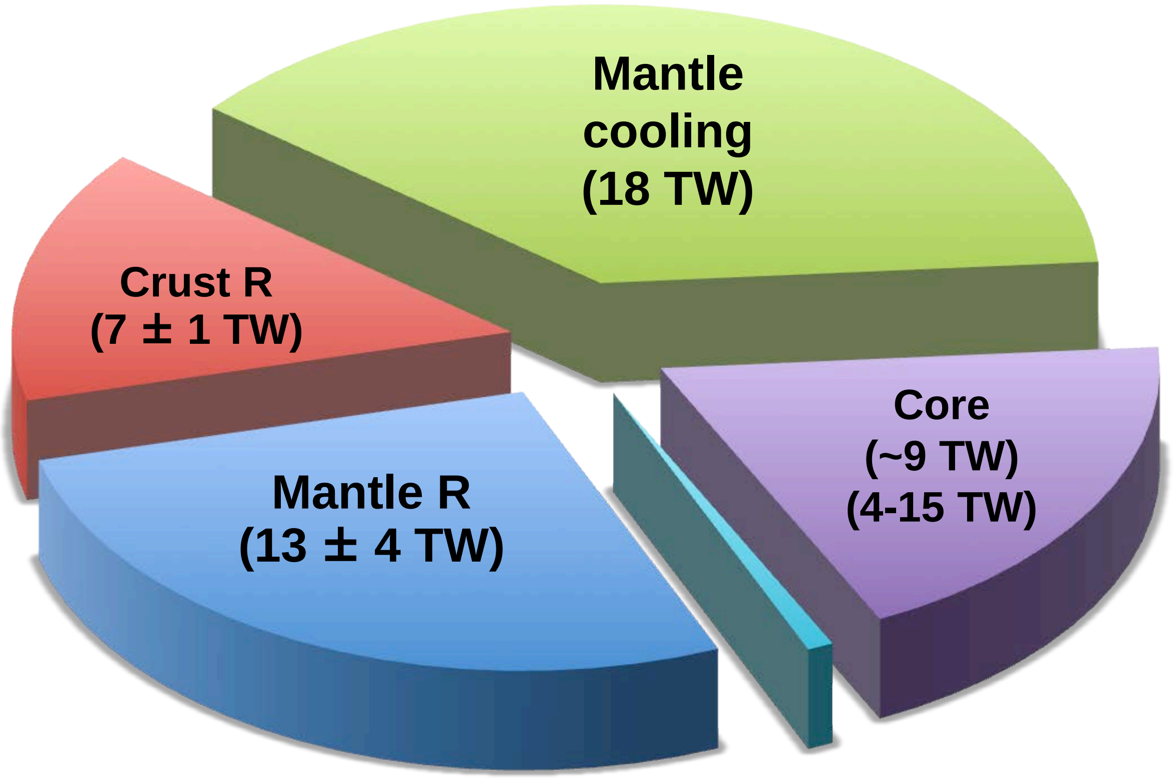
In agreement with previous estimations based on incomplete set of the same data

46±3 TW[Jaupart et al., 2007] and

44±1 TW [Pollack et al., 1993]



Earth's surface heat flow 47 ± 2 TW



total R: 20 ± 4

(0.4 TW) Tidal dissipation
Chemical differentiation

Urey=R/Tot

Primordial heat sources:
Gravitational energy
Short-lived isotopes decays
^{26}Al (7.17×10^{5} yr)

Earth models and radiogenic heat

- **Cosmochemical (based on meteorites composition)** – Earth composition is based on the enstatine chondrites (E-chondrites), the only group of chondrites identical to the Earth composition (Javoy et al., 2010) :

~10 TW

- **Geochemical (composition of Earth minerals) –** cosmochemical relative abundancies (based on carbonaceous chondrites CI) with absolute abundancies from petrology (Lyubetskaya & Korenaga,2007; McDonough & Sun, 1995; Palme & O'Neill, 2003):

~20 TW

- **Geophysical/geodynamical (parametric convection) –** convection requires viscosity consistent with surface heat flow. Uses using scaling laws to relate heat flow and viscosity, predicting the thermal evolution of the Earth (Crowley et al., 2011; Turco, 1980)**:**

~30 TW

Compared to total 47±2 TW
9 - 36 TW are left to the internal non-radiogenic heat, definening the thermal evolution and history of the Earth.

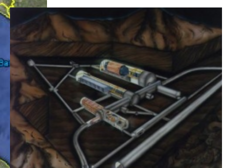
Models : mantle contribution

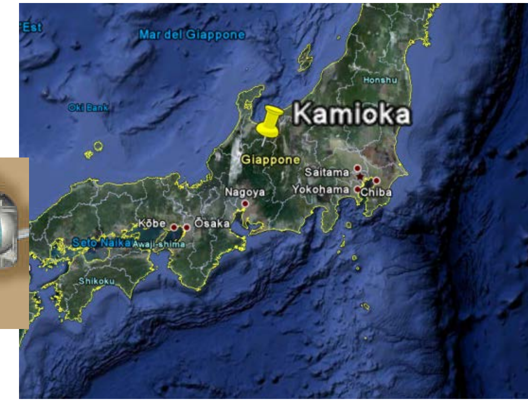
"Geophysical and geochemical constraints on geoneutrino fluxes from Earth's mantle"
Ondrej Sramek et al.

Model	Full thermal flux,TW	Mantle contribution, TW
Cosmochemical	11 ± 2	3 ±2
Geochemical	20 ± 4	12 ±4
Geophysical	33 ± 3	25 ±3

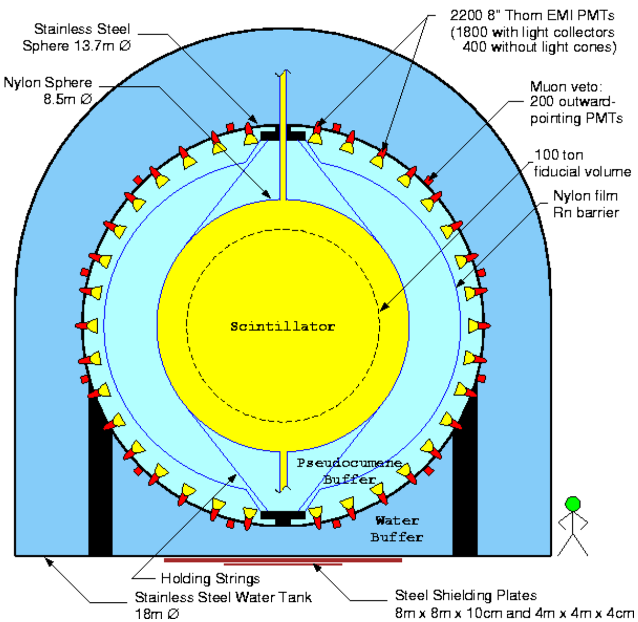
Geophysical models need relatively high contribution of radiogenic heat to explain thermal flux in the mantle (otherwise model leads to the "thermal catastrophe" in archeosoic)

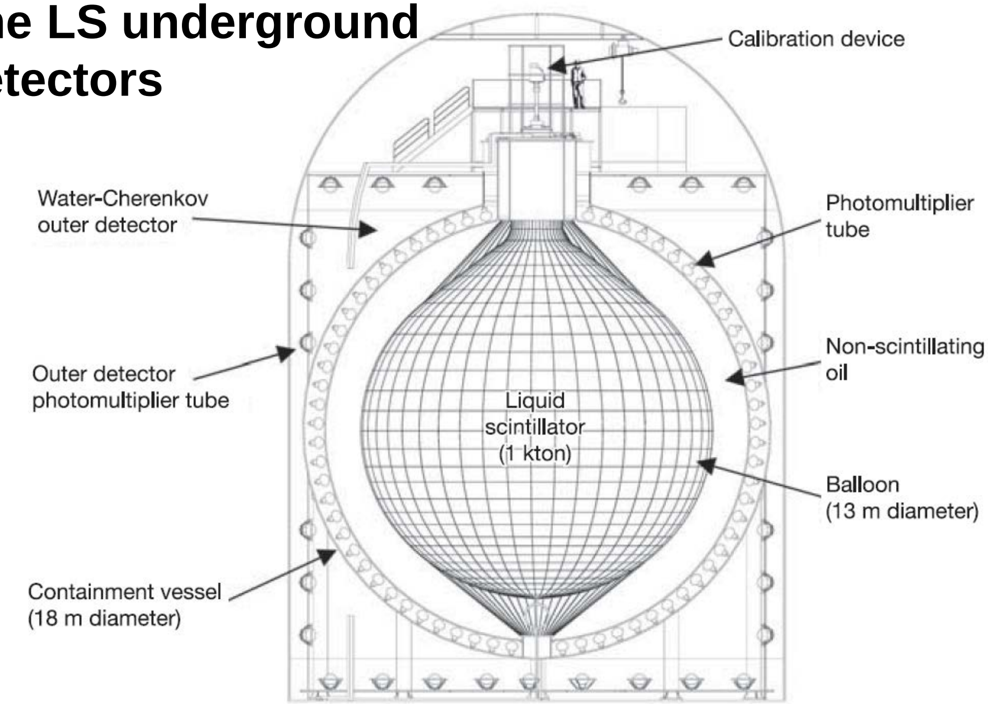
Two detectors measured geo-neutrino





Large volume LS underground detectors





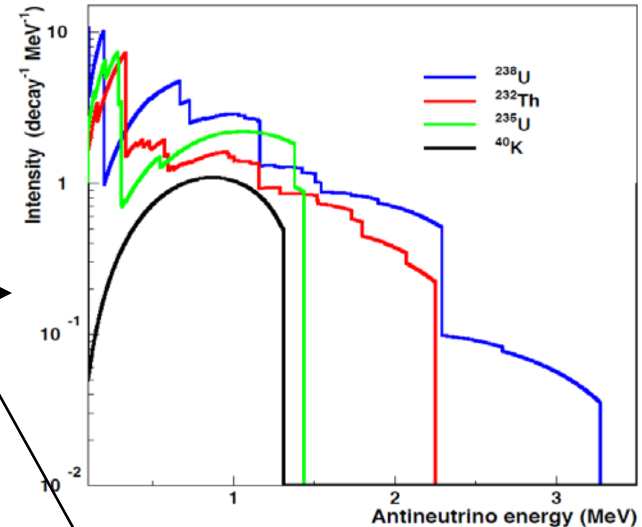
Borexino: 300 t LS (3500 mwe)

KamLAND: 1 kton LS (2200 mwe)

Detection of geo(anti)neutrino

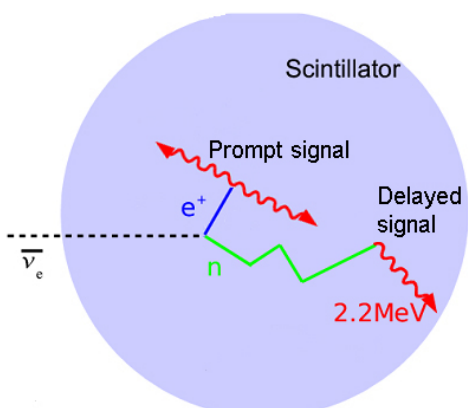
$$\Phi_{\bar{\nu}} \sim 10^6 \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

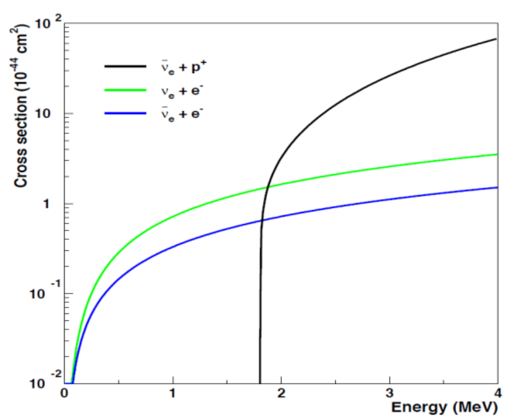
- Earth (in construst to the Sun) emits antineutrino.
- Part of antineutrino in the U and Th decay chains is emitted with E>1.8 MeV (IBD threshold)
- Contributions from U and Th are distinguishable
- Oscillations are averaged: <Pee>=0.54±0.02

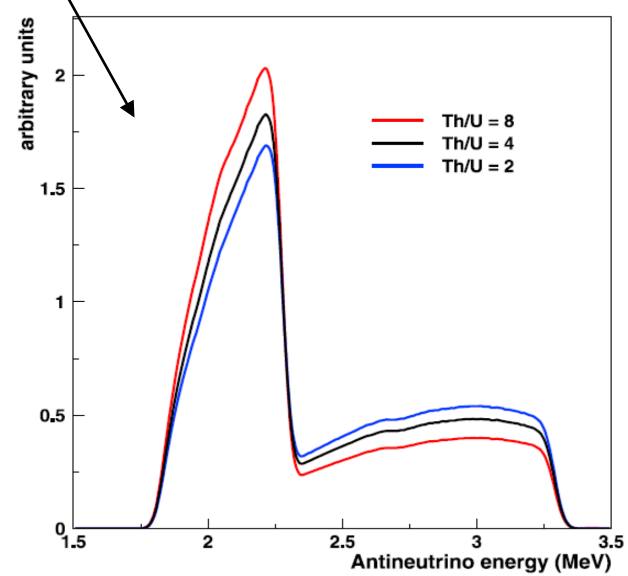


$$\bar{\nu} + p \rightarrow n + e^+$$

$$E_\nu > 1.8 \text{ MeV}$$



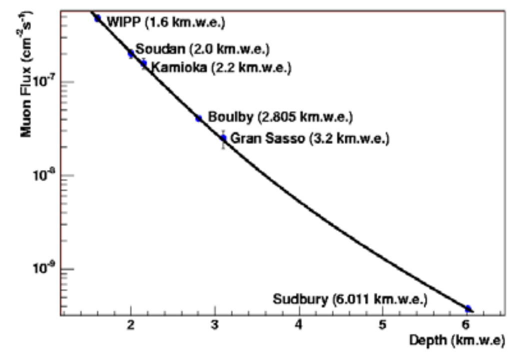




Main backgrounds in geo-neutrino measurements

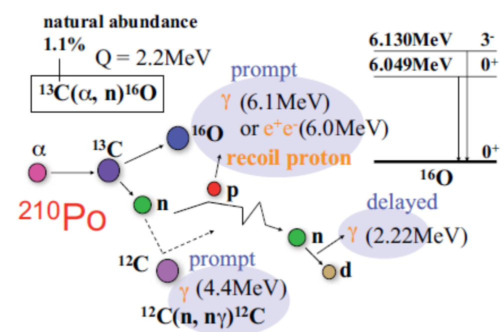
1)Reactor antineutrinos in geo-nu window [0.9-2.6 MeV];

2)Cosmic muons induced backgrounds, including cosmogenic production of (βn)-decaying isotopes

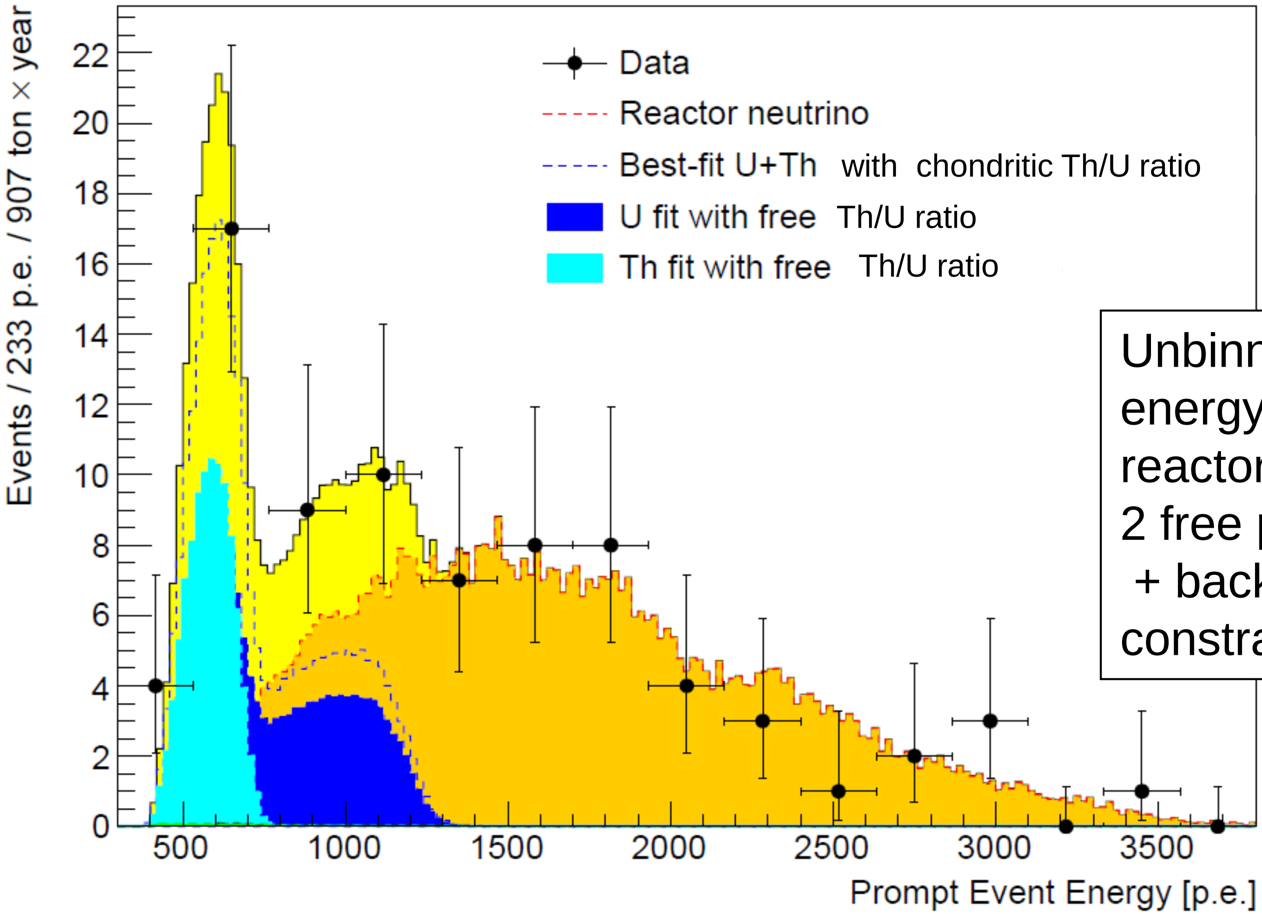


3)Internal radioactive contamination: accidental coincidences,

(αn) reactions



Borexino 2015: antineutrino spectrum (77 events)

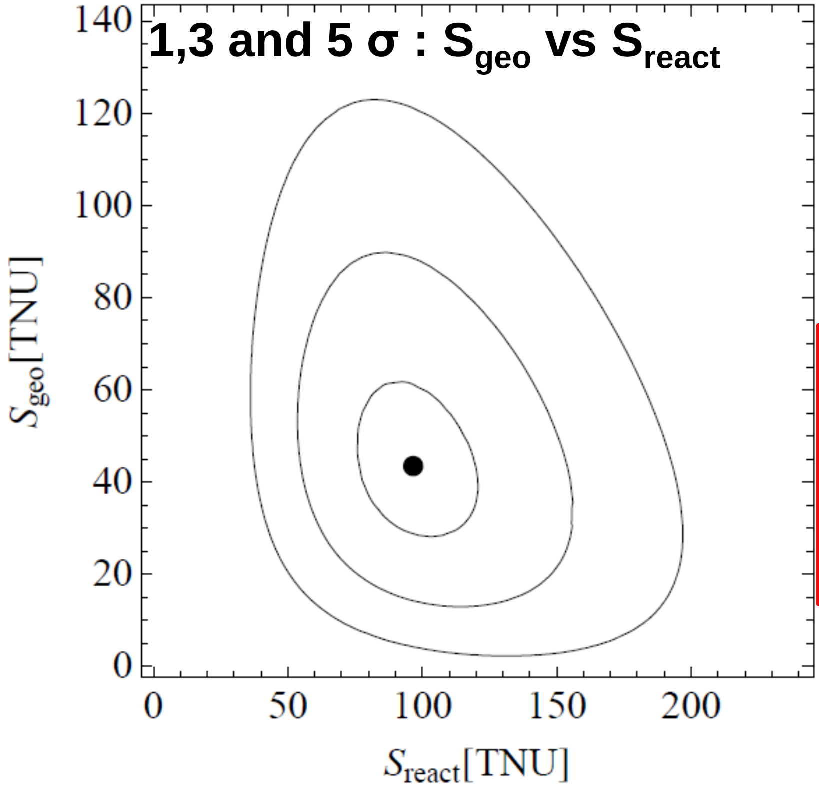


Unbinned likelihood fit using MC energy spectra for geo and the reactor antineutrinos
2 free parameters S_{geo} and S_{react}
+ backgrounds components constrained

$$Q_{vis} = 438\, p.e.(2\gamma) + Q(E_{\bar{\nu}} - 1.8 MeV)$$

~500 p.e./MeV (electrons)
gammas are quenched

Borexino: fit results for fixed M(Th)/M(U)=3.9

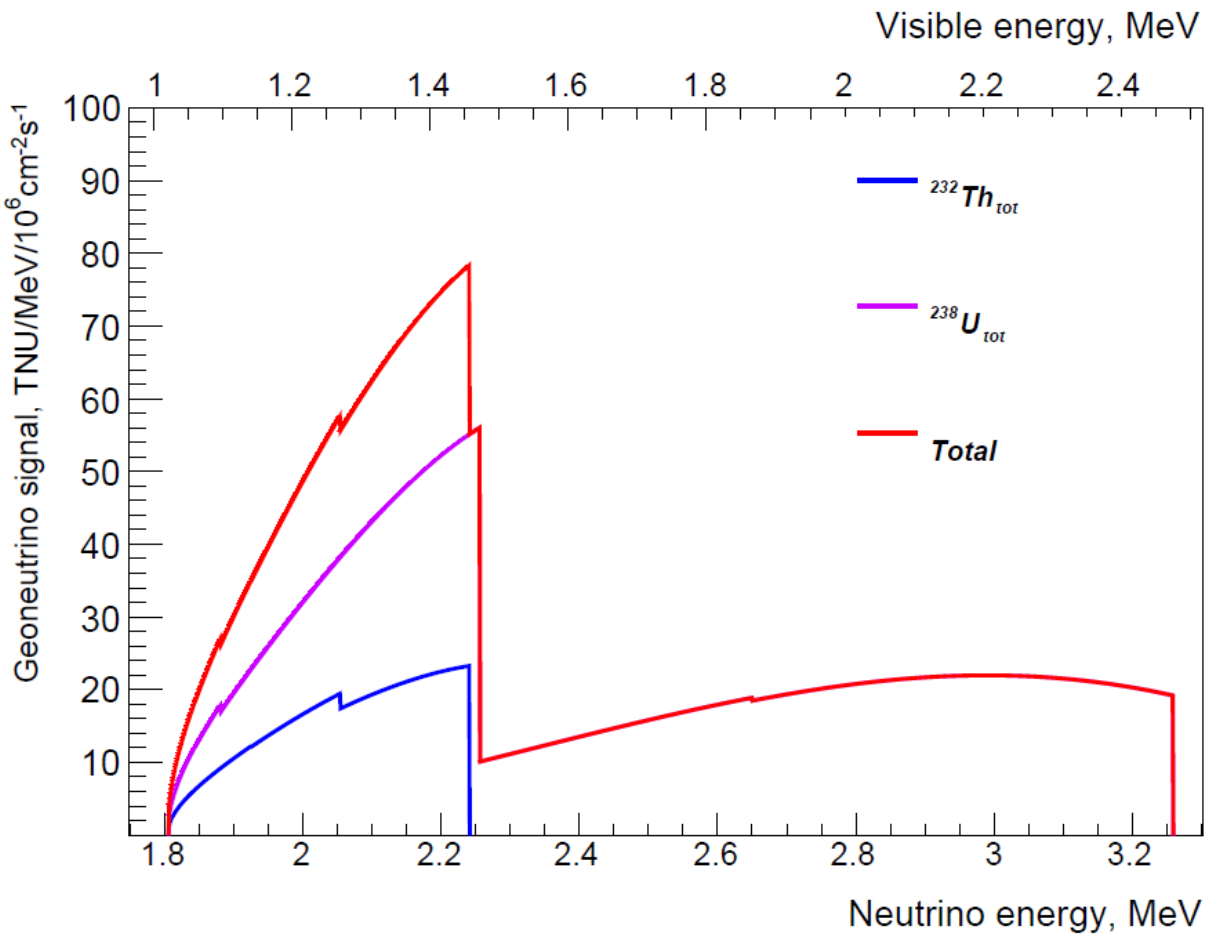


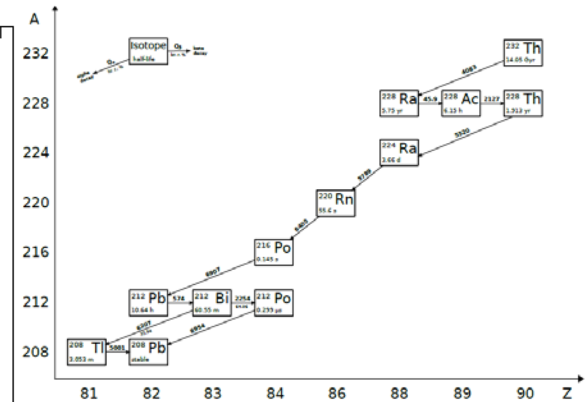
$N_{geo}=23.7^{+6.5}_{-5.7}(\text{stat})^{+0.9}_{-0.6}(\text{syst})$ events

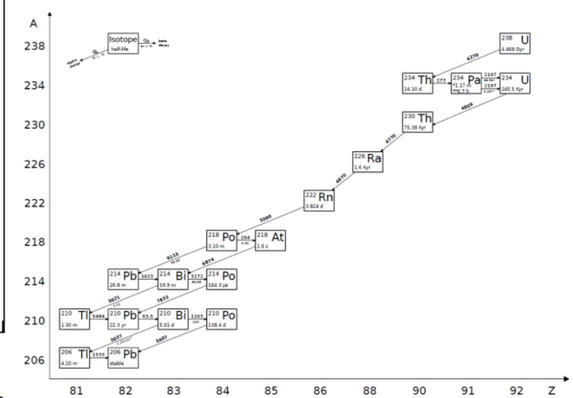
$S_{geo}=43.5^{+11.8}_{-10.4}(\text{stat})^{+2.7}_{-2.4}(\text{syst})$ TNU

- Systematics: 4.8% on FV and 1% on the energy scale
- *1 TNU = 1 event on 10^{32} protons in 1 yr (~1 kt of LS)

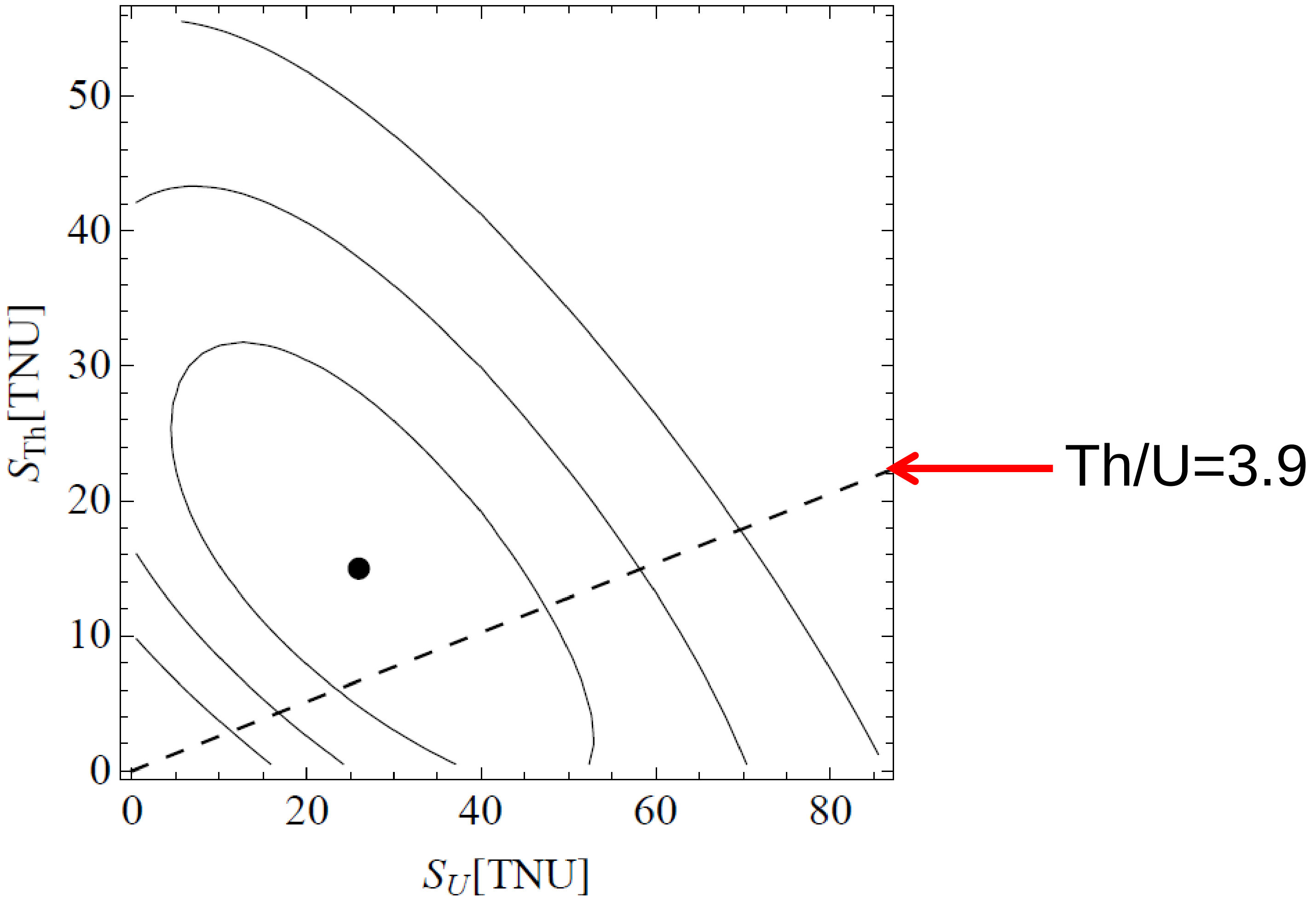
U/Th signal (no energy resolution)





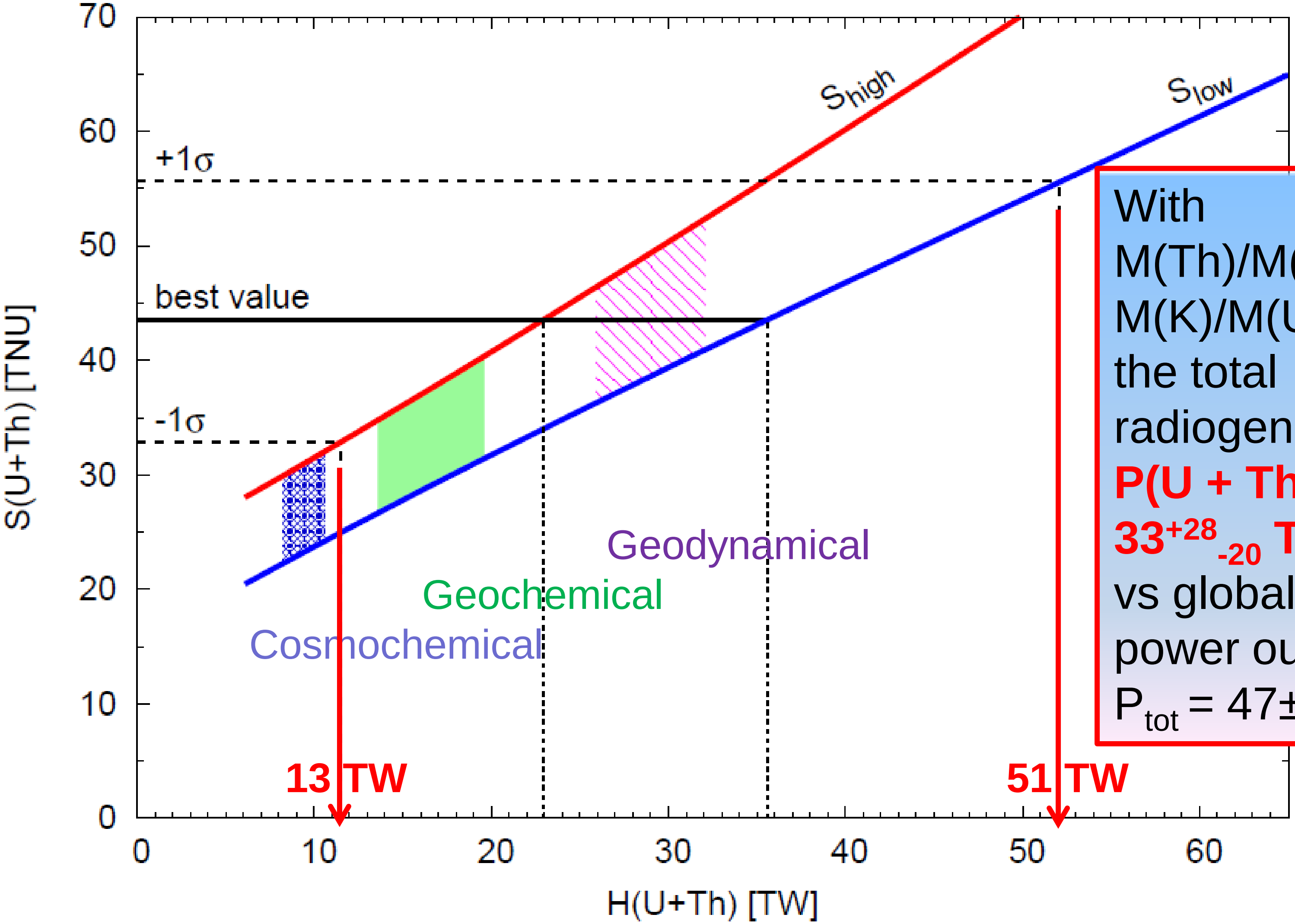


Unconstrained U/Th analysis



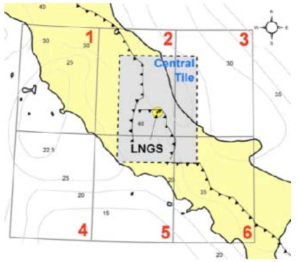
1,2 and 3 σ contours for S_U:S_{Th} signals

Radiogenic heat: Borexino



With M(Th)/M(U)=3.9 & M(K)/M(U) = 10^4 the total terrestrial radiogenic power :
P(U + Th + K) = 33^{+28}_{-20} TW,
vs global terrestrial power output
P_{tot} = 47±2 TW

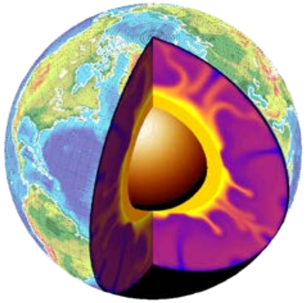
Red line: ROC+LOC+1σ, homogenios mantle
Blue line: ROC+LOC-1σ, radiogenic material on the mantle/core interface



Signal from the mantle

- ***Total contribution from the Earth crust (Coltorni et al.,* Huang et al.) *(LOC + ROC) is S_{geo}(Crust) = (23.4 ± 2.8) TNU -> 12.75 ±1.53 events (+stat.smearing)***

- **subtraction of probability distributions for the total signal (from the fit) and pdf for crust (normal approximation). Non-physical values of difference are excluded and final p.d.f. renormalized to unity.**



p.d.f.(Mantle)=p.d.f. (Geo)-p.d.f.(Crust) :

$$\boldsymbol{S_{geo}(Mantle)} = 20.9^{+15.1}_{-10.3}\ \mathrm{TNU}$$

Mantle could have as little as 1-3 TW or as much as 28 TW

with a probability of 98% we observe at least 1 event from the mantle

- Note:
  - Mean value is bigger compared to a simple difference $<S_{geo}>-<S(Crust)>=43.5-23.5=20.1$ as a result of excluding non-physical values from p.d.f.
- LOC: M. Coltorti et al., Earth Planet. Sci. Lett. 293 (2010) 259.
- ROC: Y. Huang et al. Geochemistry, Geophysics, Geosystems 14, 2003 (2013).

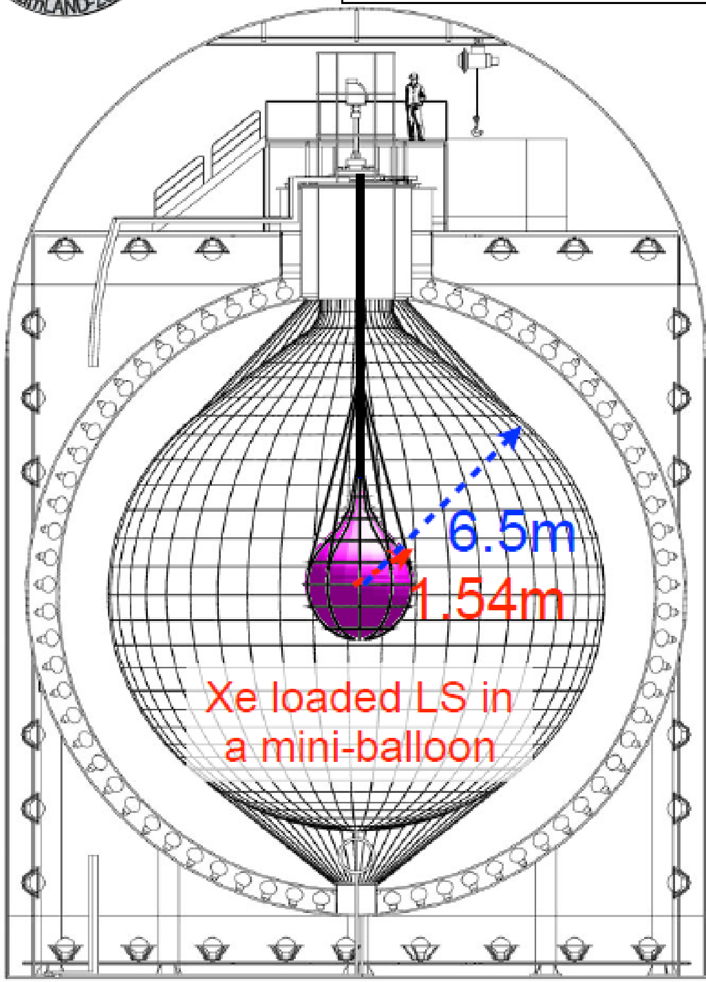
Another measurement with Borexino?

- about 3 yrs of data more in solar mode before SOX program start (+ ~50% statistics)
- tuning of the muon-veto cut following KamLAND approach will save 9% of live-time
- spectral fit in all volume (+ ~50% statistics): better understanding of “external” background (close to the IV walls) is needed

KamLAND

KamLAND-Zen
2011~

Zero Neutrino
double beta decay search

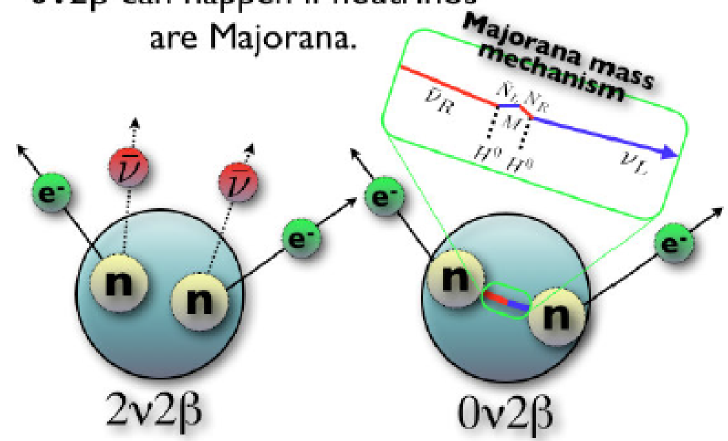


- Detector Features

  ^{136}Xe loaded LS was installed in KamLAND
  (344 kg 90% enriched ^{136}Xe installed so far)

- Physics

0ν2β can happen if neutrinos are Majorana.



neutrino-less double beta decay

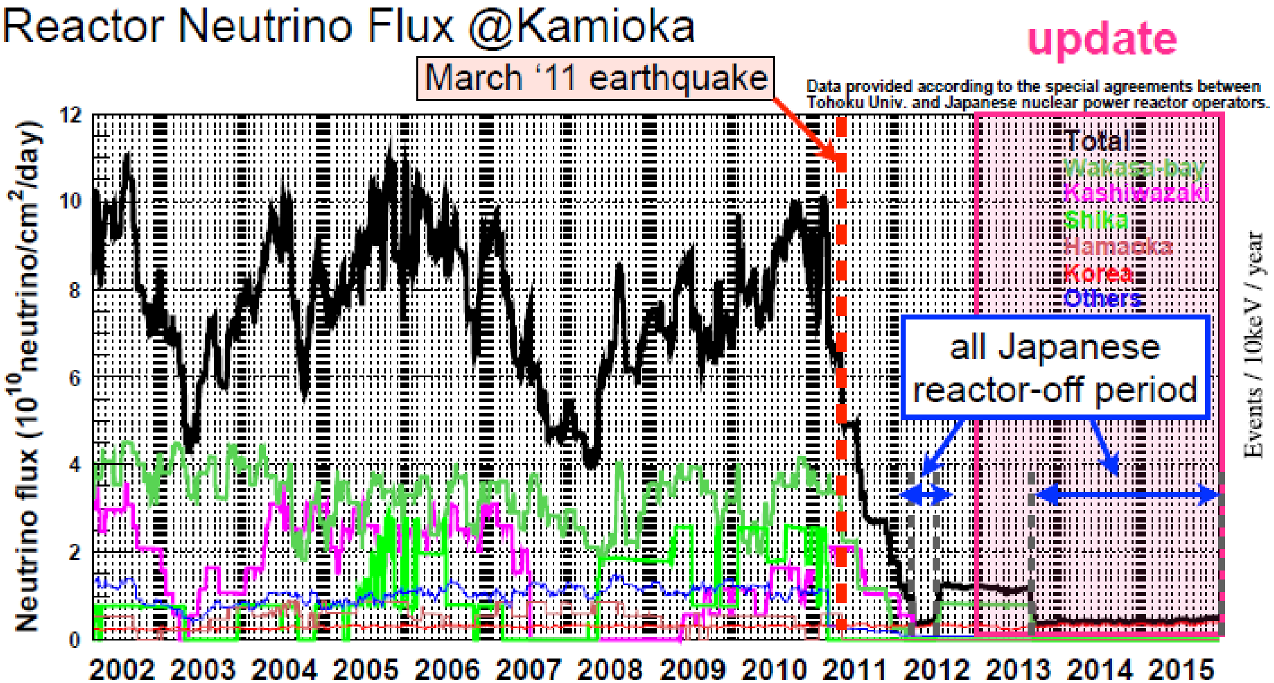
World best limit on neutrino effective mass

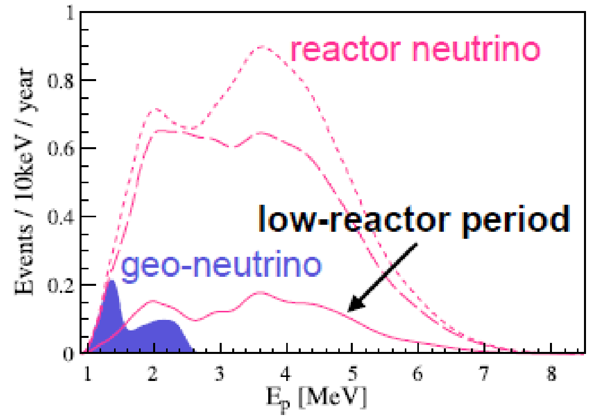
$$\langle m_{\beta\beta} \rangle < (61 - 165)\ \mathrm{meV}$$ PRL 117, 082503 (2016)

Continue to use LS volume outside of mini-balloon to measure anti-neutrino signals

From the talk by Hiroko Watanabe

Current dataset





Reactor neutrino background is decreased significantly.

PRD 88, 033001 (2013)

Preliminary

2013 data-set : 2991 days
4.90×10^{32} proton-year

2016 data-set : 3901 days
6.39×10^{32} proton-year

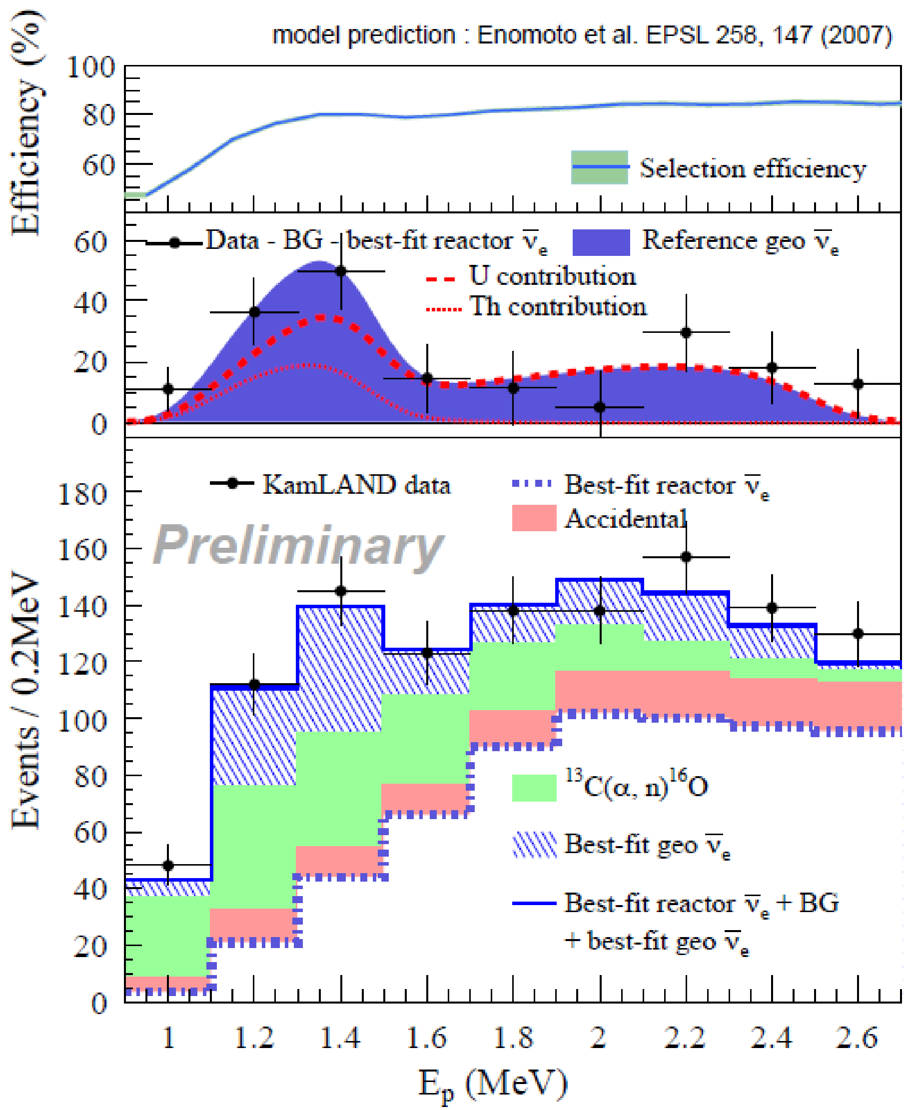
- 1.3 times of 2013 data-set

advantages
- low-reactor operation period : **~3.5 years** livetime
- **all Japanese reactor-off period : ~2.0 years** livetime

Precise understanding of reactor neutrino spectrum enhances geo-neutrino measurement.

From the talk by Hiroko Watanabe

Energy Spectrum (0.9-2.6 MeV)



2016 Preliminary Result

Livetime : 3900.9 days

Candidate : 1130 ev

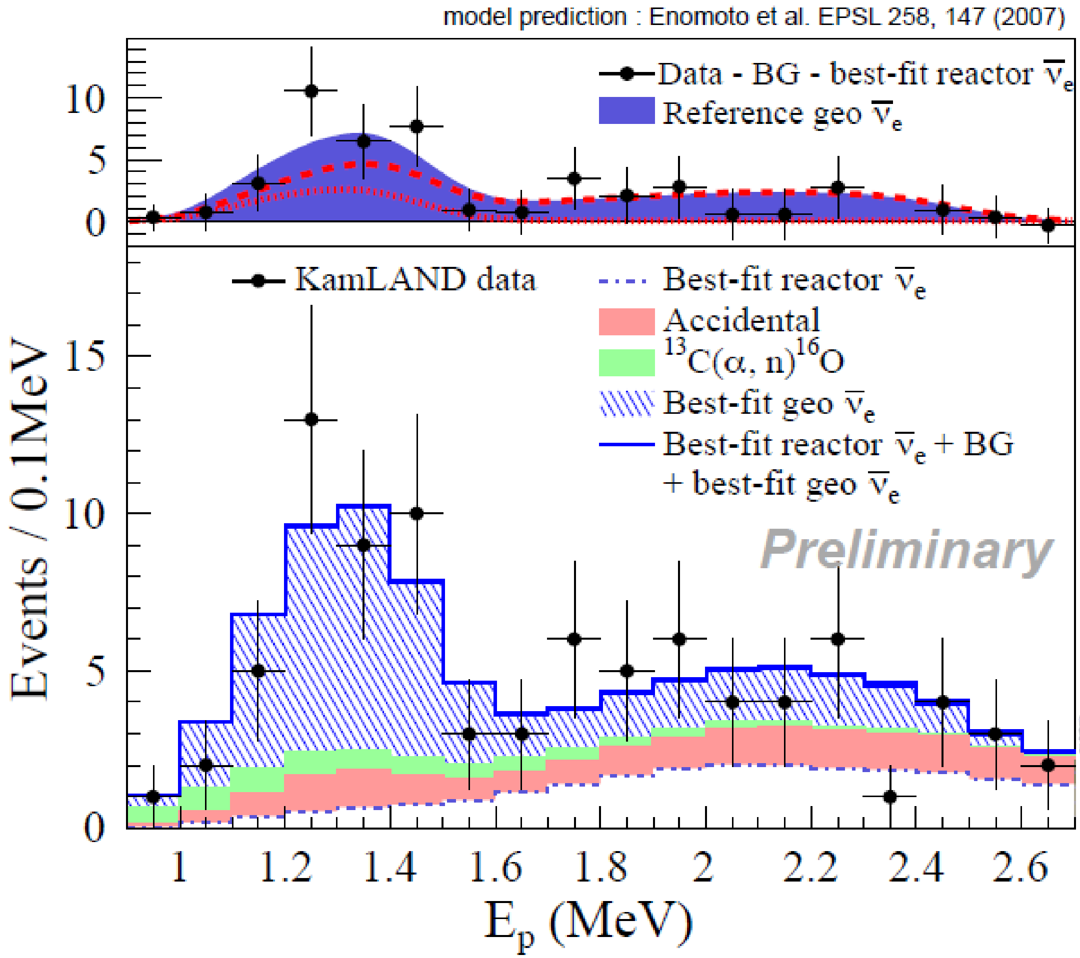
Background Summary

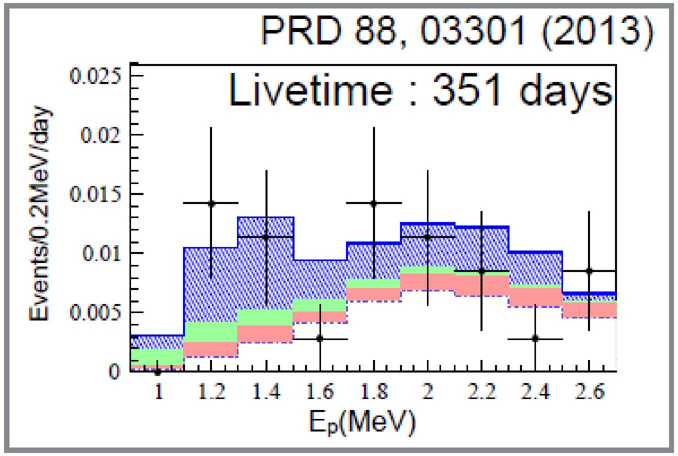
^{9}Li	3.4 ± 0.1
Accidental	114.0 ± 0.1
Fast neutron	< 4.0
$^{13}C(\alpha, n)^{16}O$	205.5 ± 22.6
Reactor $\overline{\nu}_e$	**618.9 ± 33.8**
Total	941.8 ± 40.9

From the talk by Hiroko Watanabe

Energy Spectrum, Period 3 (0.9-2.6 MeV)

Livetime : 1259.8 days 2016 Preliminary Result





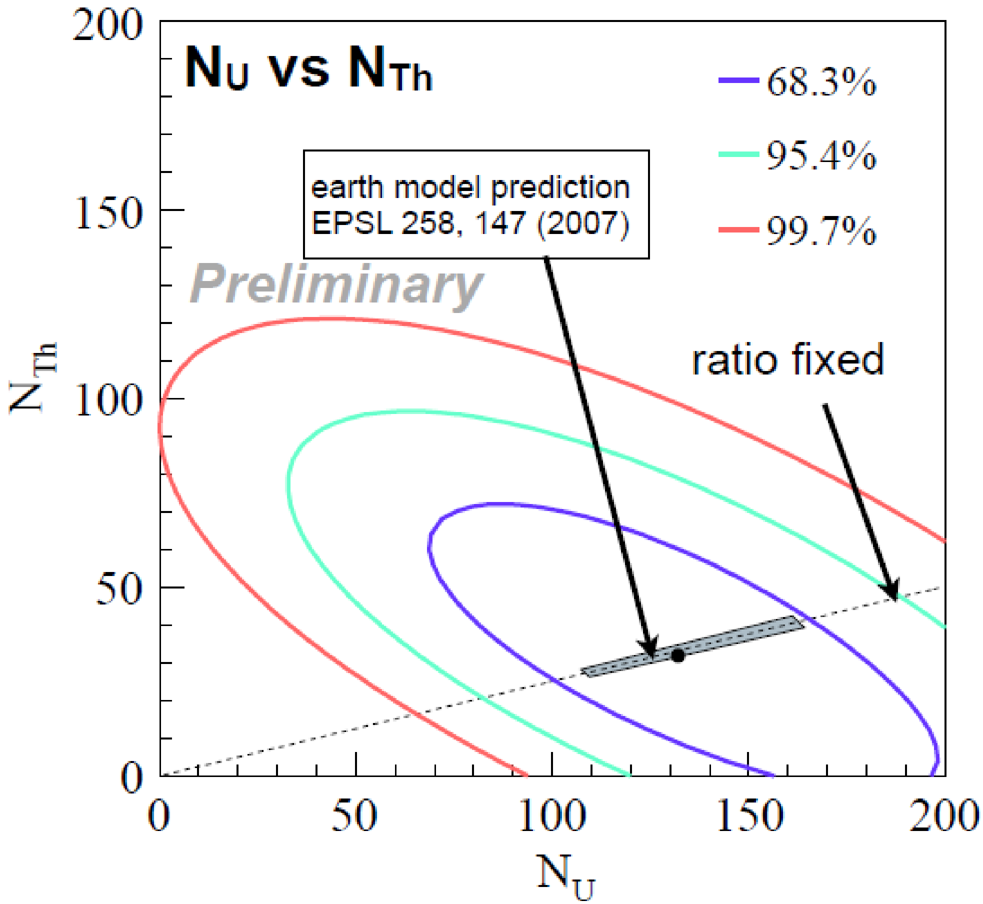
☑ We measured clear distribution of geo-neutrino events.

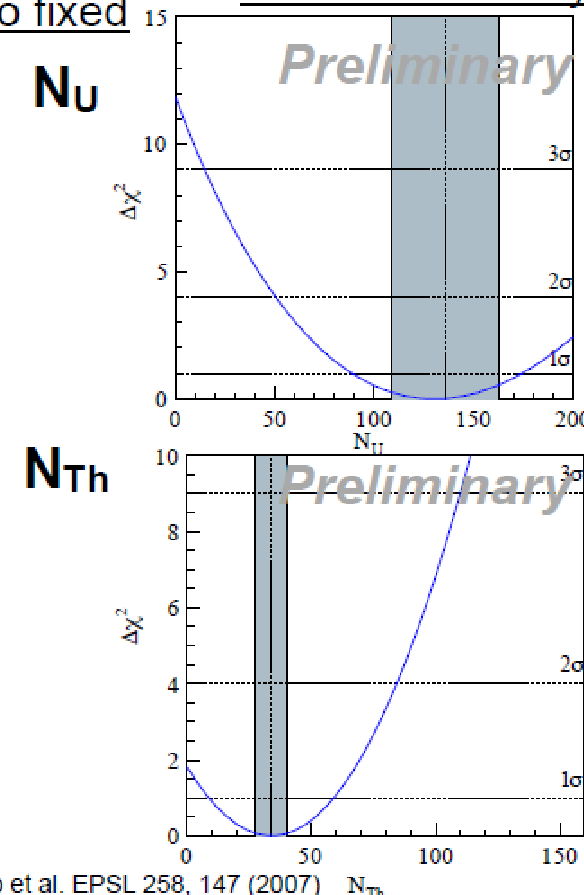
best-fit : Period 3 analysis

From the talk by Hiroko Watanabe

Rate + Shape + Time Analysis

2016 Preliminary Result





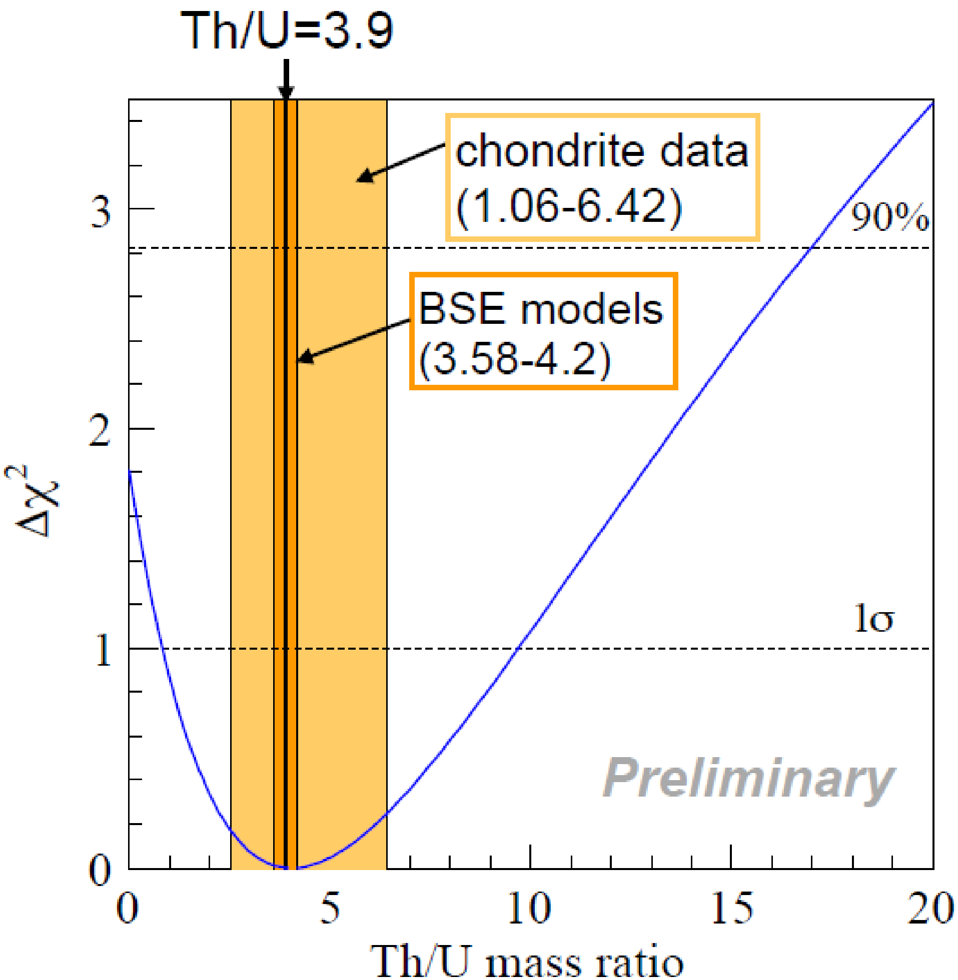
model prediction : Enomoto et al. EPSL 258, 147 (2007)

		[event]	[TNU]	Flux [×10^5 cm^{-2}s^{-1}]		0 signal rejection
				best-fit	model	
ratio fixed	U	**128 +46/-39**	27.1 +9.8/-8.3	20.8 +7.5/-6.4	22.0	**3.44σ**
	Th	**32 +27/-23**	6.9 +5.9/-5.0	17.2 +14.5/-12.5	18.6	**1.34σ**

From the talk by Hiroko Watanabe

Th/U Mass Ratio

2016 Preliminary Result



Best fit

Th/U = 4.1 $^{+5.5}_{-3.3}$

Th/U < 17.0 (90% C.L.)

ref) 2013 paper Th/U < 19 (90% C.L.)

- **We have a sensitivity of Th/U mass ratio of entire Earth.**
- **KamLAND best-fit is consistent with chondrite data and BSE models.**

ref) chondrite data

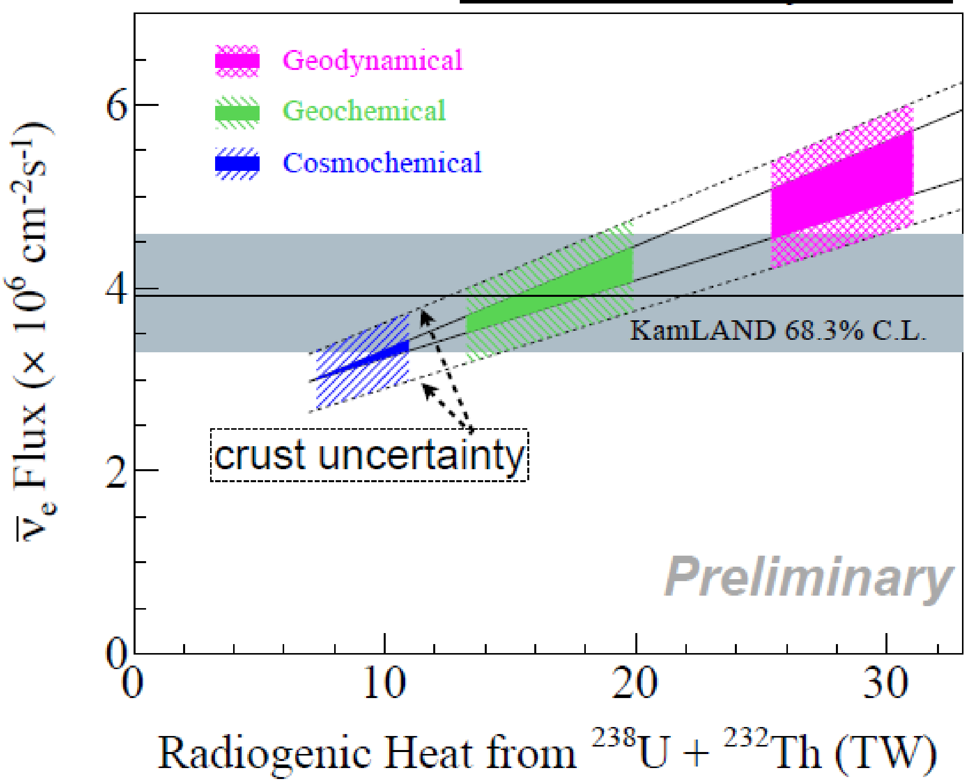
Ordinary Chondrites : J. S. Goreva & D. S. Burnett, Meteoritics & Planetary Science 36, 63-74 (2001)

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

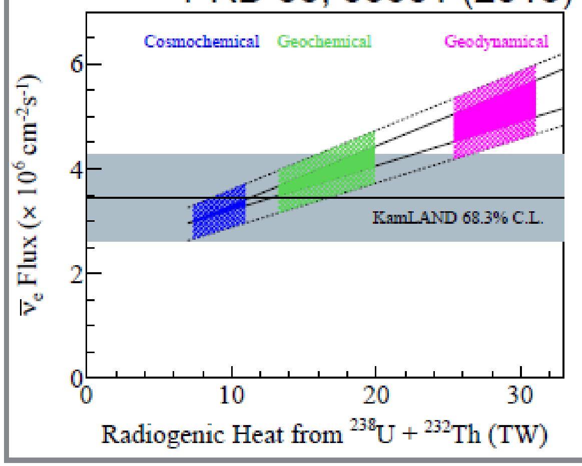
Enstatite Chondrites : M. Javoy & E. Kaminski, EPSL 407, 1-8 (2014)

Data vs Earth Models

2016 Preliminary Result



PRD 88, 03301 (2013)



[BSE composition models]

Geodynamical

based on balancing mantle viscosity and heat dissipation

Geochemical

based on mantle samples compared with chondrites

Cosmochemical

based on isotope constraints and chondritic models

From the talk by Hiroko Watanabe

Summary

- Borex: **$23.7^{+6.5}_{-5.7}$** ev (~25%; P(0) excluded @5.9σ)

both with fixed Th/U ratio

- KL : **164^{+28}_{-25}** ev (17%; P(0) excluded @7.9σ)

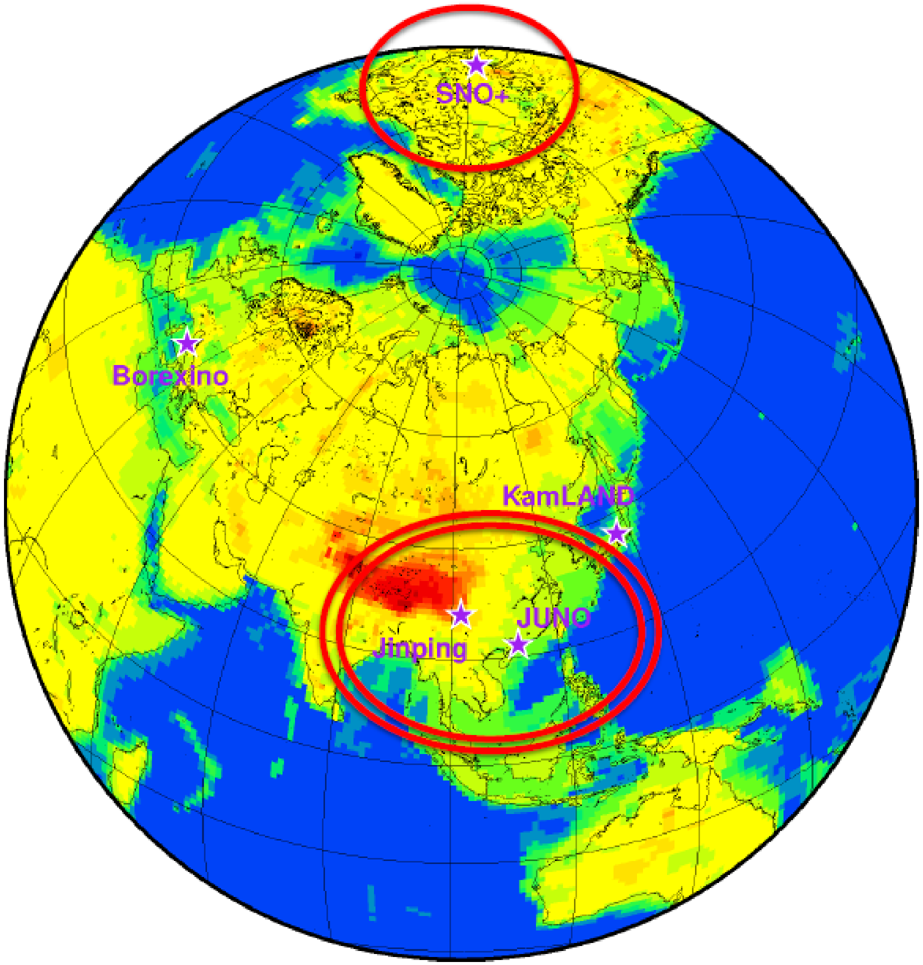
- Mantle signal:

  BRX: $20.9^{+15.1}_{-10.3}$ TNU; P(0)<0.02
  KL : $8.2^{+6.6}_{-6.0}$ TNU

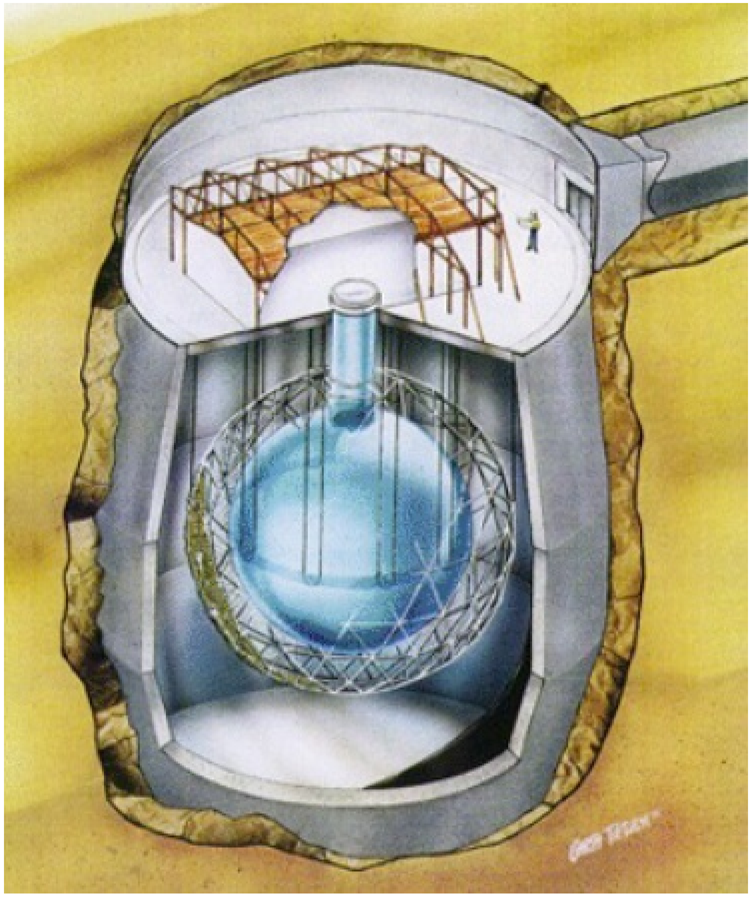
- KamLand: Th/U ratio:

  $M(Th)/M(U)=4.1^{+5.5}_{-3.3}$

Upcoming experiments



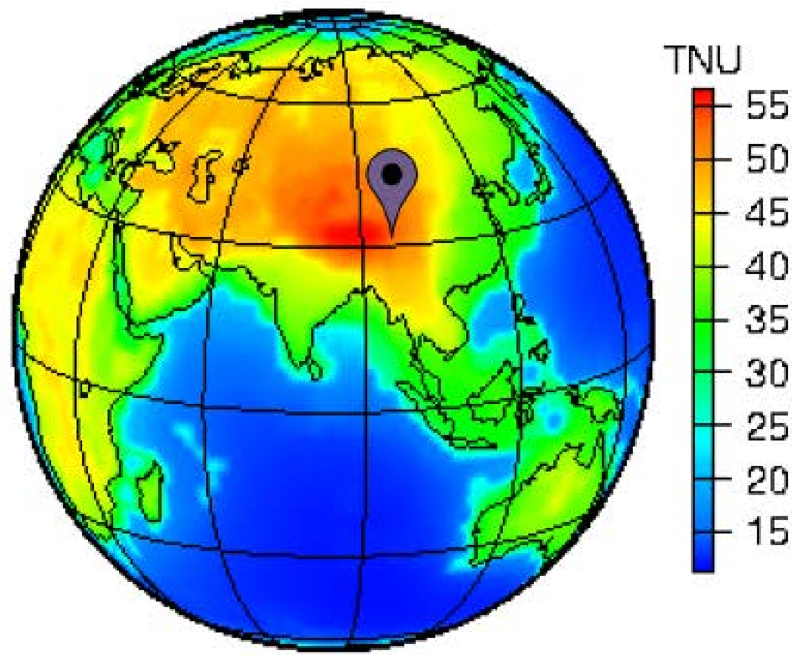
SNO+



29 geo-neutrino events per live-year (in 780 tones LAB) compared to 26 events from reactors in the same energy range

Local Geology around Sudbury ***maybe the best understood portion of crust in the world***

Jinping Neutrino Experiment (after 2020)

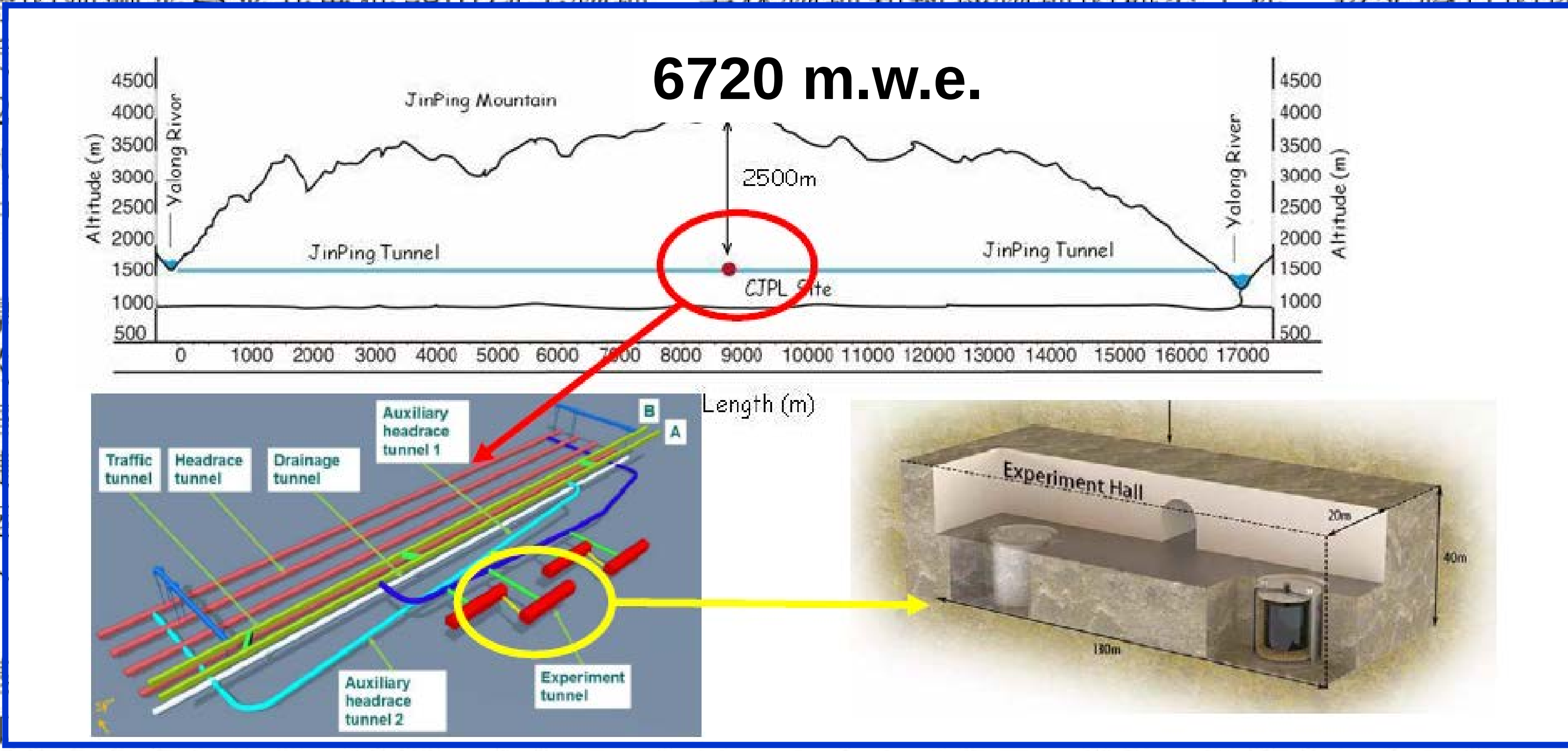


❑ Near Himalaya mountains.

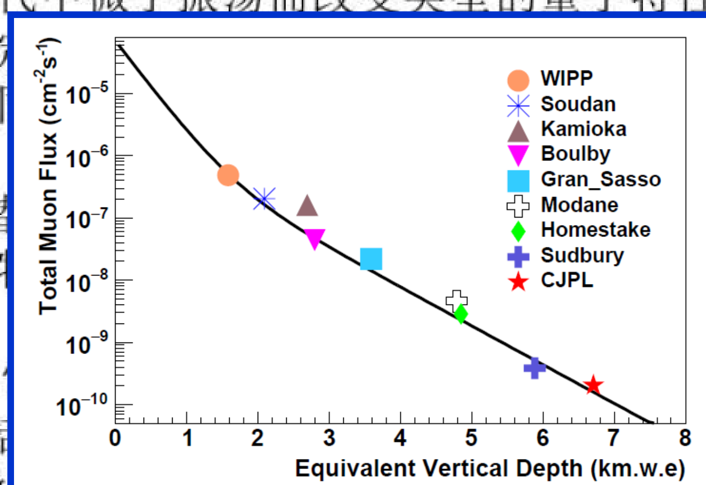
A formal laboratory inauguration was held 12 December 2010.

在本意向书中，我们建议开展锦屏中微子实验（Jinping Neutrino Experiment），利用这一

独特 … 测器靶
物质 … 靶体积
为 2 … 技术，
并和 … 势，锦
屏中 …



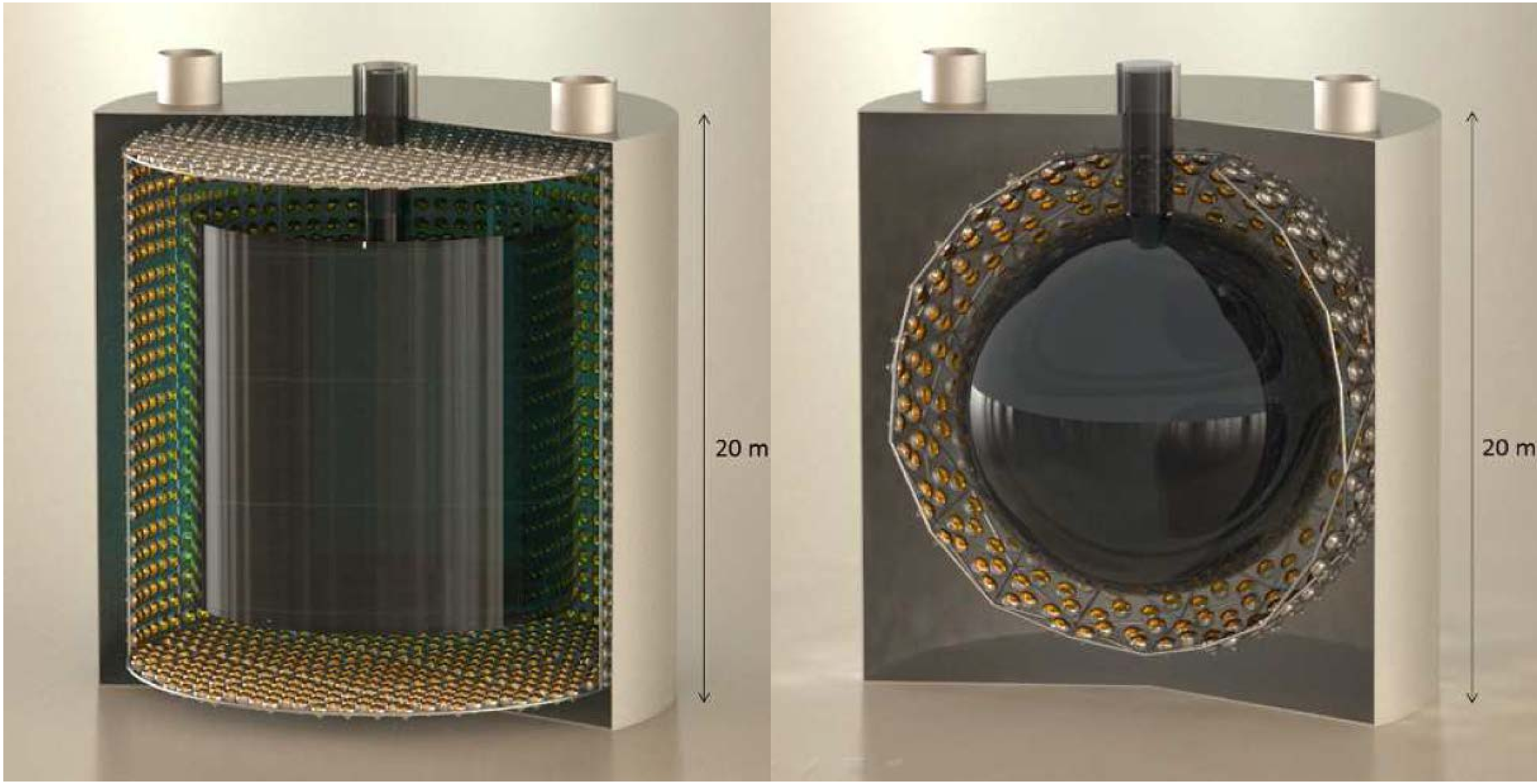
… g. 1）：
最厚 … 性、最
长的 … 微子实
验室 … 况良好
便捷 … ）已经
在这 … ，将开
挖～
… 地球科
学基 … 为研究
诸如 … 中微子
因其发生在真空与物质中的三代中微子振荡而改变类型的量子特性，使其在探索新物理方面极其敏感，包括实验上尚未精确测 … 子实验如果能与其他中微子实验相结合，将会为研究来源不 … 同时还可以给出对中微子各种属性的检验。



基于锦屏实验室的条件和潜 … 步的实验灵敏度研究，给出的结论包括在中微子物理，天体 … 实验发现，以及实验测量精度改进的估计。

锦屏中微子实验凭借其非 … 日内部聚变过程产生的能量为几个MeV 的中微子测量，包括 … 的测量（Fig. 2）。锦屏中微子实验可以精确测定太阳中微 … 度过程，从而在高密度环境下

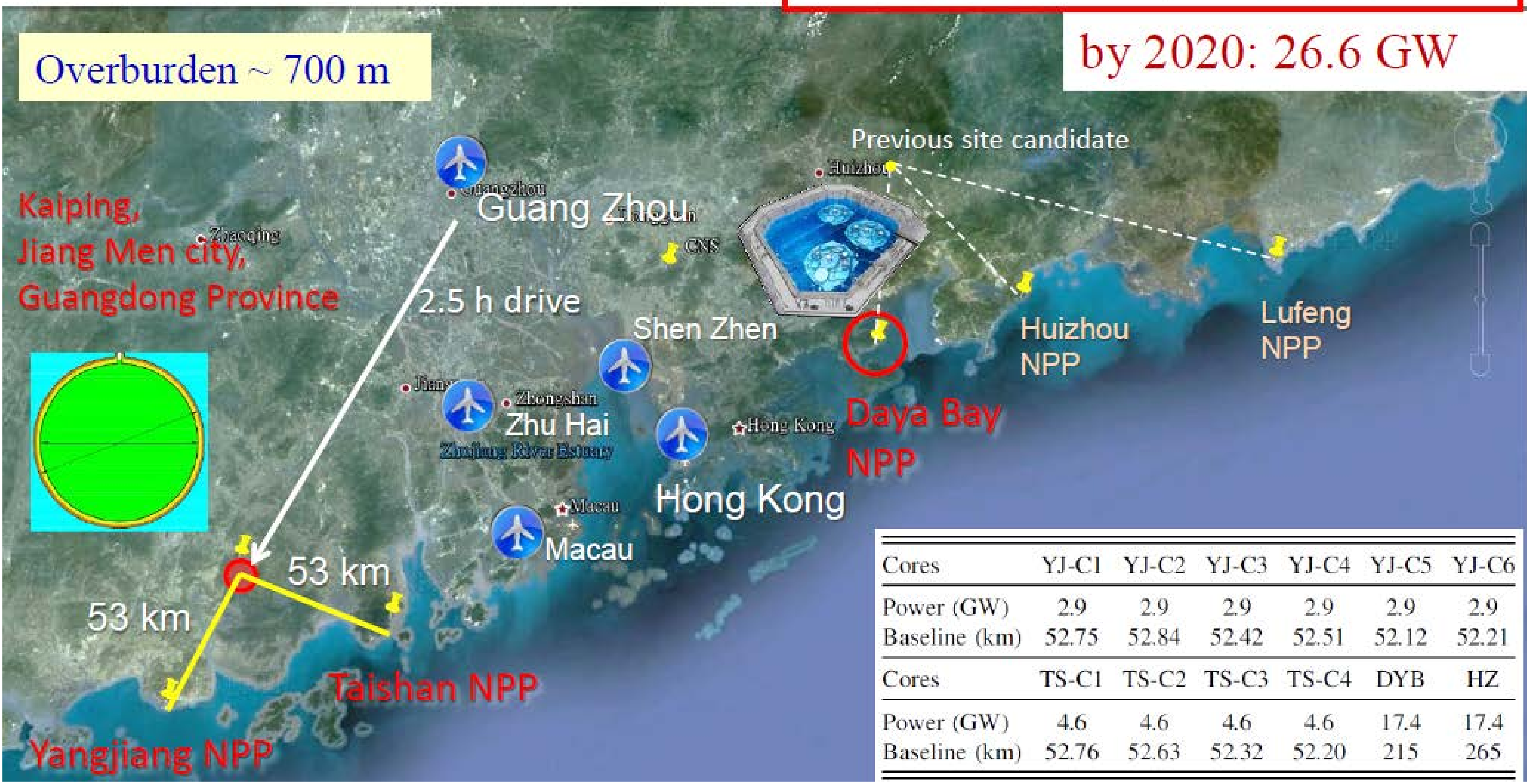
Possible options for the detector (x2)



Fiducial mass ~2 kt

JUNO (2020)

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

Expected antineutrino spectrum

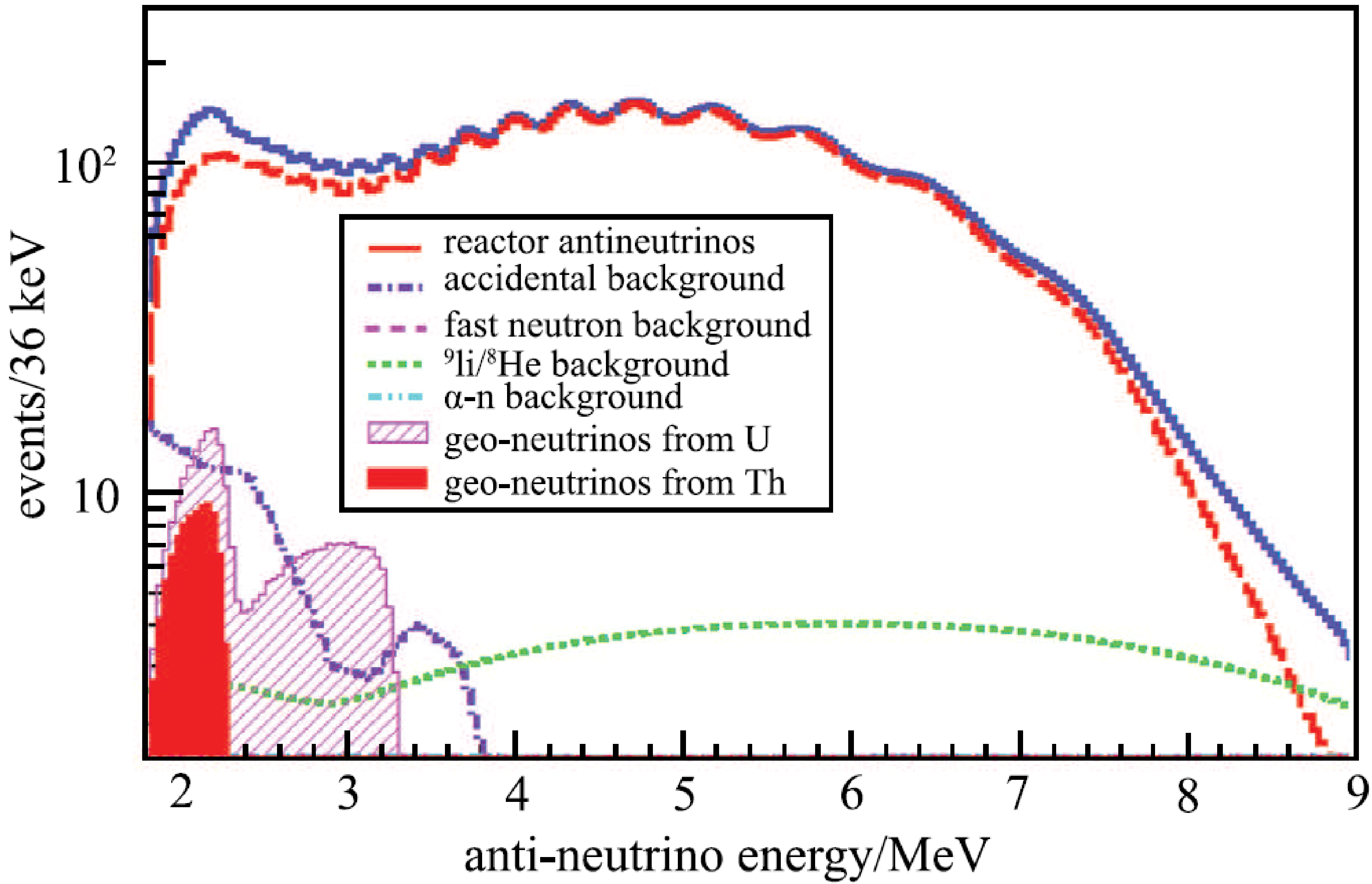


Fig. from R.Han, et al., Chinese Phys. C, Vol 40, No3 (2016) 033003

JUNO: Summary of expected rates

Source	[1.8-9.0] MeV ev/yr	[1.8-3.3] MeV ev/year	Uncertainty
geo	408	406	
reactor	16100	3653	±2.8%(rate)±1%(shape)
$^8Li/^8He$	657	105	±20%(rate)±10%(shape)
fast n	36.5	7.7	±100%(rate)±20%(shape)
αn	18.2	12.2	±50%(rate)±50%(shape)
accidental	401	348	±1%(rate)

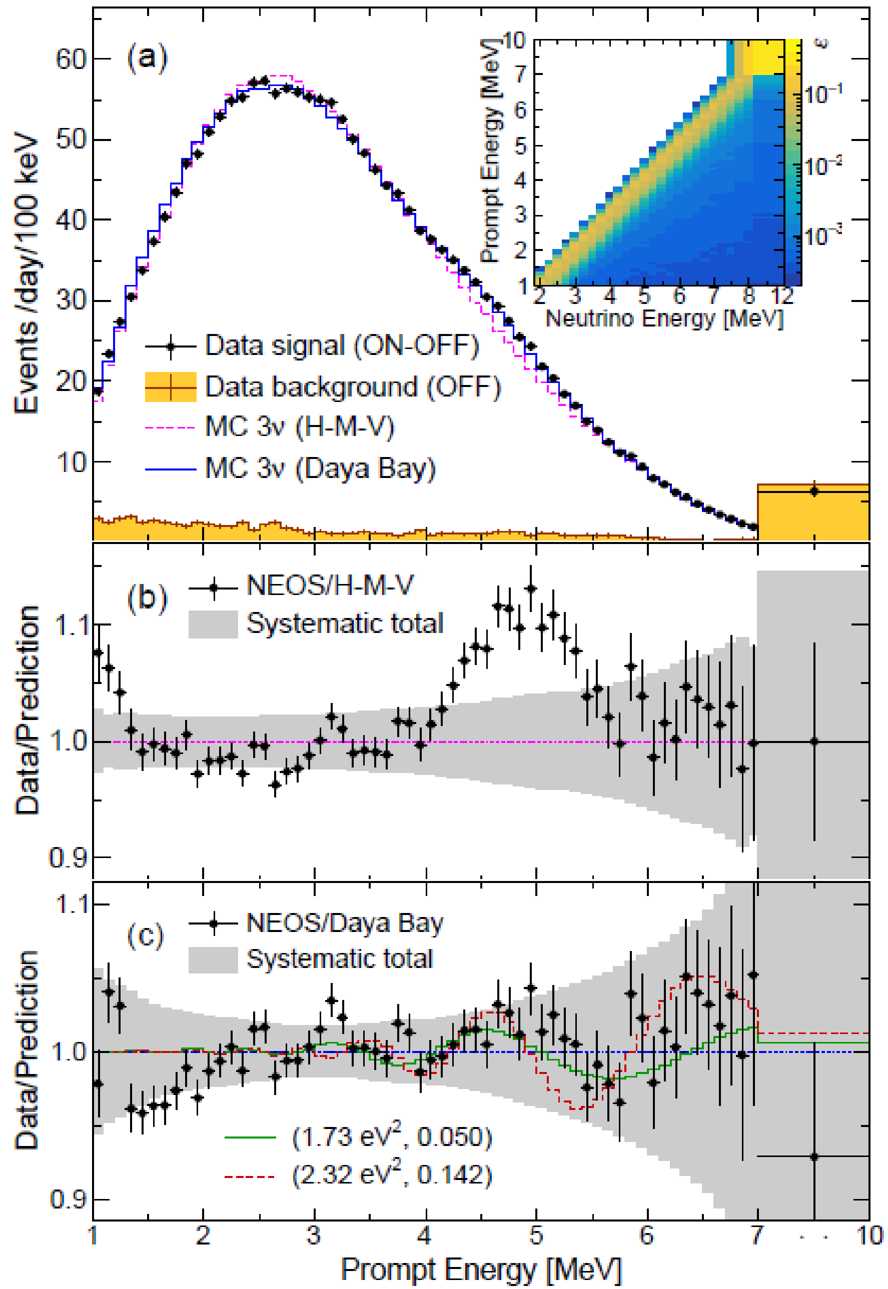
20t->FV(R<17.2m) 18.35t or $12.85 \cdot 10^{32}$ protons
ε=80% detection efficiency assumed in calculations
acrylic vessel (^{238}U: 10 ppt, ^{232}Th: 10 ppt)
LS: 10^{-15} g/g $^{238}U/^{232}Th$

Reactor spectrum

Y.J. Ko, et al., “A sterile neutrino search at NEOS Experiment”

Phys. Rev. Lett. 118, 121802 (2017)

24 m from reactor
R(E)=5% @ 1 MeV
1965 ev/day
46 days reactor OFF
180 days reactor ON



The differences between the fission fractions for the NEOS data and the ones for Daya Bay are taken into account and small corrections are made using the H-M flux model.

Geoneutrino signal extraction precision fixed M(Th)/M(U)=3.9

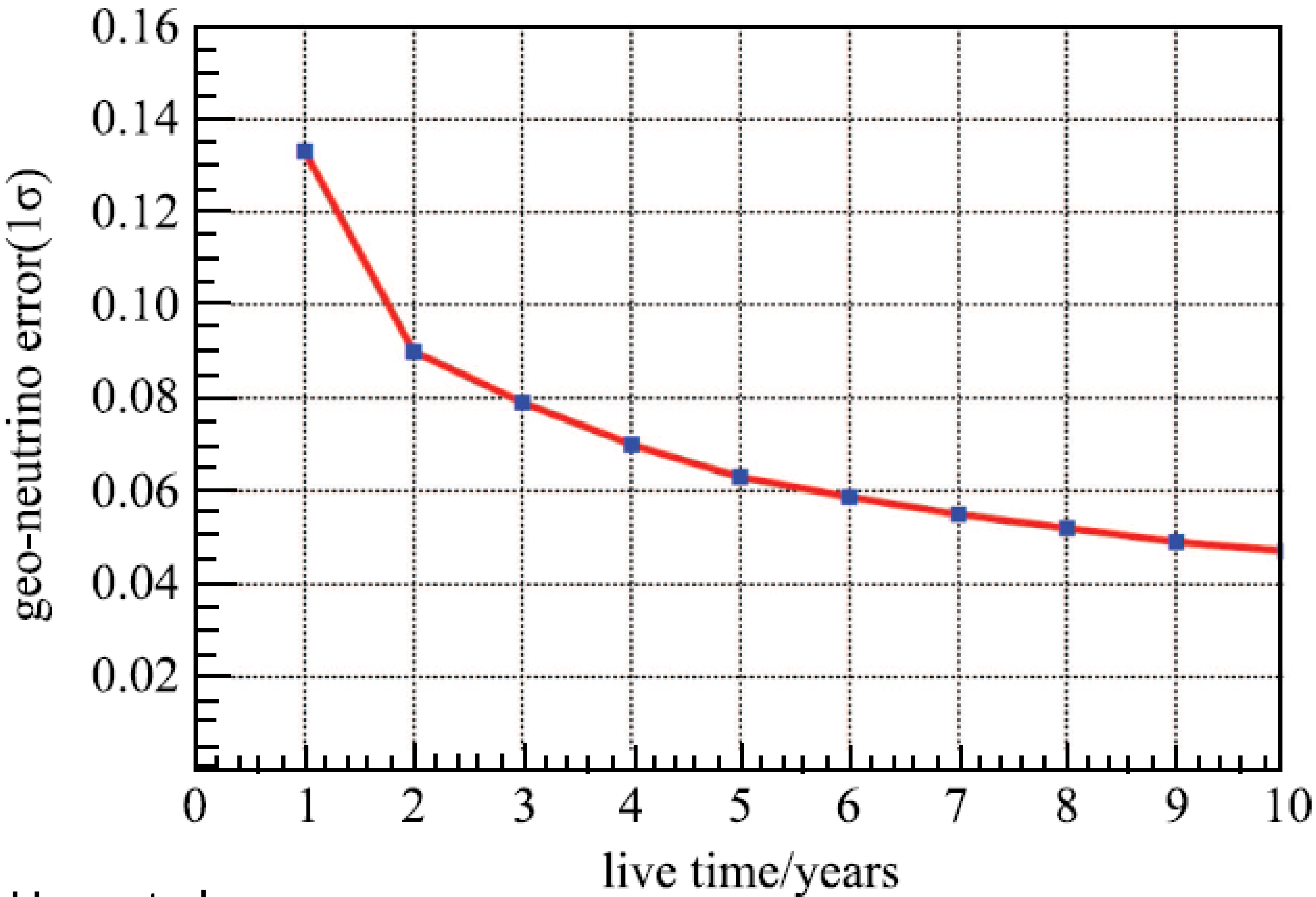
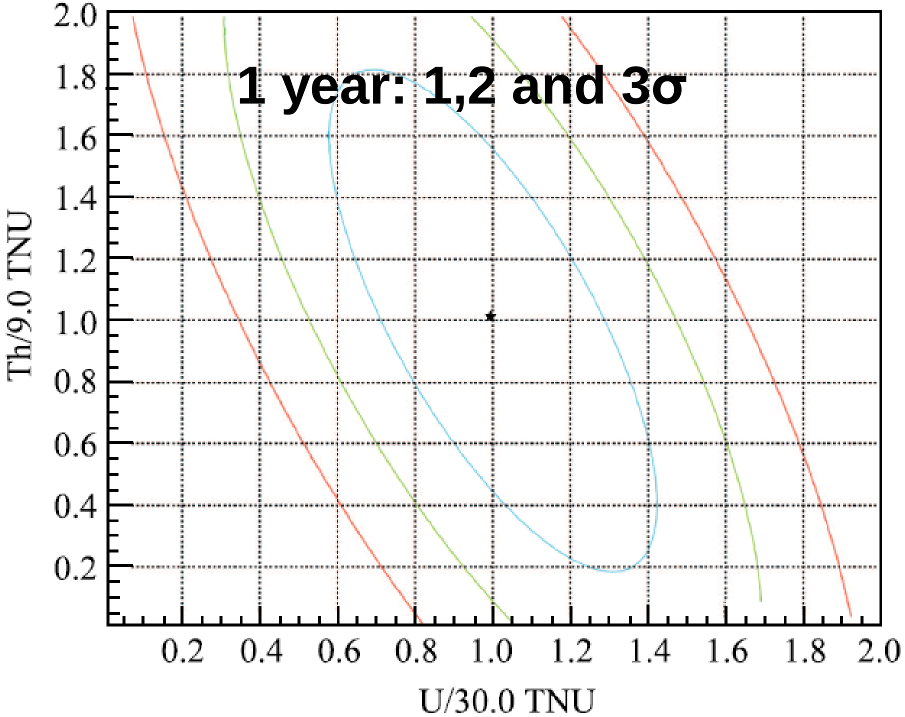


Fig. from R.Han, et al.

In JUNO publication the sensitivity was estimated as 18% for 1 yr with -4% syst.bias

Geoneutrino signal extraction precision
free Th and U components

Figs. from R.Han, et al. : no bias



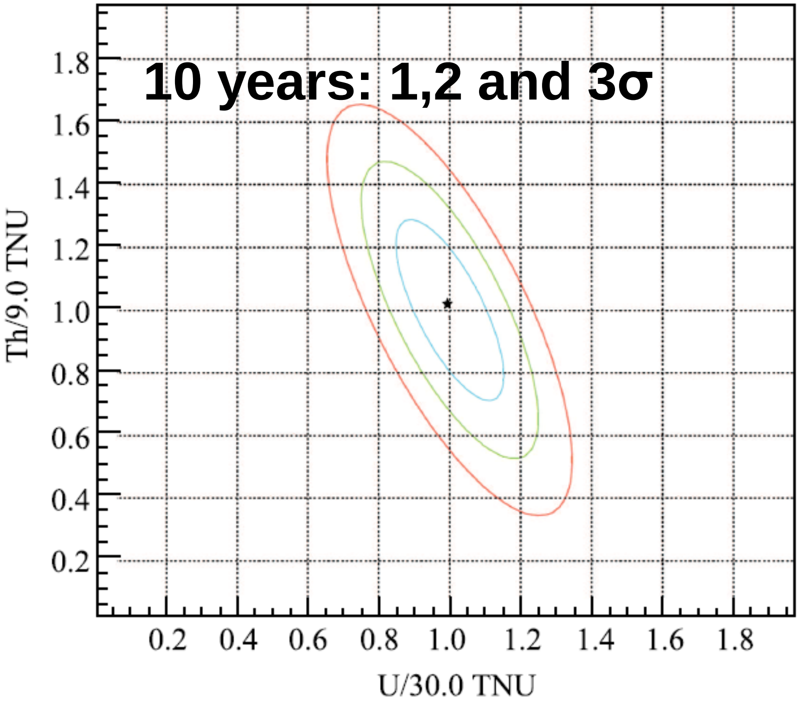


Table from JUNO publication

Number of years	U + Th (fixed chondritic Th/U ratio)	U (free)	Th (free)
1	0.96 ± 0.17	1.02 ± 0.32	0.83 ± 0.60
3	0.96 ± 0.10	1.03 ± 0.20	0.80 ± 0.38
5	0.96 ± 0.08	1.03 ± 0.16	0.80 ± 0.28
10	0.96 ± 0.06	1.03 ± 0.11	0.80 ± 0.19

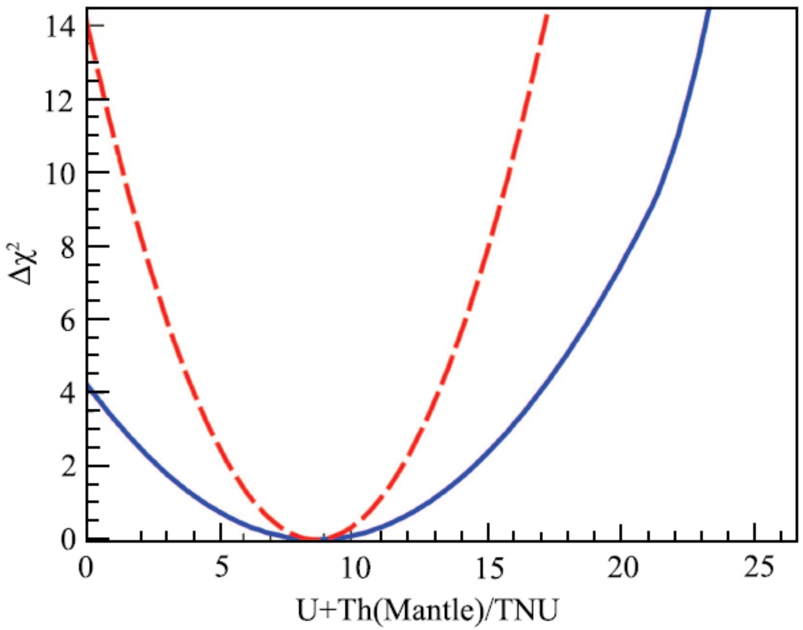
Signal from the mantle

Type equation here.Can be extracted from the measurement if crust contribution is known

R(Mantle)=R(Geo, measured)-R(Crust, predicted)

Current prediction (V. Strati, et al.) for the R(Crust) has 18% uncertainty – blue line in the plot

Red line : 8% crust contribution knowledge (KamLAND level)

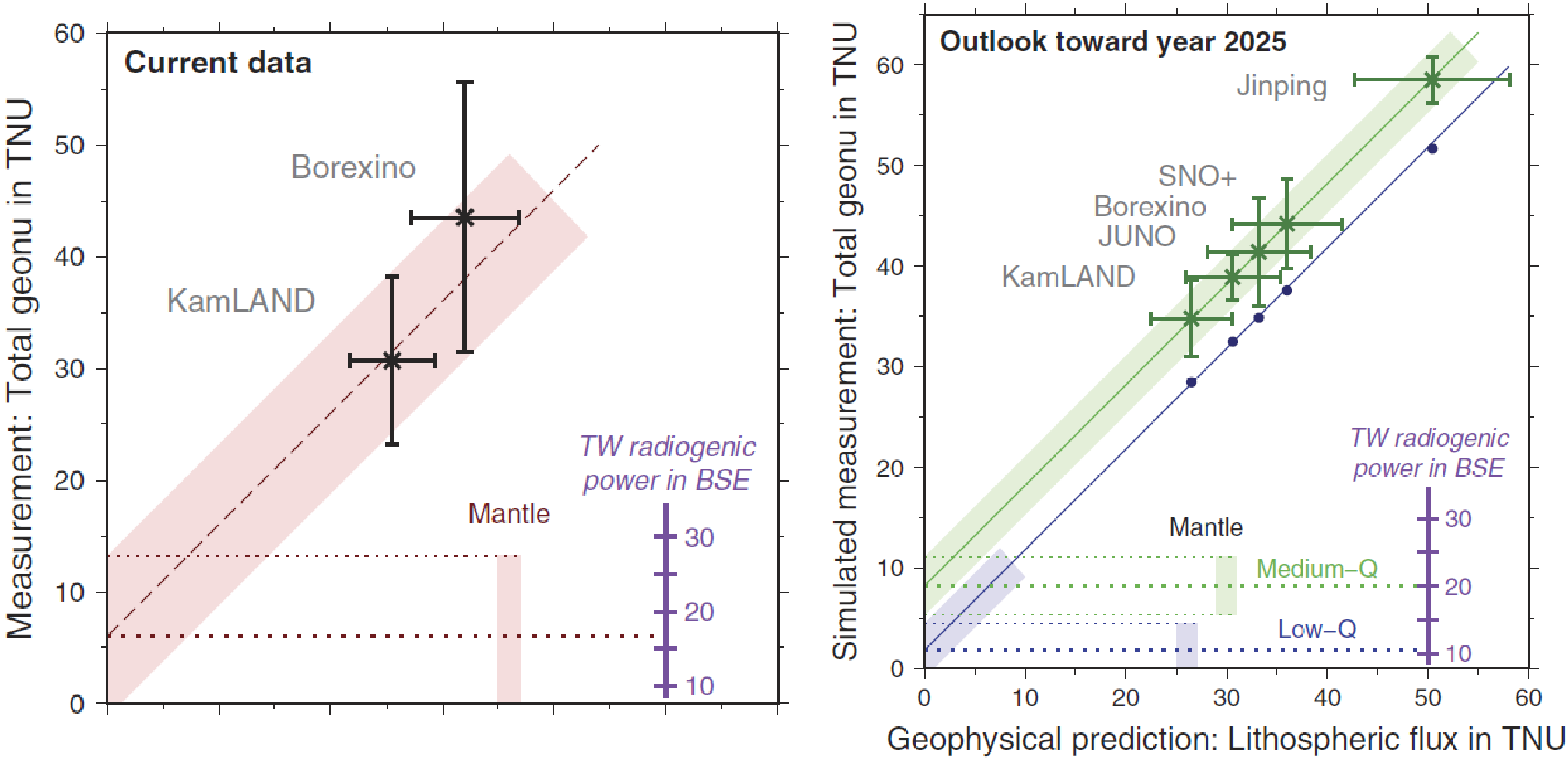


$$\Delta N_M = \sqrt{(\varepsilon_{Geo} N_{Geo})^2 + (\varepsilon_C N_C)^2 + N_C}$$

$$\varepsilon_M = \frac{1}{1 - r_C}\sqrt{(\varepsilon_{Geo})^2 + (\varepsilon_C r_C)^2 + \frac{r_C}{N_{Geo}}}$$

$$r_C \equiv \frac{N_C}{N_{Geo}} \qquad \varepsilon \equiv \frac{\Delta N}{N}$$

Mantle signal



From Ondřej Šrámek et al SCIENTIFIC REPORTS 6:33034

Directionality?

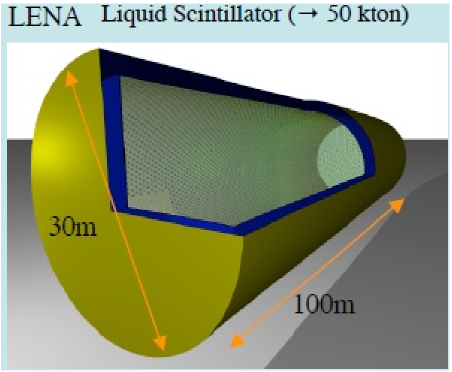
- The average forward shift of neutrons in the direction of incoming antineutrinos have been observed by reactor experiments (i.e. by CHOOZ).

- The basic idea is to search for the small statistical displacement of the capture vertex of the neutron with respect to the vertex of the prompt positron event.

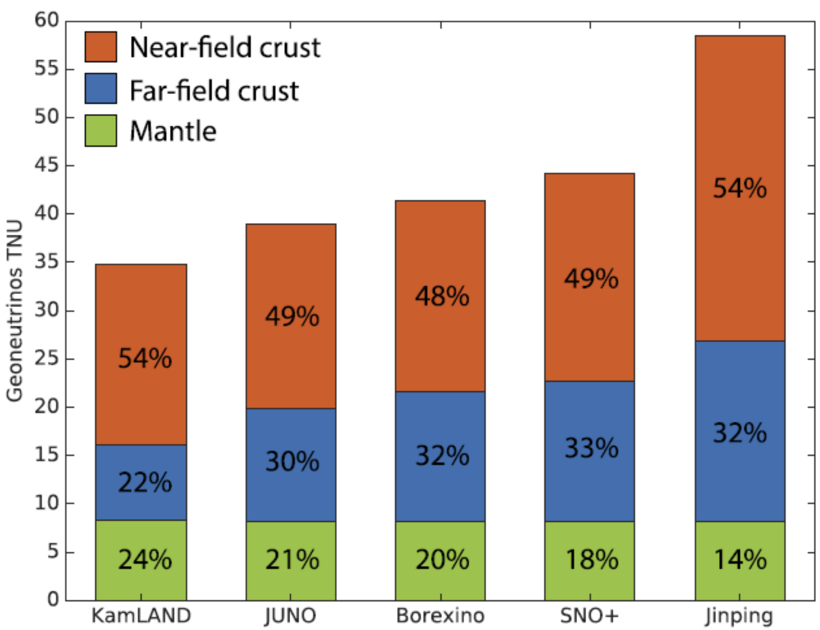
- Given the small displacement ($\sim$1.7 cm) and the large intrinsic smearing ($\sim$25 cm), the direction of the reconstructed antineutrino is only meaningful statistically and needs large statistics. Because the direction to the reactors in JUNO is known, it looks reasonable exploiting the fit of displacement distribution with predicted separate distributions from geo and reactor antineutrinos in conjunction with the spectral fit. An attempt to separate the crust and mantle geoneutrino components could be made. Both tasks need extensive MC studies.

LENA: 50 kton

~1500 geonu events/yr

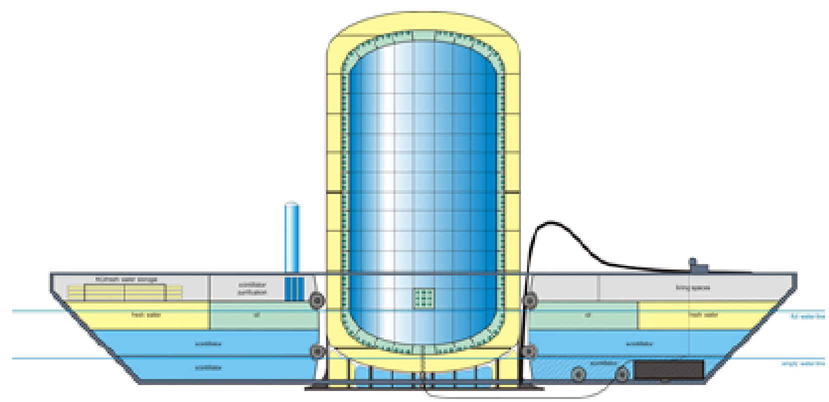


BAKSAN



Extracting mantle contribution is very important from the geophysical point of view. The combination of data from multiple sites and data from an oceanic experiment would provide valuable information.

Hanohano: 10 kton



Hanohano

(~10 kt deep ocean detector)

~100 geonu events/yr

Near future

- **JUNO represents a new opportunity to measure geoneutrinos, recording of 300 to 500 geoneutrino interactions per year. In approximately six months JUNO would match the present world sample of recorded geoneutrino interactions, which is less than 150 events.**

Experiment: events/yr

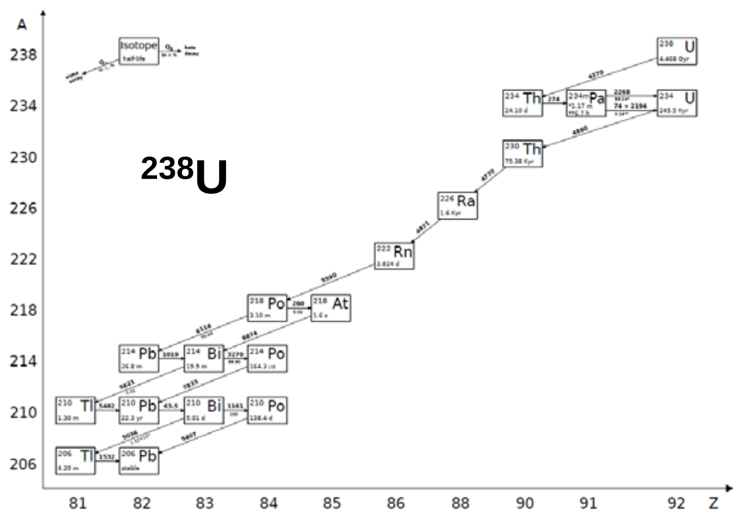
- **BRX : 4.2**
- **KL : 14**
- **SNO+ : 25**
- **Jinping : 100**
- **JUNO : 400**

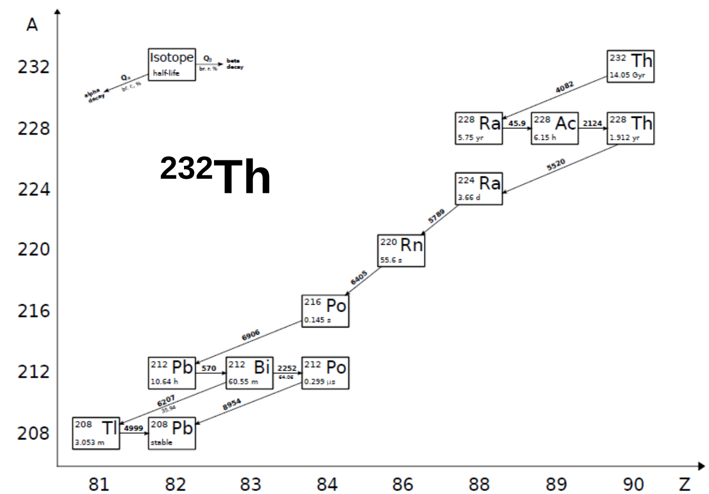
- **The statistical power of the geoneutrino signal at JUNO enables a measurement of the thorium to uranium ratio, which provides valuable insight to the Earth's origin and evolution.**
- **Mantle geoneutrino contribution can be extracted from the combined data of all experiments.**

Nuclear physics for geoneutrino studies

Contribution of elements from U and Th chains in total geoneutrino signal

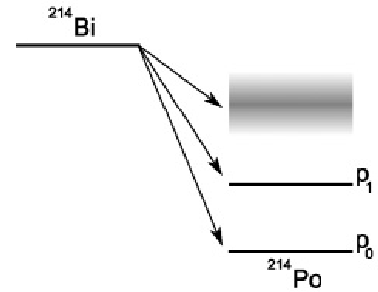
$i \to j$	$R_{i,j}$	E_{max} (keV)	I_k	ΔI_k	Type (%)	S_U (%)	S_{tot}
$^{234}Pa_m \to {}^{234}U$	**0.9984**	**2268.92**	**0.9836**	**0.002**	**first forbidden** $(0^-) \to 0^+$	**39.62**	**31.21**
$^{214}Bi \to {}^{214}Po$	**0.9998**	**3272.00**	**0.182**	**0.006**	**first forbidden** $1^- \to 0^+$	**58.21**	**45.84**
		2662.68	0.017	0.006	first forbidden $1^- \to 2^+$	1.98	1.55
		1894.32	0.0743	0.0011	first forbidden $1^- \to 2^+$	0.18	0.14
		1856.51	0.0081	0.0007	first forbidden $1^- \to 0^+$	0.01	0.01



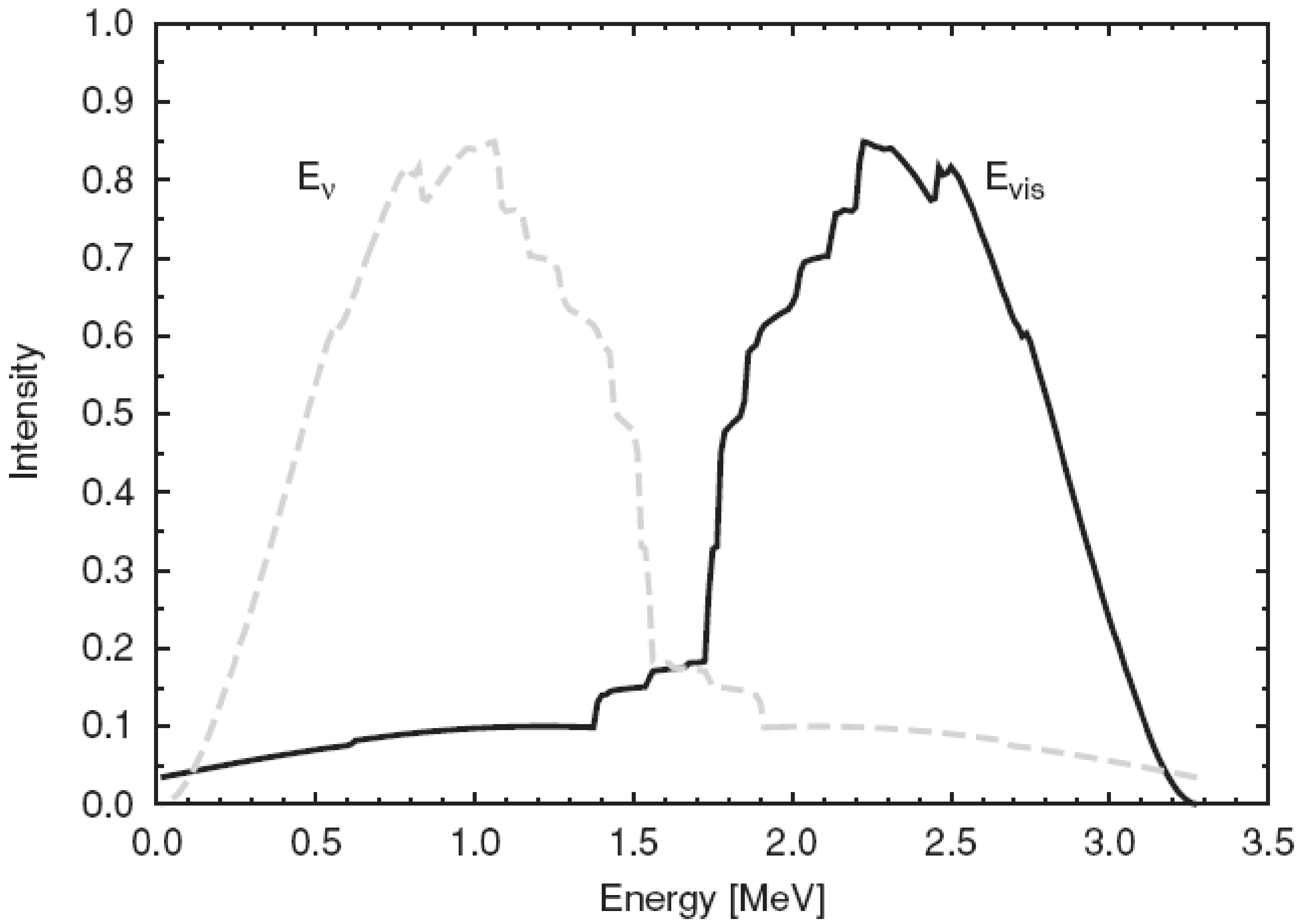


$i \to j$	$R_{i,j}$	E_{max} (keV)	I_k	ΔI_k	Type (%)	S_{Th}	S_{tot}
$^{212}Bi \to {}^{212}Po$	**0.6406**	**2254**	**0.8658**	**0.0016**	**first forbidden** $1^{(-)} \to 0^+$	**94.15**	**20.00**
$^{228}Ac \to {}^{228}Th$	1.0000	2069.24	0.08	0.06	allowed $3^+ \to 2^+$	5.66	1.21
		1940.18	0.008	0.006	allowed $3^+ \to 4^+$	0.19	0.04

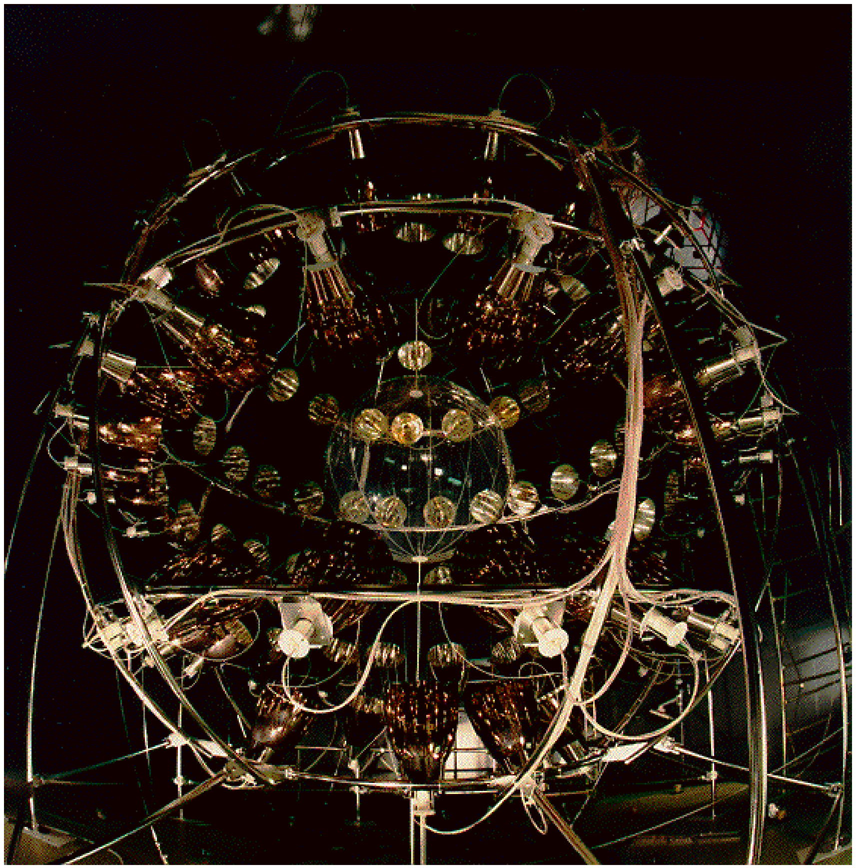
^{214}Bi

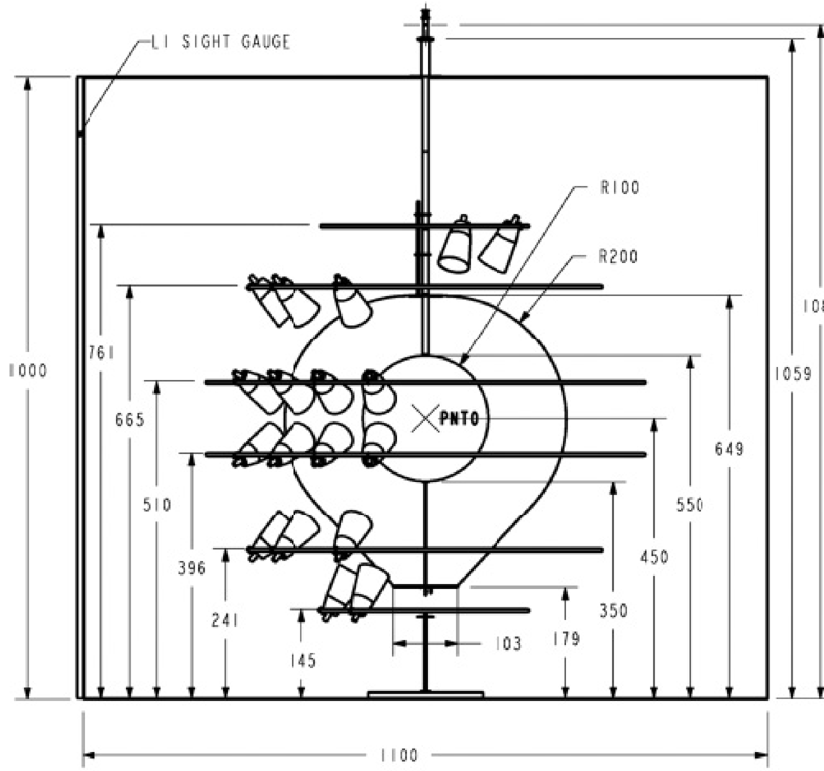


E_ν(max) [keV]	S_U [%]	S_{U+Th} [%]
...		
1894	0	0
2663	2	1.6
3272	58	42

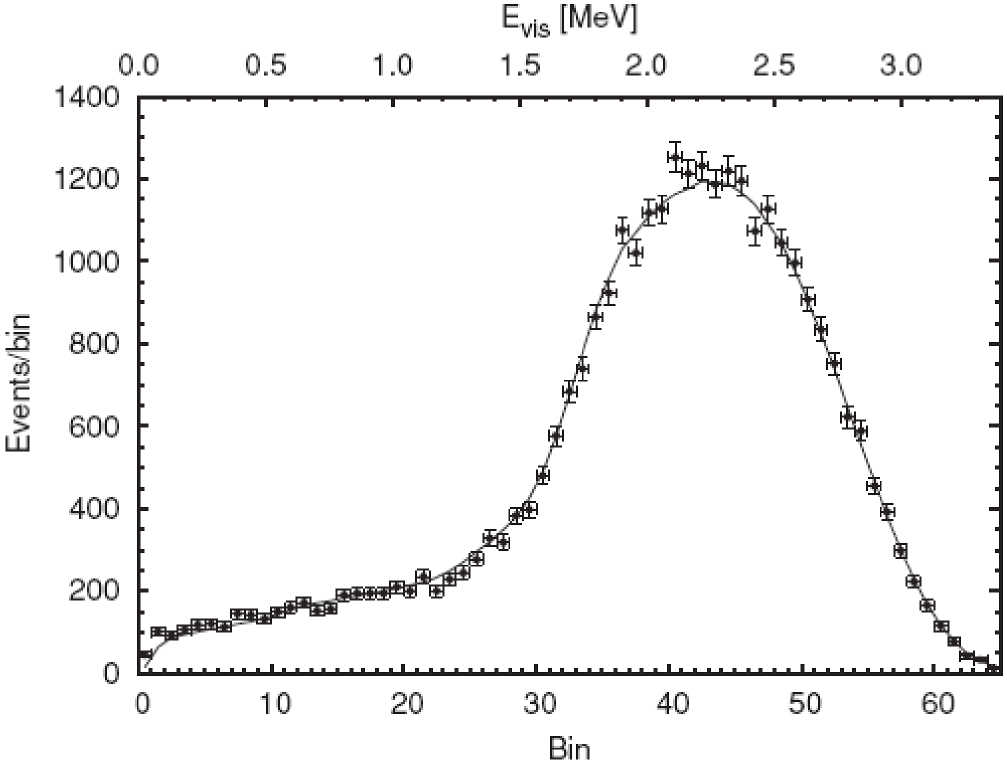


CTF (4 tonne Borexino prototype)





Experimental spectrum of ^{214}Bi (CTF) with superimposed fit



$$\text{(CTF)} \quad p_0 = 0.177 \pm 0.004 \text{ (stat)} \, ^{+0.003}_{-0.001} \text{ (sys)}. \qquad (11)$$

This value is consistent with that reported in ToI [17]: $p_0(\text{ToI}) = 0.182 \pm 0.006$.

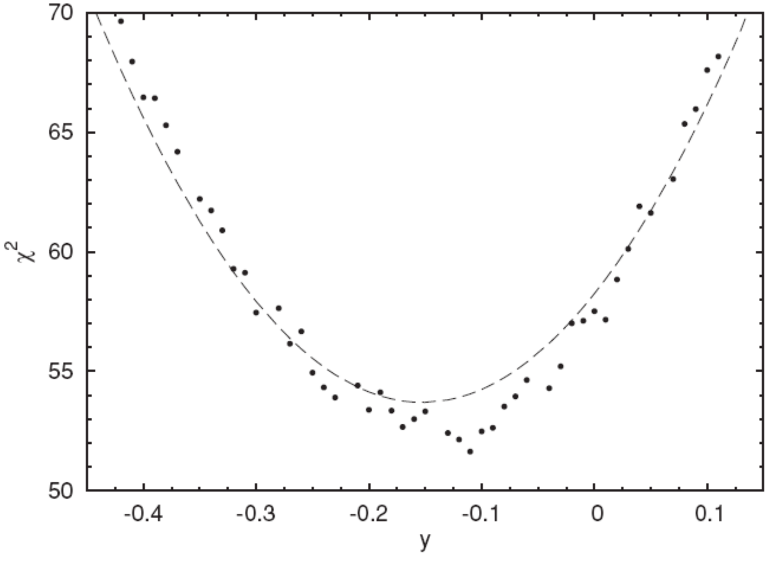
New ToI value:
p_0=0.1910±0.0017

Phys. Rev. C **81, 034602 (2010) Nuclear physics for geo-neutrino studies** G. Fiorentini et al

Deviation from the allowed (universal) shape

$$\phi(T_e) = p_0\Phi(T_e) + \sum_{n>0} p_n \Phi_{\mathrm{univ}}(T_e,\, Q - E_n)$$

$$\Phi(T_e) = \Phi_{\mathrm{univ}}(T_e,\, Q)\left(1 + y\,\frac{T_e - \langle T_e\rangle}{\langle T_e\rangle}\right)$$



Results for signal from ^{214}Bi

(CTF)

$$s(^{214}\mathrm{Bi}) = [1.42 \pm 0.03\ (\mathrm{stat})\ ^{+0.023}_{-0.008}\ (\mathrm{sys})] \times 10^{-44}\ \mathrm{cm}^2$$

(ToI)

$$s(^{214}\mathrm{Bi}) = [1.46 \pm 0.05\ (\mathrm{stat})] \times 10^{-44}\ \mathrm{cm}^2$$

With spectral deformations:

$$s(^{214}\mathrm{Bi}) = [1.48 \pm 0.01\ (\mathrm{stat}) \pm 0.03\ (\mathrm{sys})] \times 10^{-44}\ \mathrm{cm}^2$$


Thank You