Past and Present Experiments of Geo Neutrinos

The 13th International Conference on Topics in Astroparticle and Underground Physics

Sep. 9, 2013

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Geologically Produced Anti-Neutrino

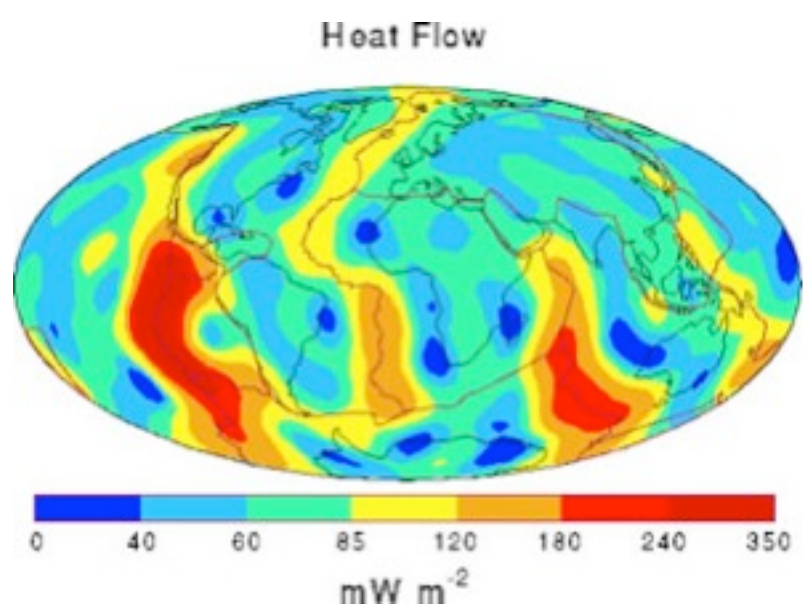
Beta-decay of radioactivities (U, Th, K) in the Earth

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,{}^{4}\mathrm{He} + 6e^{-} + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}\ \ (100\%)$$

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,{}^{4}\mathrm{He} + 4e^{-} + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}\ \ (100\%)$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e^{-} + \bar{\nu}_e + 1.31\ \mathrm{MeV}\ \ (89.28\%)$$

$$^{40}\mathrm{K} + e^{-} \rightarrow {}^{40}\mathrm{Ar} + \nu_e + 1.51\mathrm{MeV}(10.72\%)$$



Bulk Silicate Earth (BSE) model

chondrite meteorite

U : 8 TW

Th : 8 TW

K : 4 TW

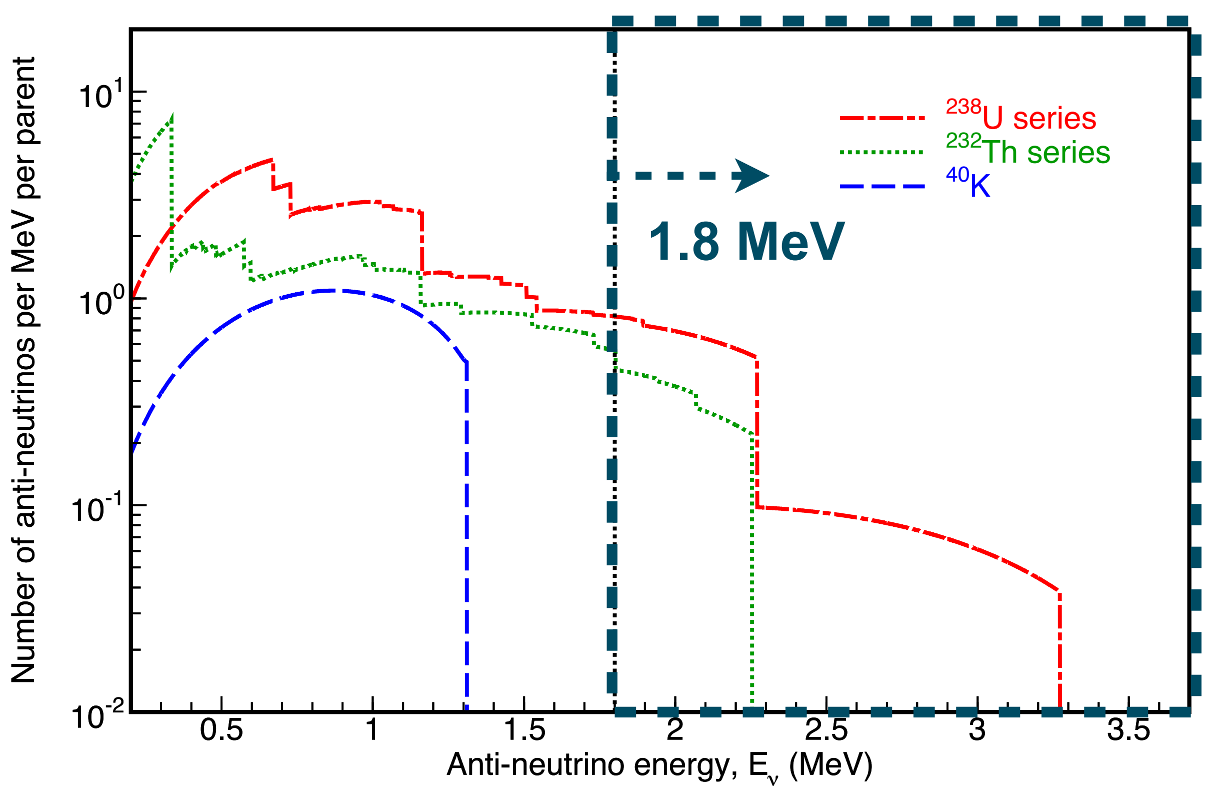
Surface heat flow 44 TW > Radiogenic heat 19 TW

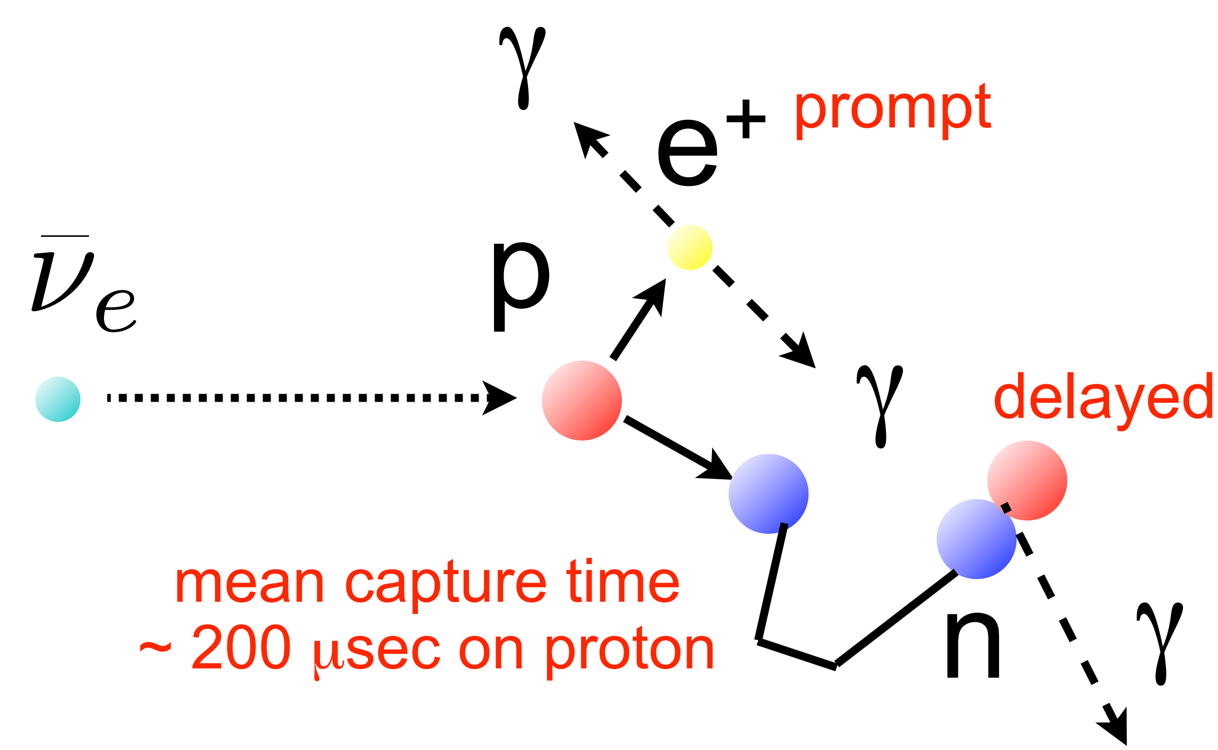
Geo Neutrino

- G. Eder (1966) — **first calculation in science literature**
- G. Marx (1969)
- L. Krauss et al. (1988)
- M. Kobayashi, Y. Fukao (1981) — **systematic search of target detector material**
- R. Raghavan et al. (1998)
- Rothschild et al. (1998)
- G. Fiorentini et al. (2003)

} **feasible plan in KamLAND and Borexino**

detailed neutrino flux calculations





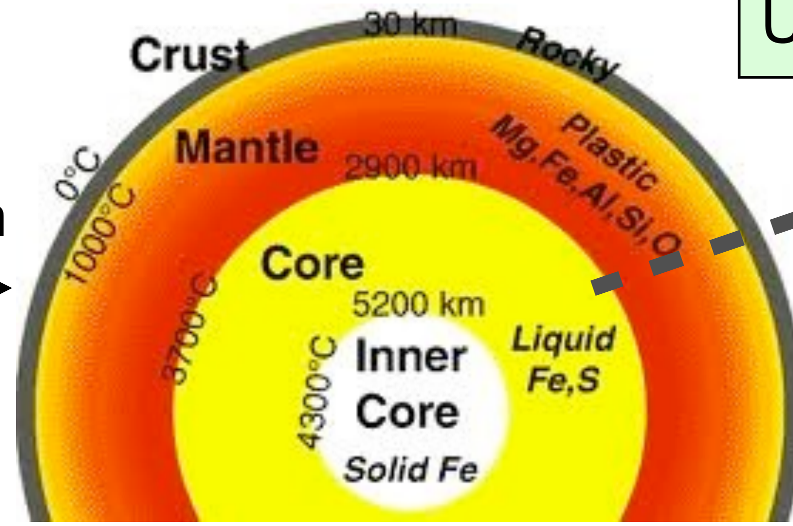
anti-neutrino detection by inverse beta-decay

Neutrino Geoscience

Heat sources in the Earth

~ 4 billion years ago

Earth formation →



Energy release by radioactive decay of U, Th, K → **radiogenic heat**

Release of gravitational energy through metallic core separation → **primordial heat**

↓

still remain ?

5 Big Questions:

- What are earth's K/U & Th/U ratios? *planetary volatility curve*
- Radiogenic contribution to heat flow? *secular cooling*
- Distribution of reservoirs in mantle? *whole vs layered convection*
- Radiogenic elements in the core?? *Earth energy budget*
- Nature of the Core-Mantle Boundary? *hidden reservoirs*

15 July 2009 McDonough-Trieste-2009

geo reactor

Experimentally investigated

Geo neutrino detector

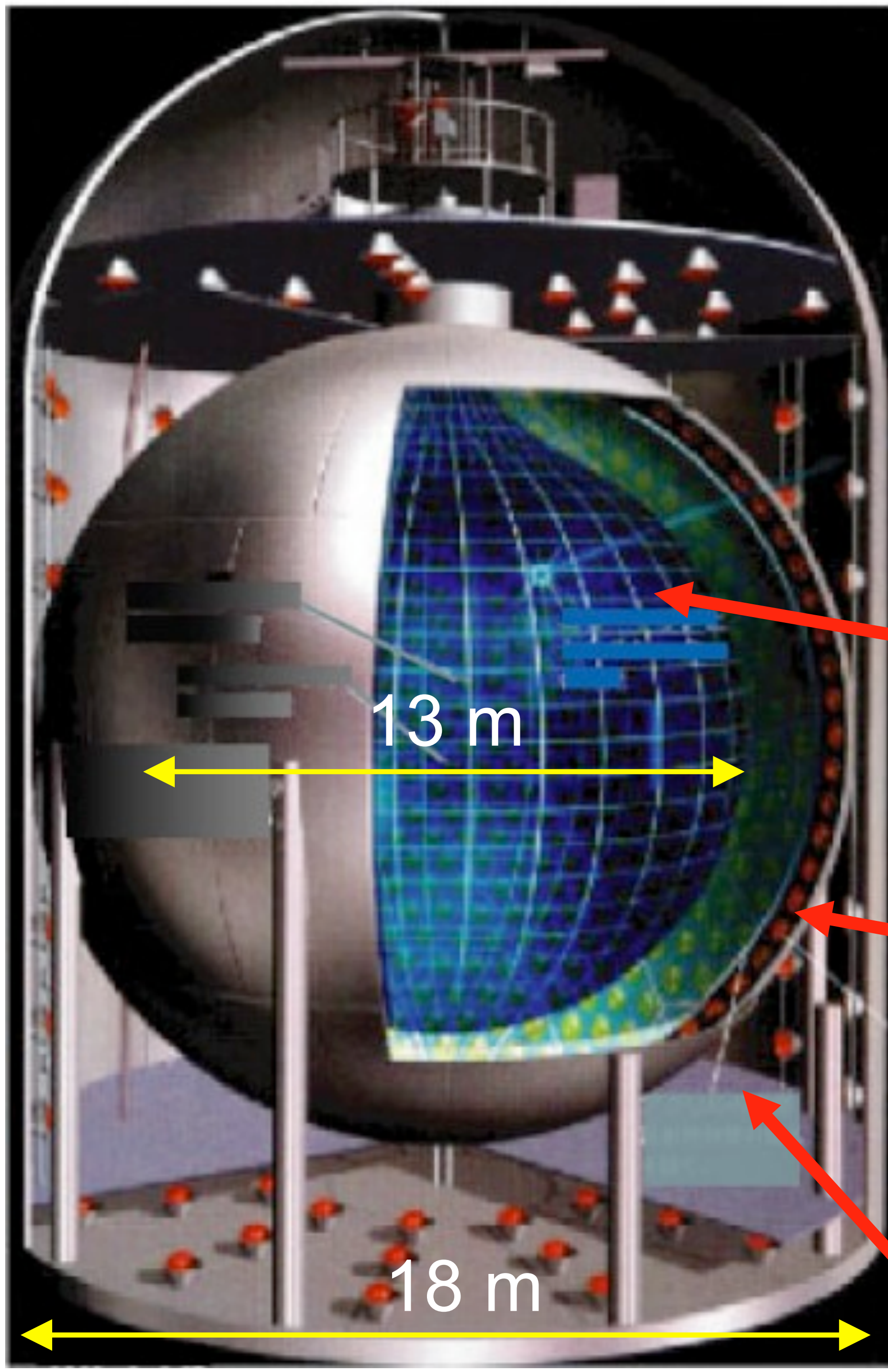
- KamLAND (Japan)
- Borexino (Italy)

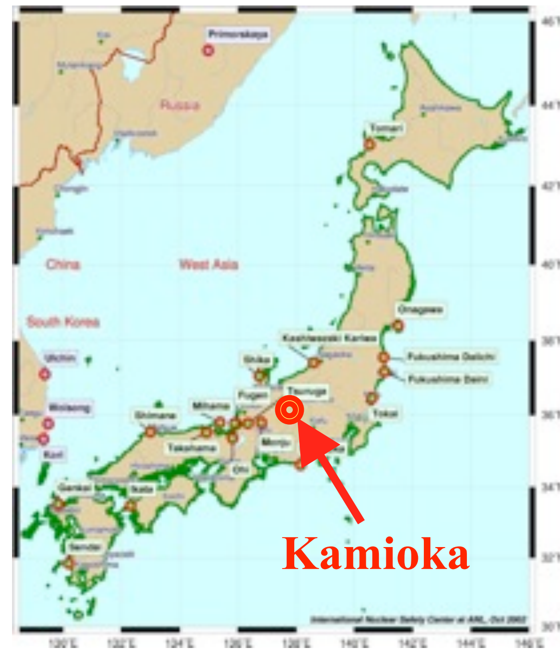
Geo neutrino experiment will play a key role in answer all the questions !

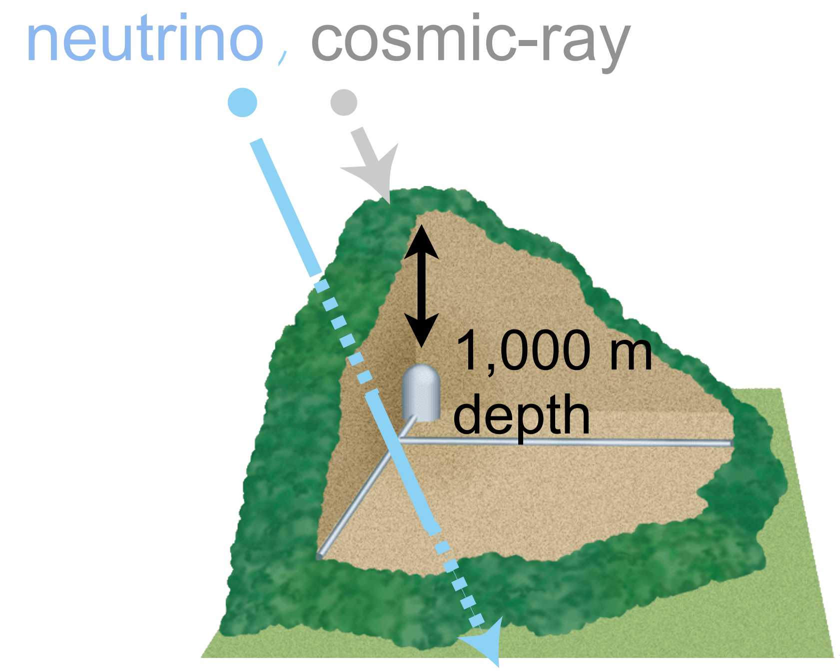
KamLAND

Kamioka Liquid Scintillator Anti-Neutrino Detector

operated since 2002







1,000 ton Liquid Scintillator

Dodecane (80%) Pseudocumene (20%) PPO (1.36 g/l)

1,325 17 inch + 554 20 inch PMTs

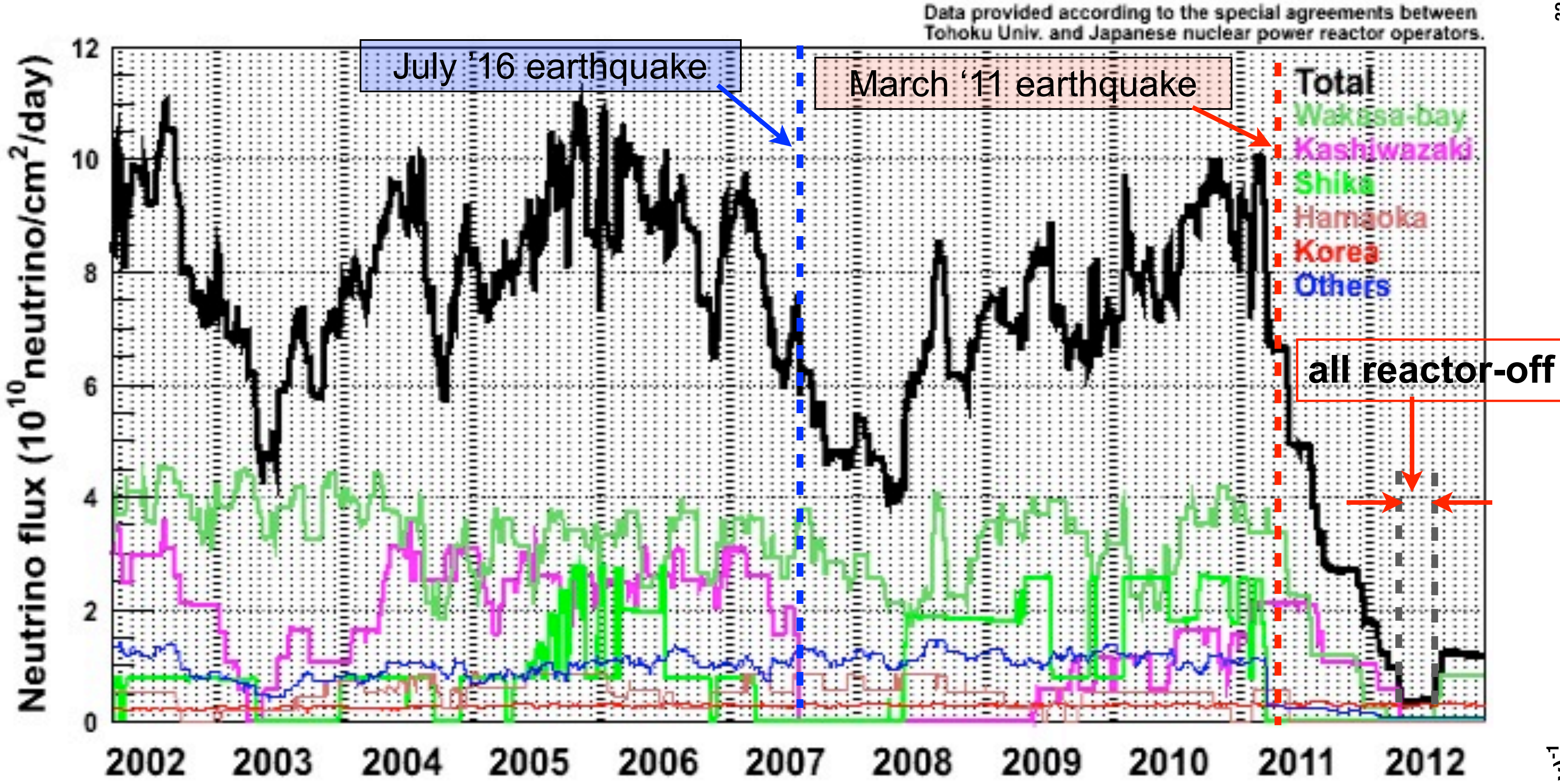
commissioned in February, 2003

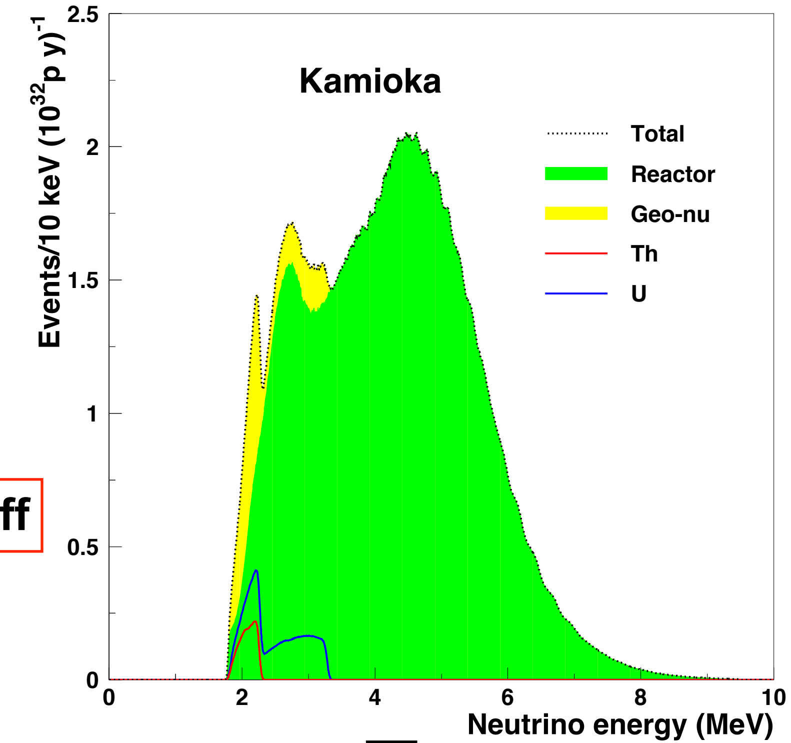
photocathode coverage : 22% → 34%

Water Cherenkov Outer Detector

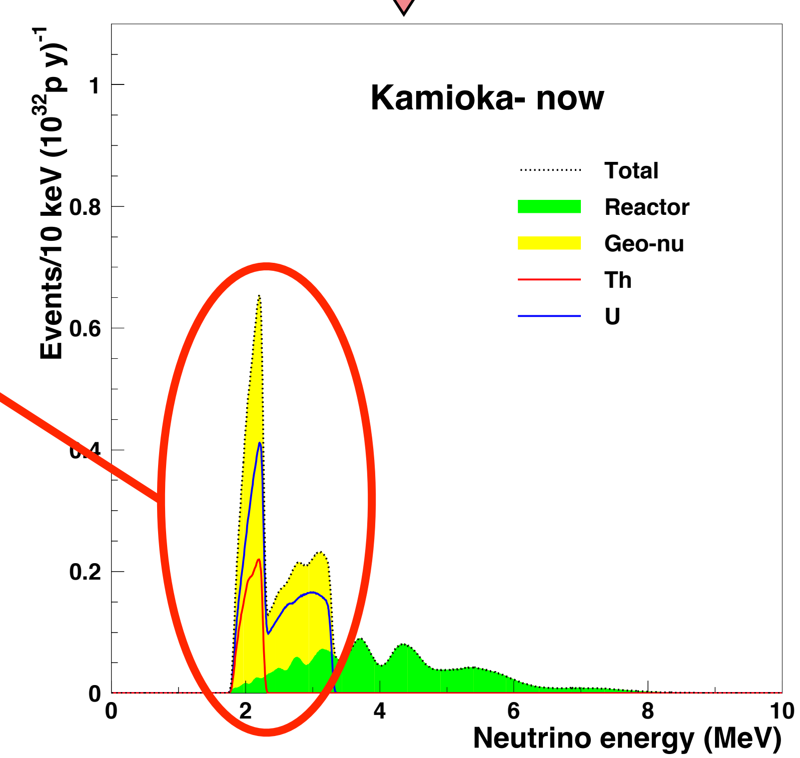
Anti-Neutrino Flux in Kamioka

time variation of neutrino flux





decrease of reactor neutrino

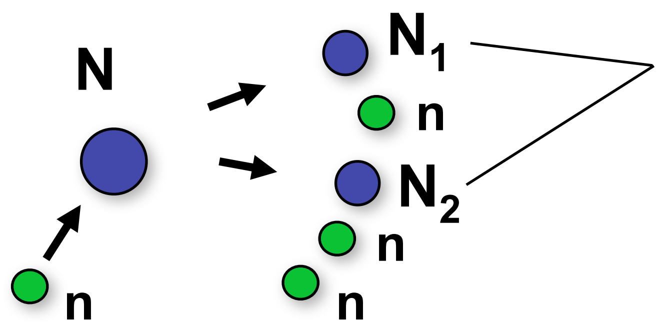


significant reduction of anti-neutrino flux from reactors after Fukushima-I accident

good data for geo neutrino observation

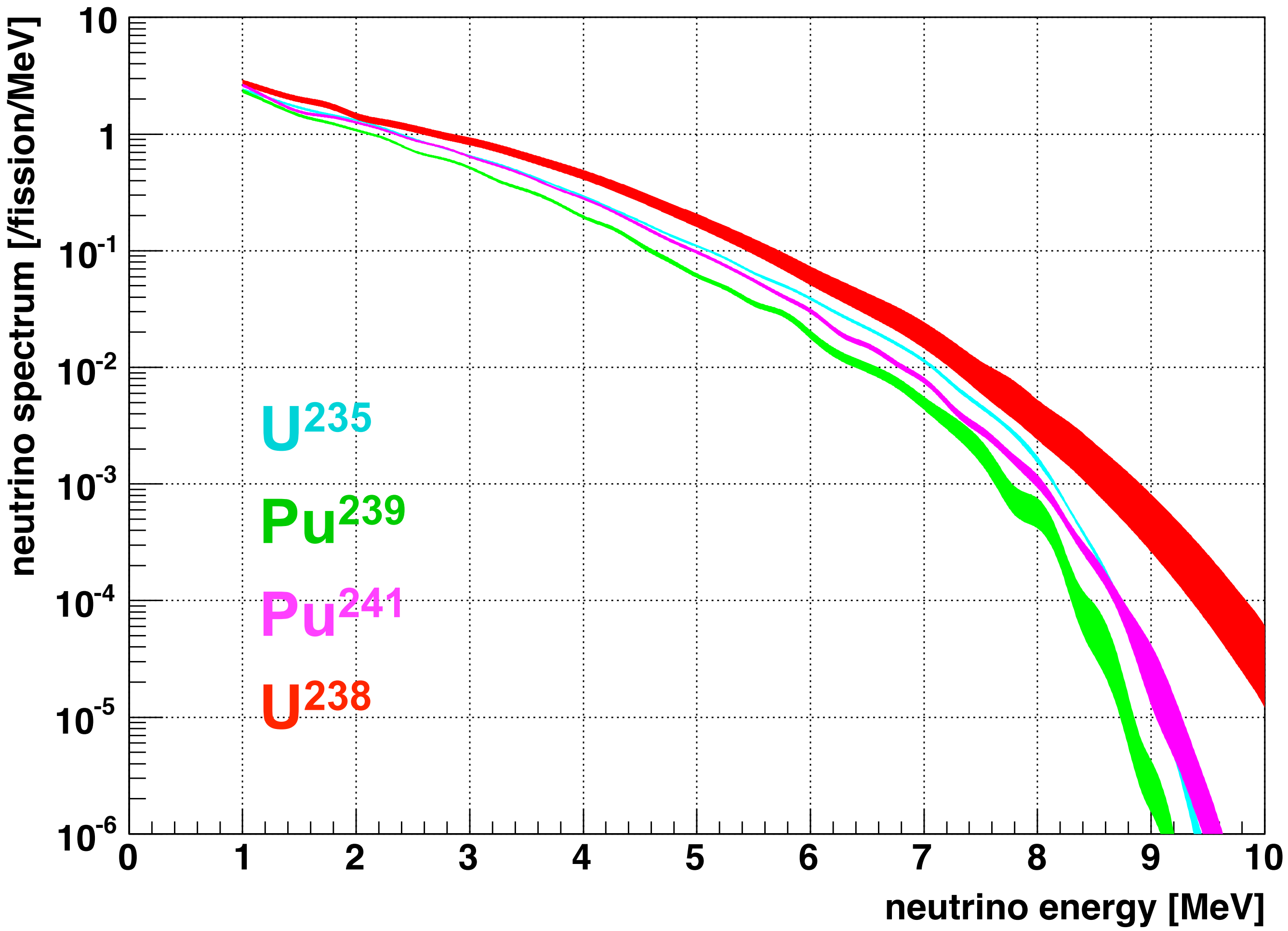
"Reactor on-off" study for neutrino oscillation and geo neutrino analysis

Reactor Neutrino Spectrum



neutron rich fission fragment

$N_2 \longrightarrow N_3 + e^- + \overline{\nu}_e$ **~ 6 $\overline{\nu}_e$ / fission**



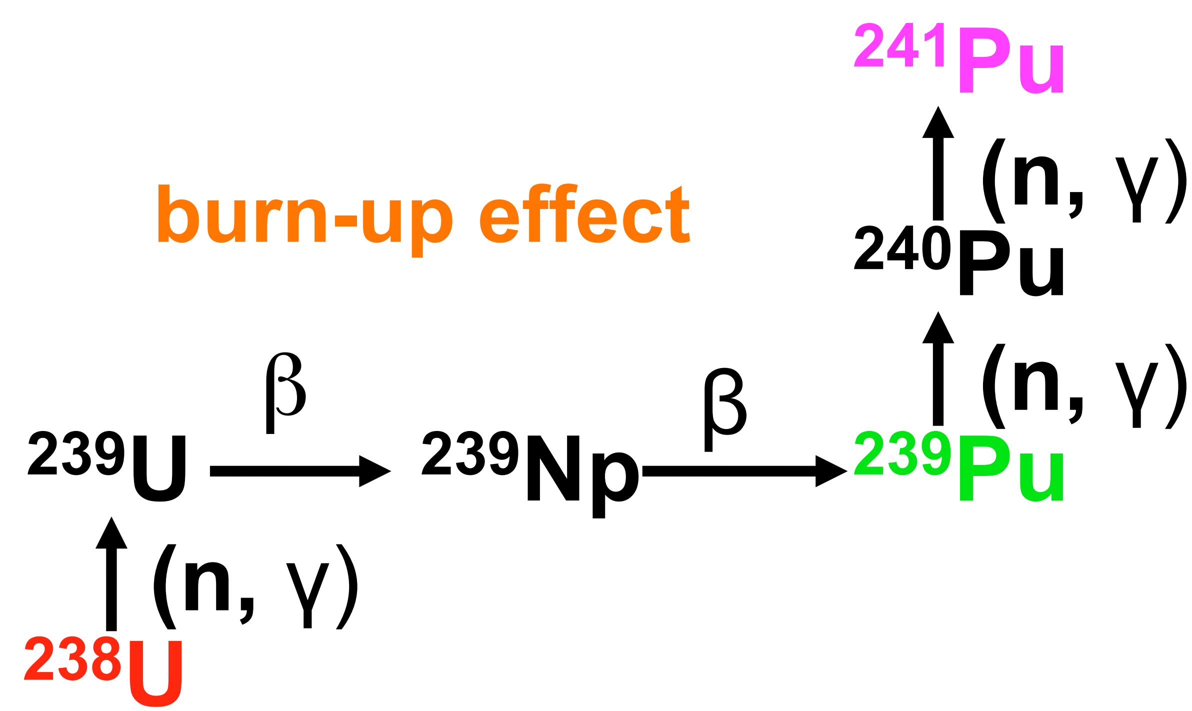
^{235}U, ^{239}Pu, ^{241}Pu: re-evaluation of ILL (P. Huber)

^{238}U: theoretical calculation (Th. Mueller et al.)

<u>Recalculation from ILL data</u>

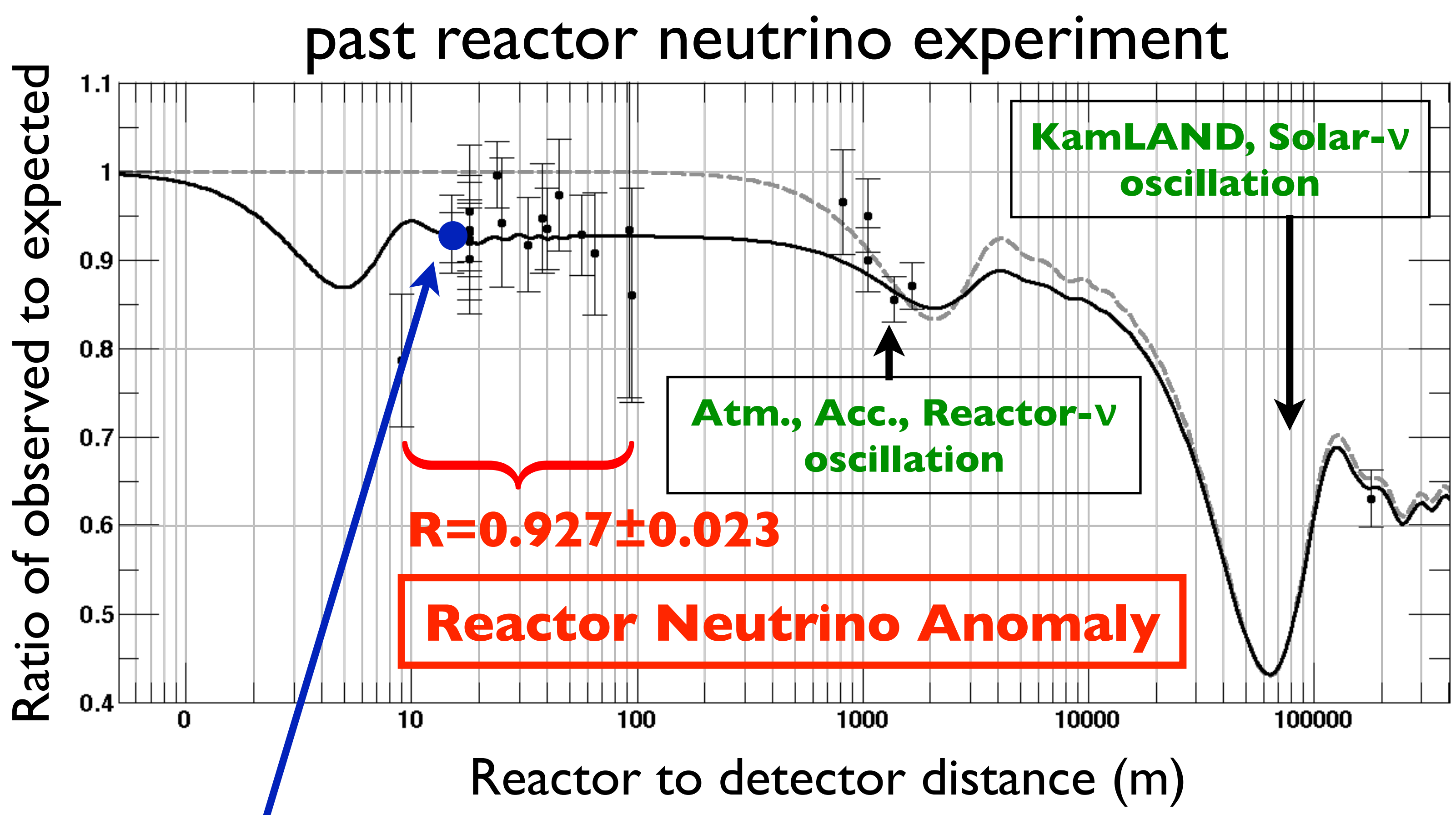
(Lhuillier/Mueller, Saclay)

- built from 845 nuclei and 10000 β-branches
- introduce a new ab-initio conversion method
- includes full error propagation and correlation



~3% upward-shift by re-evaluation of ILL data

Normalization with Near Data



possibility of systematic bias or sterile-ν oscillation?

Bugey4 accuracy on the neutrino flux is **1.4%** (L = 15 m from PWR reactor)

Normalization of cross section per fission

$$\langle\sigma\rangle_{reac.} = \langle\sigma\rangle_{Bugey4} + \sum_i (\alpha_i^{reac.} - \alpha_i^{Bugey4}) \langle\sigma\rangle_i$$ (i = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu)

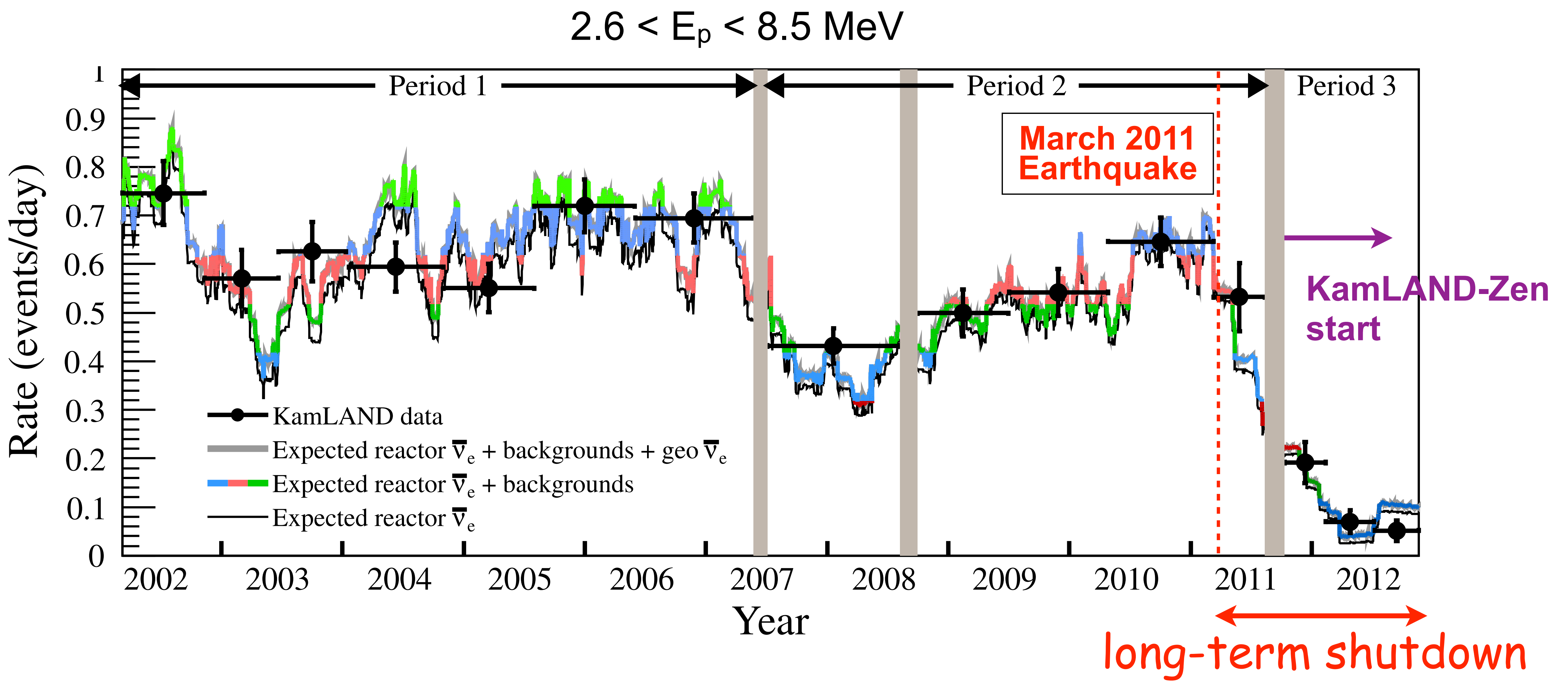
α_i : fractional fission rate $\langle\sigma\rangle_i = \int dE S_i(E)\sigma(E)$: effective cross section per fission

analysis is insensitive to "Reactor Neutrino Anomaly"

Time Variation of Event Rate

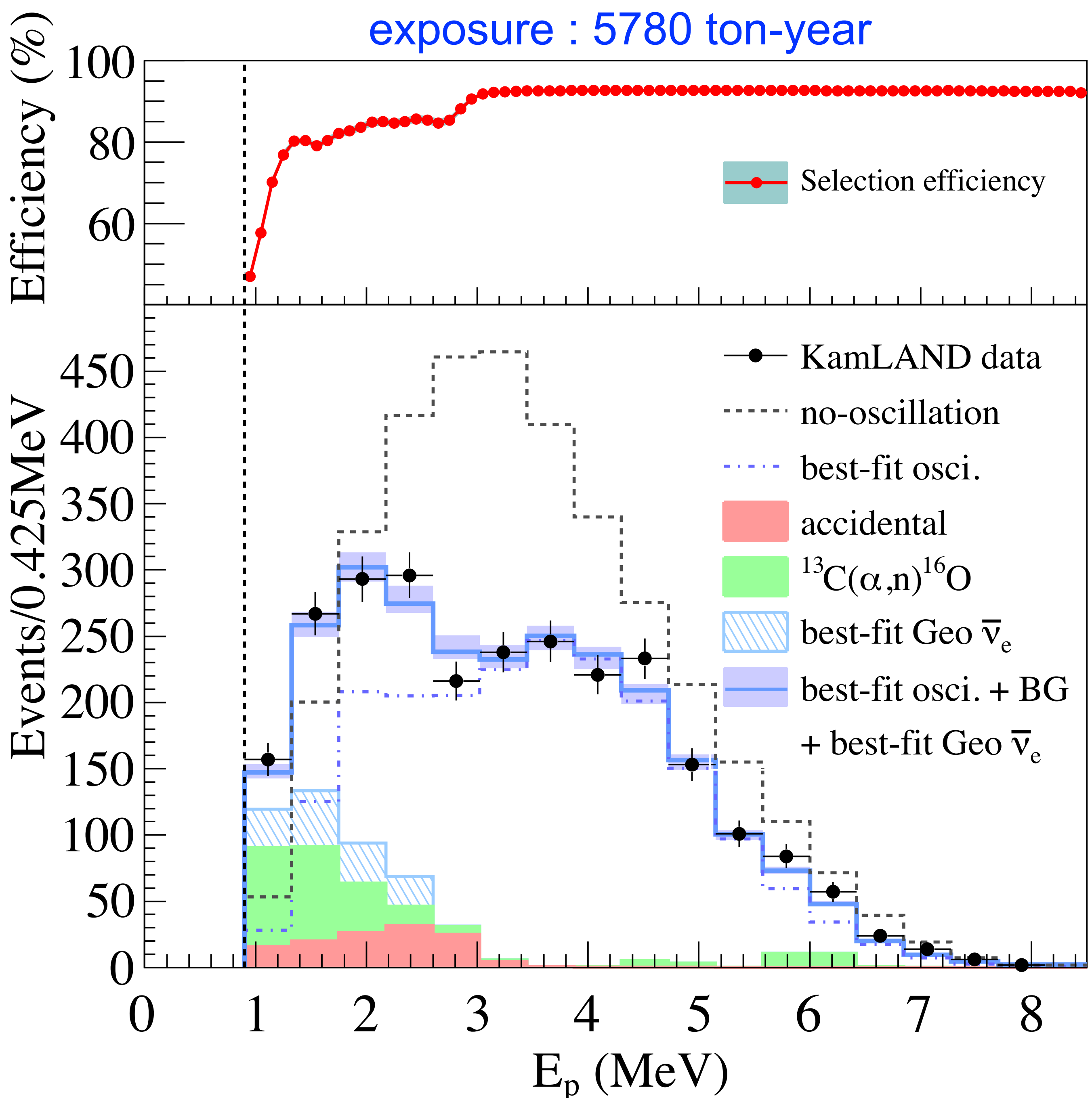
Total livetime
2991 days

Period 1: Mar. 2002 - May 2007
Period 2: May 2007 - Aug. 2011 (after LS purification)
Period 3: Oct. 2011 - Nov. 2012 (after KamLAND-Zen start)



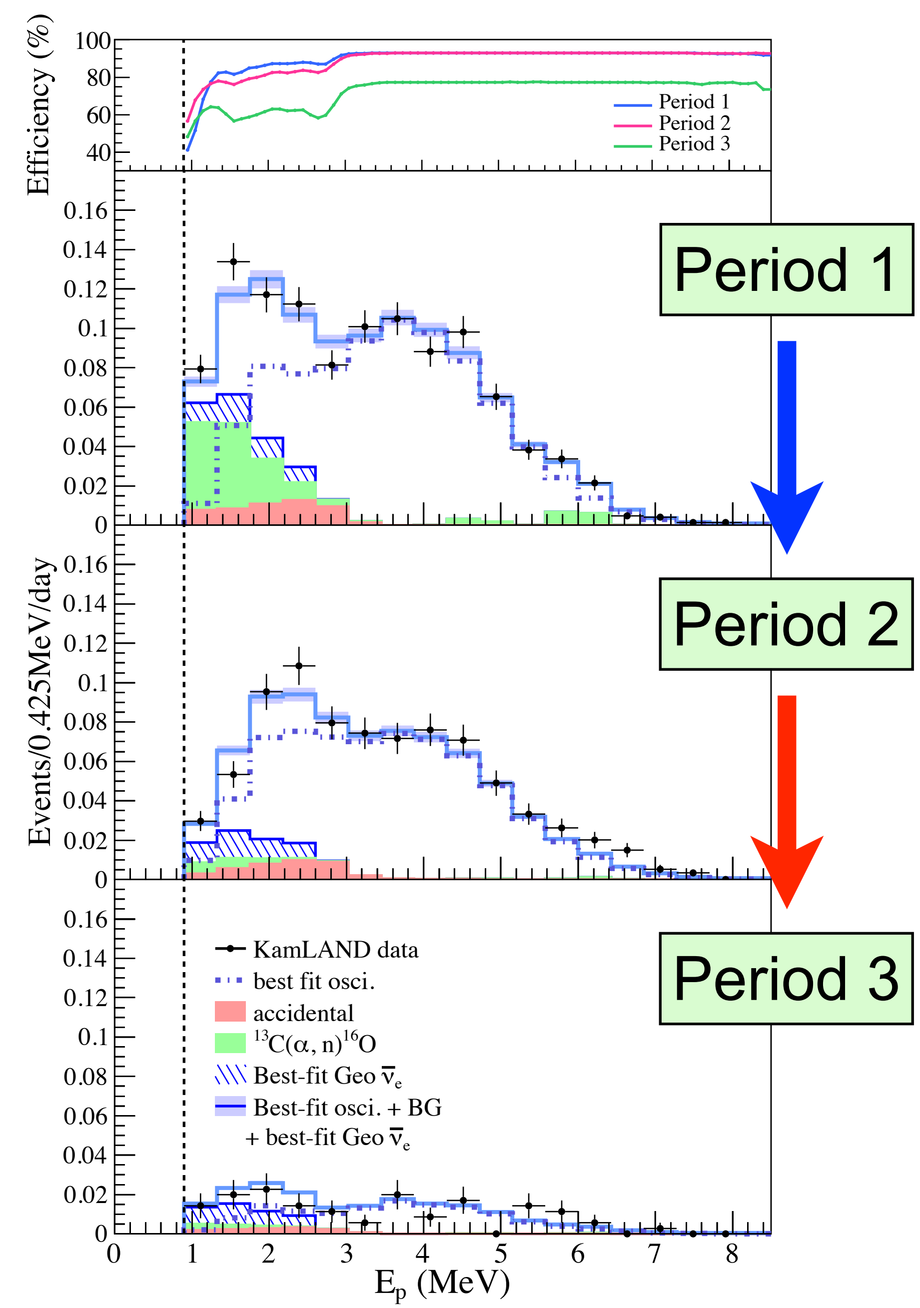
Data have good agreement with expected rate

Observed Energy Spectrum



purification **(α,n) ↓**

earthquake **reactor ↓**



KamLAND only

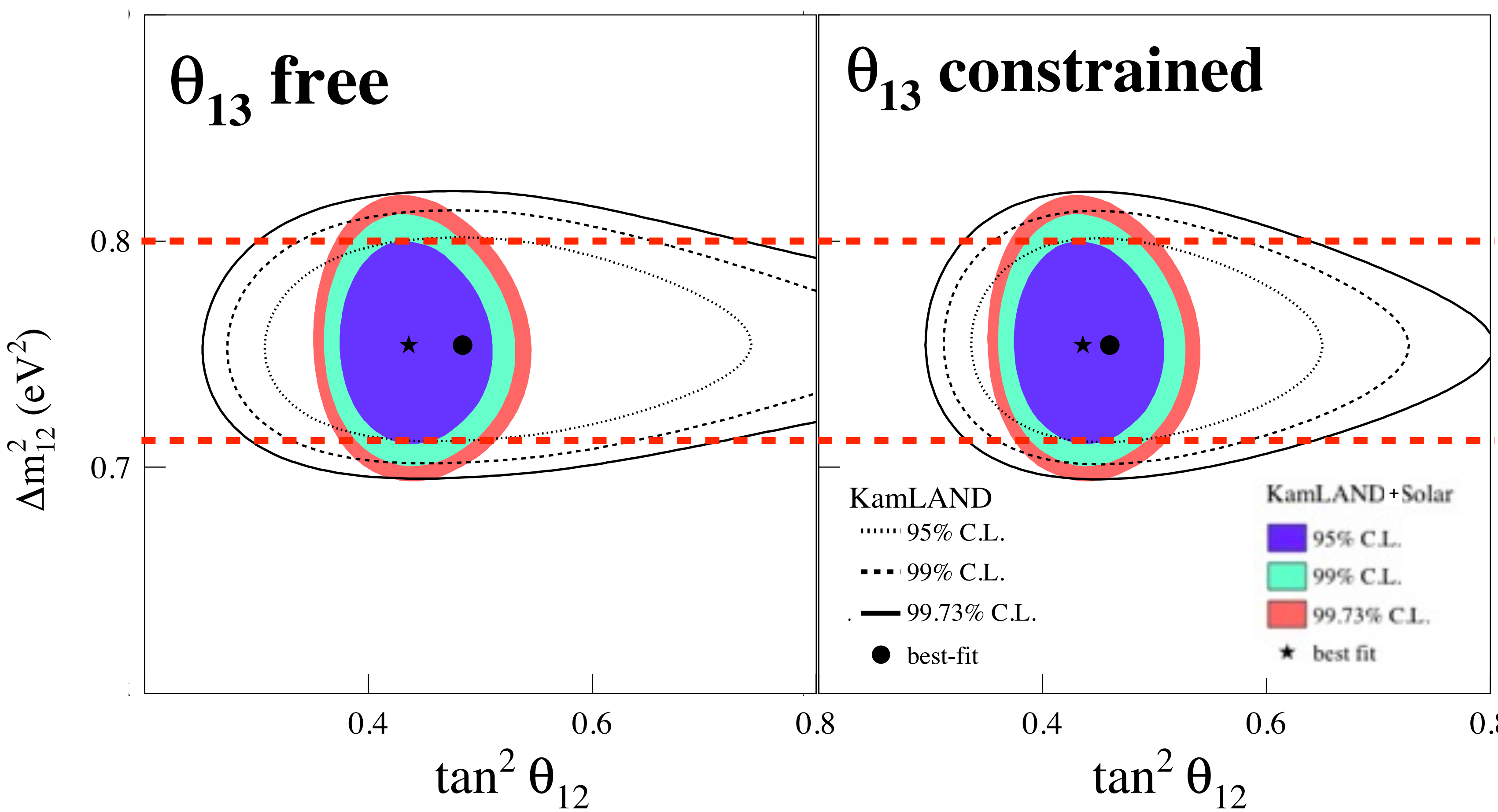
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5}\text{eV}^2$$
$$\tan^2\theta_{12} = 0.481^{+0.092}_{-0.080}$$
$$\sin^2\theta_{13} = 0.010^{+0.033}_{-0.034}$$

No osci. expected	**3564 ± 145**
Background (w/o geo neutrino)	**364 ± 31**
Observed events	**2611**

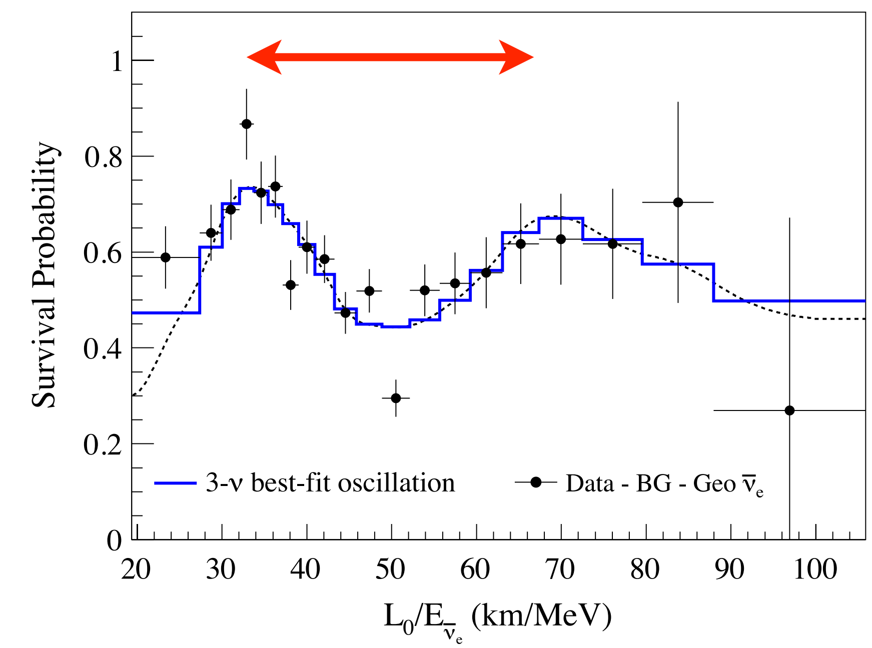
significant reduction

Neutrino Oscillation Parameter

Δm^2: systematic uncertainty 1.9%
(dominated by linear energy scale uncertainty)



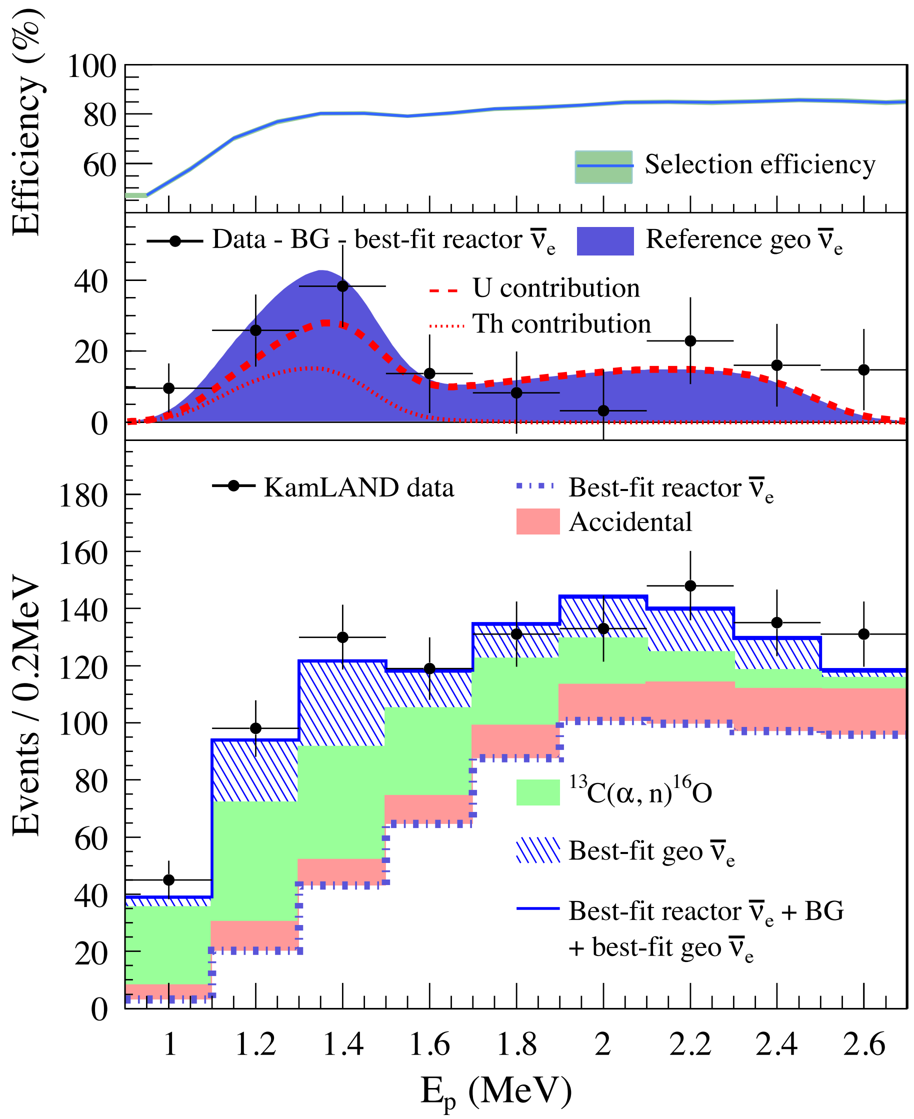
frequency meas. by KamLAND



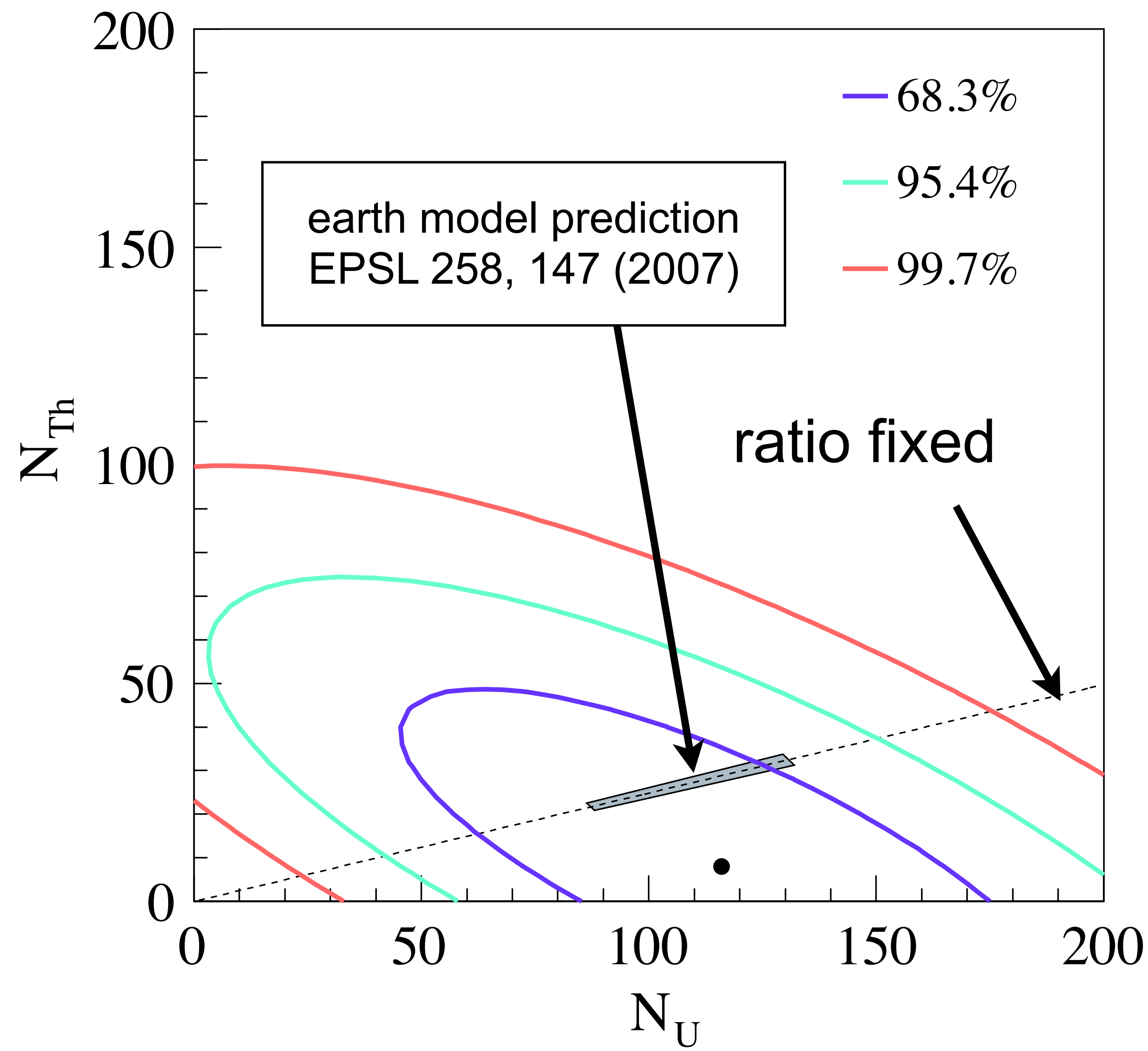
KamLAND+Solar	KamLAND+Solar+θ13	
$\Delta m^2_{21} = 7.53^{+0.19}_{-0.18} \times 10^{-5} \mathrm{eV}^2$	$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5} \mathrm{eV}^2$	← insensitive
$\tan^2\theta_{12} = 0.437^{+0.029}_{-0.026}$	$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$	← no strong impact
$\sin^2\theta_{13} = 0.023^{+0.015}_{-0.015}$	$\sin^2\theta_{13} = 0.023^{+0.002}_{-0.002}$	θ_{13} constraint

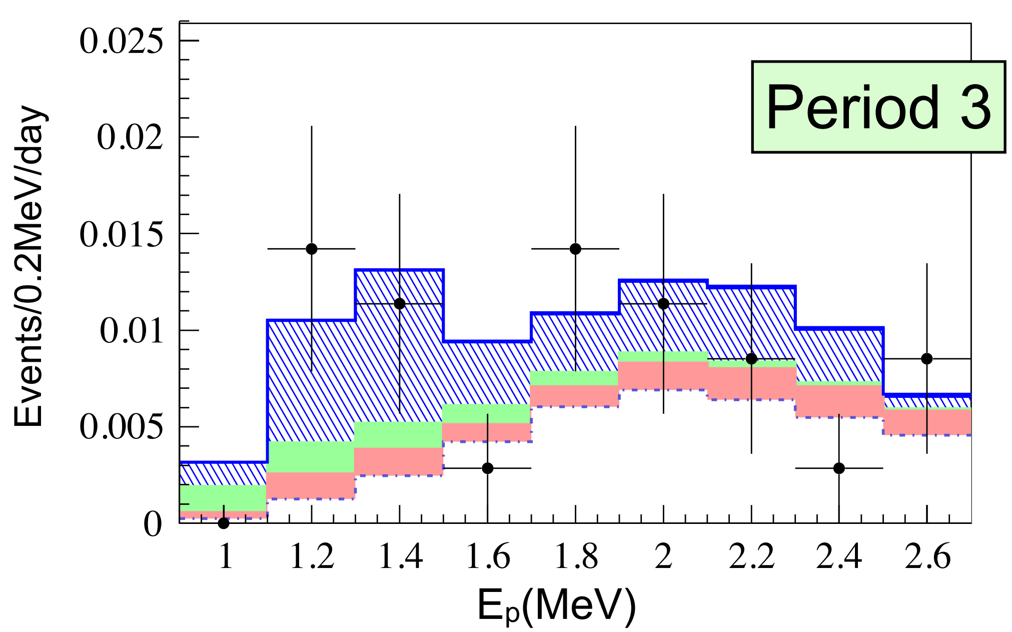
Survival probability of geo $\bar{\nu}_e$ = 0.511 ± 0.014 (2.7%)

Fit with U/Th components



best-fit (N_U, N_{Th}) = (116,8)





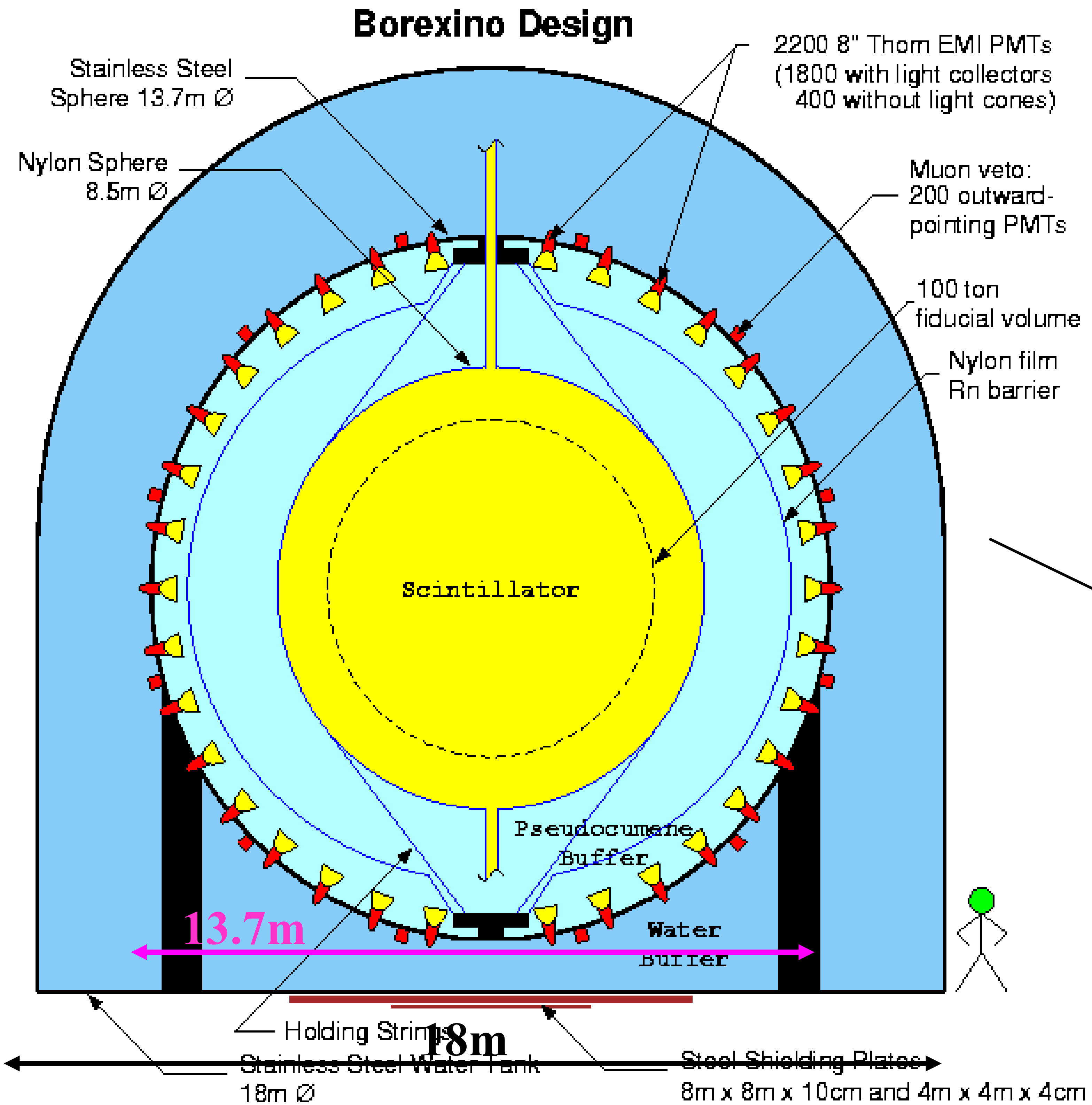
$N_{geo} = 116^{+28}_{-27}$ events

$F_{geo} = 3.4^{+0.8}_{-0.8} \times 10^6$ /cm^2/sec

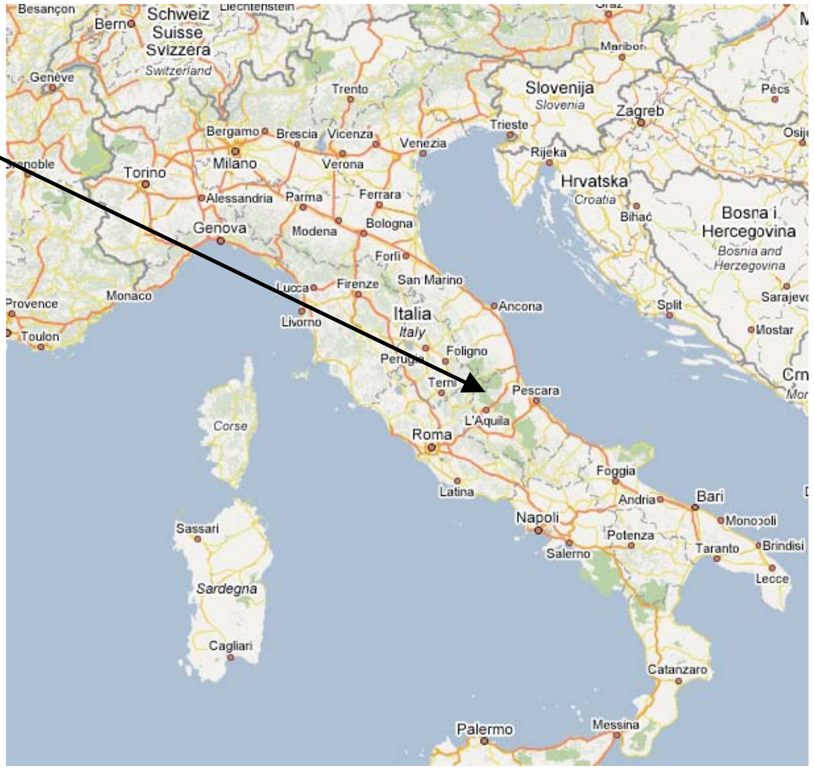
$(30.7^{+7.5}_{-7.3}$ TNU)

Borexino

Smirnov, TAUP 2011

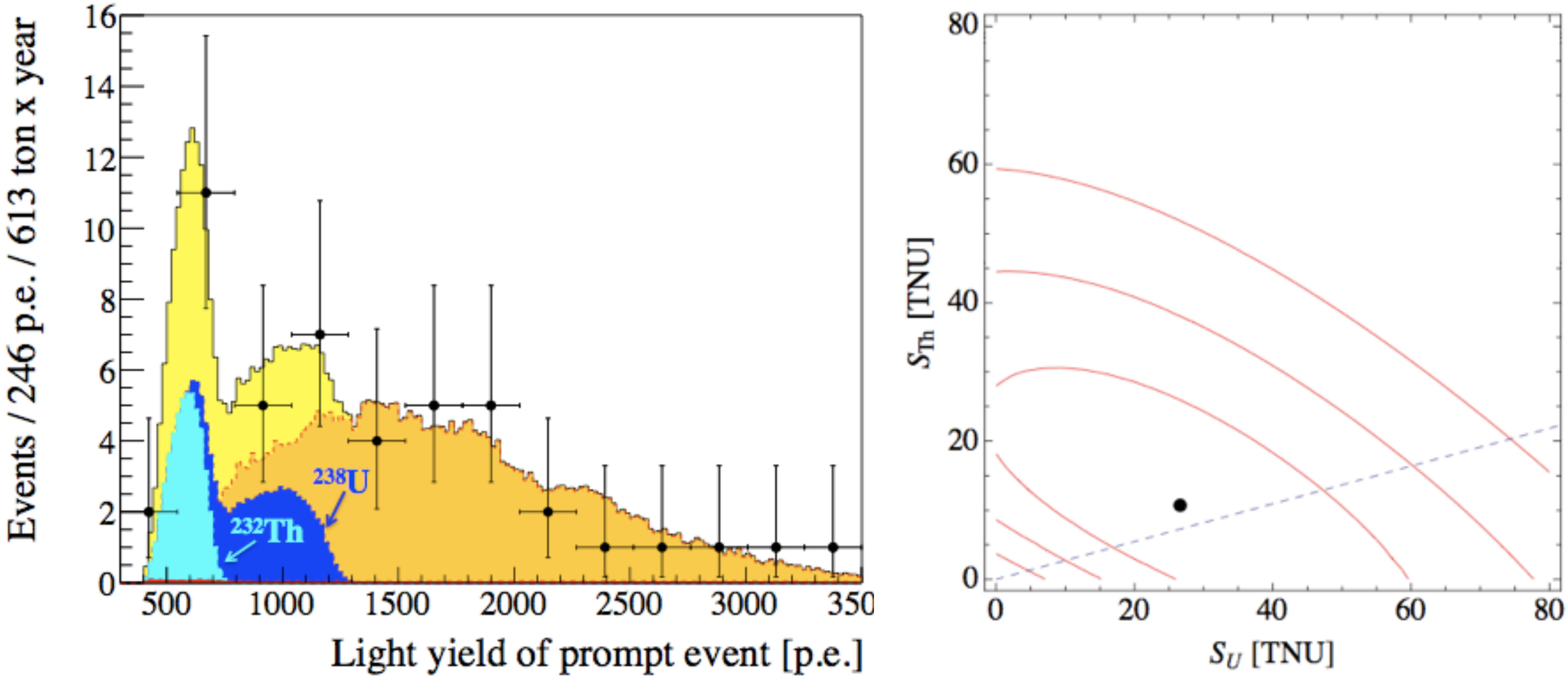


- •278 t of liquid organic scintillator PC + PPO (1.5 g/l)
- • (ν,e)-scattering with 200 keV threshold
- •Outer muon detector



Fit with U/Th components

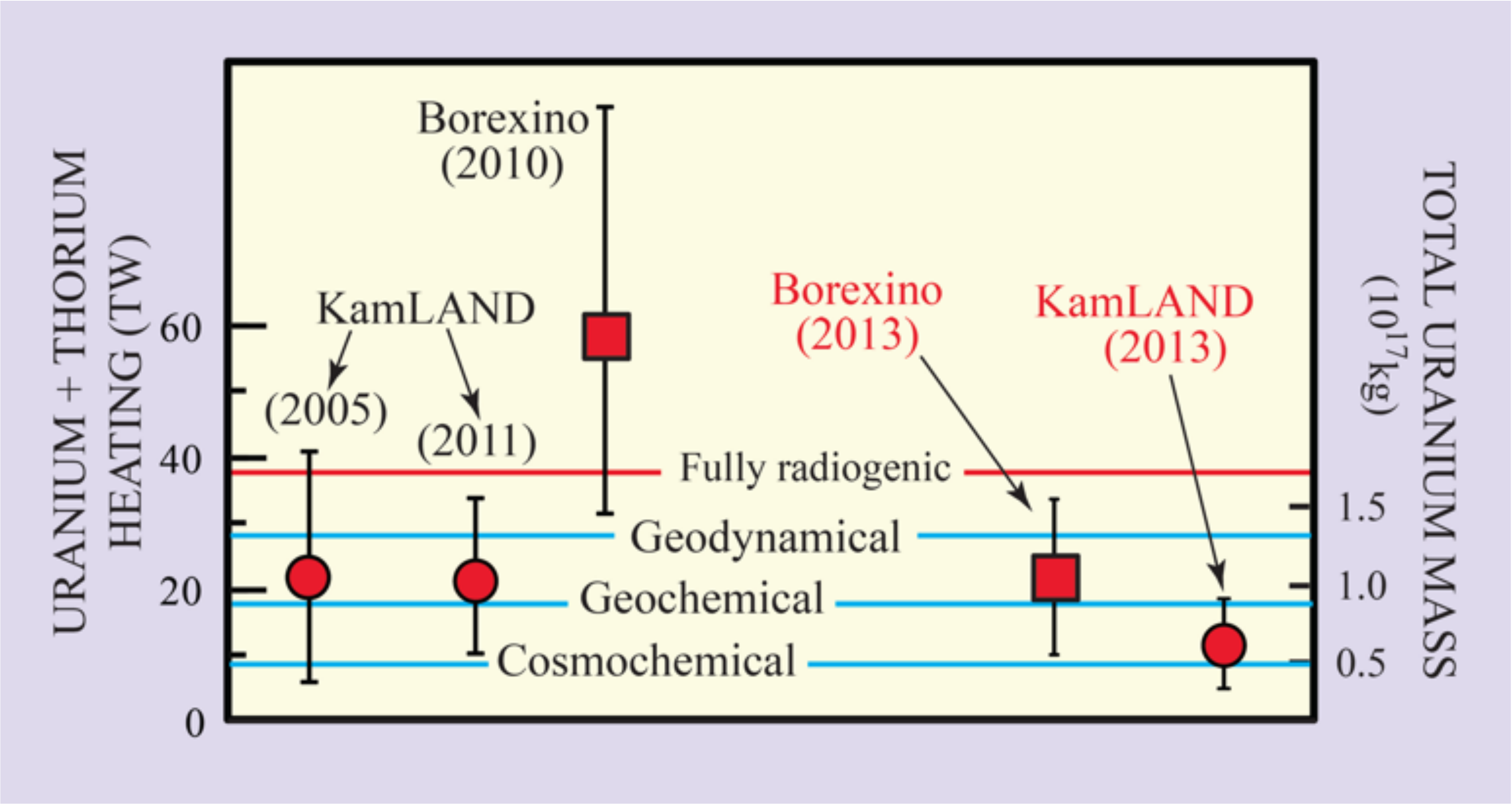
Zavatarelli, Neutrino Geoscience 2013



$N_{reactor}$ Expected with osc.	$N_{reactor}$ Expected no osc.	Others back.	N_{geo} measured	$N_{reactor}$ measured	N_{geo} measured	$N_{reactor}$ measured
events	events	events	events	events	TNU	TNU
33.3±2.4	60.4±4.1	0.70±0.18	14.3±4.4	$31.2_{-6.1}^{+7}$	38.8±12.0	$84.5^{+19.3}_{-16.9}$

Summary of Geo Neutrino Results

McDonough, Neutrino Geoscience 2013



MODELS'
Cosmochemical:'uses'meteorites'–'*O'Neill'&'Palme'('08);'Javoy'et'al'('10);'Warren'('11)'*
Geochemical:'uses'terrestrial'rocks'–'*McD'&'Sun''95;'Allegre'et'al''95;'Palme'O'Neil''03'*
Geodynamical:'parameterized'convecBon'–'*Schubert'et'al;'TurcoHe'et'al;'Anderson'*

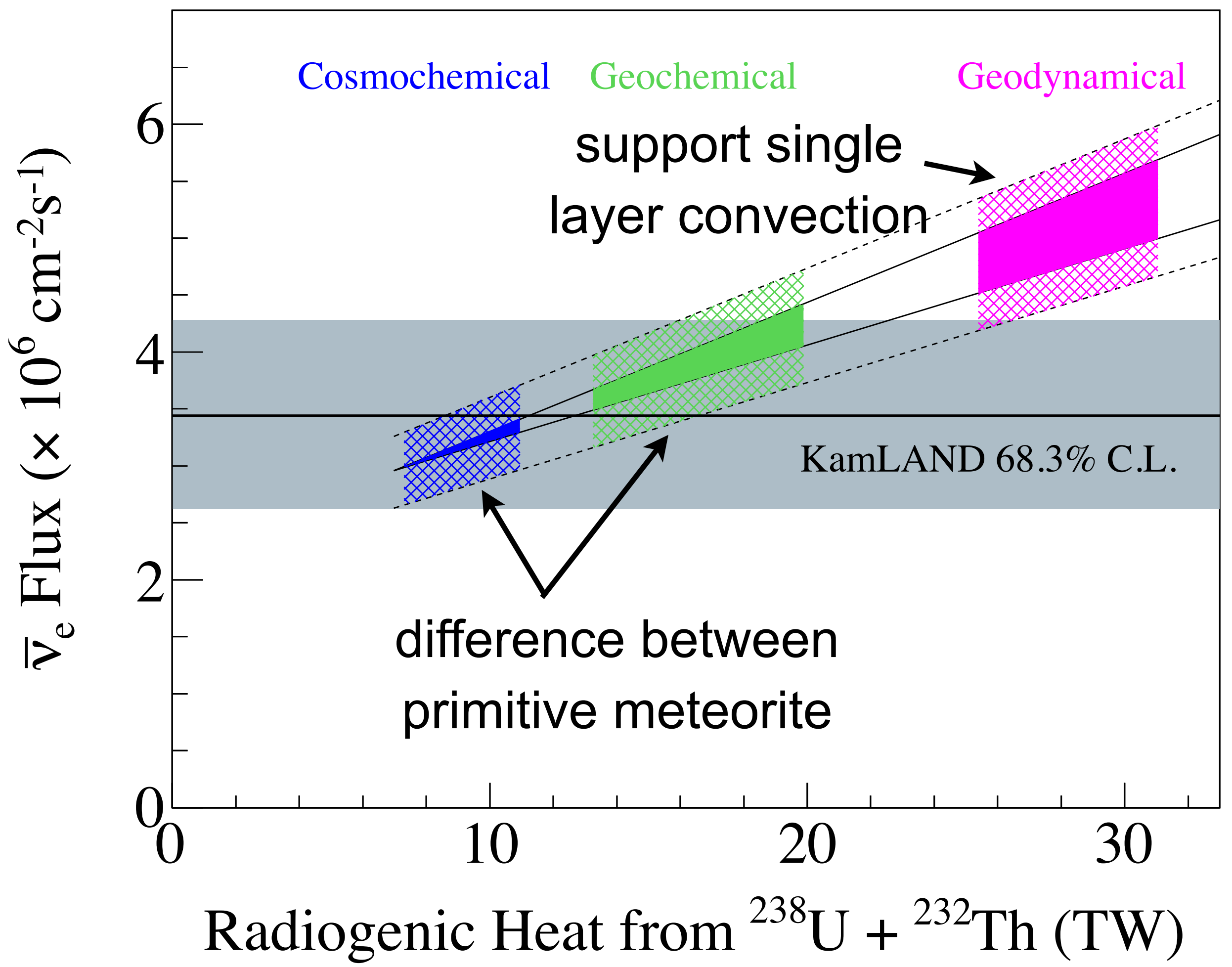
Agreement of results at multi-site

Earth Model Comparison

Three classes BSE compositional estimates

O. Šramek et al. Earth. Plan. Sci. Letters 361 (2013) 356–366

Model	Cosmochem.	Geochem.	Geodyn.
A_U (ppb)	12 ± 2	20 ± 4	35 ± 4
A_{Th} (ppb)	43 ± 4	80 ± 13	140 ± 14
A_K (ppm)	146 ± 29	280 ± 60	350 ± 35
Th/U	3.5	4.0	4.0
K/U	12000	14000	10000
Tot. Power (TW)	11 ± 2	20 ± 4	33 ± 3
Mantle power (TW)	3.3 ± 2.0	12 ± 4	25 ± 3
Mantle Urey ratio	0.08 ± 0.05	0.3 ± 0.1	0.7 ± 0.1



KamLAND result (2013)

radiogenic **$14.2^{+7.9}_{-5.1}$TW**

heat low from Earth's surface 47±2 TW

Geodynamical prediction with homogeneous hypothesis is disfavored at 89% C.L.

All composition models are still consistent within ~2σ

Geo-ν measurement is in agreement with BSE models

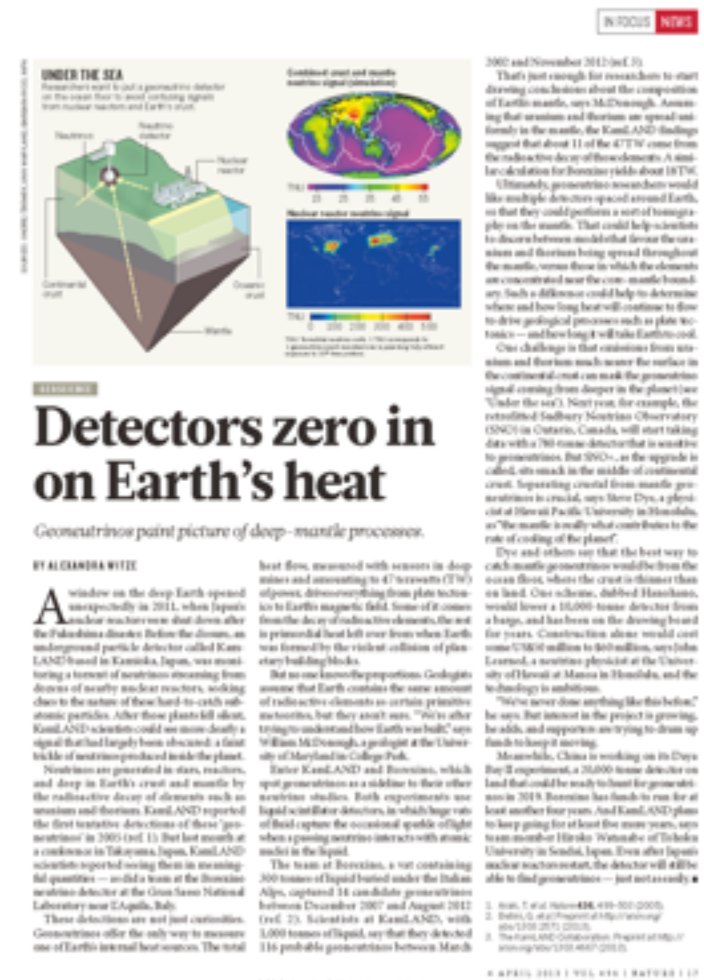
Physicist/Geoscientist Collaborative Work

Neutrino Geoscience 2013

International Workshop
(Takayama in Japan)

http://www.awa.tohoku.ac.jp/geoscience2013/

Nature News in April 2013


Detectors zero in on Earth's heat

Geoneutrinos paint picture of deep-mantle processes.

http://www.nature.com/polopoly_fs/1.12707!/menu/main/topColumns/topLeftColumn/pdf/496017a.pdf

"Neutrino Geoscience" is developing

- Earth model from geophysics and geochemistry
- Multi-site measurement by neutrino detectors

↓

detailed map of neutrino source inside the Earth

International scientific community is organized

Summary

• Multi-site measurements by KamLAND and Borexino have just started.

• Geo neutrino experiments showed

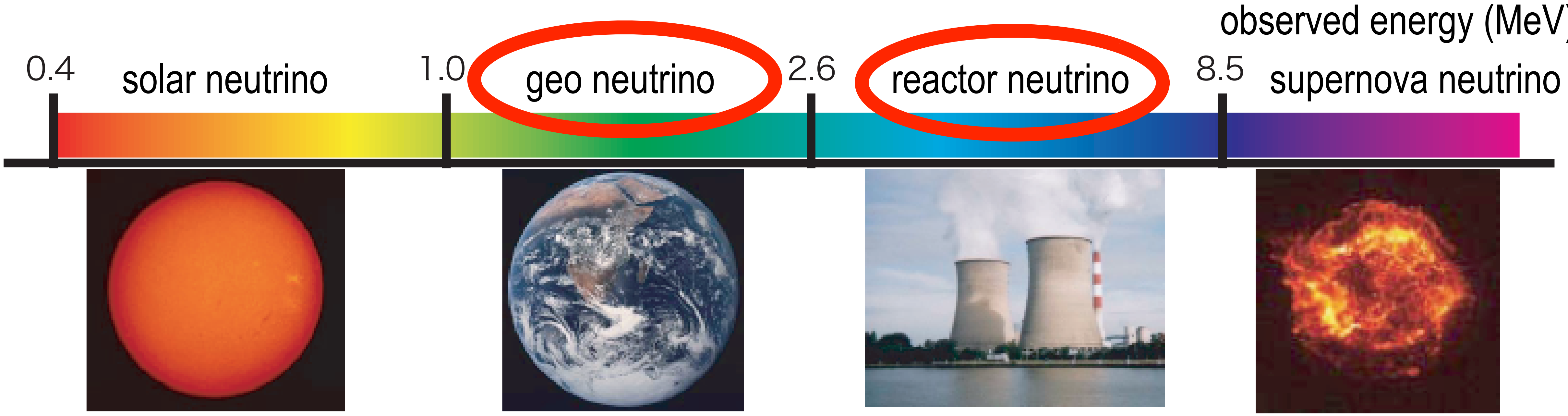
- Observed flux is still consistent with all BSE models
- Radiogenic heat contributes only half of Earth's total heat flow → primordial heat still remain

• Tests of primitive meteorite and mantle convection model are the next target.

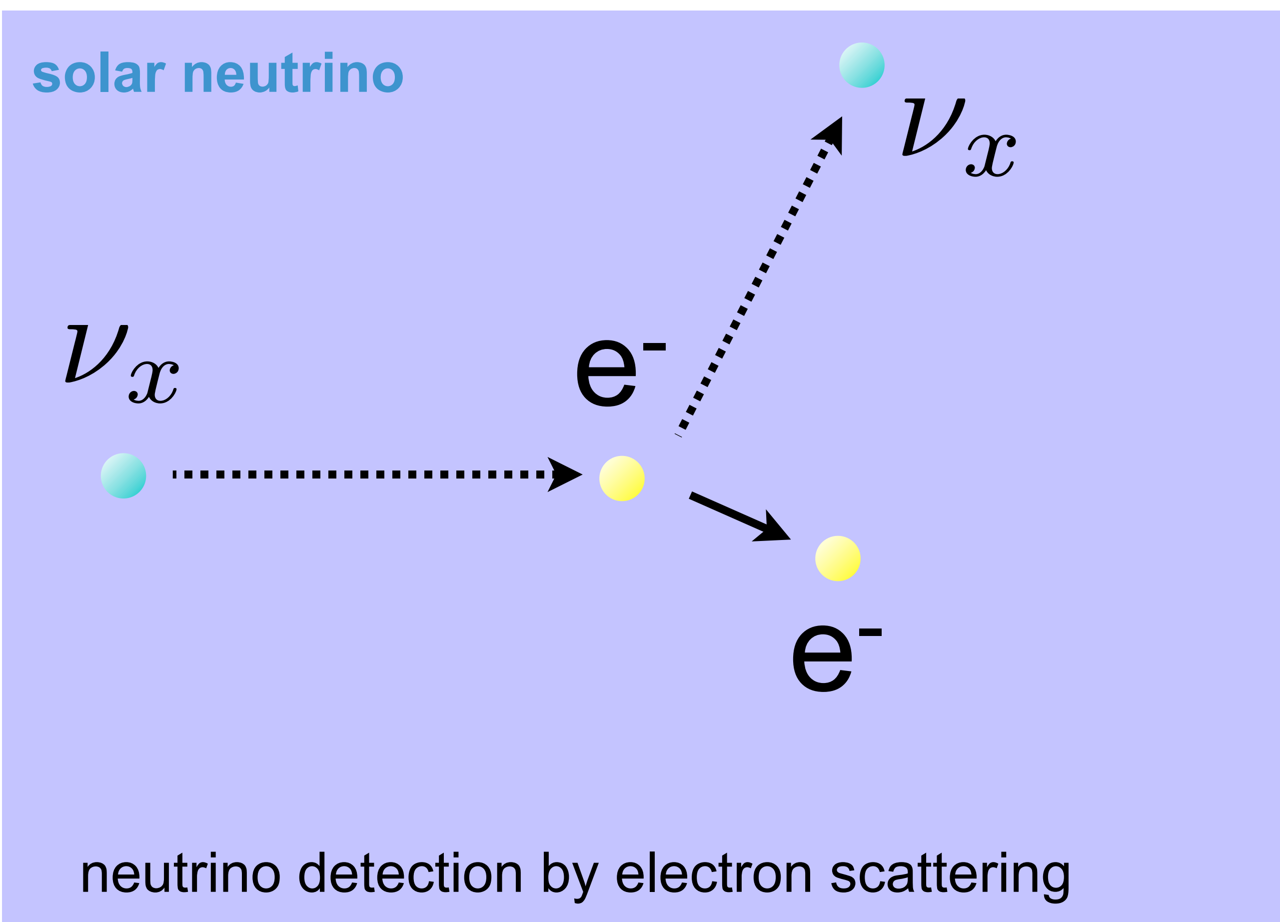
• Multi-site measurements at geologically different locations will be important for the tests.

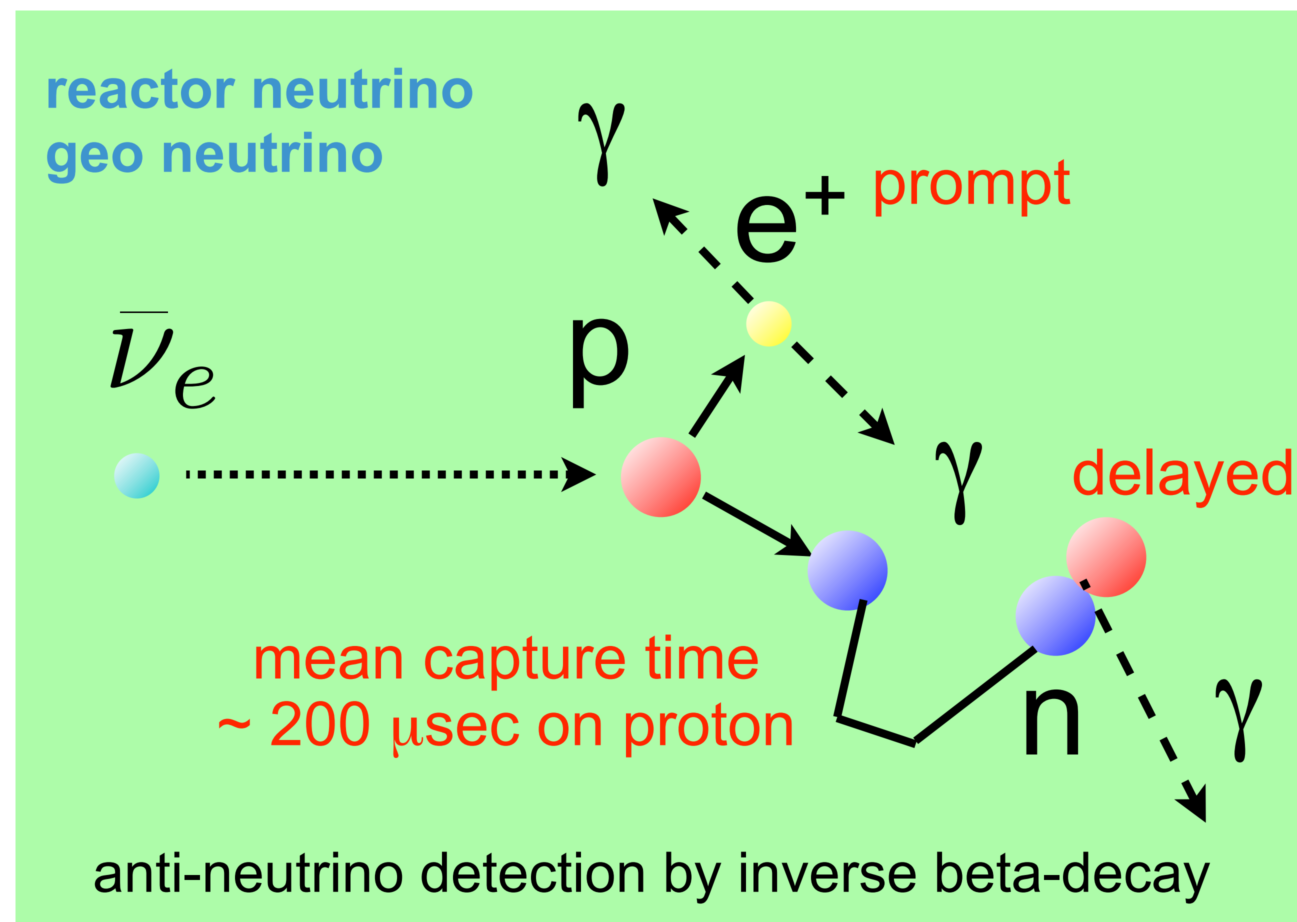
Backup

Physics Target in KamLAND



Mar. 2013 new result (hep-ex/1303.4667)

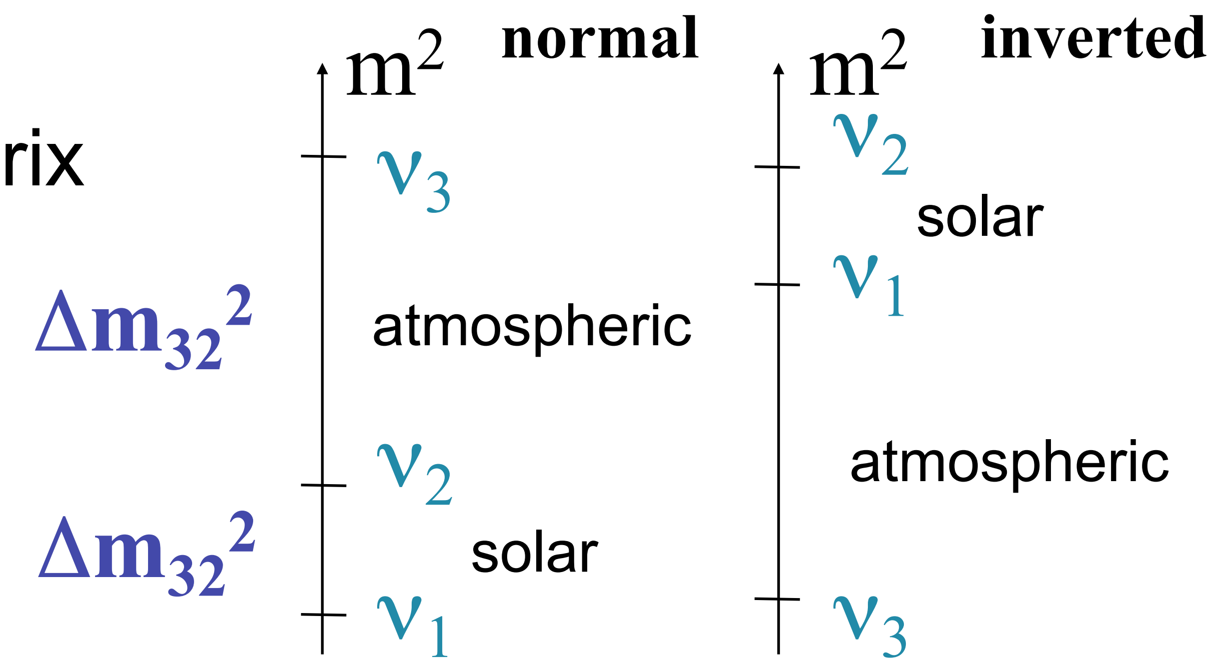




Neutrino Oscillation

MNS (Maki-Nakagawa-Sakata) Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu1} & V_{\mu2} & V_{\mu3} \\ V_{\tau1} & V_{\tau2} & V_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



θ_{23} θ_{13}, CP phase θ_{12} Majorana phase

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric solar

6 parameters : 3 mixing angle, 2 mass difference, 1 CP phase

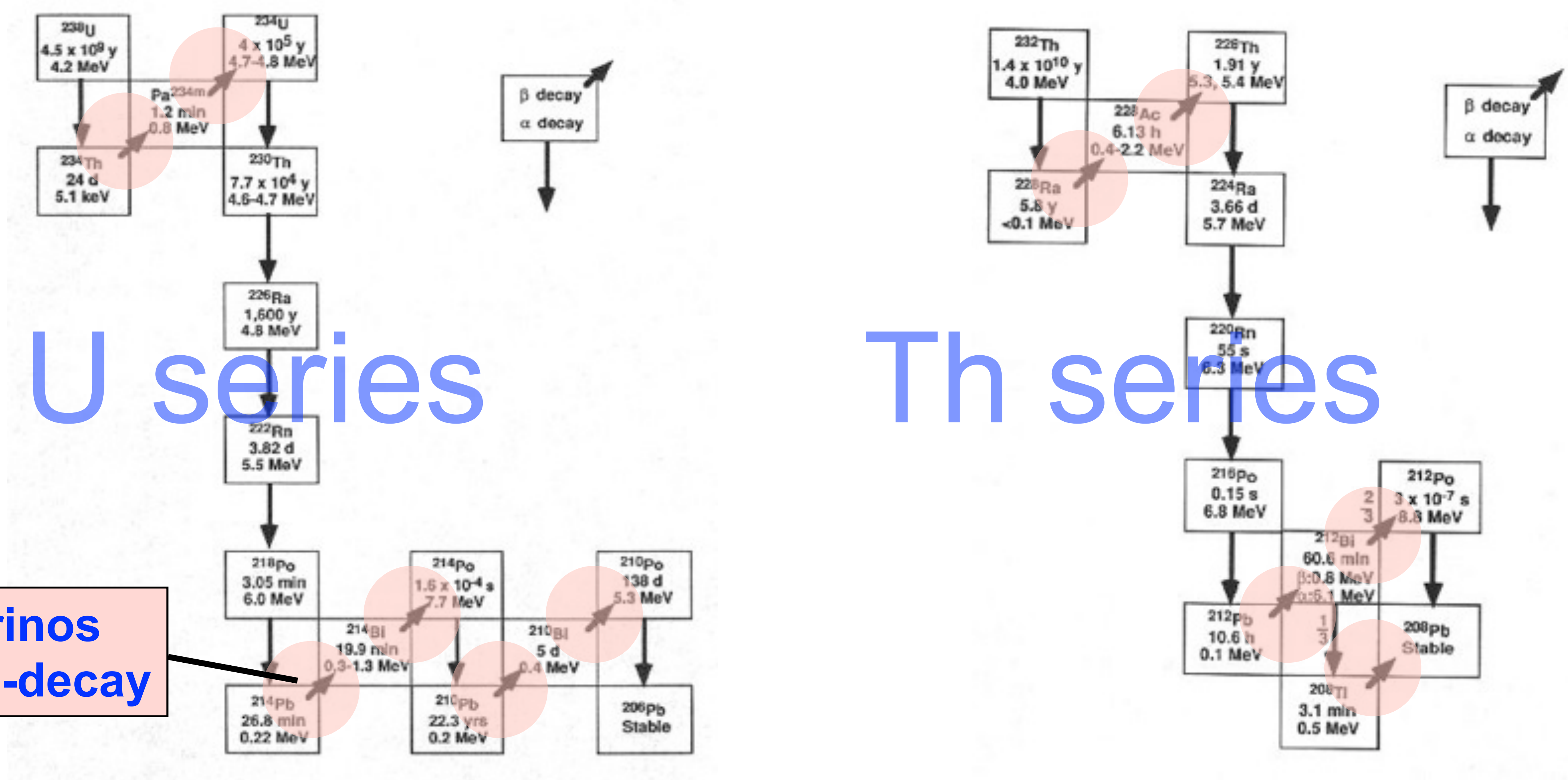
+ 2 Majorana phase

investigated by neutrino oscillation experiments
(solar, atmospheric, accelerator and reactor neutrinos)

Neutrino from the Earth

Heat sources in the Earth

(1) Radiogenic heat from U, Th, K decay
(2) Release of gravitational energy through accretion or metallic core separation
(3) Latent heat from the growth of inner core

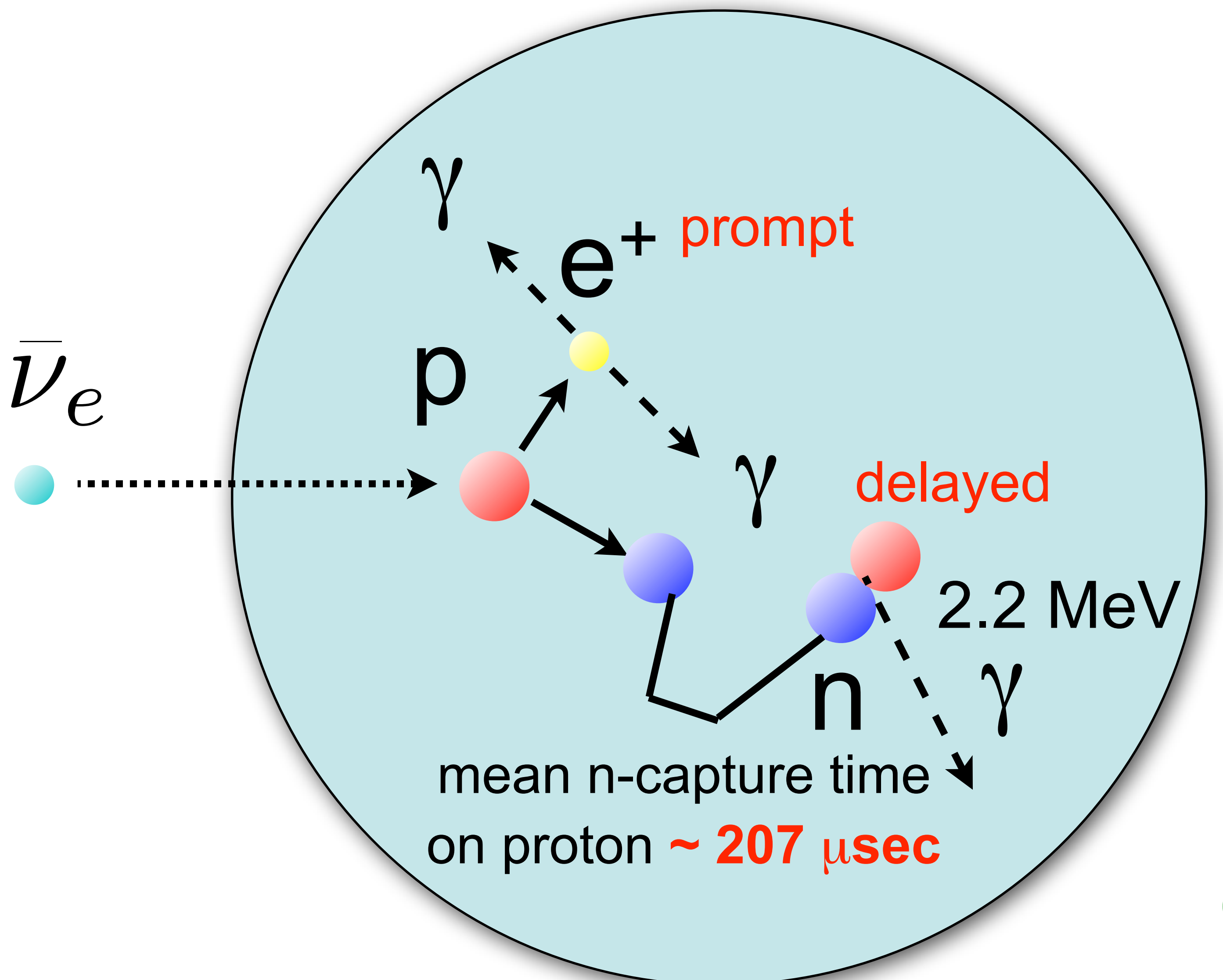


anti-neutrinos from beta-decay

Radiogenic heat : α-decay or β-decay emitting "anti-neutrinos"

Anti-Neutrino Detection

inverse beta-decay reaction



(a) accidental B.G. discrimination

- $0.5 < \Delta T < 1000$ μs
- $\Delta R < 2$ m
- 1.8 MeV $< E_{delayed} <$ 2.6 MeV or 4.0 MeV $< E_{delayed} <$ 5.8 MeV
- 0.9 MeV $< E_{prompt} <$ 8.5 MeV
- R_{prompt}, $R_{delayed} < 6.0$ m
- L-selection from 6 parameters

(b) μ spallation cut

- $\Delta T_\mu > 2$ s after showing μ
- $\Delta T_\mu > 2$ s or $\Delta L > 3$ m after non-showering μ ($\Delta Q < 10^6$ p.e.)

Tight background rejection by delayed coincidence

Reactor and Geo Neutrino Analysis

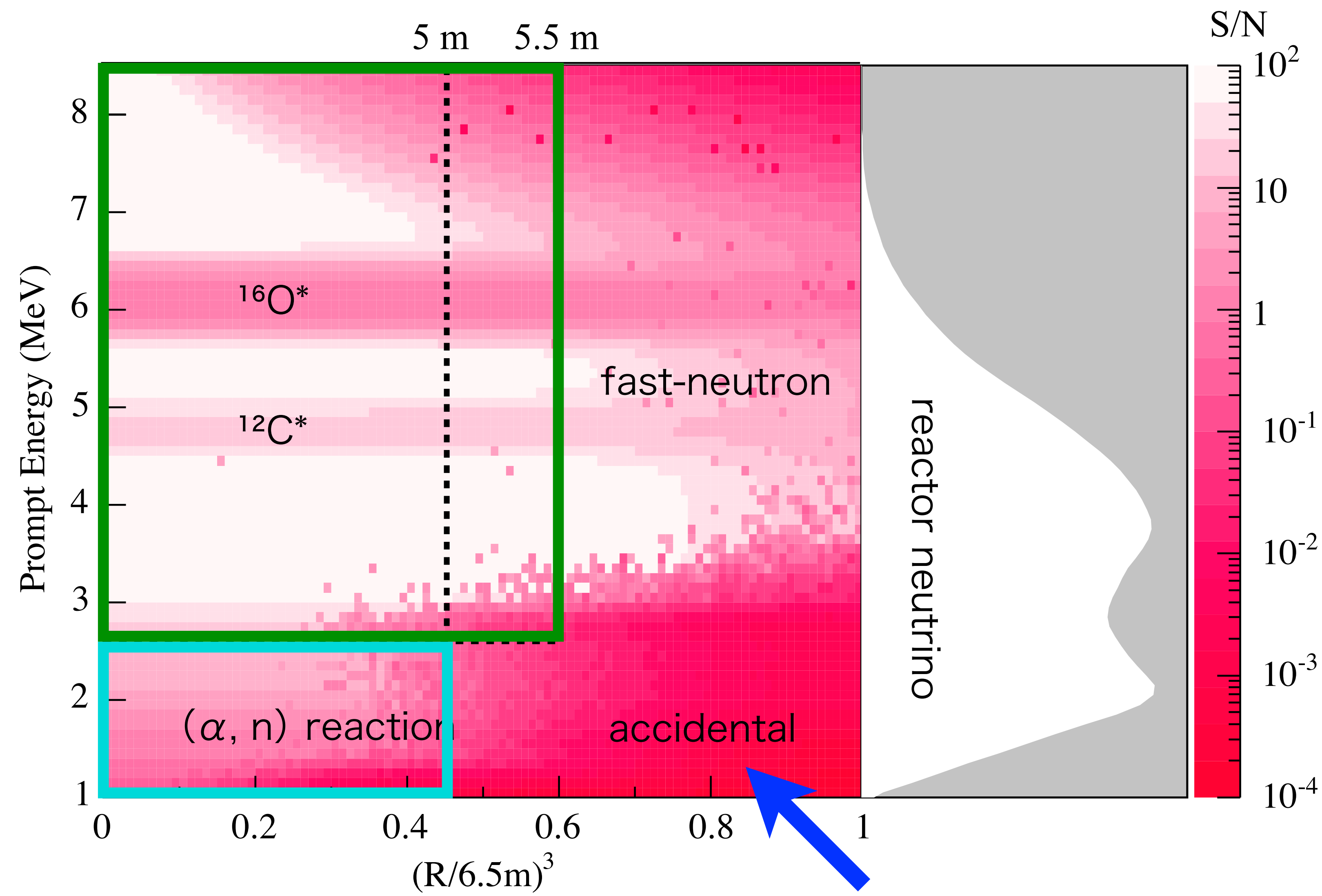
previous result

separated analysis window for reactor and geo neutrinos

reactor neutrino
(2.6 - 8.5 MeV, R 5.5 m)

geo neutrino
(0.9 - 2.6 MeV, R 5.0 m)

S / B ratio map (energy v.s. radius)



large accidental B.G.
caused by external γ-rays

Analysis improvement

(1) efficient accidental background rejection
(2) combined analysis of reactor and geo neutrinos

Anti-Neutrino Event Selection

(a) Accidental B.G. discrimination

discriminator based on 5 parameters (E_d, ΔR, ΔT, R_p, R_d)

$$L_{ratio} = f_{\bar{\nu}} / (f_{\bar{\nu}} + f_{accidental})$$

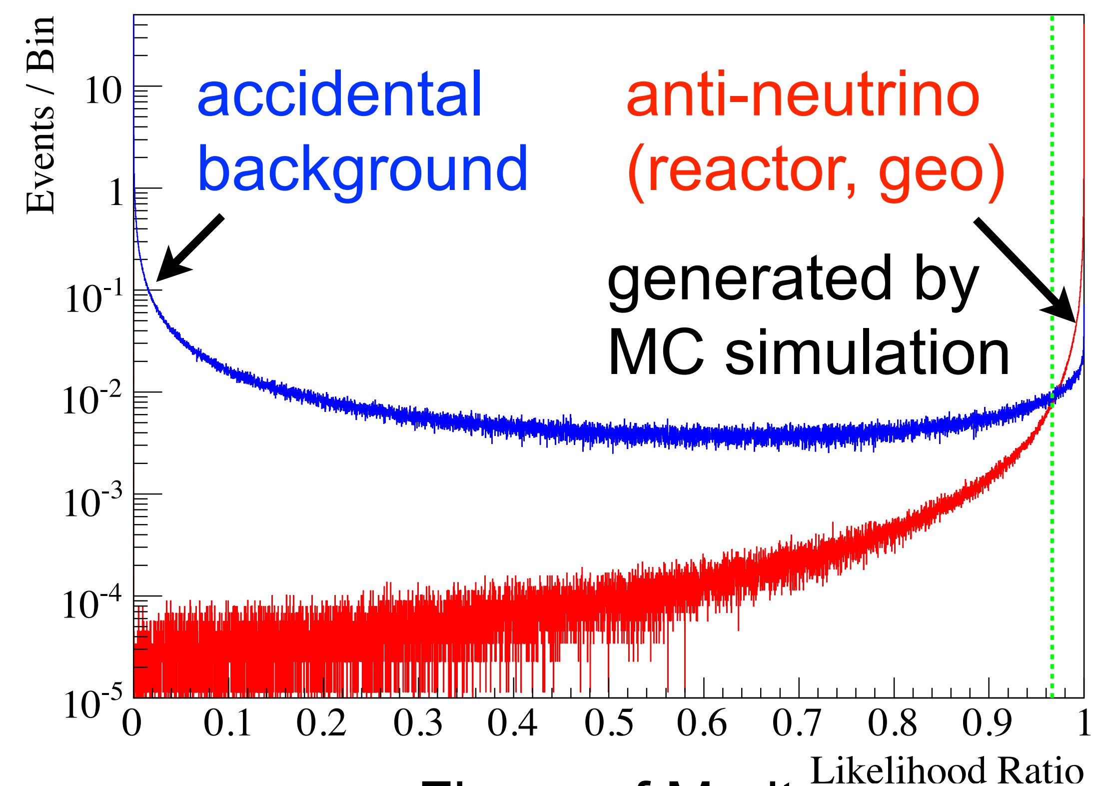
f : PDF

Selection : Maximize "Figure of Merit" $\frac{S}{\sqrt{S + B_{accidental}}}$

(b) μ spallation cut

- $\Delta T_\mu > 2$ s after showing μ ($\Delta Q > 10^6$ p.e.)
- $\Delta T_\mu > 2$ s or $\Delta L > 3$ m after non-showering μ

2.2 < E_{prompt} < 2.3 MeV



Detection efficiency

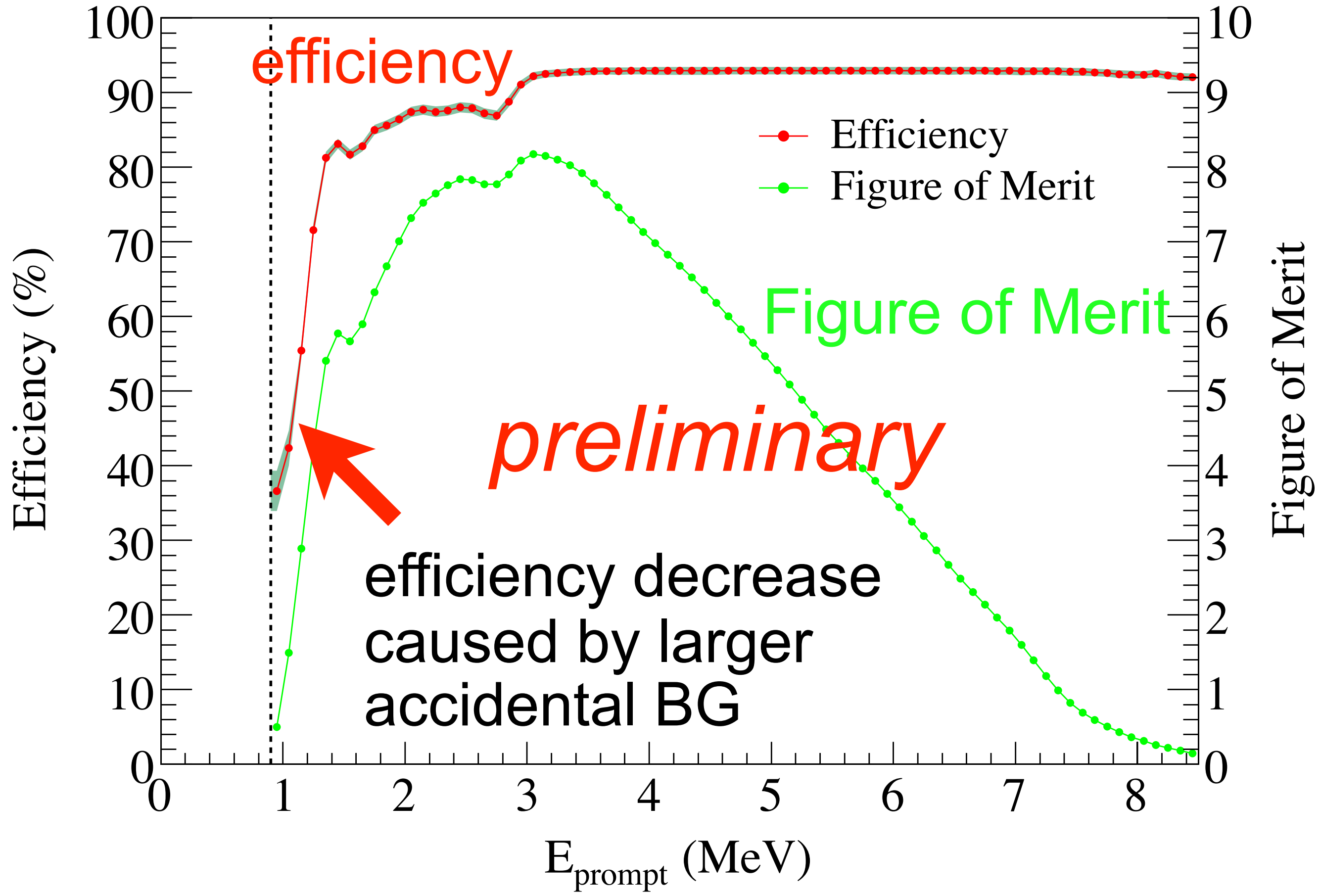
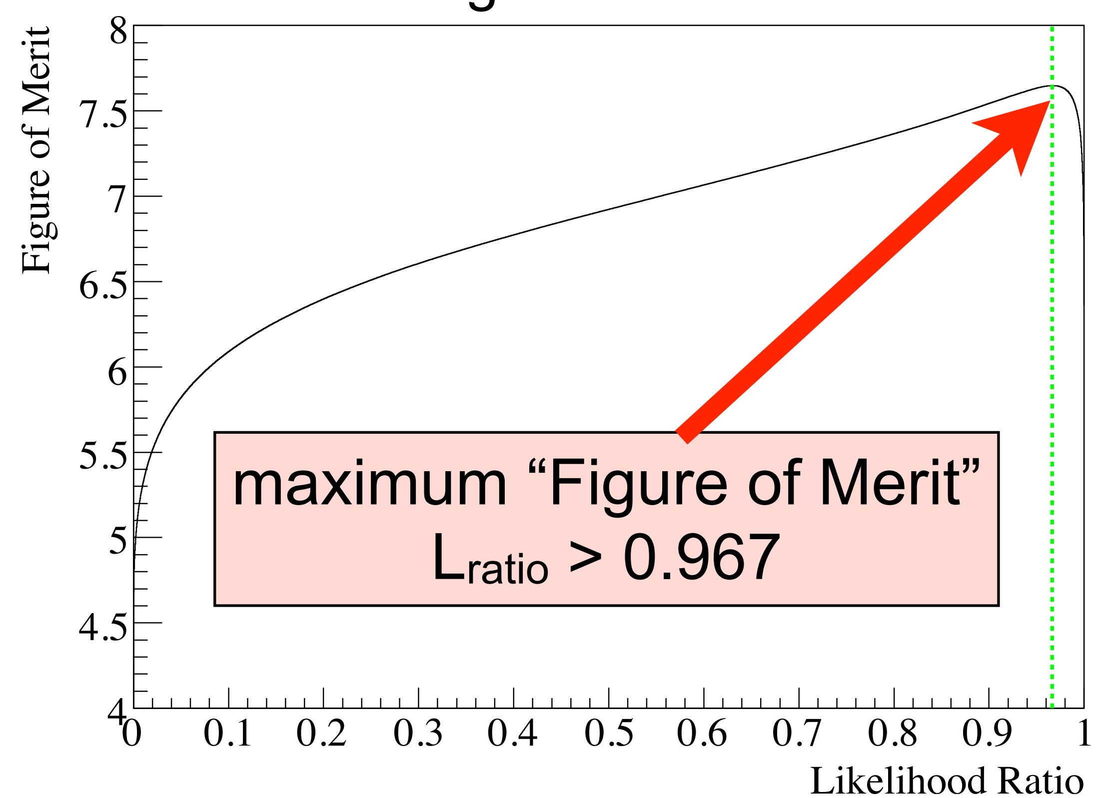


Figure of Merit

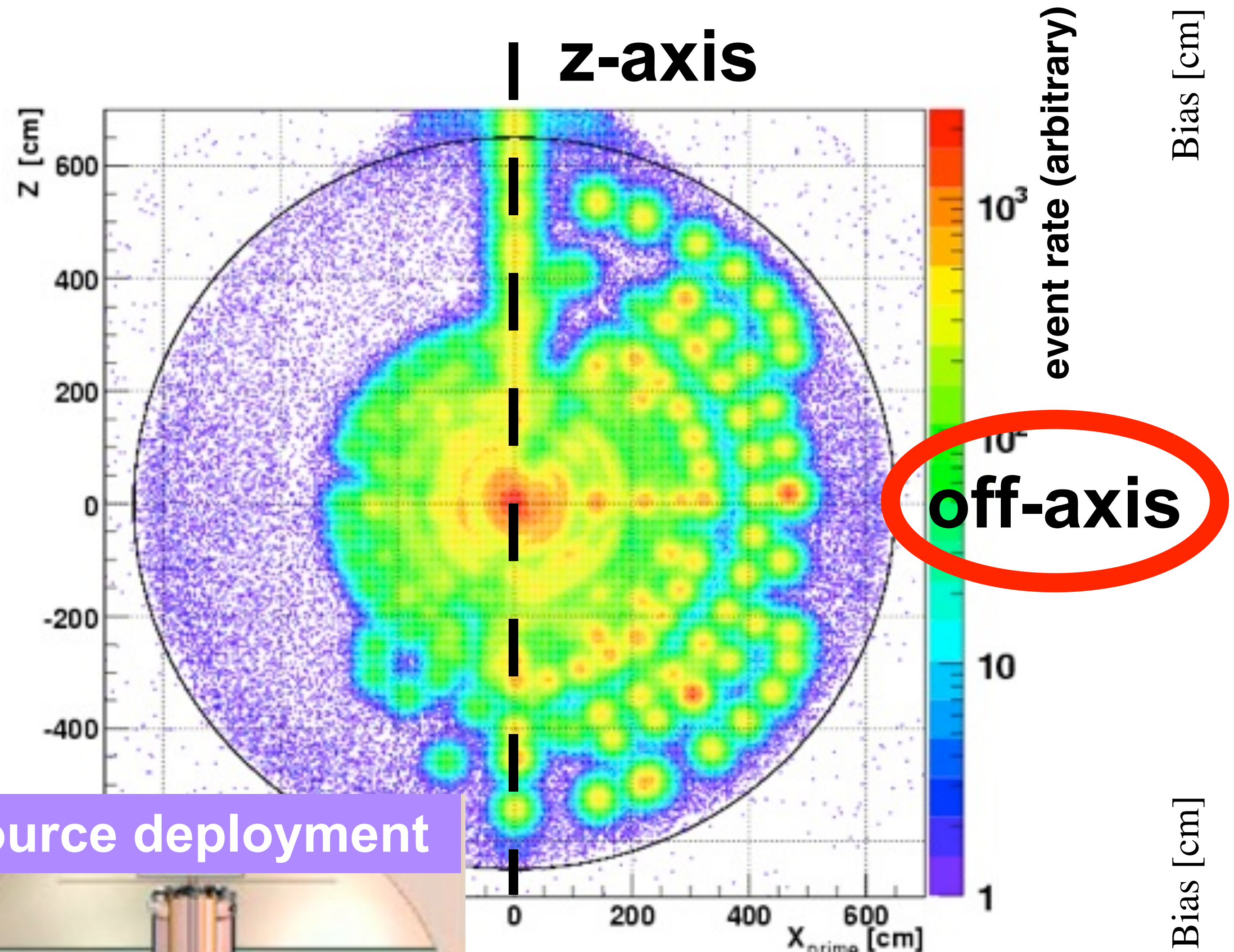


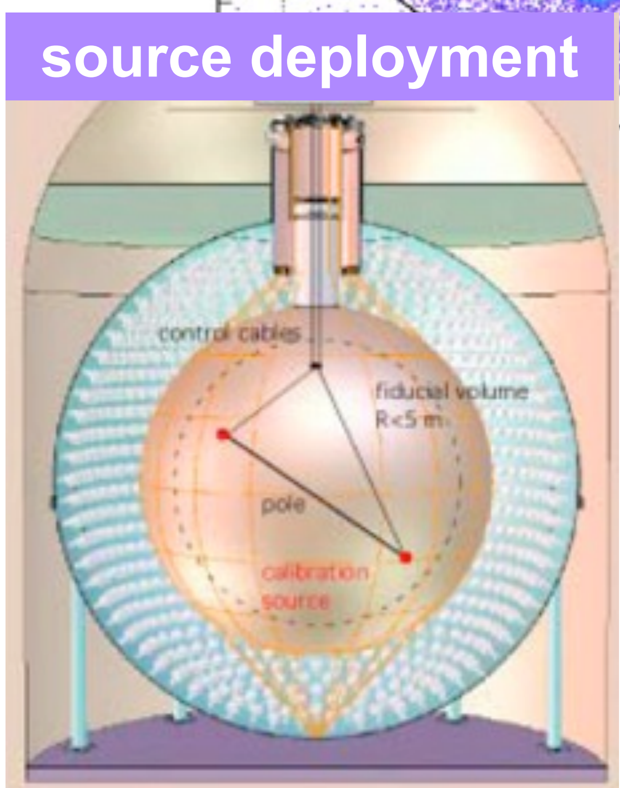
Systematic Uncertainty

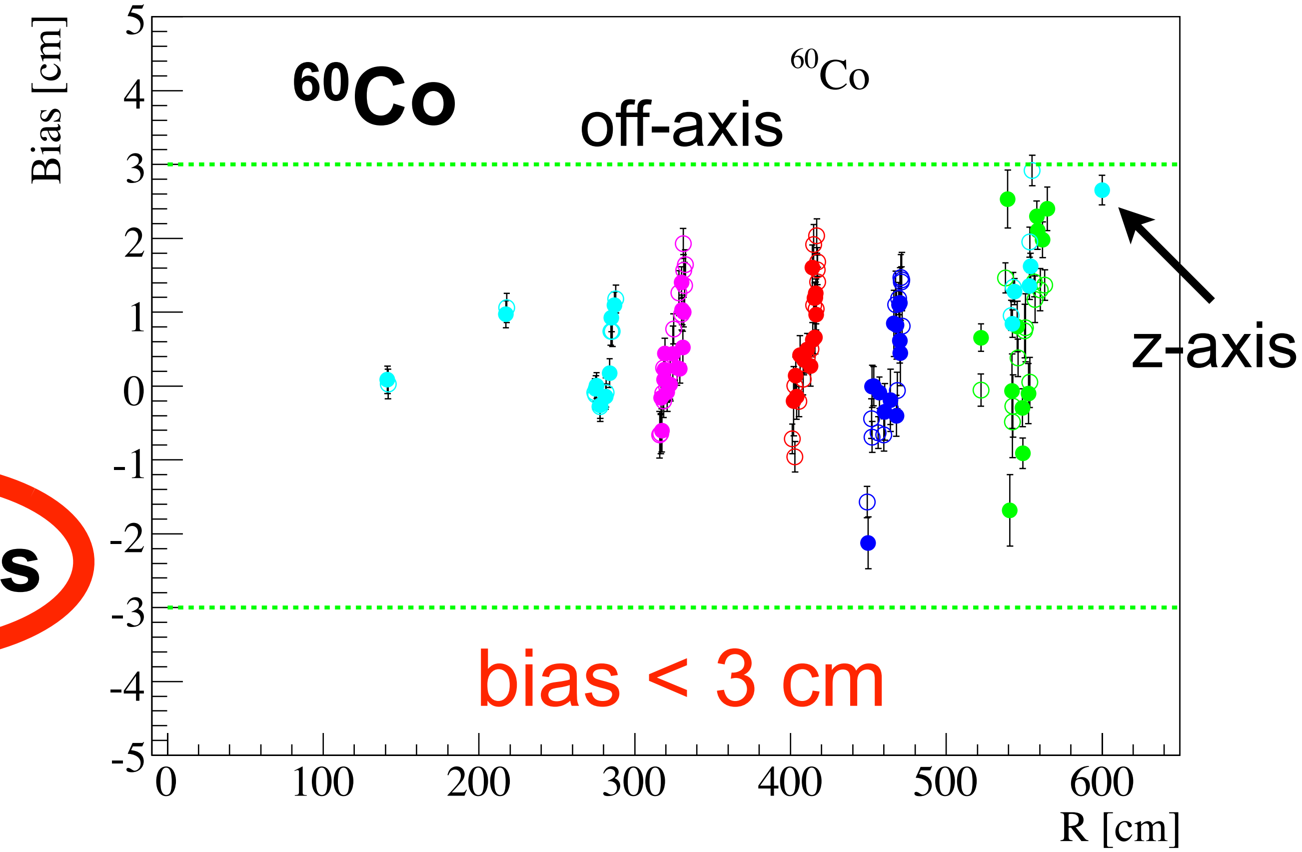
before / after purification

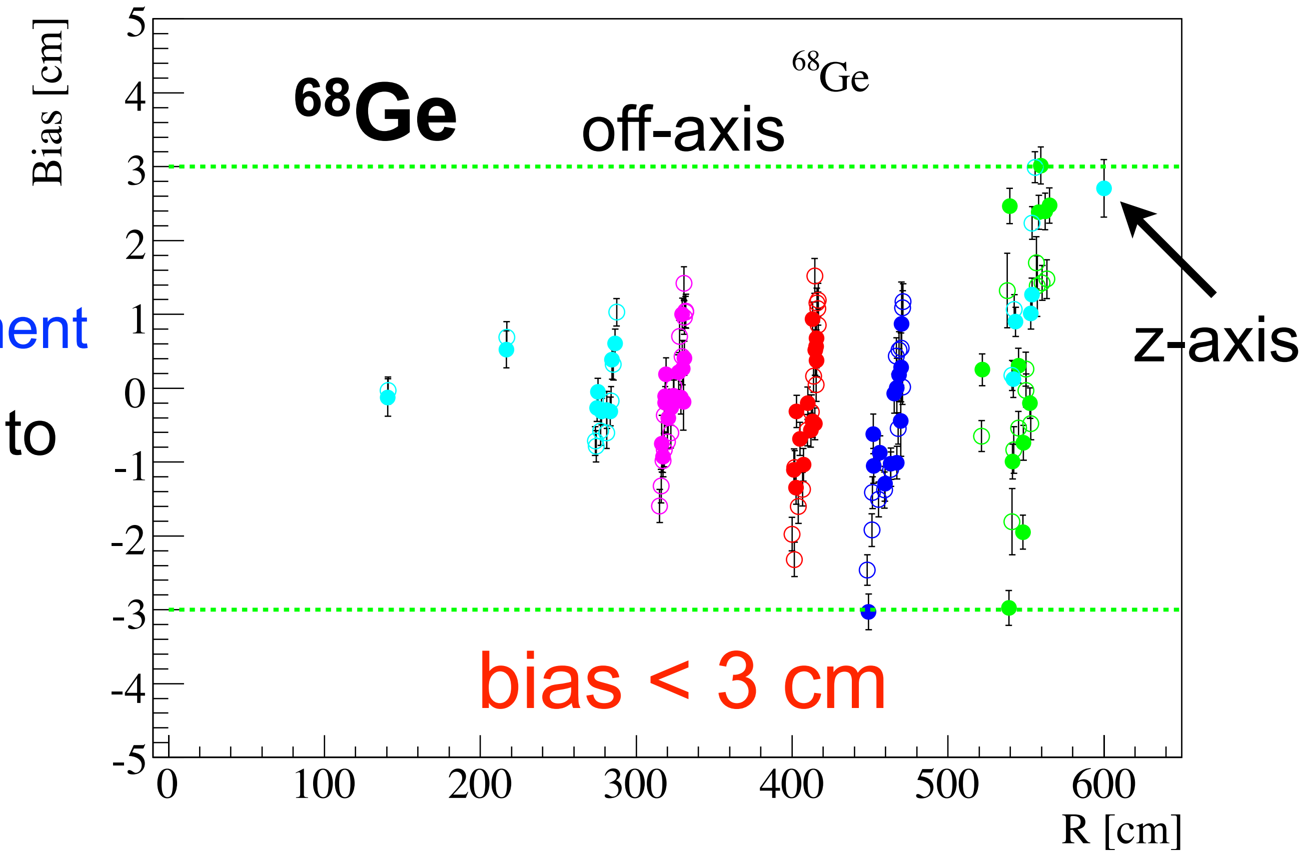
	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.8 / 1.8	$\overline{\nu}_e$-spectra [21]	0.6 / 0.6
Rate	Fiducial volume	1.8 / 2.5	$\overline{\nu}_e$-spectra	1.4 / 1.4
	Energy scale	1.1 / 1.3	Reactor power	2.1 / 2.1
	$L_{cut}(E_{\rm p})$ eff.	0.7 / 0.8	Fuel composition	1.0 / 1.0
	Cross section	0.2 / 0.2	Long-lived nuclei	0.3 / 0.4
	Total	2.3 / 3.0	Total	2.7 / 2.8

Full Volume Calibration







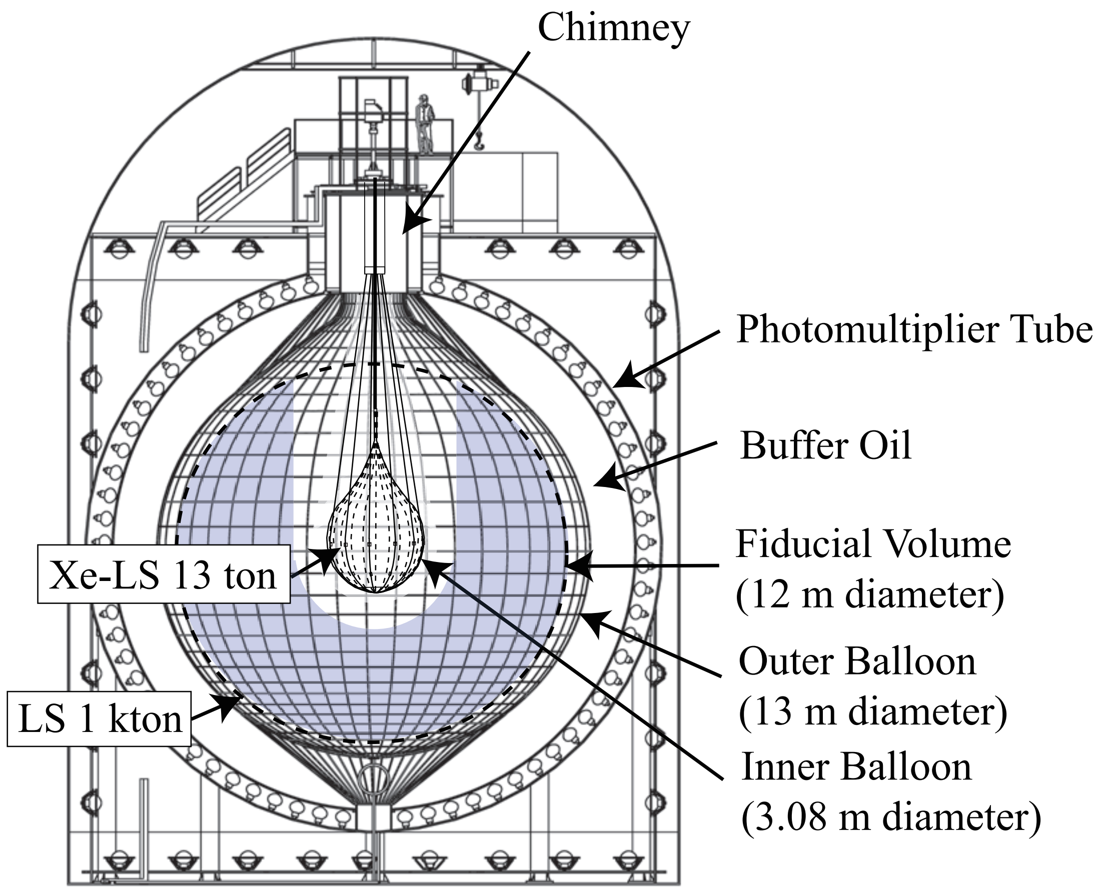


"4pi calibration" system for the off-axis source deployment

bias < 3 cm corresponds to 1.8% volume uncertainty

↓

cross-checked by $^{12}B/^{12}N$ uniformity



- Vertex cut conditions

To minimize accidental coincidences, we apply Xe LS cut for KamLAND-Zen Phase in R < 6.0m fiducial volume.

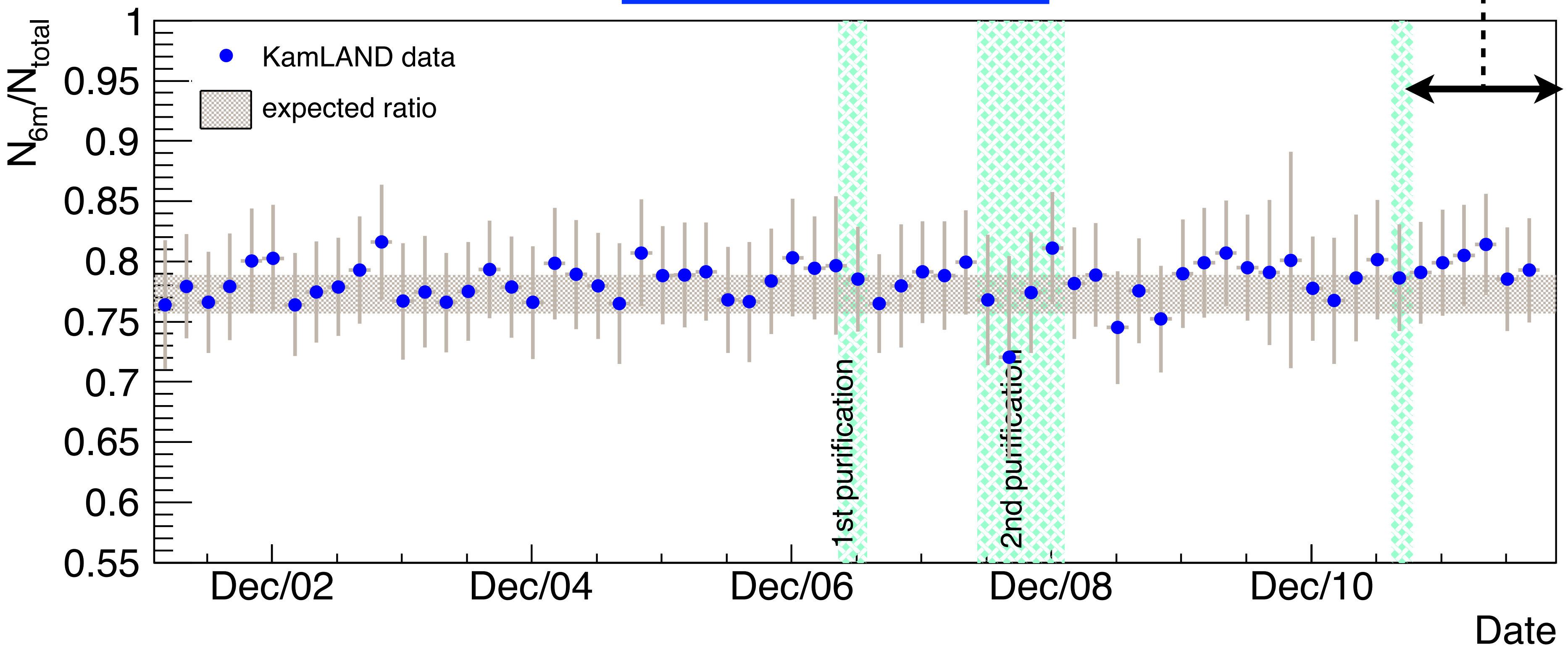
R > 2.5m, cylinder cut (ρ > 2.5m, Z > 0)
(cut out volume 16.6% of R<6m)

- Data stability of KamLAND region

^{12}B N_{6m}/N_{total} vs time

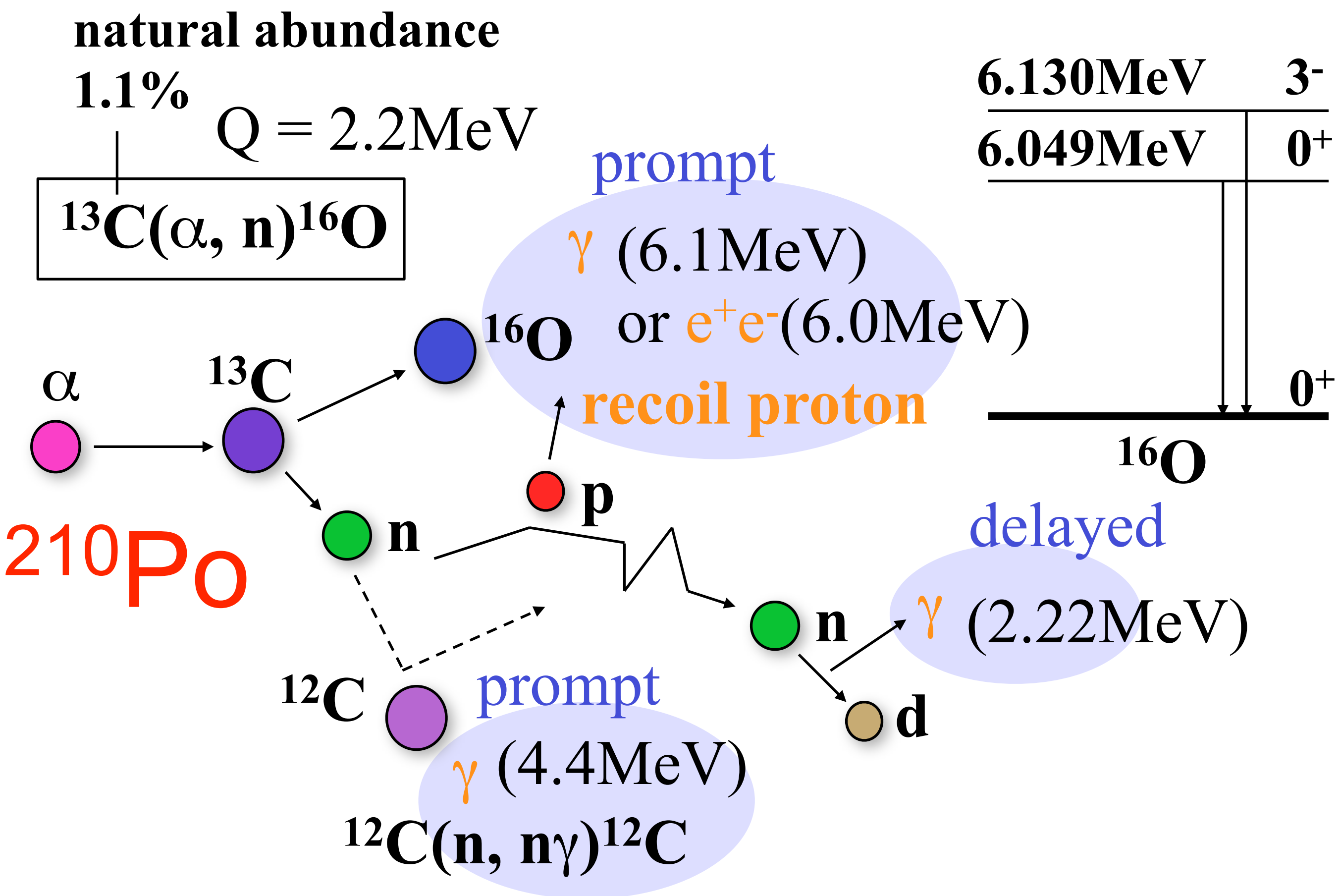
with Xe LS Cut

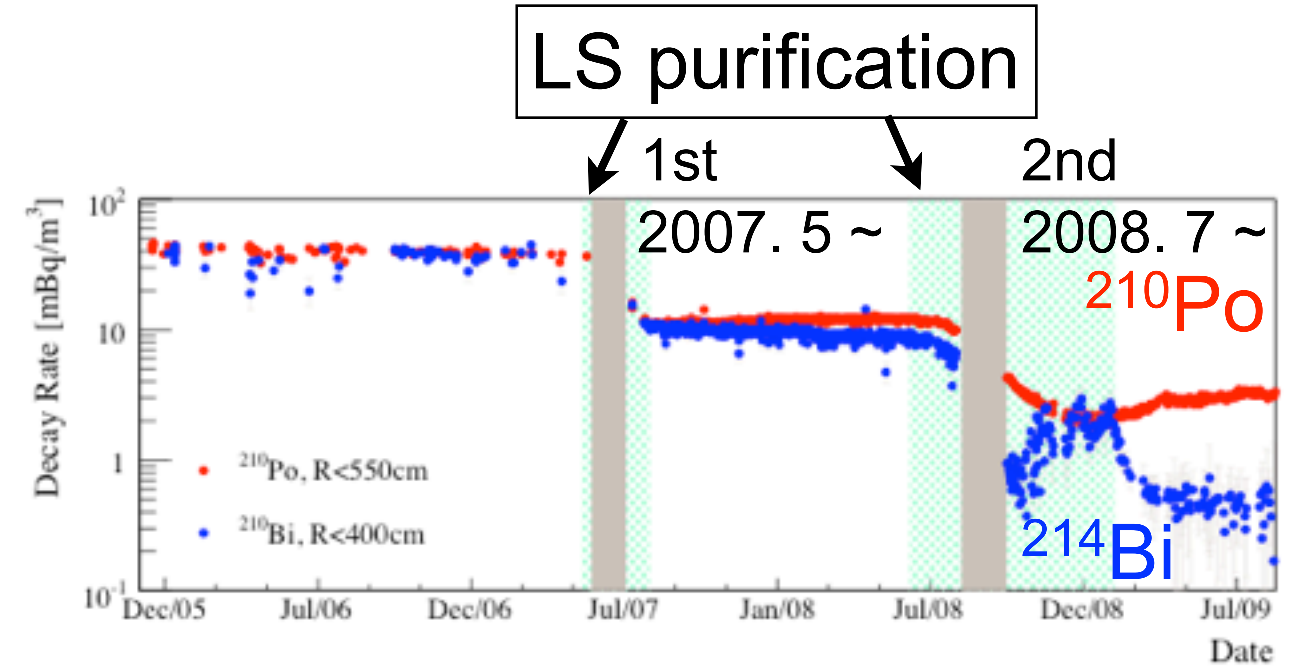
KamLAND-Zen Phase

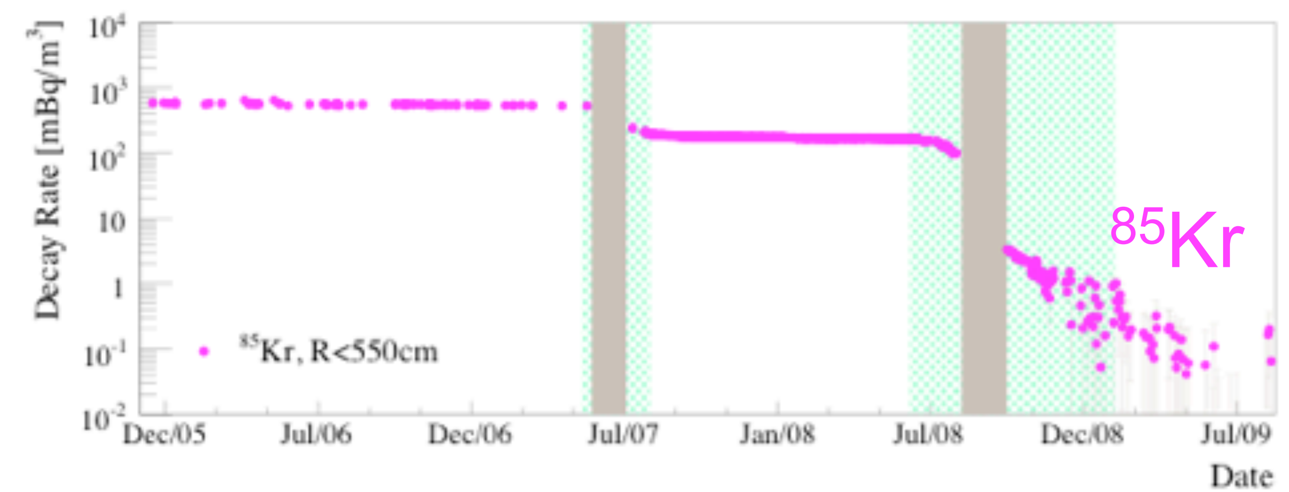


- Event rate has been stable.
- difference before and after purification : 2.5%

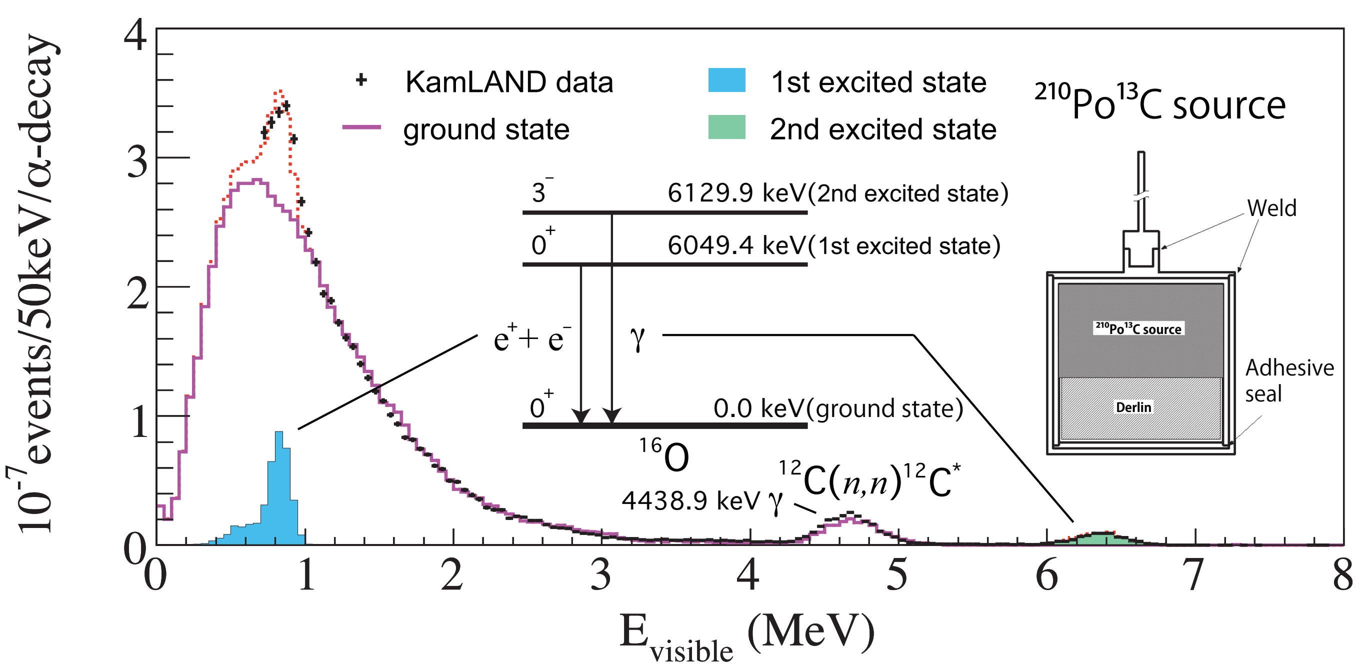
Background Estimation







in-situ calibration with $^{210}Po^{13}C$



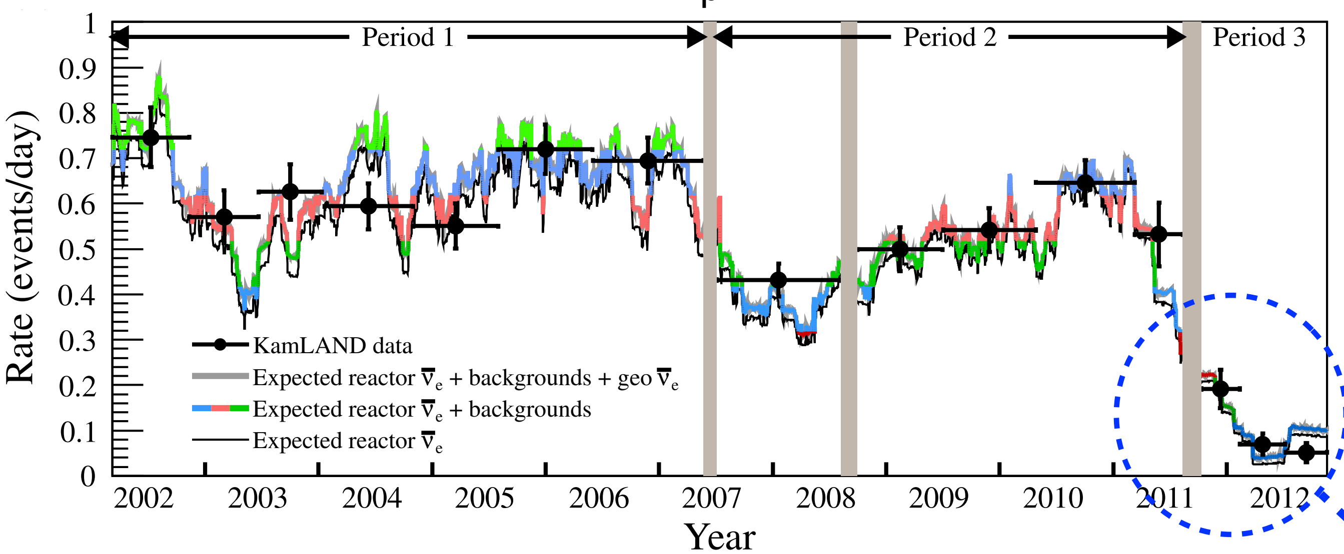
(1) dominant BG source (α, n) has been reduced by down to ~ 1 / 20

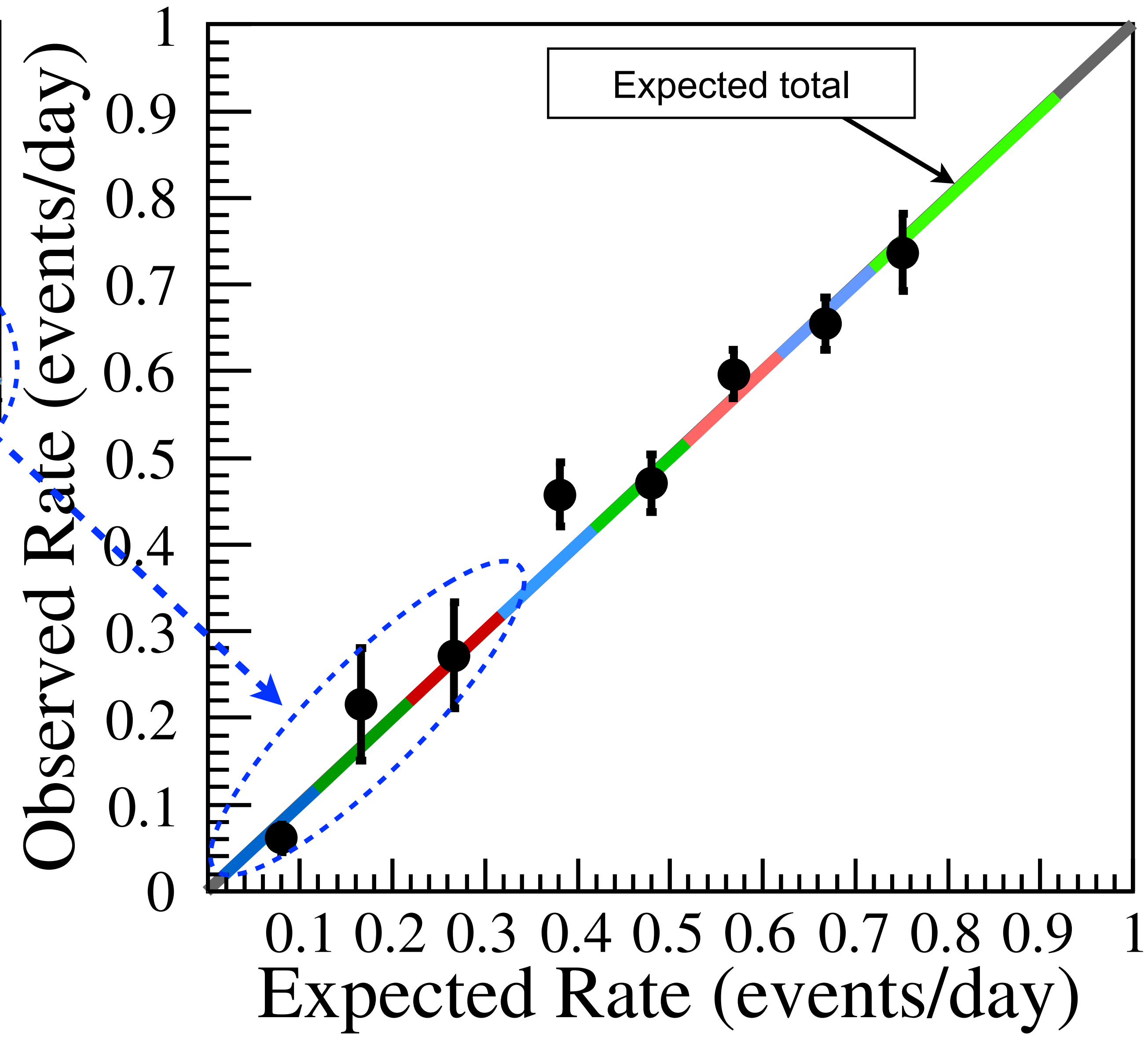
(2) determination of the cross section is improved by in-situ calibration

uncertainty: 11% for ground state

Correlation Plot

2.6 < E_p < 8.5 MeV





provide good data to confirm our background

↓

"Rate + Shape + Time" analysis

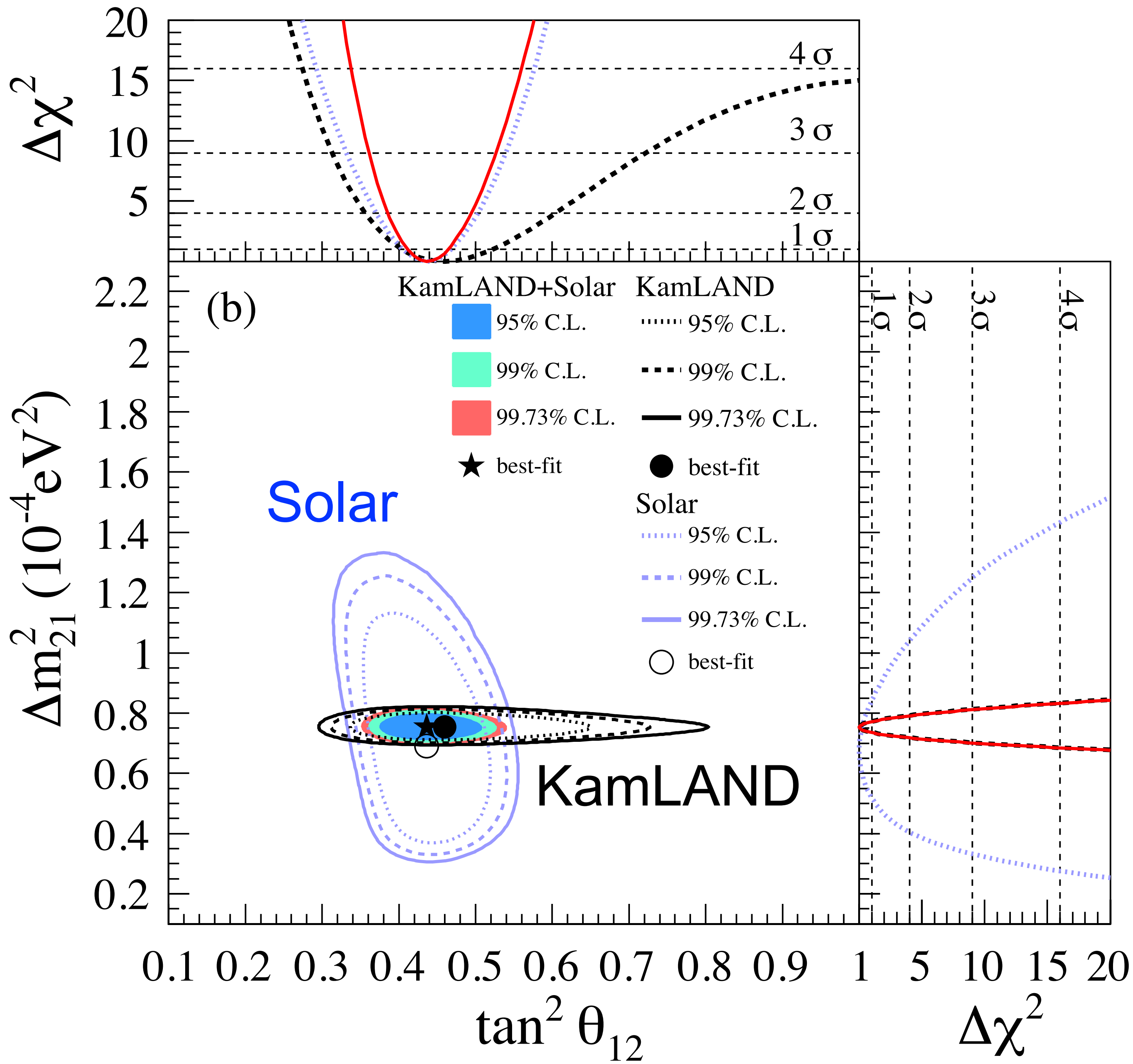
$$\chi^2 = \chi^2_{\rm rate}(\theta_{12}, \theta_{13}, \Delta m^2_{21}, N_{\rm BG1\to5}, N^{\rm geo}_{\rm U,Th}, \alpha_{1\to4})$$
$$-2\ln L_{\rm shape}(\theta_{12}, \theta_{13}, \Delta m^2_{21}, N_{\rm BG1\to5}, N^{\rm geo}_{\rm U,Th}, \alpha_{1\to4})$$
$$+\chi^2_{\rm BG}(N_{\rm BG1\to5}) + \chi^2_{\rm syst}(\alpha_{1\to4})$$
$$+\chi^2_{\rm osci}(\theta_{12}, \theta_{13}, \Delta m^2_{21}) .$$

time dependent

3-Flavor Oscillation Parameters

θ_{12}: Solar constraint is dominant

Δm^2: KamLAND constraint is dominant



survival probability

$$P_{ee}^{3\nu} = \cos^4\theta_{13} P_{e'e'}^{2\nu} + \sin^4\theta_{13}$$

electron density

matter effect $N_{e'} \rightarrow N_e \cos^2\theta_{13}$

atmospheric oscillation length is completely averaged out ~~Δm^2_{31}~~

solar + KamLAND + θ_{13} experiments

$$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$$

$$\sin^2\theta_{13} = 0.023^{+0.002}_{-0.002}$$

Reference Earth Model

UCC U : 2.8 ppm / Th : 10.7 ppm

MCC U : 1.6 ppm / Th : 6.1 ppm

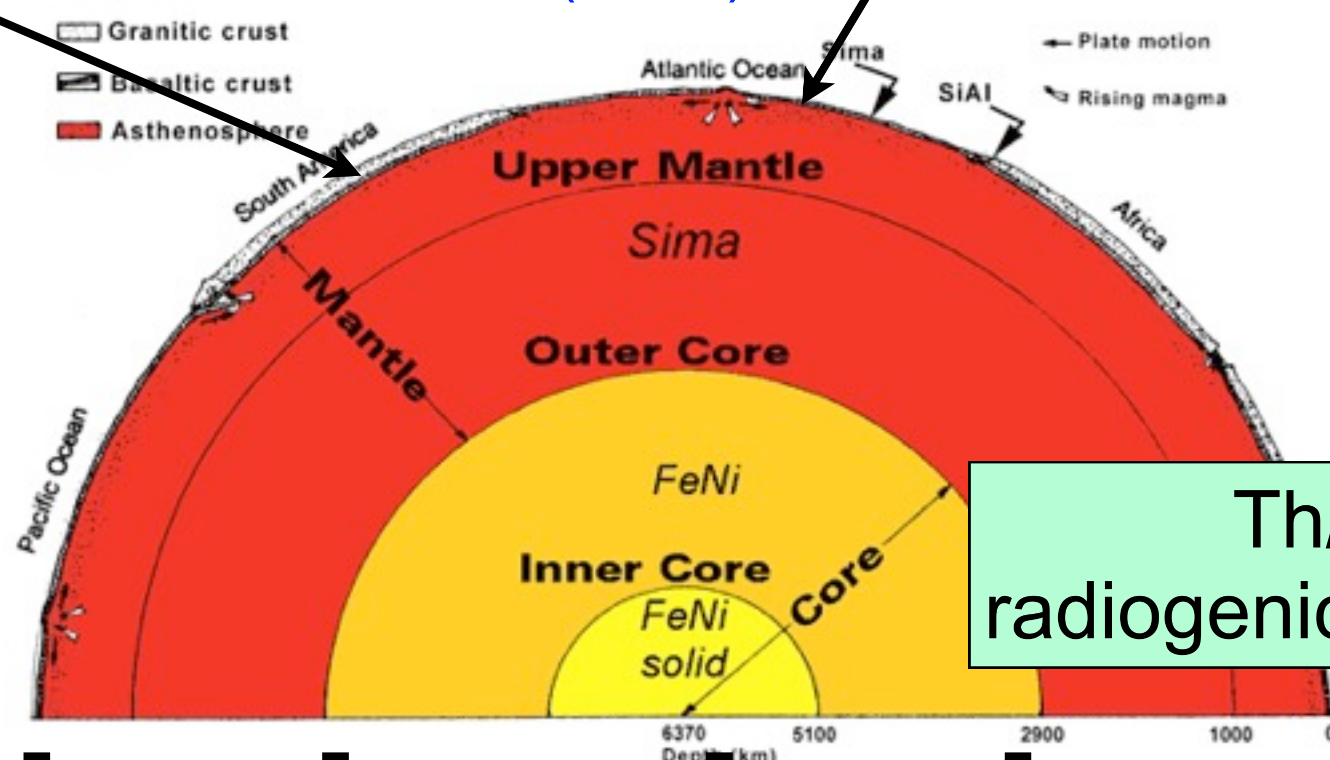
LCC U : 0.2 ppm / Th : 1.2 ppm

Rudnick et al. (1995)

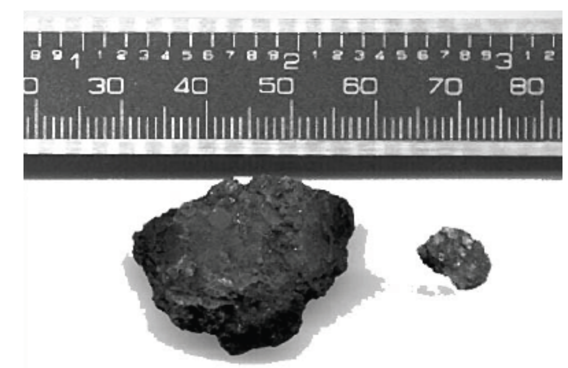
oceanic crust

U : 0.10 ppm / Th : 0.22 ppm

continental crust



chondrite meteorite



Th/U ~ 3.9

radiogenic heat ~ 16 TW

mantle

U : 0.012 ppm / Th : 0.048 ppm

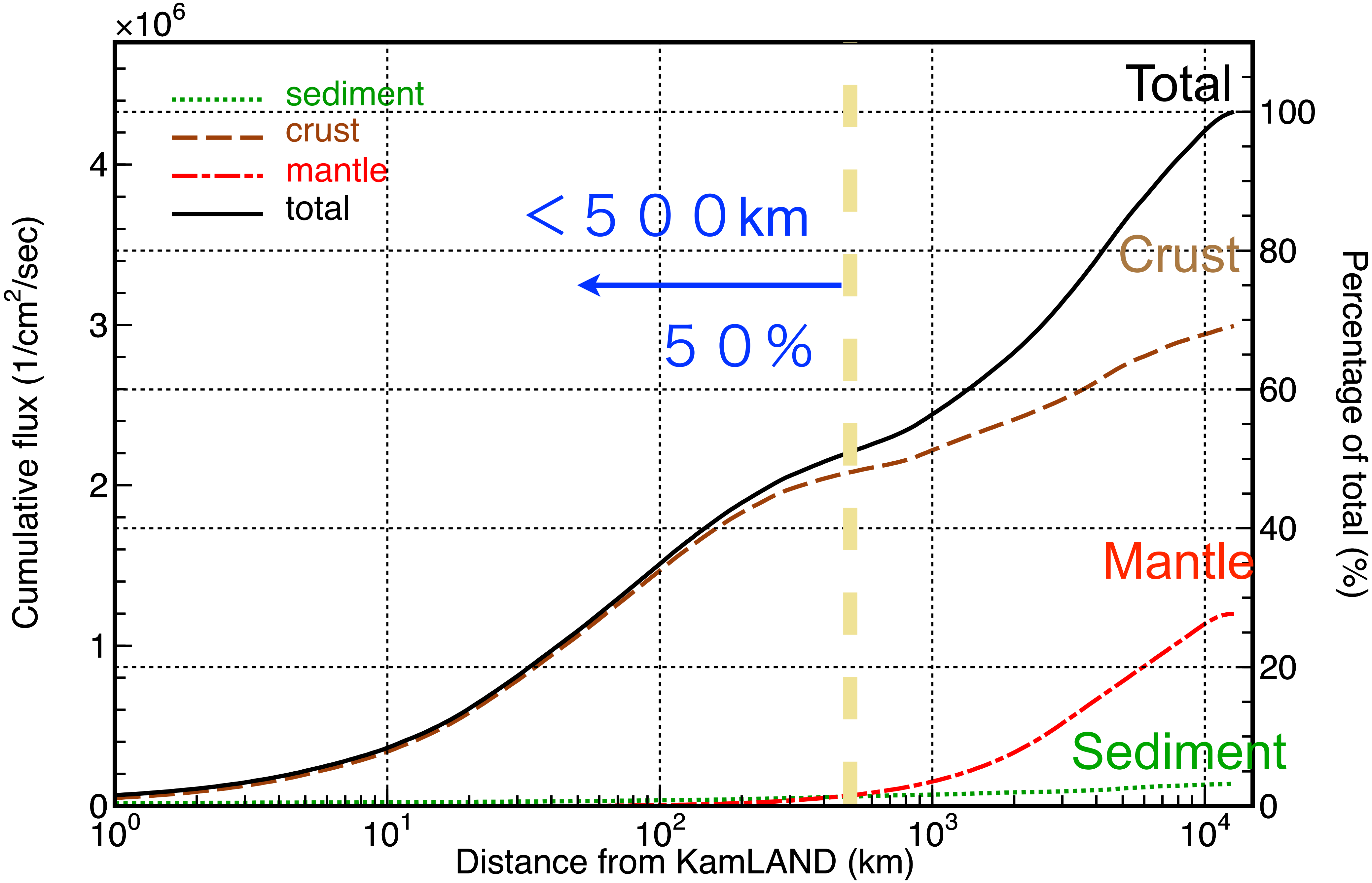
core

U : 0 ppm / Th : 0 ppm

no U/Th in core

Mantle = BSE (Primitive Mantle) − Crust

Distance and Cumulative Flux

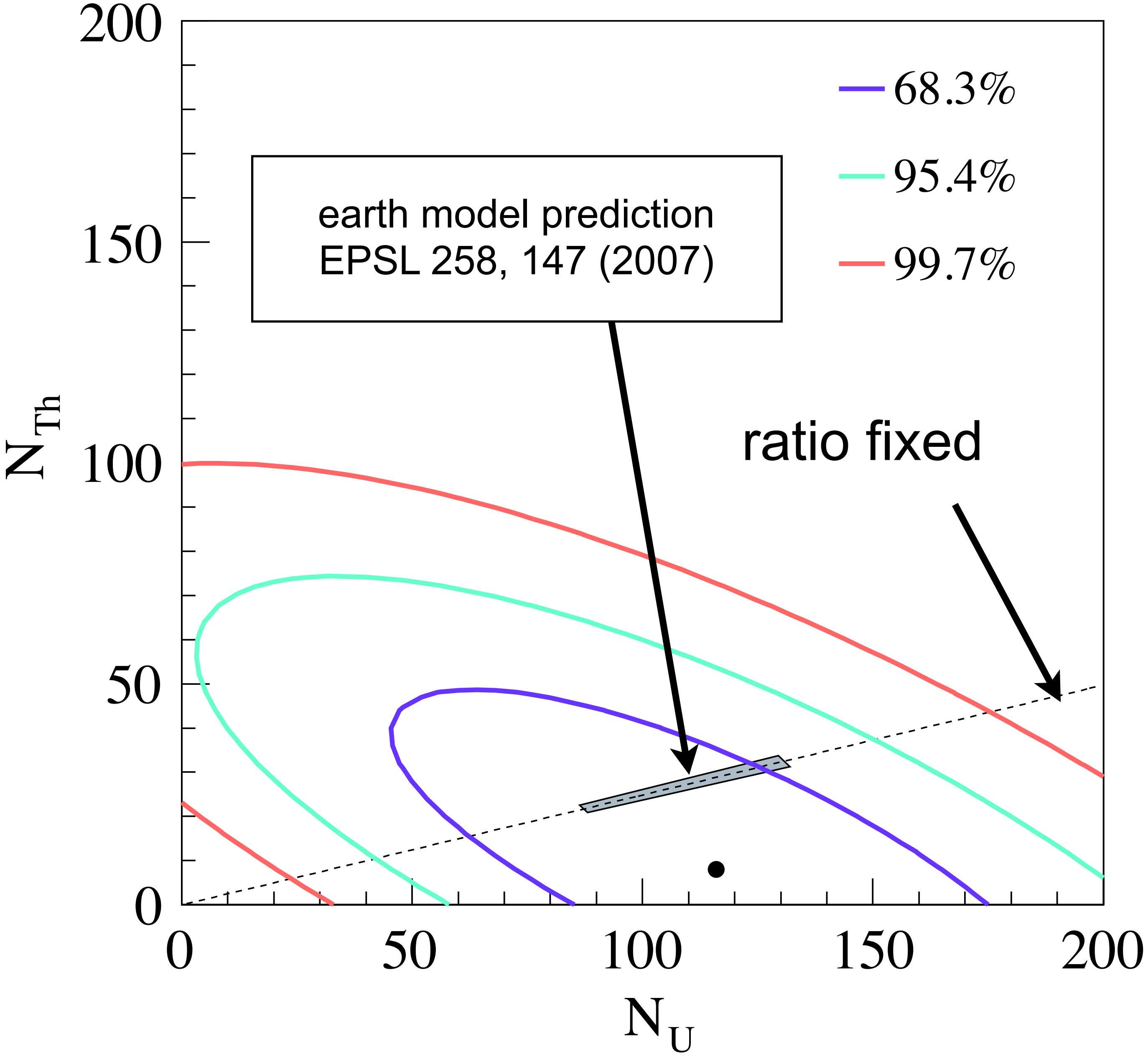


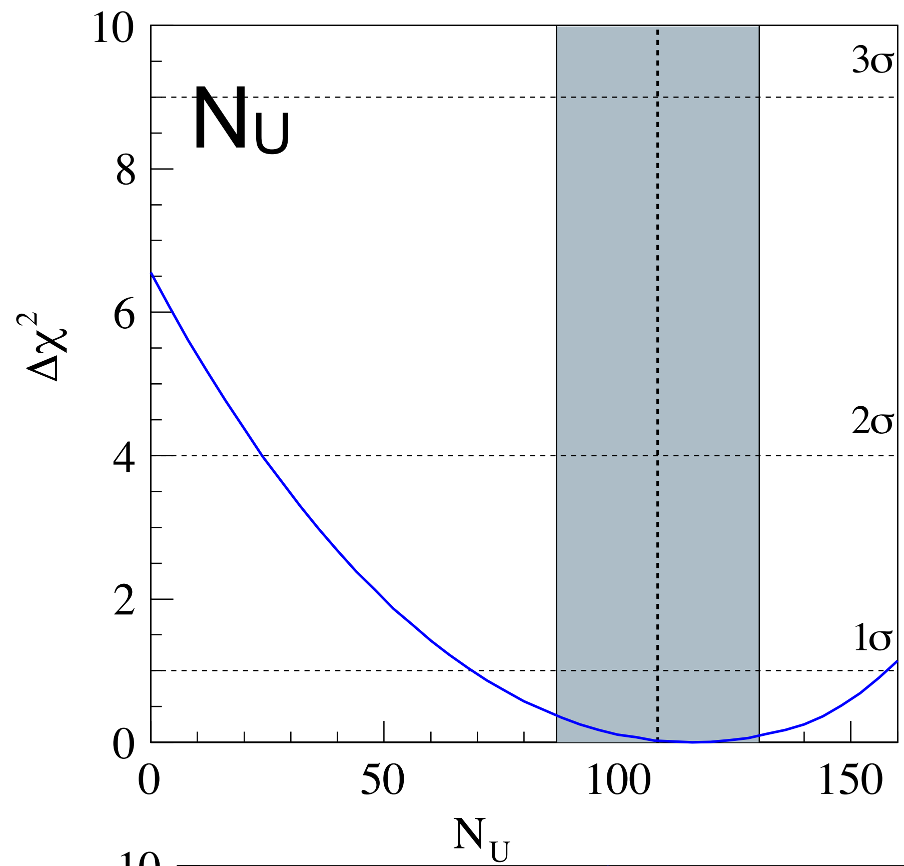
neutrino oscillation

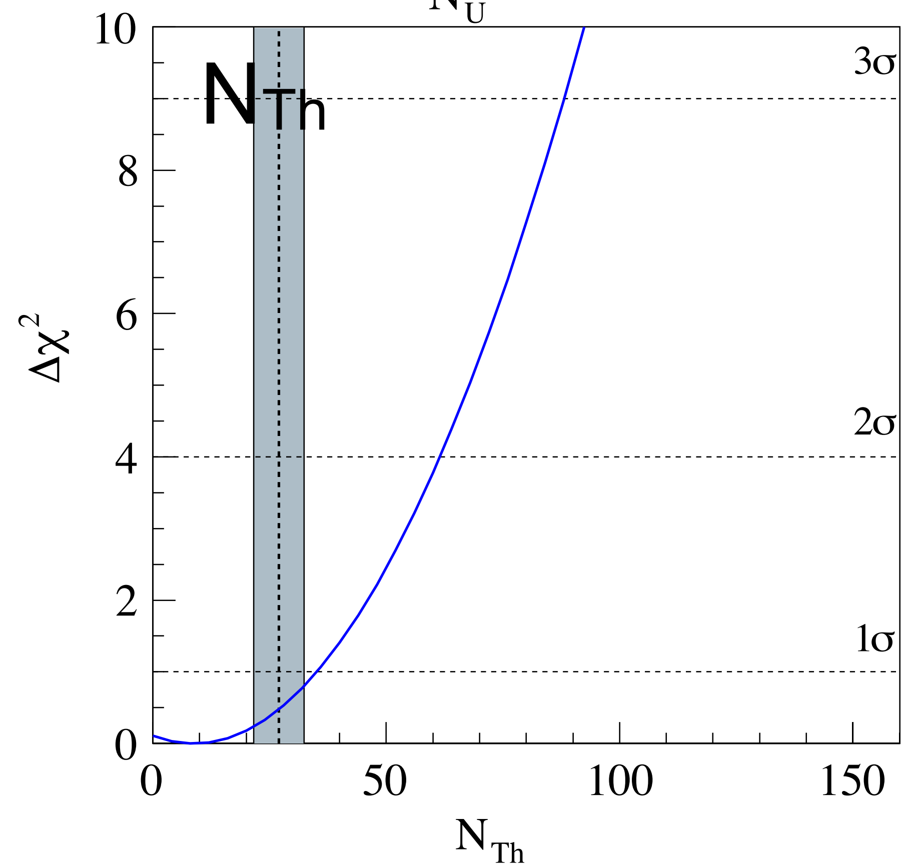
$$P(E,L) \sim 1 - \frac{1}{2}\sin^2 2\theta_{12}$$ (constant suppression)

50% of the total flux originates within 500 km

N_U vs N_{Th}



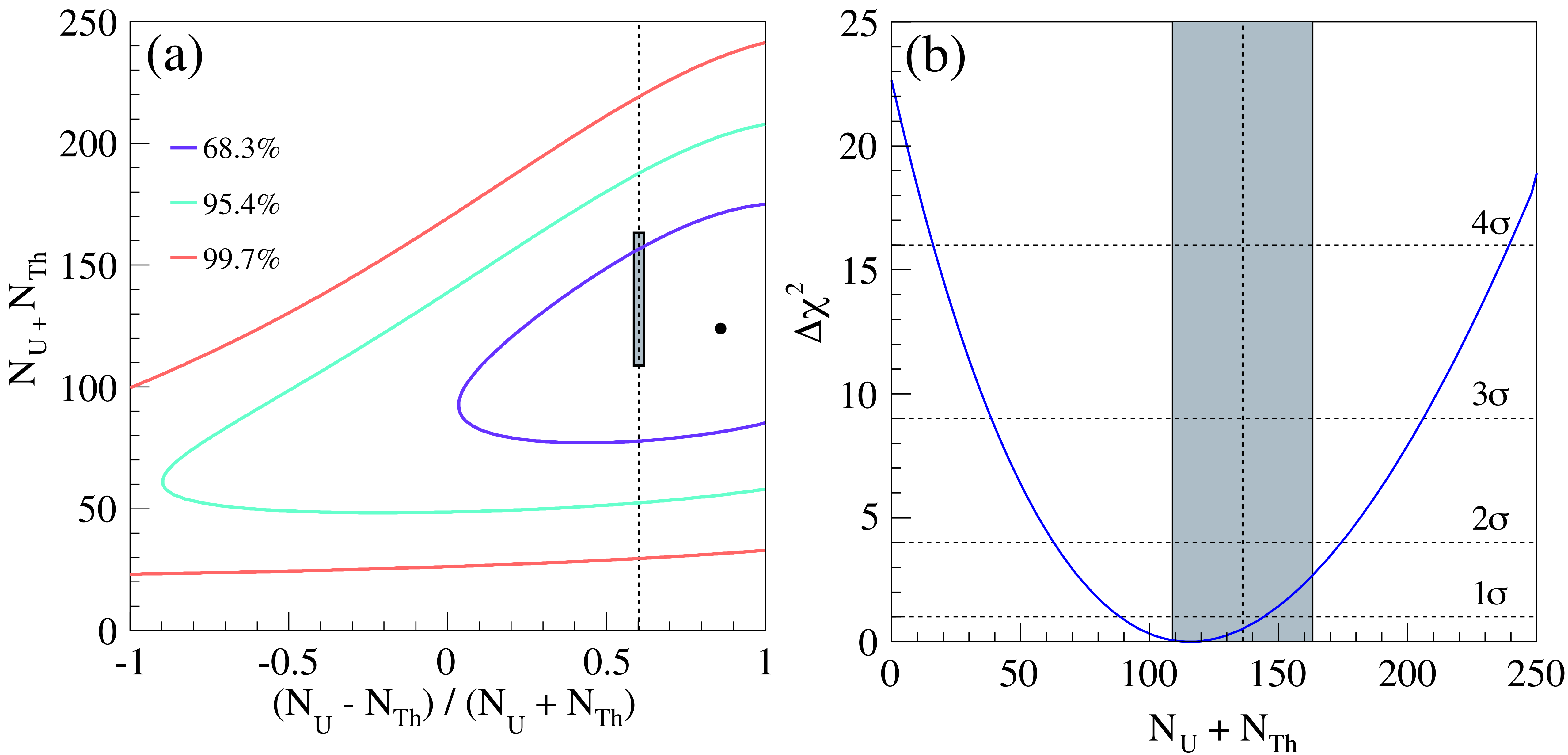




best-fit $(N_U, N_{Th}) = (116,8)$

N_U 0 signal : rejected at 2.6σ (99.0%)

$N_U + N_{Th}$

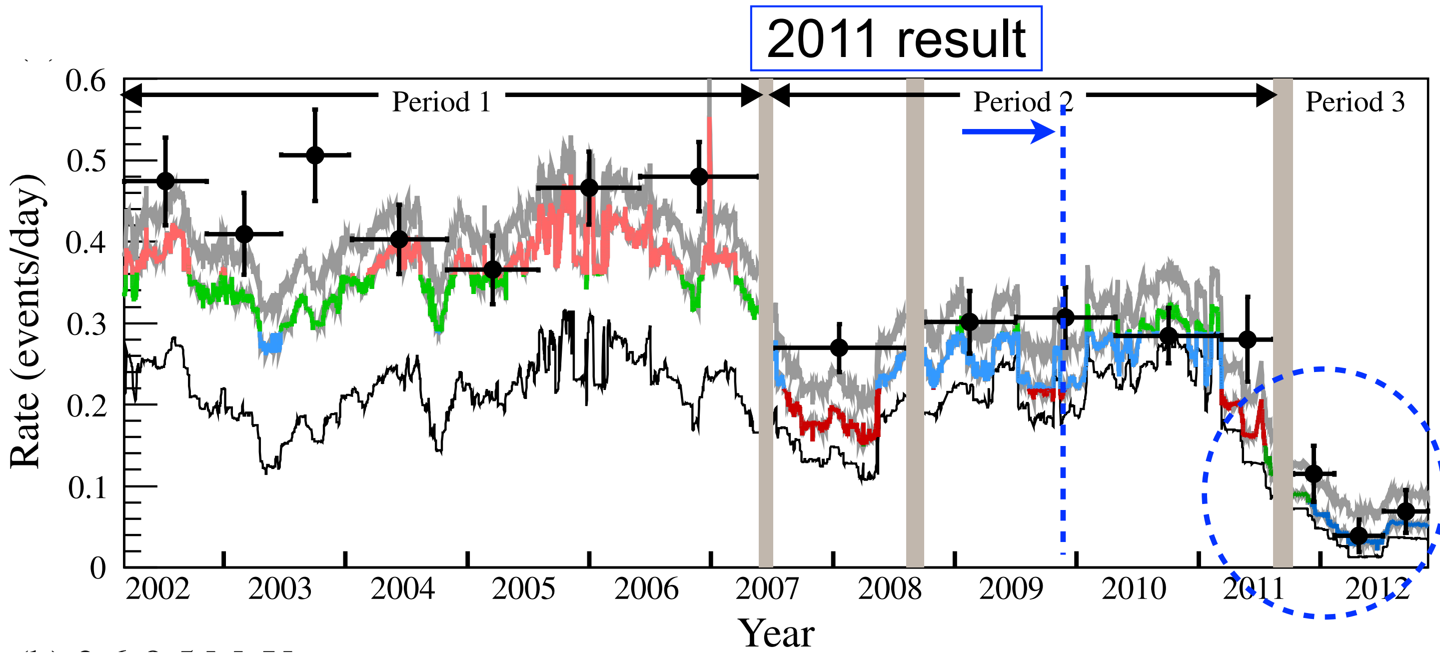


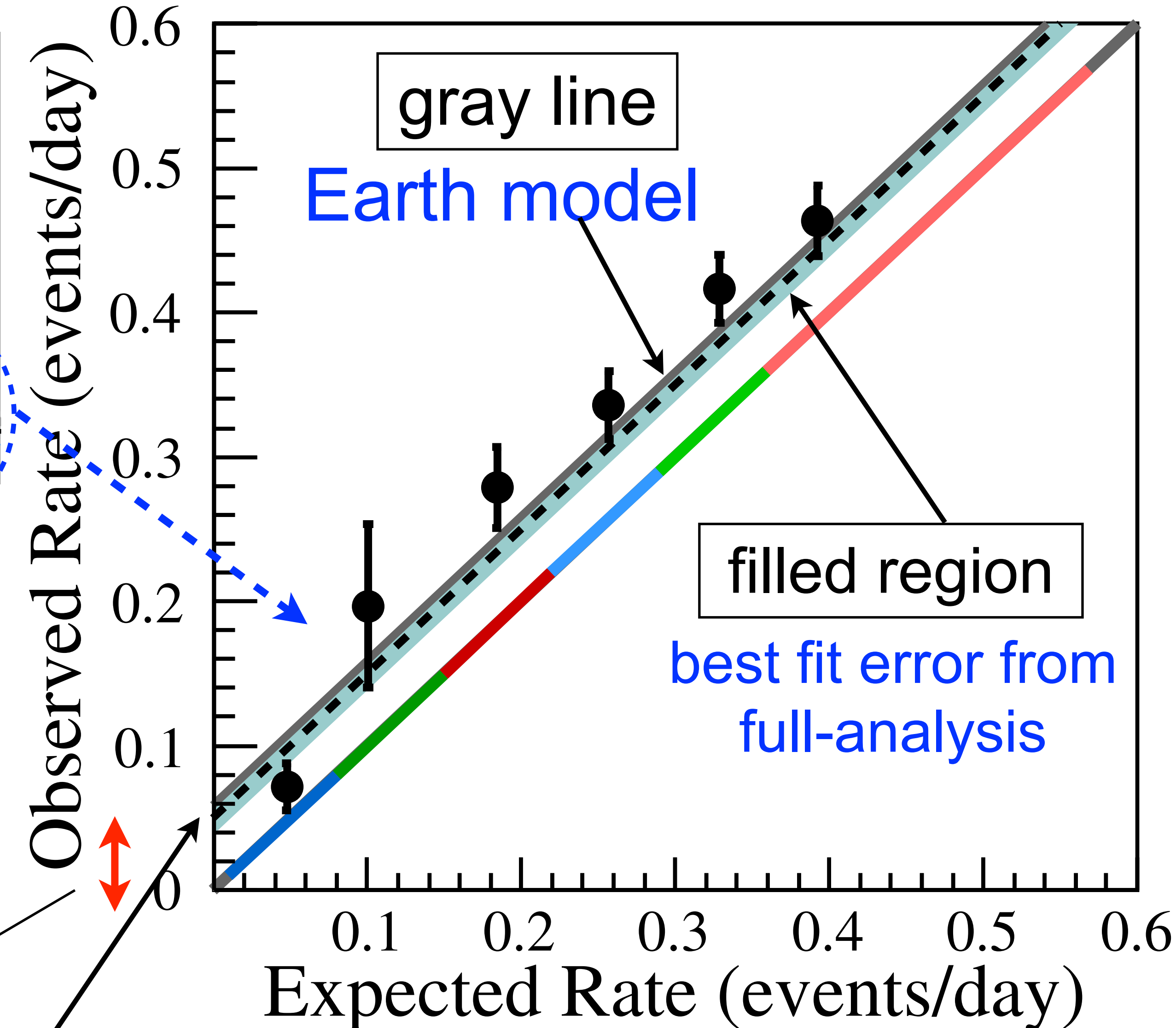
best-fit $N_U+N_{Th} = 116^{+28}_{-27}$

Flux : $3.4^{+0.8}_{-0.8} \times 10^6$ cm^{-2}s^{-1}

0 signal rejected at 99.9998% C.L. (2×10^{-6})

- Expected Rate vs Observed Rate (0.9-2.6 MeV)





- Lower three data points can be added by using low-reactor operation period.

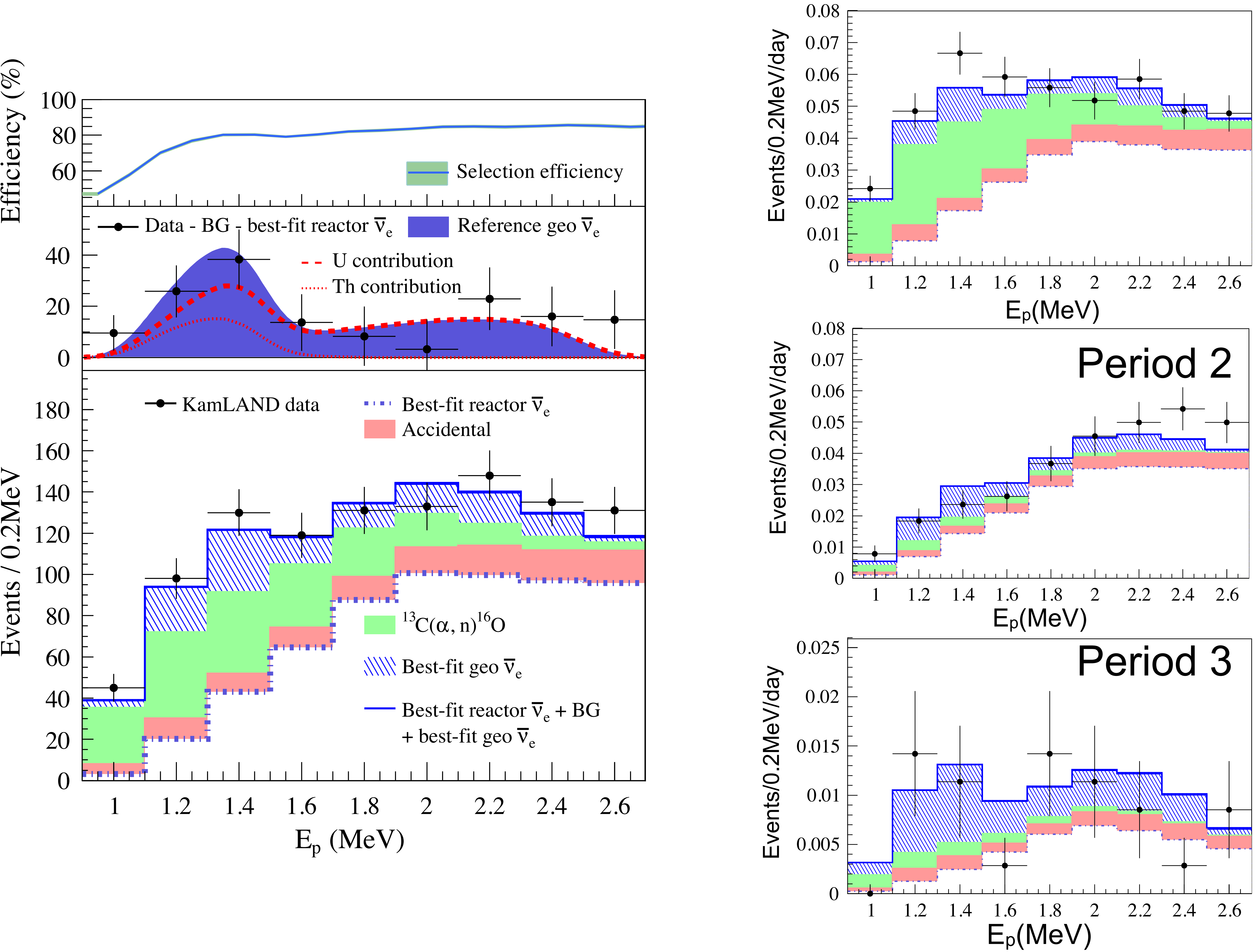
- Strong correlation between expected and observed event rate.

constant contribution of geo-neutrino

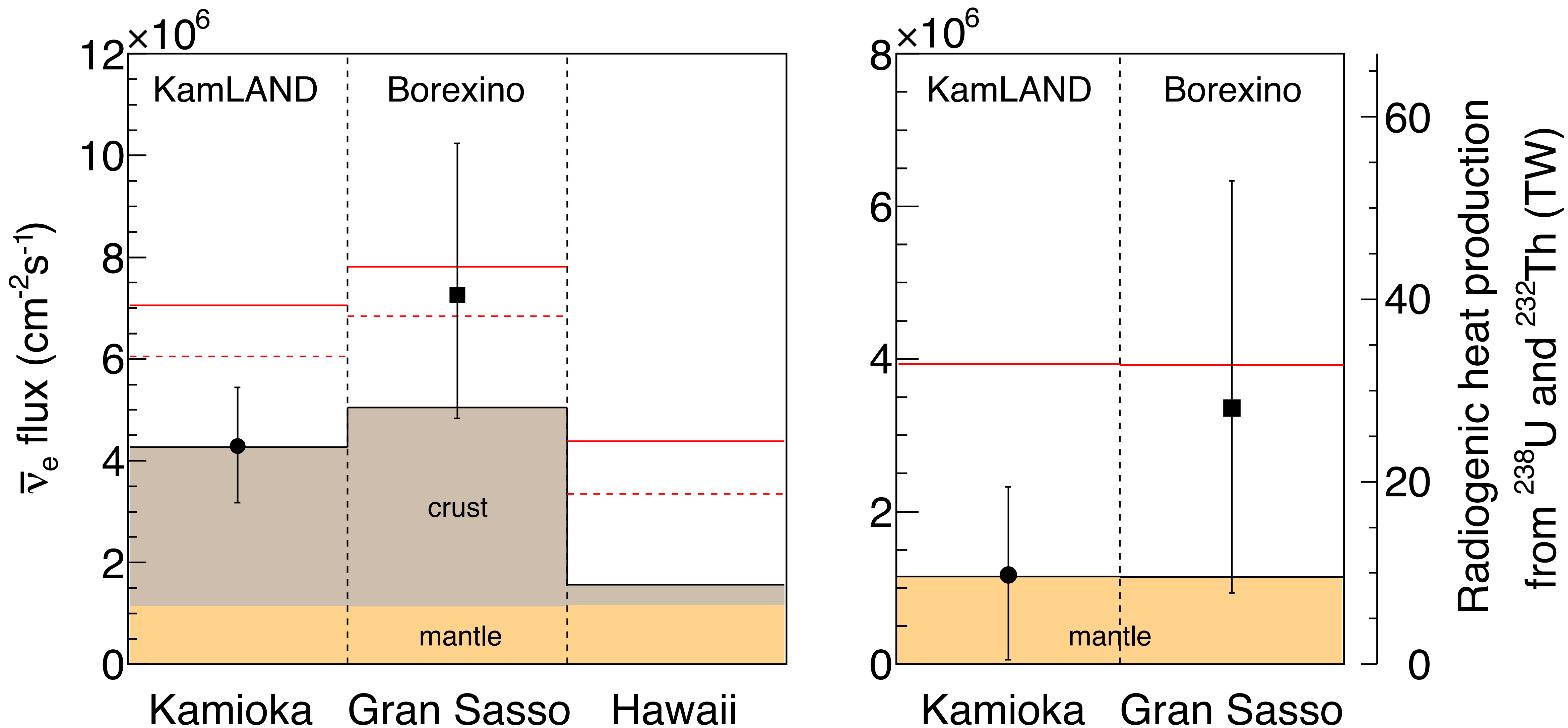
doted line's intercept

best fit from full-analysis
(Rate+Shape+Time)
116 +28/-27 events

reactor anti-neutrino + other backgrounds


Efficiency (%)
Selection efficiency
Data - BG - best-fit reactor $\bar{\nu}_e$
Reference geo $\bar{\nu}_e$
U contribution
Th contribution
KamLAND data
Best-fit reactor $\bar{\nu}_e$
Accidental
$^{13}C(\alpha, n)^{16}O$
Best-fit geo $\bar{\nu}_e$
Best-fit reactor $\bar{\nu}_e$ + BG
+ best-fit geo $\bar{\nu}_e$
Events / 0.2MeV
E_p (MeV)
Events/0.2MeV/day
E_p(MeV)
Period 2
Period 3

Test of Fully-Radiogenic Model

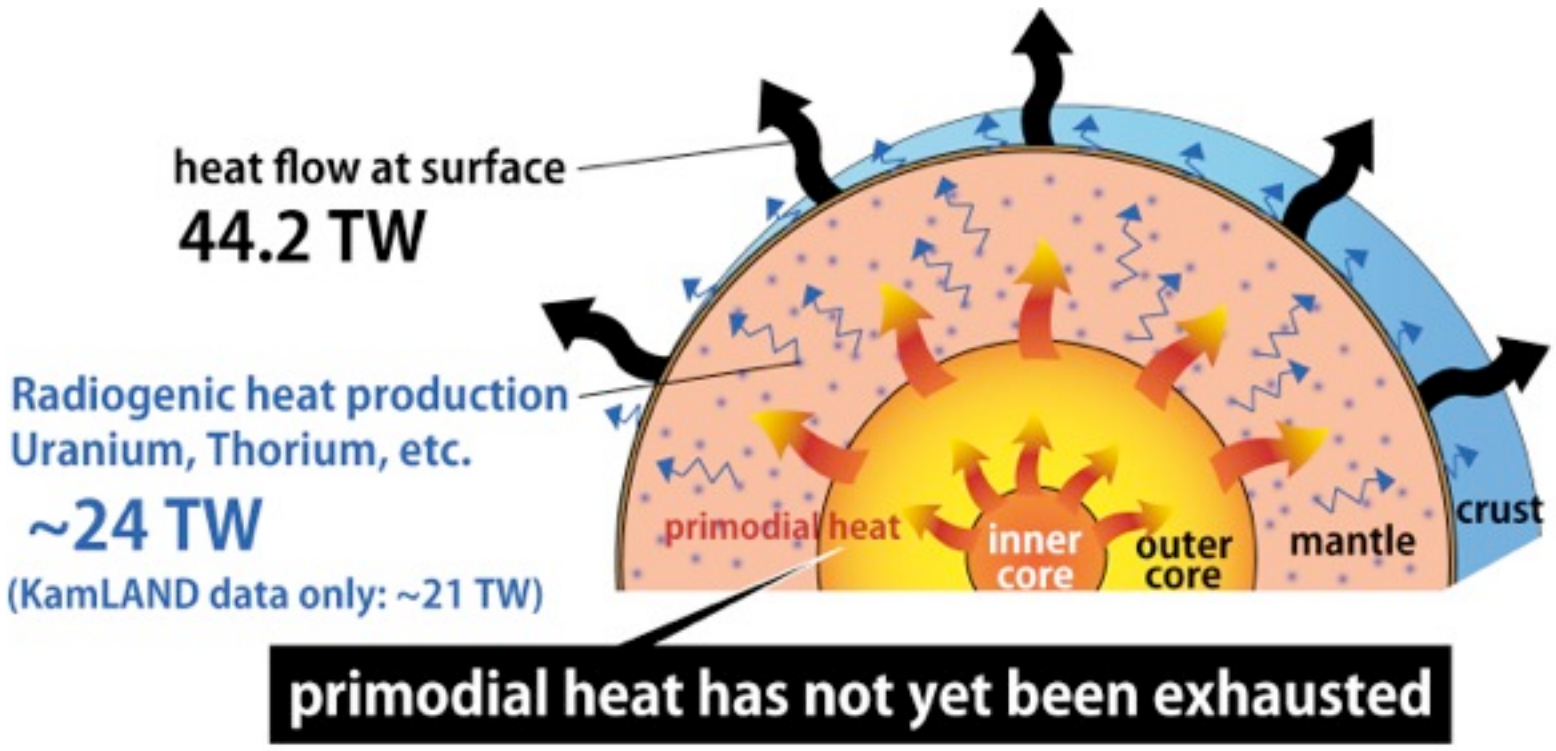


- Radiogenic heat production from ^{238}U and ^{232}Th is $20.0^{+8.8}_{-8.6}$ TW
- Fully-radiogenic models are disfavored at

KamLAND only 98.1% C.L. KamLAND + Borexino 97.2% C.L.

Measured Heat Balance

<u>Result from geo neutrino experiment</u>



"heat flow at surface: 44.2 ± 1.0 TW" − "radiogenic heat production: $24.3^{+8.8}_{-8.6}$ TW"

⟶ primordial heat when the Earth formed

- Geo neutrino data showed radiogenic heat ~24 TW contributes only half of Earth's total outgoing heat flux
- Geo reactor at the center of the Earth is constrained

KamLAND	< 5.2 TW (90% C.L.)
Borexino	< 3 TW (95% C.L.)