KamLAND

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for the KamLAND Collaboration

Contents

Contents

KamLAND Collaboration

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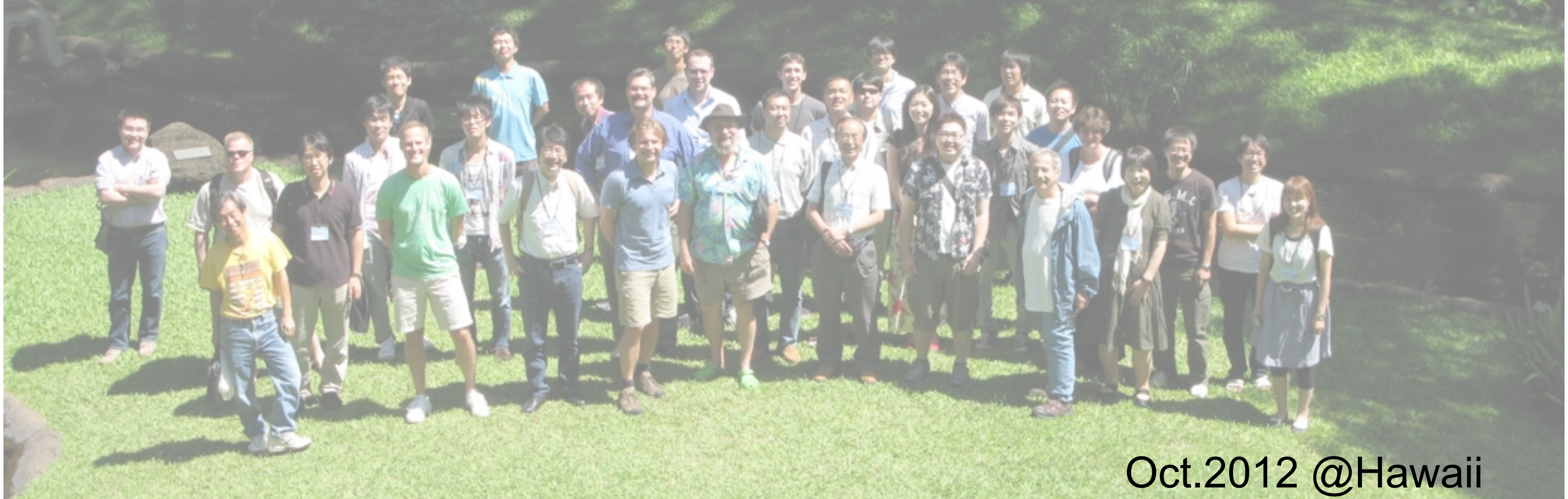
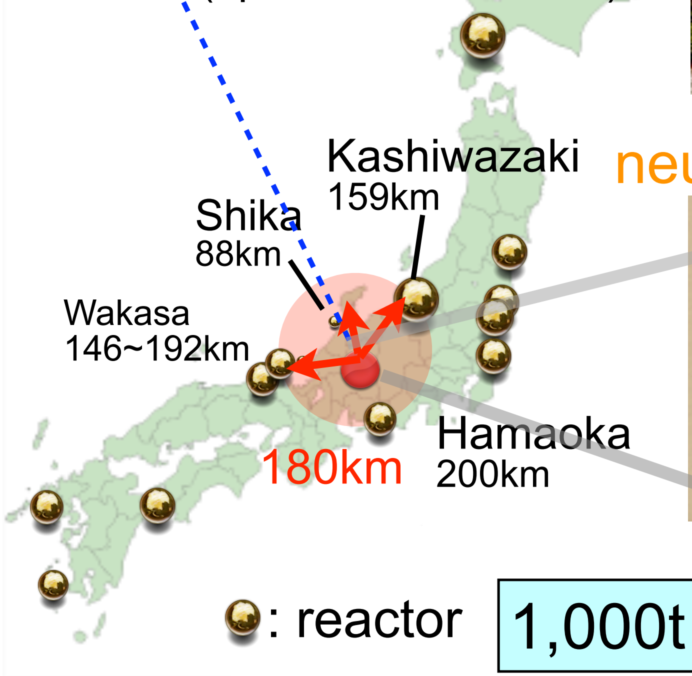
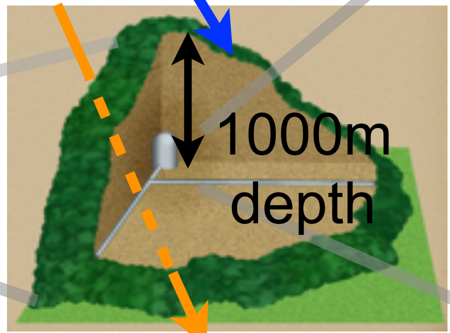


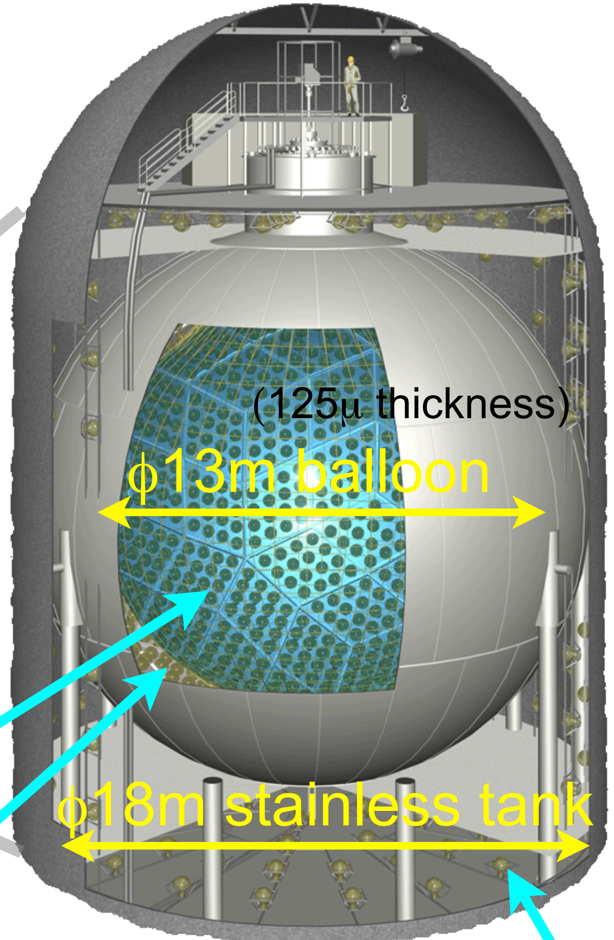
KamLAND Site & Detector

KamLAND

Kamioka **L**iquid Scintillator **A**nti-**N**eutrino **D**etector (operated since 2002)







1,000t Liquid Scintillator

* Dodecane (80%) Pseudocumene (20%) PPO (1.36 g/l)
* extremely low impurily (^{238}U:3.5×10^{-18}g/g, ^{232}Th:5.2×10^{-17}g/g)

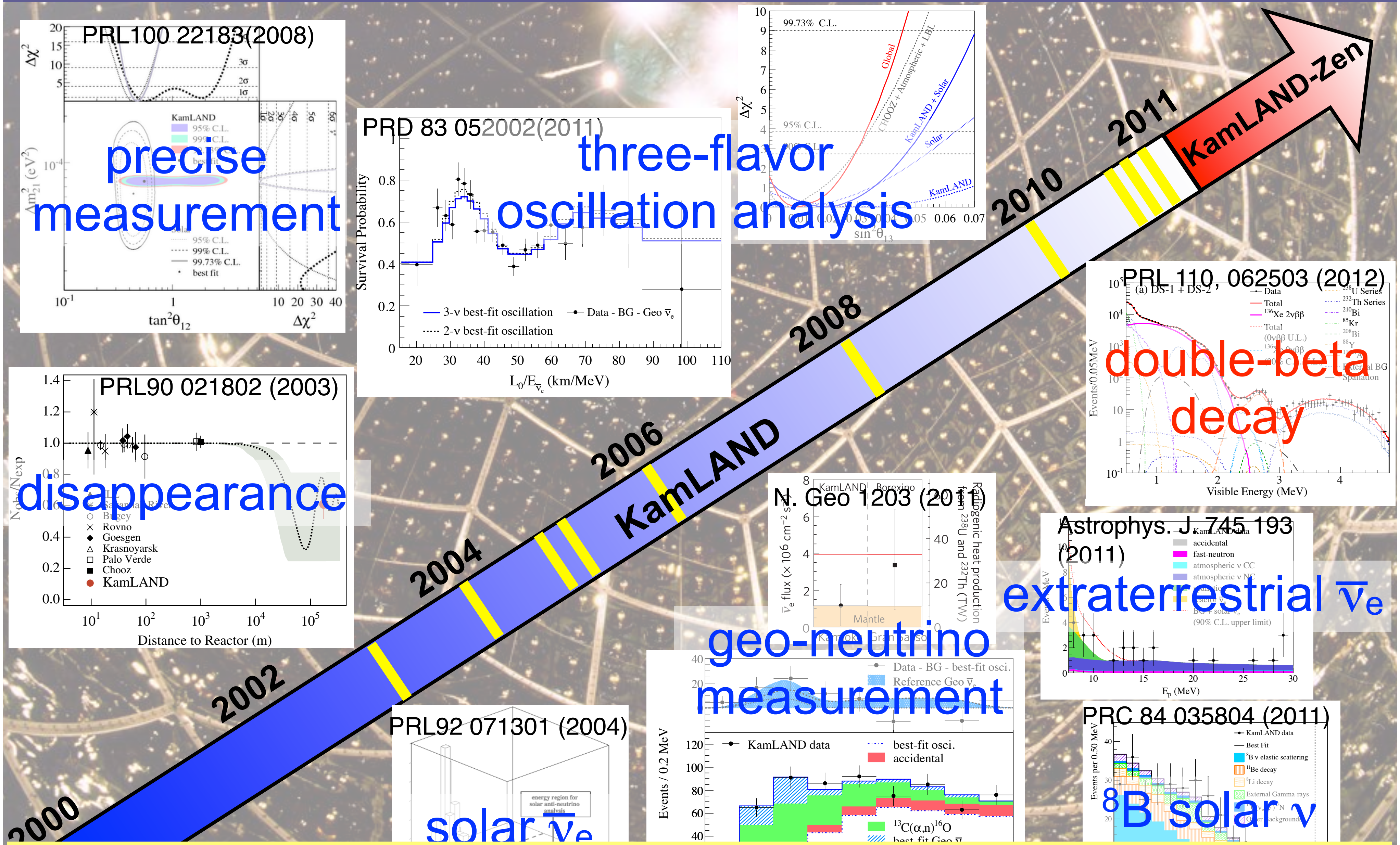
1,325 17inch + 554 20inch PMTs

* Photo coverage 34%

Water Cherenkov Outer Detector

* Muon veto

Overview of KamLAND Neutrino Physics

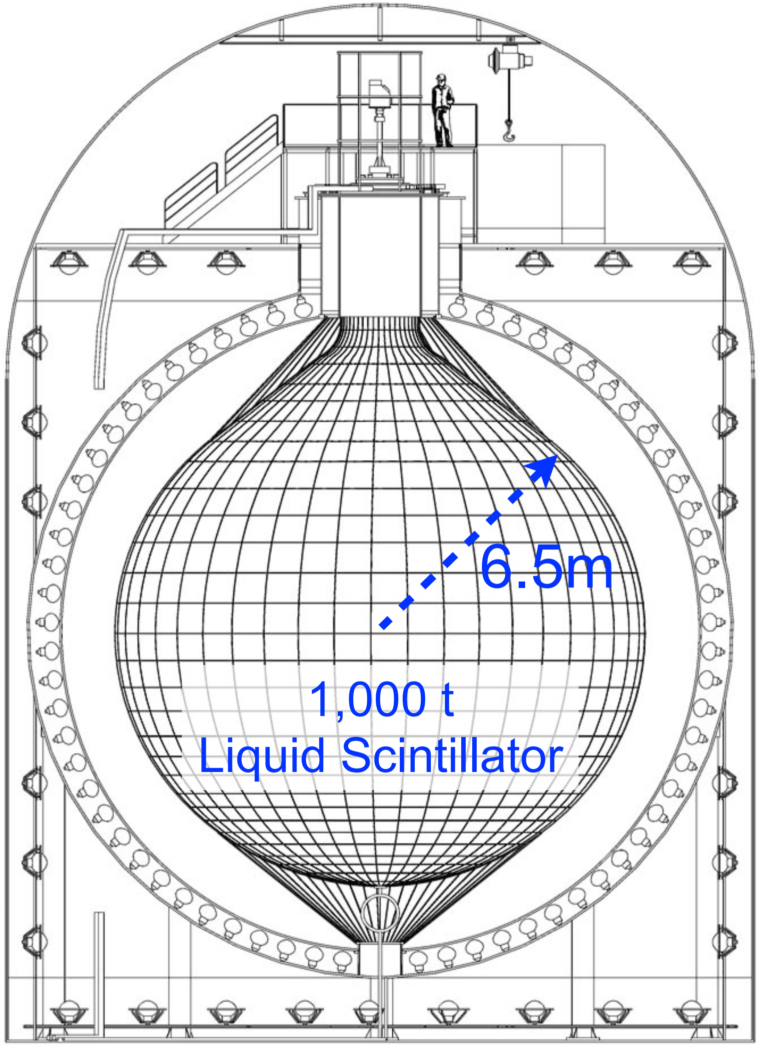


We continue to study neutrino physics with KamLAND.

KamLAND

KamLAND

2000~



Detector Features

1,000t ultra-pure liquid scintillator

^{232}U: 3.5x10^{-18} g/g, ^{238}Th: 5.2x10^{-17} g/g

Physics

solar neutrinos
PRC 84, 035804 (2011)

geo neutrinos
Nature Vol. 436 (2005)
Nature Geoscience 4, 647-651 (2011)

reactor neutrinos
PRL 100, 221803 (2008)
PRD 83, 052002 (2011)

supernova neutrinos, etc.
PRL 92, 071301 (2004)
Astrophys. J. 745, 193 (2011)

Different neutrino physics in a wide energy range

KamLAND-Zen

KamLAND-Zen

2011~

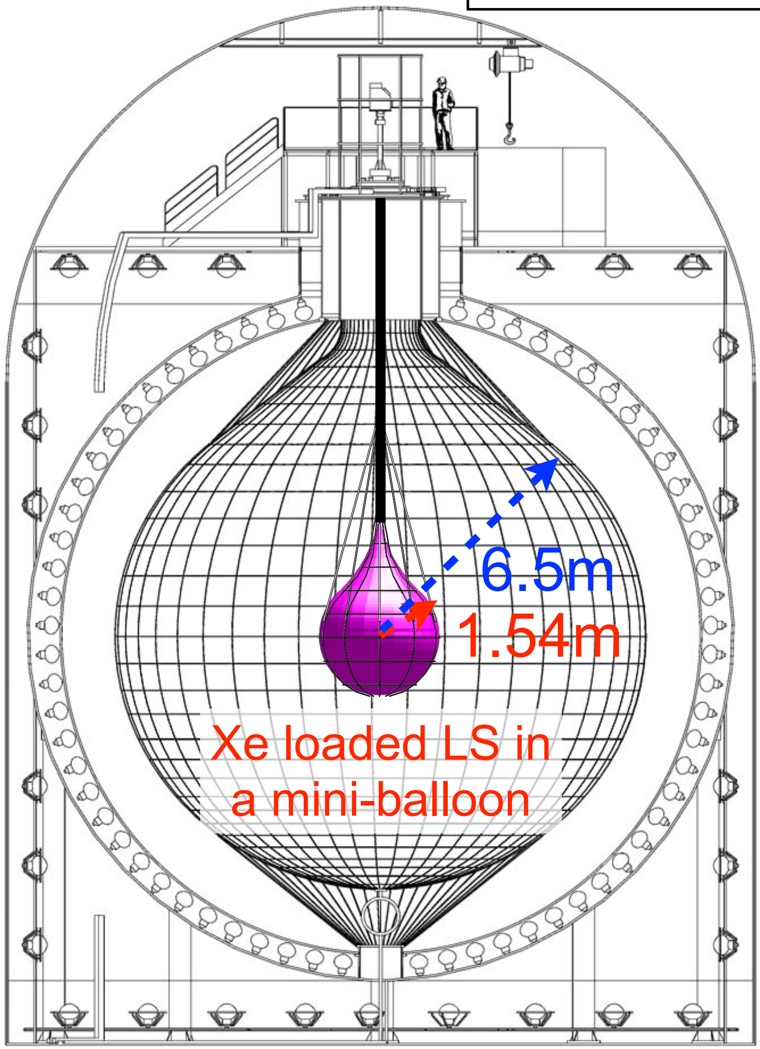
Zero Neutrino
double beta decay search

March 14, Session VIII
talk by K. Nakamura

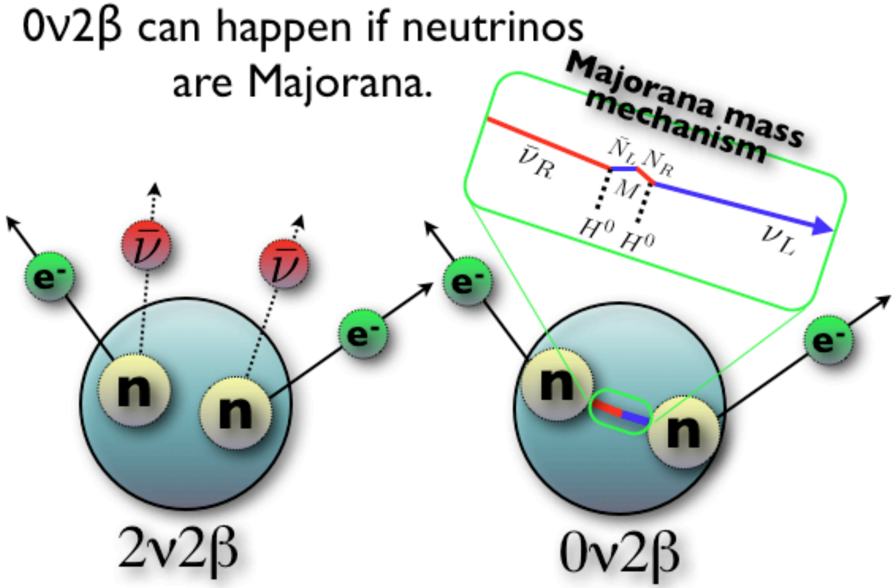
Detector Features

^{136}Xe loaded LS was installed in KamLAND

(~320kg 90% enriched ^{136}Xe installed so far)



Physics

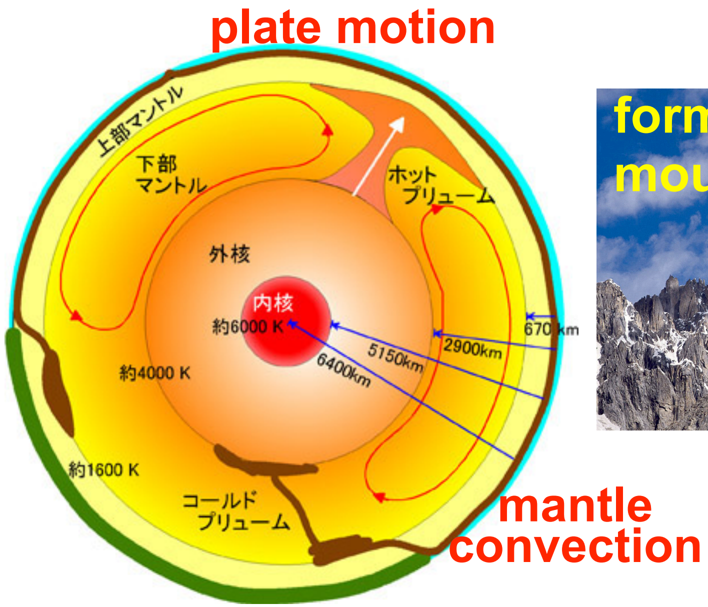


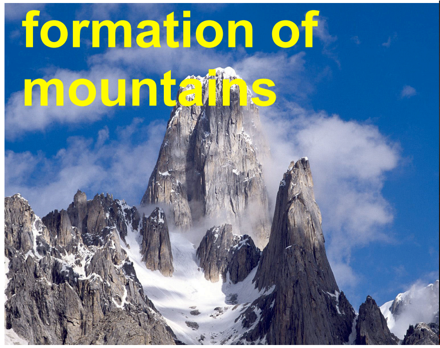
neutrino-less double beta decay

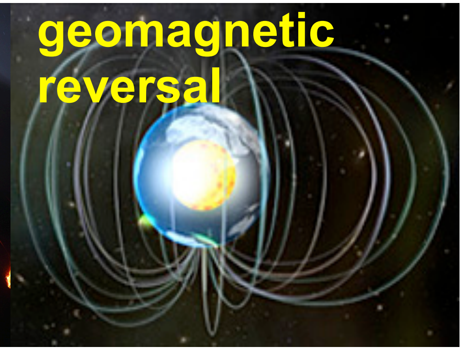
Continue to use LS volume outside of mini-balloon to measure anti-neutrino signals

Contents

Terrestrial Heat - Geophysical Activity







Question on geophysical activity

- What are energy sources? How much energy?
- How is the mantle convection going; single or multi-layer convection?
- Why does the reversal of the geomagnetism happen, and why so frequently and randomly.

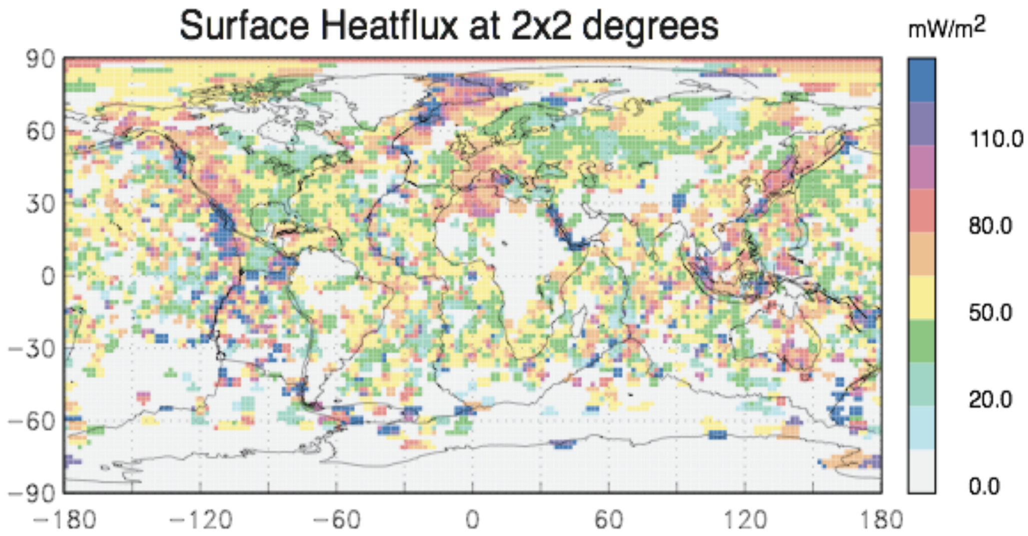
→ It is important to find out the origin of the terrestrial heat.

Terrestrial Heat - Heat Balance

☑ **Surface heat flow : 44.2±1.0 TW** Rev. of Geophys. 31, 267-280 (1993)
(recent analysis 47±2 TW Solid Earth 1, 5 (2010))

5 Big Questions: McDonough in Neutrino 2008

- What is the Planetary K/U ratio? *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*

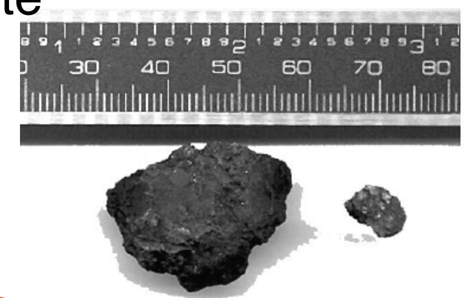


☐ **Radiogenic heat : 20 TW**

→ In this model, the radiogenic heat contribution is nearly half of the Earth's total heat flow.

Bulk Silicate Earth (BSE) model
chondrite meteorite

U : 8 TW
Th : 8 TW
K : 4TW



Direct measurement can answer this question.

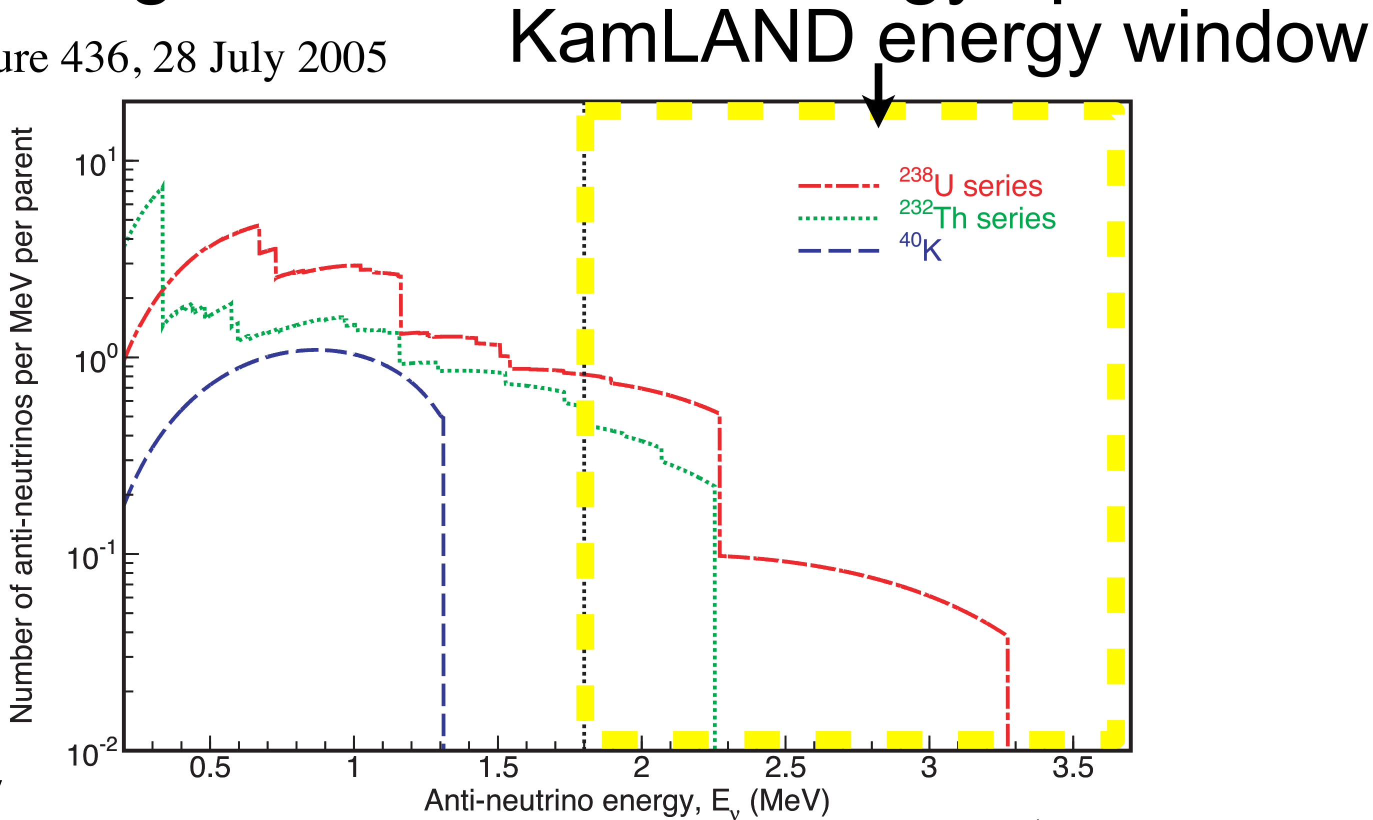
Geo neutrino directly tests radiogenic heat production.

Geo Neutrino at KamLAND

Geo neutrinos are a unique, direct window into the interior of the Earth !

- calculation of geo antineutrino energy spectrum

Nature 436, 28 July 2005



beta-decay

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

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

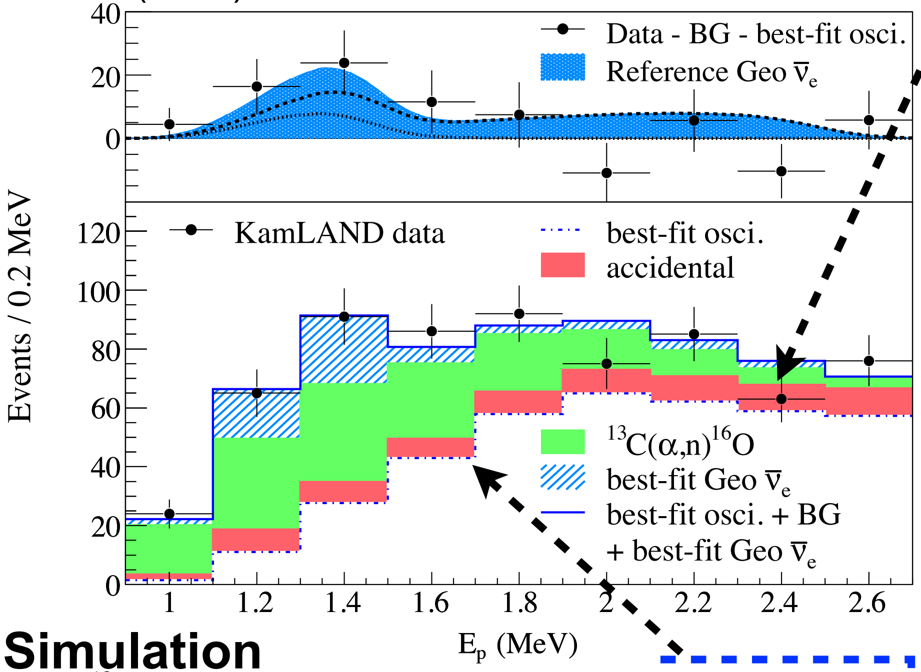
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + 1.311\,\mathrm{MeV}\ (89.28\%)$$

KamLAND can detect !

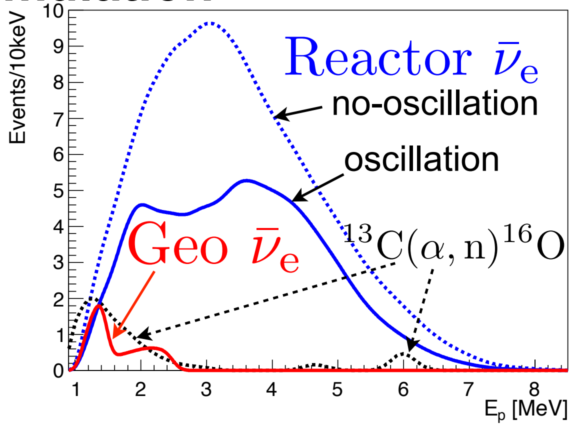
▸Backgrounds for Geo-neutrino

In our past publications, major backgrounds were
Non-ν: ^{13}C (^{210}Po α, n)^{16}O , accidental Reactor-ν.

PRL100(2008)221803

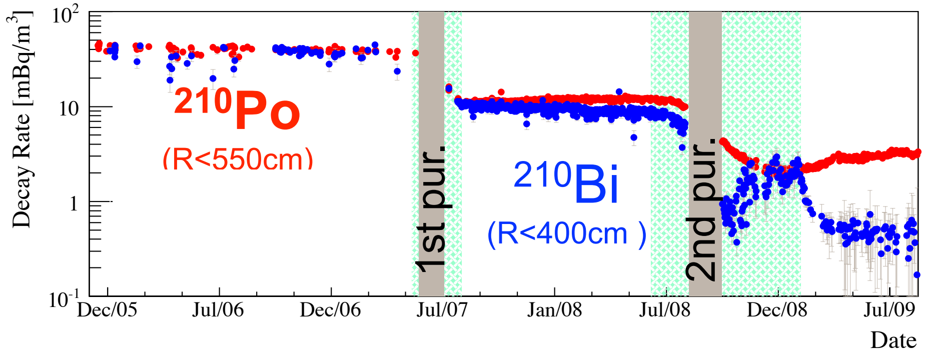


Simulation



^{13}C (^{210}Po α, n)^{16}O

(1) Dominant BG source (α, n) was reduced by factor ~ 20 (2 times distillation)



(2) Determination of the cross section is improved by in-situ calibration uncertainty
: 11% for ground state

Reactor-ν

(3) Operational issues at the power reactor and serious earthquakes reduced the reactor neutrino flux.

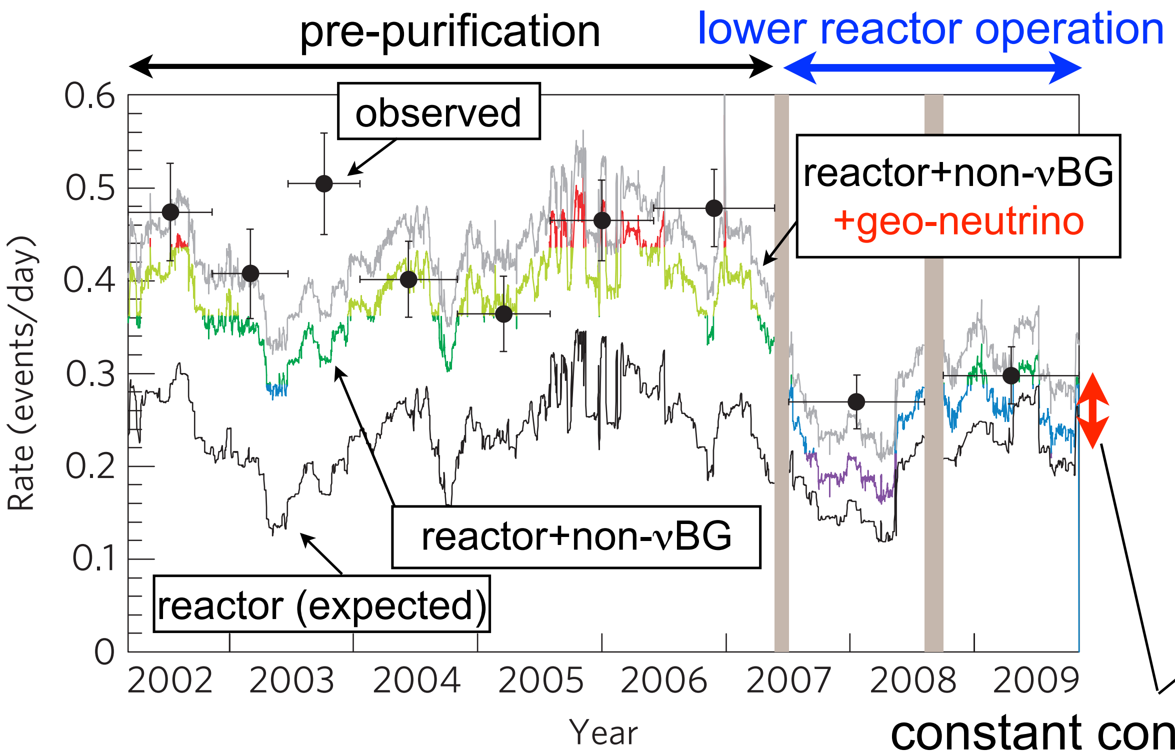
① **July 2007~**, extended shutdown of Kashiwazaki-Kariwa nuclear power station →~60% of normal operation

② **March 2011~**, shutdown of entire Japanese nuclear reactor industry →~5% of normal operation (discussed later)

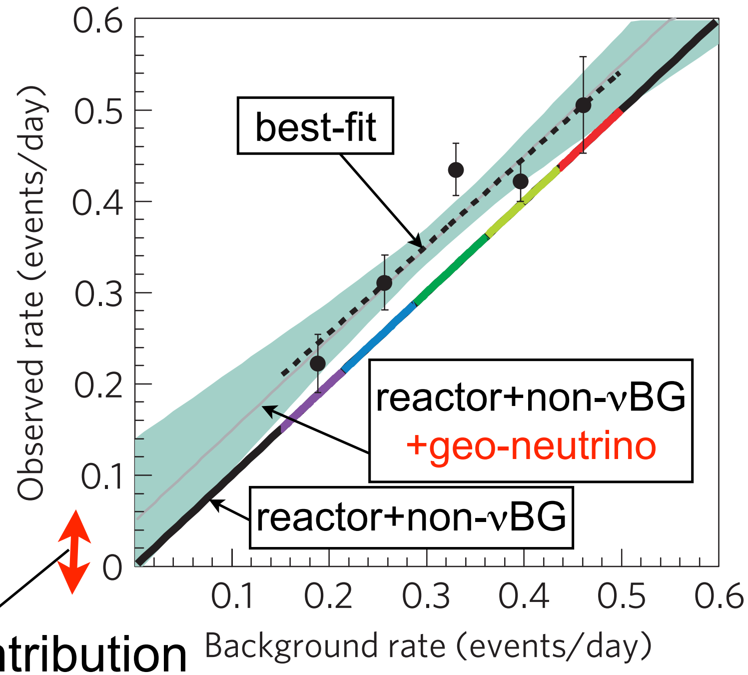
Nature Geosci. 4, 647 (2011)

expected event rate (best-fit oscillation, BG estimation, Earth Model)

time variation



correlation



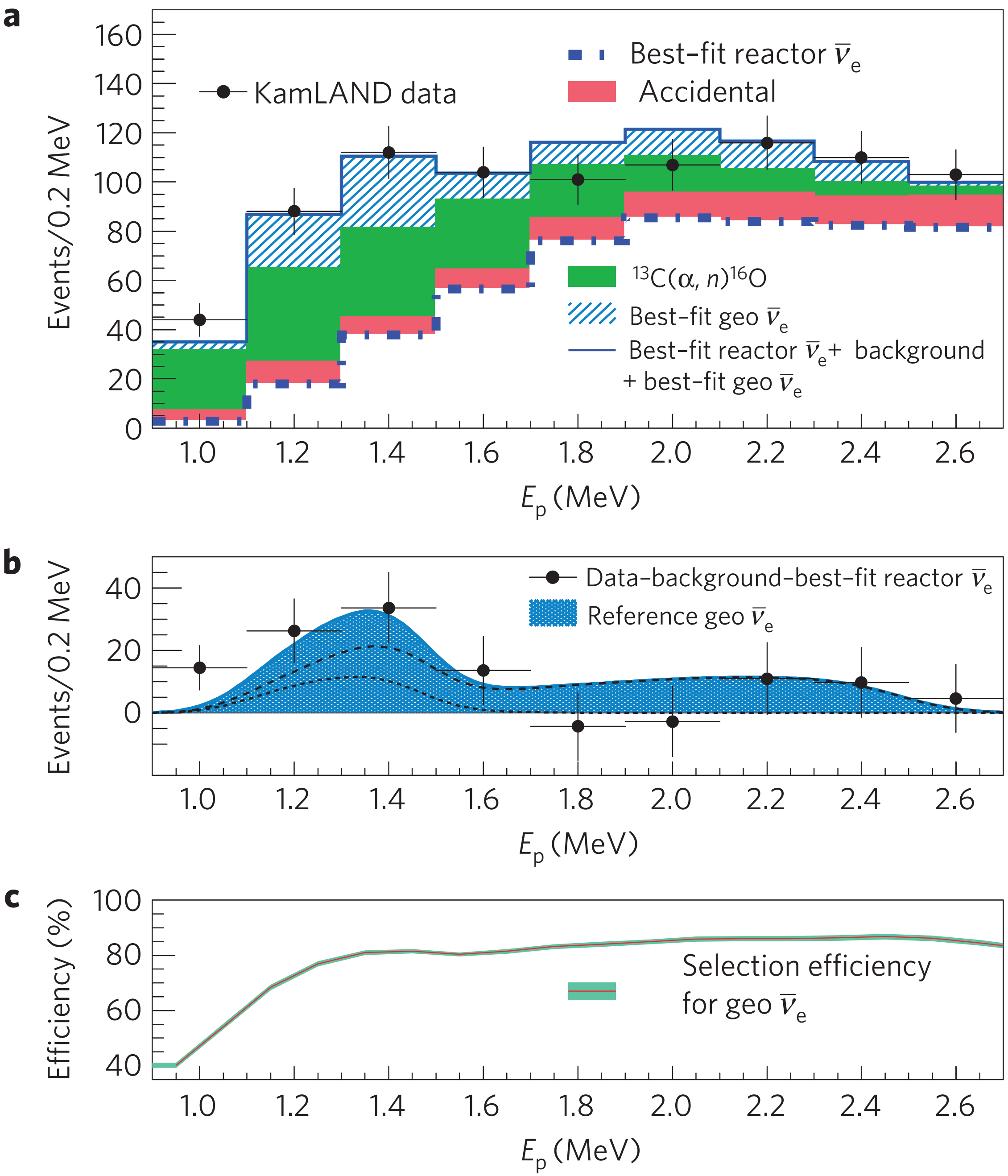
constant contribution of geo-neutrino

- The non-nu background for geo-neutrino was decreased by half from what it was before 2007.

- Constant contribution of geo-neutrino is seen above the estimated reactor neutrino + non-neutrino background in the energy range 0.9 - 2.6 MeV.

→ Time information is useful to extract the geo-neutrino signal

▸Analysis - Observed Energy Spectrum (0.9-2.6 MeV)



Nature Geosci. 4, 647 (2011)

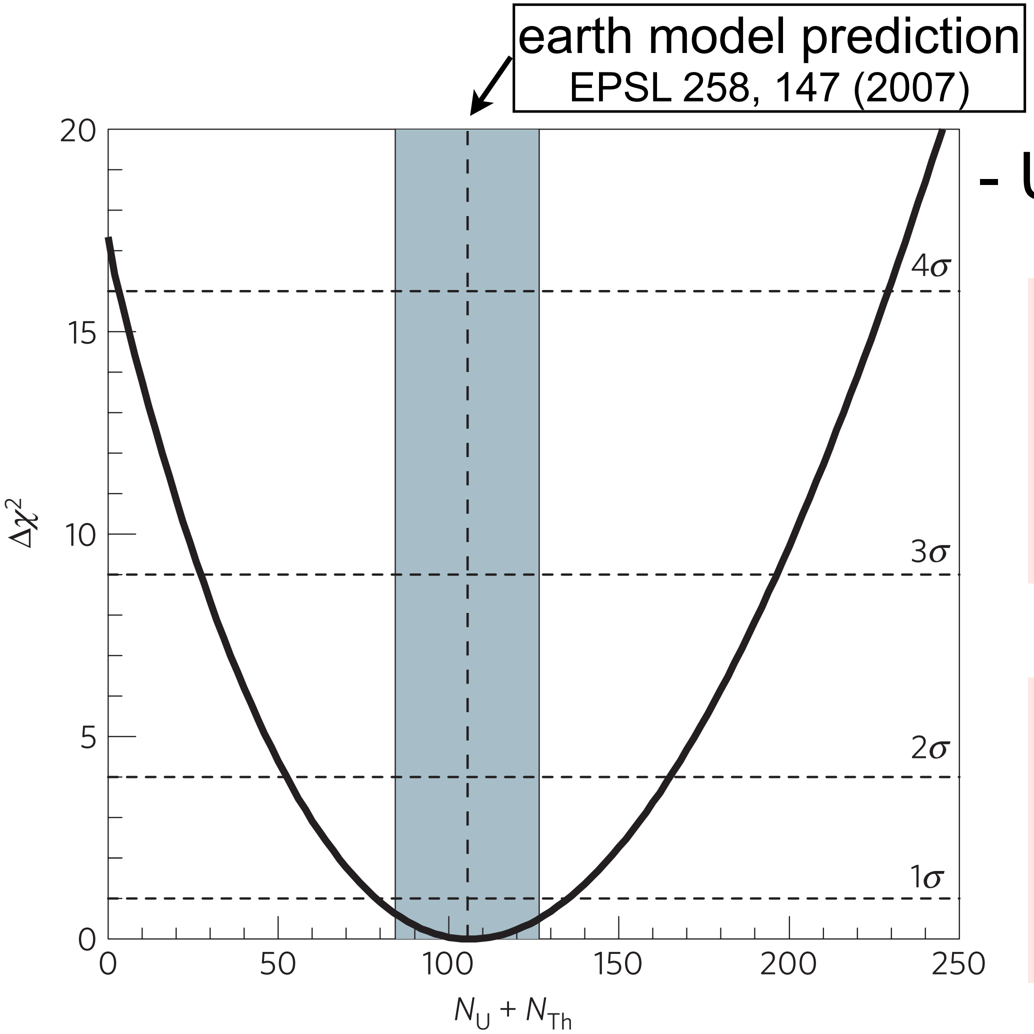
- exposure : 4126 ton-year
  (4.9 times larger than 2005)
- result

candidates	841
^9Li	2.0 ± 0.1
Accidental	77.4 ± 0.1
Fast neutron	< 2.8
(α, n)	165.3 ± 18.2
Reactor ν	484.7 ± 26.5
BG total	729.4 ± 32.3
excess	111^{+45}_{-45} events

Null signal exclusion (rate)
99.55 % C.L.

Analysis - Rate+Shape+Time Analysis

Nature Geosci. 4, 647 (2011)



- U/Th mass ratio fixed (Th/U = 3.9)

$N_{geo} = 106^{+29}_{-28}$ events

$F_{geo} = 4.3^{+1.2}_{-1.1} \times 10^6/cm^2/sec$

($38.3^{+10.3}_{-9.9}$ TNU)

0 signal rejected at
99.997% C.L.
(> 4σ C.L.)

▸Analysis - Radiogenic Heat and Flux

fully-radiogenic model
EPSL 258, 147 (2007)

crust (^{238}U, ^{232}Th) 7.0 TW
^{40}K, ^{235}U 4.3 TW
mantle (44.2-7.0-4.3)TW

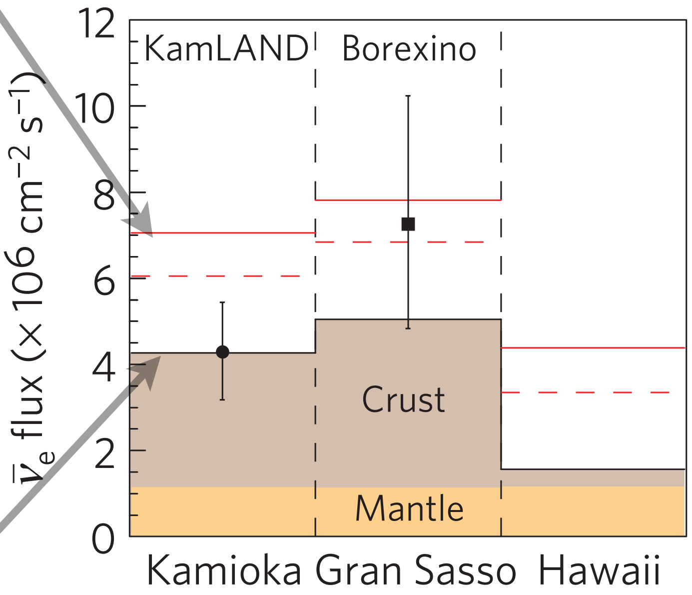
uniform mantle (solid line)
mantle bottom only (dashed line)

earth model prediction
EPSL 258, 147 (2007)

^{238}U, ^{232}Th 16 TW
^{40}K, ^{235}U 4.3 TW

※ assume homogeneous mantle

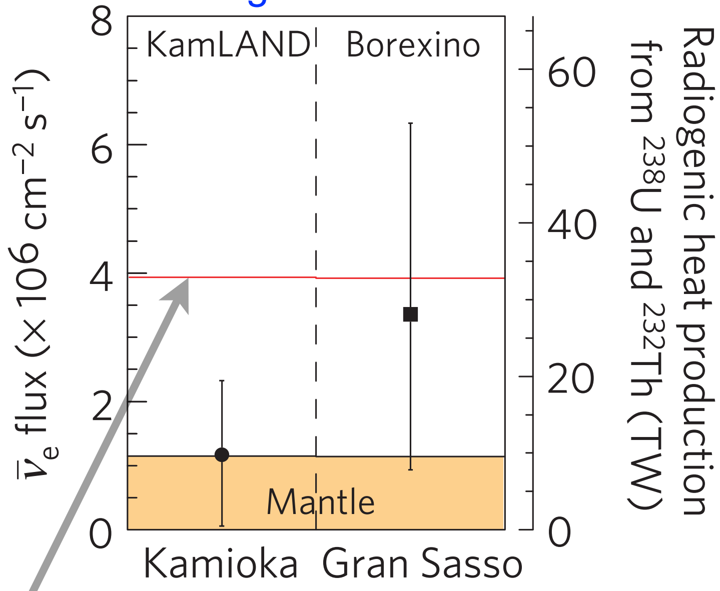
Mantle+Crust



Mantle

Nature Geosci. 4, 647 (2011)

No modelling uncertainties are shown.



total heat flow (44.2 TW)
- crust contribution (7.0 TW)
- other isotopes (4.3 TW)

✓The observed flux is consistent with the 20 TW model

^{238}U+^{232}Th (10±9 TW, KamLAND data) + crust (7.0 TW) + other isotopes (4.3 TW) ~ 21 TW

✓Fully-radiogenic models are disfavored

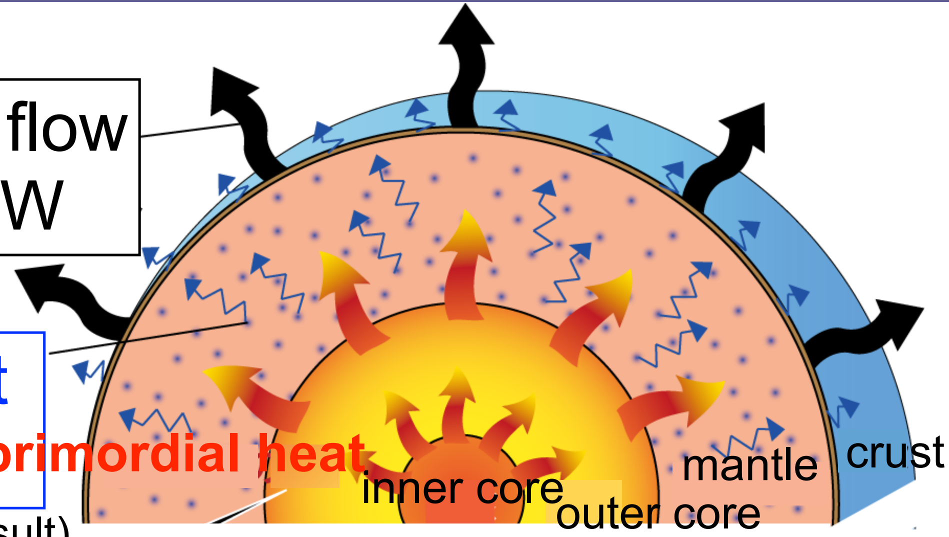
KamLAND only	2.4 σ C.L.
KamLAND + Borexino	2.3 σ C.L.

Analysis - Earth’s Primordial Heat

surface heat flow
44.2±1.0 TW

radiogenic heat
~ 21 TW

(based on KamLAND measurement result)



surface heat flow
44.2±1.0 TW

−

radiogenic heat
~ 21 TW

Earth’s primordial heat

KamLAND observation shows that heat from radioactive decay contributes about half of Earth’s total heat flux.
→ Earth’s primordial heat supply has not yet been exhausted.

Contents

1. Introduction

2. Recent Results

(1) Geo Neutrino

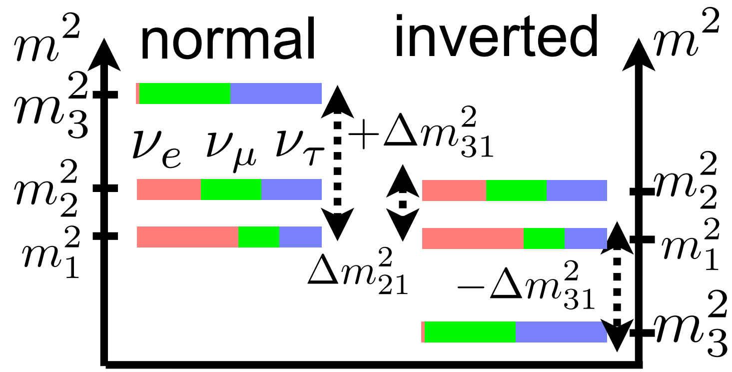
(2) Reactor Neutrino

preliminary results including
low-reactor operation period.

3. Summary

The three flavor eigenstates (ν_e, ν_μ, ν_τ)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\rm PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Unitary matrix $U_{\rm PMNS}$: 6 parameters

3 mixing angle, 2 mass difference, 1 CP phase

θ_{23} θ_{13} , CP phase θ_{12}

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

$\sin^2\theta_{23}$ ~0.5 → atmospheric

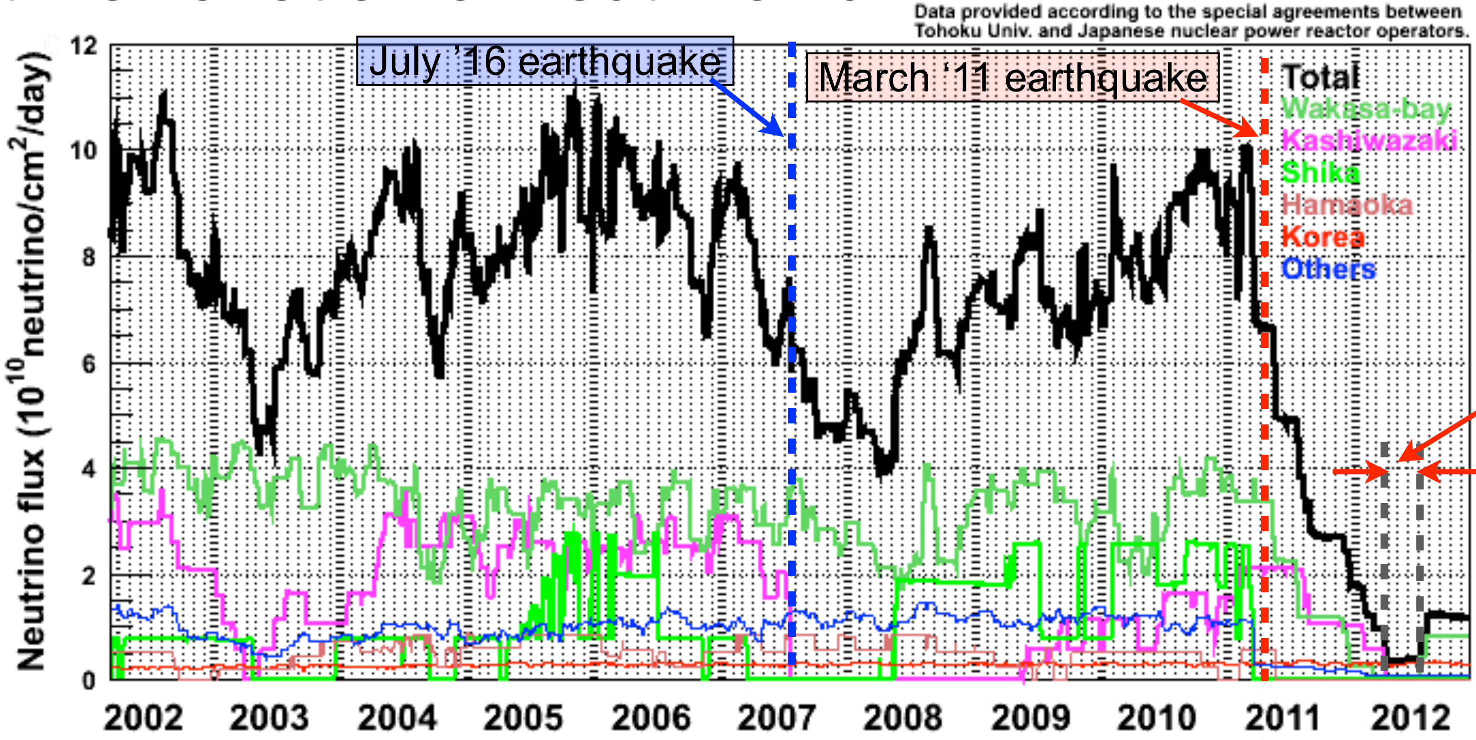
$\sin^2\theta_{13}$ ~0.02 → reactor

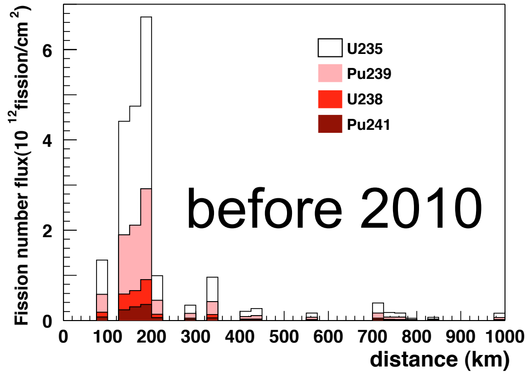
$\sin^2\theta_{12}$ ~0.3 → solar, KamLAND

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

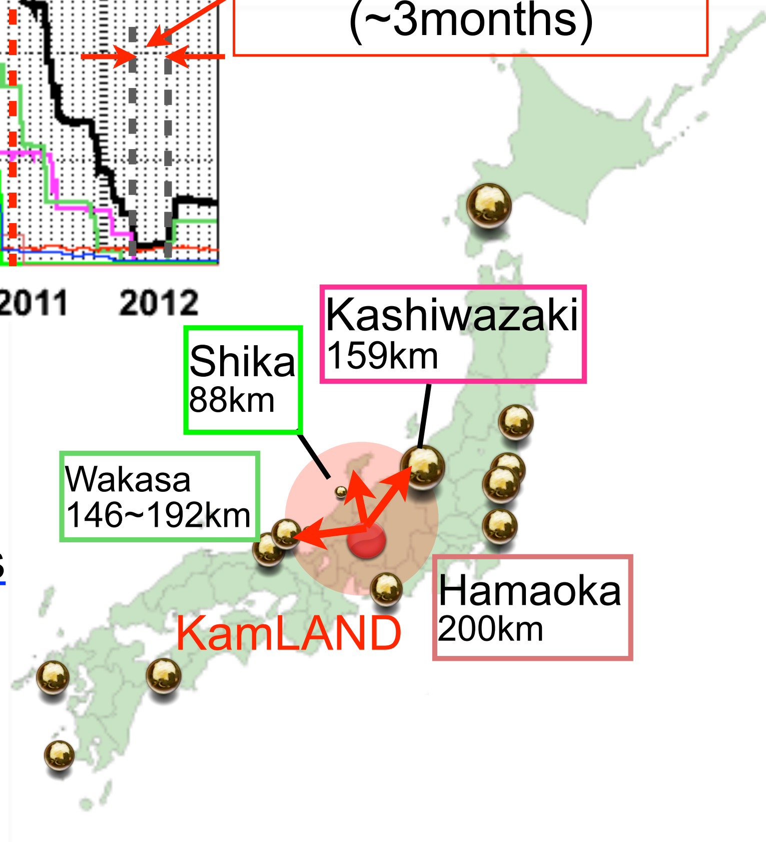
Recent Condition : reactor operation in Japan

time variation of neutrino flux





all reactor-off period (~3months)



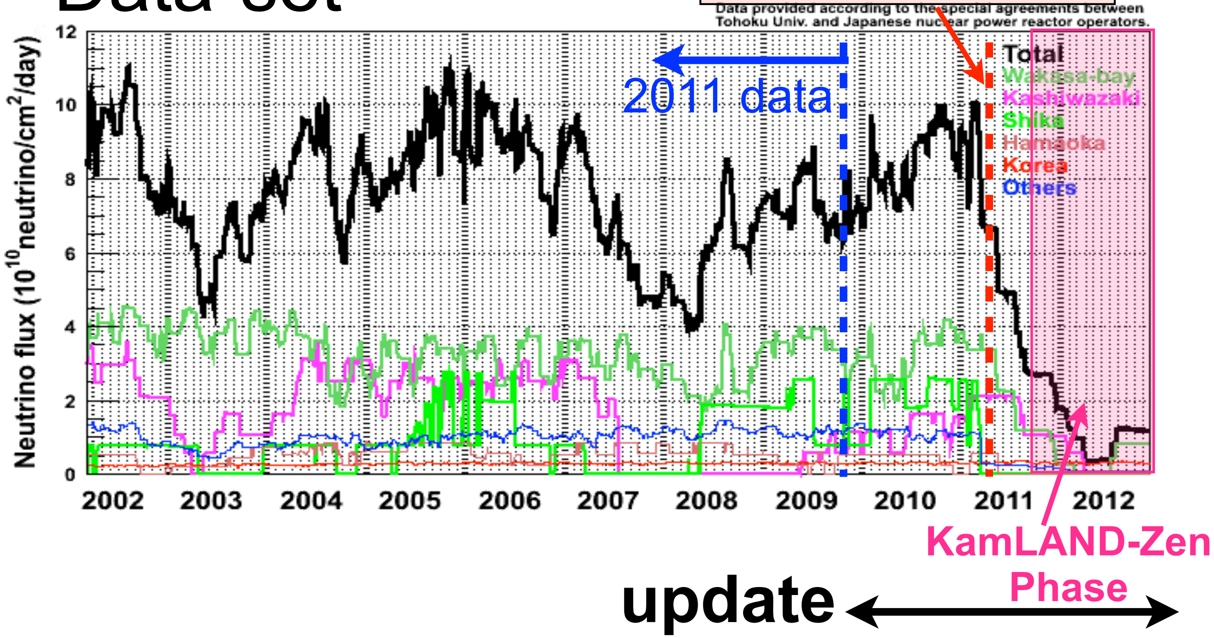
- Reactor neutrino flux, which is outside the control of the experiment, was significantly reduced.

- Following the Fukushima nuclear accident in March 2011, <u>the entire Japanese nuclear reactor industry has been subjected to protected shutdown</u>.

- This situation allows for a "reactor on-off" study of backgrounds for KamLAND neutrino oscillation and geoneutrino analysises.

Data-set & Systematic Uncertainties

- Data-set



PRD 83, 052002 (2011)

2011 data-set : 2135 days
3.49×10^{32} proton-year

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

- 1.4 times of 2011 data-set
- Includes ~1year low-reactor operation period
- Data collected after KamLAND-Zen construction is also included.

- Systematic Uncertainties

before/after purification

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.8 / 1.8	$\overline{\nu}_e$-spectra	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

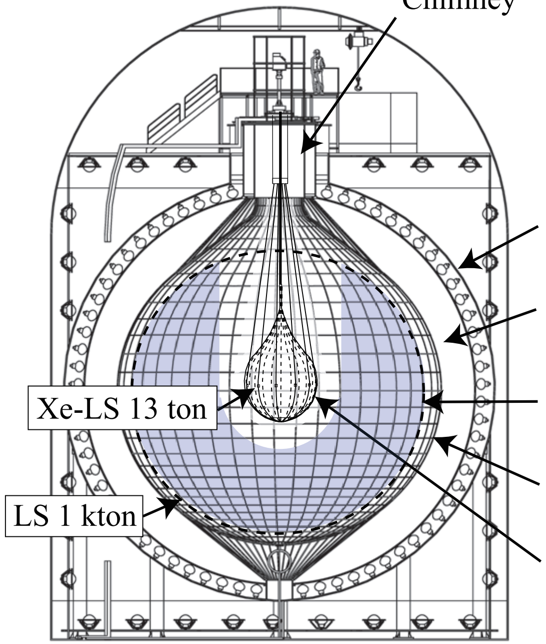
- Anti-neutrino spectra were updated

235U, 239Pu, 241Pu: re-evaluation of ILL (P. Huber)
238U: theoretical calculation (Th. Mueller et al.)

- Normalization by Bugey-4 was used (same method as Double Chooz result)

* Bugey-4 : short baseline (14m), performed most precise measurement of the neutrino inverse beta decay cross section.
* The cross section per fission was normalized.

▸Anti-neutrino Analysis in KamLAND-Zen Phase



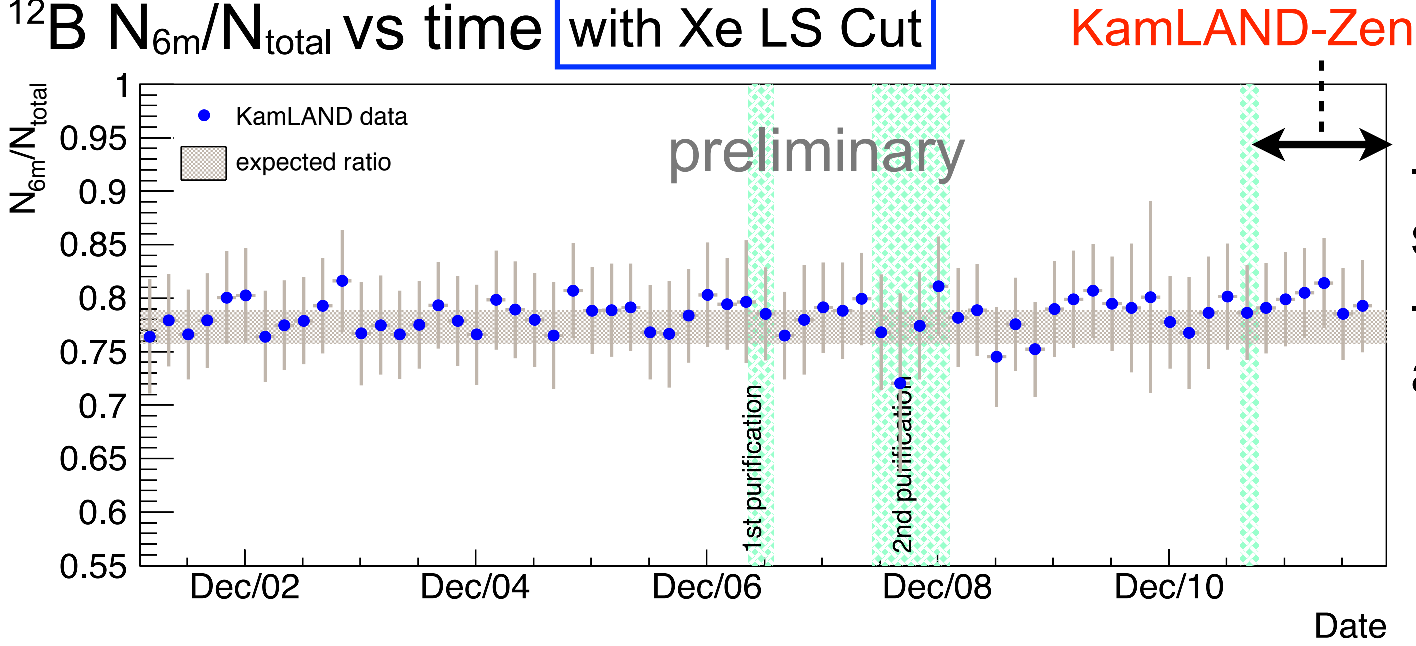
- Vertex cut conditions

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

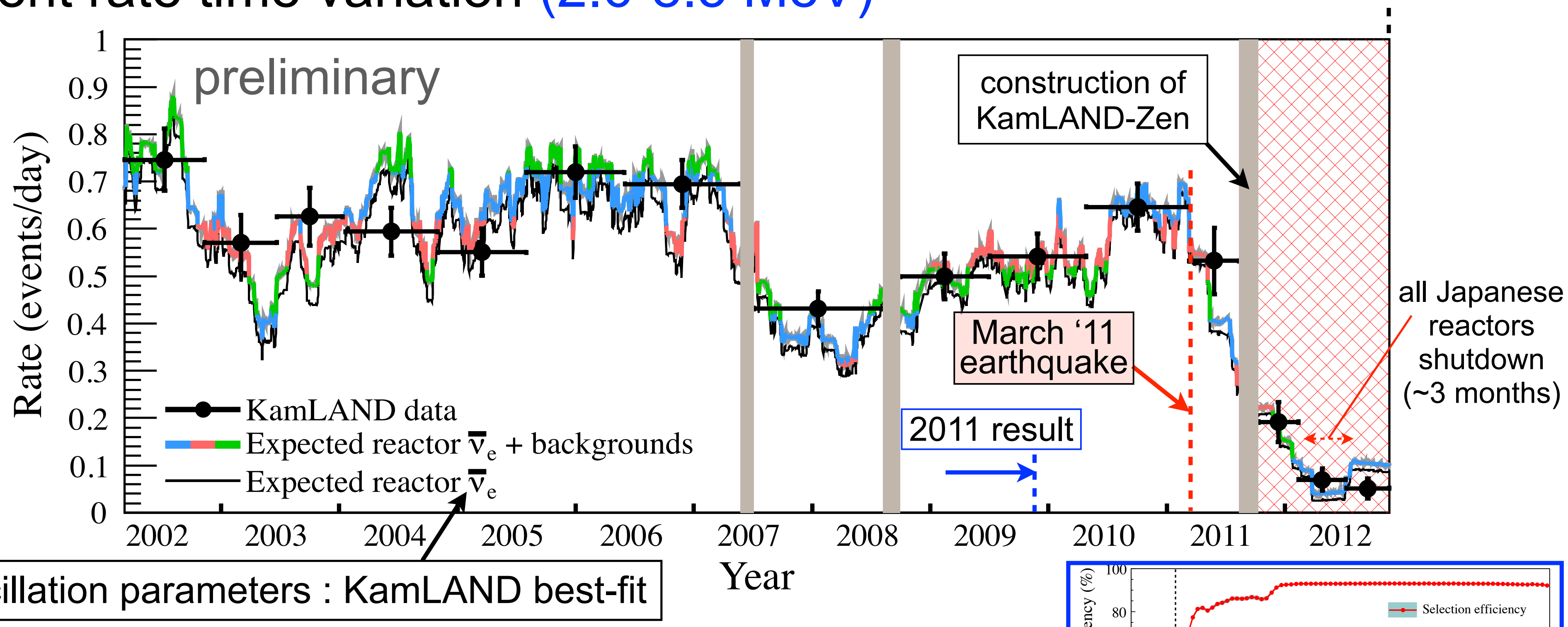
^{12}B N_{6m}/N_{total} vs time **with Xe LS Cut**

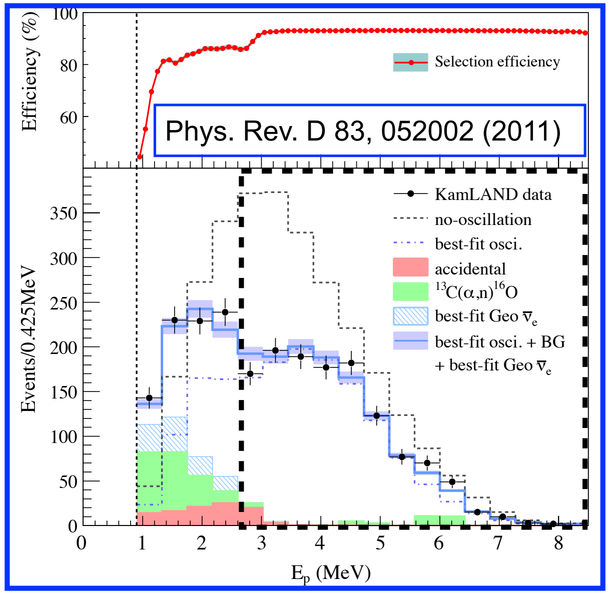


- Event rate has been stable.
- difference before and after purification : 2.5%

Analysis - Event rate (2.6-8.5 MeV)

- event rate time variation (2.6-8.5 MeV)





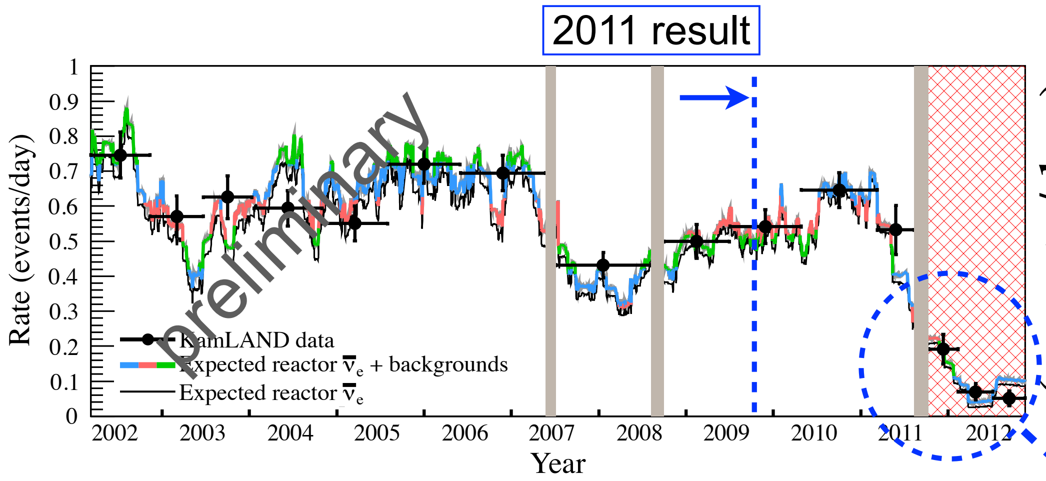
- We continue to collect data for anti-neutrino analysis after KamLAND-Zen construction.

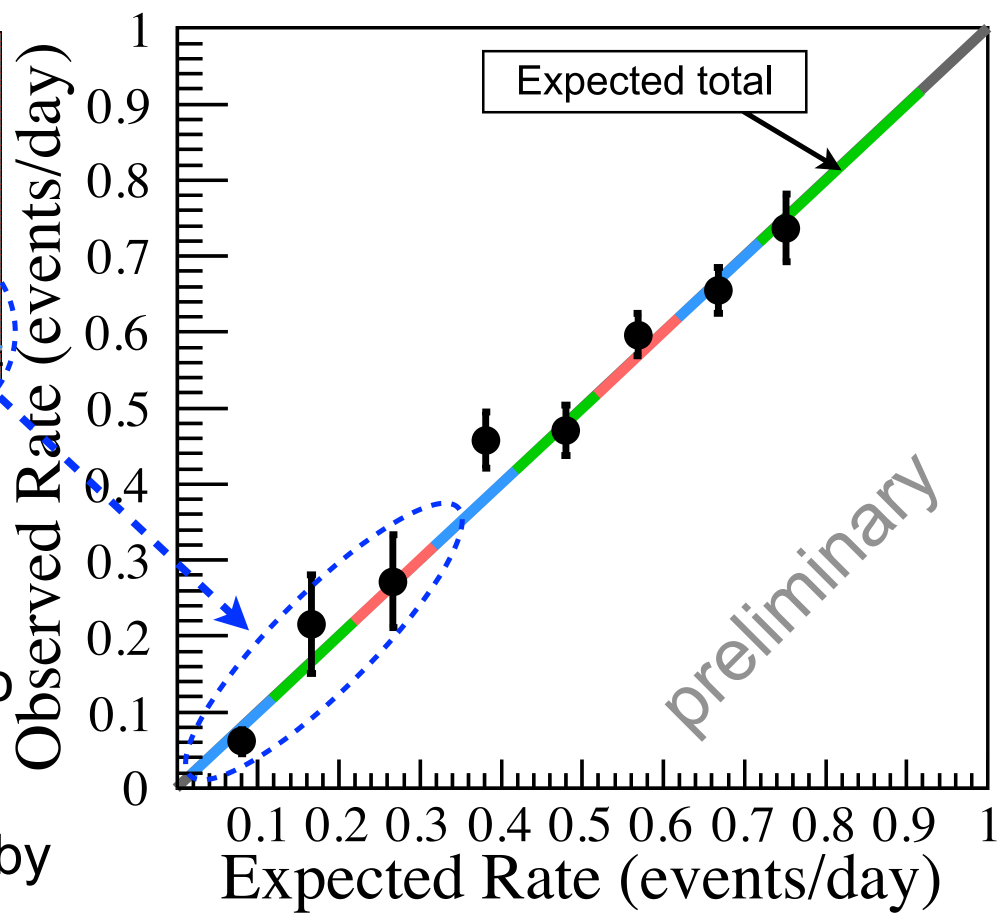
- The recent long-term shutdown of Japanese nuclear reactors has resulted in significant reduced reactor anti-neutrino fluxes.

- Data points have good agreement with expected rate.

Analysis - Correlation (2.6-8.5 MeV)

- Expected Rate vs Observed Rate (2.6-8.5 MeV)



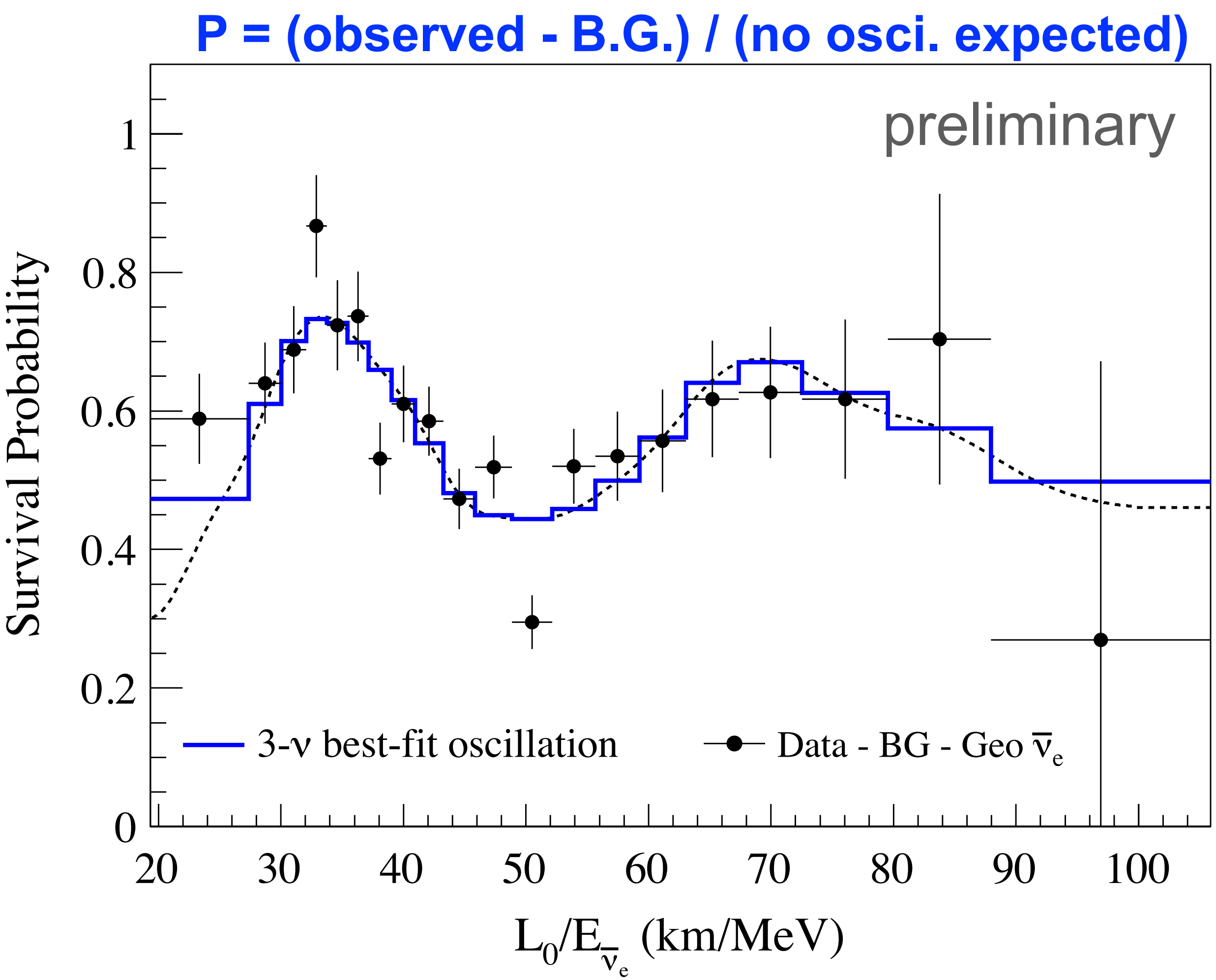


- Recent condition provides a unique opportunity to confirm and constrain backgrounds for the reactor anti-neutrino oscillation analysis.

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

- Strong correlation between expected and observed event rate.

‣Analysis : L/E plot



※L_0=180km fixed

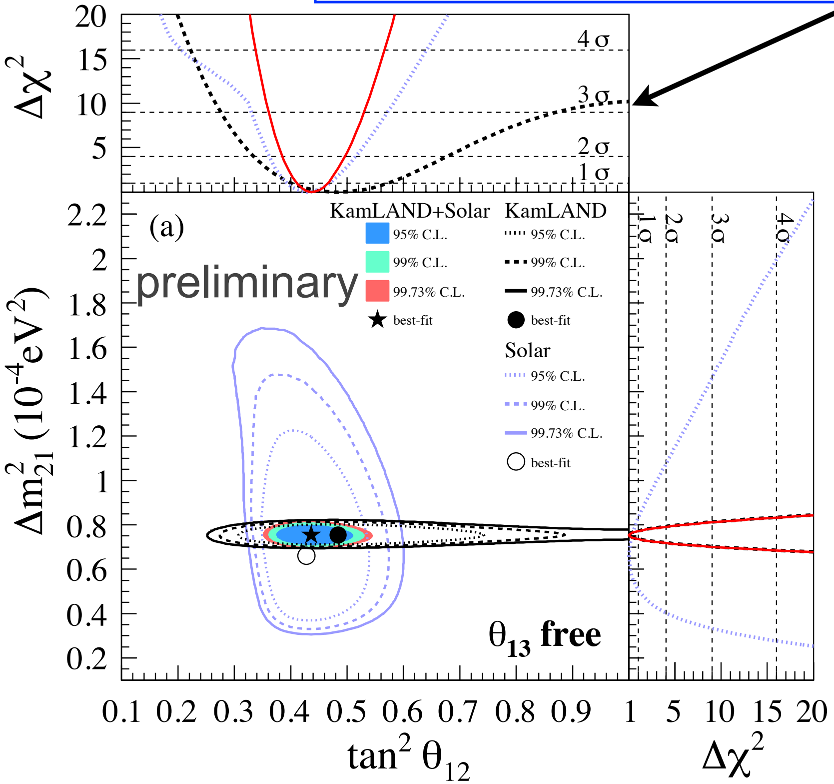
best-fit parameters (KamLAND only)

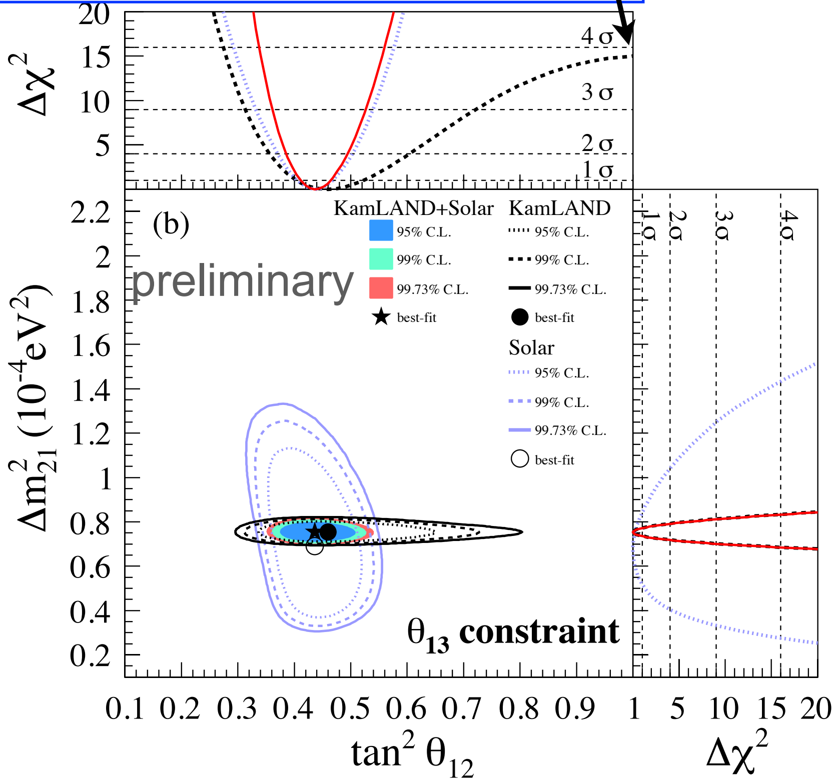
$$\Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \times 10^{-5} \mathrm{eV}^2$$
$$\tan^2\theta_{12} = 0.481^{+0.092}_{-0.080}$$
$$\sin^2\theta_{13} = 0.010^{+0.033}_{-0.034}$$

~2 cycles of oscillation measured precisely

Analysis : Oscillation Parameters Measurement (1)

KamLAND
full mixing is rejected at 3.20σ (99.860%) / 3.87σ (99.989%)





solar + KamLAND

$$\Delta m^2_{21} = 7.53^{+0.19}_{-0.18} \times 10^{-5}\text{eV}^2$$
$$\tan^2\theta_{12} = 0.437^{+0.029}_{-0.026}$$
$$\sin^2\theta_{13} = 0.023^{+0.015}_{-0.015}$$

solar

Cl, Ga, Borexino, SK, SNO I + II + III (All)

blue : updated after 2011 result

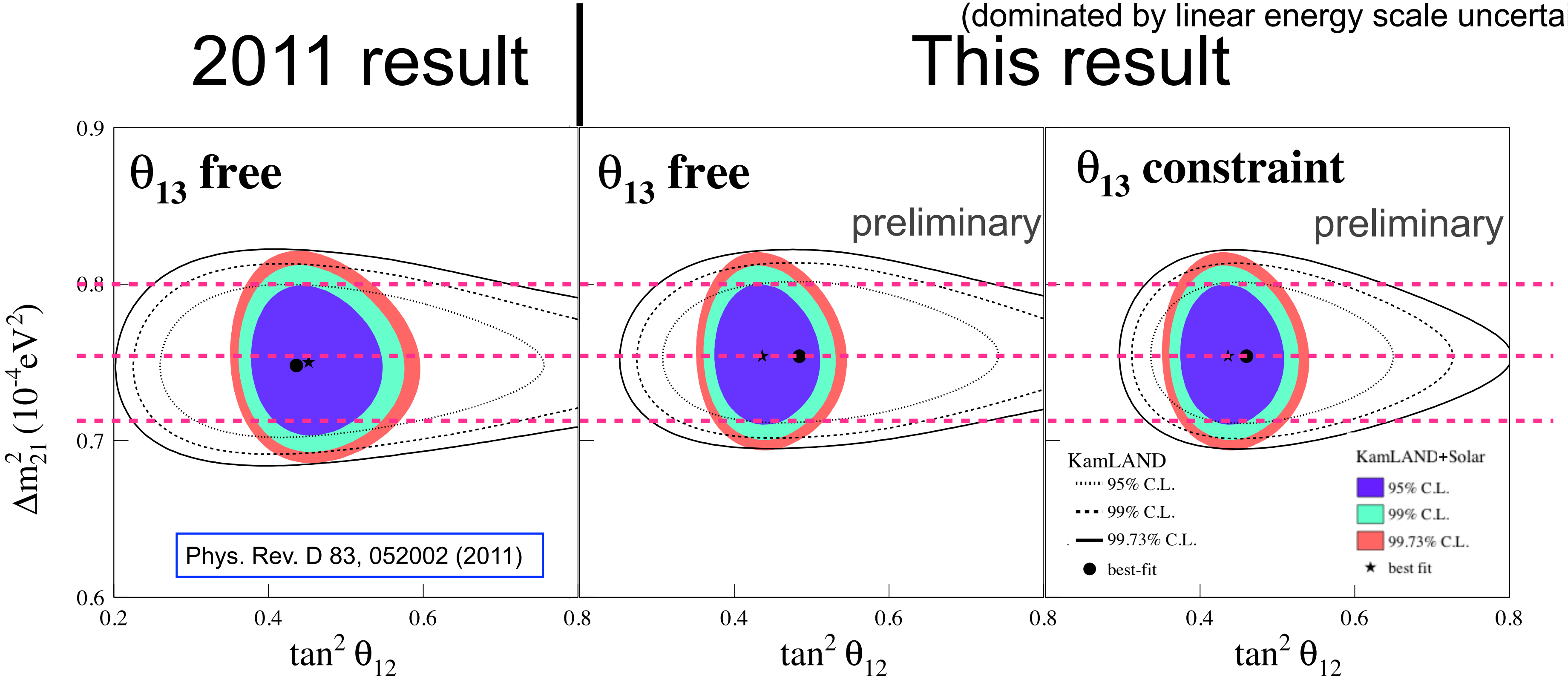
solar + KamLAND + Theta13 experiments

$$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\text{eV}^2$$
$$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$$
$$\sin^2\theta_{13} = 0.023^{+0.002}_{-0.002}$$

accelerator (T2K, MINOS) + short baseline reactor neutrinos (Double Chooz, Daya Bay, RENO)

Analysis : Oscillation Parameters Measurement (2)

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



KamLAND+Solar	KamLAND+Solar	KamLAND+Solar+Theta13
$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\mathrm{eV}^2$	$\Delta m^2_{21} = 7.53^{+0.19}_{-0.18} \times 10^{-5}\mathrm{eV}^2$	$\Delta m^2_{21} = 7.53^{+0.18}_{-0.18} \times 10^{-5}\mathrm{eV}^2$
$\tan^2\theta_{12} = 0.450^{+0.037}_{-0.031}$	$\tan^2\theta_{12} = 0.437^{+0.029}_{-0.026}$	$\tan^2\theta_{12} = 0.436^{+0.029}_{-0.025}$
$\sin^2\theta_{13} = 0.020^{+0.016}_{-0.016}$	$\sin^2\theta_{13} = 0.023^{+0.015}_{-0.015}$	$\sin^2\theta_{13} = 0.023^{+0.002}_{-0.002}$

- Δm^2 is measured at 2.3% precision
- $\tan^2\theta_{12}$ uncertainty is improved by a factor 1.2

Contents

Summary

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

- **Geo-neutrino (available at Nat. Geosci.4, 647 (2011))**

- Neutrino measurement started to examine Earth models
- KamLAND firstly showed such result

- **Reactor-neutrino (preliminary result)**

- The updated data benefits from the significant reduction of reactor anti-neutrino's due to the long-term shutdown of commercial nuclear reactors in Japan.
- The anti-neutrino analysis results including KamLAND-Zen phase are presented for the first time.

- Geo-neutrino analysis results including low-reactor period data will be presented at Neutrino Geoscience 2013 in Takayama, Japan.