Low energy neutrino physics at KamLAND

Hiroko Watanabe
Research Center for Neutrino Science (Tohoku Univ.)
for the KamLAND Collaboration

Contents

Contents

KamLAND Collaboration

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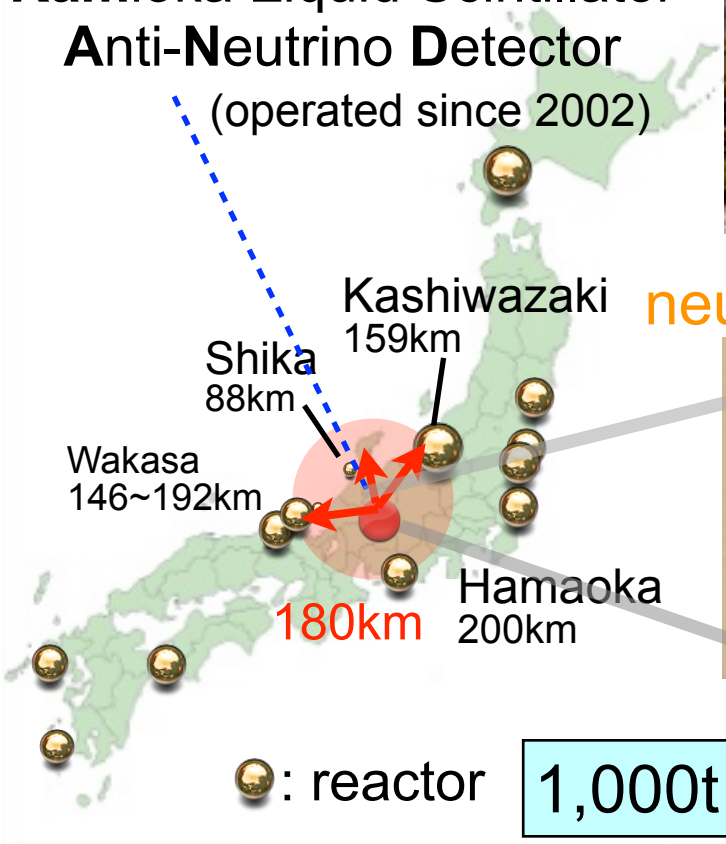
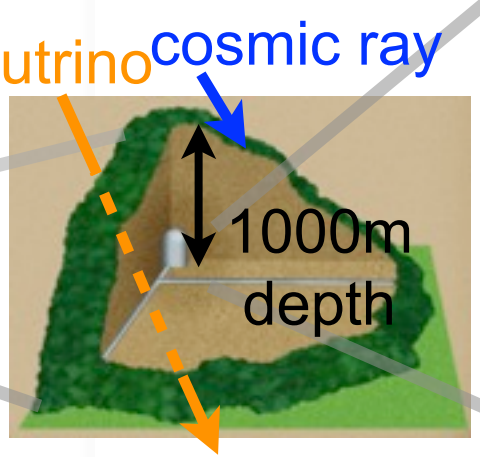
Sep.2010 @Amsterdam

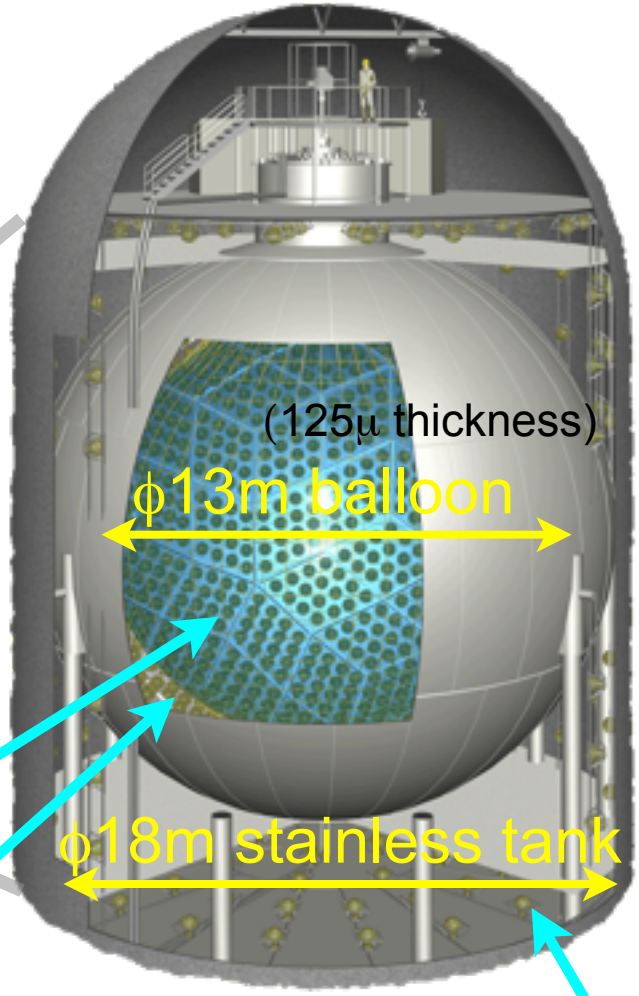
KamLAND Site & Detector

KamLAND

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







1,000t Liquid Scintillator

* Dodecane (80%) Pseudocumene (20%) PPO (1.36 g/l)
* extremely low impurily ($^{238}U<1.5\times10^{-19}$g/g, $^{232}Th<1.9\times10^{-17}$g/g)

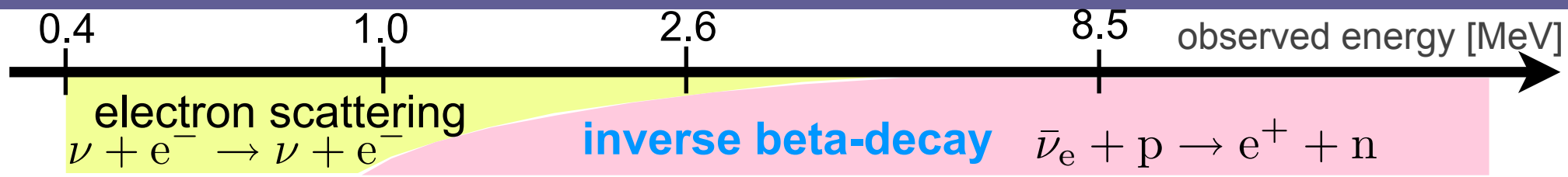
1,325 17inch + 554 20inch PMTs

* Photo coverage 34%

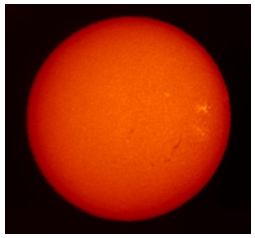
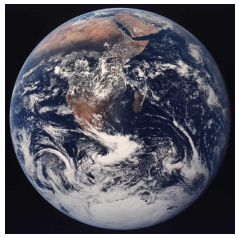
Water Cherenkov Outer Detector

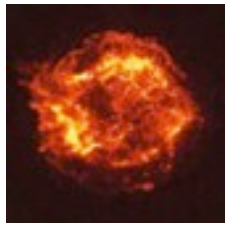
* Muon veto

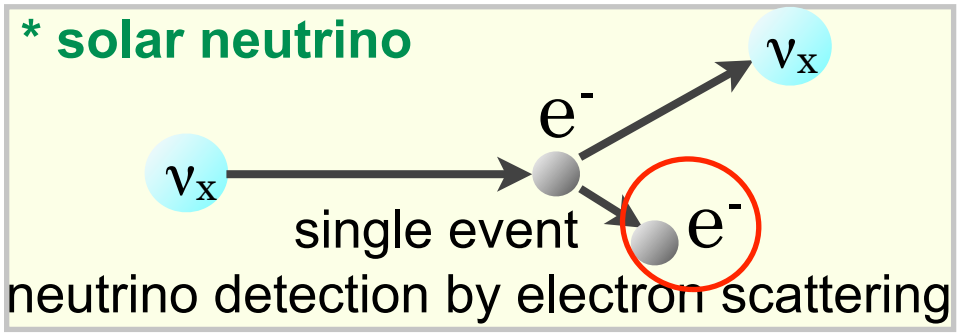
Physics Target in KamLAND

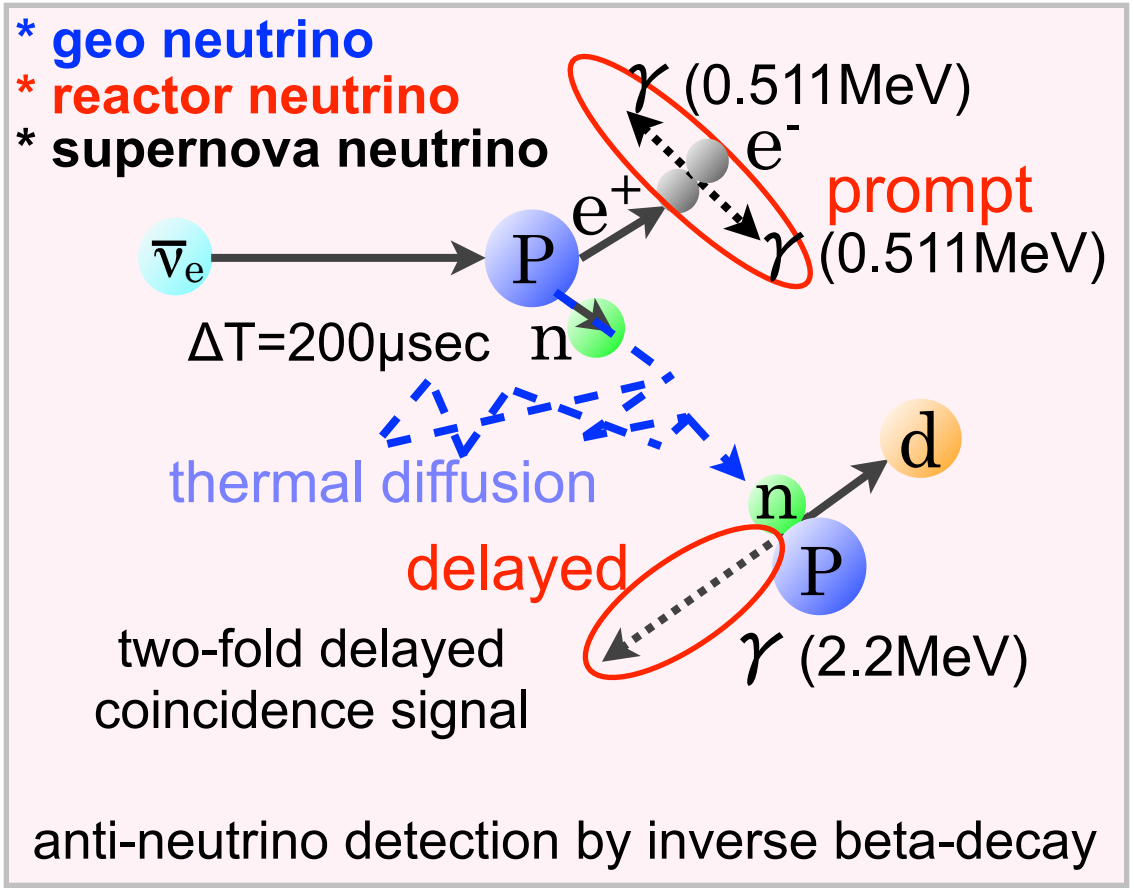


solar neutrino **geo neutrino** **reactor neutrino** **supernova neutrino, etc.**







this talk's topics

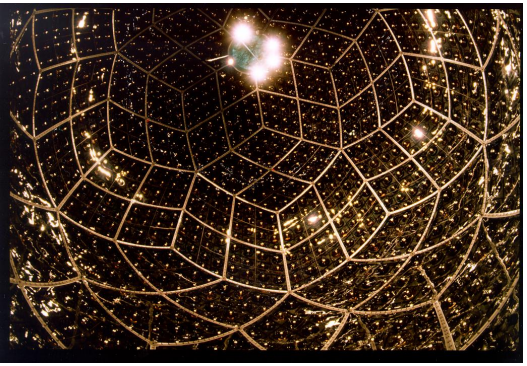
new results

* **solar neutrino**
  hep-ex/1106.0861 (2011)
* **geo neutrino**
  Nature Geoscience 4, 647-651 (2011)
* **reactor neutrino**
  Phys. Rev. D 83, 052002 (2011)
* **extraterrestrial neutrino**
  astro-ph.HE/1105.3516 (2011)

History of KamLAND and Neutrino Physics

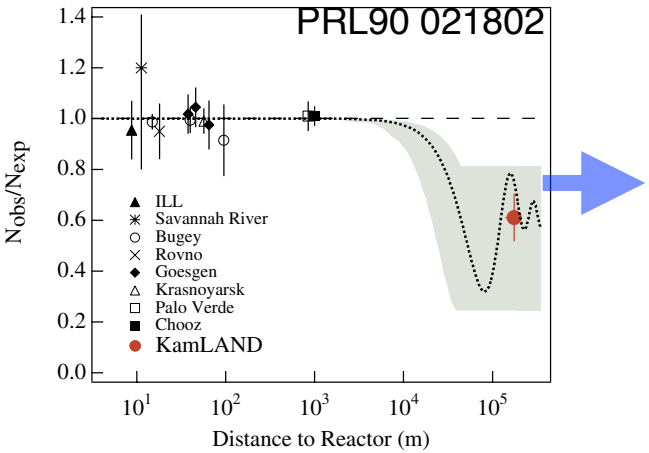
2000 2002 2005 2008 2011

construction



History of KamLAND and Neutrino Physics

disappearance



solve “solar neutrino problem”

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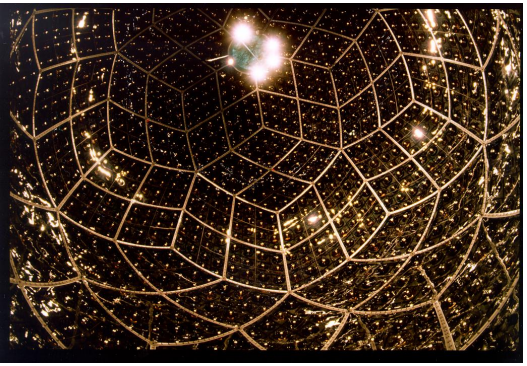

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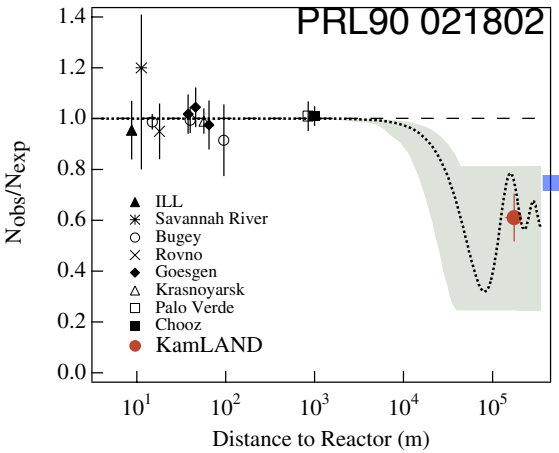
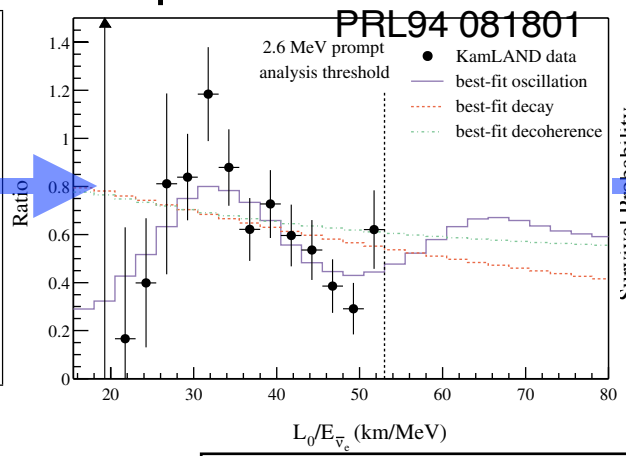
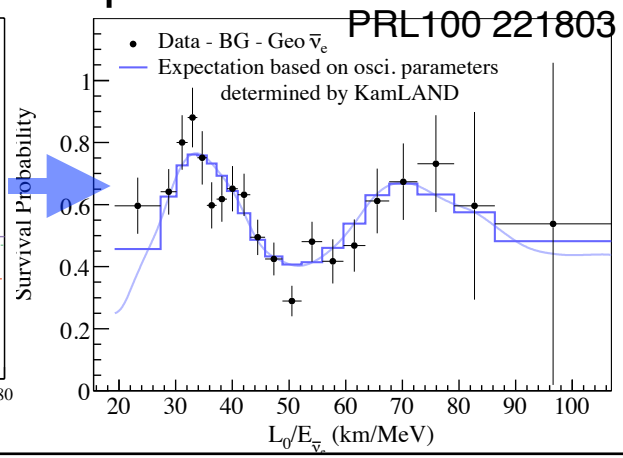


spectral distortion



precise measurement



solve "solar neutrino problem"

precise measurement of neutrino oscillation

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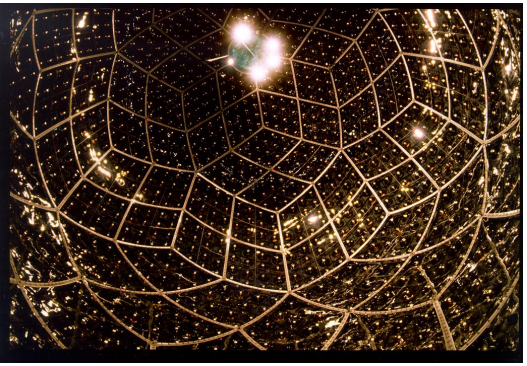

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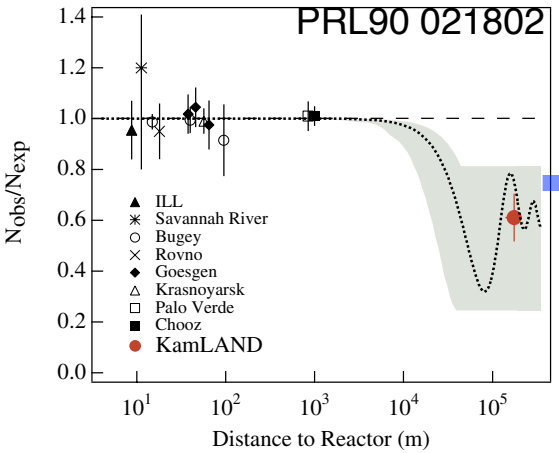

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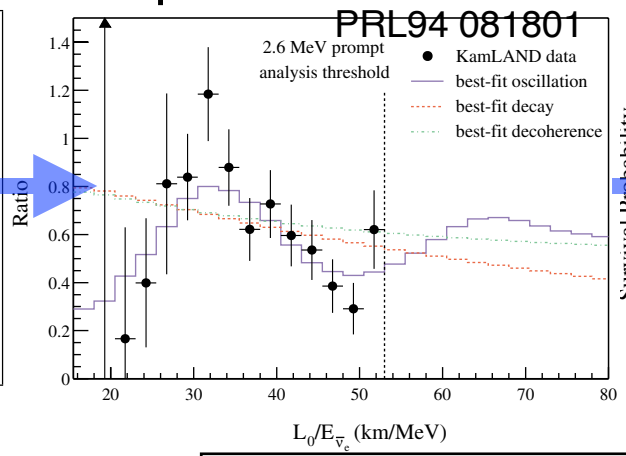

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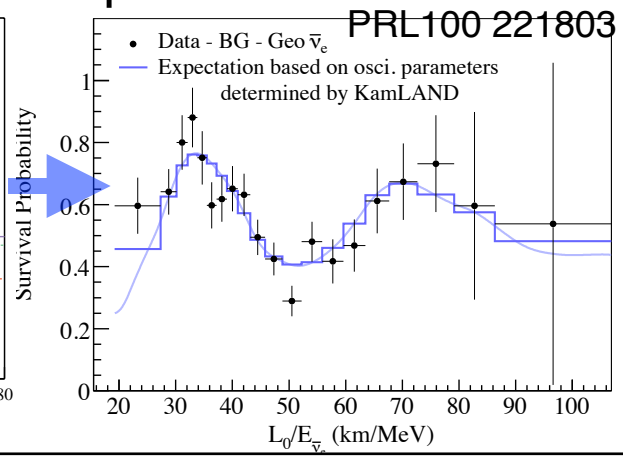


solve "solar neutrino problem"

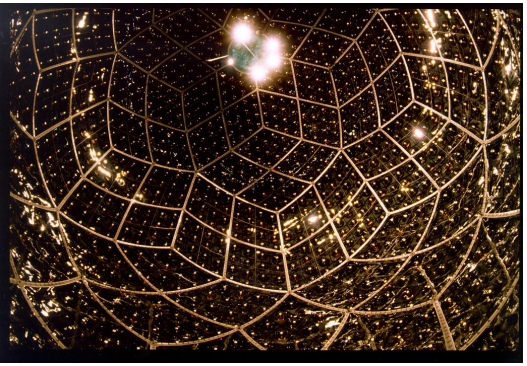
precise measurement of neutrino oscillation

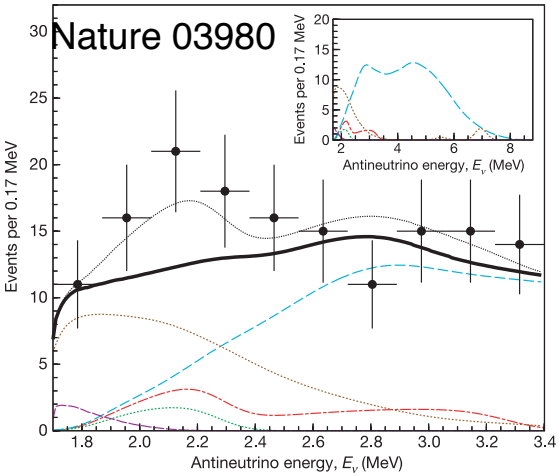
2000 2002 2005 2008 2011

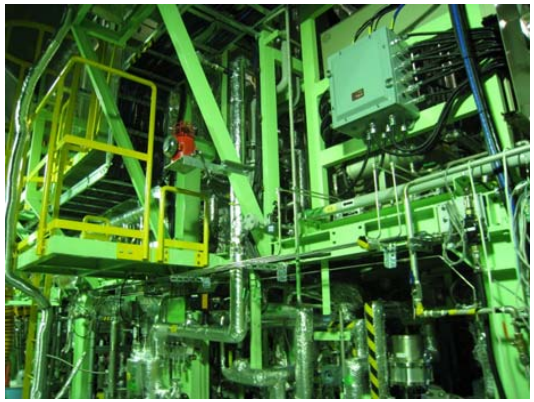
construction

first measurement of geo-neutrino

distillation







History of KamLAND and Neutrino Physics

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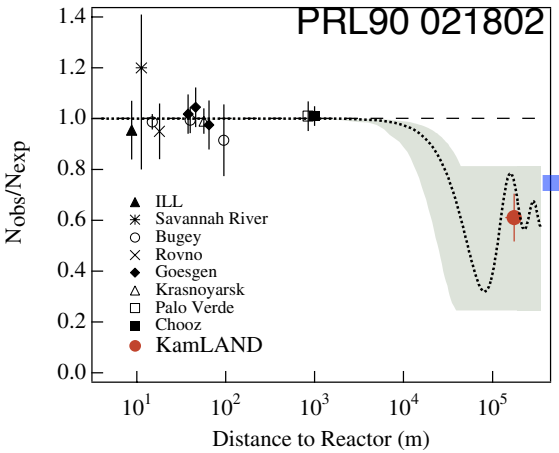

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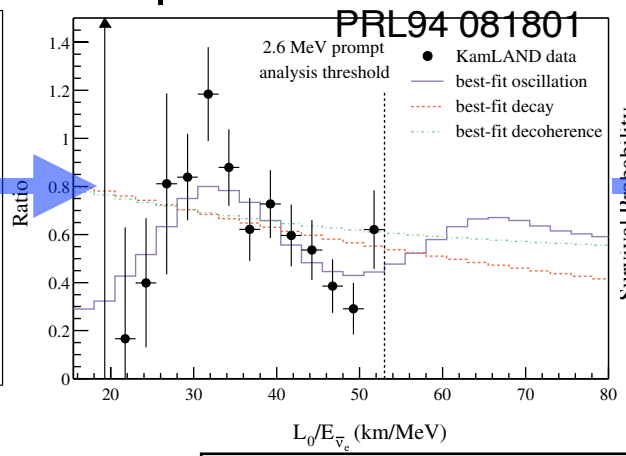

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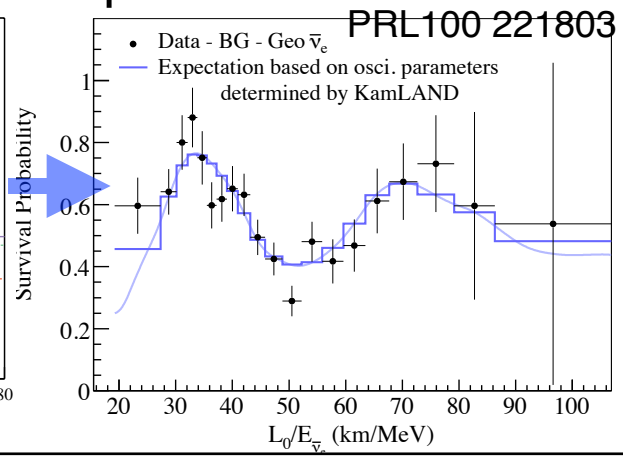

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2000 — 2002 — 2005 — 2008 — 2011

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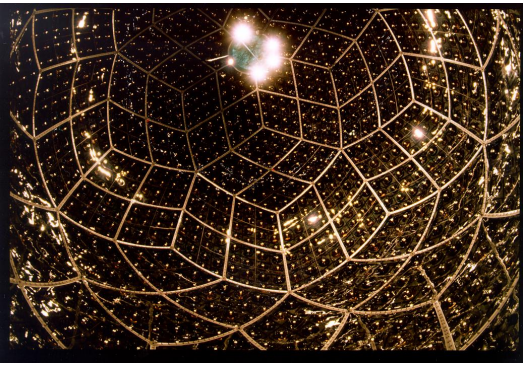
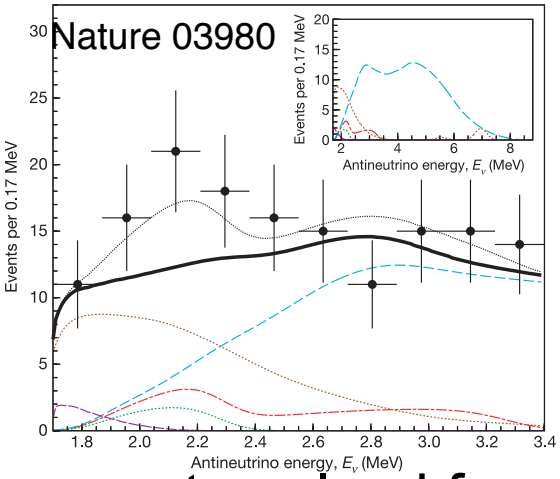
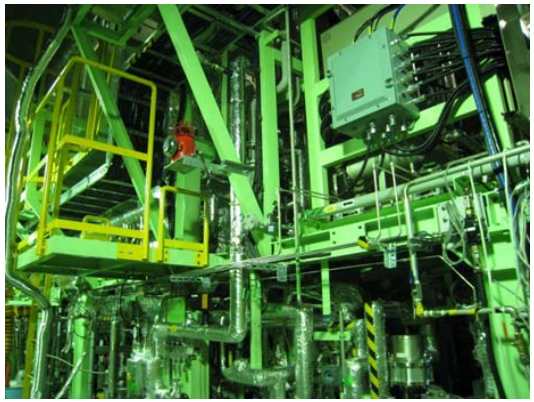




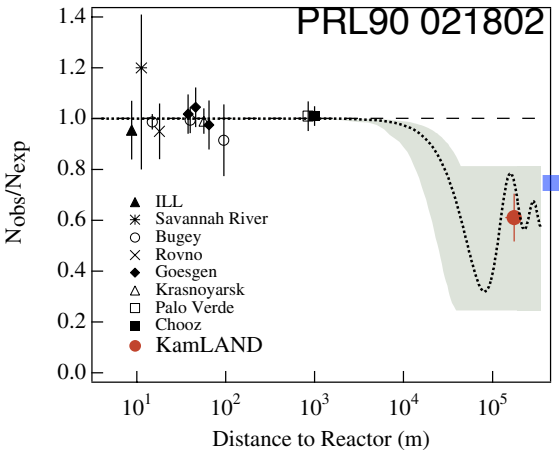


* solar neutrino
* geo neutrino
* reactor neutrino
* extraterrestrial neutrino

☑ Neutrino measurement evolved from understanding of neutrino properties to utilization of neutrino as a "probe".

History of KamLAND and Neutrino Physics

disappearance



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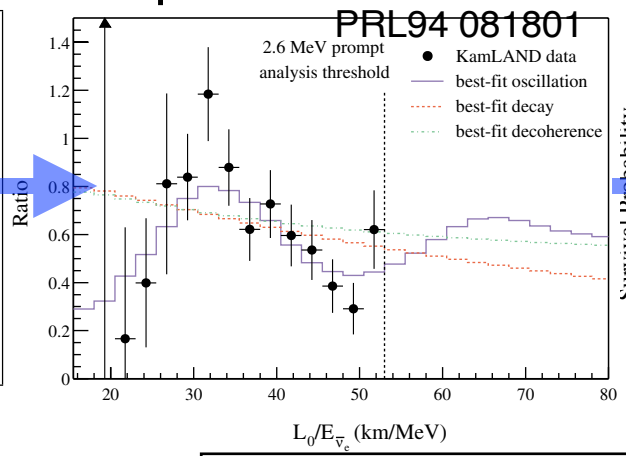
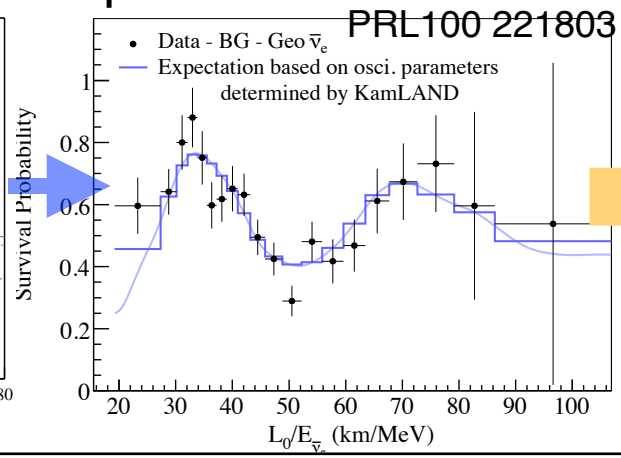


precise measurement



solve "solar neutrino problem"

precise measurement of neutrino oscillation

2000 2002 2005 2008 2011

construction

first measurement of geo-neutrino

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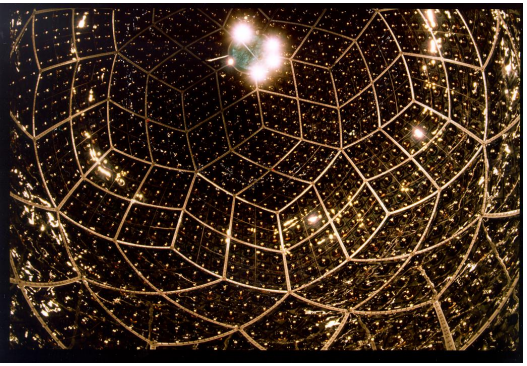
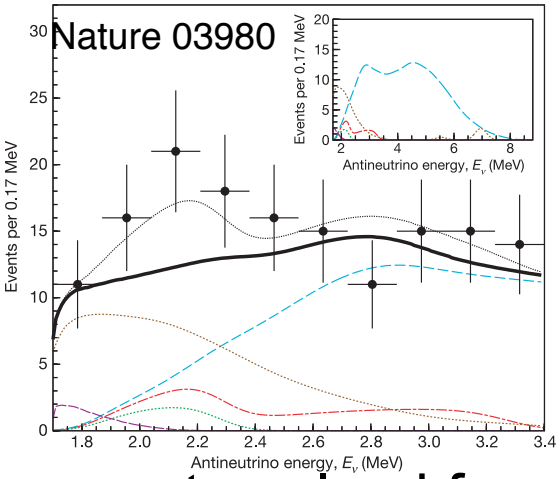
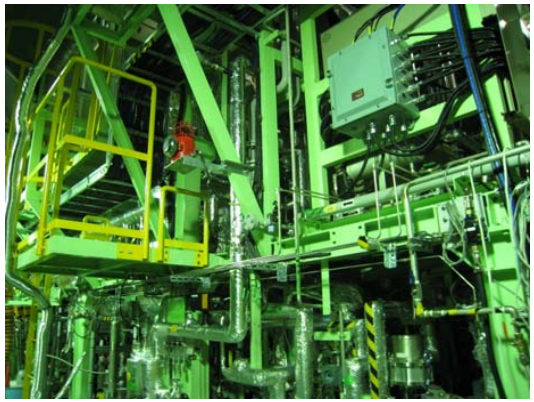






* solar neutrino
* geo neutrino
* reactor neutrino
* extraterrestrial neutrino

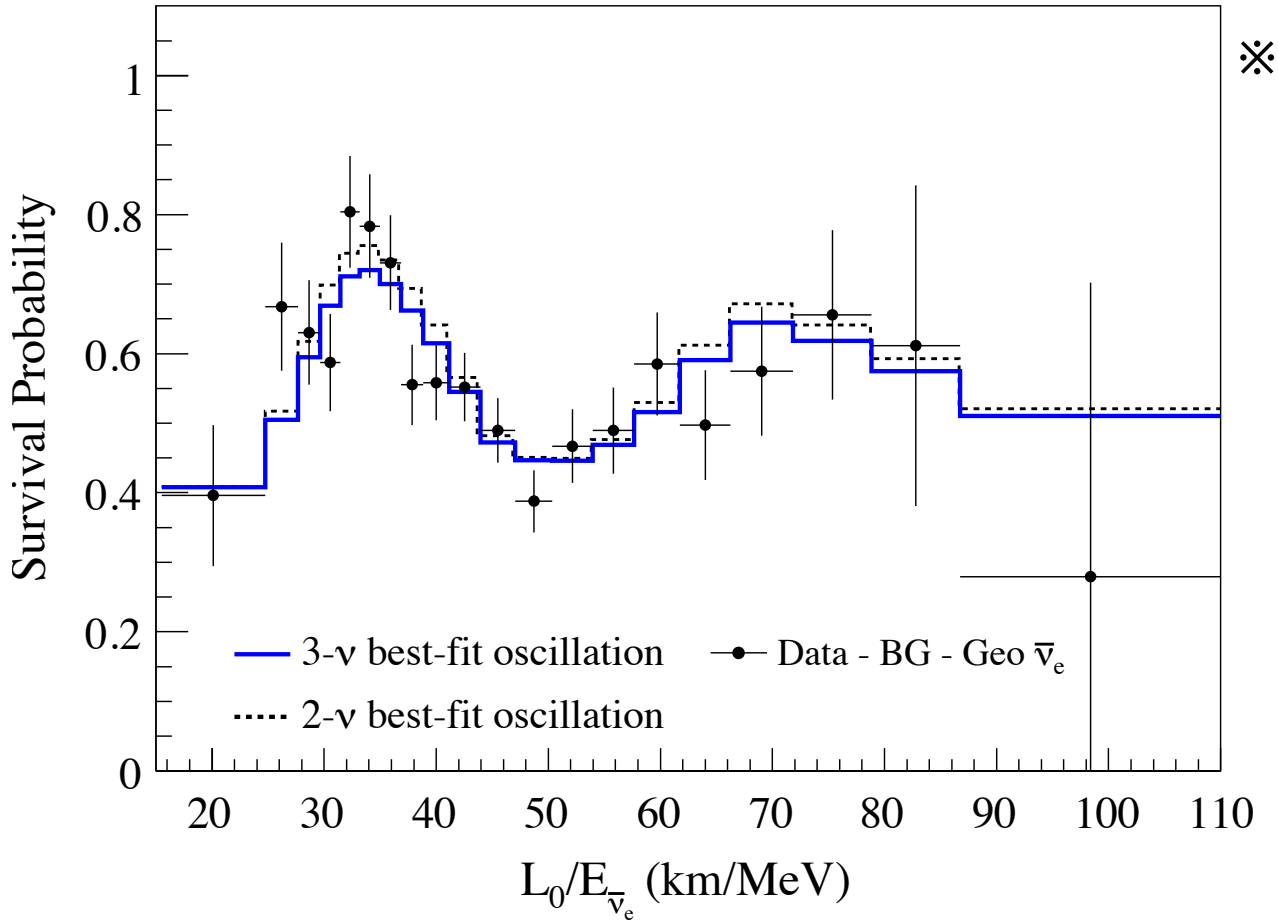
☑ Neutrino measurement evolved from understanding of neutrino properties to utilization of neutrino as a "probe".

Reactor Neutrino - L/E Plot

Constraints on θ_{13} from A Three-Flavor Oscillation Analysis of Reactor Antineutrinos at KamLAND
Phys. Rev. D 83, 052002 (2011)

P = (observed - B.G.) / (no osci. expected)

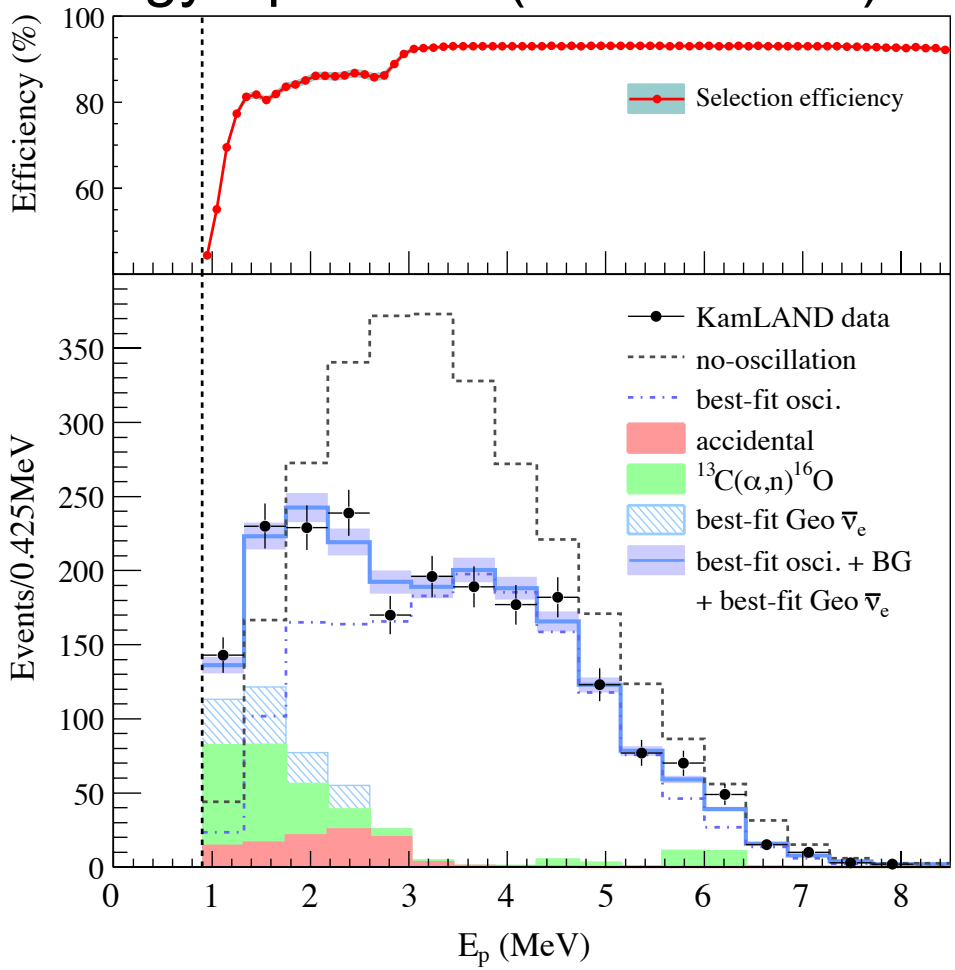
※L_0=180km fixed



- 3-flavor oscillation analysis is presented
- KamLAND data covers almost 2 cycle of oscillation
  → clear evidence of neutrino oscillation

Reactor Neutrino - Energy Spectrum & Oscillation Parameters

- Energy Spectrum (0.9-8.5 MeV)

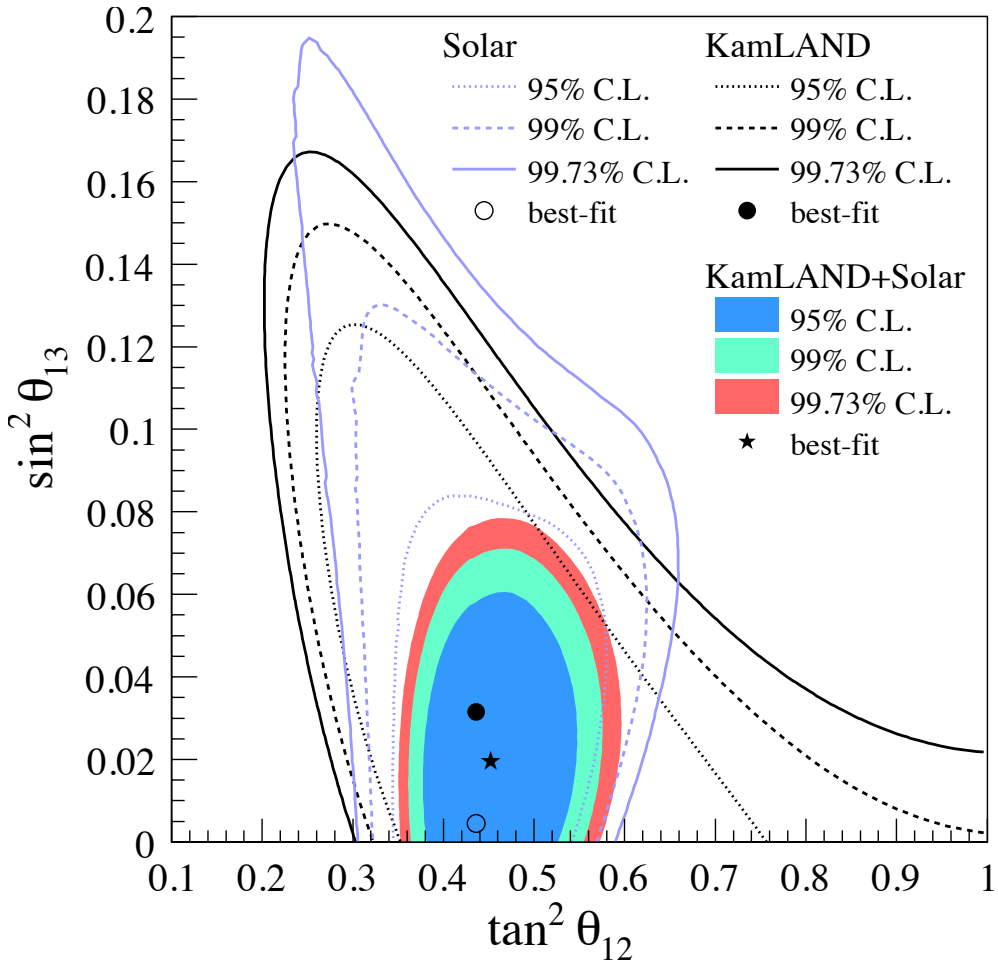


- exposure : 4126 ton-year

(1.4 times larger the 2008 result)

No osci. expected	2879±118
background (w/o geo-nu.)	325.9±26.1
observed	2106

- Oscillation Parameters: 3 flavor



Solar + KamLAND

$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.452^{+0.035}_{-0.033}$$

$$\sin^2\theta_{13} = 0.020^{+0.016}_{-0.016}$$

Contents

Partial radiogenic heat model for Earth revealed by geoneutrino measurements
Nature Geoscience 4, 647-651 (2011)

- Backgrounds
- Terrestrial Heat
  - Geophysical Activity
  - Heat Balance
- Geo Neutrino
- Analysis
  - Observed Energy Spectrum
  - Rate+Shape+Time Analysis
  - Radiogenic Heat and Flux
  - Earth's Primordial Heat

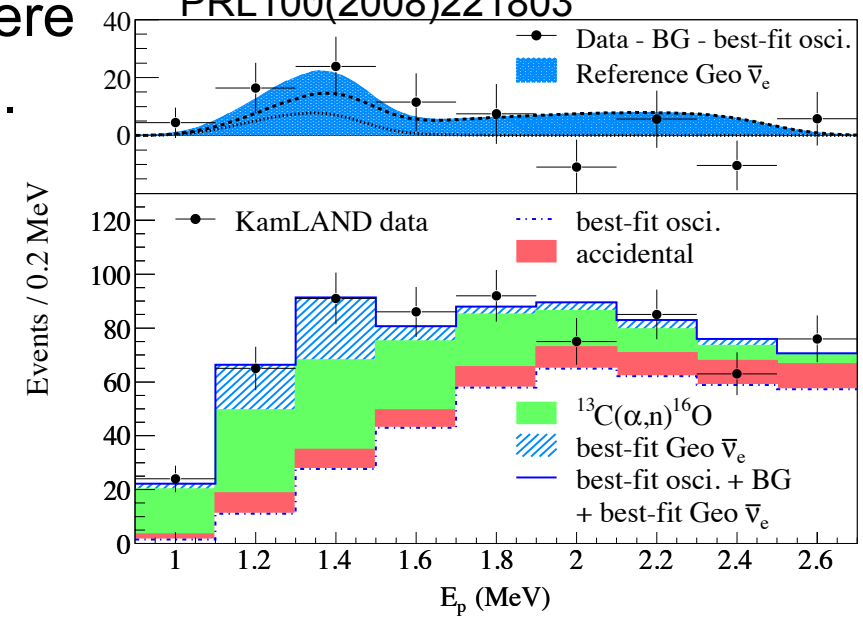
Backgrounds

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

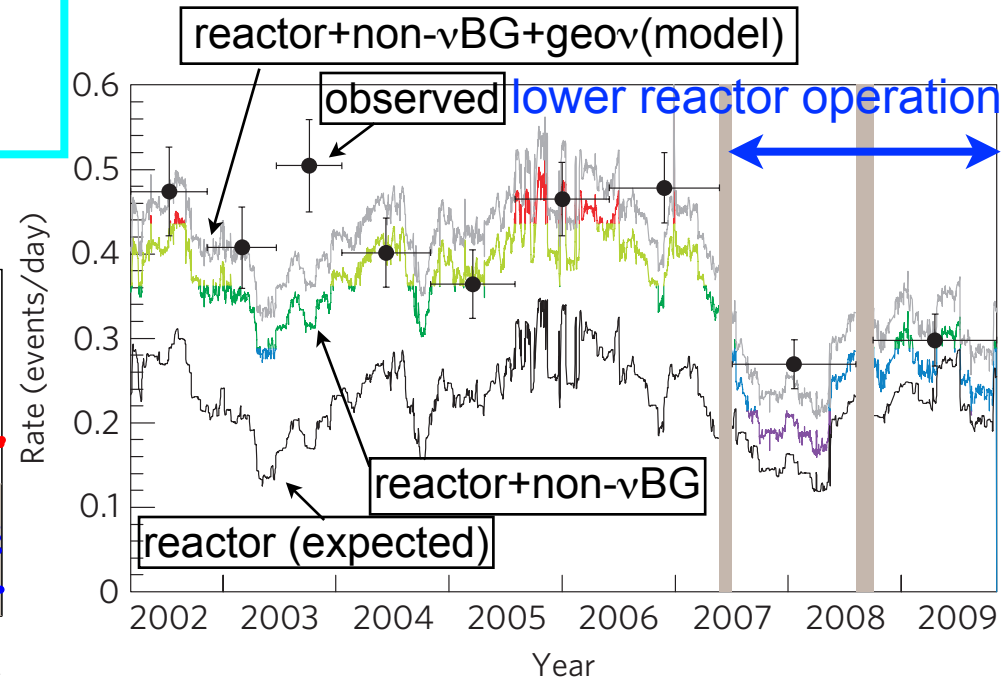
- Improvement in Background

(1) Dominant BG source (α, n) has been reduced by down to ~ 1 / 20 (2 times distillation)
(2) Operational issues at the power reactor and a serious earthquake (2007) reduced the reactor neutrino flux.
(3) Determination of the cross section is improved by in-situ calibration uncertainty : 11% for ground state

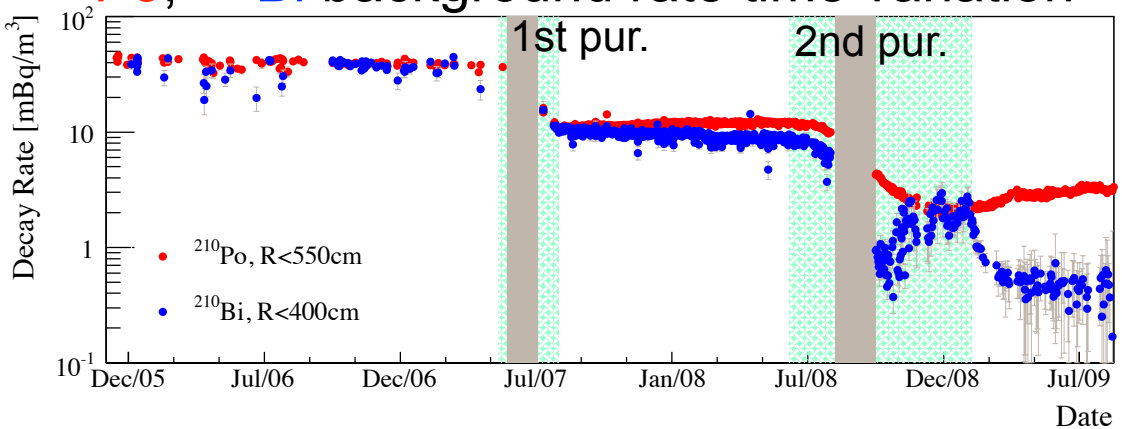
PRL100(2008)221803



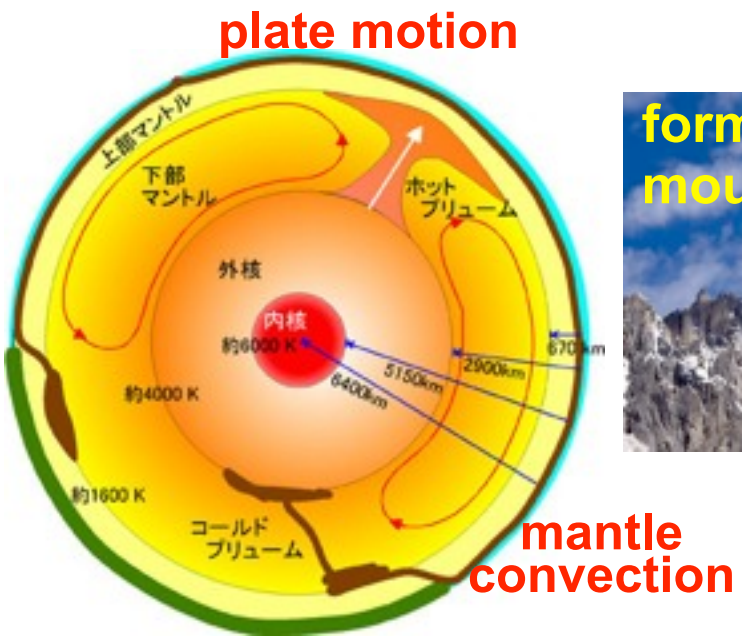
0.9-2.6 MeV time variation

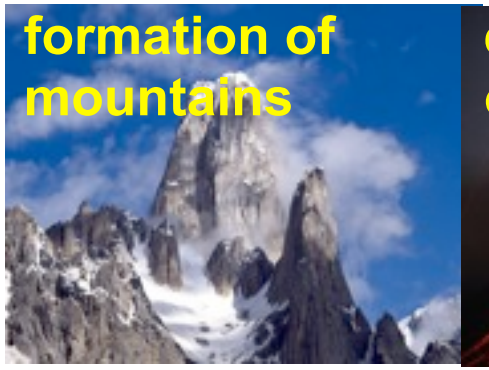


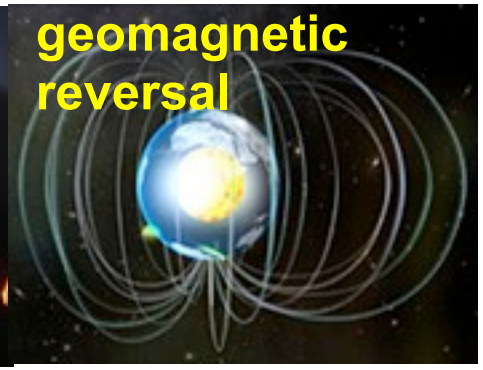
^{210}Po, ^{210}Bi background rate time variation



Terrestrial Heat - Geophysical Activity







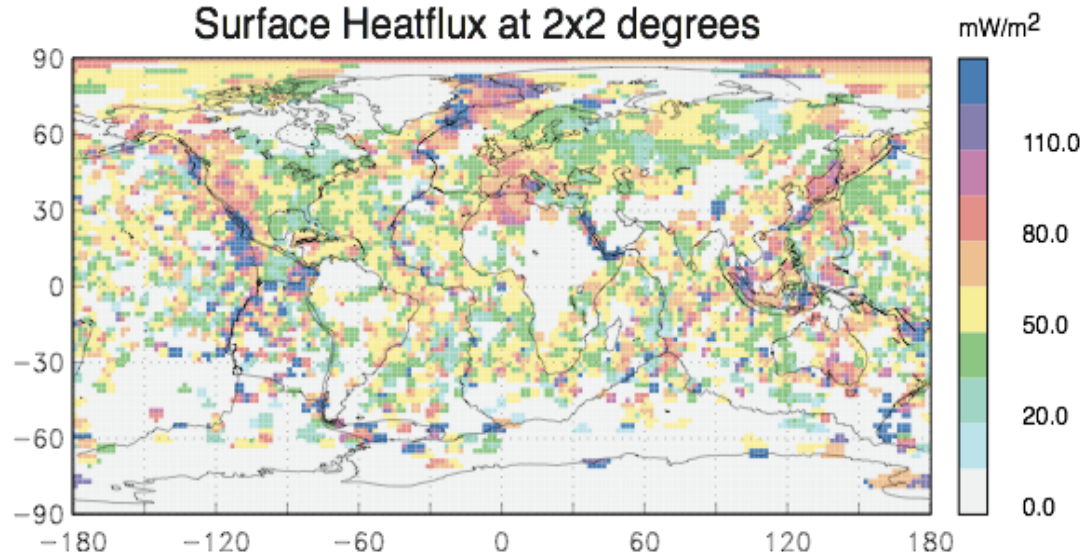
Question on geophysical activity

- What are energy sources? How much energy?
- How is the mantle convecting, single or multi-layer convection?
- Why is the frequency of geomagnetic reversals random?

→ It is important to find out the terrestrial heat.

Terrestrial Heat - Heat Balance

☑ Surface heat flow : **44.2±1.0 TW** Rev. of Geophys. 31, 267-280 (1993)



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.

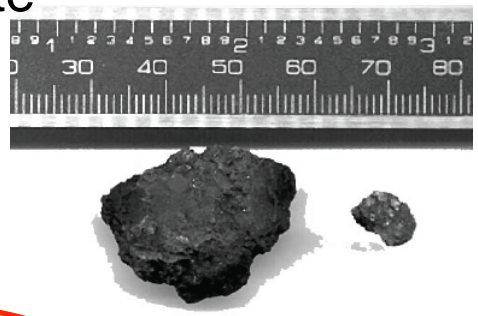
Bulk Silicate Earth (BSE) model

chondrite meteorite

U : 8 TW

Th : 8 TW

K : 4TW



Direct measurement can answer this question.

Geo neutrino directly tests radiogenic heat production.

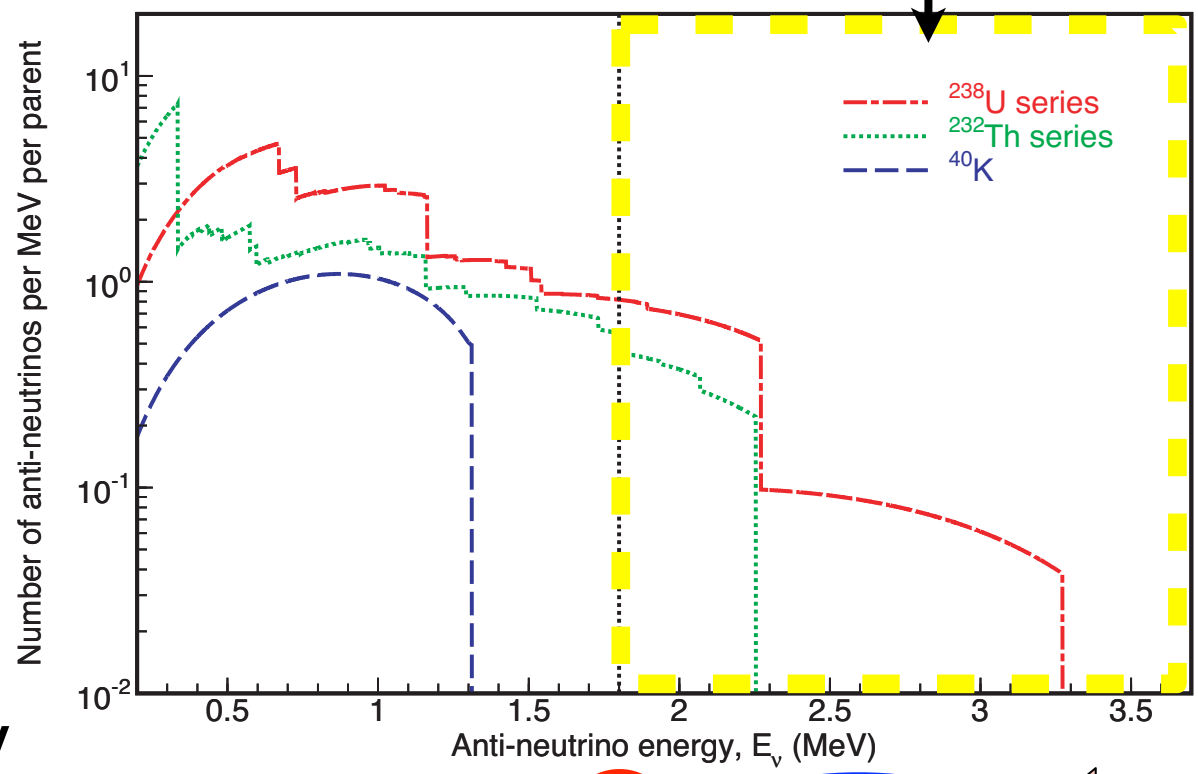
Geo Neutrino

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

- calculation of geo antineutrino energy spectrum

Nature 436, 28 July 2005

KamLAND energy window



beta-decay

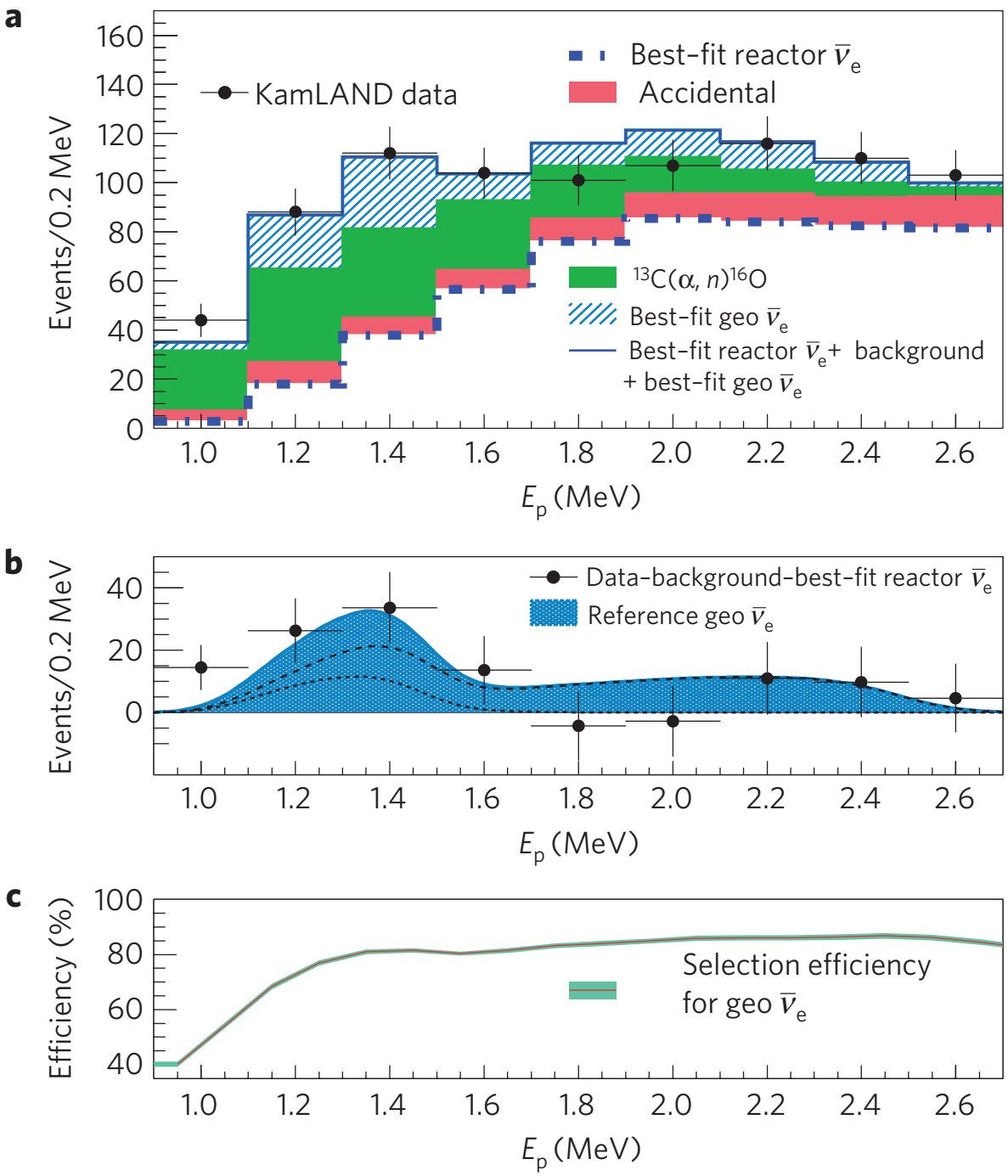
$$^{238}\mathrm{U} \rightarrow ^{206}\mathrm{Pb} + 8\alpha + 6\mathrm{e}^- + 6\bar{\nu}_\mathrm{e} + 51.7\,\mathrm{MeV}$$

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

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

KamLAND can detect !

Analysis - Observed Energy Spectrum (0.9-2.6 MeV)

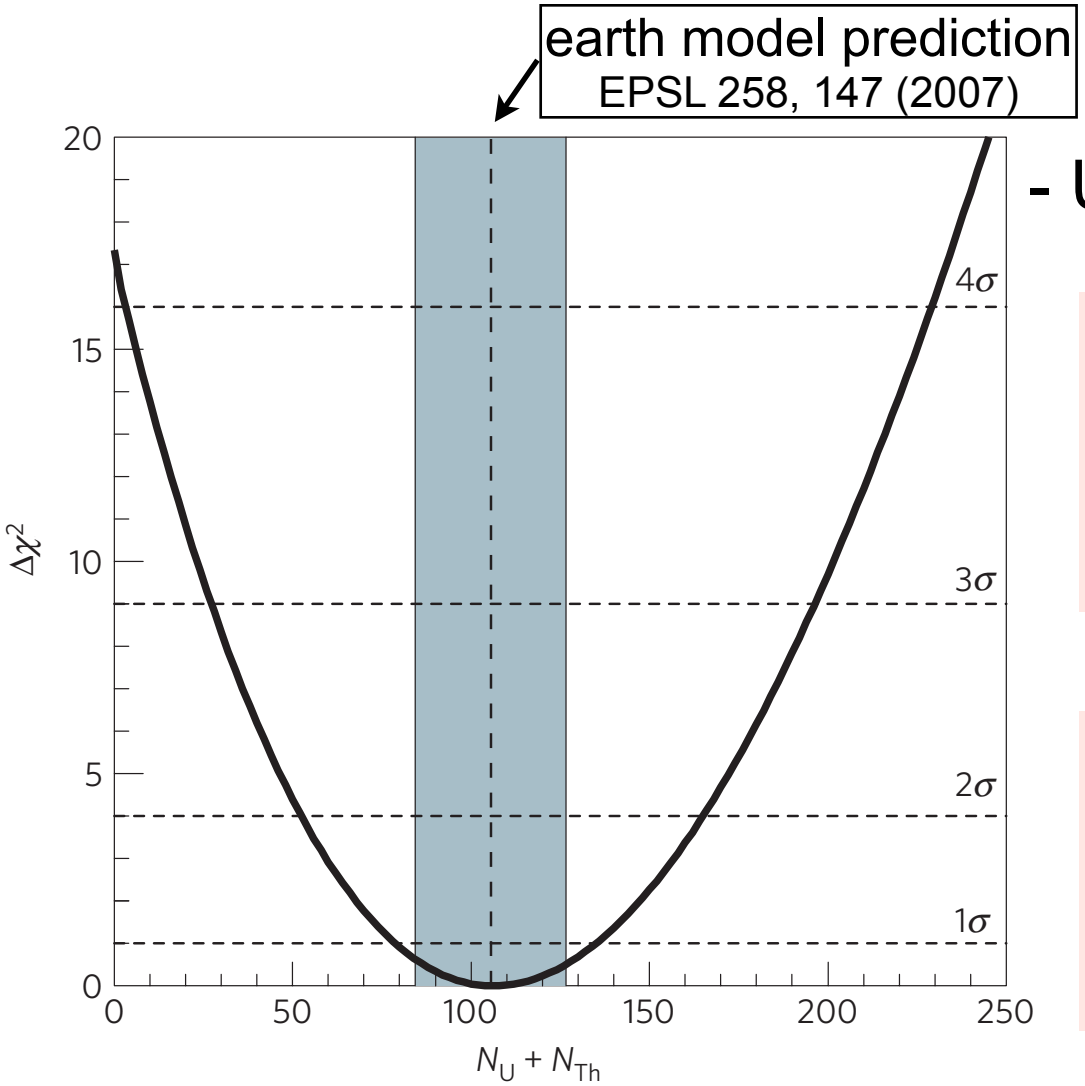


- exposure : 4126 ton-year
  (4.9 times larger the 2005 result)
- result

candidate	841
^{9}Li	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



- 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

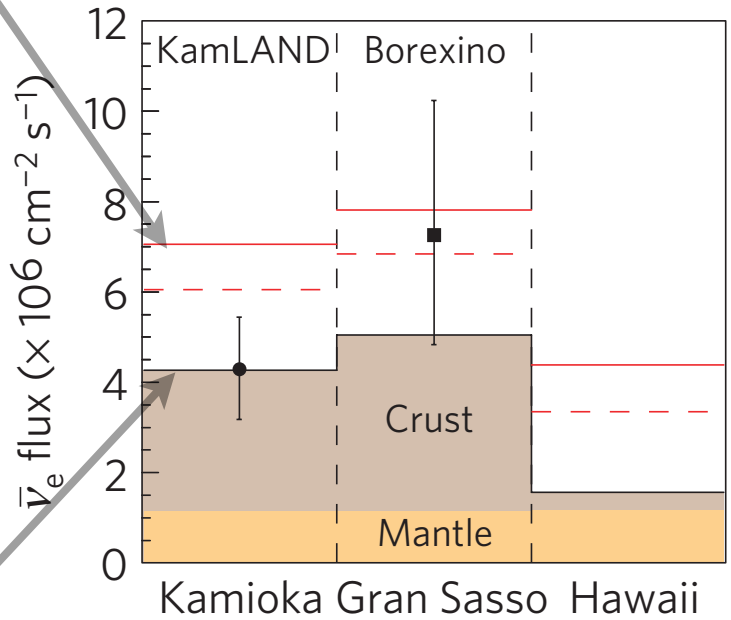
uniform mantle
mantle bottom only

earth model prediction
EPSL 258, 147 (2007)

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

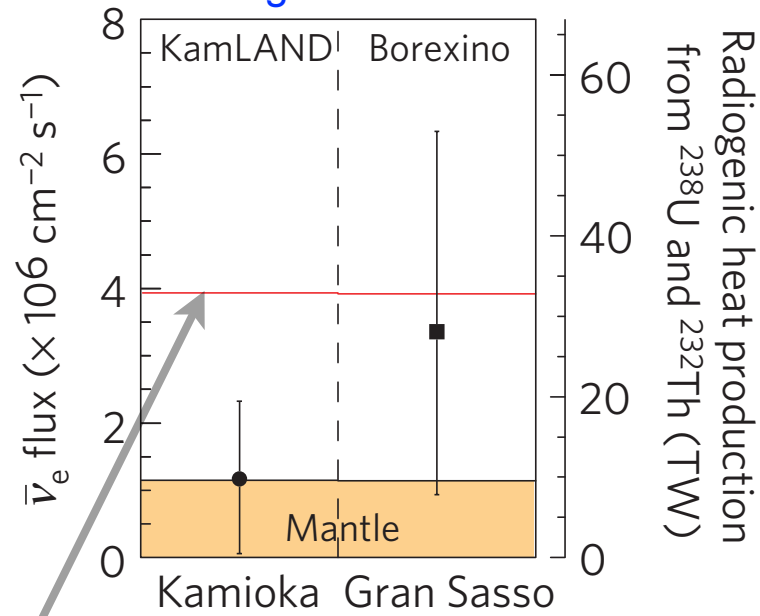
※ assume homogeneous mantle

Mantle+Crust



Mantle

No modelling uncertainties are shown.



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

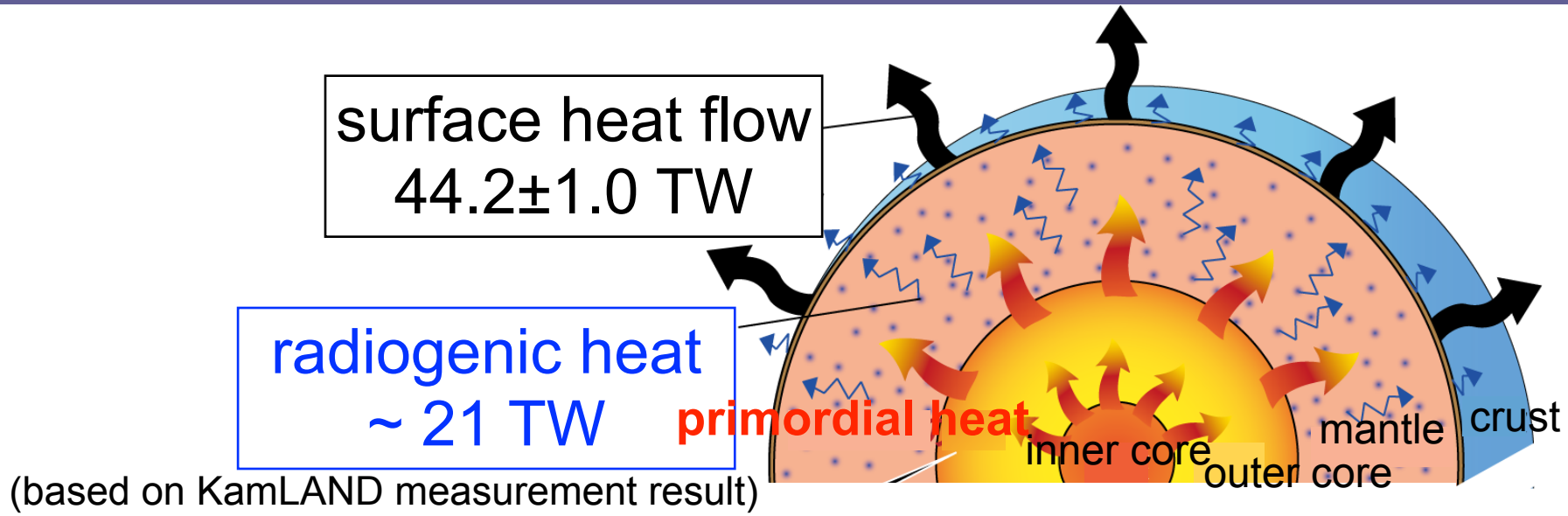
✓The observed flux is consistent with the 20 TW model

^{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

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.

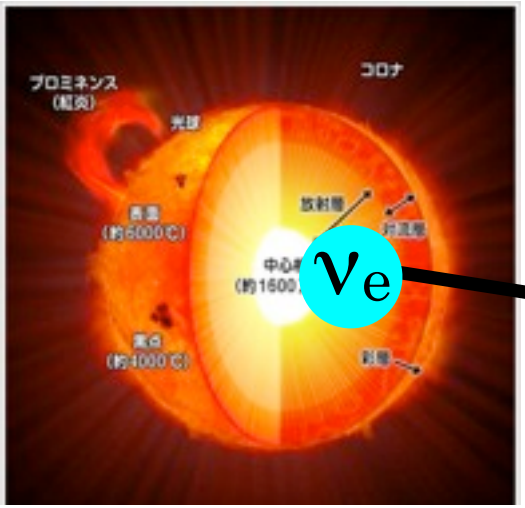
Contents

A study of extraterrestrial antineutrino sources with the KamLAND detector
astro-ph.HE/1105.3516 (2011)

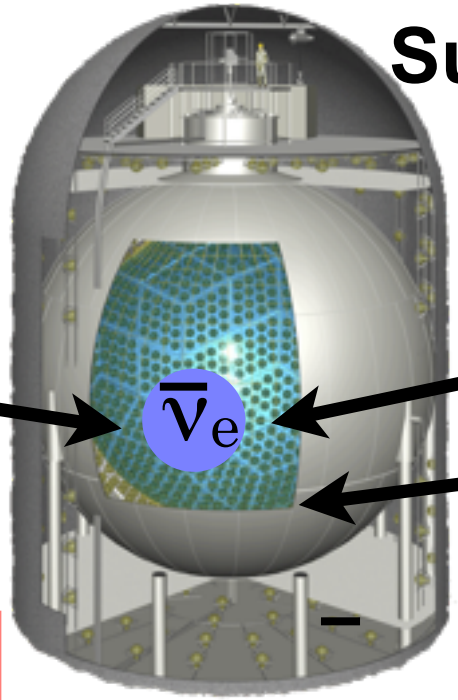
Extraterrestrial Antineutrino

- motivation @ higher reactor antineutrino (8~15 MeV)
  - diffuse supernova
  - exotic generation mechanism
    (e.g. solar antineutrino, light dark matter annihilation)

Solar Antineutrino

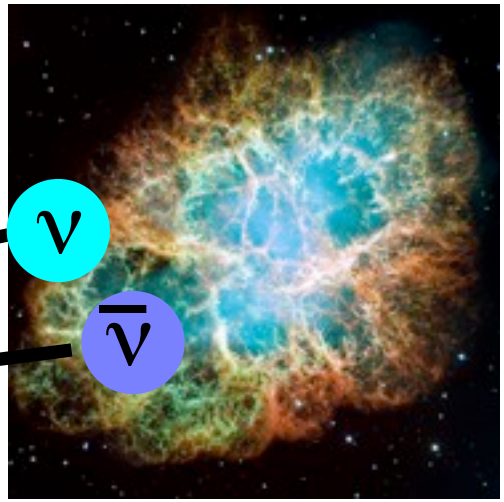


ν_e



$\bar{\nu}_e$

Supernova Antineutrino



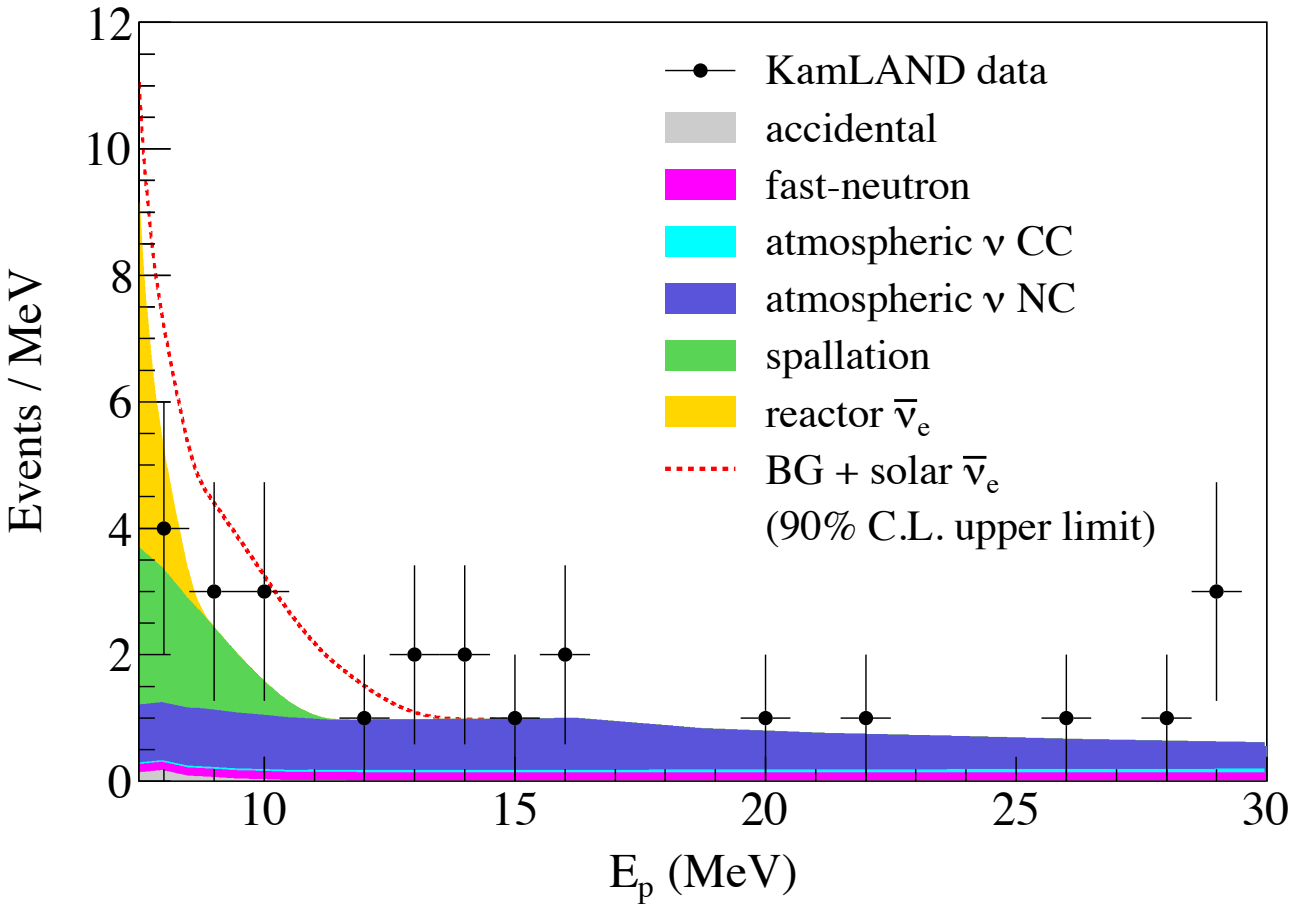
ν

$\bar{\nu}$

- neutrino has a non-zero magnetic moment
- strong solar magnetic field

KamLAND motivation : search lower energy than other experiment. (SK, Borexino, SNO...)

Analysis - Event Distribution (7.5-30 MeV)



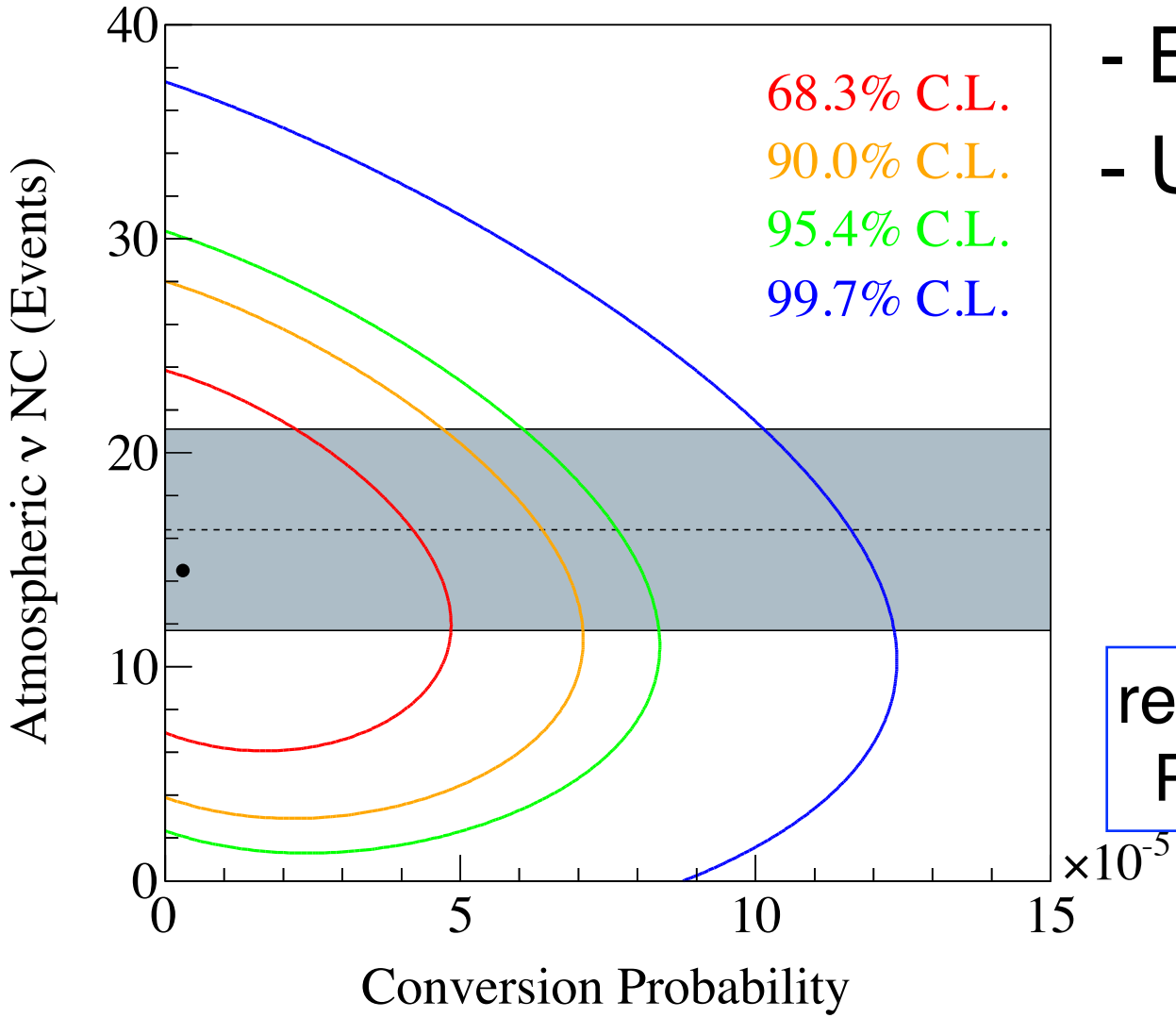
- exposure : 4.53 kt-year
(16times larger than 2005 result)

- result

Observed	25
Random coincidence	0.22 ± 0.01
Reactor ν_e	2.2 ± 0.7
^{9}Li	4.0 ± 0.3
Atmospheric ν (CC)	0.9 ± 0.2
Atmospheric ν (NC)	16.4 ± 4.7
Fast-neutron	3.2 ± 3.2
Total BG	26.9 ± 3.2

All of the candidate events can be attributed to background.

Analysis - Conversion Provability



- $E_{\bar{\nu}_e} \geqq$ 8.3 MeV
- Upper Limit :

$P(\nu_e \rightarrow \bar{\nu}_e) < 5.3\times10^{-5}$

(90% C.L.)

$\Phi(\bar{\nu}_e) < 93\ cm^{-2}s^{-1}$

factor 2.5 improvement

ref) previous limit

$P(\nu_e \rightarrow \bar{\nu}_e) < 1.3\times10^{-4}$(90% C.L.)

(Borexino, Bellini et al.Phys. Lett. B 696, p. 191-196, 2011)

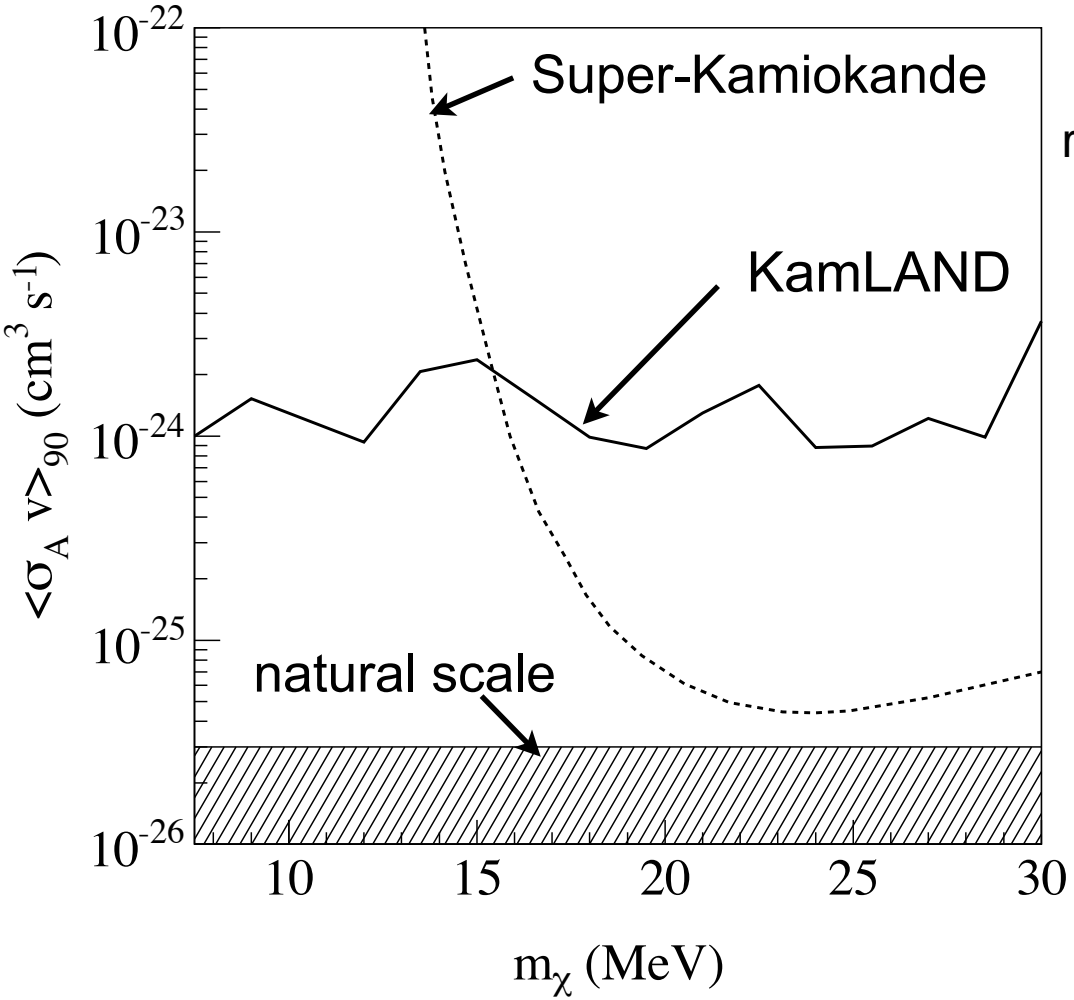
NC : assuming zero solar $\bar{\nu}_e$

$14.8^{+5.8}_{-5.4}$ ev ← good agree with calculation (16.4 ± 4.7 ev)

Analysis - Upper Limit (1)

The upper limit for the monochromatic $\overline{\nu}_e$ flux at each energy can be translated to a limit for the dark matter annihilation cross section (Palomares-Ruiz & Pascoli 2008).

- dark matter annihilation cross section (90% C.L.)

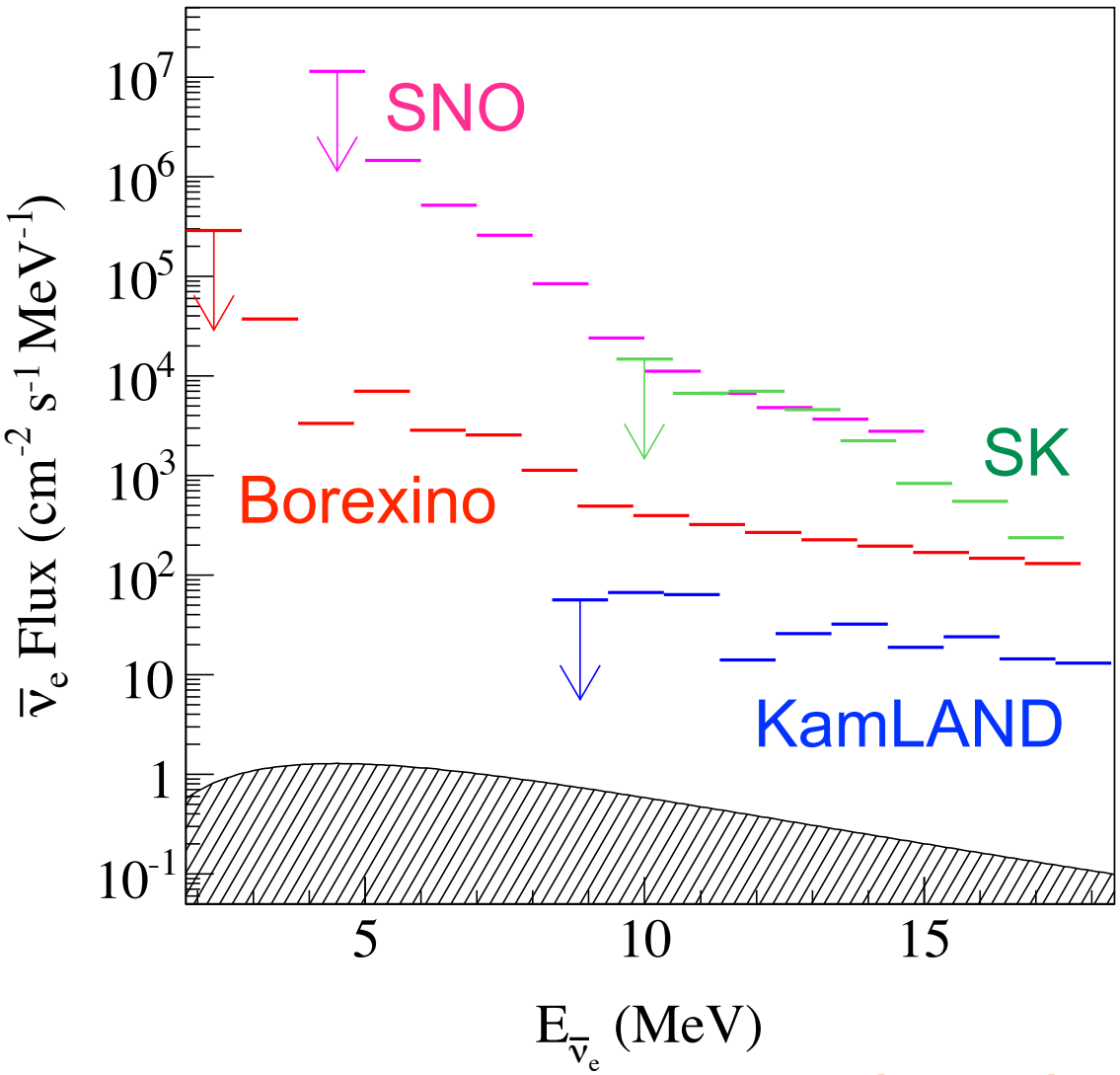


ref) SK : Palomares-Ruiz, S., & Pascoli, S. 2008, Phys. Rev. D, 77, 025025

most stringent limit below 15 MeV

Analysis - Upper Limit (2)

- $\bar{\nu}_e$ flux model independent upper limit (90% C.L.)



ref)

Borexino : Bellini, G., et al. 2011, Phys. Lett. B, 696, 191

SNO : Aharmim, B., et al. 2004, Phys. Rev. D, 70, 093014

SK : Gando, Y., et al. 2003, Phys. Rev. Lett., 90, 171302

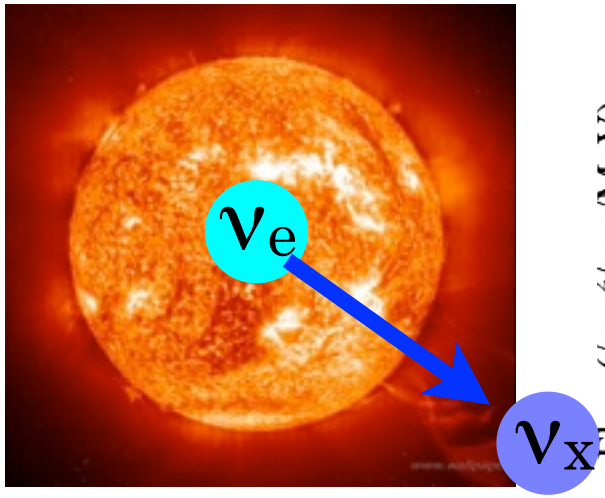
shaded curve : diffuse supernova flux for the reference model prediction (Ando, S., & Sato, K. 2004, New J. Phys., 6)

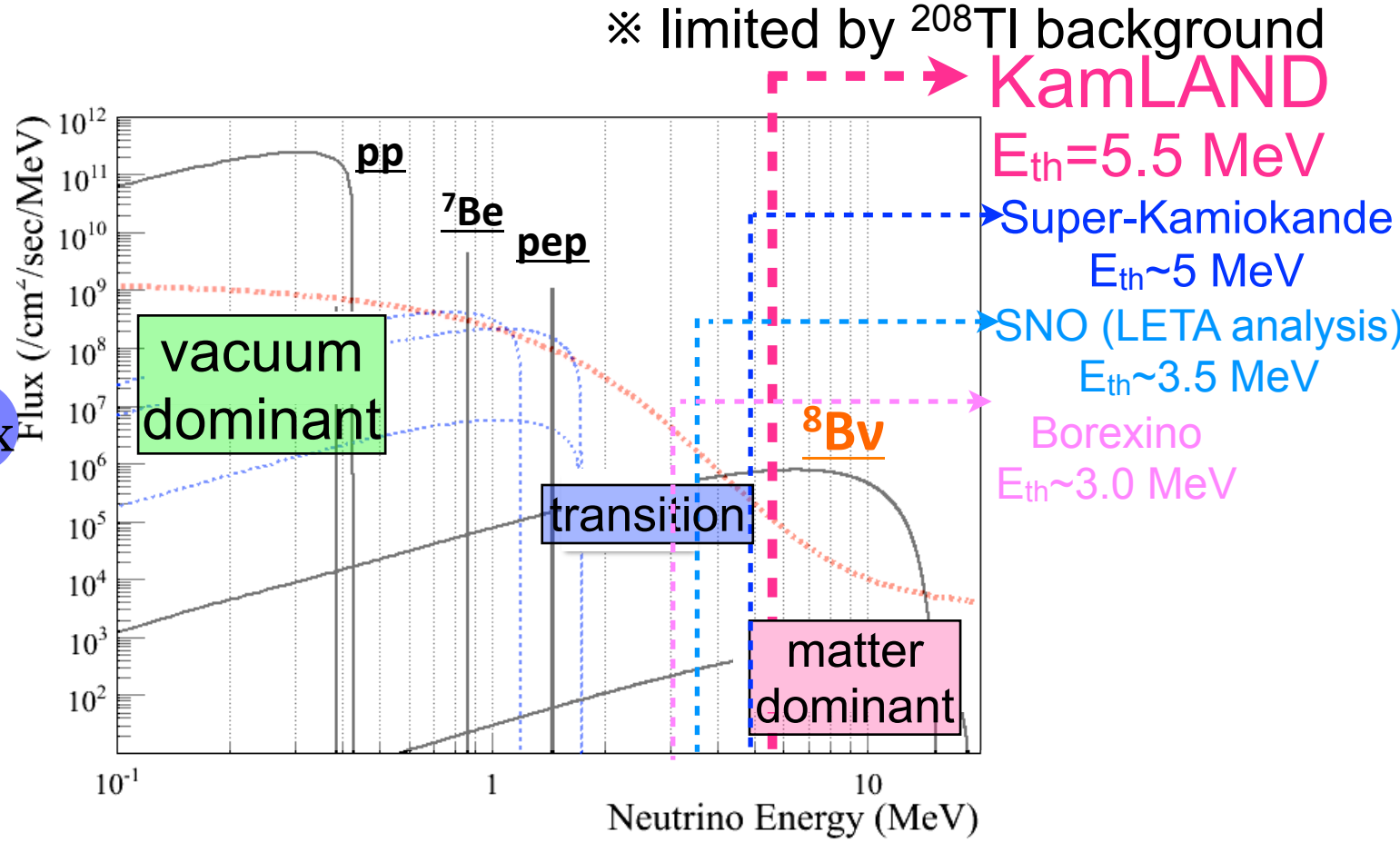
best limit in 8.3 MeV < $E_{\bar{\nu}_e}$ < 18.3 MeV

Contents

Measurement of the ^{8}B Solar Neutrino Flux with the KamLAND Liquid Scintillator Detector
hep-ex/1106.0861 (2011)

▸^{8}B Solar Neutrino

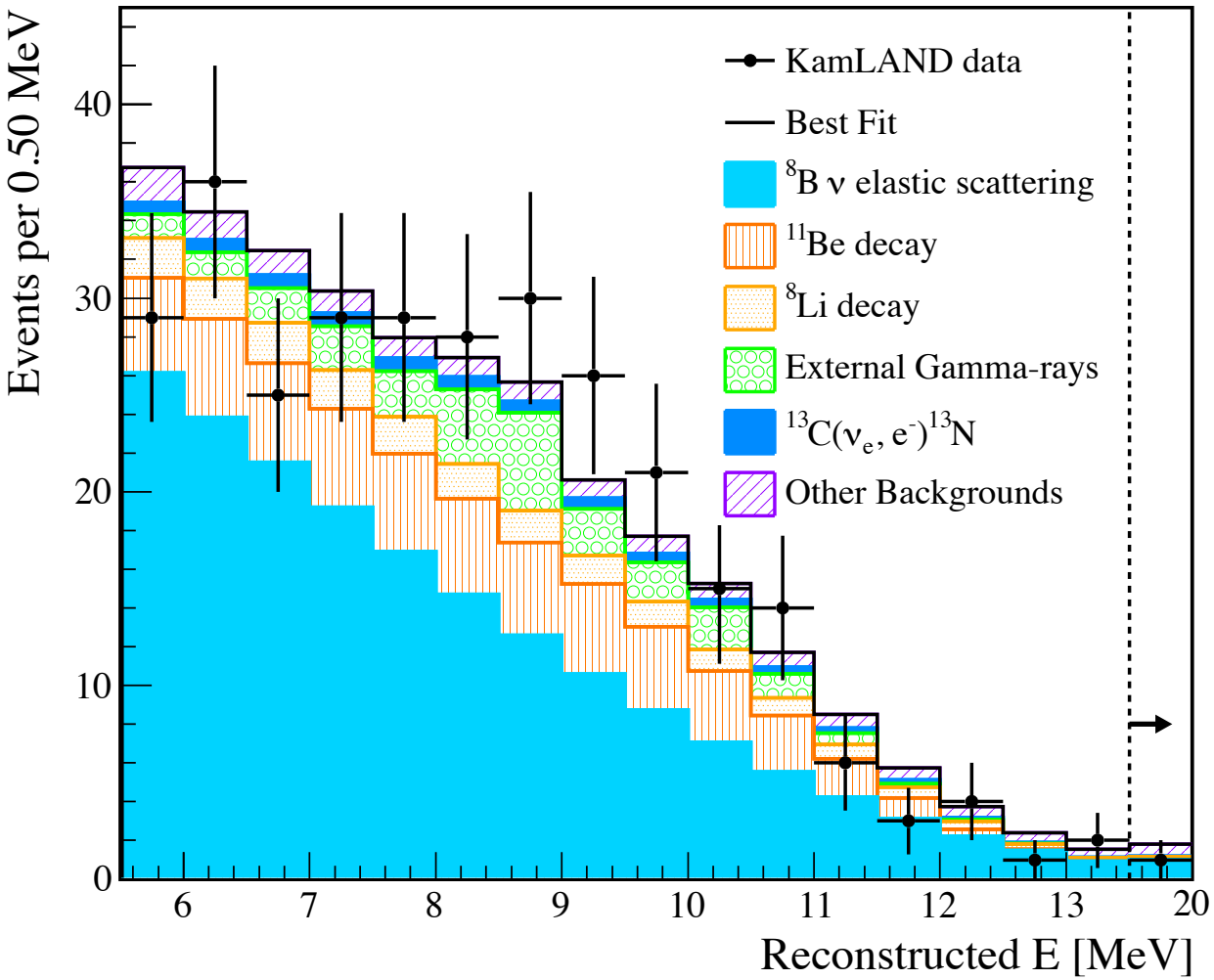




^{8}B beta-decay (Q~18MeV) dominate the high-energy portion of the solar neutrino spectrum.

It has established flavor change through Large Mixing Angle neutrino-oscillation with matter effect (MSW effect).

Analysis - Energy Spectrum (5.5-20 MeV)



- exposure : 123 t-year

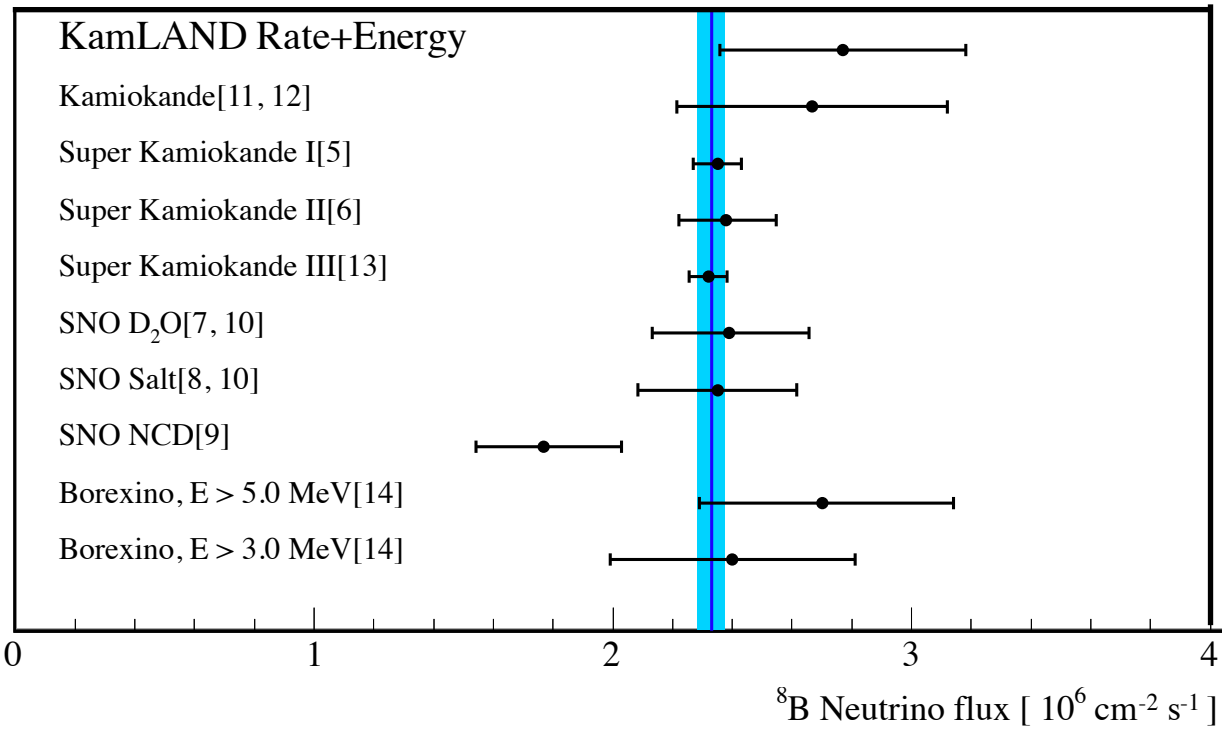
- result

Background	Counts
Spallation ^{11}Be	89.1 ± 19.1
Spallation ^{8}Li	20.5 ± 4.0
Spallation ^{8}B	11.0 ± 3.0
Spallation Other	0.4 ± 0.6
External gamma rays	25.2 ± 12.6
^{8}B CC on ^{13}C GND	5.8 ± 1.4
Reactor $\overline{\nu}_e$	1.6 ± 0.1
^{8}B CC on ^{13}C 3.51 MeV	1.1 ± 0.4
hep ES	0.6 ± 0.1
Atmospheric ν	2.0 ± 2.0
Total	157.3 ± 23.6

best fit rate : 1.49±0.14(stat)±0.17(syst) ev/kt-day (goodness-of-fit of 49%)

ϕ_{ES} = 2.77 ± 0.26 (stat) ± 0.32 (syst) × 10^6 cm^{-2} s^{-1}

Analysis - Summary of ^{8}B Flux Measurement



mean : ϕ_{ES} = 2.33 ± 0.05 × 10^6 cm^{-2} s^{-1}

※ weighted by experiment's uncertainties
(dominated by very precise SK measurement)

The measured rate is consistent with existing measurements and with Standard Solar Model predictions which include matter enhanced neutrino oscillation.

Contents

Summary

- The KamLAND experiment has many scientific results of low energy neutrino physics.

thanks to low non-ν background after pur. and low reactor neutrino flux
(After 3.11 earthquake, we continue to take lower reactor b.g. data.)

- Anti-neutrino
  - Reactor Neutrino
    Clear evidence of neutrino oscillation
  - Geo Neutrino
    Neutrino measurement starts to examine Earth model
    KamLAND firstly shows such result
  - Supernova Neutrino
    In the lower energy region, most stringent limits are presented
  - Solar Neutrino
    ^{8}B solar neutrino rate is consistent with existing measurements

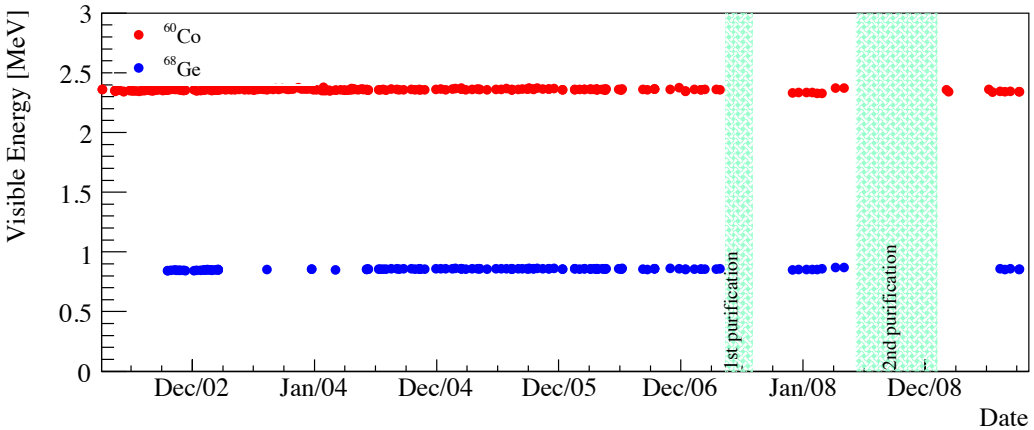
Current Status

We are almost finished preparations for KamLAND-Zen, aiming at the effective mass below 100 meV. (A.Kozlov talk)

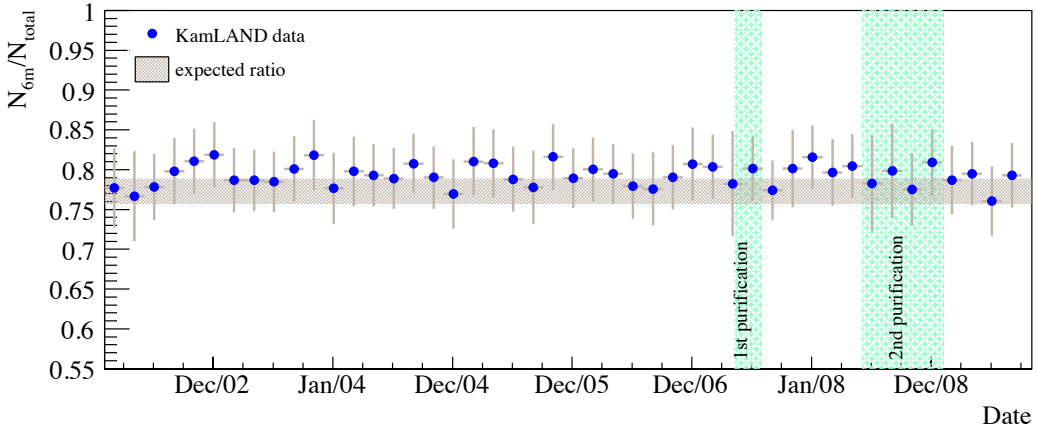
Backup

Stability of Event Reconstruction

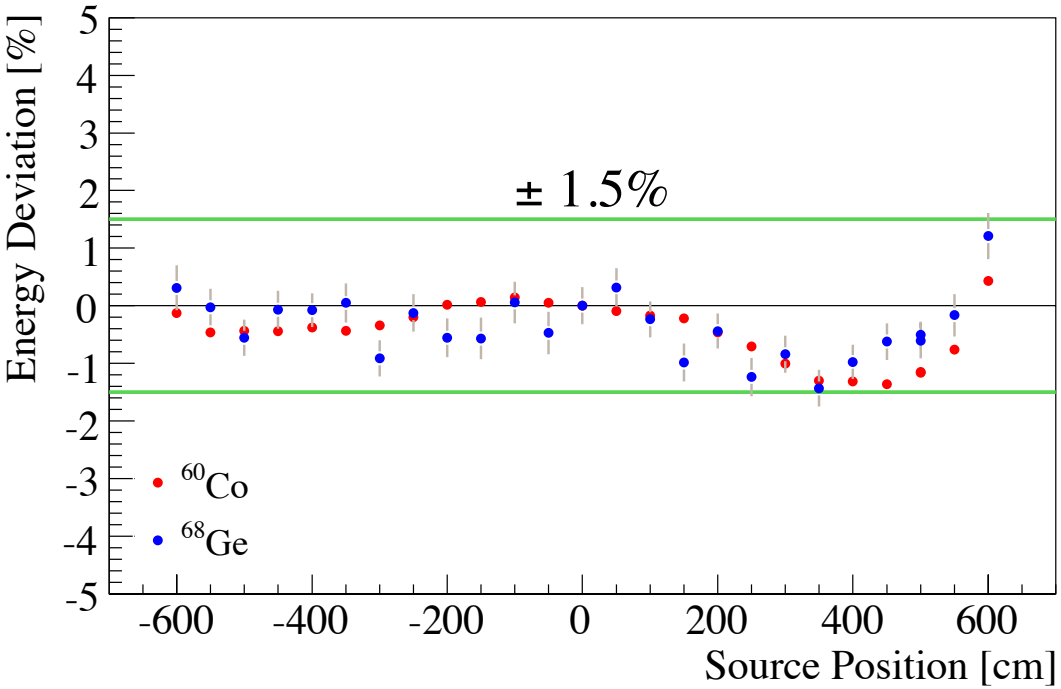
^{68}Ge/^{60}Co Energy time variation



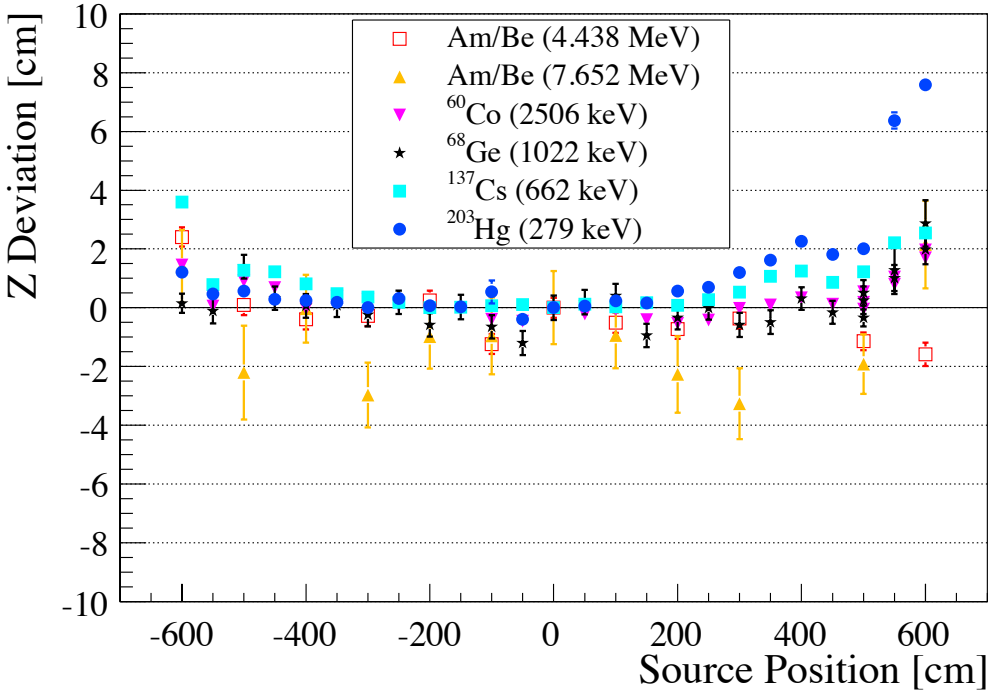
^{12}B N_{6m}/N_{all} time variation



^{68}Ge/^{60}Co Energy z-position variation

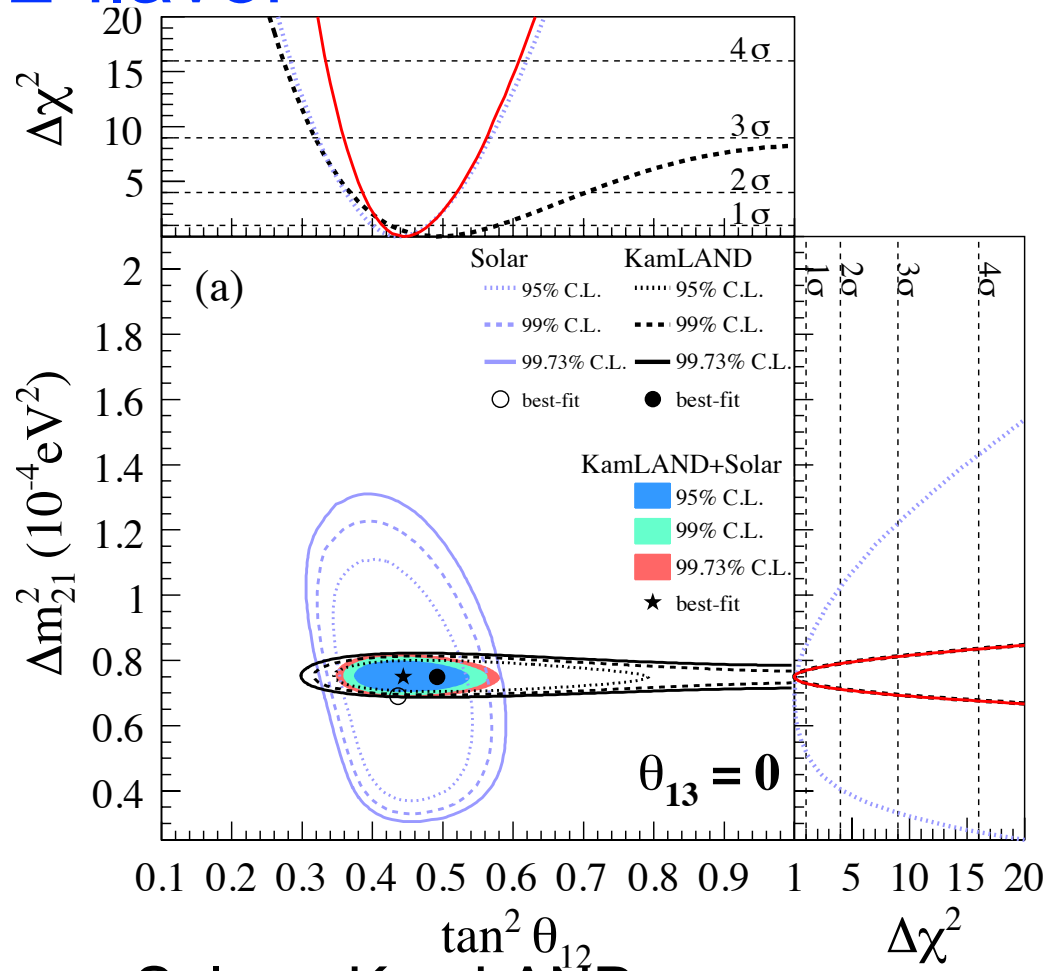


source z-position variation



Reactor Neutrino - Oscillation Parameters

2-flavor

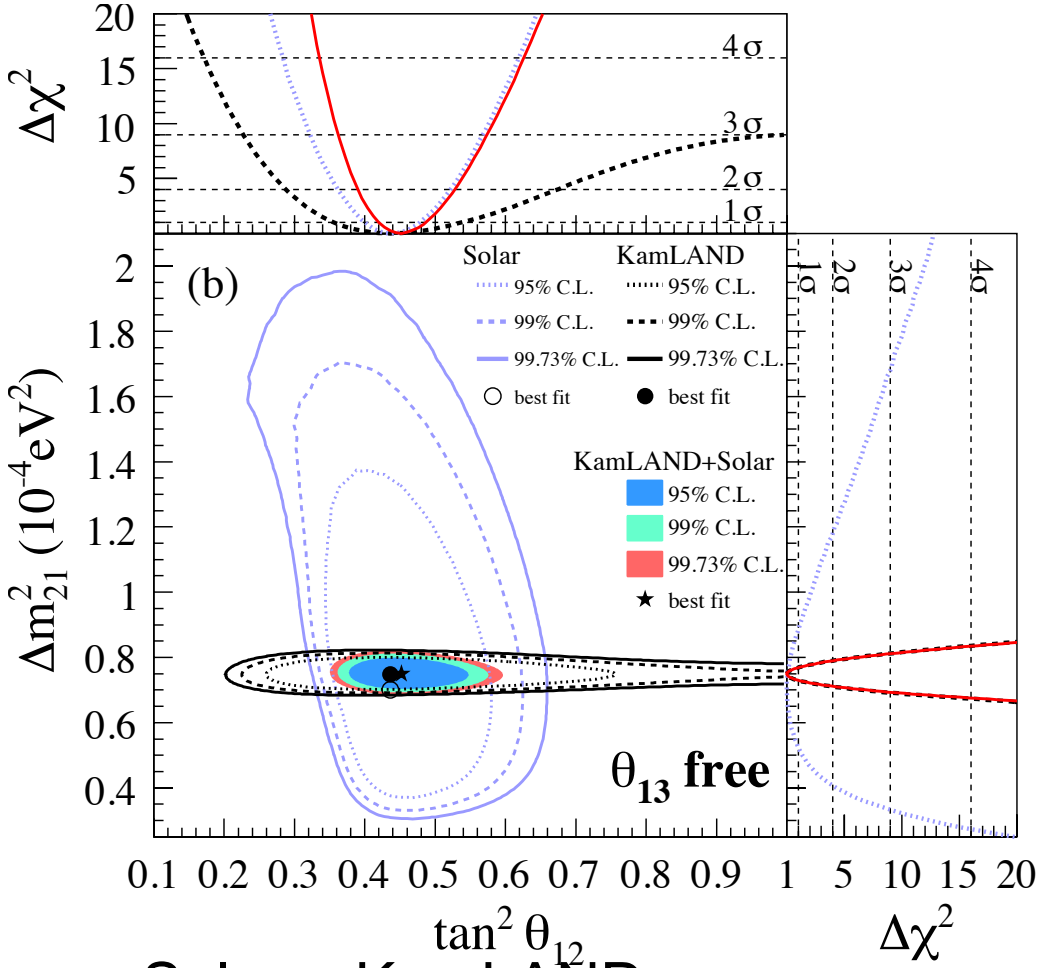


Solar + KamLAND

$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.444^{+0.036}_{-0.030}$$

3-flavor



Solar + KamLAND

$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.452^{+0.035}_{-0.033}$$

$$\sin^2\theta_{13} = 0.020^{+0.016}_{-0.016}$$

Reactor Neutirno - Oscillation Parameters

3-flavor oscillation analysis

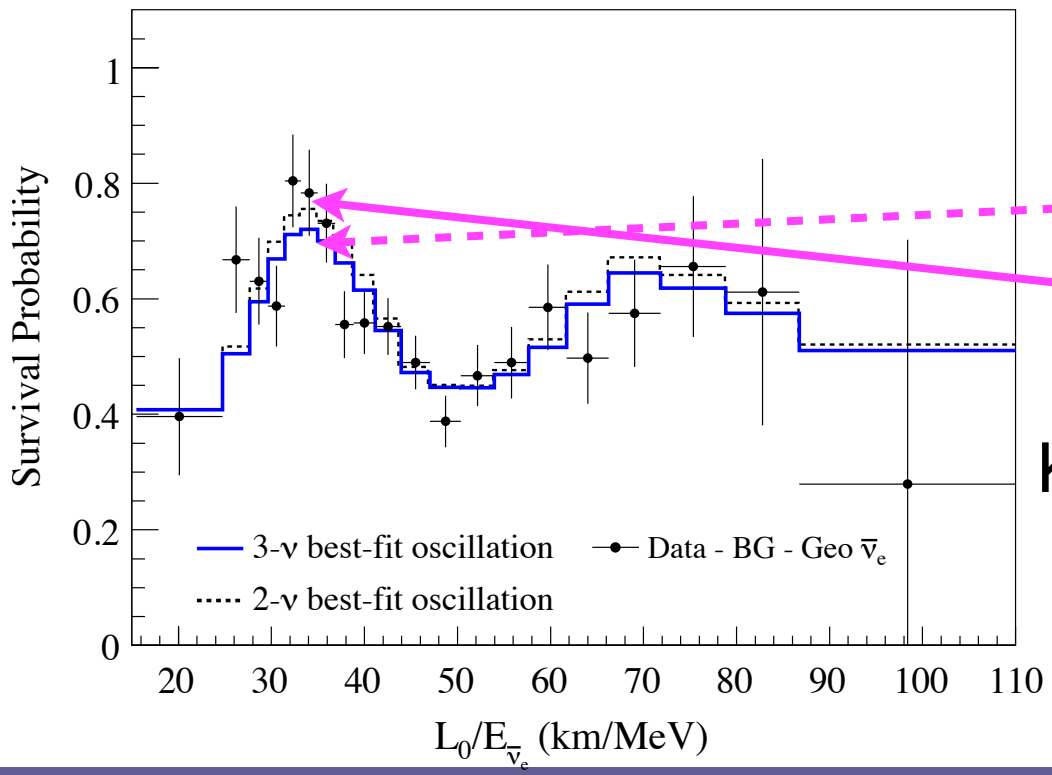
survival probability

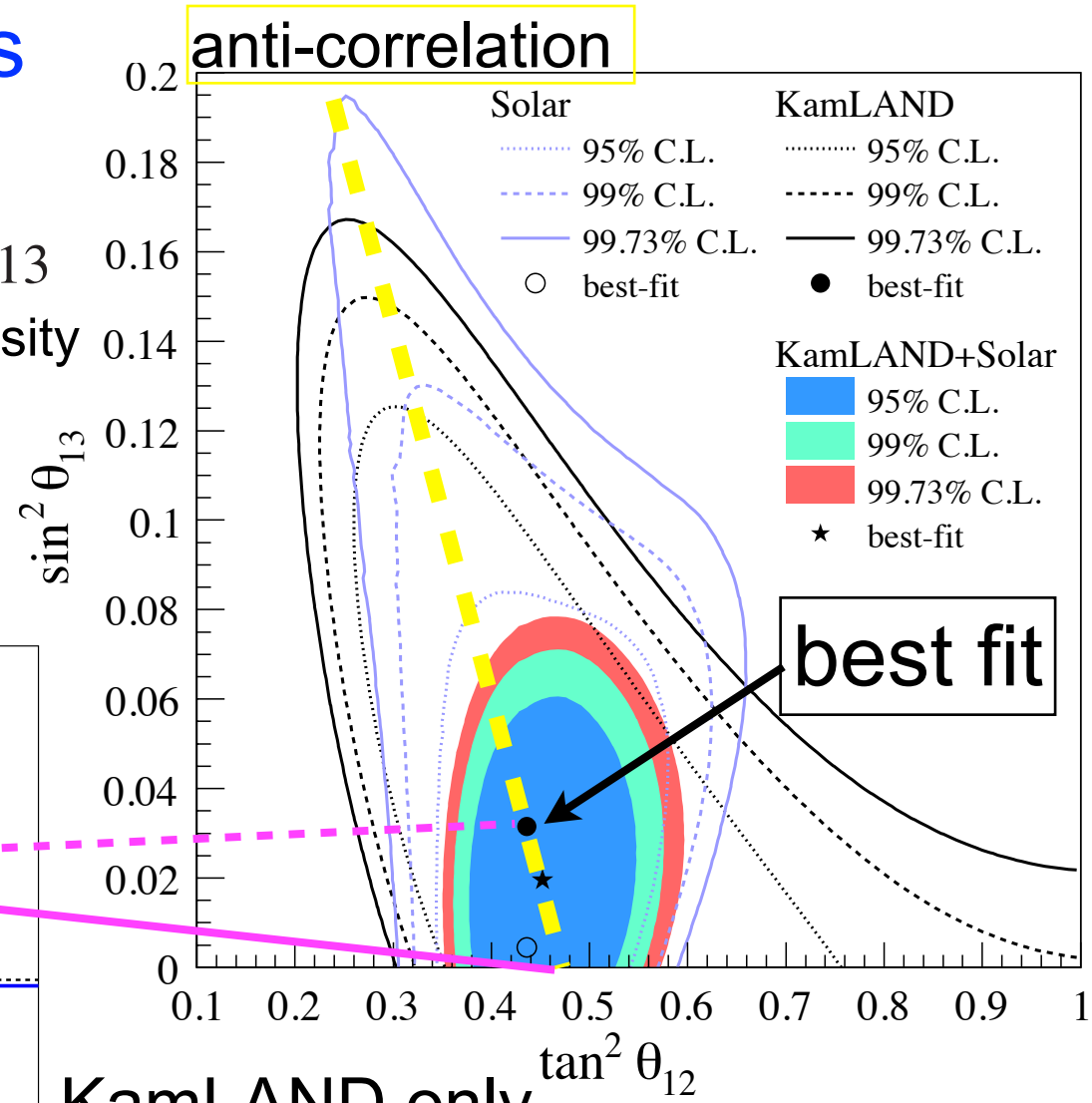
$$P_{ee}^{3\nu} = \cos^4\theta_{13}\tilde{P}_{ee}^{2\nu} + \sin^4\theta_{13}$$

electron density

matter effect $\tilde{N}_e = N_e \cos^2\theta_{13}$

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





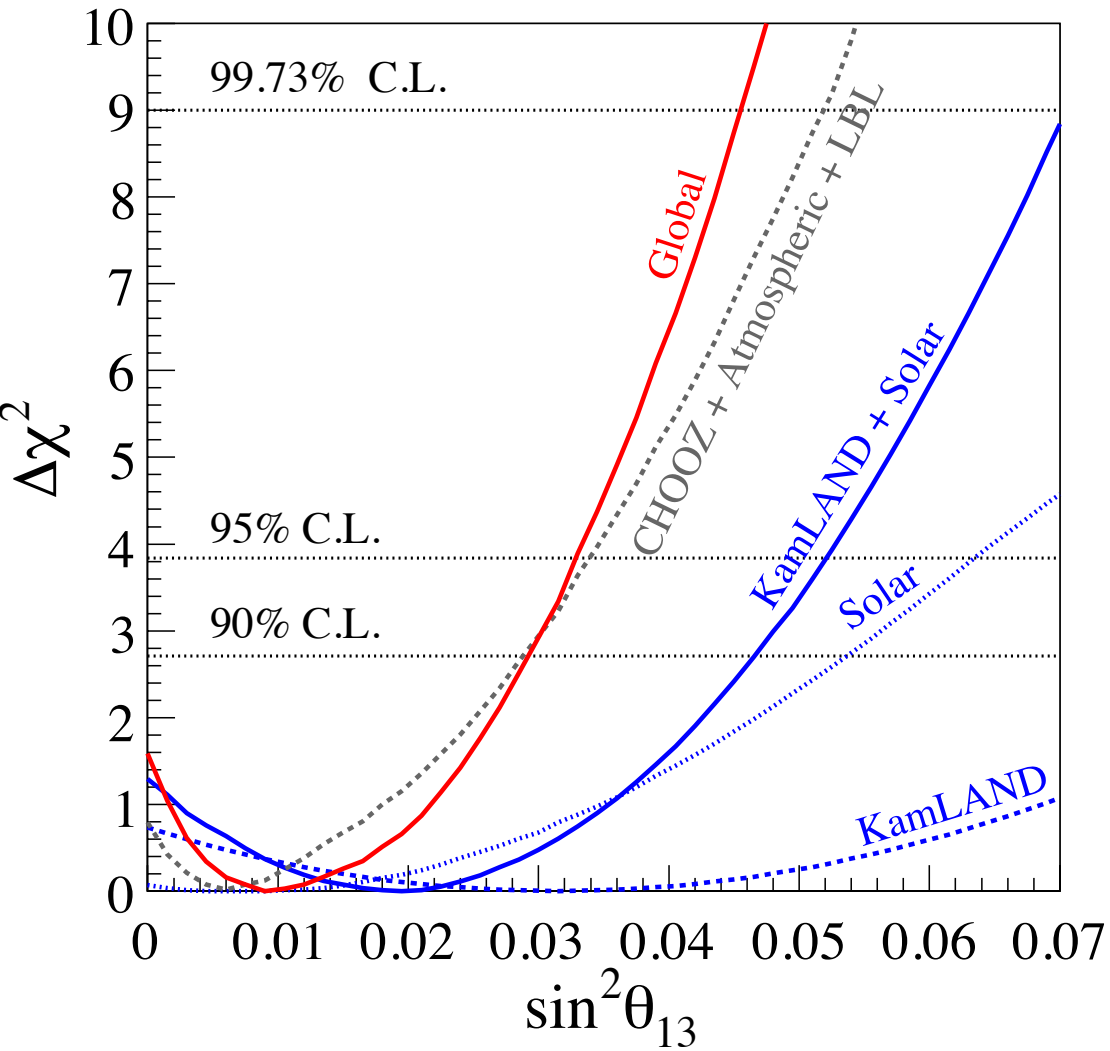
KamLAND only

$$\Delta m^2_{21} = 7.49^{+0.20}_{-0.20} \times 10^{-5}\mathrm{eV}^2$$

$$\tan^2\theta_{12} = 0.436^{+0.102}_{-0.081}$$

$$\sin^2\theta_{13} = 0.032^{+0.037}_{-0.037}$$

Reactor Neutrino - Global Analysis



Solar

- rate : Chlorine and Gallium experiments, Borexino, SNO III
- zenith spectra : Super-Kamiokande phase I
- day-night spectra : SNO phase I and II (low threshold analysis)

LBL (appearance + disappearance)

ref) M. Gonzalez-Garcia, et al. arXiv:1001.4524v3 include MINOS electron neutrino appearance result (Phys. Rev. D 82, 051102)

best-fit : $\sin^2\theta_{13} = 0.009^{+0.013}_{-0.007}$

nonzero θ_{13} : 79% C.L.