KamLAND Results

Neutrino Oscillation Workshop

Sep. 8, 2008

I. Shimizu (Tohoku Univ.)

KamLAND Collaboration

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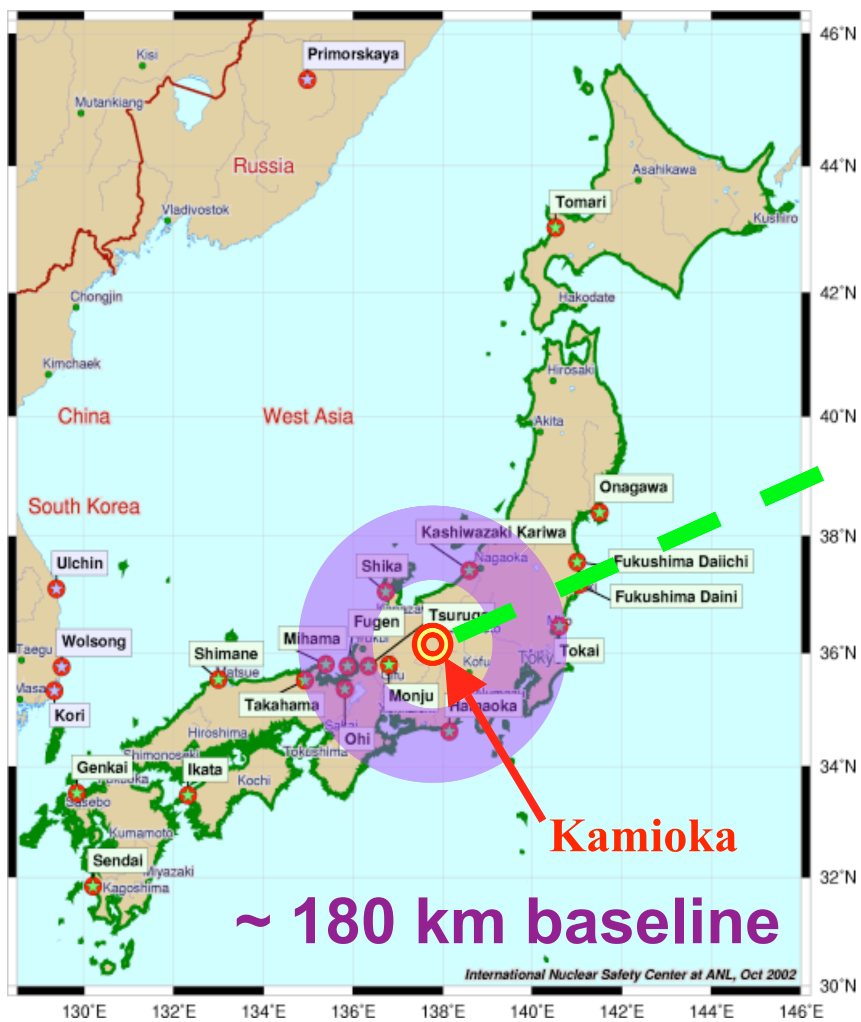
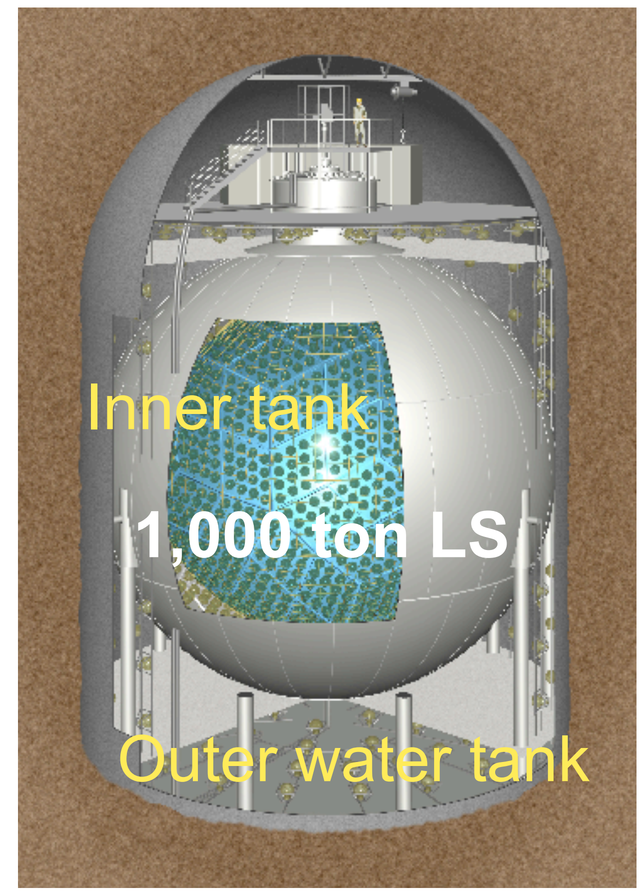
Reactor Neutrino

KamLAND

Kamioka Liquid Scintillator Anti-Neutrino Detector





34% photo-coverage with
1325 17” and 554 20” PMTs

2 flavor neutrino oscillation

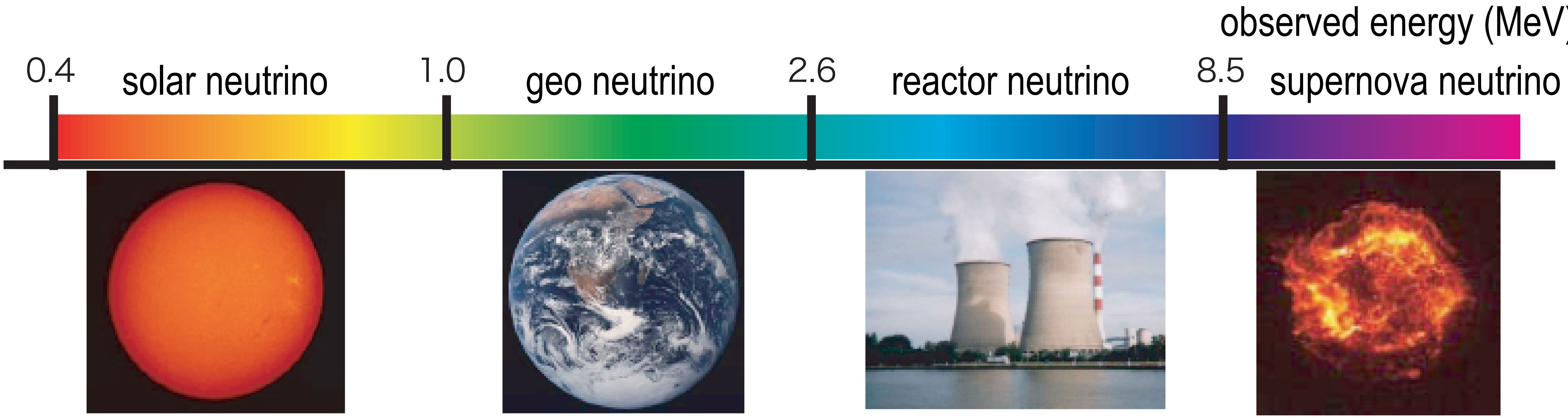
$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2]l[m]}{E[\mathrm{MeV}]}\right)$$

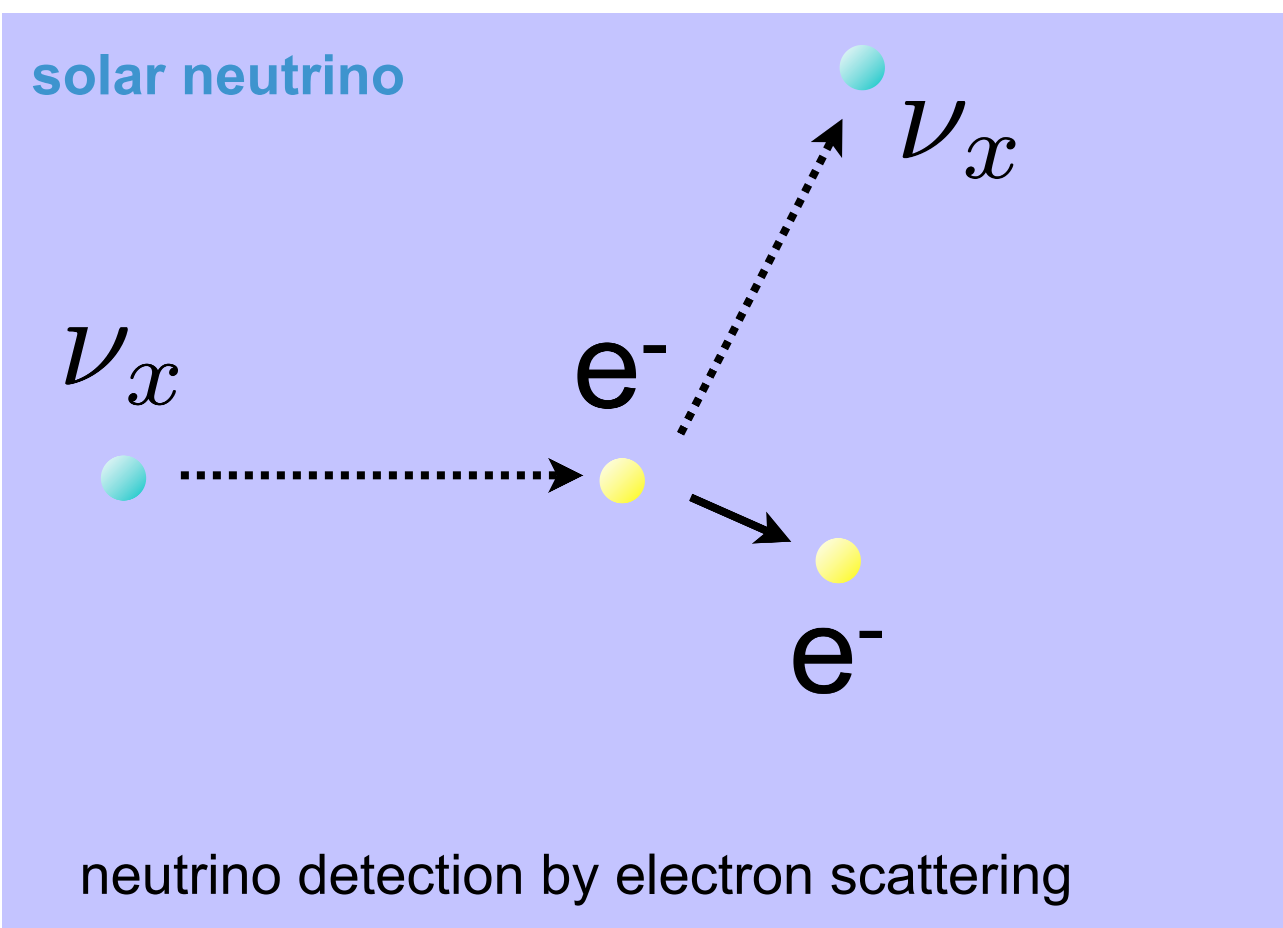
most sensitive region

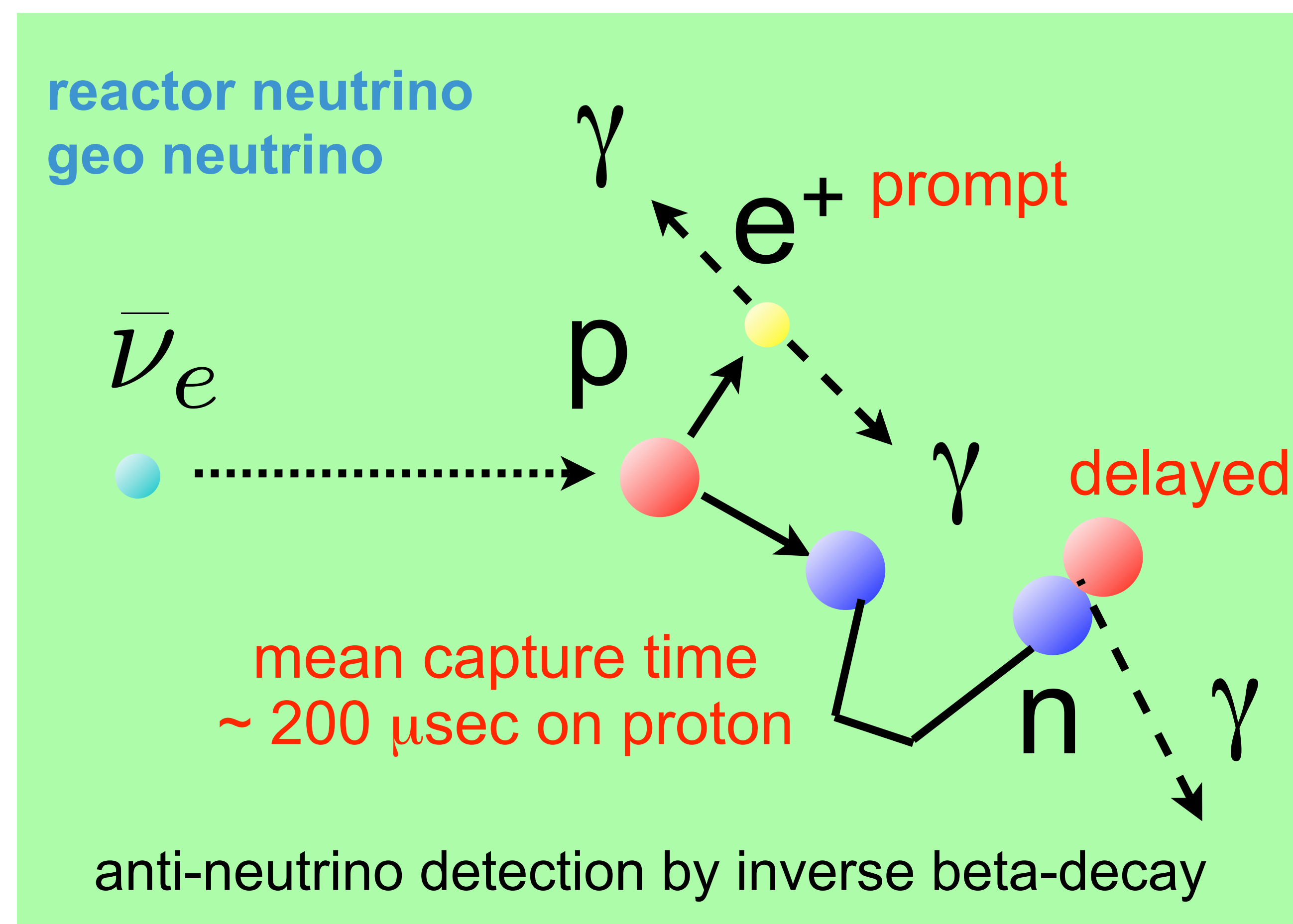
$$\Delta m^2 = (1/1.27)\cdot(E[\mathrm{MeV}]/L[m])\cdot(\pi/2)$$
$$\sim 3\times 10^{-5}\mathrm{eV}^2$$

reactor neutrino : sensitive to LMA solution

Physics Target in KamLAND







Reactor and Geo Neutrino Analysis

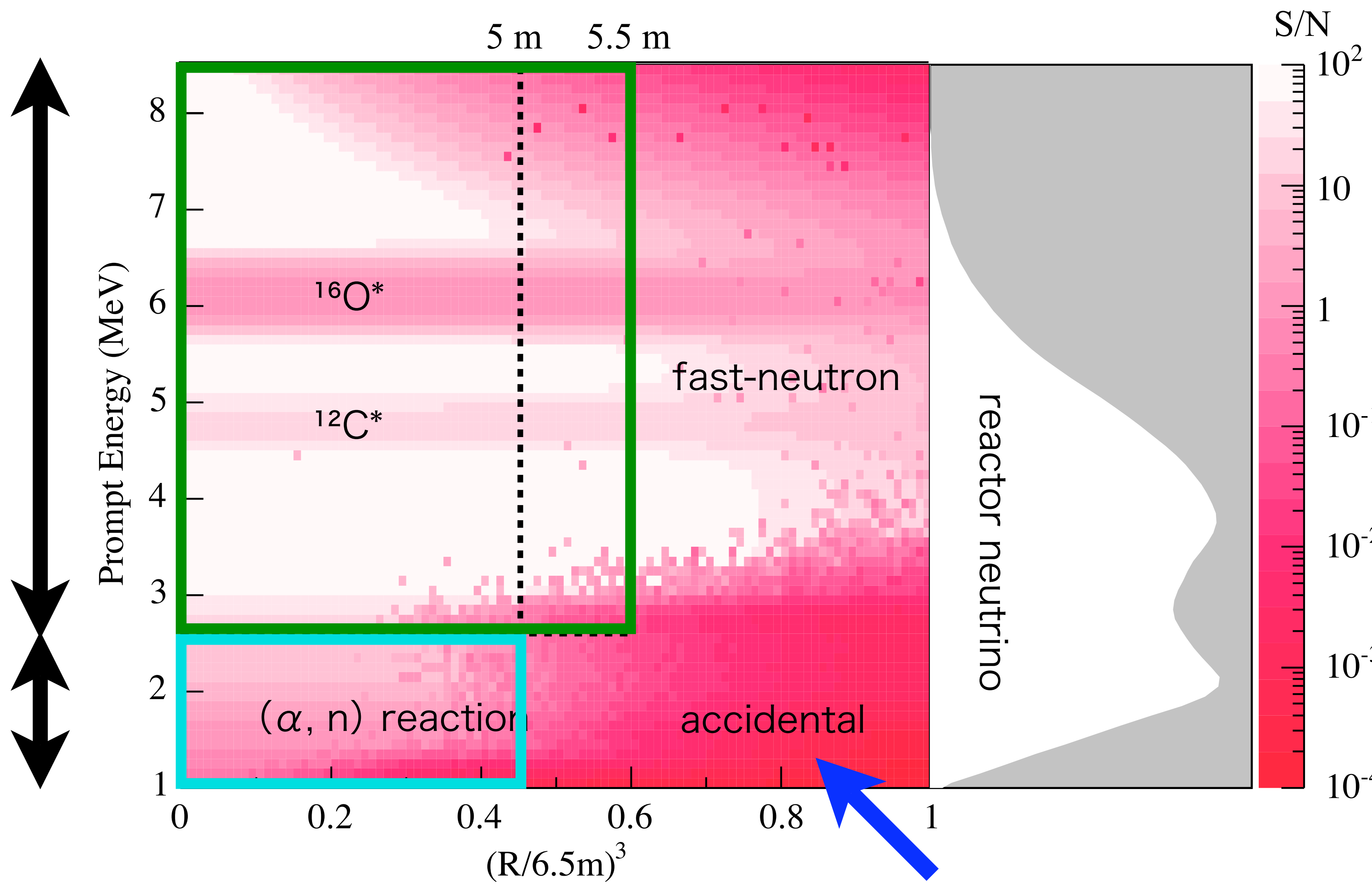
previous result

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

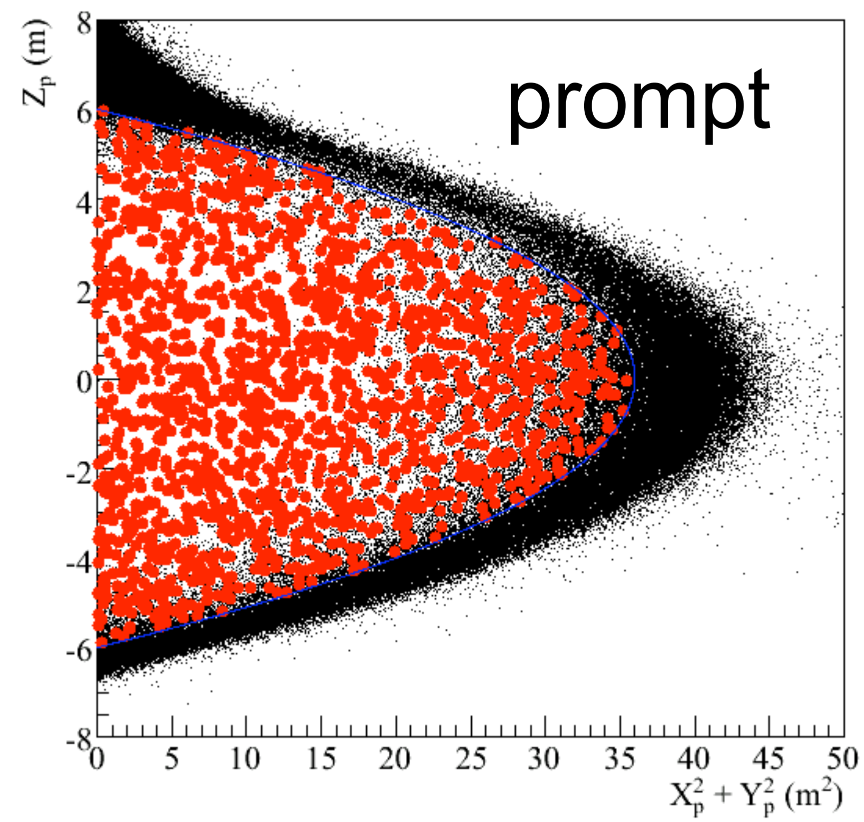
- $0.5 < \Delta T < 1000$ μs
- $\Delta R < 2$ m
- 1.8 MeV $< E_{delayed} <$ 2.6 MeV or

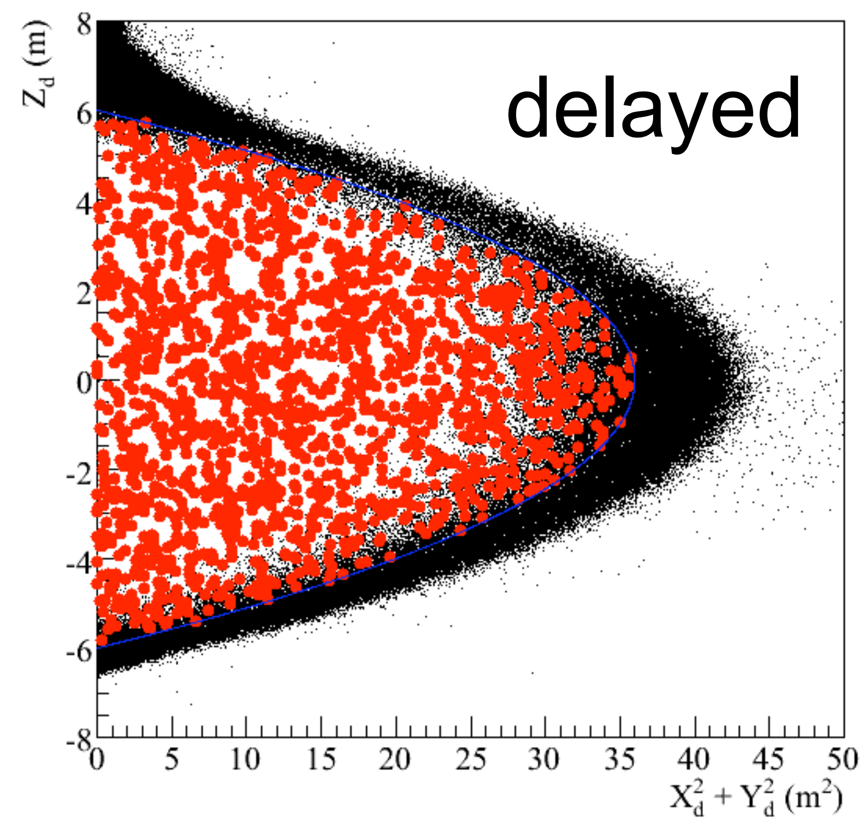
  4.0 MeV $< E_{delayed} <$ 5.8 MeV
- 0.9 MeV $< E_{prompt} <$ 8.5 MeV
- R_{prompt}, $R_{delayed} < 6.0$ m
- L-selection from 6 parameters

(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.)





Likelihood Selection

L-selection for accidental B.G. discrimination

Accidentals PDF $f_{acc}(E_p, E_d, \Delta R, \Delta T, R_p, R_d)$

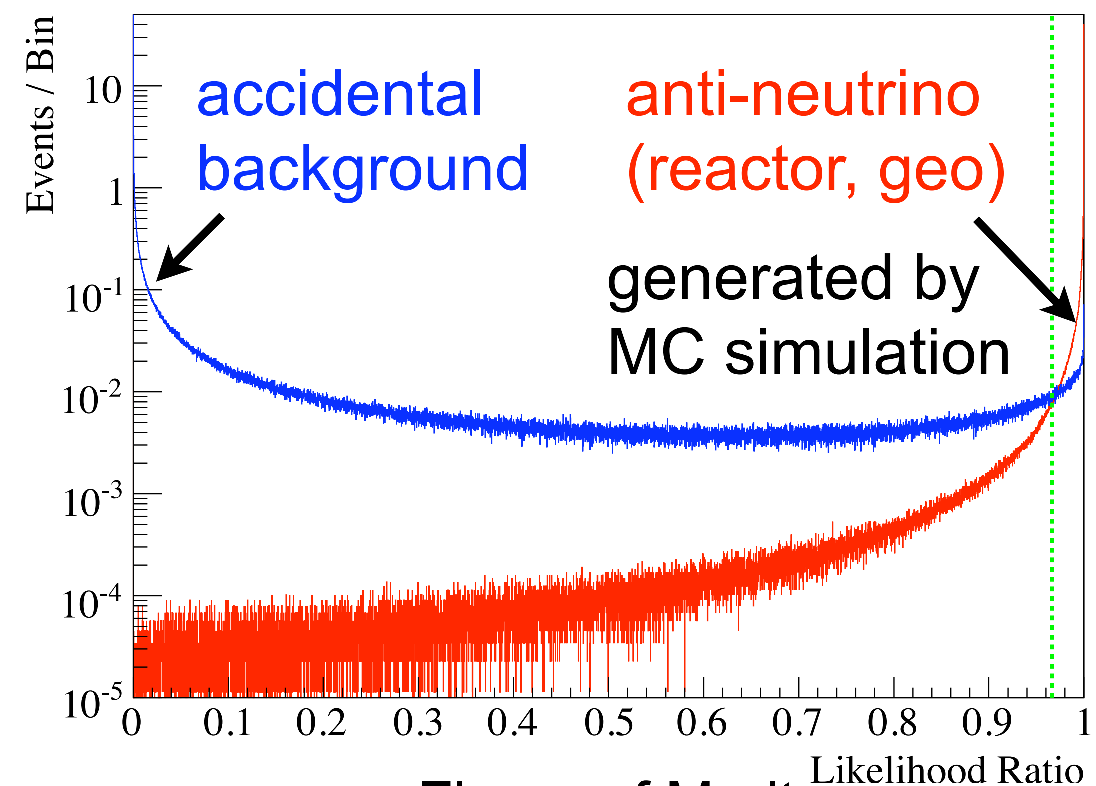
Signal PDF $f_{\bar{\nu}_e}(E_p, E_d, \Delta R, \Delta T, R_p, R_d)$

L-selector
$$L = \frac{f_{\bar{\nu}_e}}{f_{\bar{\nu}_e} + f_{acc}}$$

Maximize "Figure of Merit" for each E_p bin

$$FOM = \frac{S}{\sqrt{S + B_{acc}}}$$

2.2 < E_{prompt} < 2.3 MeV



Detection efficiency

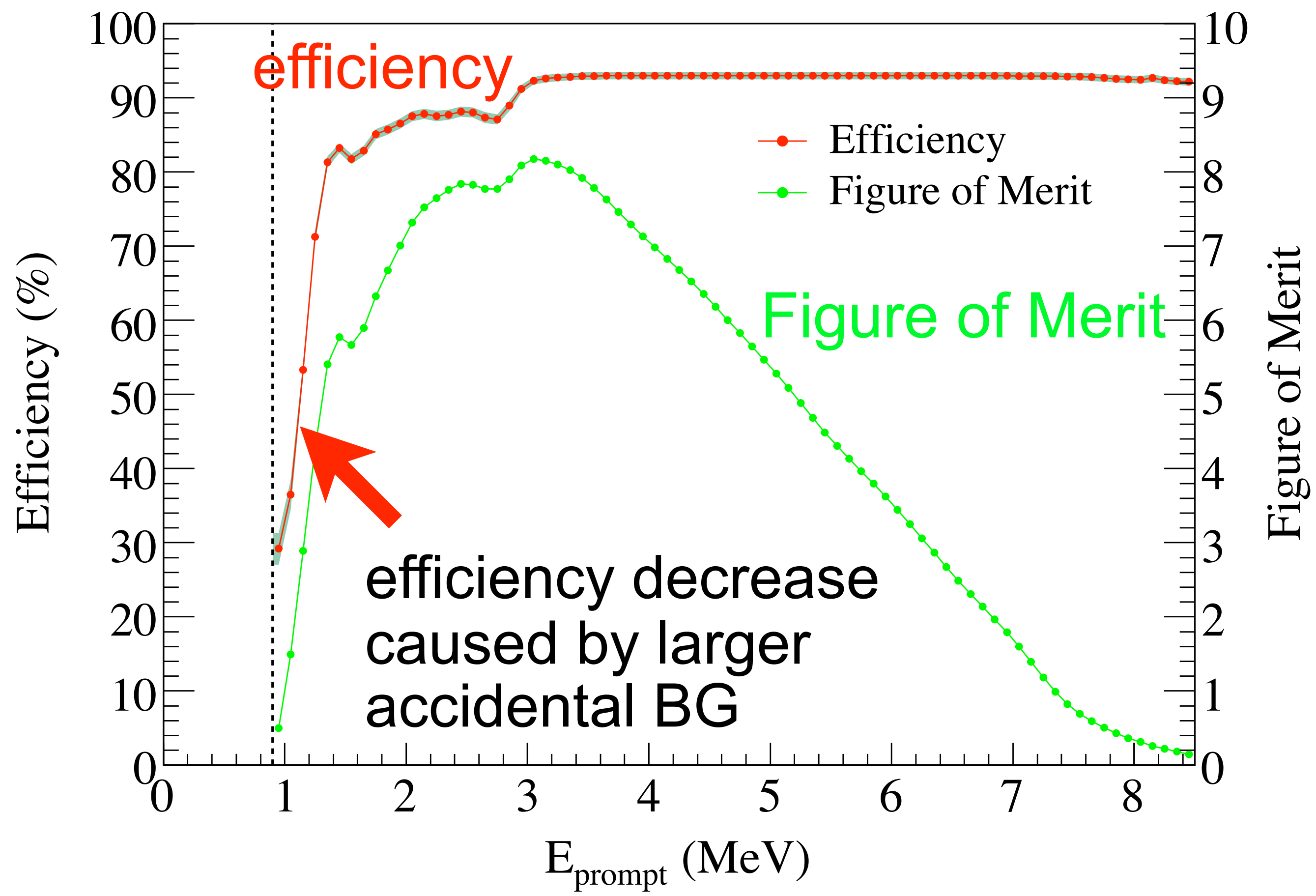
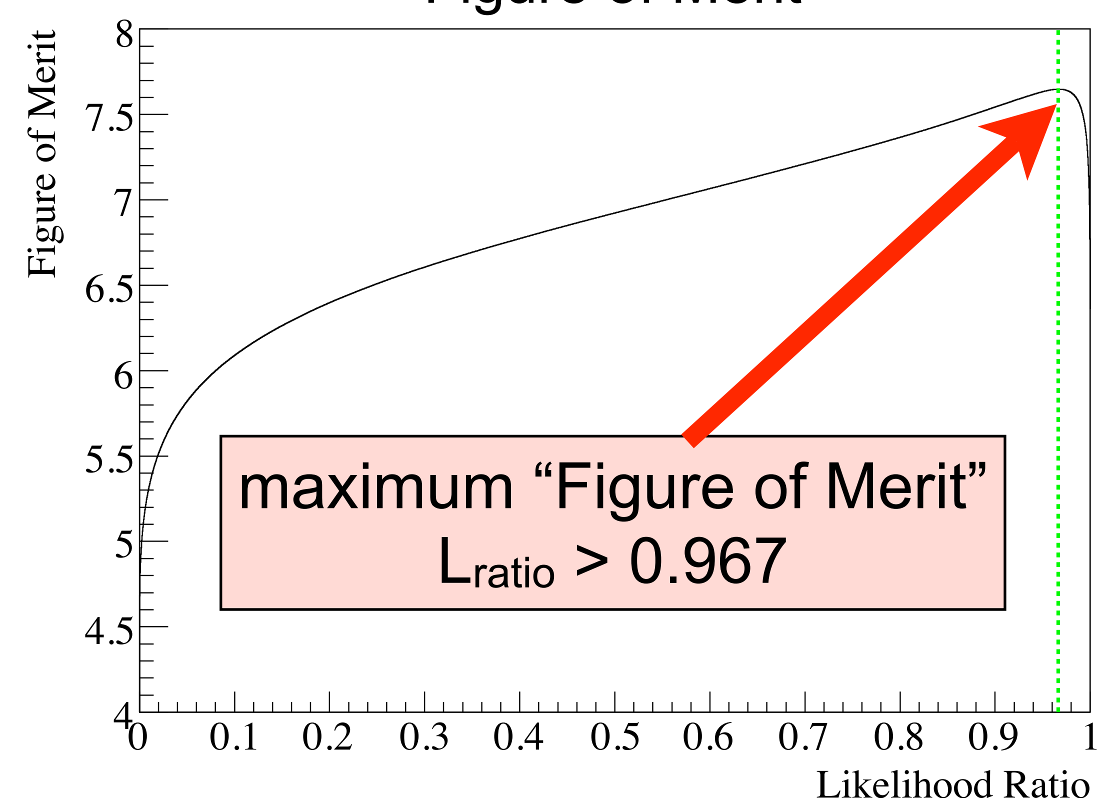


Figure of Merit



Systematic Uncertainty

"full volume" calibration lowered the fiducial volume error

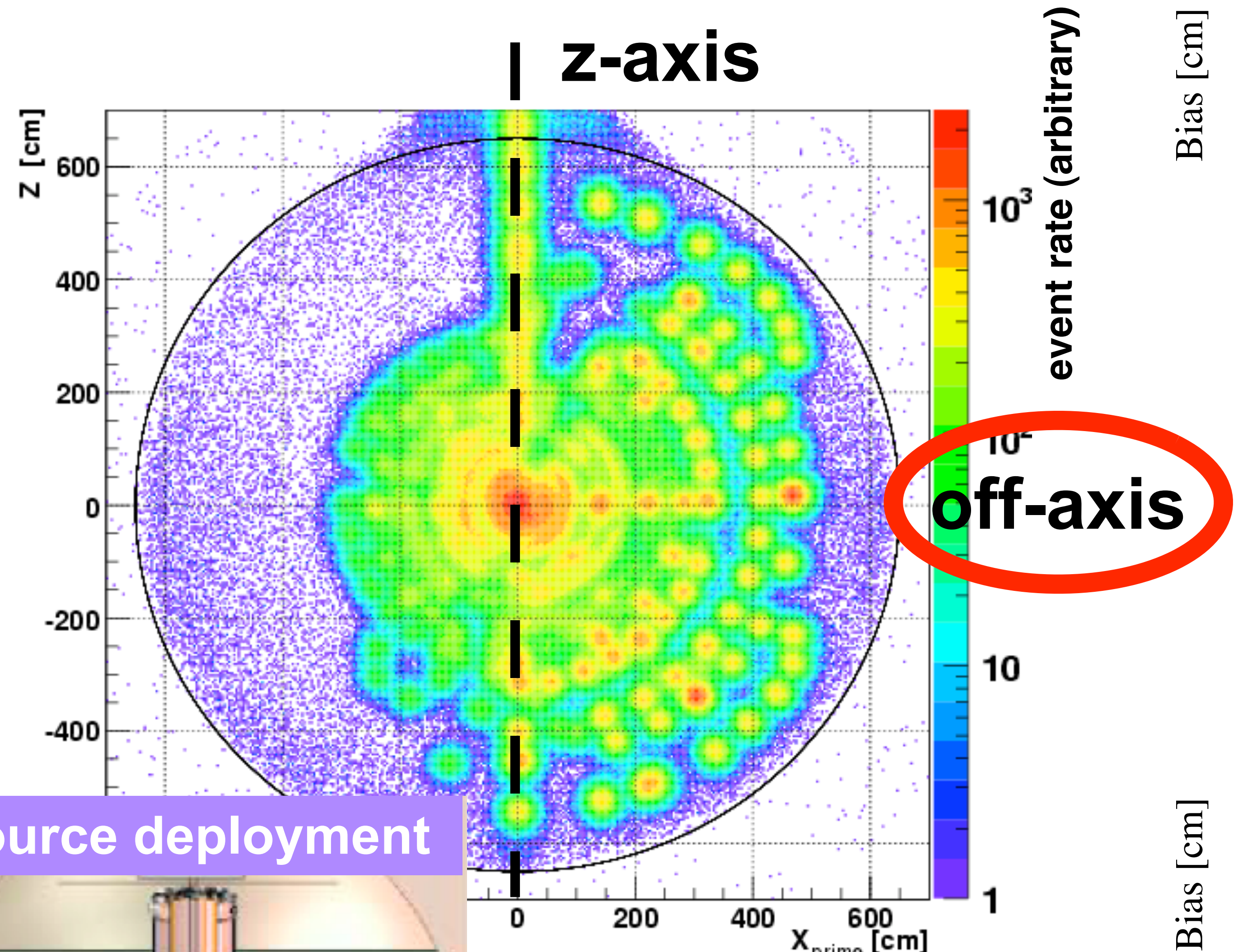
(4.7% in previous analysis)

Detector related	
Fiducial volume	1.8%
Energy scale	1.5%
L-selection eff.	0.6%
OD veto	0.2%
Cross section	0.2%
	2.4%

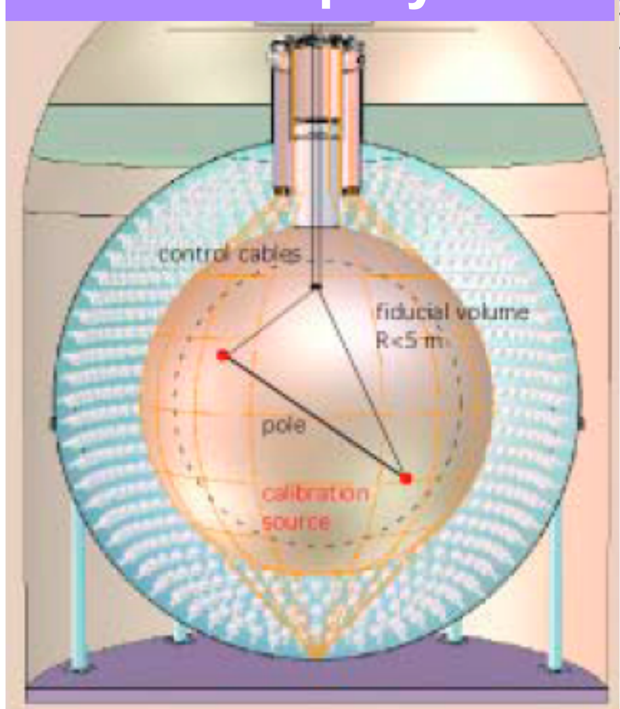
Reactor related	
$\overline{\nu}_e$ spectra	2.4%
Reactor power	2.1%
Fuel composition	1.0%
Long-lived nuclei	0.3%
Time lag	0.01%
	3.4%

Total systematic uncertainty : 4.1%

Full Volume Calibration



source deployment

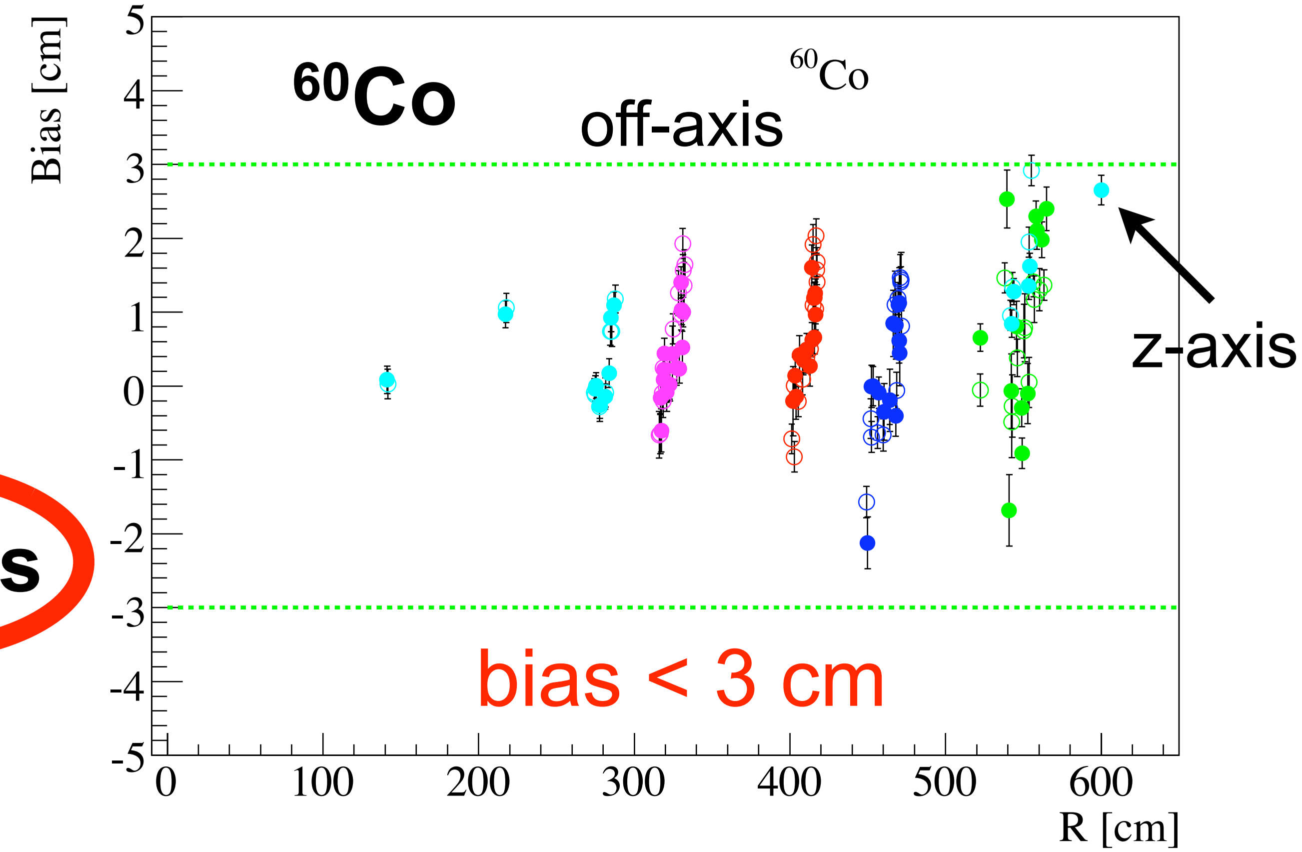


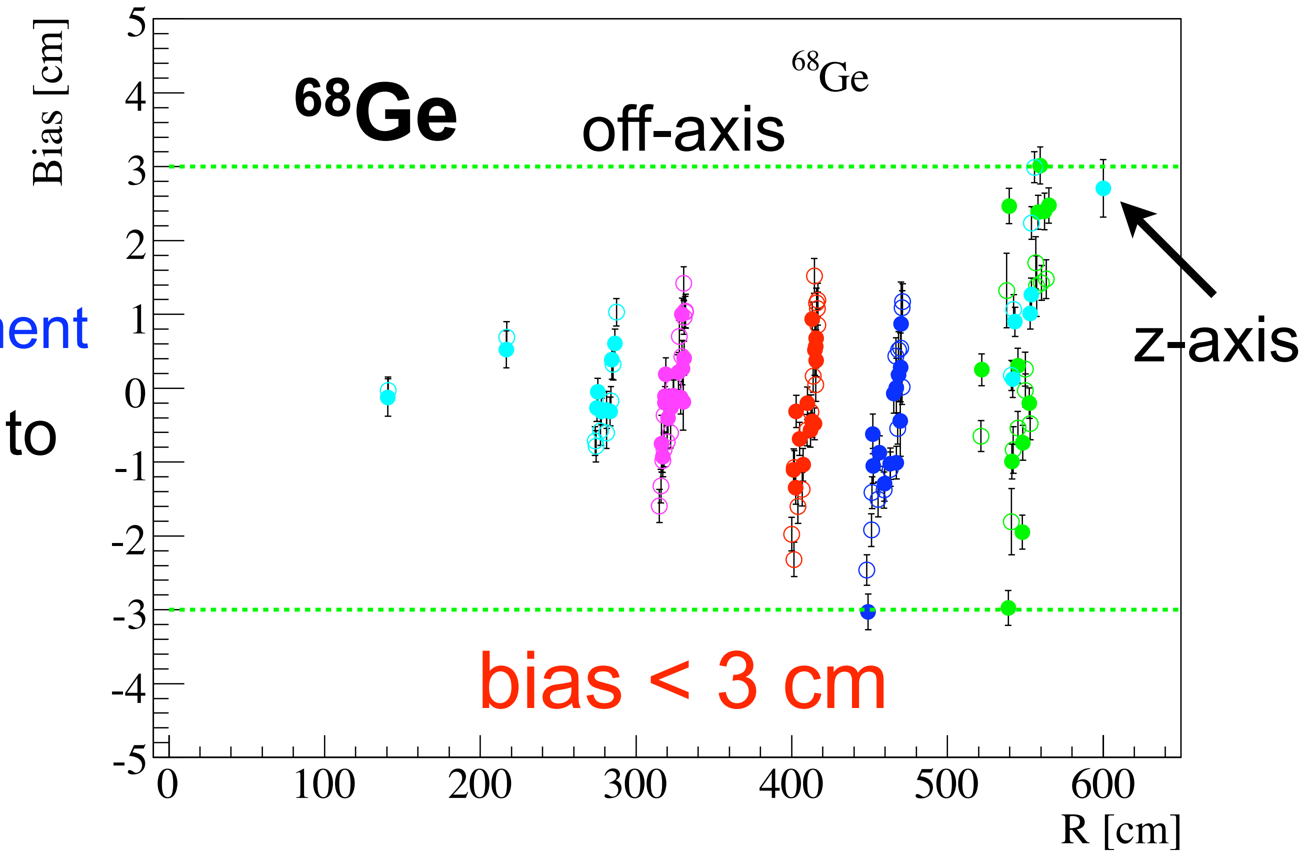
“4pi calibration” system for the off-axis source deployment

bias < 3 cm corresponds to 1.8% volume uncertainty

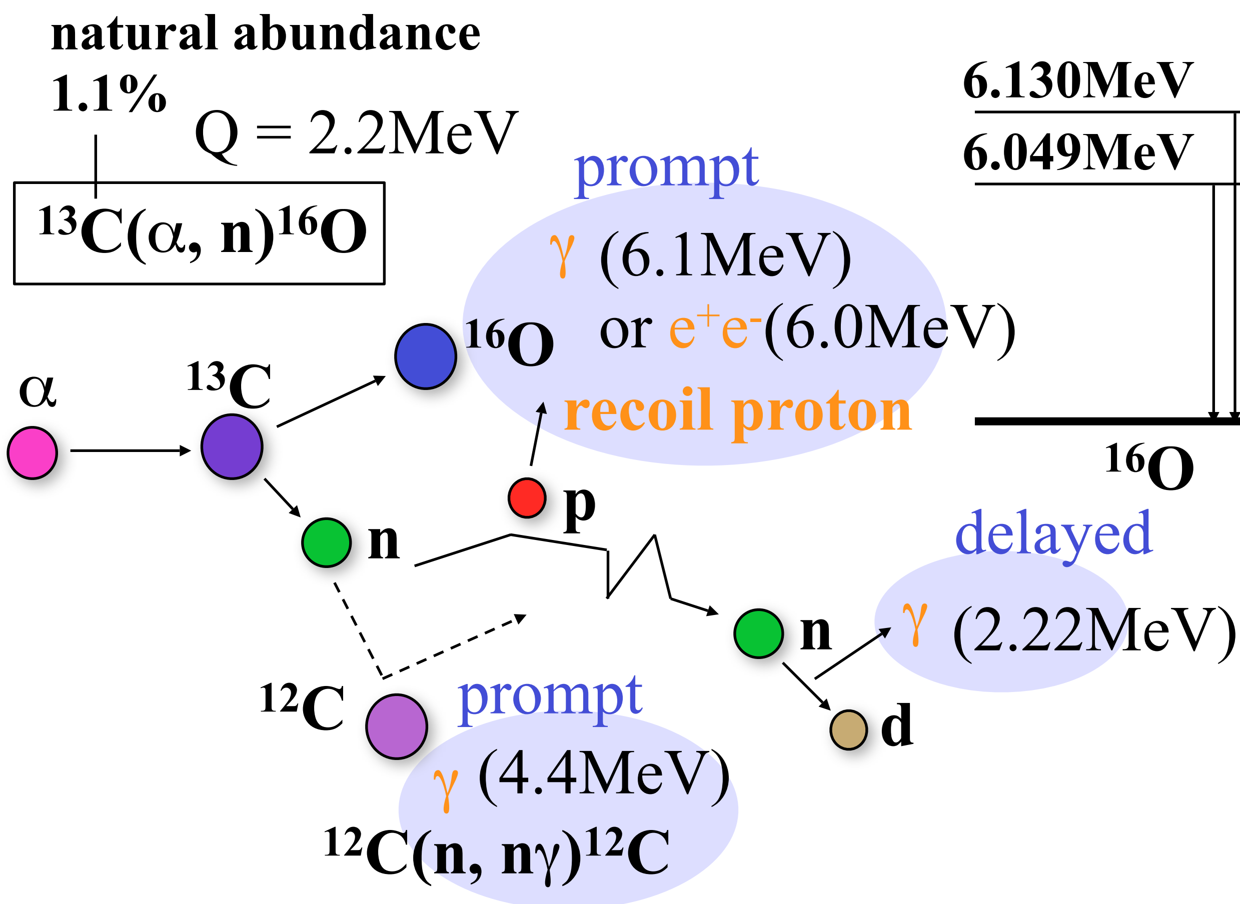
↓

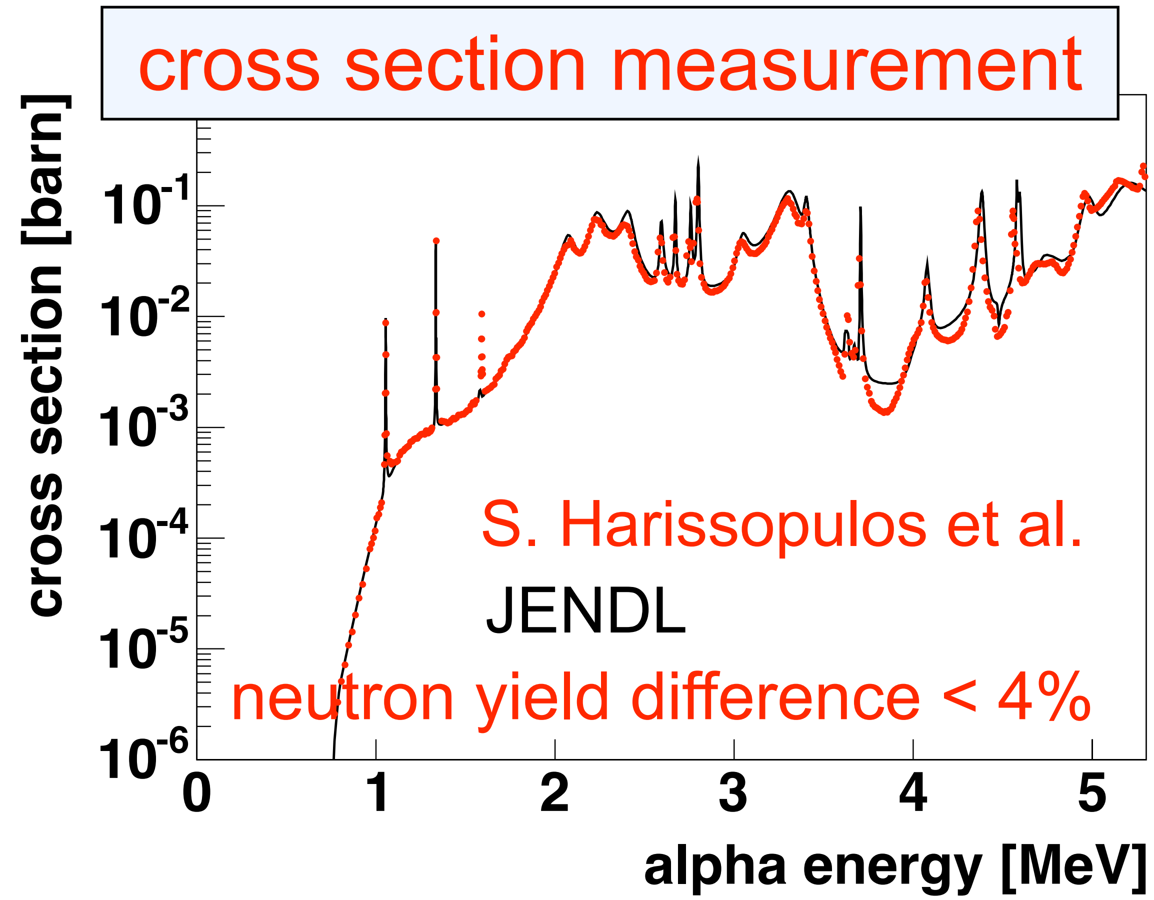
cross-checked by $^{12}B/^{12}N$ uniformity





(α, n) Background Estimation





total cross section was determined precisely

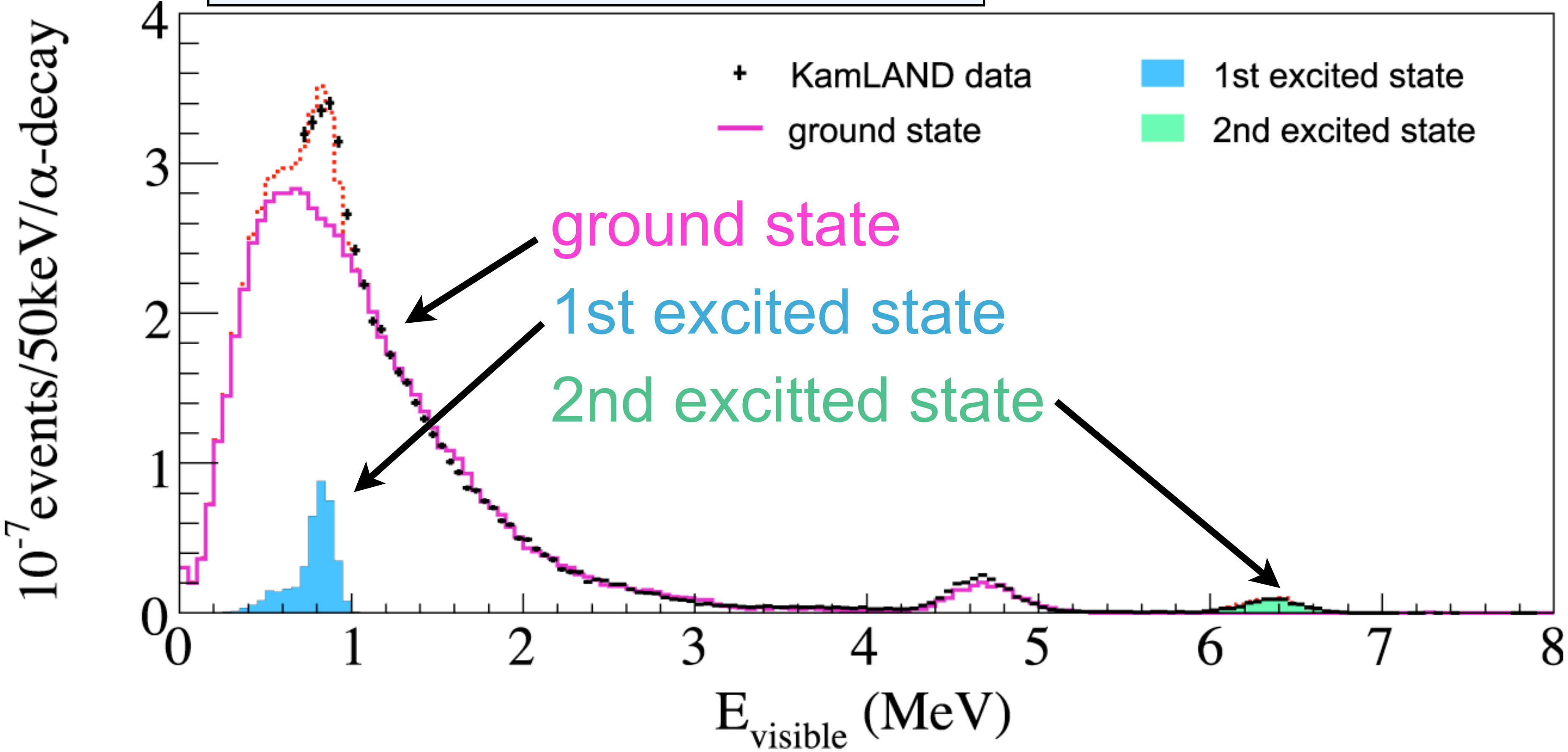
1. low energy	$^{13}C(\alpha, n)^{16}O$ (g.s.)	n
2. 4.4MeV	$^{13}C(\alpha, n)^{16}O$ (g.s.)	n
	→ $^{12}C(n, n\gamma)^{12}C$	γ + n
3. 6MeV	$^{13}C(\alpha, n)^{16}O^*$ (1st e.s. 6.049MeV)	e^+e^-
	$^{13}C(\alpha, n)^{16}O^*$ (2nd e.s. 6.130MeV)	γ + n

Cross section for each branch should be measured

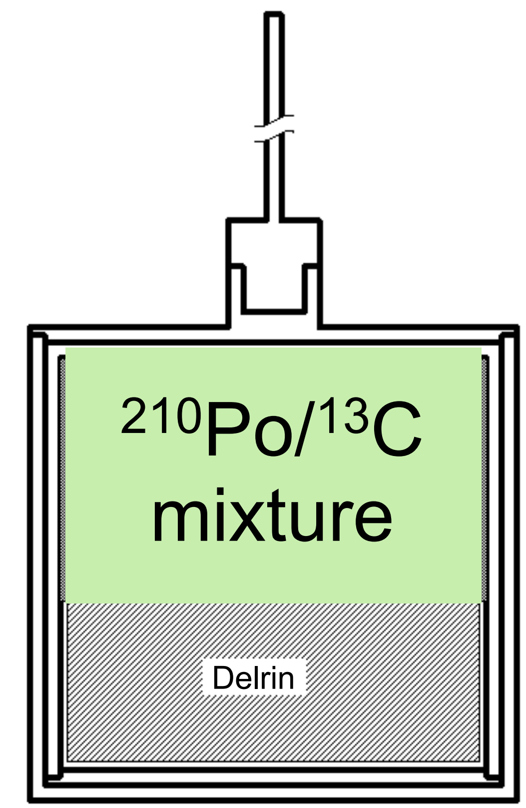
Cross Section Measurement

direct measurement of $^{13}C(\alpha, n)^{16}O$ reaction in KamLAND

Po^{13}C source calibration



Po^{13}C source



(α, n) background estimation

163.3 ± 18.0 events for ground state

18.7 ± 3.7 events for excited state

Estimation uncertainty

11% for ground state

20% for excited state

Rate Analysis above 2.6 MeV

"Reactor" rate analysis
(2.6 MeV threshold)

No osci. expected	**1554**
Background	**63**
Observed events	**985**

Ratio = (obs. - B.G.) / No osci.

0.593 ± 0.020(stat) ± 0.026(syst)

8.5σ disappearance significance

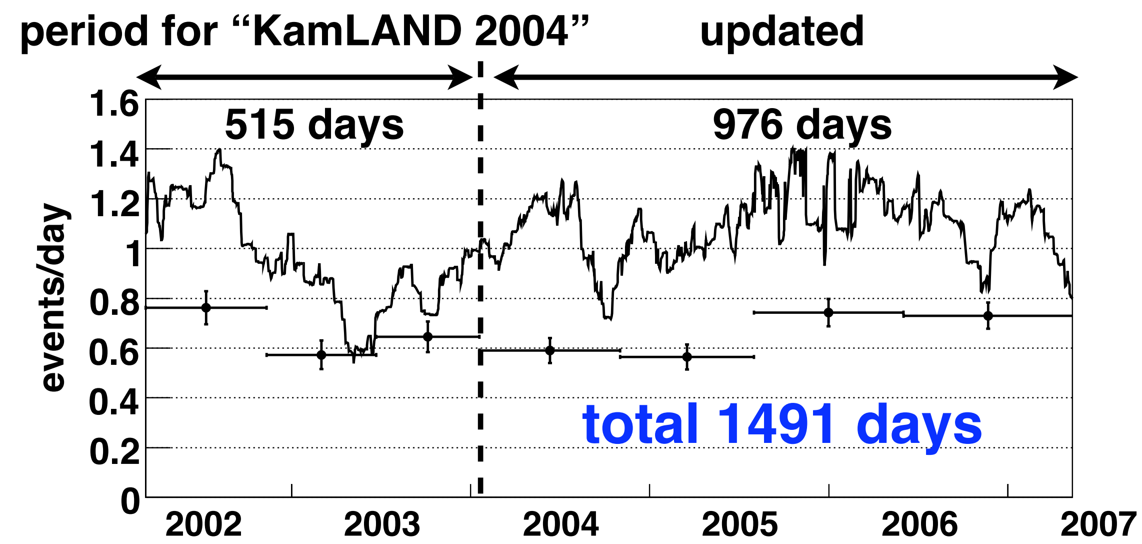
Fit constrained through B.G. expected

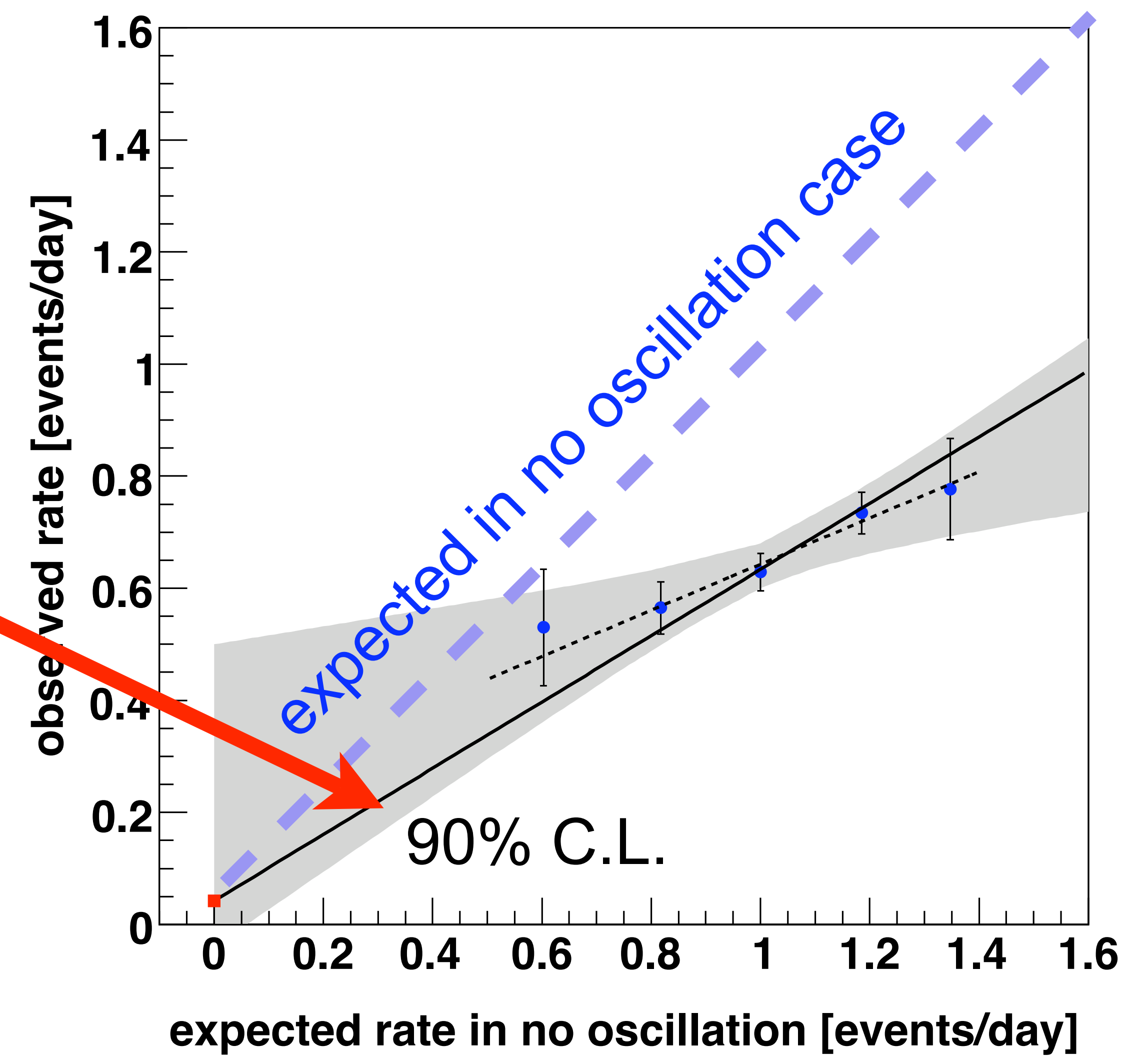
χ^2 / ndf = 2.8 / 4

Fit with a horizontal line

χ^2 / ndf = 12.0 / 4

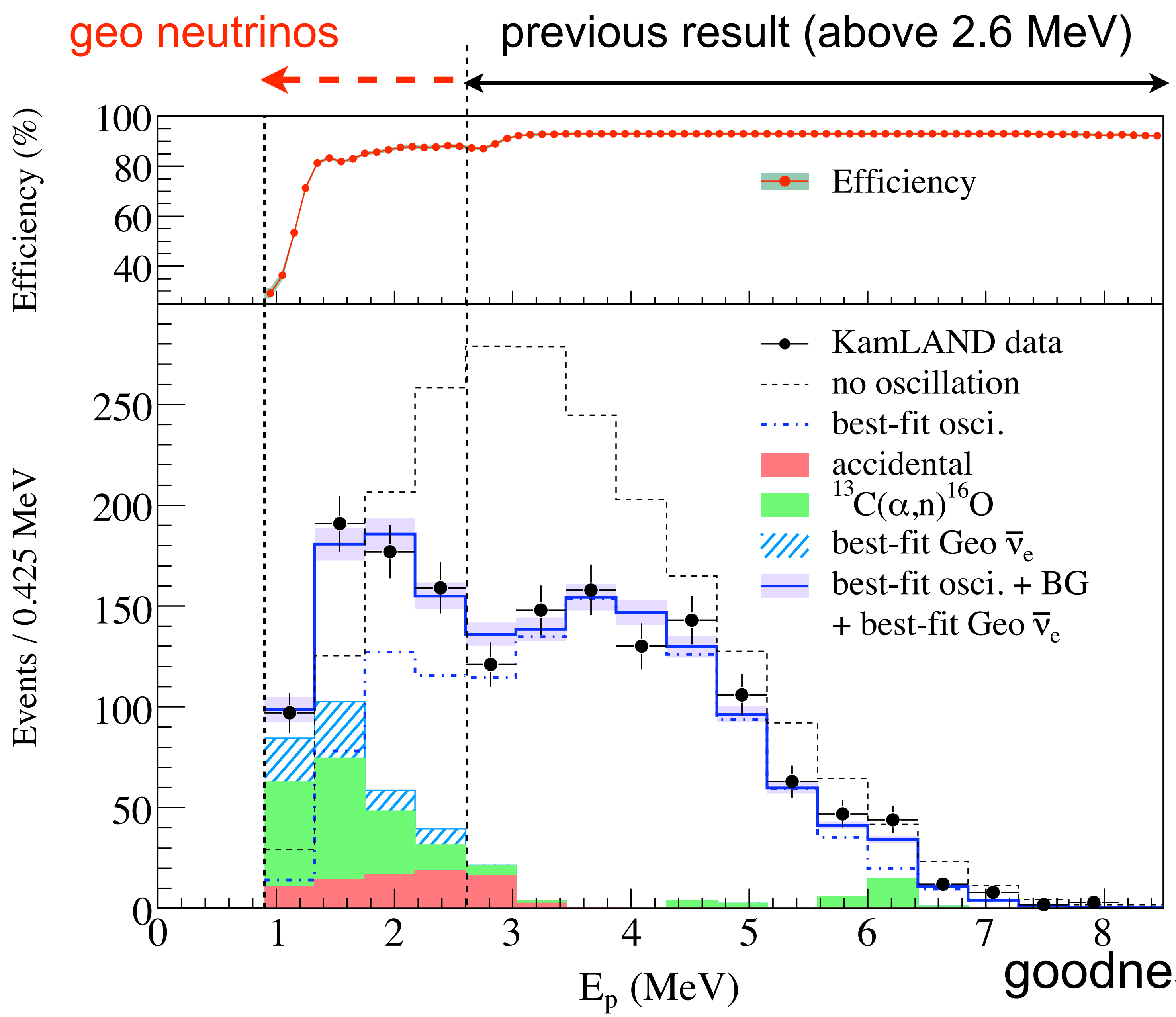
(1.7% C.L.)





Energy Spectrum above 0.9 MeV

exposure : 2881 ton-year (3.8 × 766 ton-year for "KamLAND 2004")



"Geo + Reactor" combined analysis

No osci. expected 2179

Background (w/o geo neutrino) 276

Observed events 1609

best-fit

$(\tan^2\theta, \Delta m^2)$
$= (0.56, 7.58 \times 10^{-5}\ eV^2)$

free parameter : geo neutrinos
(U, Th) = (37.1, 30.2) events

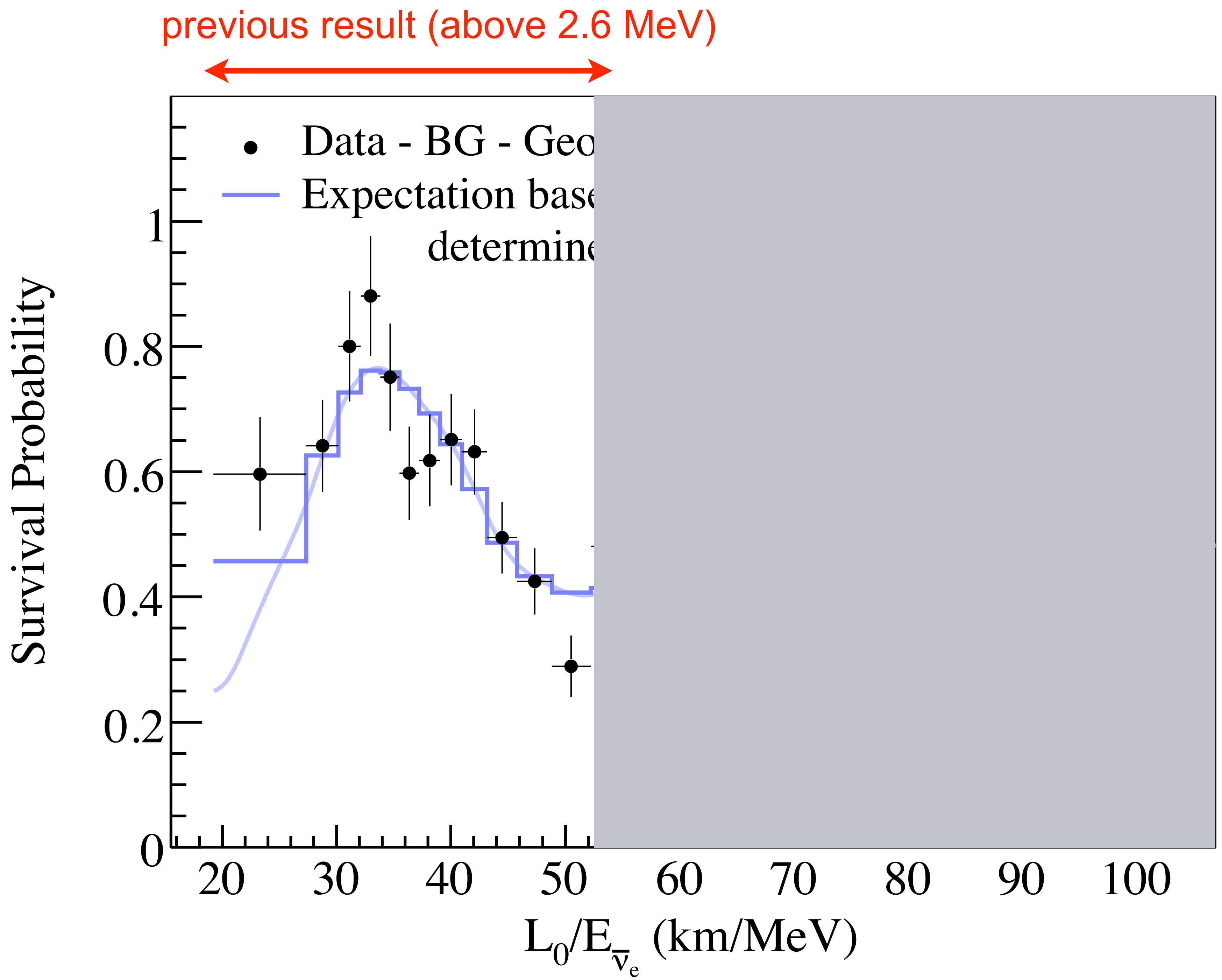
goodness of fit using equal probability bins

best-fit χ^2 / ndf = 20.9 / 16 (18.4% C.L.)

no osci. χ^2 / ndf = 63.6 / 17

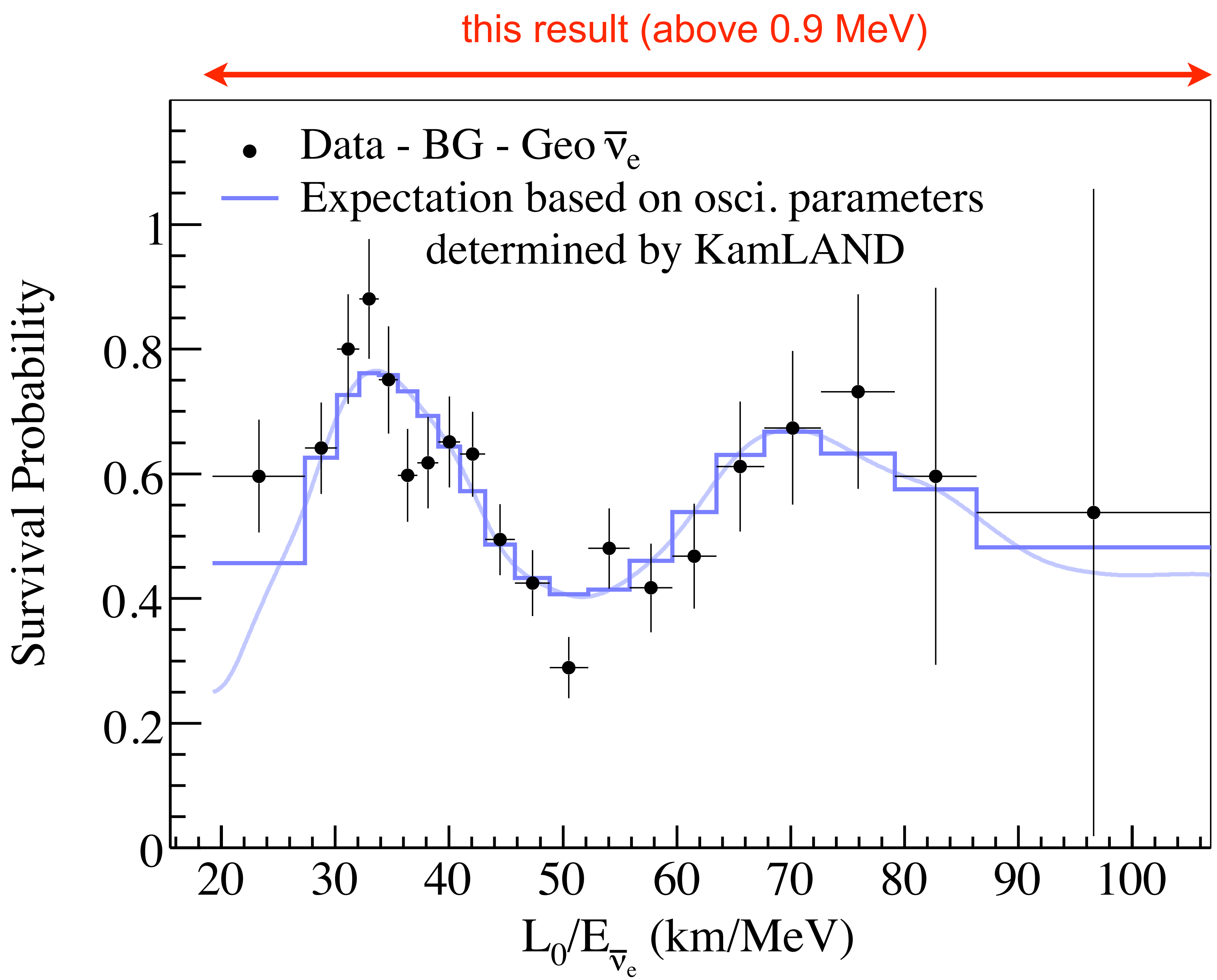
Scaled no oscillation spectrum is excluded at 5.1 σ

L/E Plot



~ 1 cycle of oscillation

L/E Plot



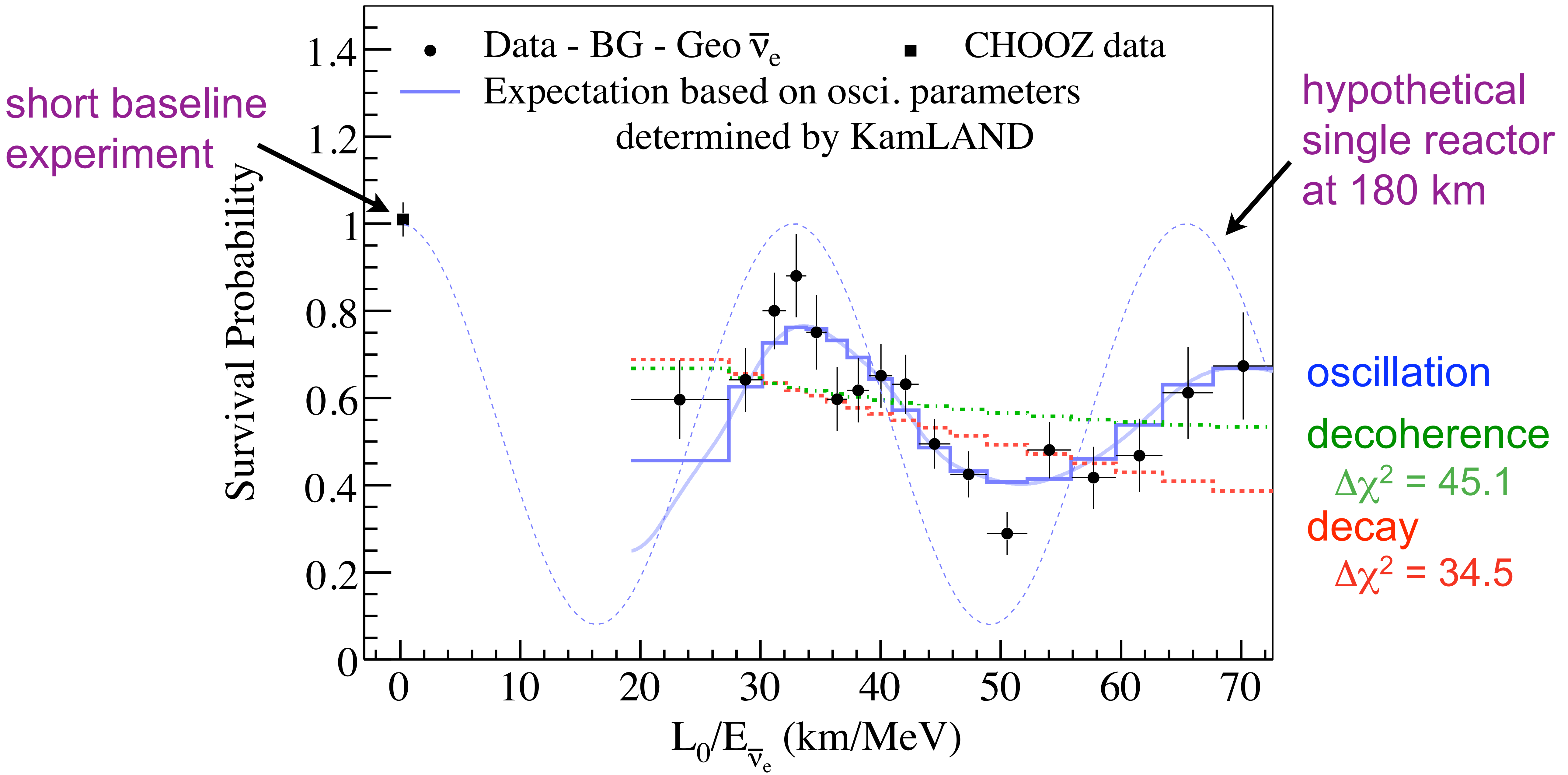
~ 2 cycle of oscillation

strong evidence of neutrino oscillation

Alternate Hypothesis

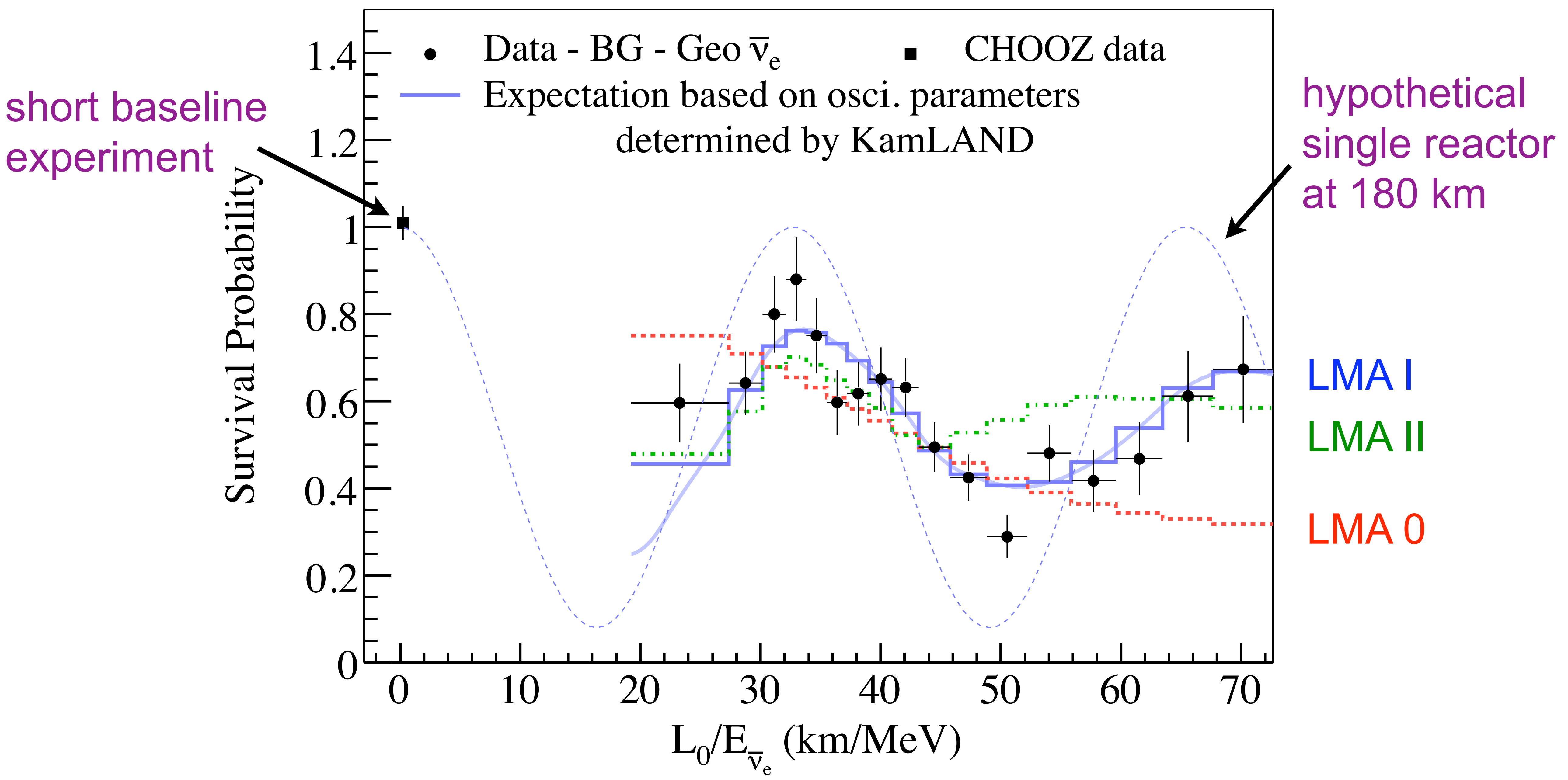
V. D. Barger et al., Phys. Rev. Lett. 82, 2640 (1999)

E. Lisi et al, Phys. Rev. Lett. 85, 1166 (2000)



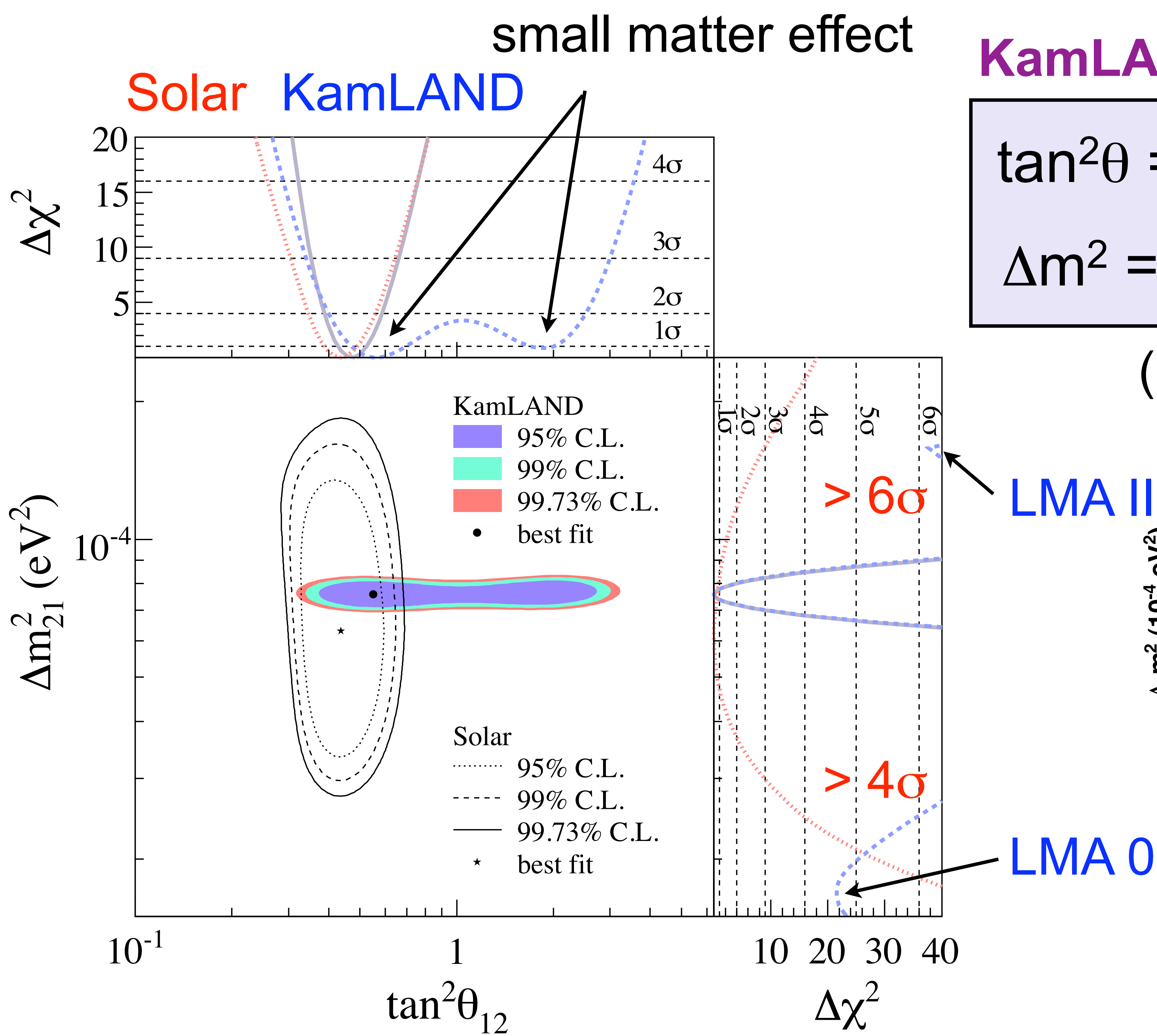
best model is neutrino oscillation

Alternate Wavelength



LMA 0 and LMA II are disfavored at more than 4σ

Oscillation Parameters

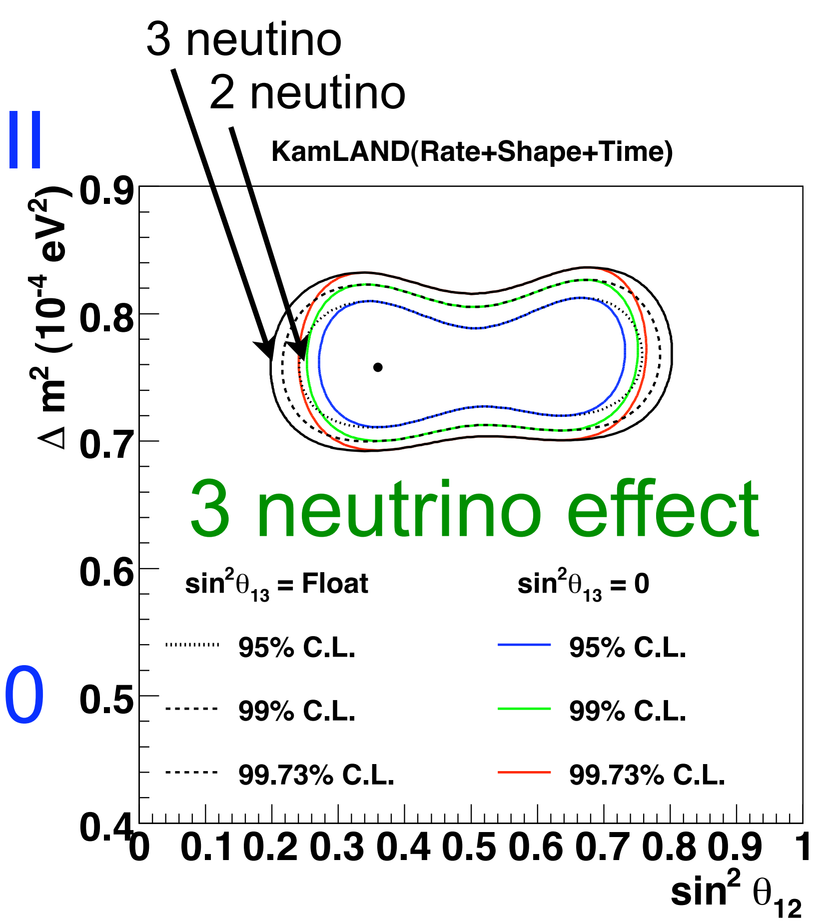


KamLAND only

$$\tan^2\theta = 0.56^{+0.14}_{-0.09}$$

$$\Delta m^2 = 7.58^{+0.21}_{-0.20} \times 10^{-5}\ eV^2$$

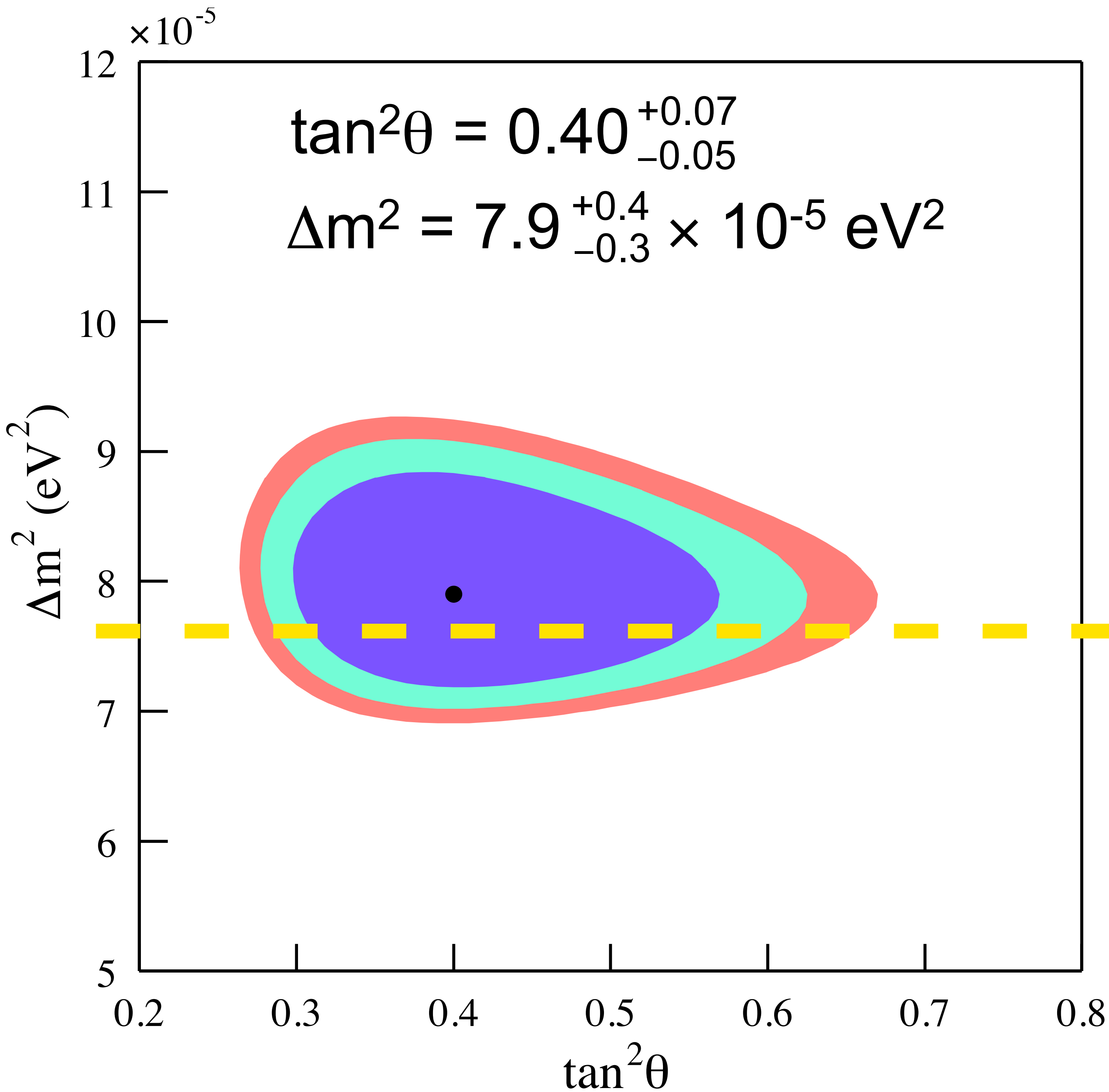
(marginalized error)



same result for Δm^2

Precise Measurement of Δm^2

KamLAND 2004



This result

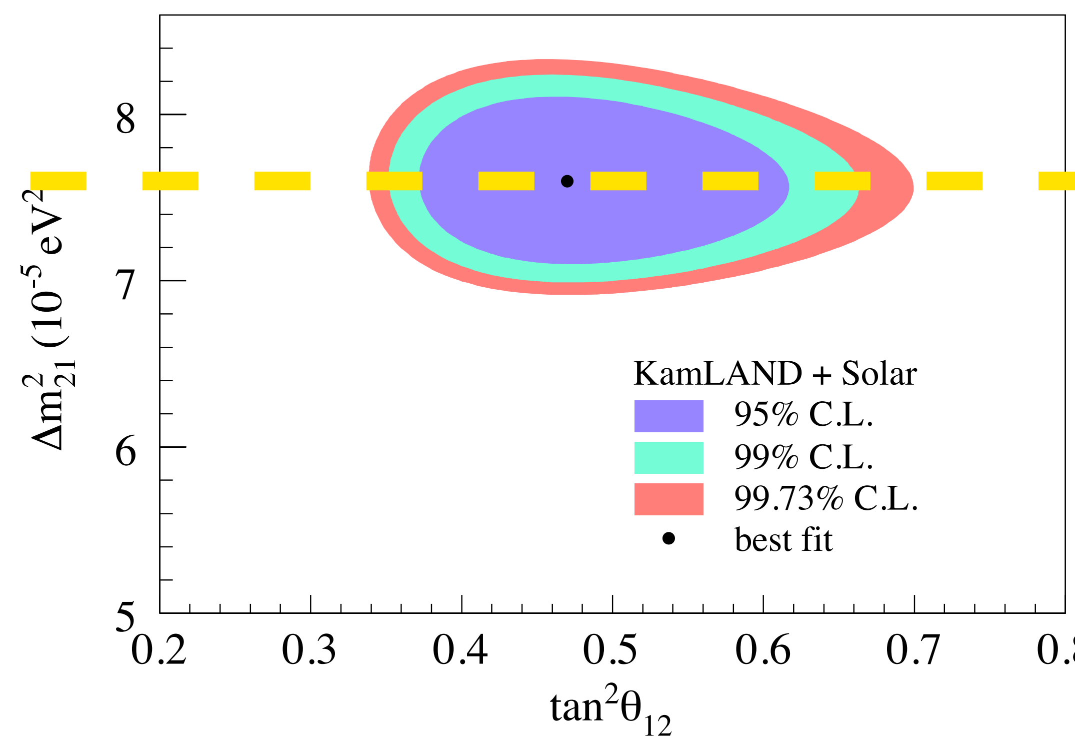
KamLAND + Solar

$\tan^2\theta = 0.47^{+0.06}_{-0.05}$

$\Delta m^2 = 7.59^{+0.21}_{-0.21} \times 10^{-5}\ eV^2$

Δm^2 : systematic uncertainty 2.0%

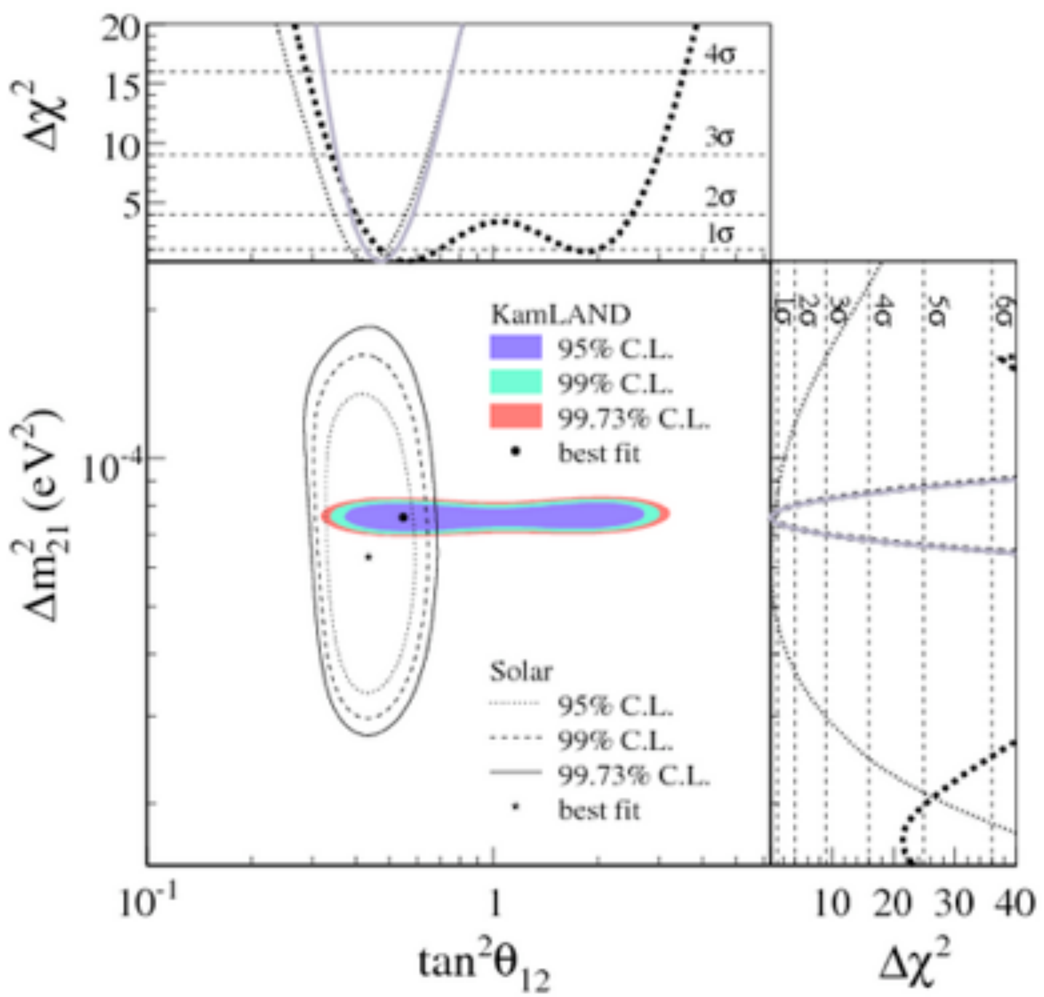
dominated by linear energy scale uncertainty



Δm^2 is measured at 2.8% precision by KamLAND

χ^2 Map Release

http://www.awa.tohoku.ac.jp/KamLAND/chi2map_3rdresult/chi2map.html



'KamLAND-only'

best-fit parameters :
$(\tan^2\theta, \Delta m^2) = (0.56, 7.58 \times 10^{-5}\ \mathrm{eV}^2)$

'KamLAND + Solar'

best-fit parameters :
$(\tan^2\theta, \Delta m^2) = (0.47, 7.59 \times 10^{-5}\ \mathrm{eV}^2)$

Please use the constraints on oscillation parameters

Geo Neutrino

Inner Structure of the Earth

- Inner structure of the earth was investigated by the seismic wave measurement

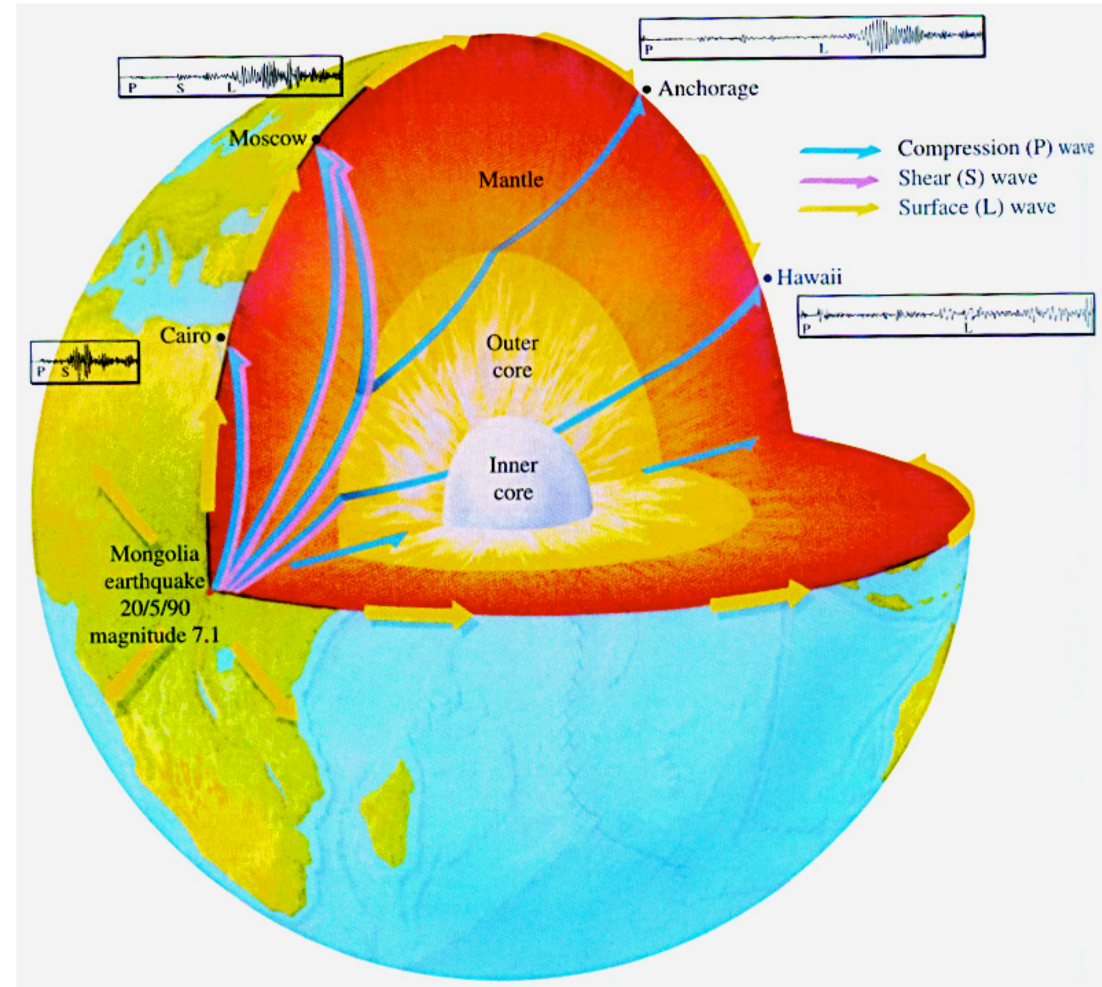
- Total heat flow from the earth

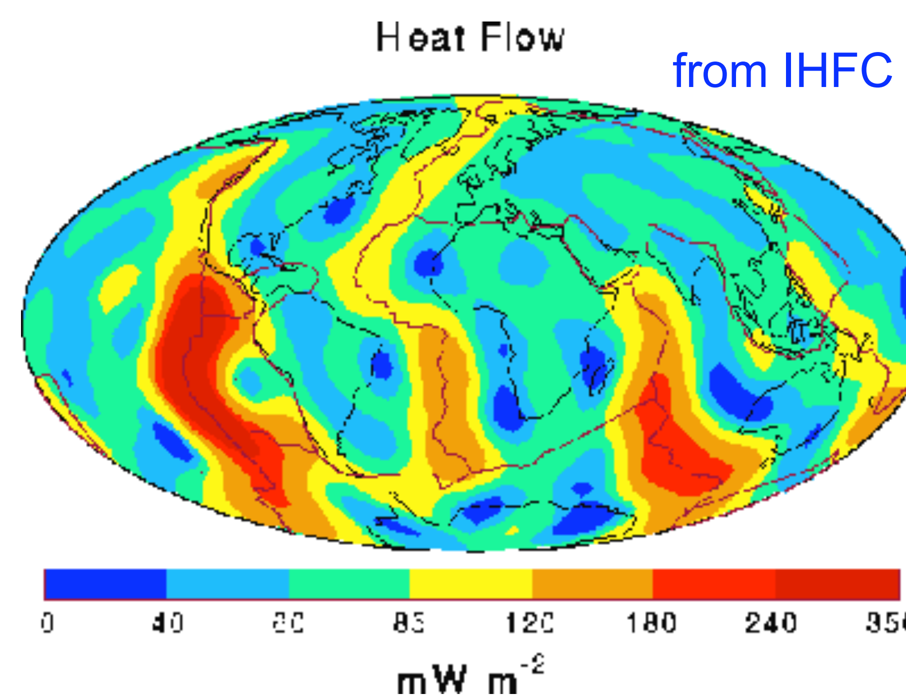
44TW or 31 TW

radiogenic heat generation	others (primordial heat, latent heat)
19 TW	

(U ~ 8 TW, Th ~ 8 TW, K ~ 3 TW)

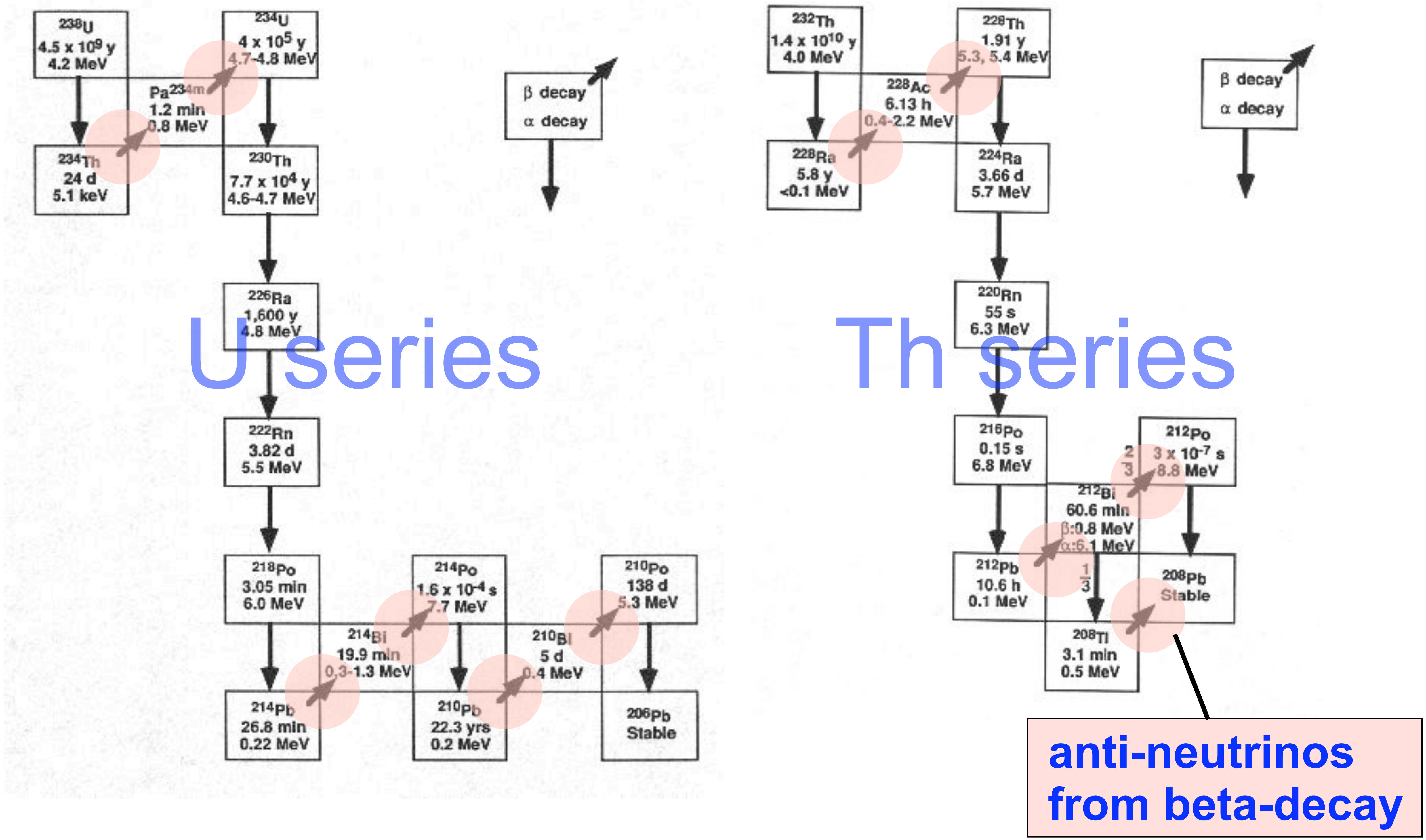
Radiogenic heat contribution is important to understand the earth dynamics





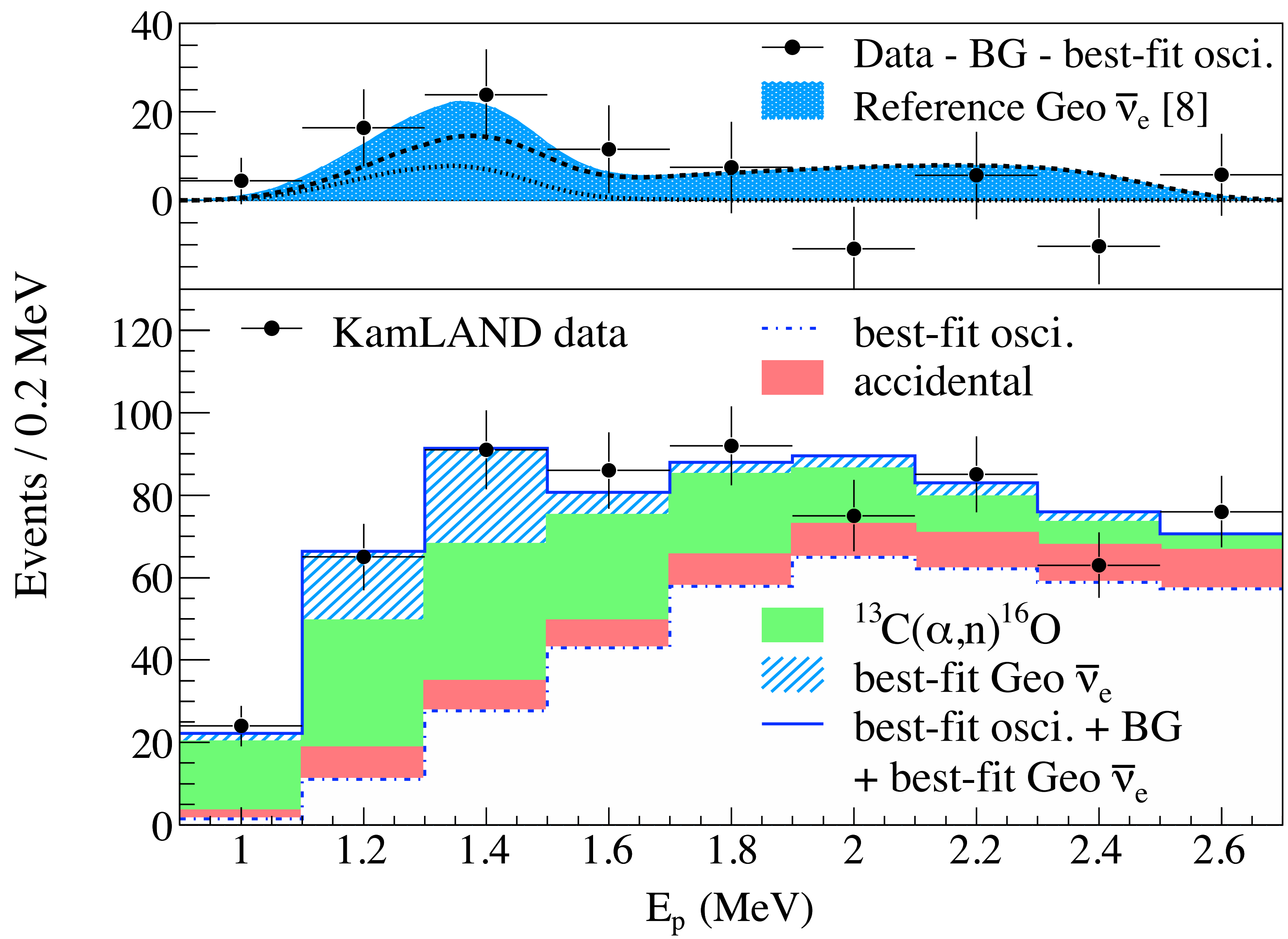
from IHFC

Neutrino from the Earth



"Geo neutrino" directly tests radiogenic heat generation

Geo Neutrino Estimation



Reference model (16 TW)

U : 56.6 event (29.2 TNU)
Th : 13.1 event (7.7 TNU)

total : 36.9 TNU

U+Th = $74.9^{+27.3}_{-27.2}$ event

$38.9^{+14.4}_{-14.2}$ TNU

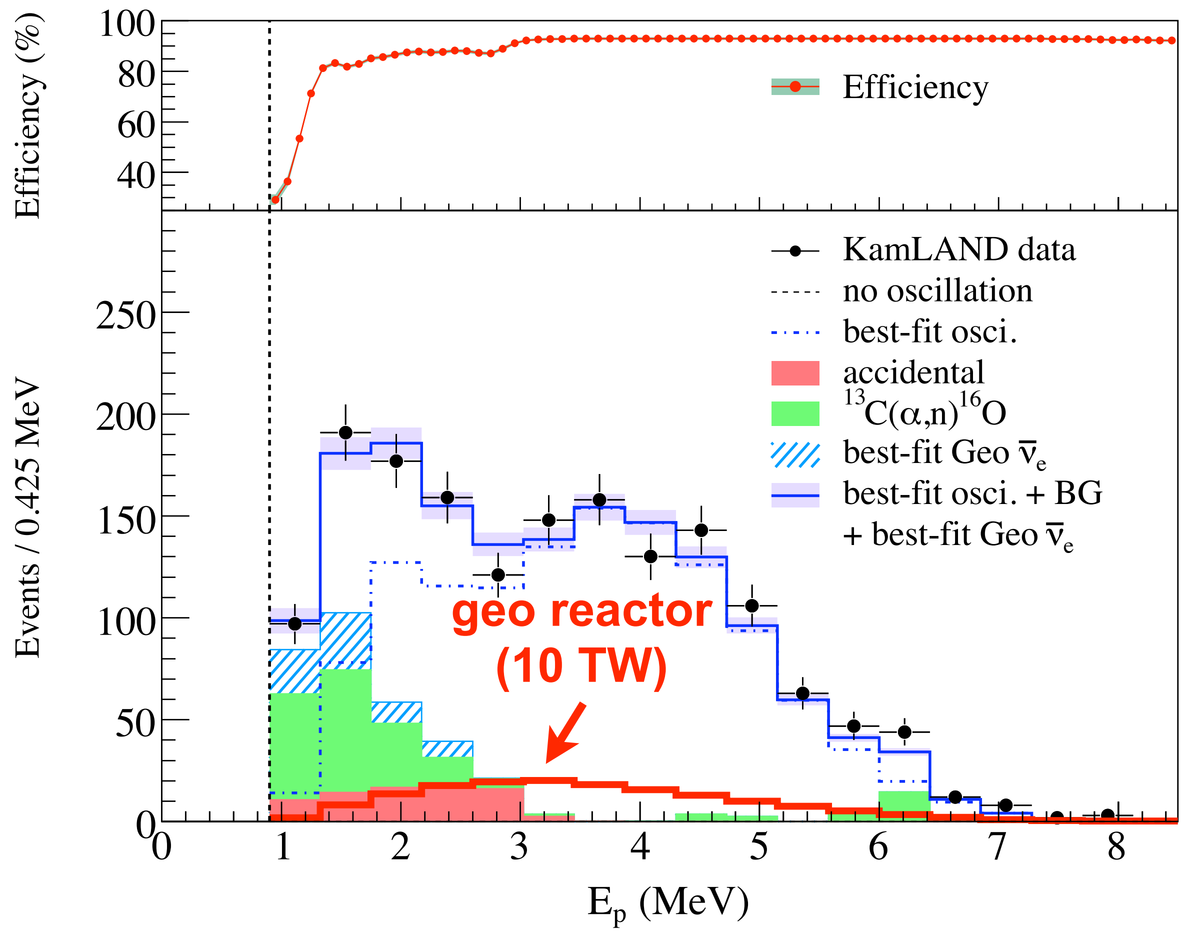
(previous result : $57.4^{+32.0}_{-30.0}$ TNU)

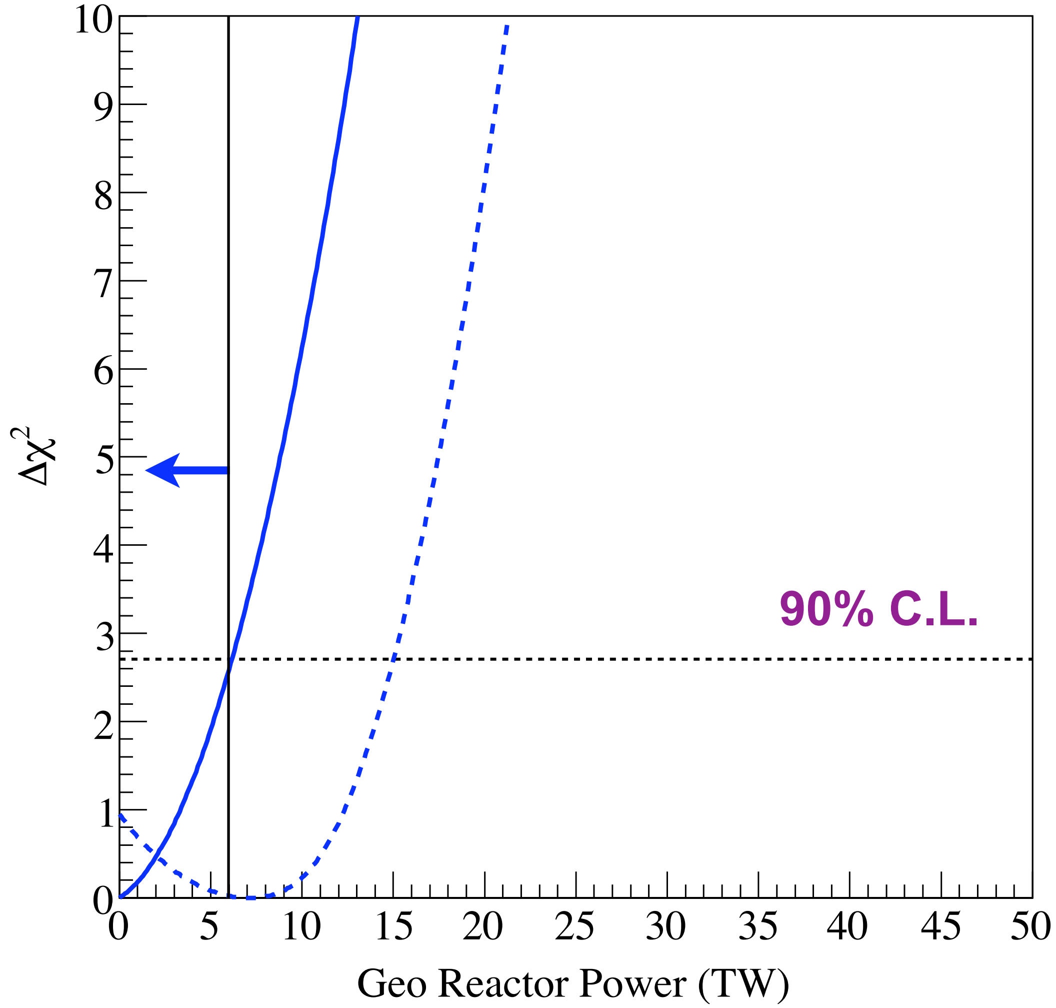
TNU (Terrestrial Neutrino Unit) = events/10^{32} target-proton/year

Geo Reactor Constraint

Natural nuclear fission reactor at the Earth's center

- small contribution to total heat flow?
- energy source of geo-magnetic field?



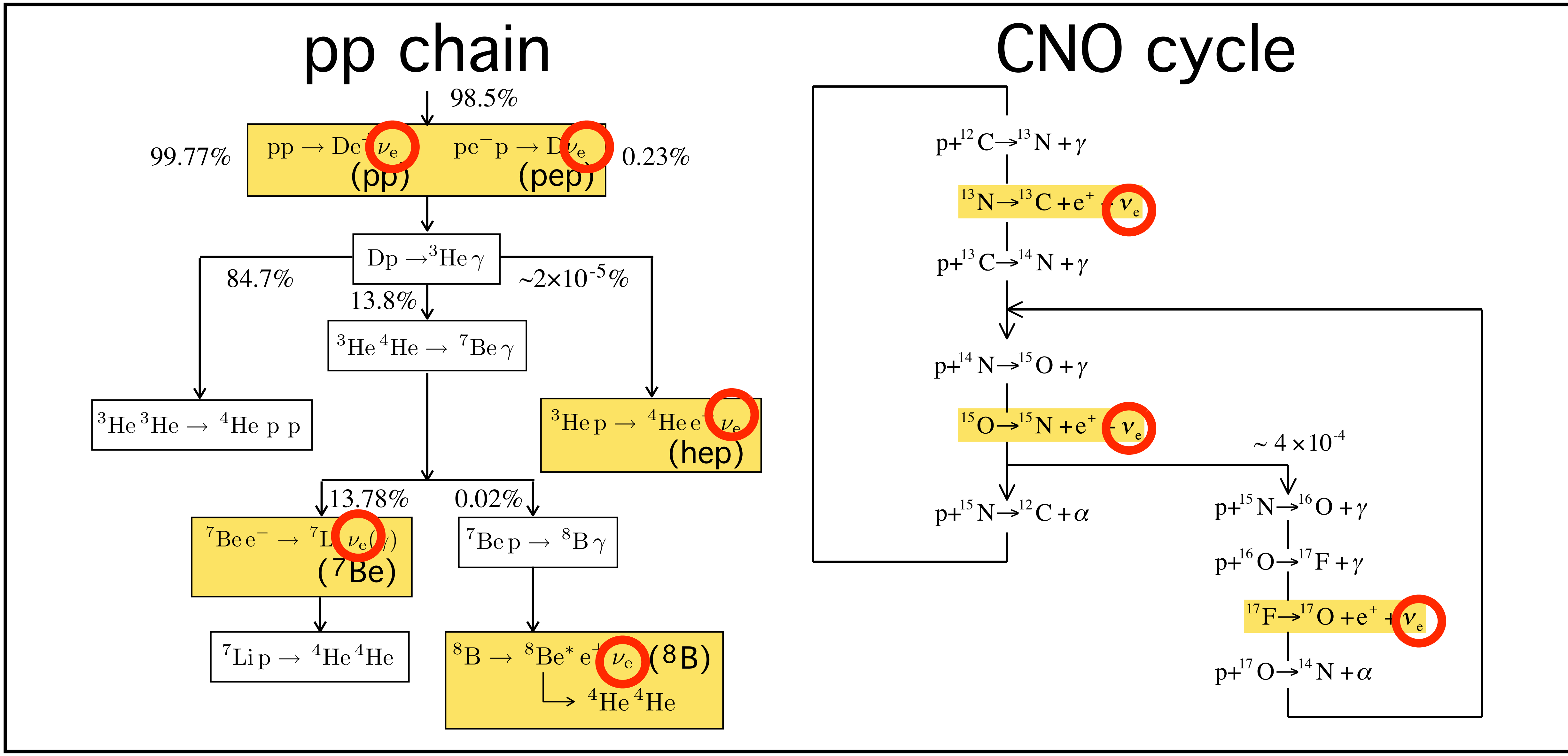


KamLAND data with the solar oscillation constraints

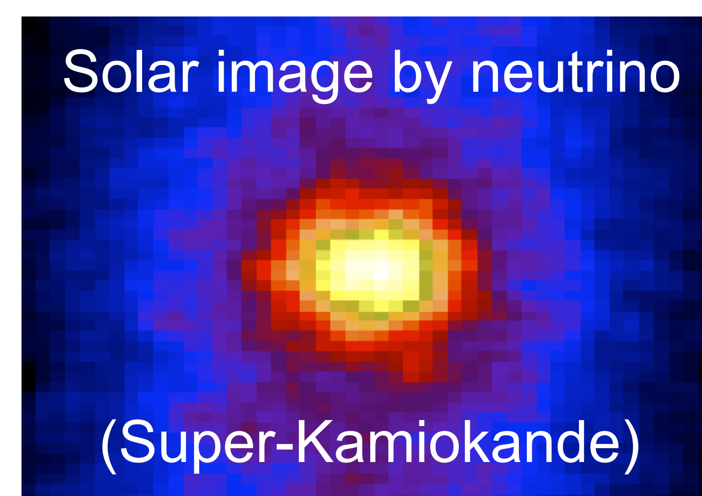
Geo reactor power < 6.2 TW (90% C.L.)

Future Prospects (Solar Phase)

Neutrino from the Sun



- Solar neutrinos are produced by nuclear fusion reactions in the sun
- Small fraction from the CNO cycle (no direct measurement by neutrinos)



Standard Solar Model

- **New abundance model**
  strongly disagree with helioseismological measurement
- **Precise nuclear cross section**
  LUNA result : $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$

J.N. Bahcall and A.M. Serenelli, Astro. Phys. J. 621, 85 (2005)

	Model	pp	pep	hep	^{7}Be	^{8}B	^{13}N	^{15}O	^{17}F
	BP04(Yale)	5.94	1.40	7.88	4.86	5.79	5.71	5.03	5.91
	BP04(Garching)	5.94	1.41	7.88	4.84	5.74	5.70	4.98	5.87
	BS04	5.94	1.40	7.86	4.88	5.87	5.62	4.90	6.01
	BS05(^{14}N)	5.99	1.42	7.91	4.89	5.83	3.11	2.38	5.97
GS98	BS05(OP)	5.99	1.42	7.93	4.84	5.69	3.07	2.33	5.84
AGS05	BS05(AGS,OP)	6.06	1.45	8.25	4.34	4.51	2.01	1.45	3.25
	BS05(AGS,OPAL)	6.05	1.45	8.23	4.38	4.59	2.03	1.47	3.31

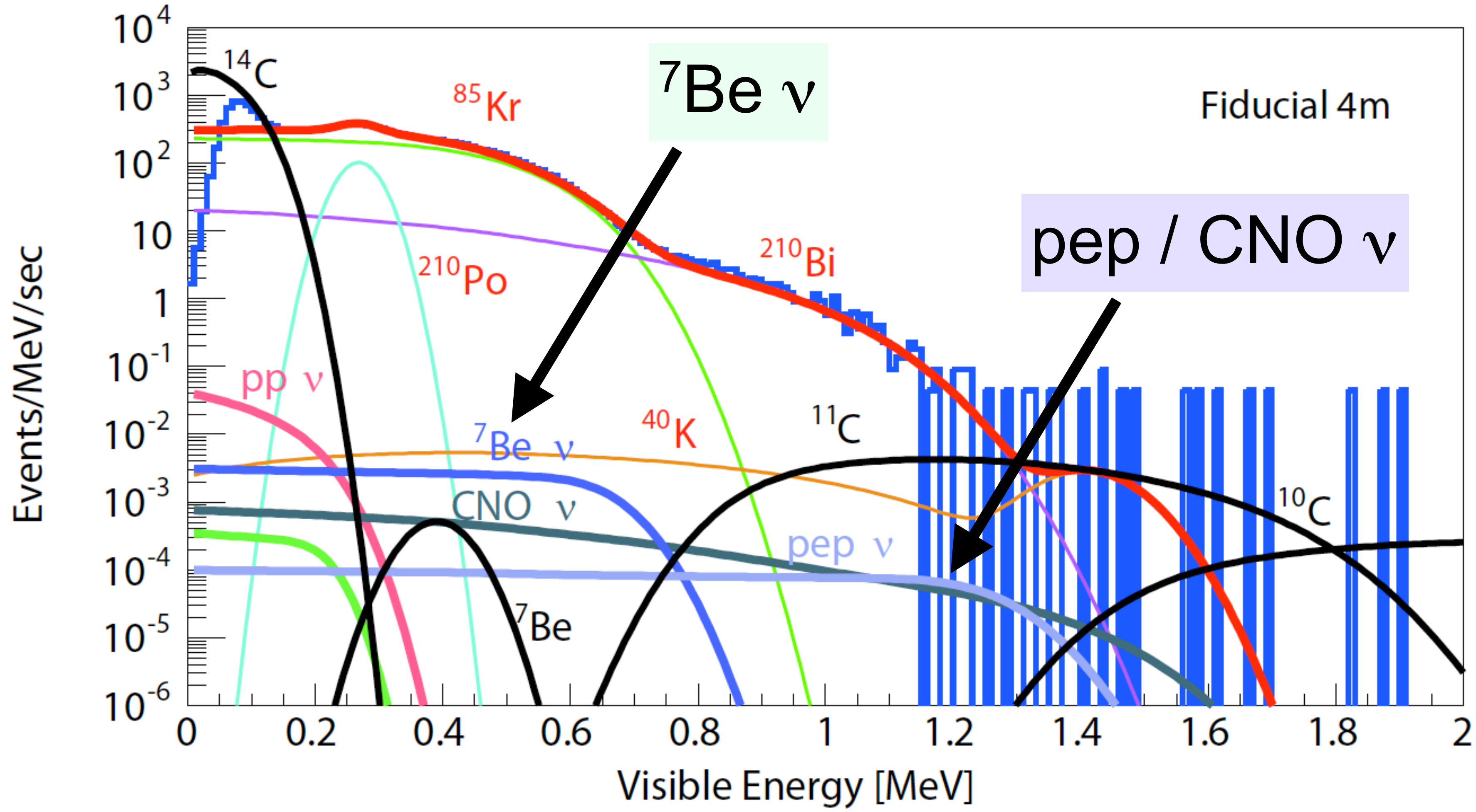
-10% (S_{34} : 2.5%)

-38% ($S_{1,14}$: 8.4%)

KamLAND will measure ^{7}Be and CNO solar neutrinos and test the lower abundance of heavy element (AGS05)

Solar Neutrino Observation

KamLAND singles spectra



^{7}Be ν

pep / CNO ν

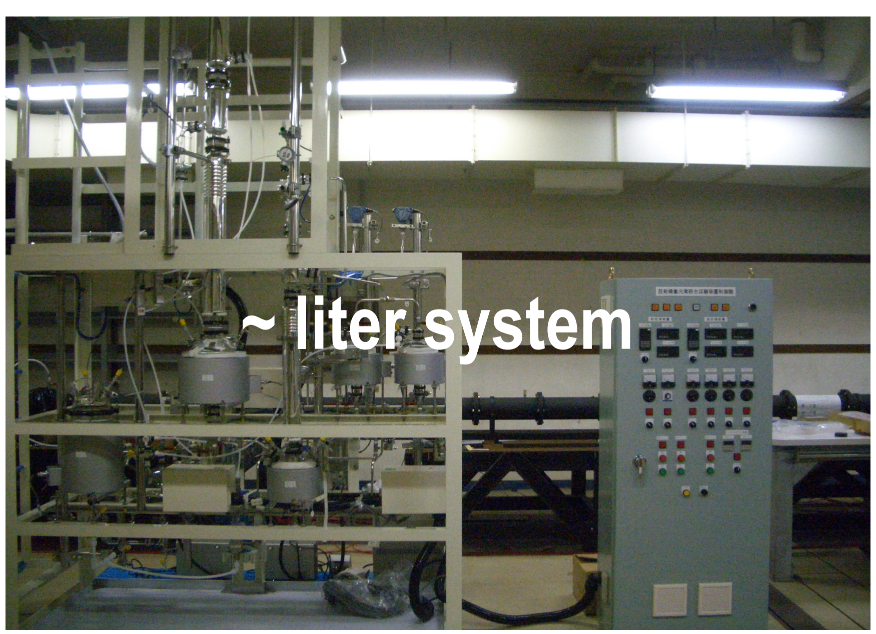
^{7}Be ν observation

B.G. reduction requirement ~ 1 μBq / m^3

Purification of Liquid Scintillator

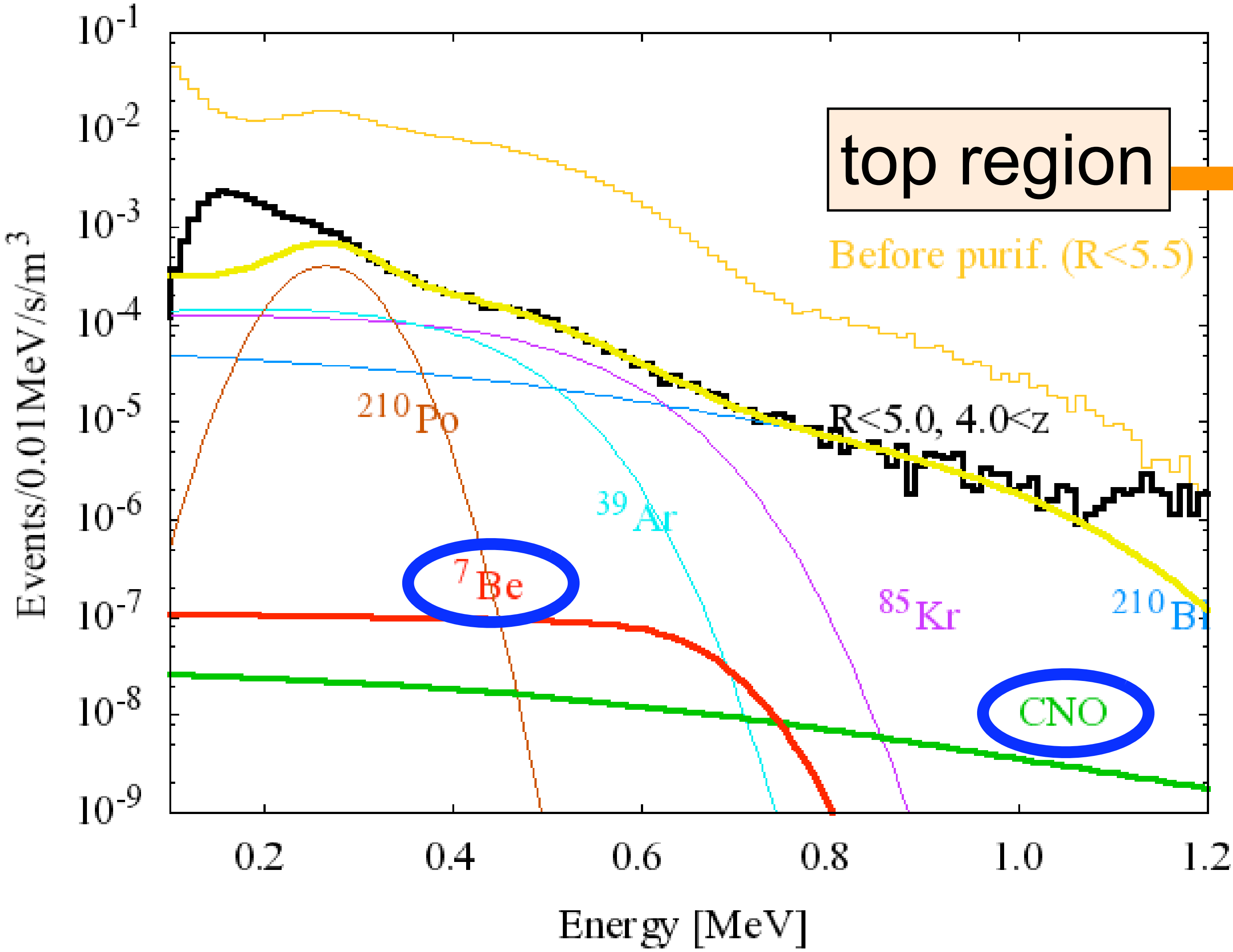
distillation method

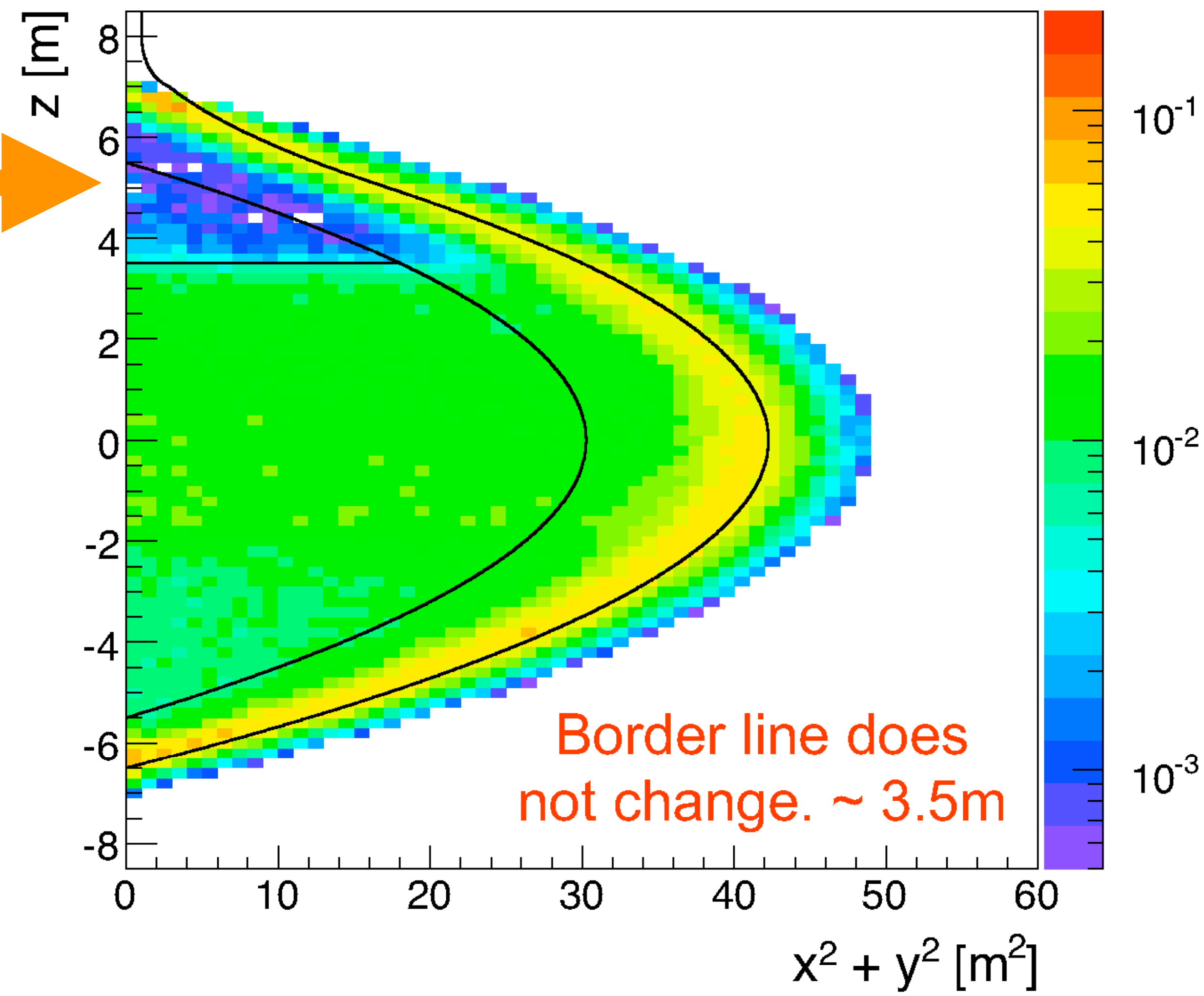
separation of substances based on boiling point differences



1st Purification (2007)

- Total 1699 m^3 of LS was purified through Aug. 1, 2007
- Purified volume / KamLAND volume = 1.4





Reduction efficiency is not sufficient

2nd Purification (2008)

Improvement of purification

(1) Avoid mixing of Liquid Scintillator

- precise control of LS density and temperature
- boundary monitoring by onsite analysis tool

(2) Find gas leakage in distillation system and detector

- Fixed some leakage points at PPO distillation tower and near top of the detector

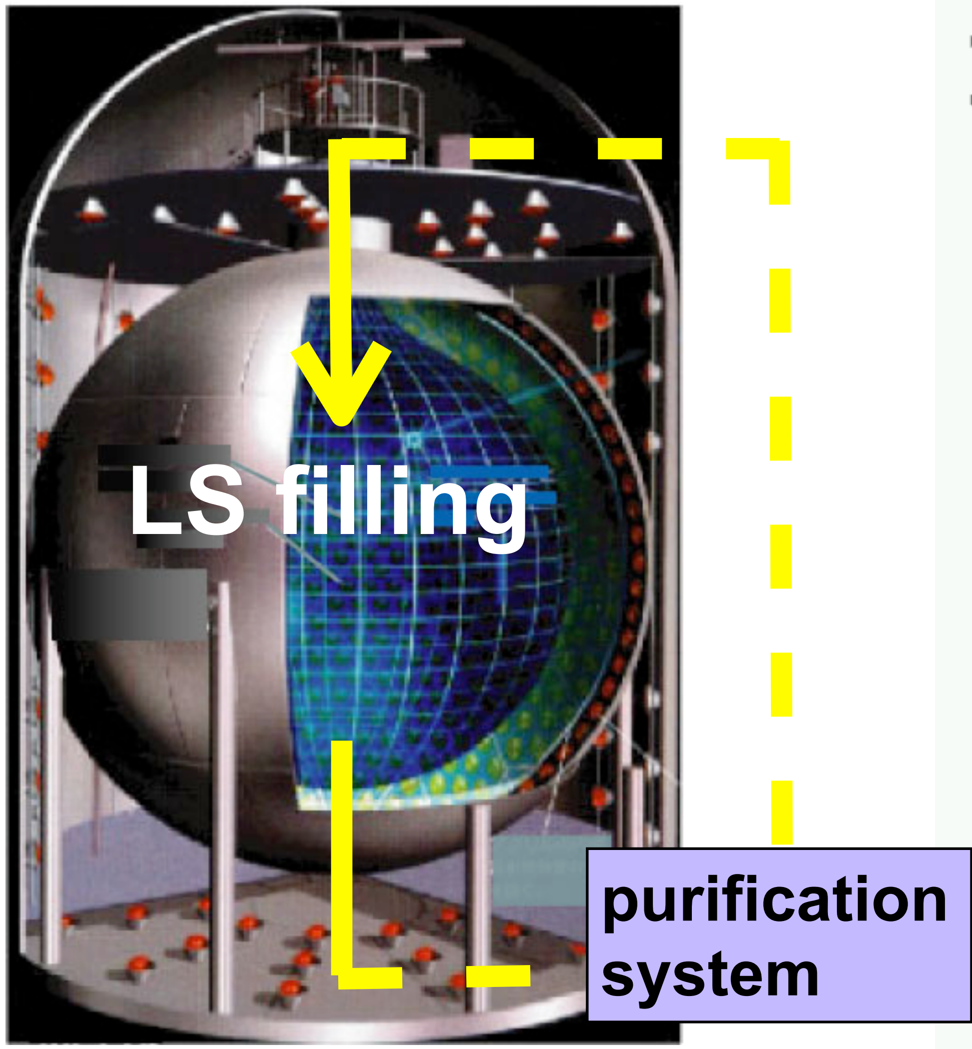
(3) Upgrade of PPO tower for better performance

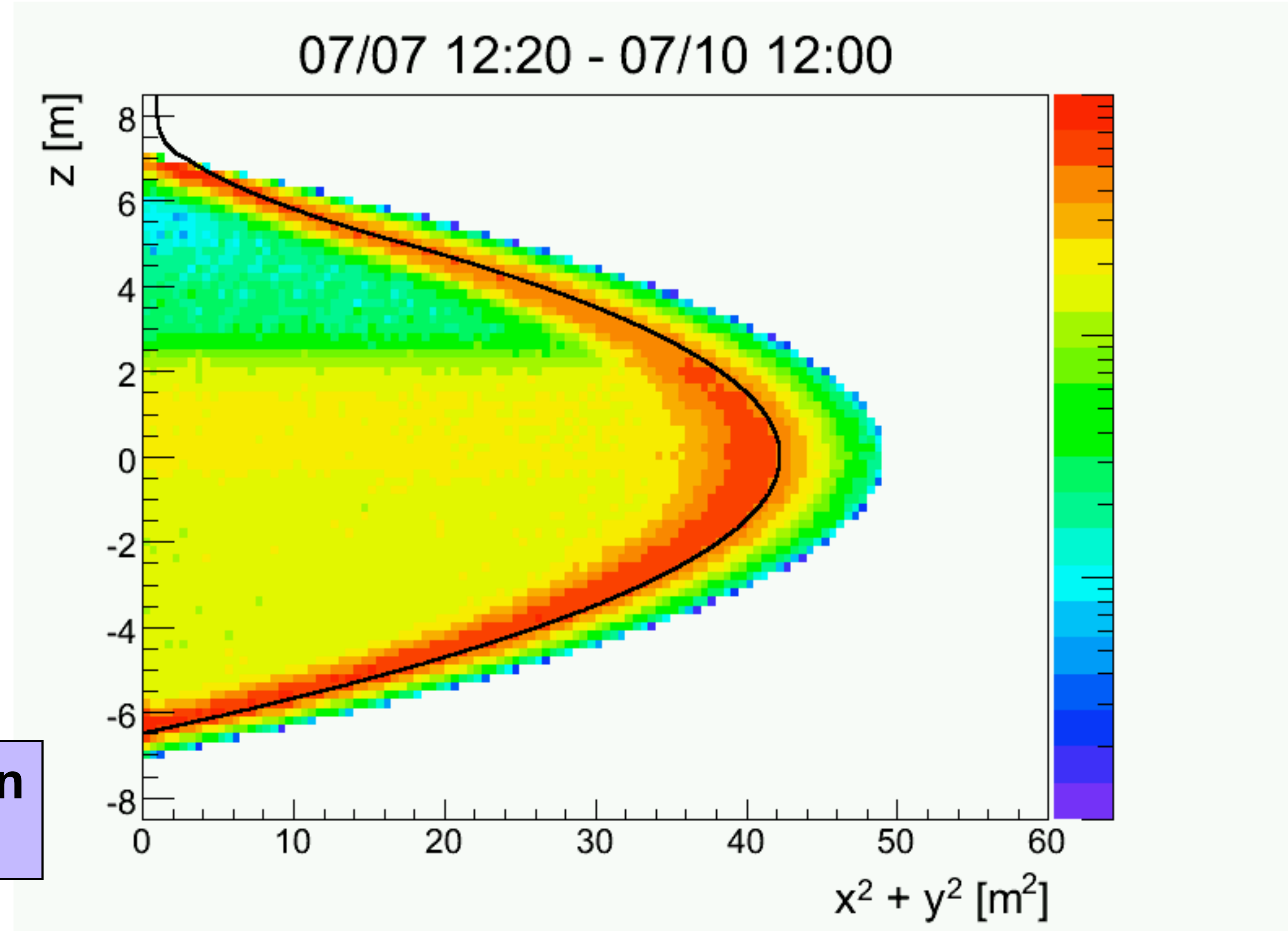
- Low pressure (low temperature) distillation gives efficient removal of impurities in LS

We started the 2nd purification in June

Total purified volume (~ Aug. 31) = 1,200 m^3

2nd Purification Status





- We can keep the LS boundary by the precise density control
- The ^{85}Kr background was reduced by almost two orders of magnitude for full volume LS circulation ~ 1,200 m^3

need ~ a few more cycle?

Summary

- KamLAND improved sensitivity to $\overline{\nu}_e$ observation.

data-set : 766 ton-yr → 2881 ton-yr
E threshold : 2.6 MeV → 0.9 MeV
syst. uncertainty : 6.5% → 4.1%

(α, n) B.G. uncertainty :
32% → 10% (ground state)
100% → 20% (excited state)

- In the reactor neutrino analyses, we showed

- Oscillatory shape ~ 2 cycle of neutrino oscillation.
- Exclusion of LMA II and 0 at more than 4σ C.L.
- Precise measurement of oscillation parameters.

- Geo neutrino flux was measured with better precision.

- We started the 2nd purification in June (total purified volume = 1,200 m^3), it is going on, and the B.G. reduction status will be reported soon.