KamLAND Results

Week Interactions and Neutrinos (WIN'09)

Sep. 15, 2008

I. Shimizu (Tohoku Univ.)

KamLAND Collaboration

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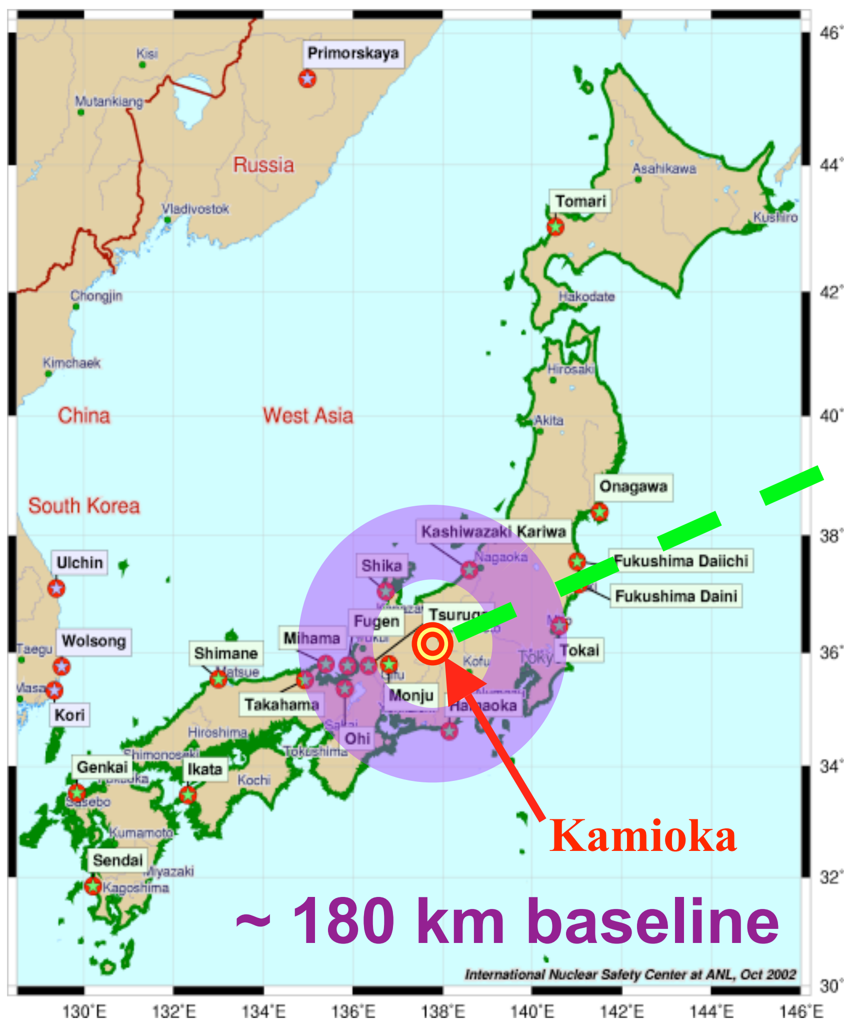
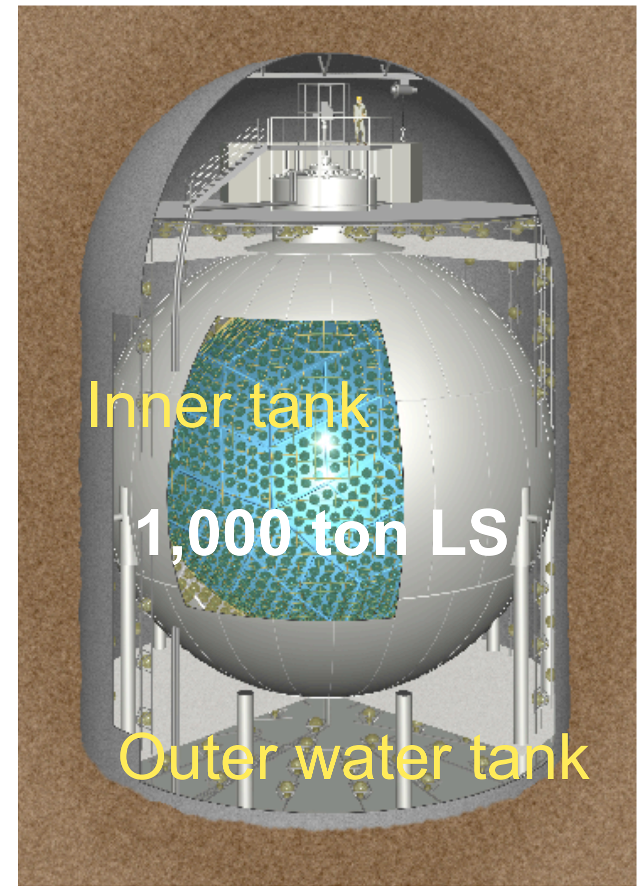
KamLAND

Kamioka Liquid Scintillator Anti-Neutrino Detector



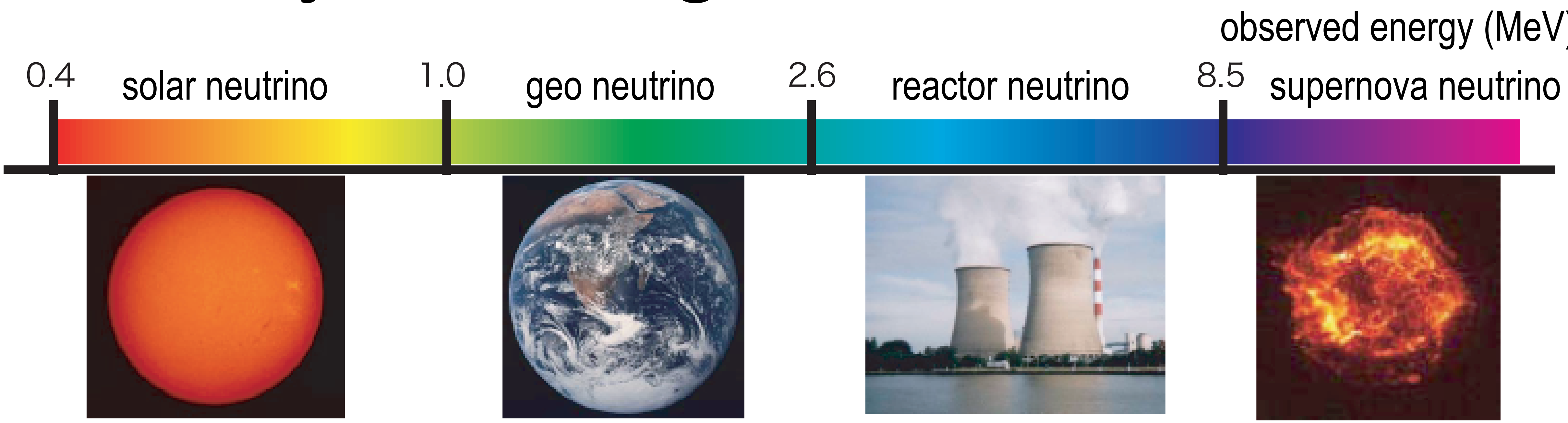


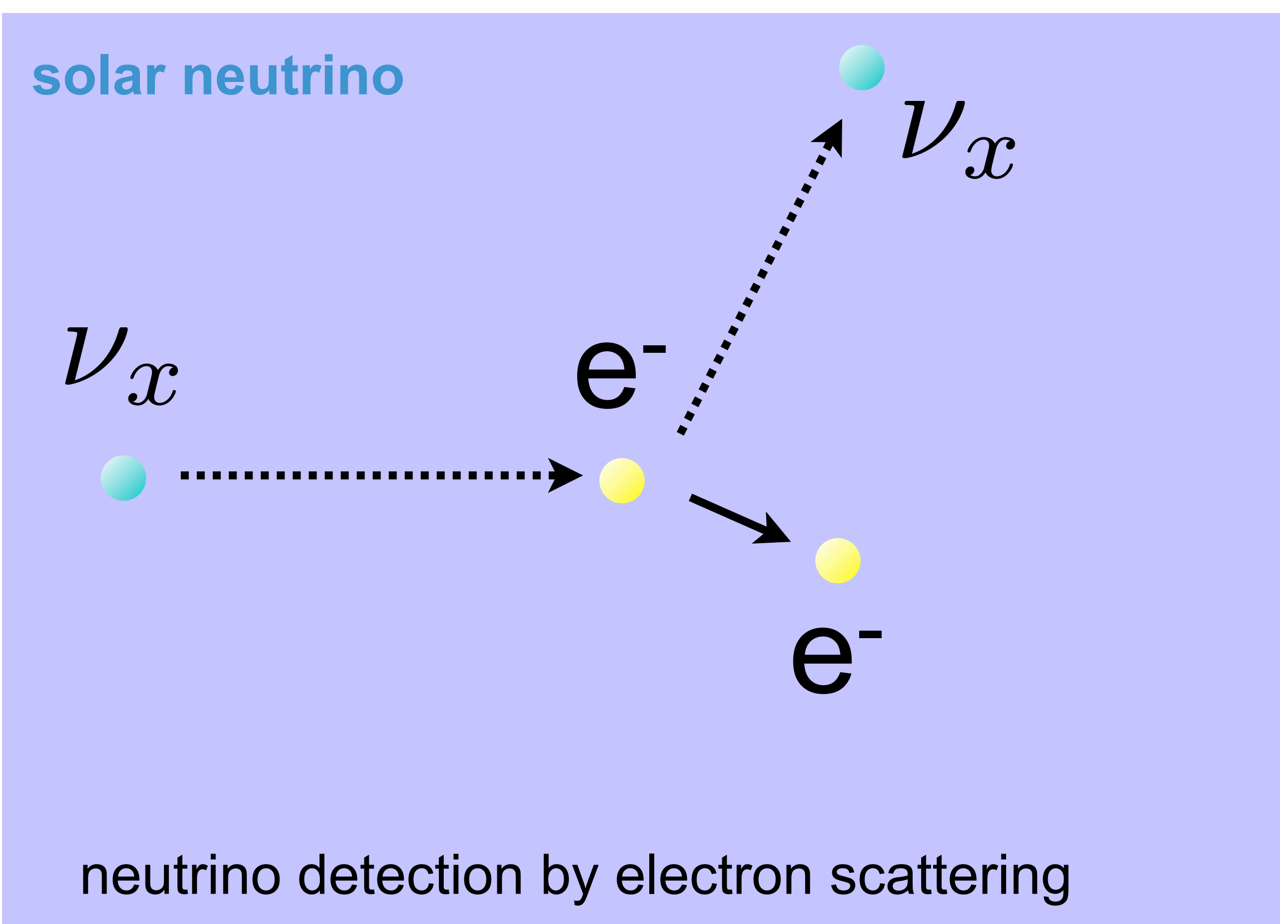
34% photo-coverage with 1325 17” and 554 20” PMTs

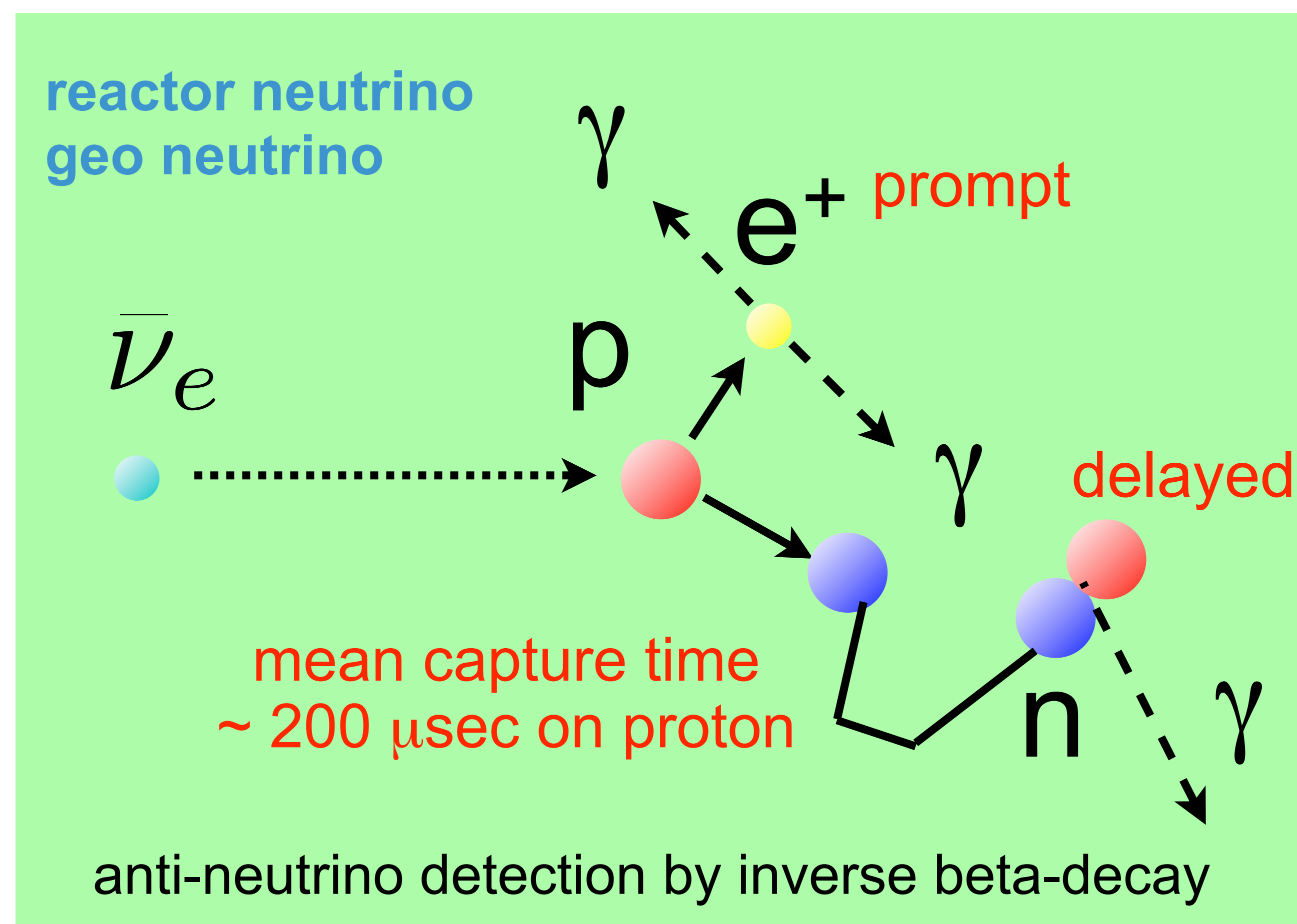
Reactor neutrino : sensitive to LMA solution

<u>1st result (Dec. 2002)</u>	disappearance of $\overline{\nu}_e$
<u>2nd result (Jun. 2004)</u>	spectral distortion of $\overline{\nu}_e$
<u>3rd result (Jan. 2008)</u>	precise measurement of oscillation parameters

Physics Target in KamLAND







Reactor and Geo Neutrino Analysis

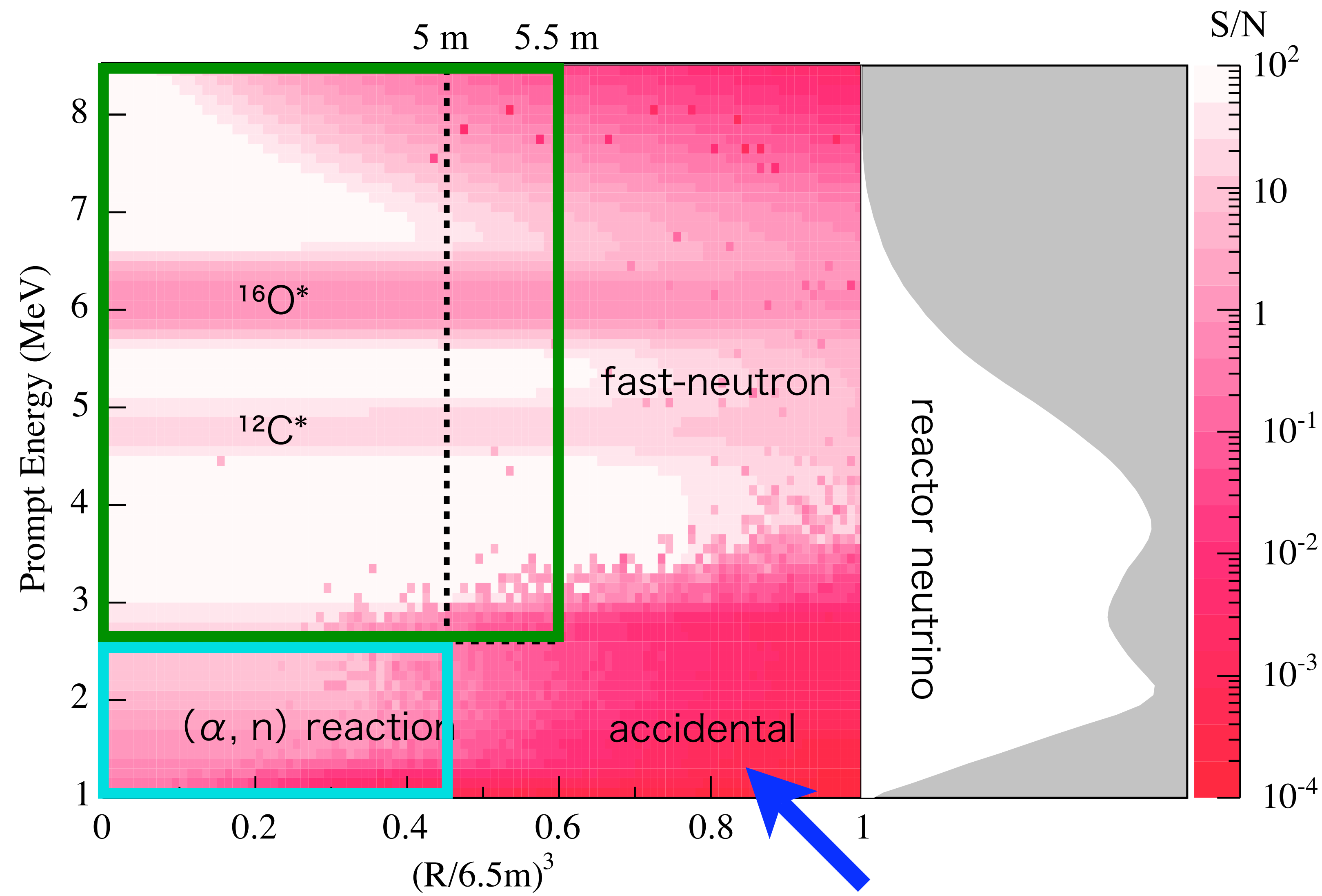
previous result

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

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)



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

Analysis improvement

(1) efficient accidental background rejection

(2) combined analysis of reactor and geo neutrinos

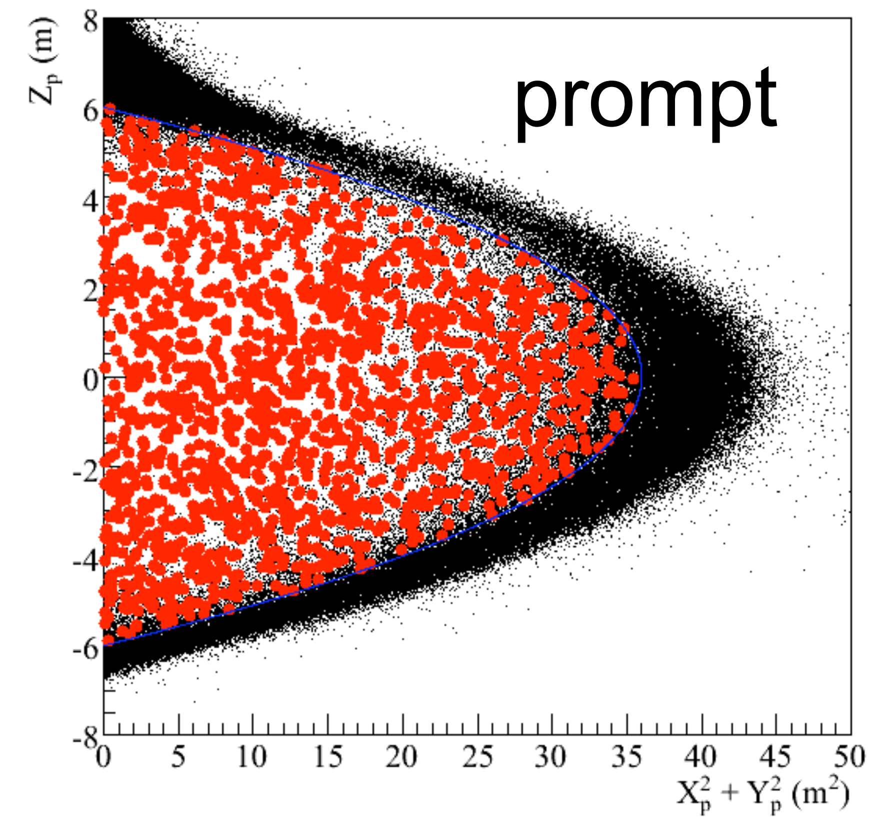
Anti-Neutrino Event Selection

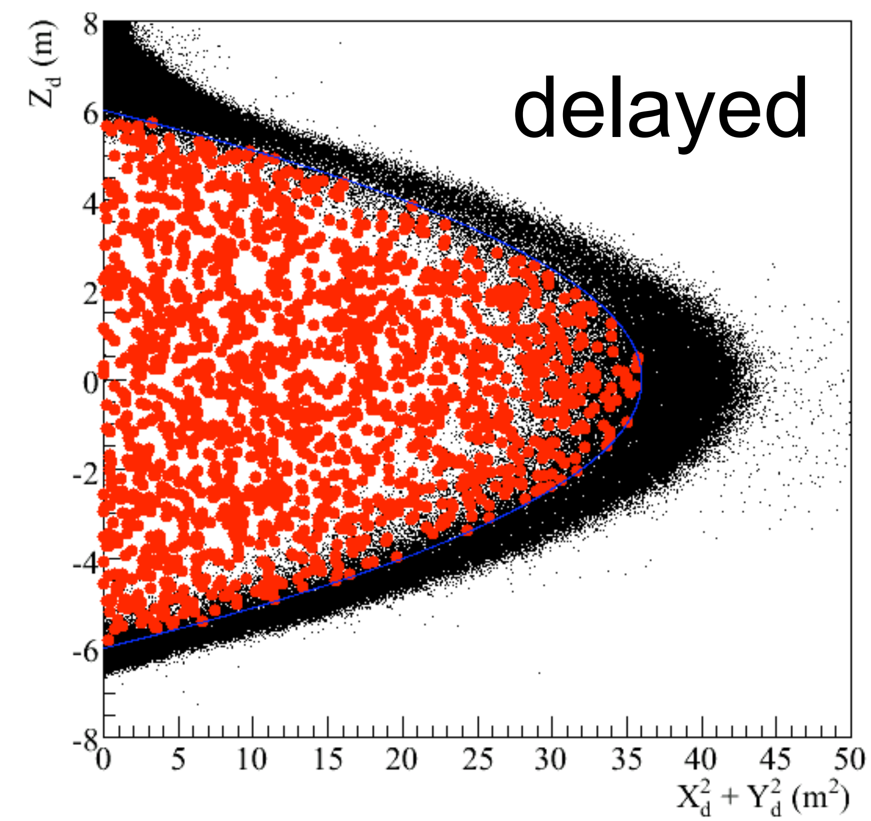
(a) accidental B.G. discrimination

- $0.5 < \Delta T < 1000\ \mu s$
- $\Delta R < 2$ m
- $1.8\ \text{MeV} < E_{delayed} < 2.6\ \text{MeV}$ or $4.0\ \text{MeV} < E_{delayed} < 5.8\ \text{MeV}$
- $0.9\ \text{MeV} < E_{prompt} < 8.5\ \text{MeV}$
- 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 $f_{acc}(E_p, E_d, \Delta R, \Delta T, R_p, R_d)$

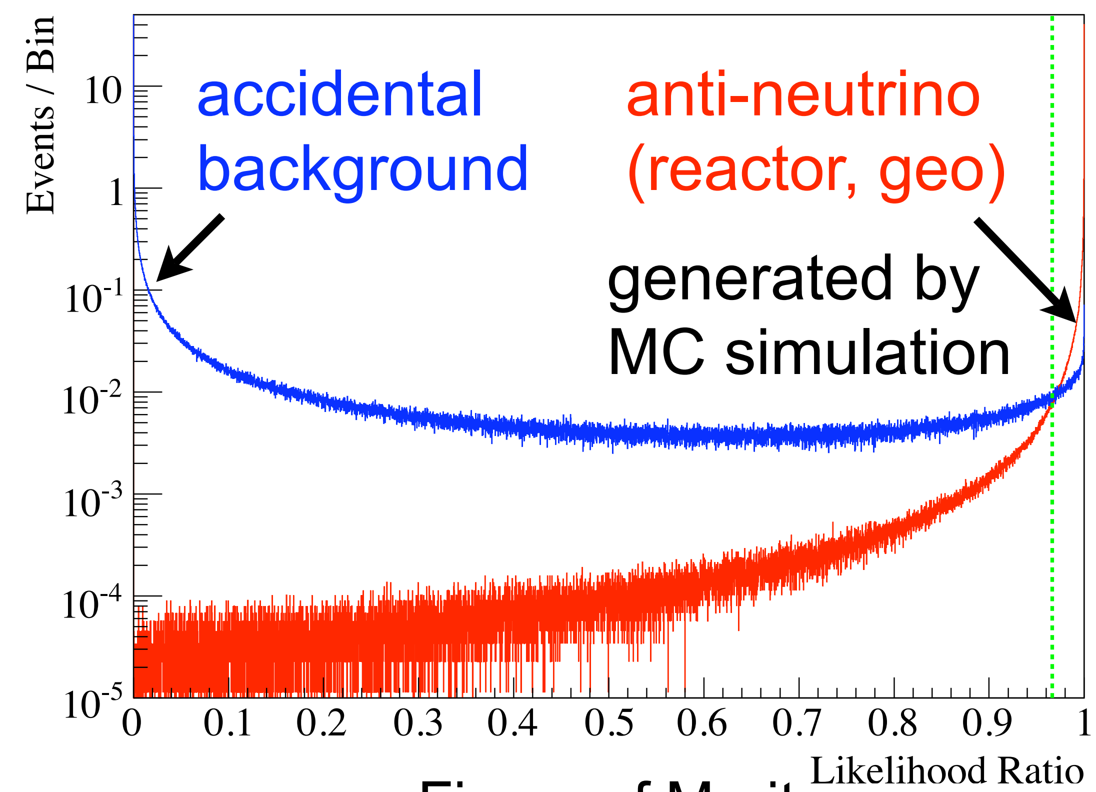
Signal PDF $f_{\bar{\nu}_e}(E_p, E_d, \Delta R, \Delta T, R_p, R_d)$

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

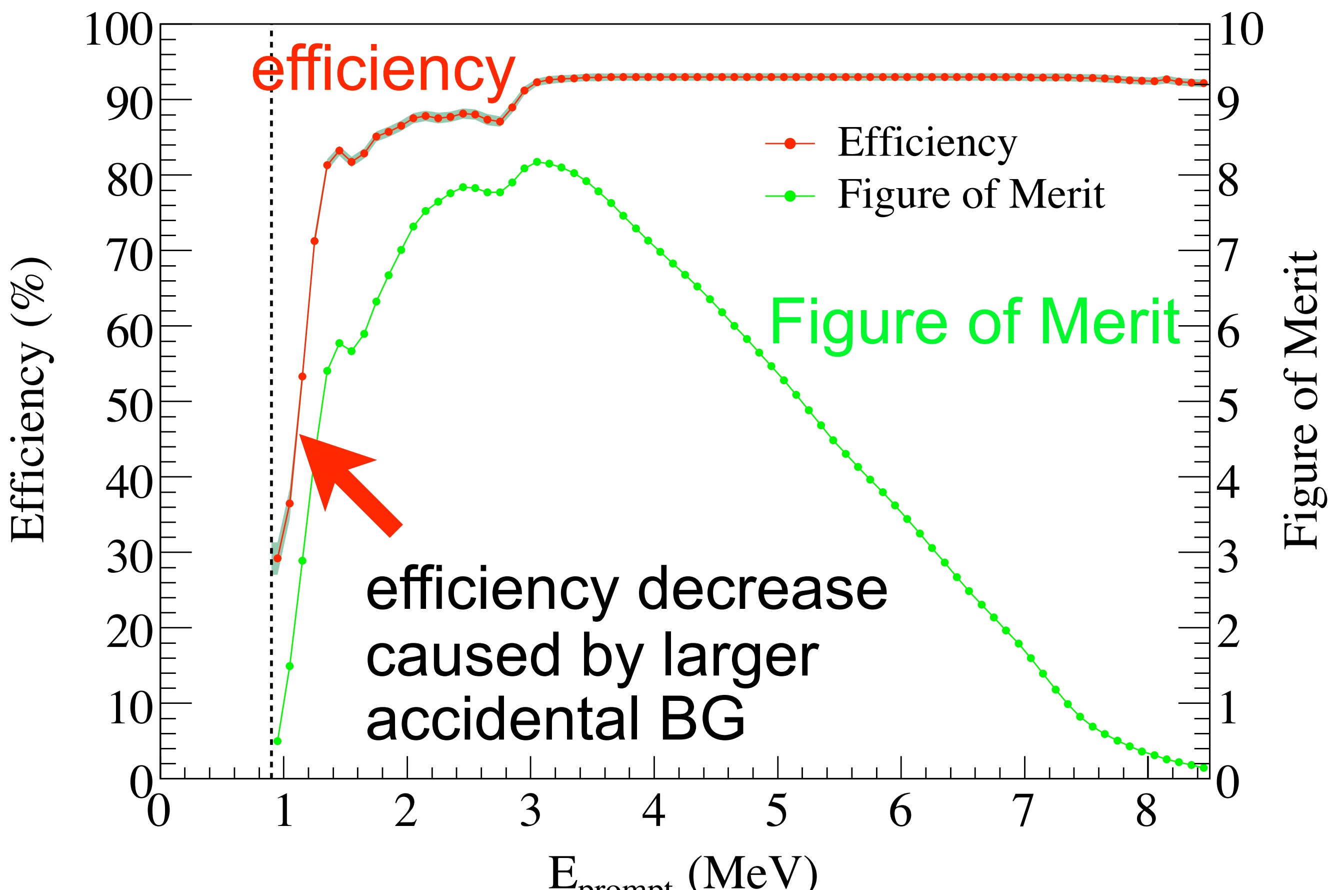
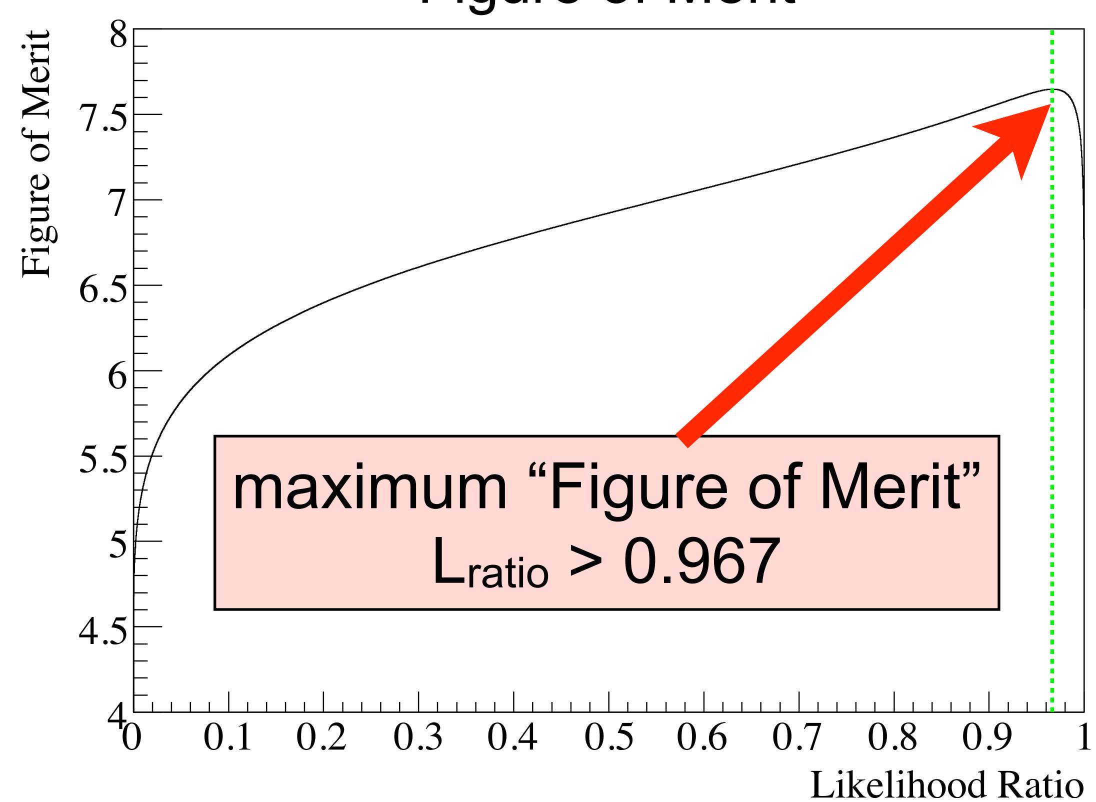


Figure of Merit



Systematic Uncertainty

“full volume” calibration lowered the fiducial volume error

(4.7% in previous analysis)

Detector related

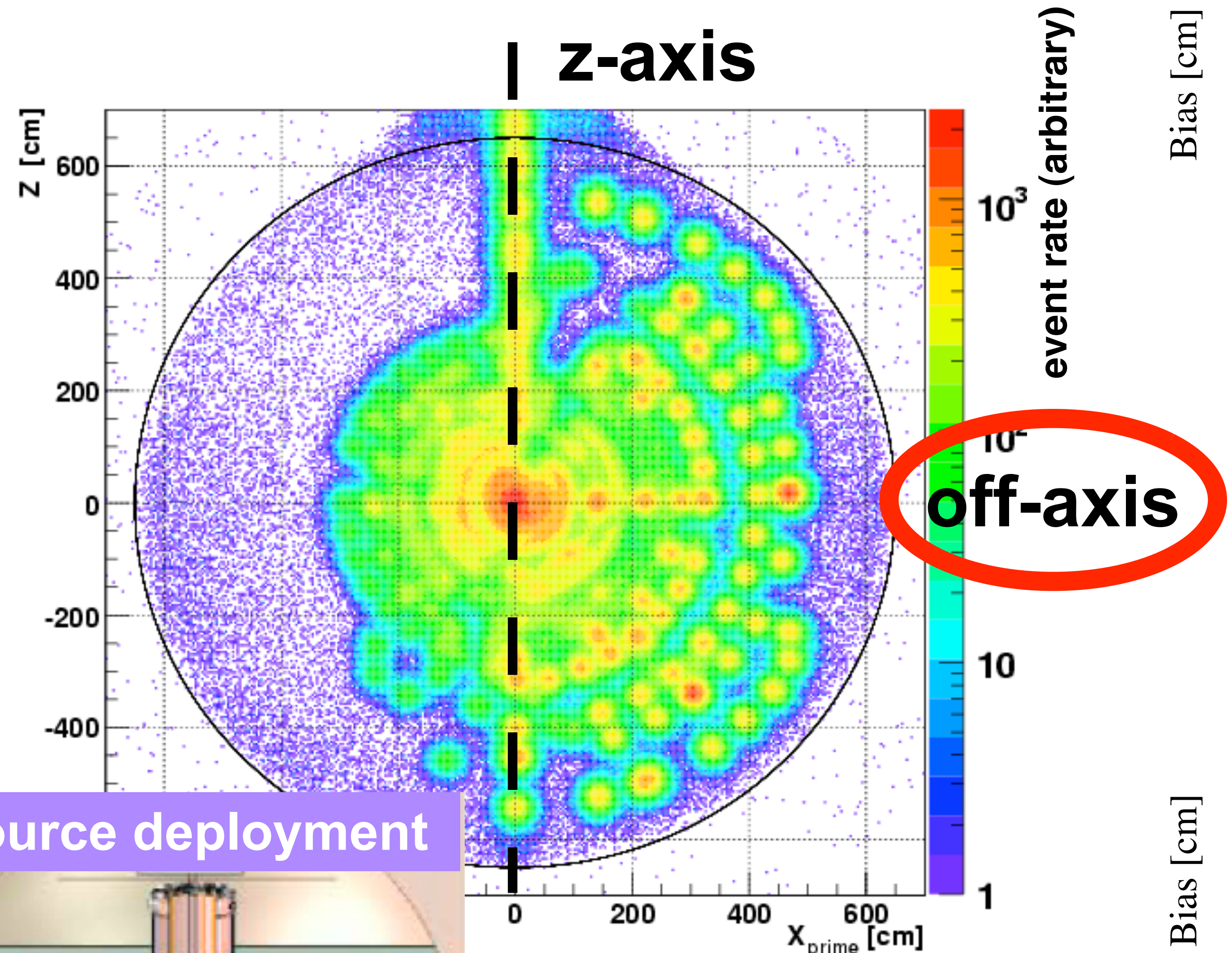
Fiducial volume	1.8%
Energy scale	1.5%
L-selection eff.	0.6%
OD veto	0.2%
Cross section	0.2%
	2.4%

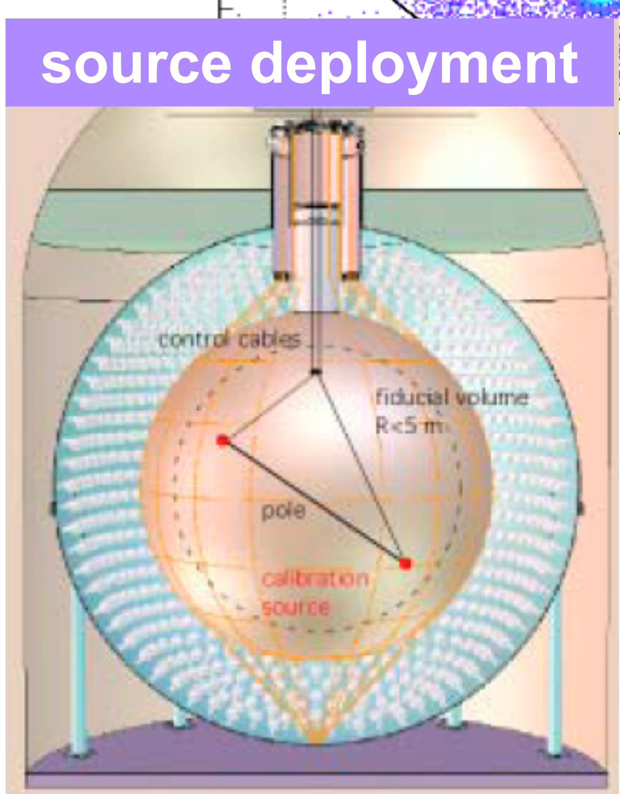
Reactor related

$\bar{\nu}_e$ 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



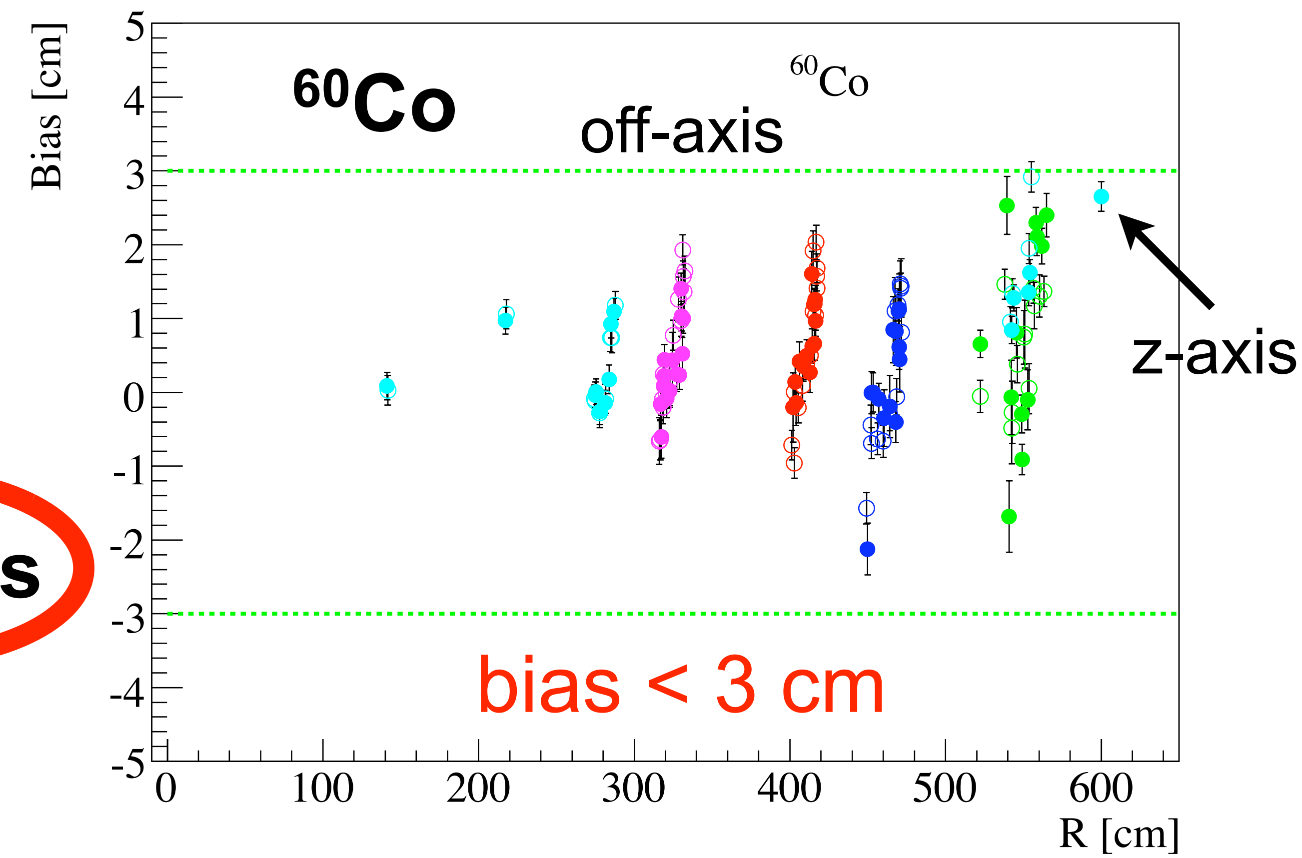


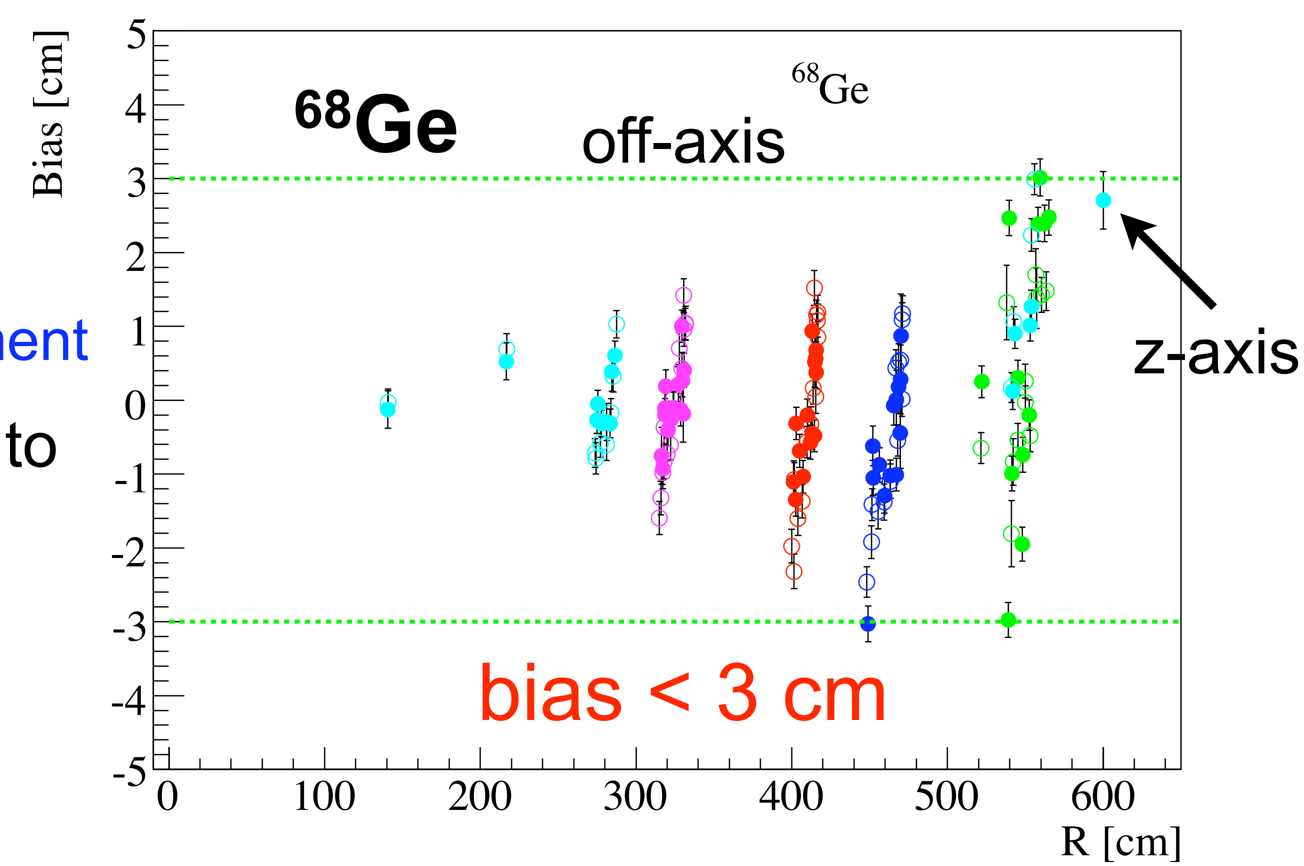
“4pi calibration” system for the off-axis source deployment

bias < 3 cm corresponds to 1.8% volume uncertainty

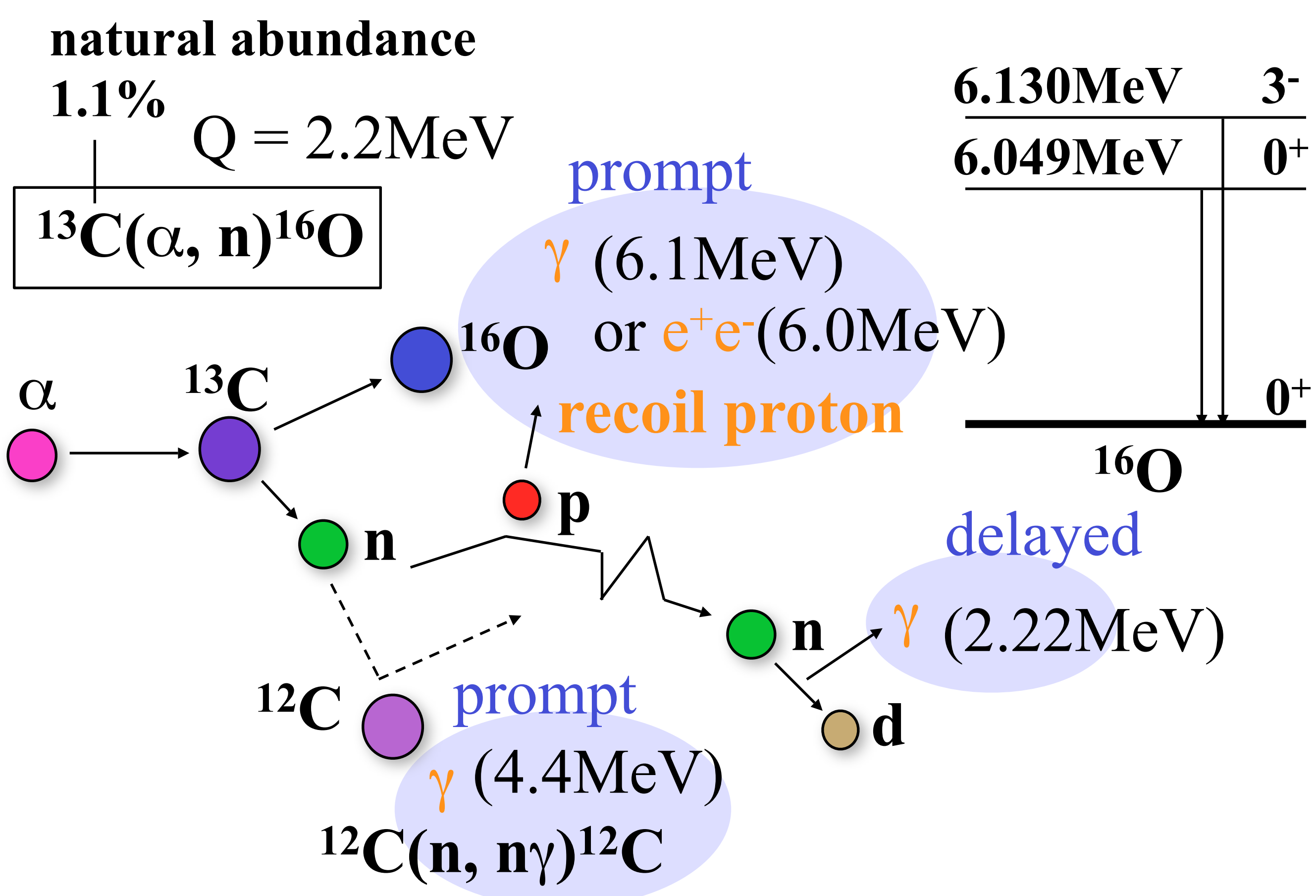
↓

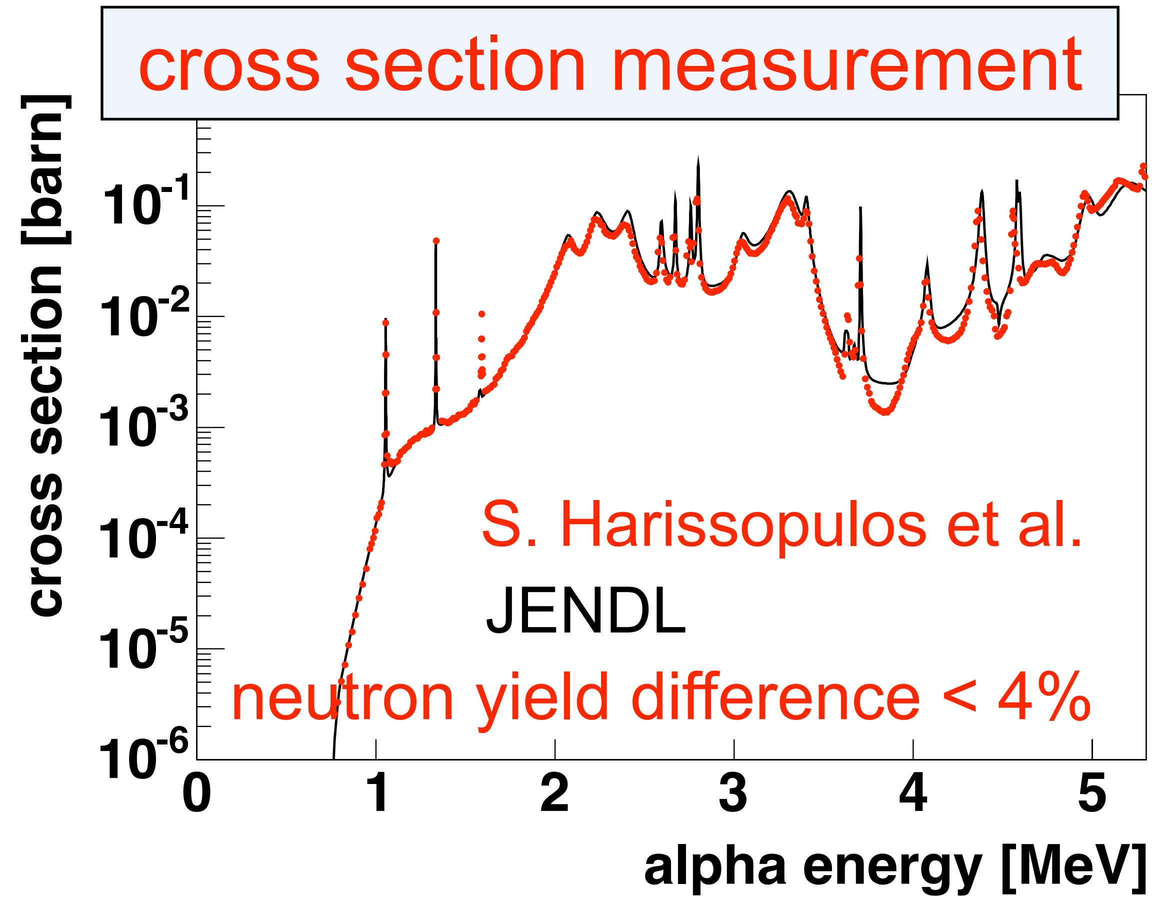
cross-checked by $^{12}B/^{12}N$ uniformity





(α, n) Background Estimation





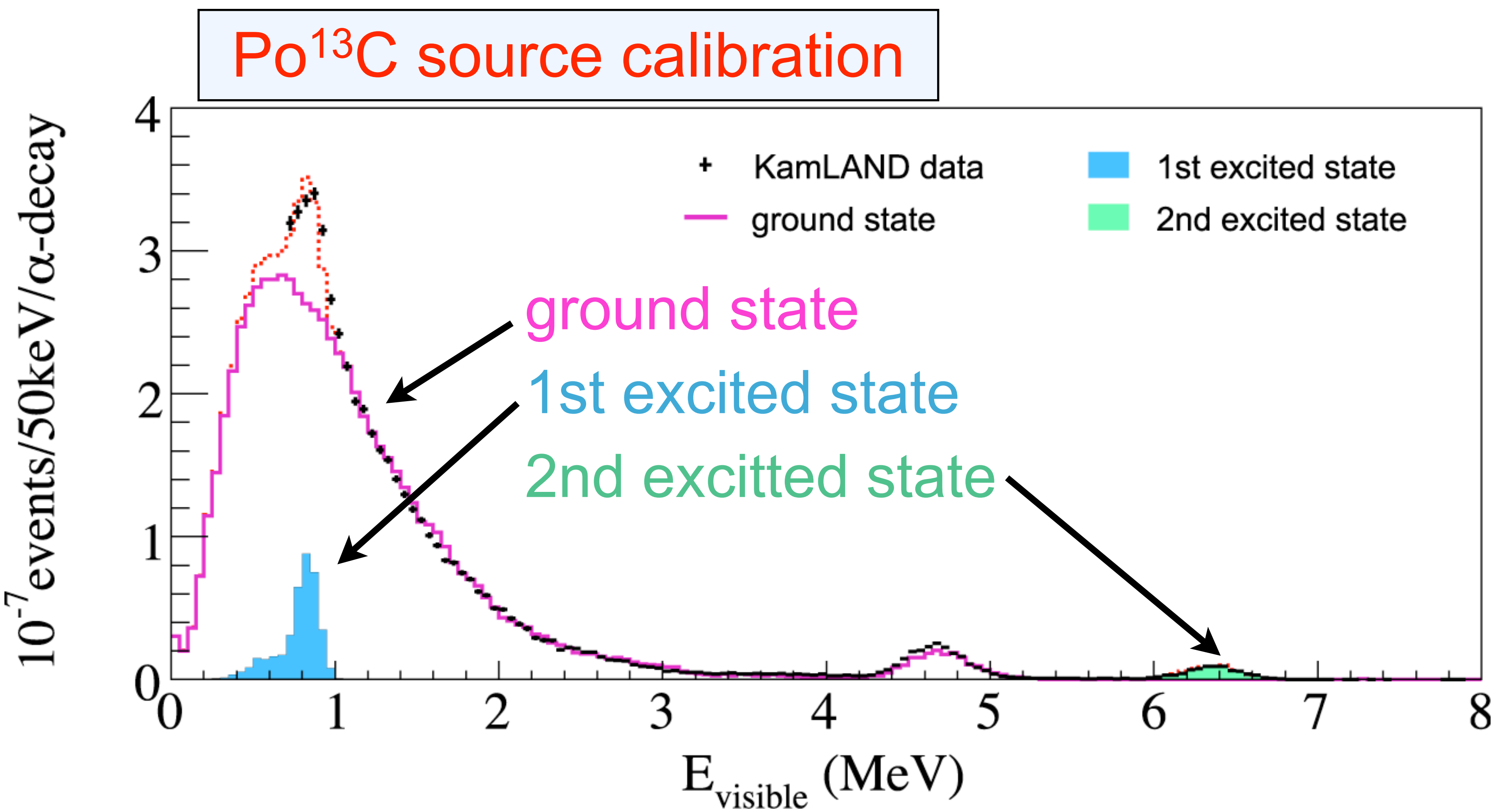
total cross section was determined precisely

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

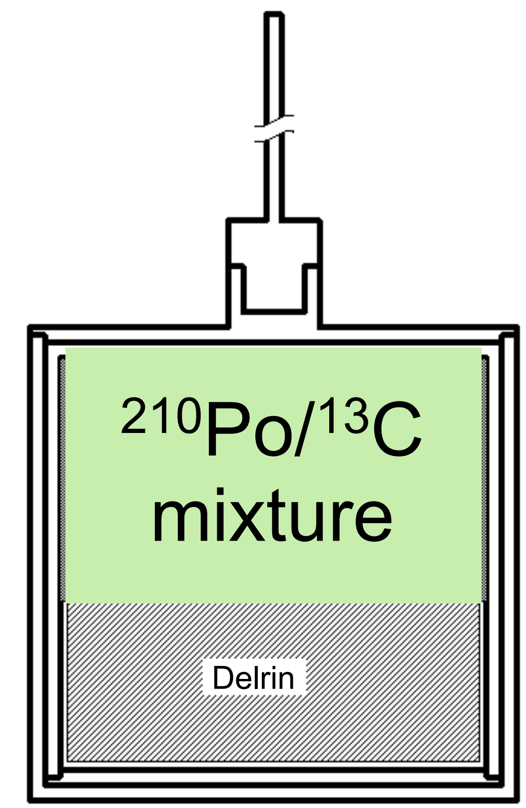
Cross section for each branch should be measured

Cross Section Measurement

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



Po^{13}C source



(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

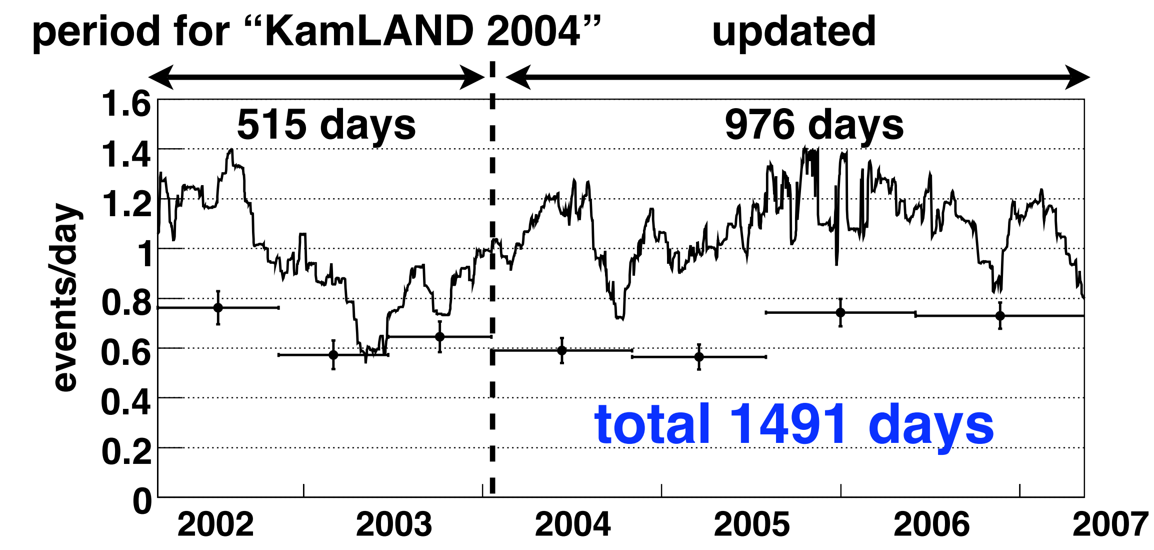
Fit constrained through B.G. expected

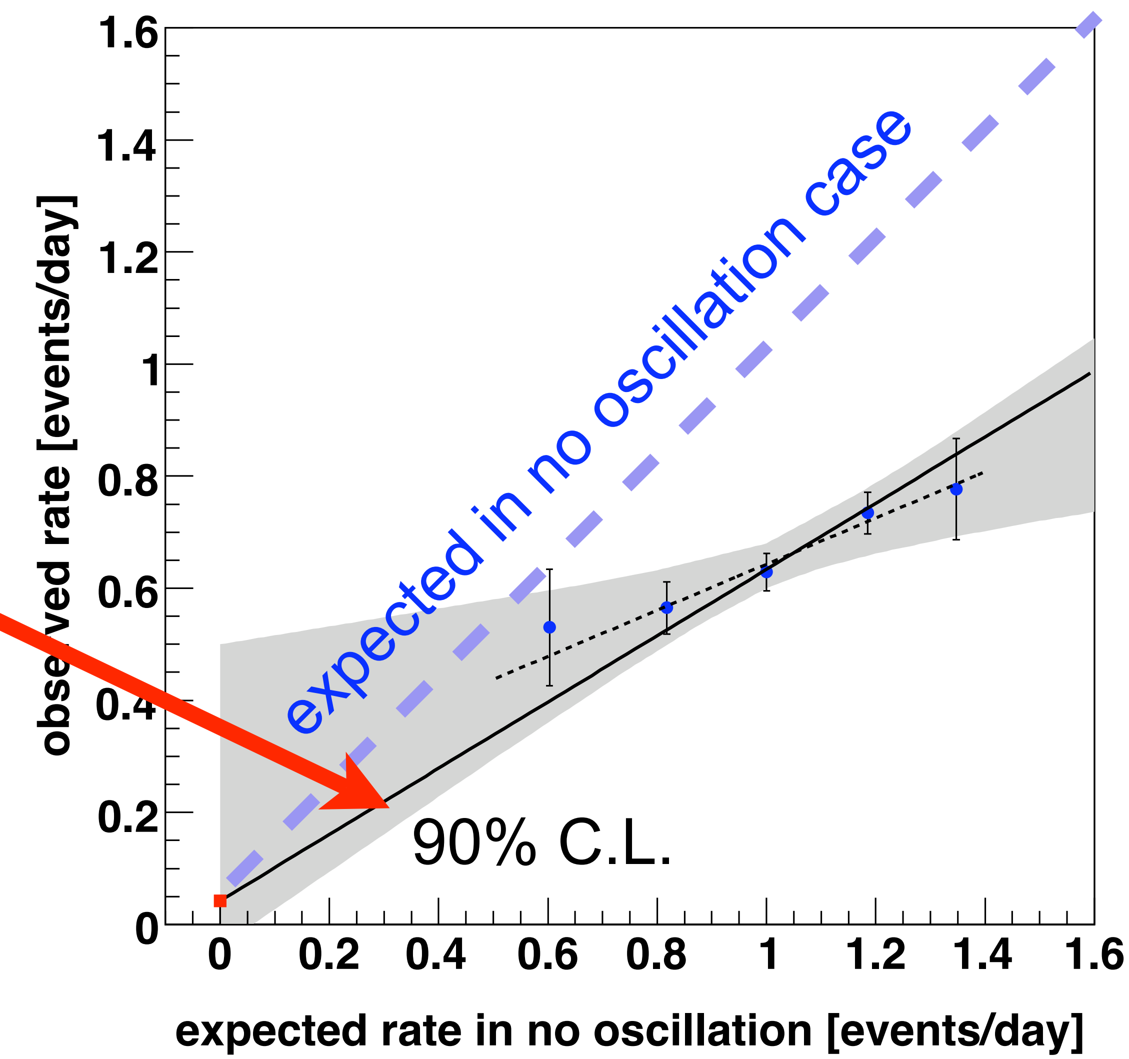
χ^2 / ndf = 2.8 / 4

Fit with a horizontal line

χ^2 / ndf = 12.0 / 4

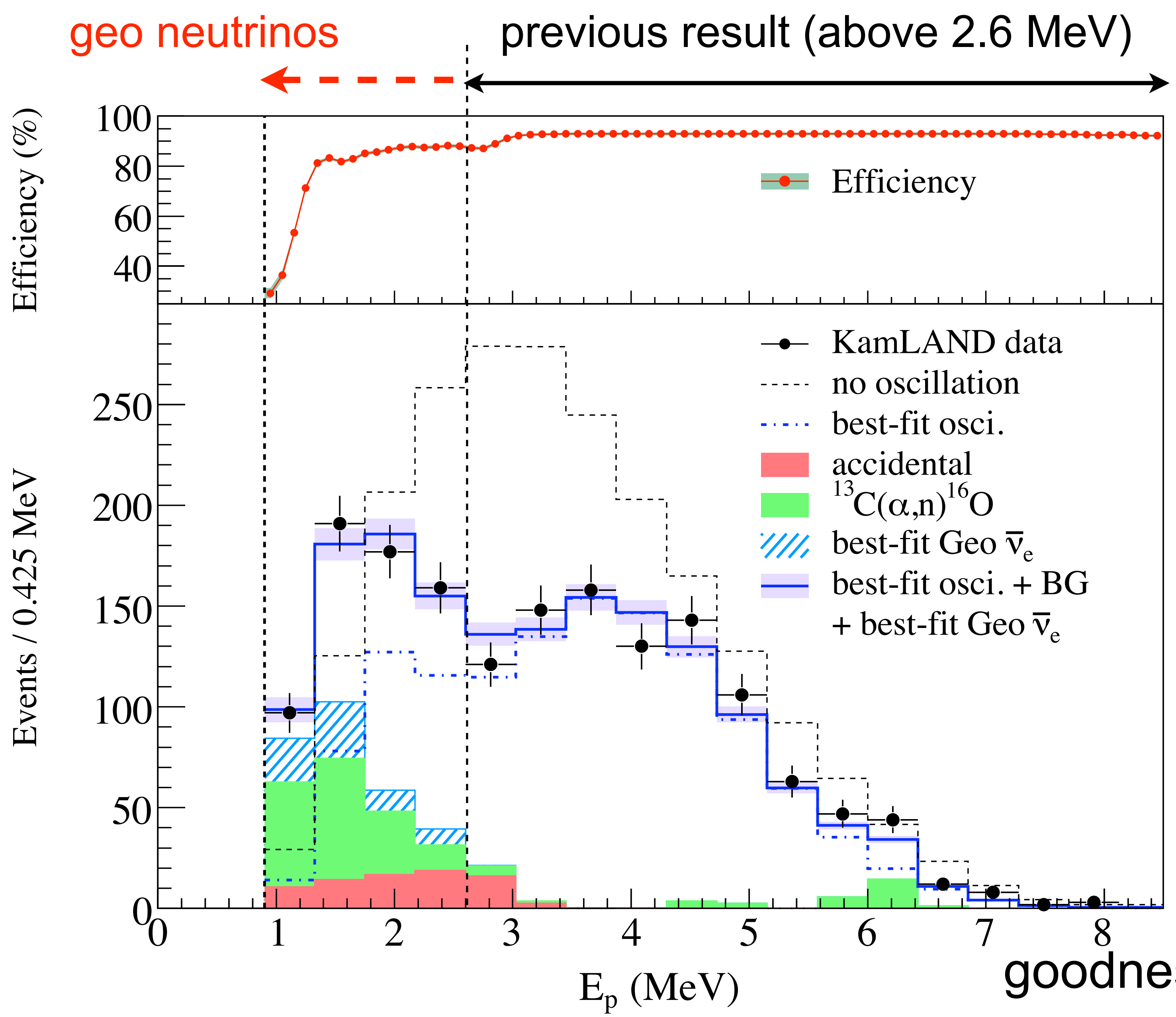
(1.7% C.L.)





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

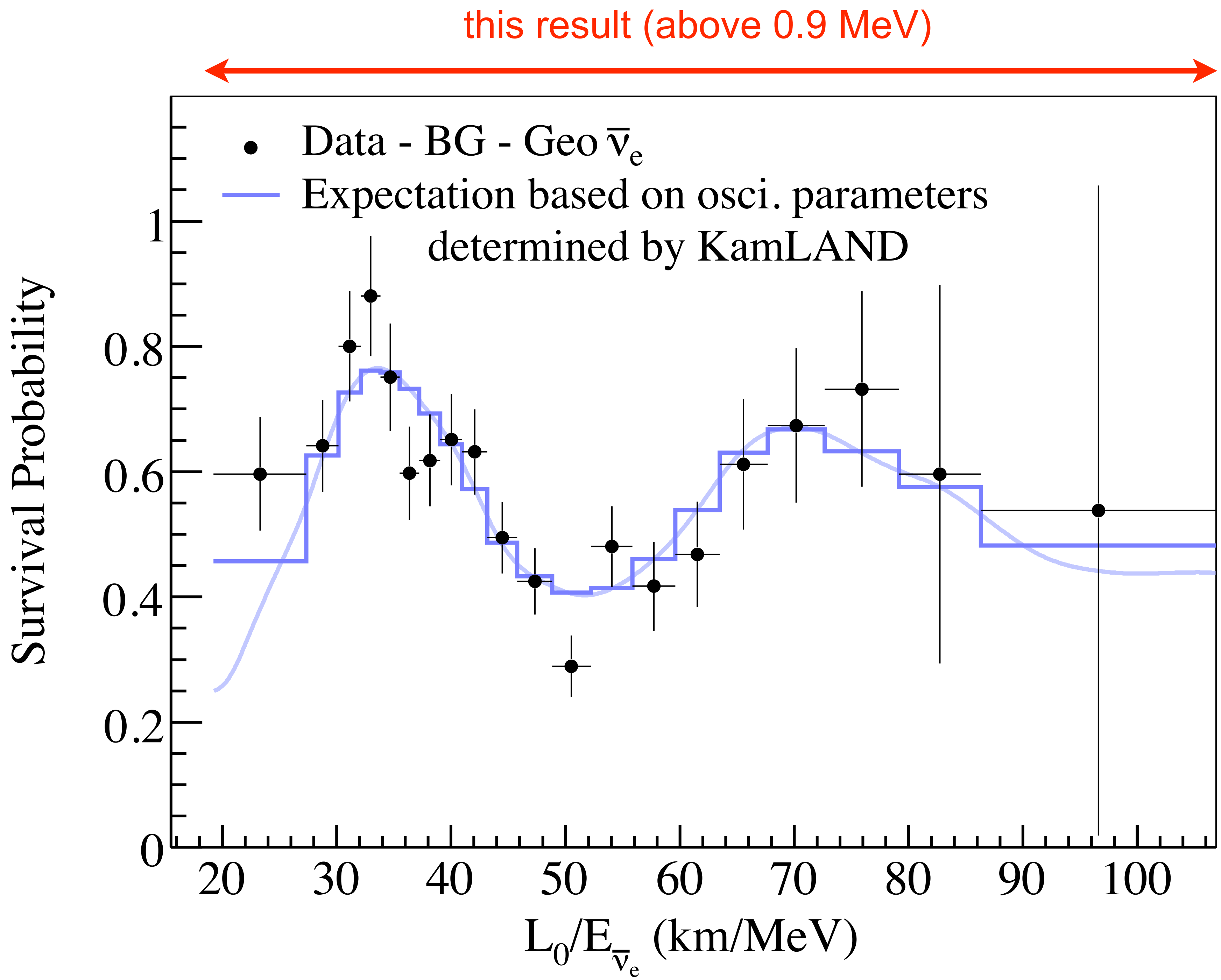
goodness of fit using equal probability bins

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



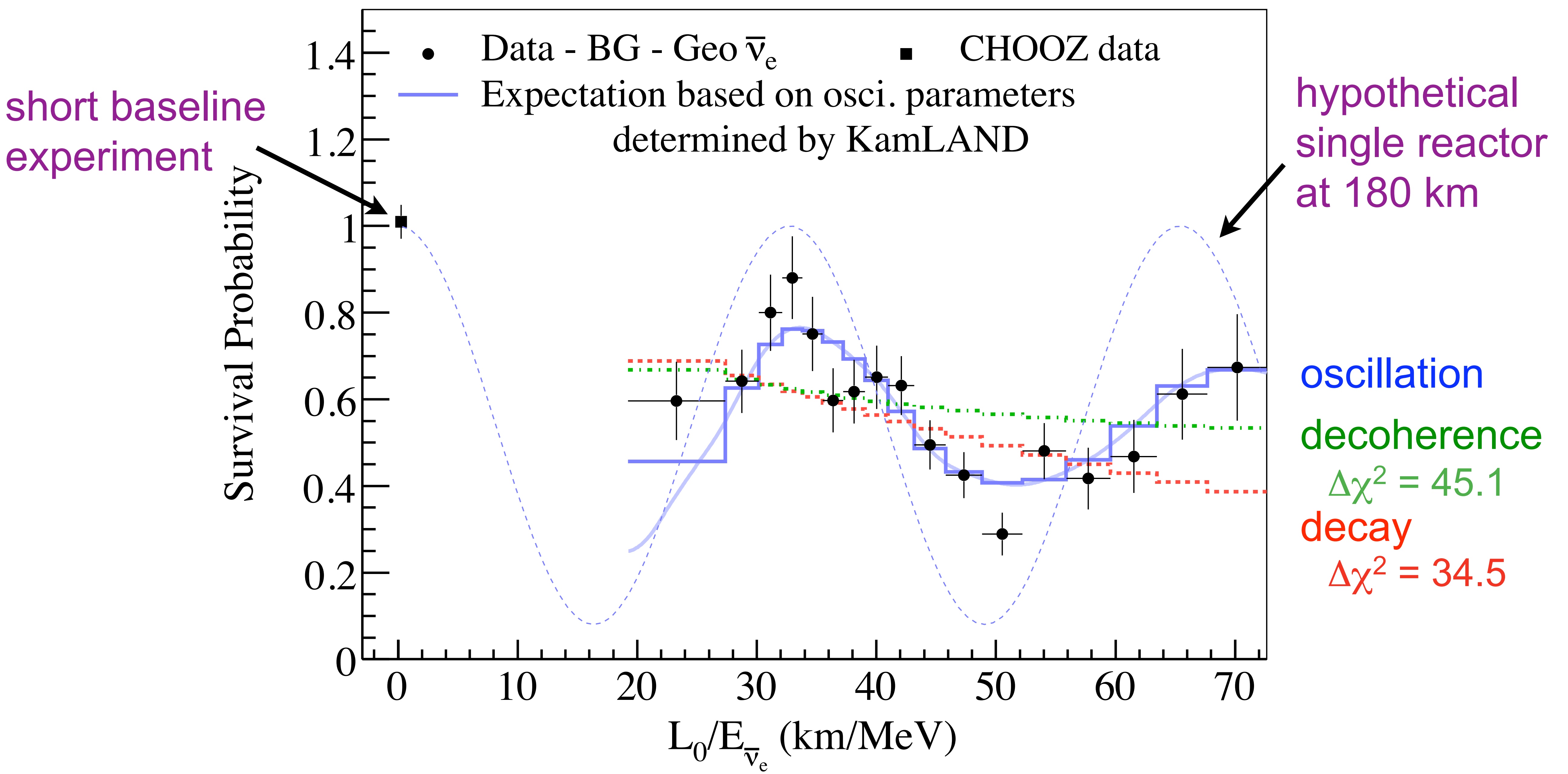
~ 2 cycle of oscillation

strong evidence of neutrino oscillation

Alternate Hypothesis

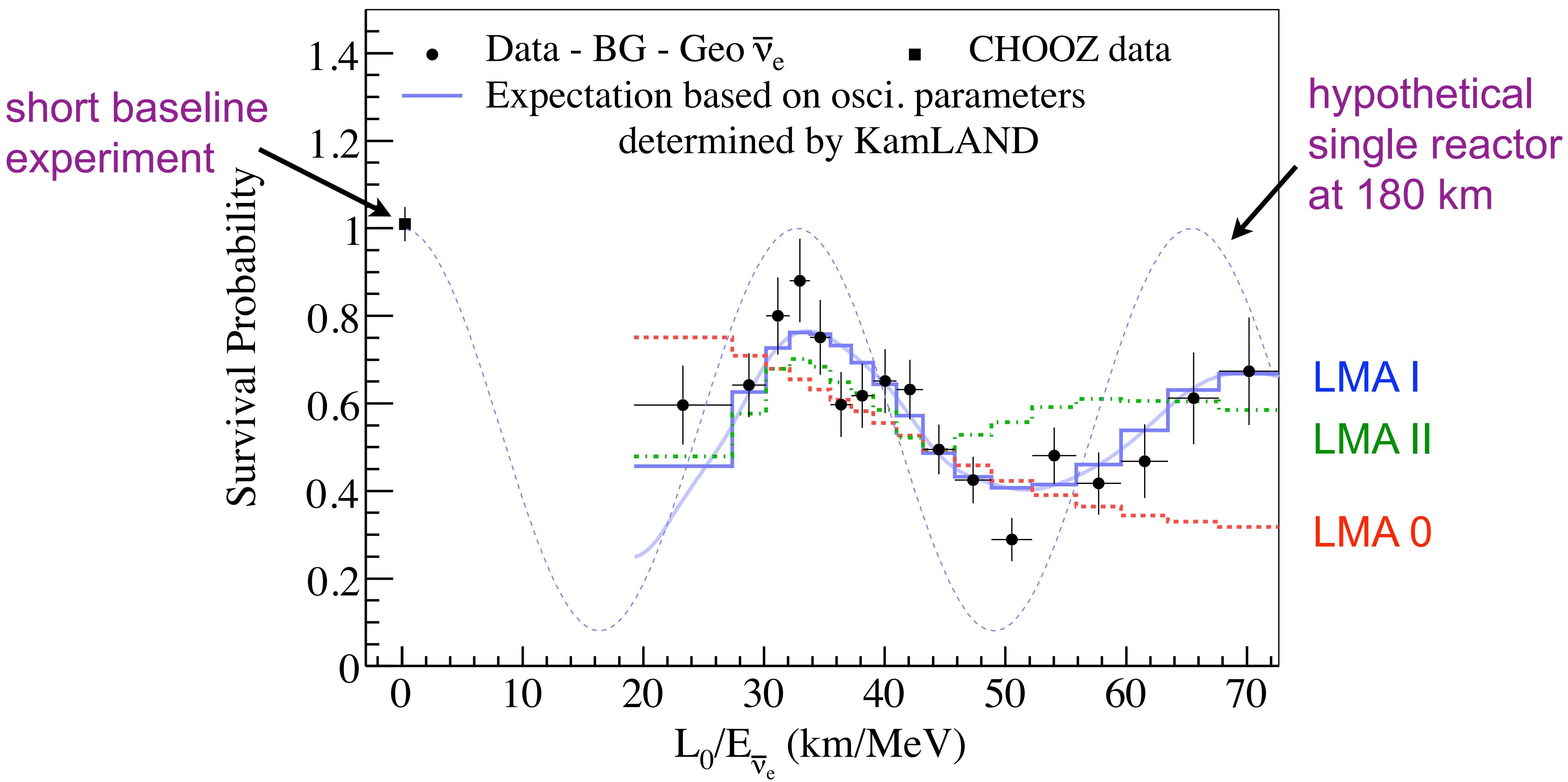
V. D. Barger et al., Phys. Rev. Lett. 82, 2640 (1999)

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



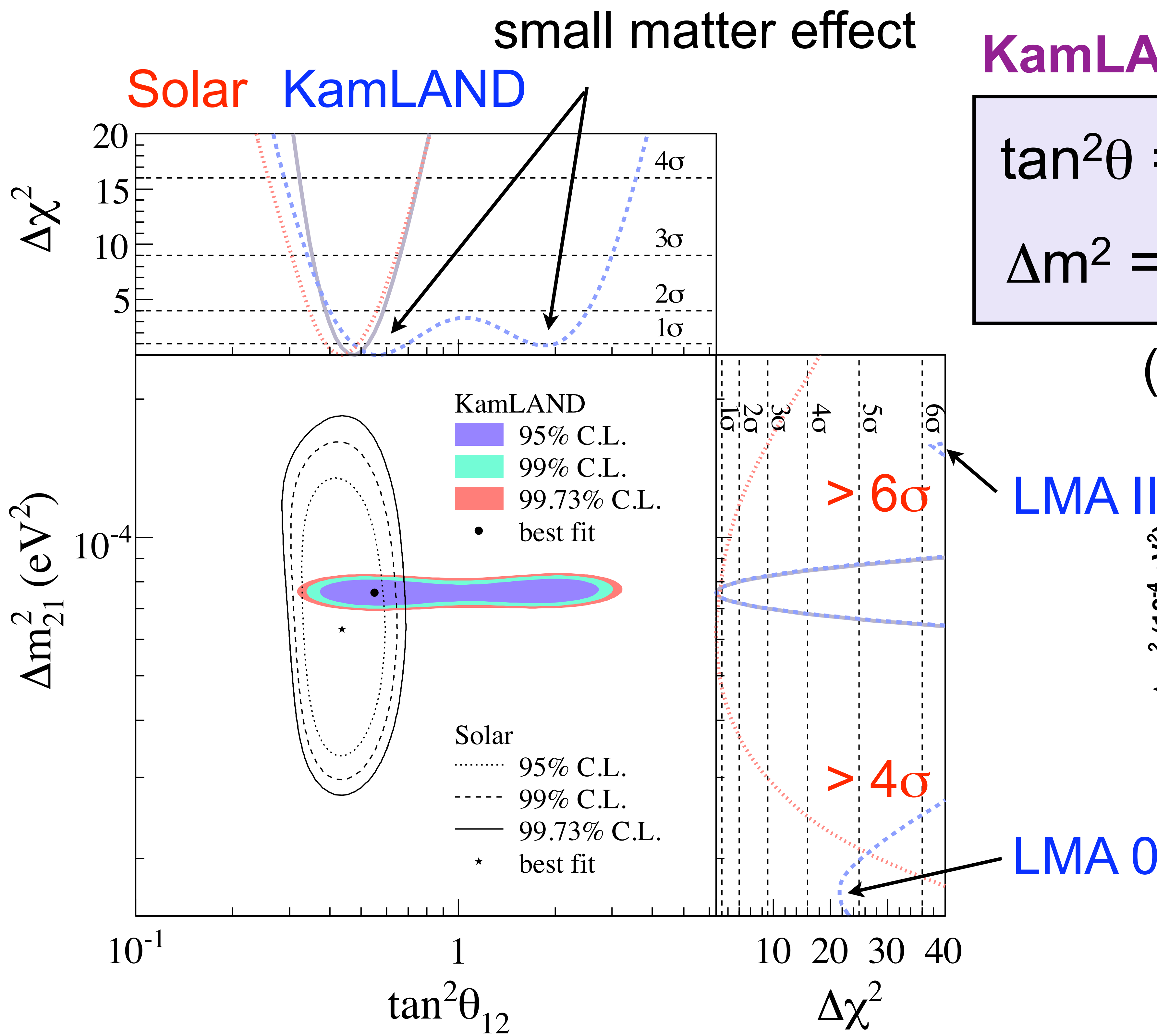
best model is neutrino oscillation

Alternate Wavelength



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

Oscillation Parameters

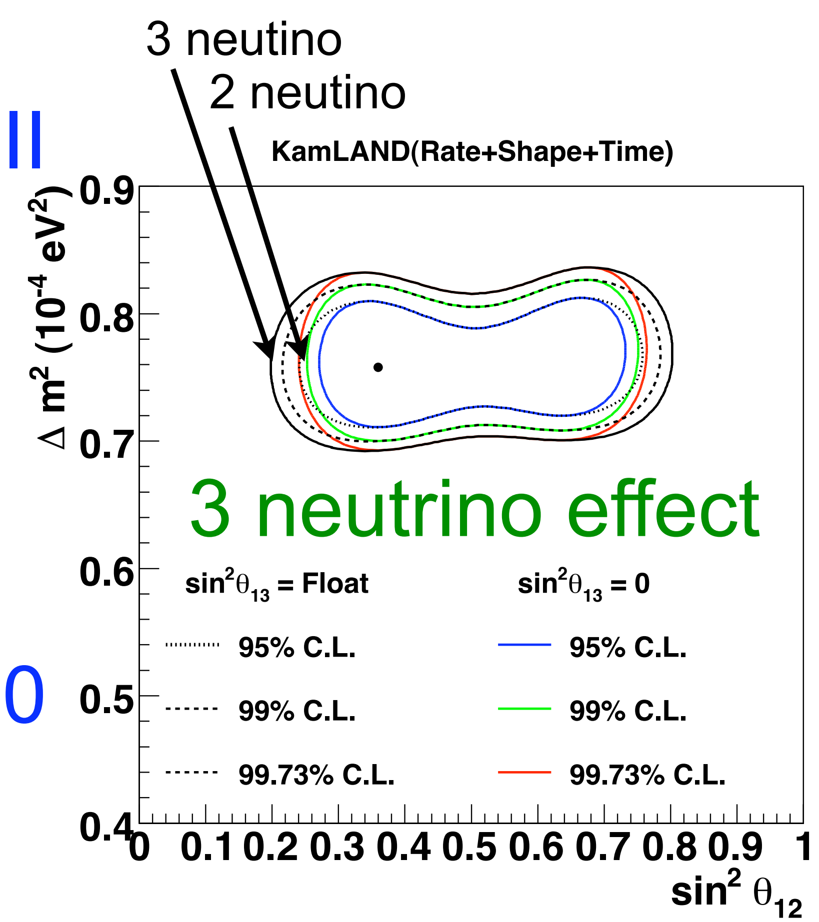


KamLAND only

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

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

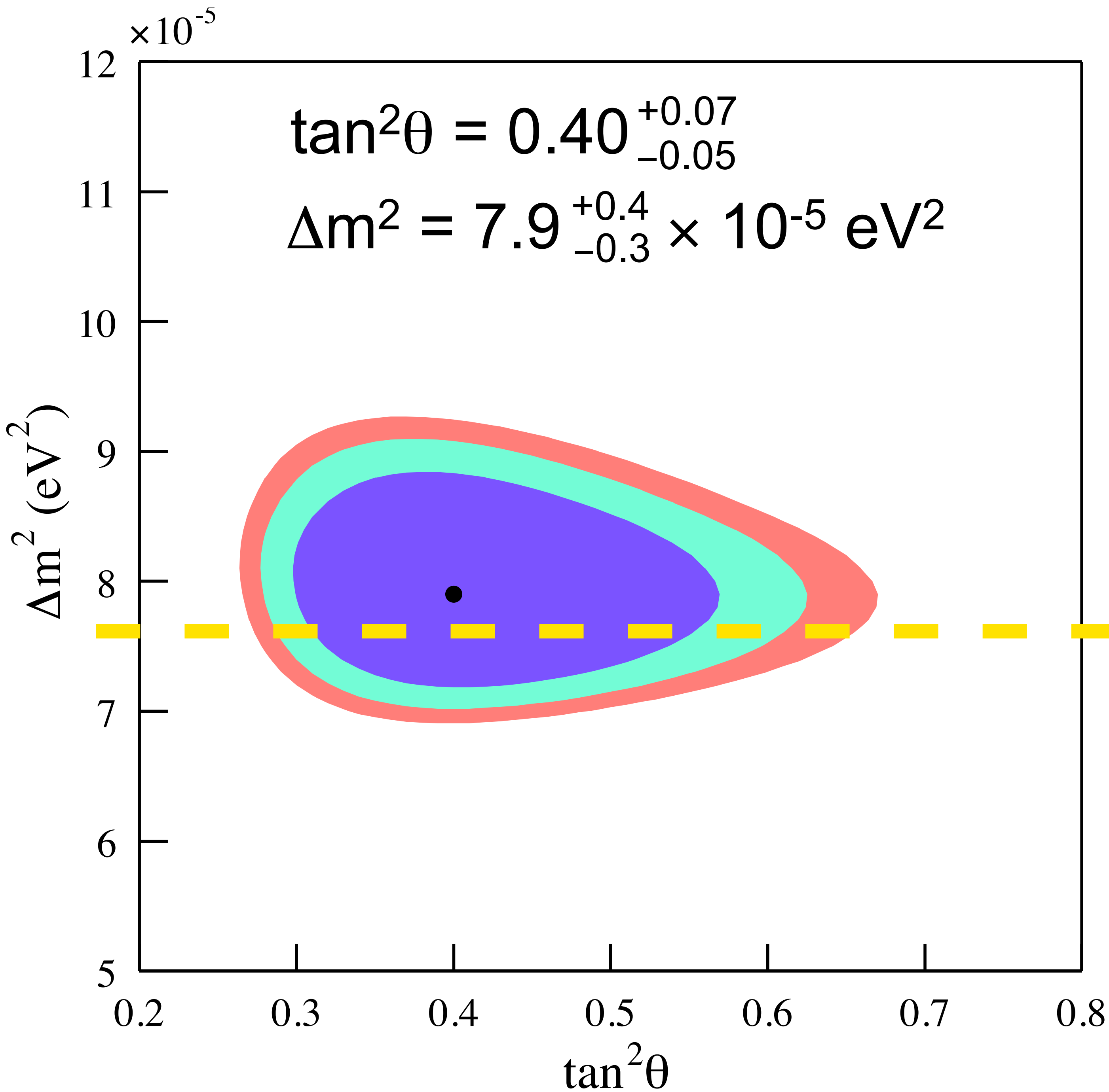
(marginalized error)



same result for Δm^2

Precise Measurement of Δm^2

KamLAND 2004



This result

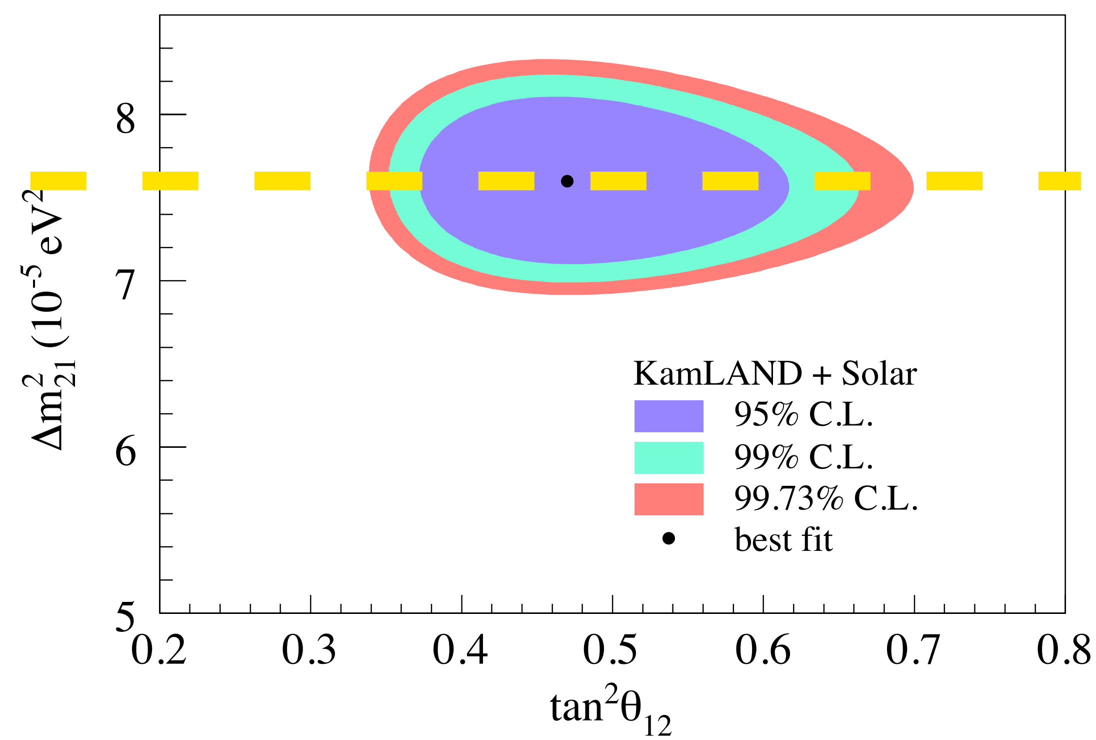
KamLAND + Solar

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

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

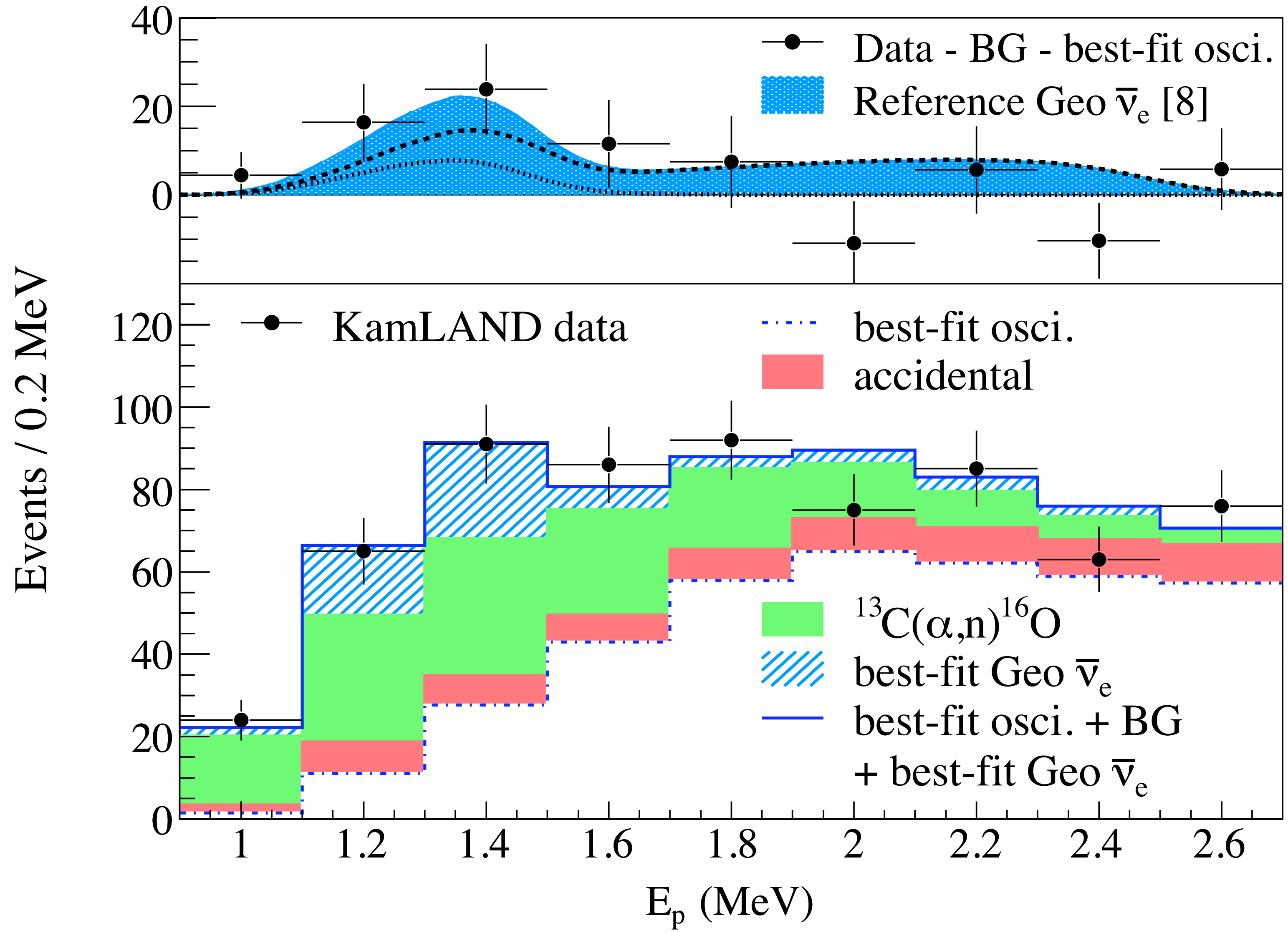
Δm^2 : systematic uncertainty 2.0%

dominated by linear energy scale uncertainty



Δm^2 is measured at 2.8% precision by KamLAND

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)

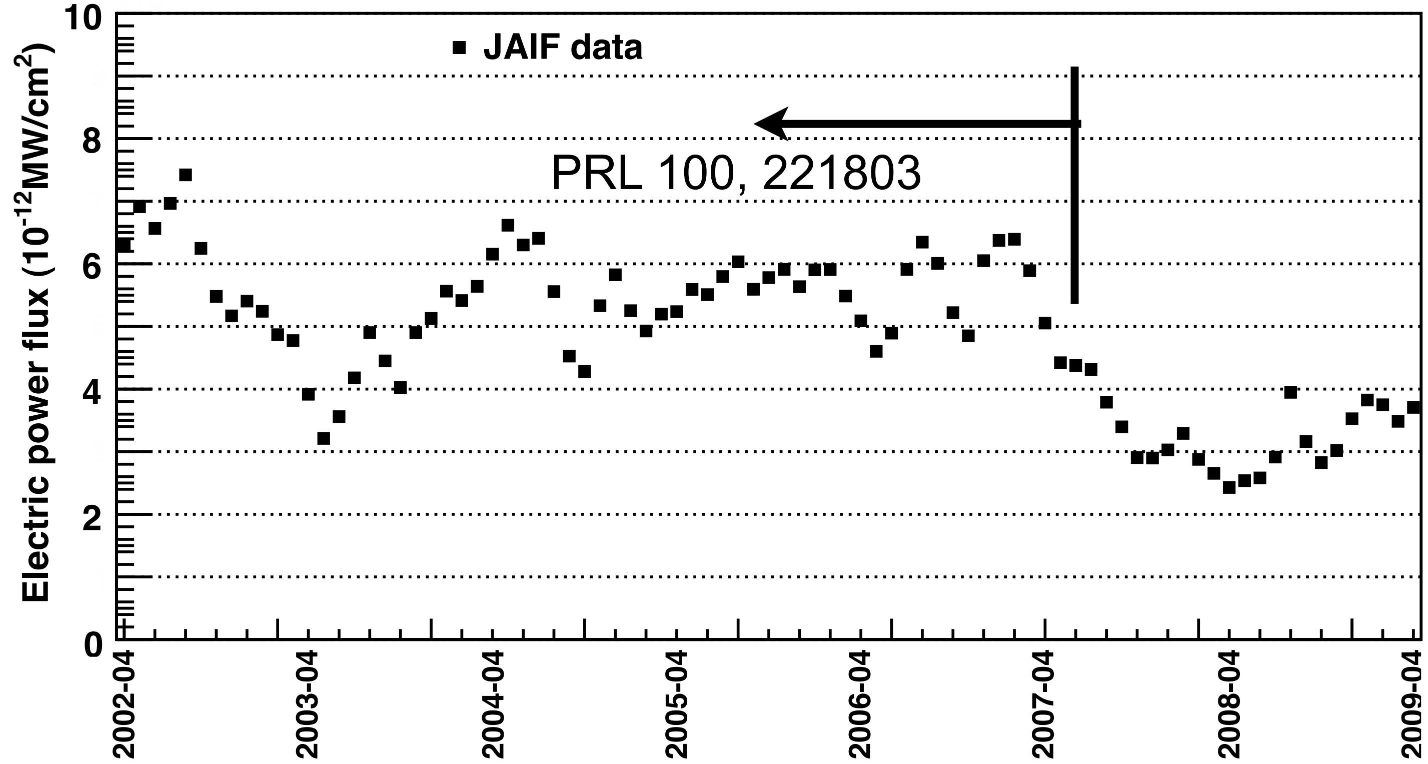
TNU (Terrestrial Neutrino Unit) = events/10^{32} target-proton/year

Future Prospects

Status after PRL data-set

(1) Japanese nuclear reactor is operated on low-power recently

(2) After the purification of the LS, the geo neutrino observation will be improved by the (α, n) background reduction

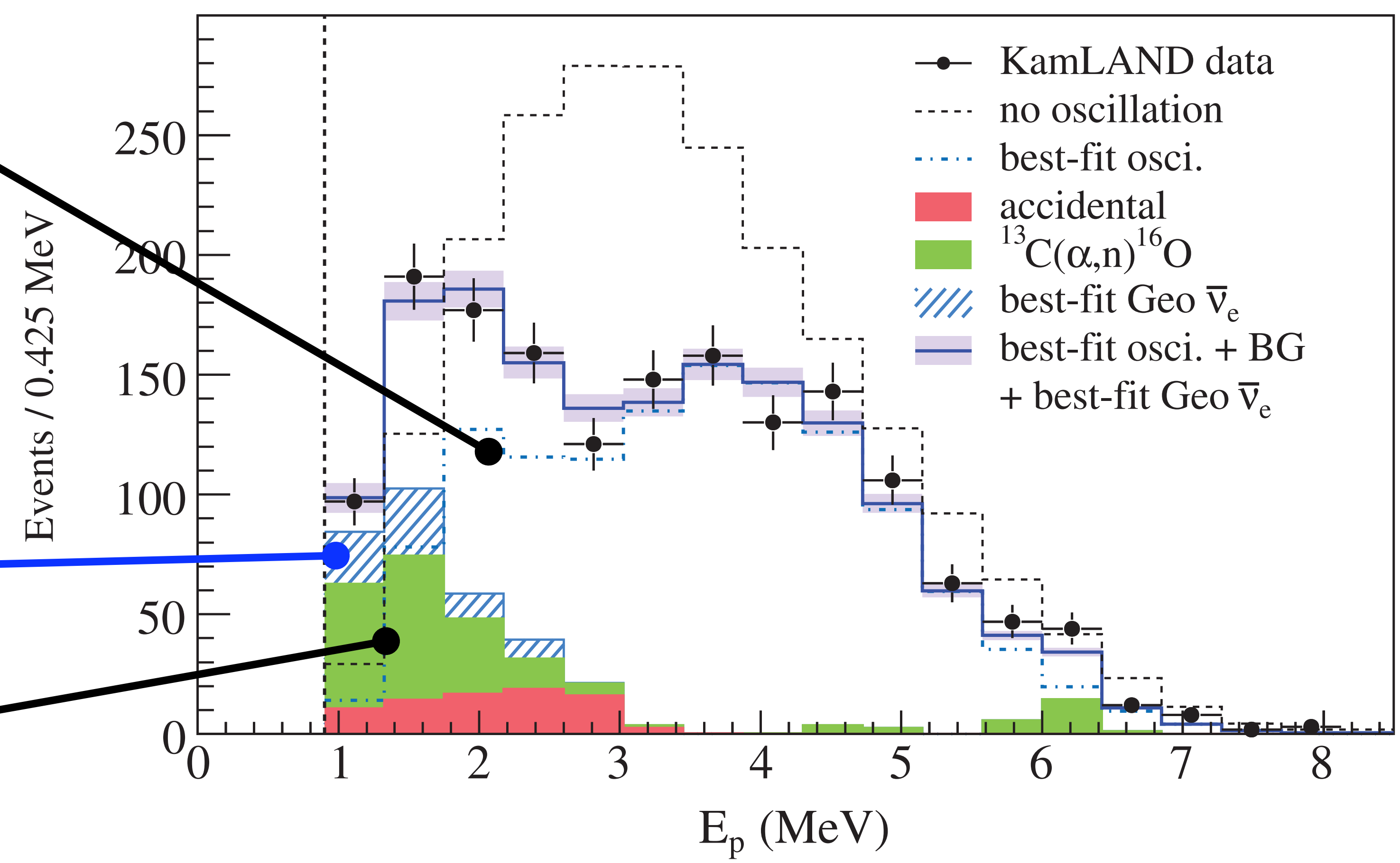


good data for geo neutrino

reactor neutrino is low

geo-neutrinos are being highlighted

(α, n) BG is eliminated



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.

- We will continue the $\overline{\nu}_e$ observation to further reduce the uncertainties on the oscillation parameters and geo neutrino fluxes.