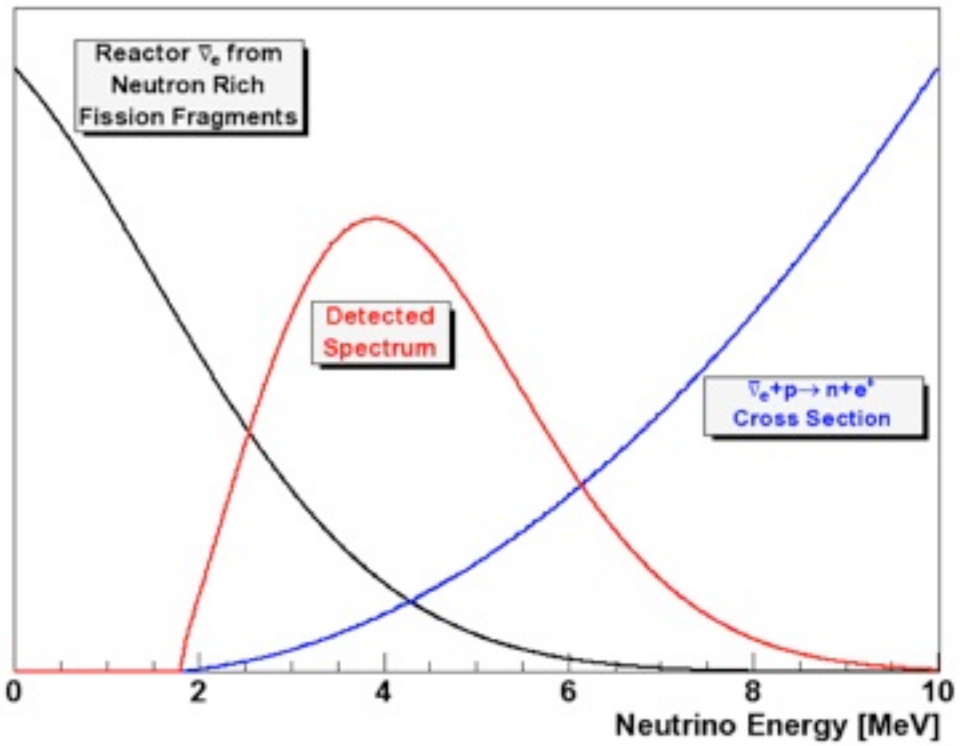
Measurements of Reactor Neutrinos at Long Baselines: KamLAND and Beyond

Brian Kurt Fujikawa

Lawrence Berkeley National Laboratory

2011 APS April Meeting

Reactor Anti-Neutrino Disappearance Experiments

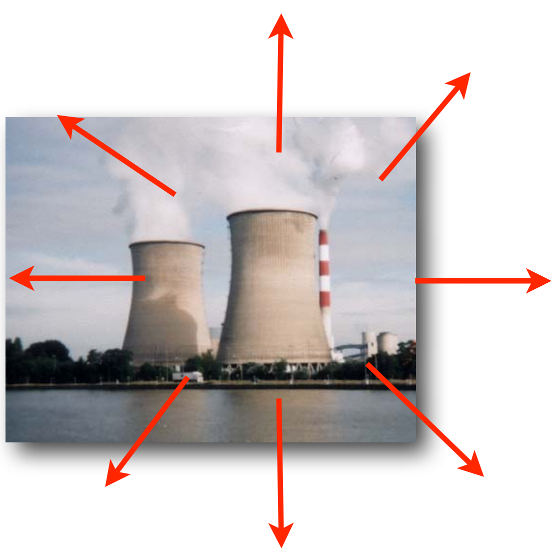


Beta Decay of Neuron Rich Fission Fragments

$$(A,Z) \rightarrow (A,Z+1) + e^- + \overline{\nu}_e \rightarrow \quad \rightarrow \overline{\nu}_e + p \rightarrow n + e^+$$

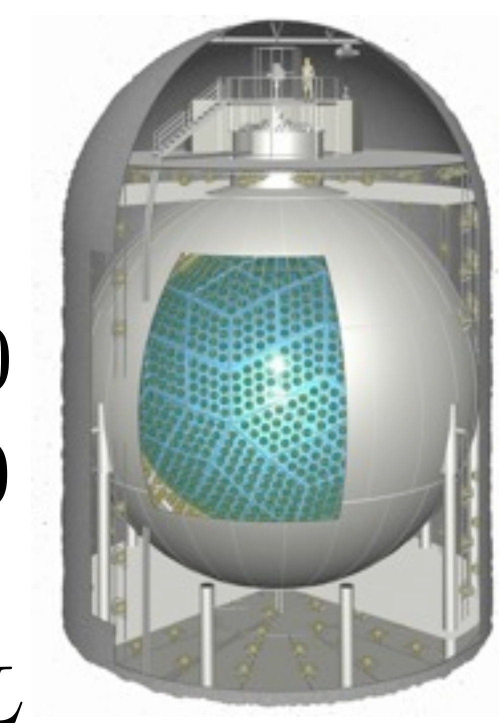
$\rightarrow$ ~~$\overline{\nu}_\mu + p \rightarrow n + \mu^+$~~

$\rightarrow$ ~~$\overline{\nu}_\tau + p \rightarrow n + \tau^+$~~



$\overline{\nu}_e$

$$N_{e^+}$$
$$N_{\mu^+} = 0$$
$$N_{\tau^+} = 0$$

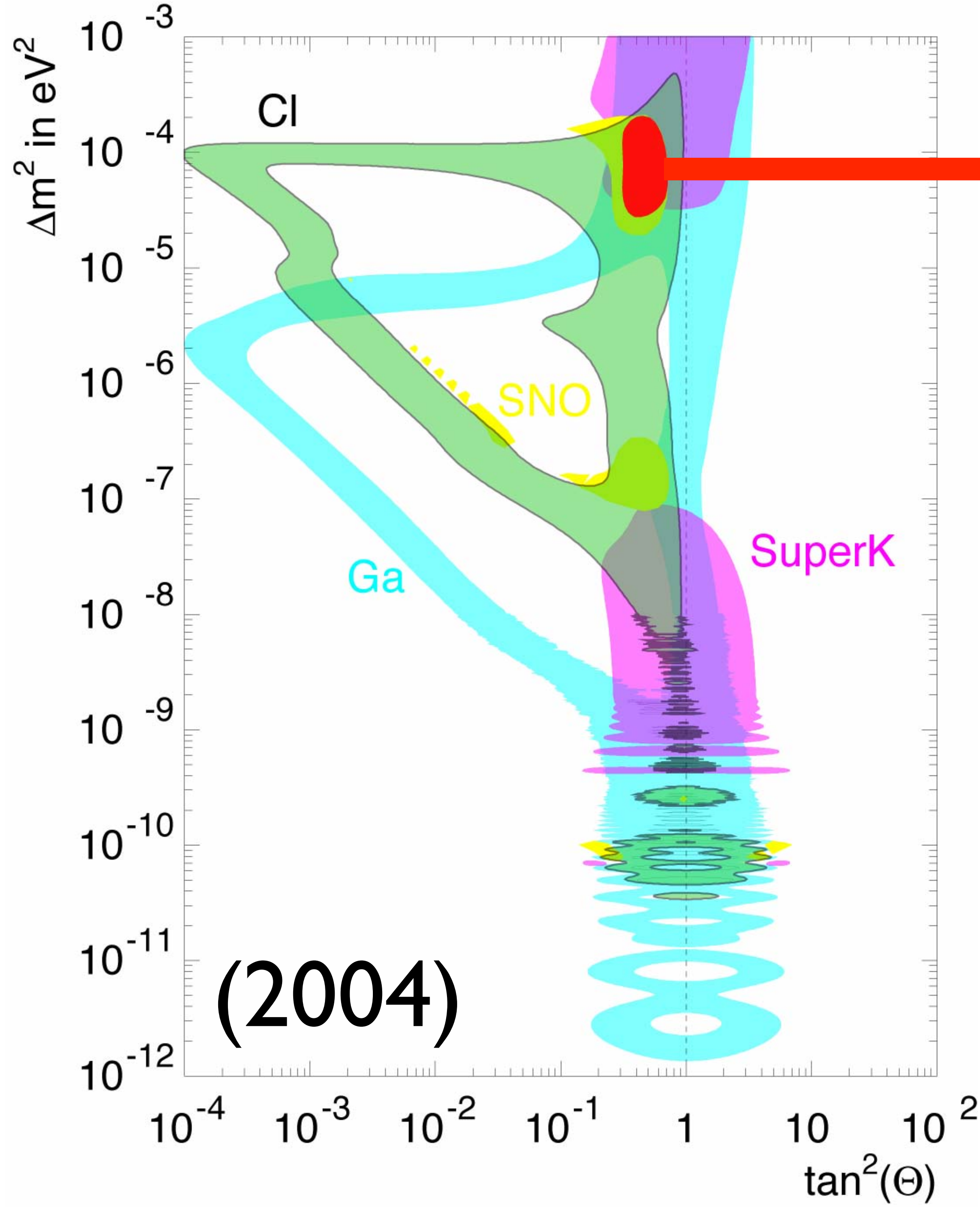


$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta \, \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

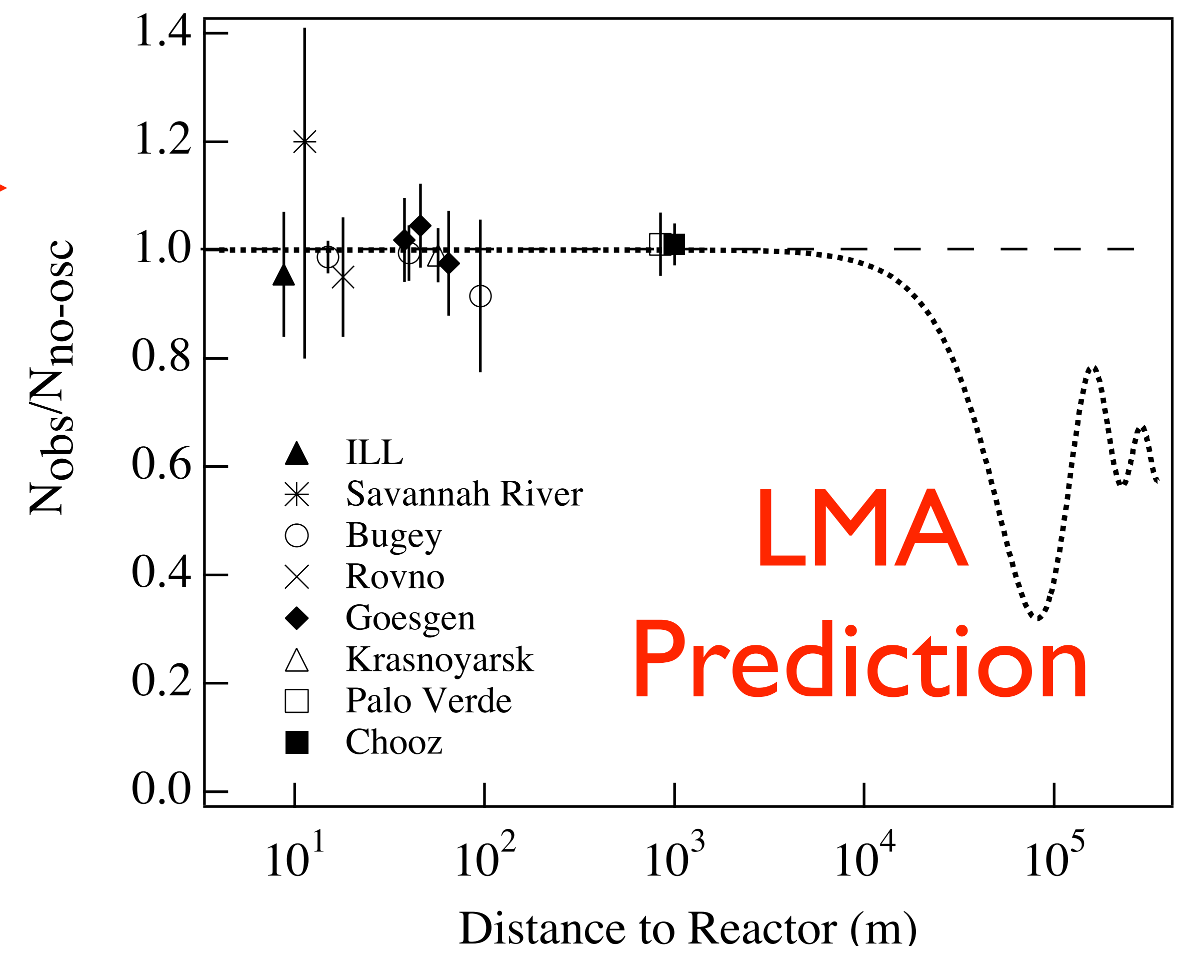
L

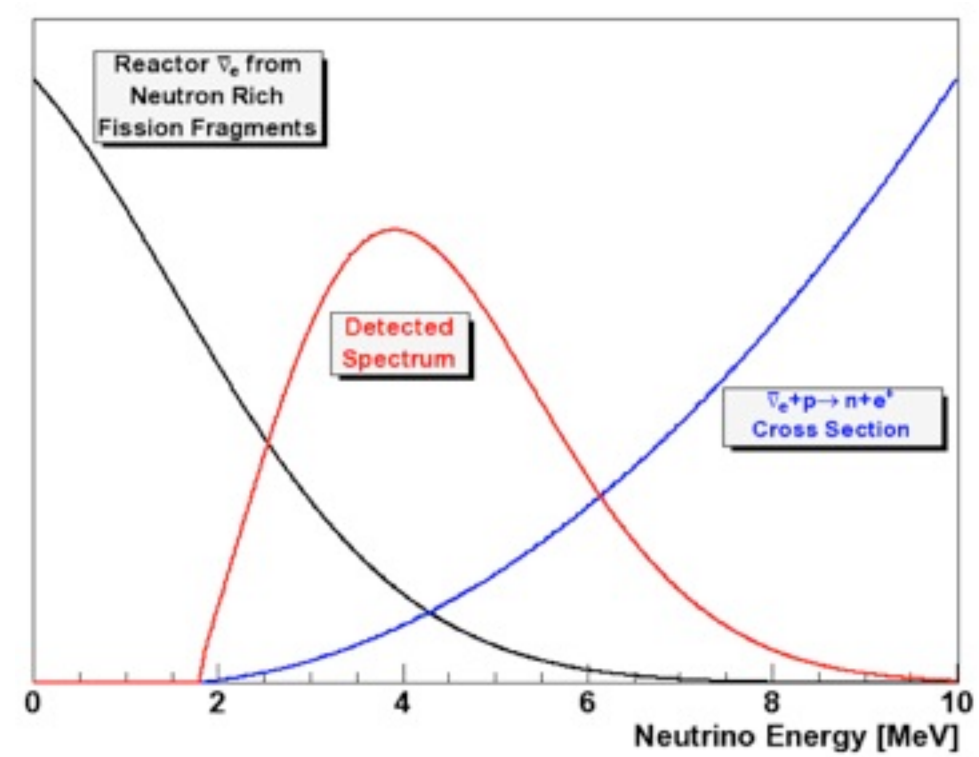
Long Baseline Reactor Neutrino Experiments

Large Mixing Angle (LMA) Solution to the Solar Neutrino Problem



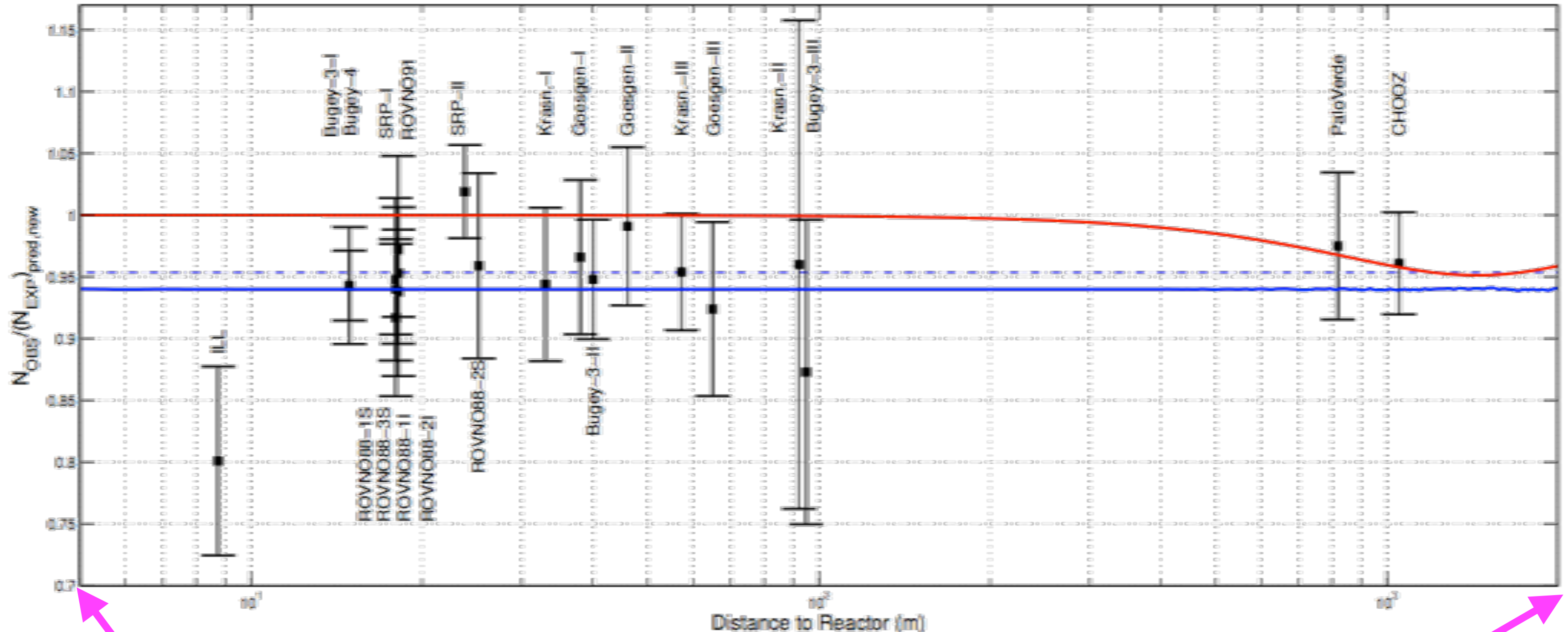
http://hitoshi.berkeley.edu/neutrino/



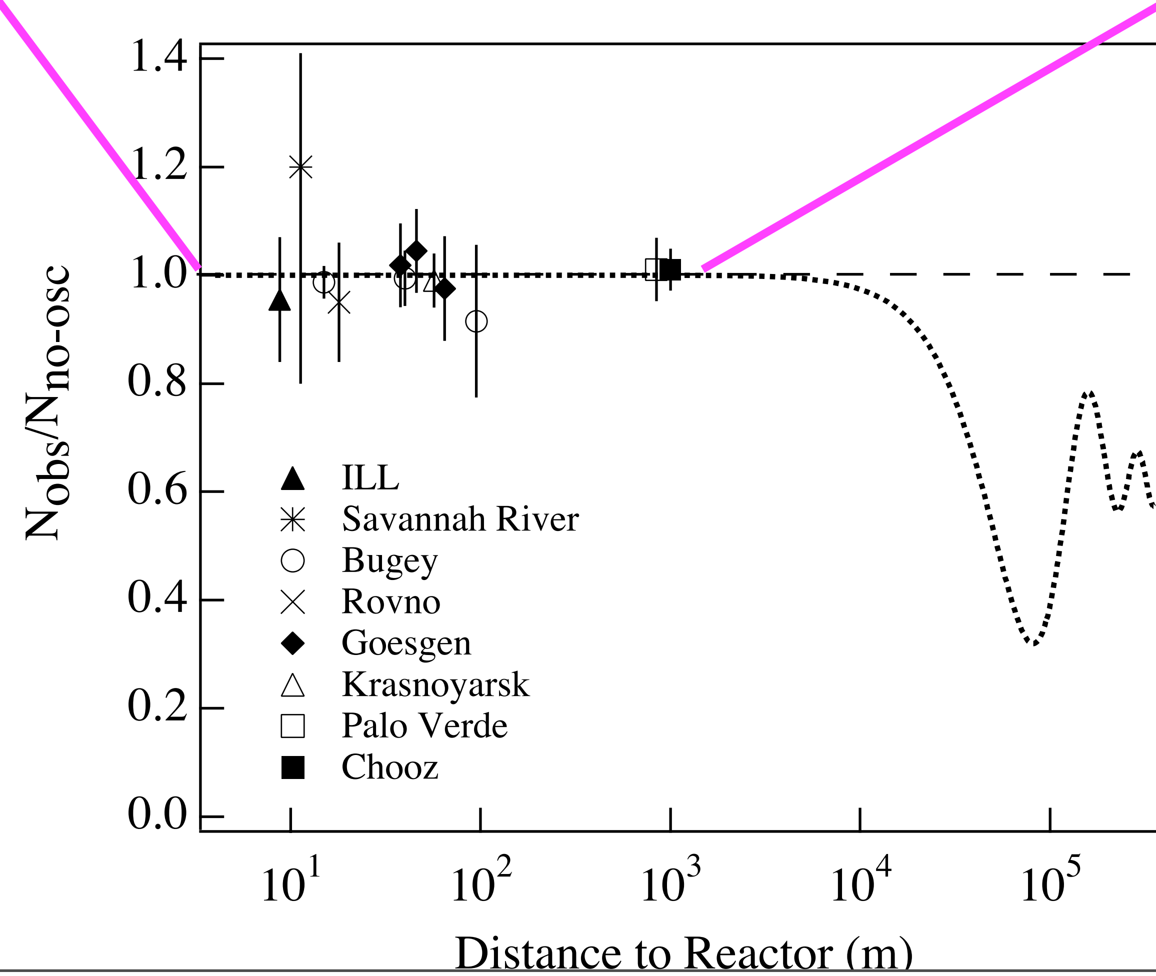


Updated Reactor Neutrino Spectrum Predictions

arXiv:1101.2663
arXiv:1101.2755



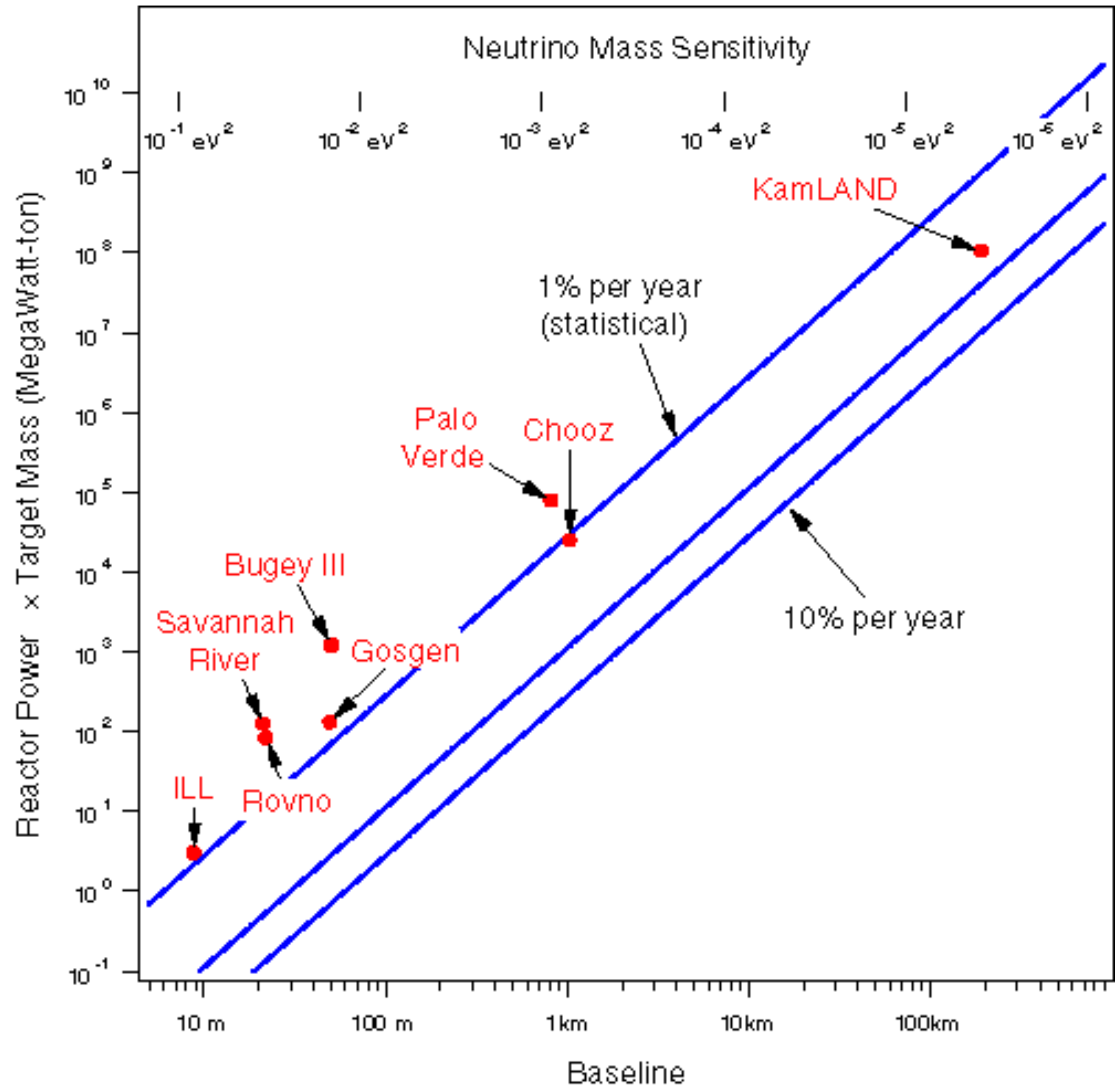
Th. Lasserre (CEA-Saclay, Irfu APC & SPP)

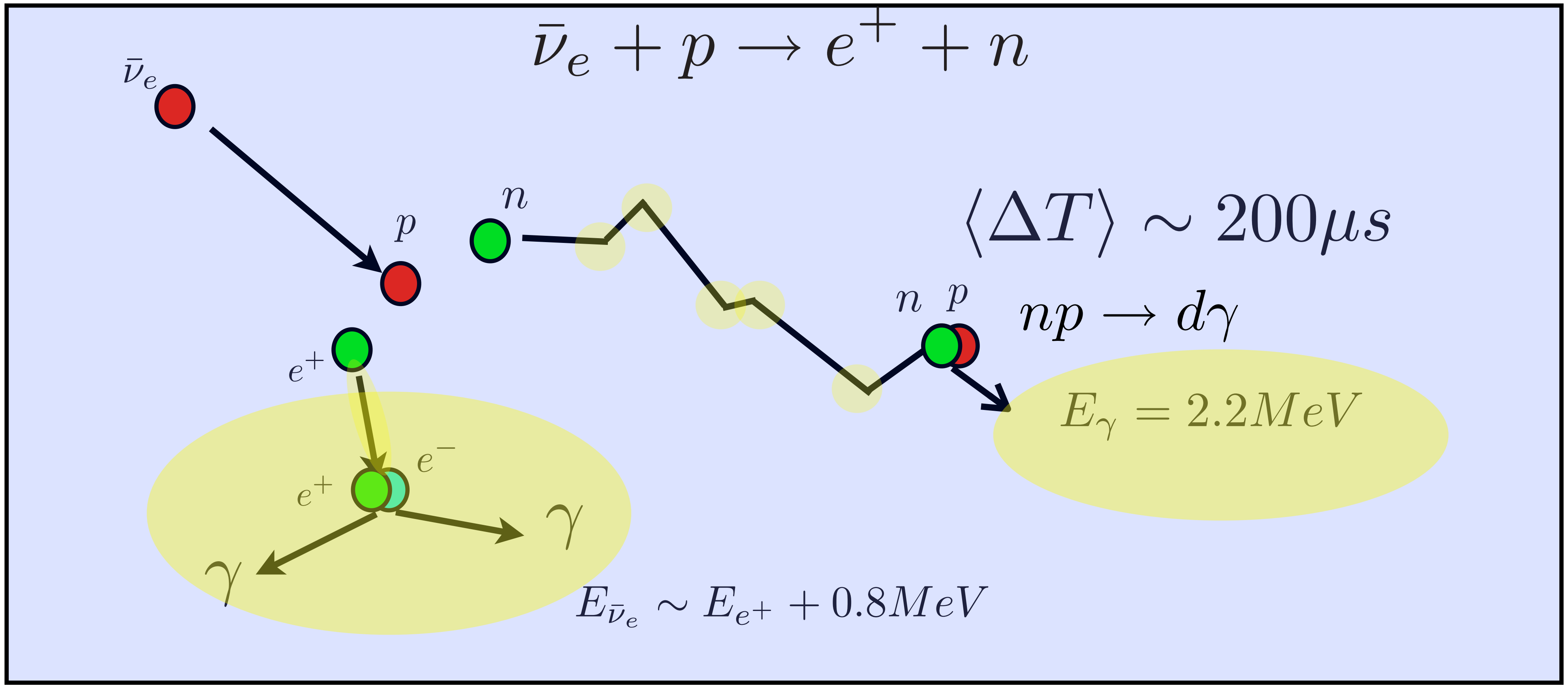


Motivation

- Test Solar LMA solution with a terrestrial experiment that uses a man-made neutrino source.
- The LMA region is very "flat" with respect to Δm^2 from the Solar Neutrino experiments alone. Long Baseline Reactor Neutrino experiment compliment the Solar Neutrino experiments by measuring Δm^2.

Scaling Short Baseline Reactor Neutrino Experiments to Long Baselines





<u>Backgrounds:</u>

- accidental coincidences
- spallation products from cosmic-ray μ's
  - ^{9}Li/^{8}He β-delayed neutron emitters
- neutrons produced externally by μ's
- (α,n) reactions

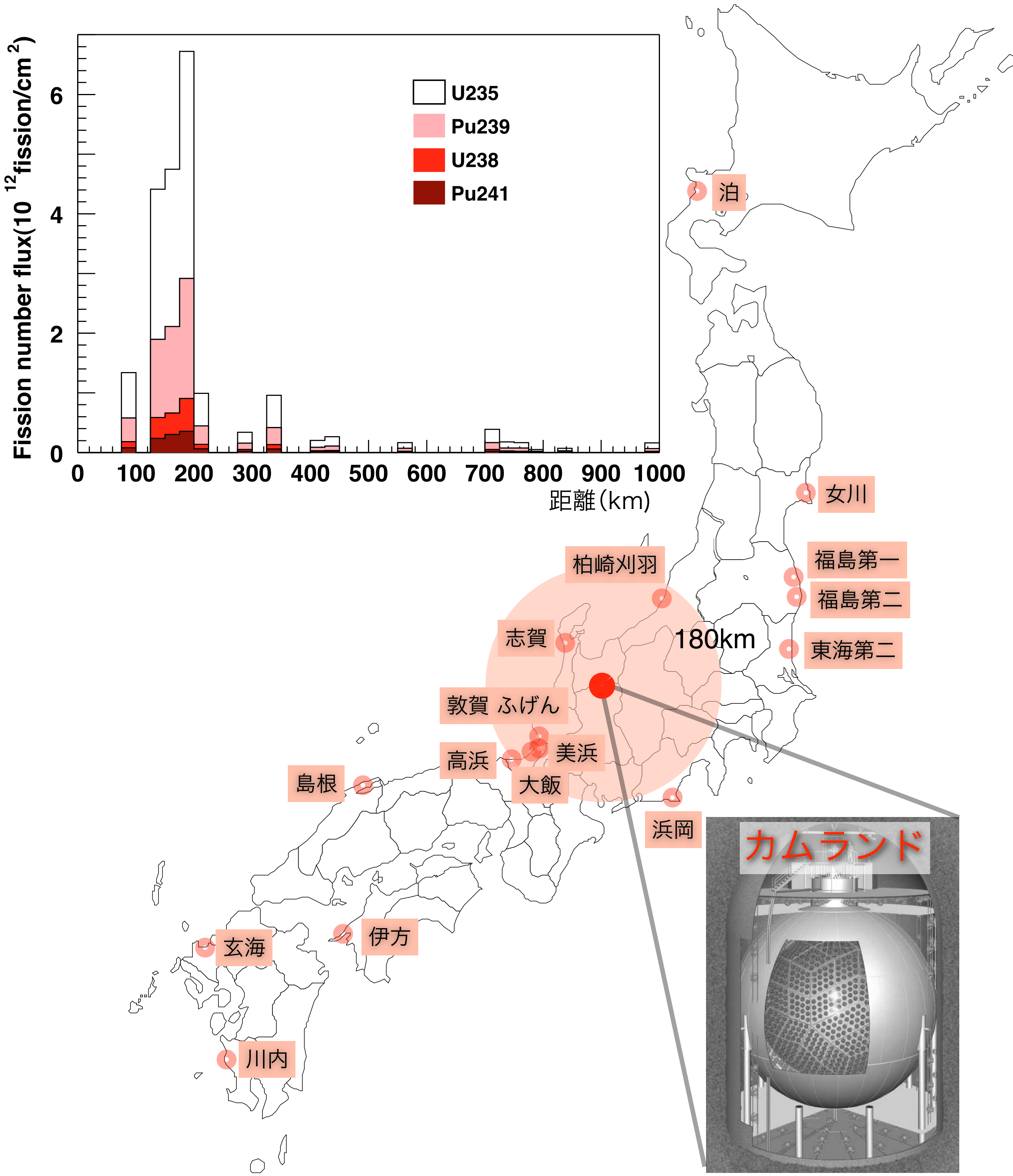
Geoneutrino Background (or Signal)?

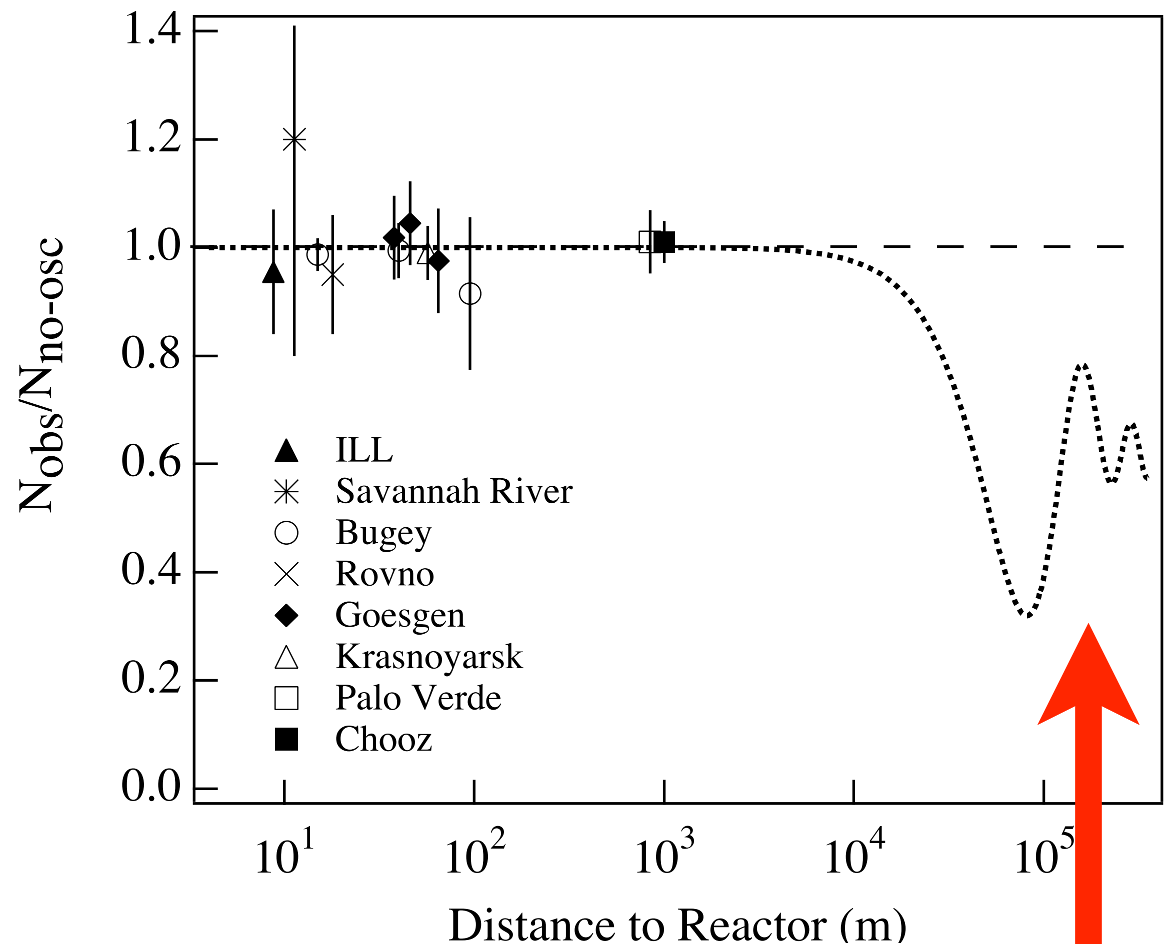
- Geoneutrinos is a background when measuring Reactor Neutrinos
- Ironically, Reactor Neutrinos are a background when measuring Geoneutrinos
- Simultaneous measurement of Geo and Reactor Neutrinos

Long Baseline Reactor Neutrino Experiments Require:

1. High Reactor Power
2. Large Target Mass
3. Low Background
    - Underground to shield from cosmic ray μ's
    - Radiopurity

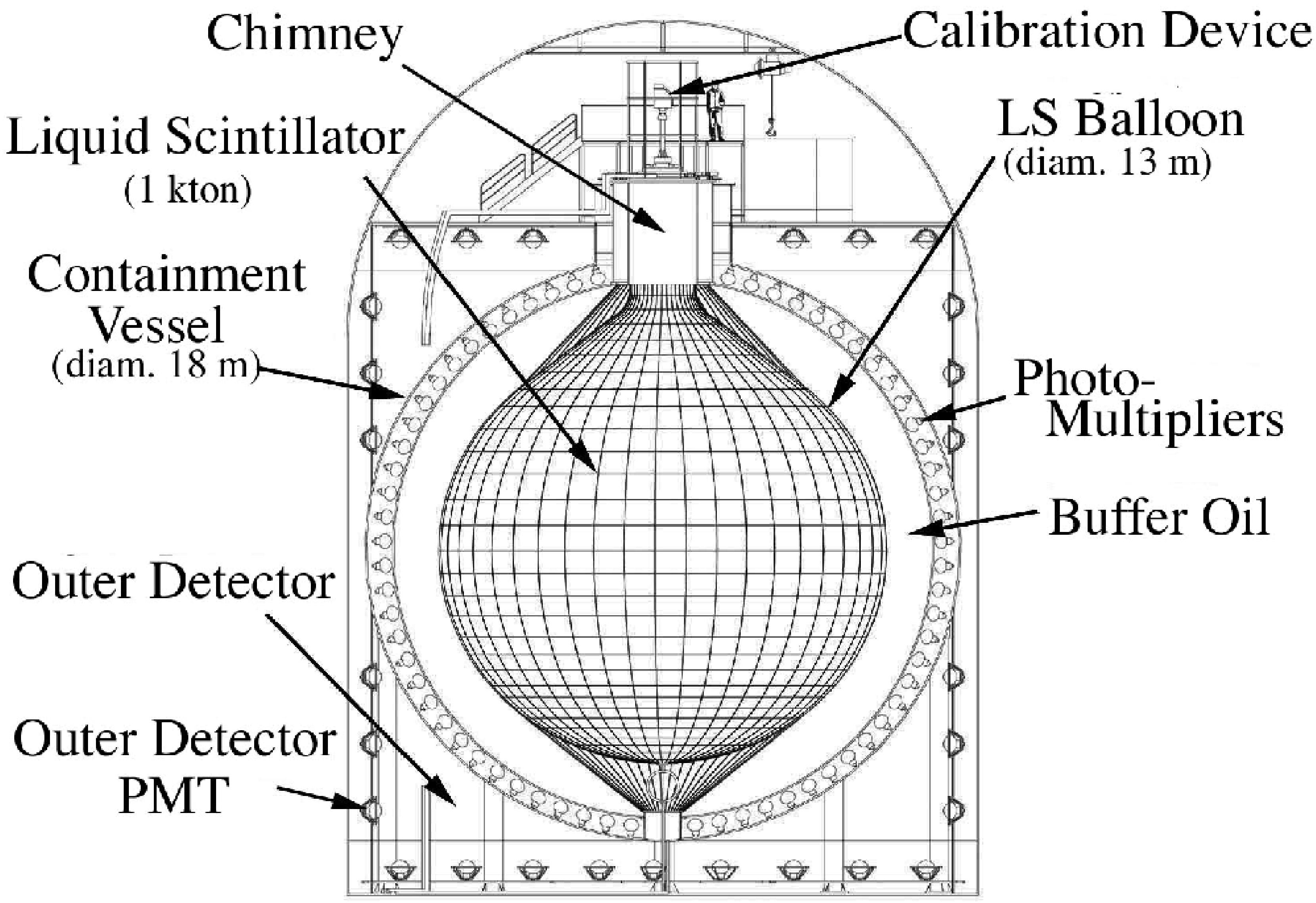
LMA and KamLAND

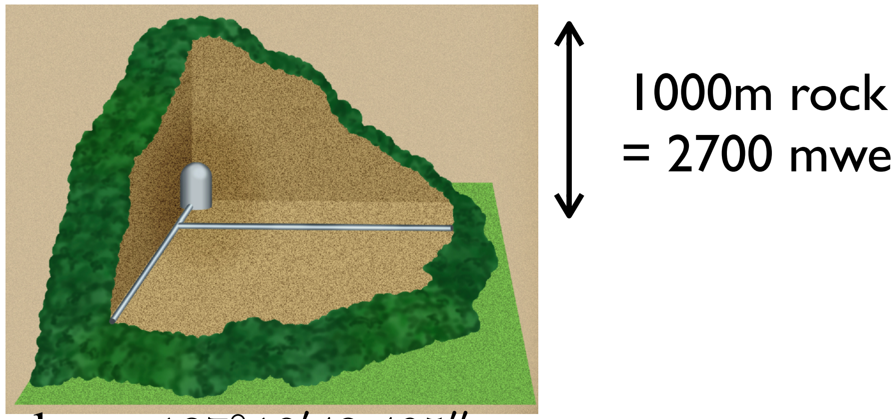




180 km

The KamLAND Detector





long. $137°18'43.495''$
lat. $36°25'35.562''$
alt. $358\,\mathrm{m}$

1st KamLAND Reactor Result

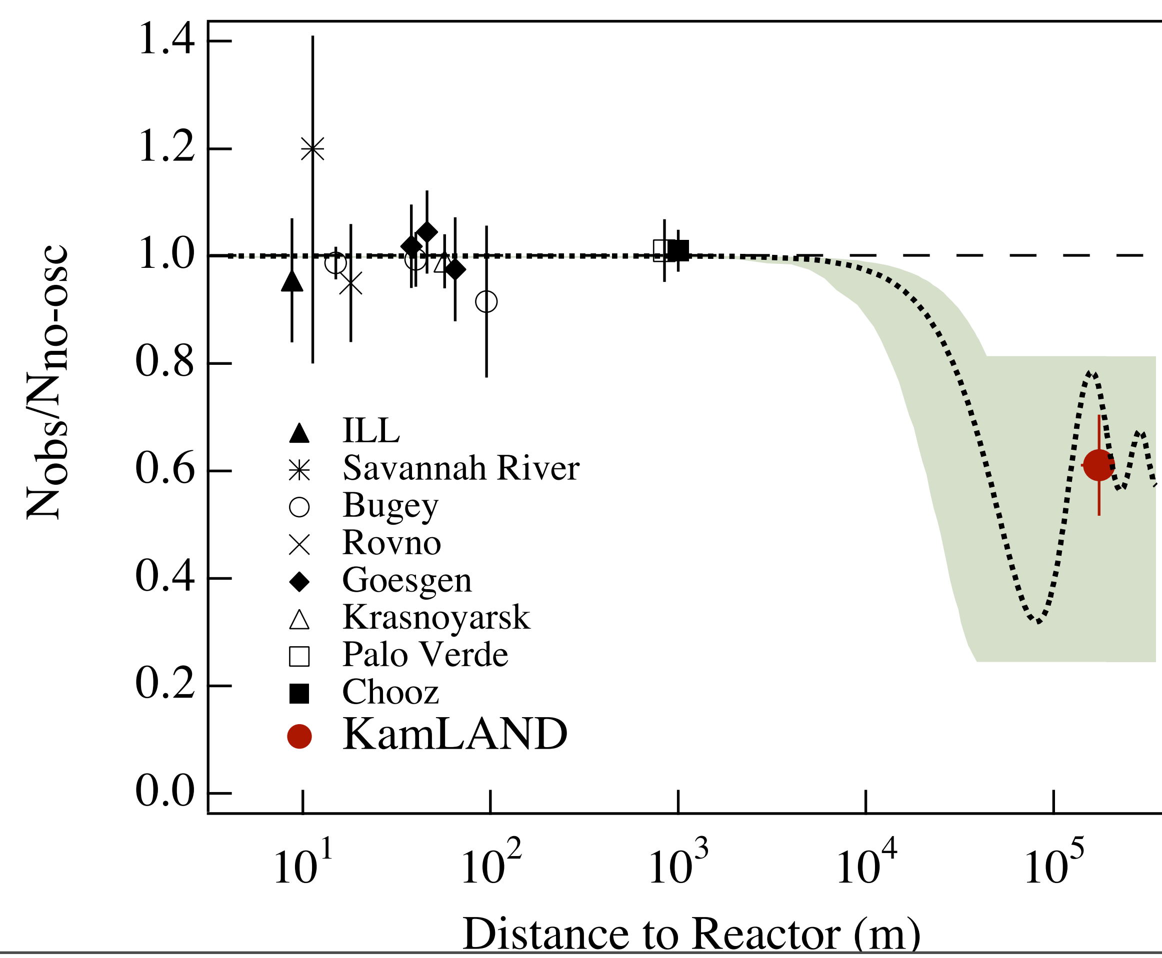
VOLUME 90, NUMBER 2 PHYSICAL REVIEW LETTERS week ending 17 JANUARY 2003

First Results from KamLAND: Evidence for Reactor Antineutrino Disappearance

K. Eguchi,[1] S. Enomoto,[1] K. Furuno,[1] J. Goldman,[1] H. Hanada,[1] H. Ikeda,[1] K. Ikeda,[1] K. Inoue,[1] K. Ishihara,[1] W. Itoh,[1] T. Iwamoto,[1] T. Kawaguchi,[1] T. Kawashima,[1] H. Kinoshita,[1] Y. Kishimoto,[1] M. Koga,[1] Y. Koseki,[1] T. Maeda,[1] T. Mitsui,[1] M. Motoki,[1] K. Nakajima,[1] M. Nakajima,[1] T. Nakajima,[1] H. Ogawa,[1] K. Owada,[1] T. Sakabe,[1] I. Shimizu,[1] J. Shirai,[1] F. Suekane,[1] A. Suzuki,[1] K. Tada,[1] O. Tajima,[1] T. Takayama,[1] K. Tamae,[1] H. Watanabe,[1] J. Busenitz,[2] Z. Djurcic,[2] K. McKinny,[2] D.-M. Mei,[2] A. Piepke,[2] E. Yakushev,[2] B. E. Berger,[3] Y. D. Chan,[3] M. P. Decowski,[3] D. A. Dwyer,[3] S. J. Freedman,[3] Y. Fu,[3] B. K. Fujikawa,[3] K. M. Heeger,[3] K.T. Lesko,[3] K.-B. Luk,[3] H. Murayama,[3] D. R. Nygren,[3] C. E. Okada,[3] A.W. P. Poon,[3] H. M. Steiner,[3] L. A. Winslow,[3] G. A. Horton-Smith,[4] R. D. McKeown,[4] J. Ritter,[4] B. Tipton,[4] P. Vogel,[4] C. E. Lane,[5] T. Miletic,[5] P.W. Gorham,[6] G. Guillian,[6] J. G. Learned,[6] J. Maricic,[6] S. Matsuno,[6] S. Pakvasa,[6] S. Dazeley,[7] S. Hatakeyama,[7] M. Murakami,[7] R. C. Svoboda,[7] B. D. Dieterle,[8] M. DiMauro,[8] J. Detwiler,[9] G. Gratta,[9] K. Ishii,[9] N. Tolich,[9] Y. Uchida,[9] M. Batygov,[10] W. Bugg,[10] H. Cohn,[10] Y. Efremenko,[10] Y. Kamyshkov,[10] A. Kozlov,[10] Y. Nakamura,[10] L. De Braeckeleer,[11] C. R. Gould,[11] H. J. Karwowski,[11] D. M. Markoff,[11] J. A. Messimore,[11] K. Nakamura,[11] R. M. Rohm,[11] W. Tornow,[11] A. R. Young,[11] and Y.-F. Wang[12]

(KamLAND Collaboration)

$$\frac{N_{obs} - N_{bkgd}}{N_{no-osc}} = 0.611 \pm 0.085_{stat} \pm 0.041_{syst}$$



Latest (4th) KamLAND Reactor Neutrino Result

PHYSICAL REVIEW D **83**, 052002 (2011)

Constraints on θ_{13} from a three-flavor oscillation analysis of reactor antineutrinos at KamLAND

A. Gando,[1] Y. Gando,[1] K. Ichimura,[1] H. Ikeda,[1] K. Inoue,[1,2] Y. Kibe,[1,*] Y. Kishimoto,[1] M. Koga,[1,2] Y. Minekawa,[1] T. Mitsui,[1] T. Morikawa,[1] N. Nagai,[1] K. Nakajima,[1] K. Nakamura,[1,2] K. Narita,[1] I. Shimizu,[1] Y. Shimizu,[1] J. Shirai,[1] F. Suekane,[1] A. Suzuki,[1] H. Takahashi,[1] N. Takahashi,[1] Y. Takemoto,[1] K. Tamae,[1] H. Watanabe,[1] B. D. Xu,[1] H. Yabumoto,[1] H. Yoshida,[1] S. Yoshida,[1] S. Enomoto,[2,†] A. Kozlov,[2] H. Murayama,[2,3] C. Grant,[5] G. Keefer,[4,‡] A. Piepke,[2,4] T. I. Banks,[3] T. Bloxham,[3] J. A. Detwiler,[3] S. J. Freedman,[2,3] B. K. Fujikawa,[2,3] K. Han,[3] R. Kadel,[3] T. O'Donnell,[3] H. M. Steiner,[3] D. A. Dwyer,[5] R. D. McKeown,[5] C. Zhang,[5] B. E. Berger,[6] C. E. Lane,[7] J. Maricic,[7] T. Miletic,[7,§] M. Batygov,[8,‖] J. G. Learned,[8] S. Matsuno,[8] M. Sakai,[8] G. A. Horton-Smith,[2,9] K. E. Downum,[10] G. Gratta,[10] Y. Efremenko,[2,11] O. Perevozchikov,[11,¶] H. J. Karwowski,[12] D. M. Markoff,[12] W. Tornow,[12] K. M. Heeger,[2,13] and M. P. Decowski[2,3,14]

(The KamLAND Collaboration)

Please see R7.00002: "A three-flavor oscillation analysis of a new KamLAND data set" Thomas O'Donnell (1:42 pm, May 2, Grand E)

Exposure:

- 3.49×10^{42} target-proton-years

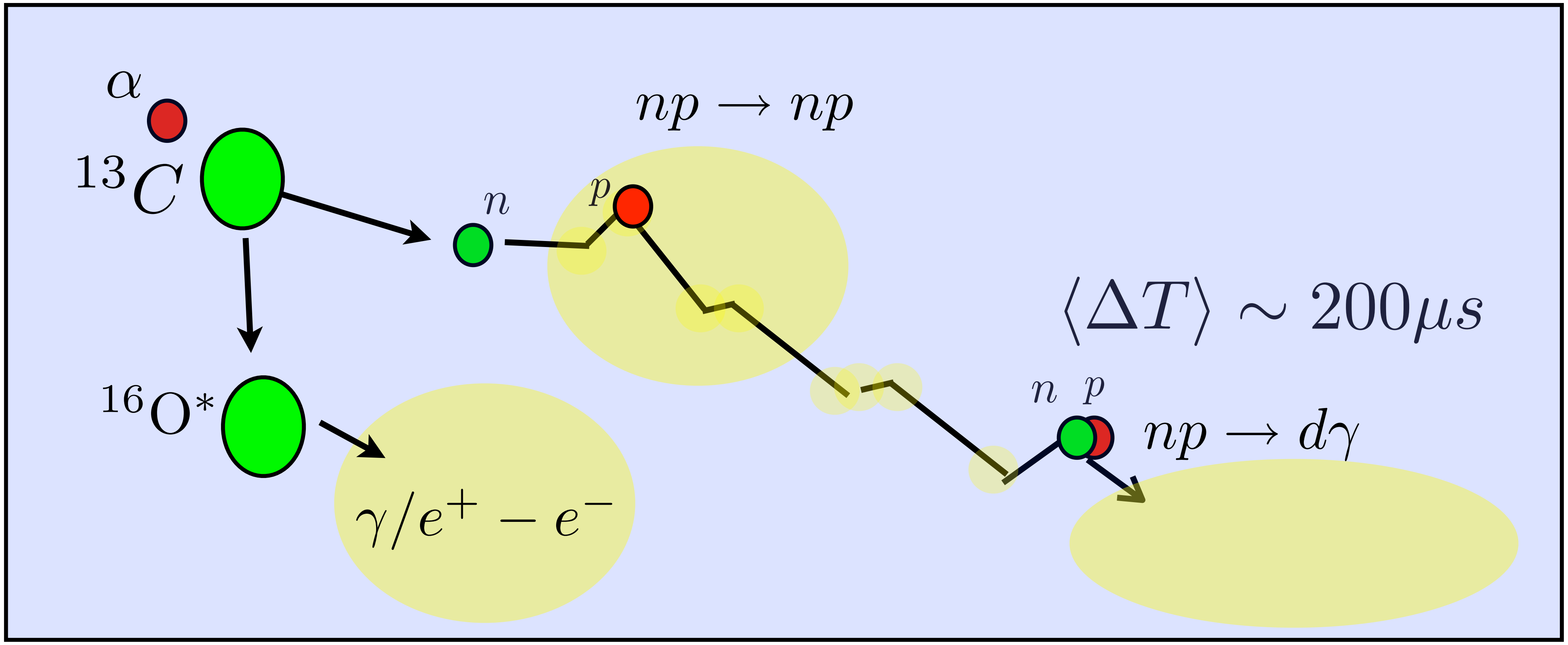
Candidate Event Selection:

- Delayed coincidence pairs (in time & space)
- Prompt energy window
- Delayed energy window (near 2.2 MeV or 4.7 MeV)
- Likelihood discriminator
- Isolation from cosmic ray μ's (μ veto)

Background		Contribution
1	Accidental	102.5 ± 0.1
2	^{9}Li/^{8}He	24.8 ± 1.6
3	$^{13}C(\alpha, n)^{16}O_{g.s.}$, $np \to np$	171.7 ± 18.2
	$^{13}C(\alpha, n)^{16}O_{g.s.}$, $^{12}C(n, n')^{12}C^*$ (4.4 MeV γ)	7.3 ± 0.8
4	$^{13}C(\alpha, n)^{16}O$, 1st e.s. (6.05 MeV e^+e^-)	15.9 ± 3.3
	$^{13}C(\alpha, n)^{16}O$, 2nd e.s. (6.13 MeV γ)	3.7 ± 0.7
5	Fast neutron and atmospheric neutrino	< 12.3
Total		325.9 ± 26.1

Events expected from reactors (no oscillation)	2879 +/- 118
Events expected from background (ex. geo-nu)	325.9 +/- 26.1
Observed events	2106

(α,n) Background



- Primarily from ^{210}Po α's
- 2007-2009 KamLAND liquid scintillator purification campaigns (in preparation for solar ^{7}Be neutrino detection)
- Reduced ^{210}Po contamination by a factor of 20.
- (α,n) backgrounds are greatly reduced for the post-purification period.

3-Flavor Analysis

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle \qquad \alpha = e, \mu, \tau$$

PMNS Matrix

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

$$s_{ij} = \sin\theta_{ij} \quad c_{ij} = \cos\theta_{ij}$$

Survival Probability at KamLAND

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

Matter Effects from Propagating Through the Earth

$$\widetilde{P}_{ee}^{2\nu} = 1 - \sin^2 2\theta_{12M} \sin^2 \left(\frac{1.27 \Delta m_{21M}^2 L}{E} \right)$$

$$\sin^2 2\theta_{12M} = \frac{\sin^2 2\theta_{12}}{(\cos 2\theta_{12} - A/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}}$$

$$\Delta m_{21M}^2 = \Delta m_{21}^2 \sqrt{(\cos 2\theta_{12} - A/\Delta m_{21}^2)^2 + \sin^2 2\theta_{12}}$$

$$A = -2\sqrt{2} G_F \widetilde{N}_e E$$

Un-binned Maximum Likelihood Analysis

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

Include Time Depend Effects:

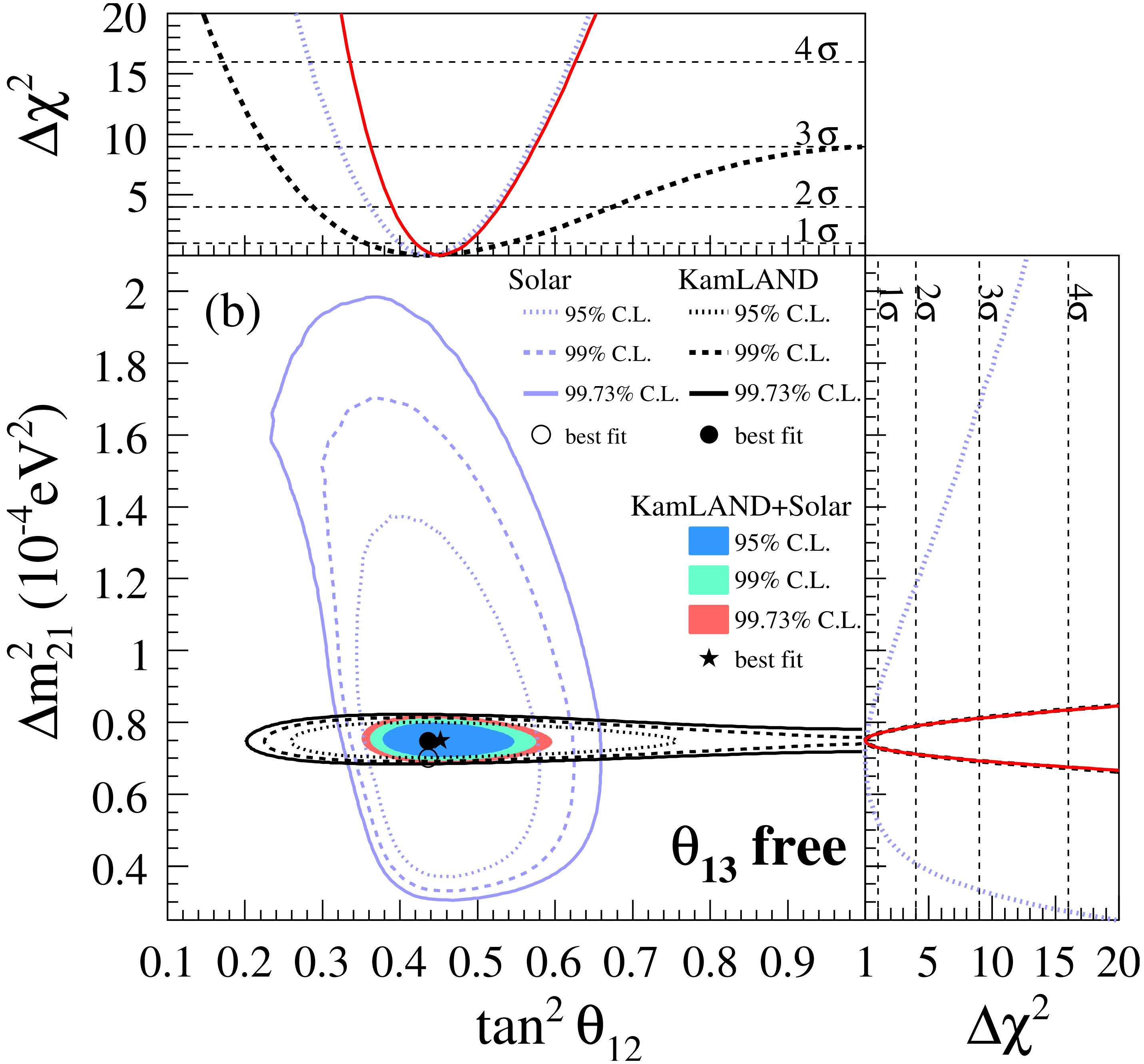
- Fluctuations in reactor power.
- Pre/Post-Purification changes in background, e.g. (α,n).
- Pre/Post-Purification changes in detector performance.

Systematic Error Table

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.8 / 1.8	$\overline{\nu}_e$-spectra [33]	0.6 / 0.6
Rate	Fiducial volume	1.8 / 2.5	$\overline{\nu}_e$-spectra	2.4 / 2.4
	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	3.3 / 3.4

data set before purification / data set after purification

Results of the 3-Flavor Analysis



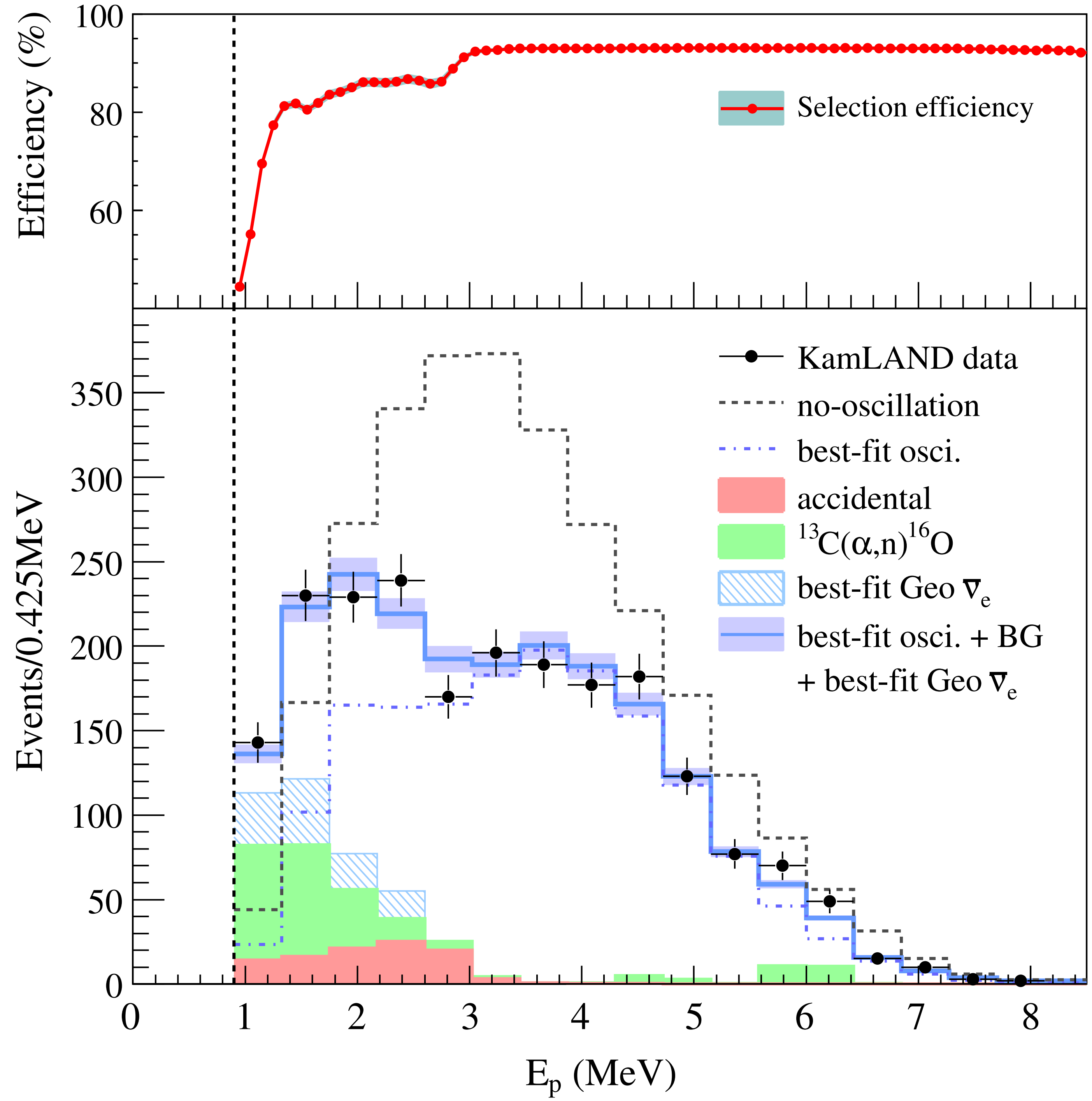
KamLAND Best Fit

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

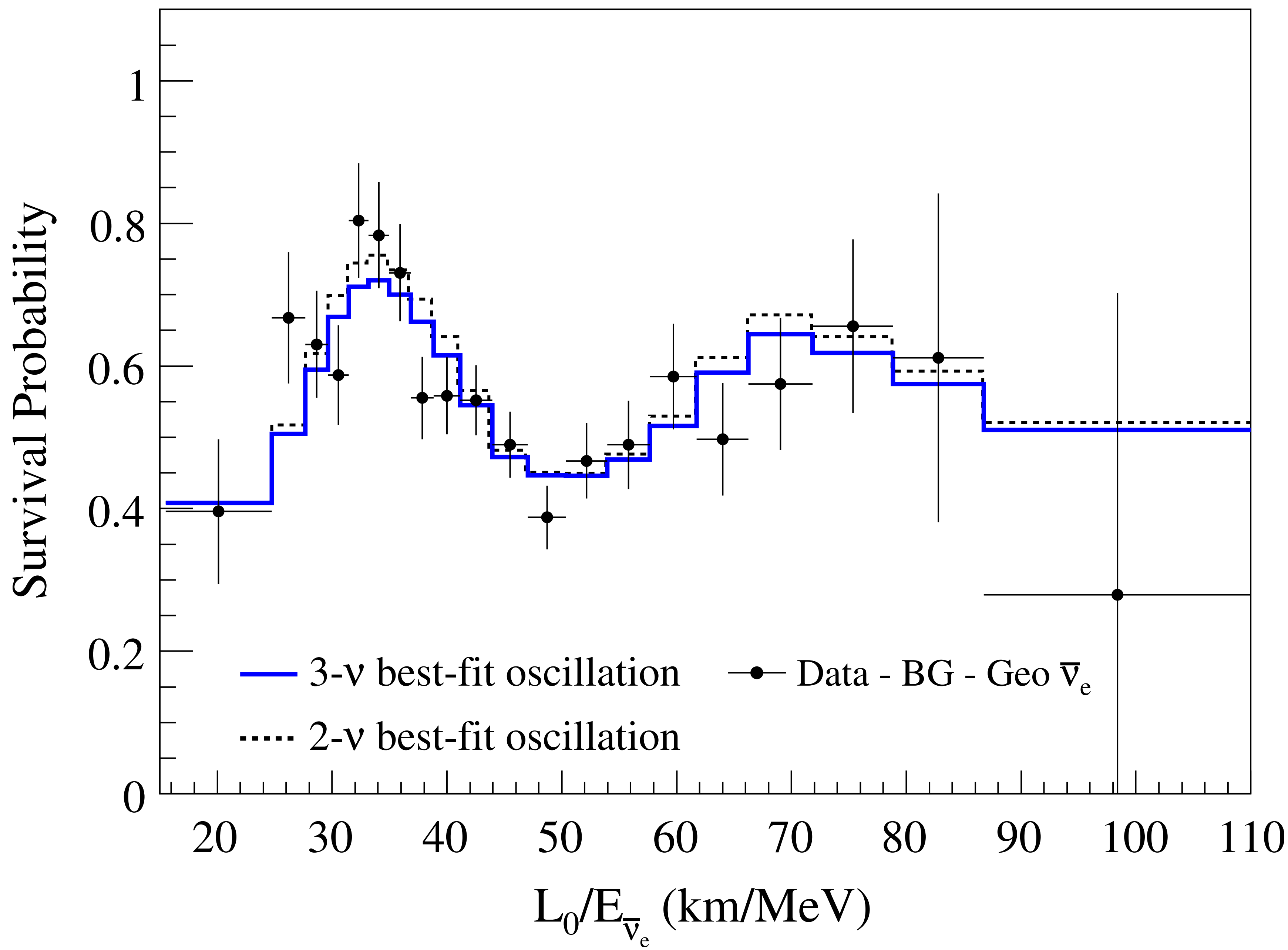
$$\Delta m^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$$

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

Prompt Energy Distribution



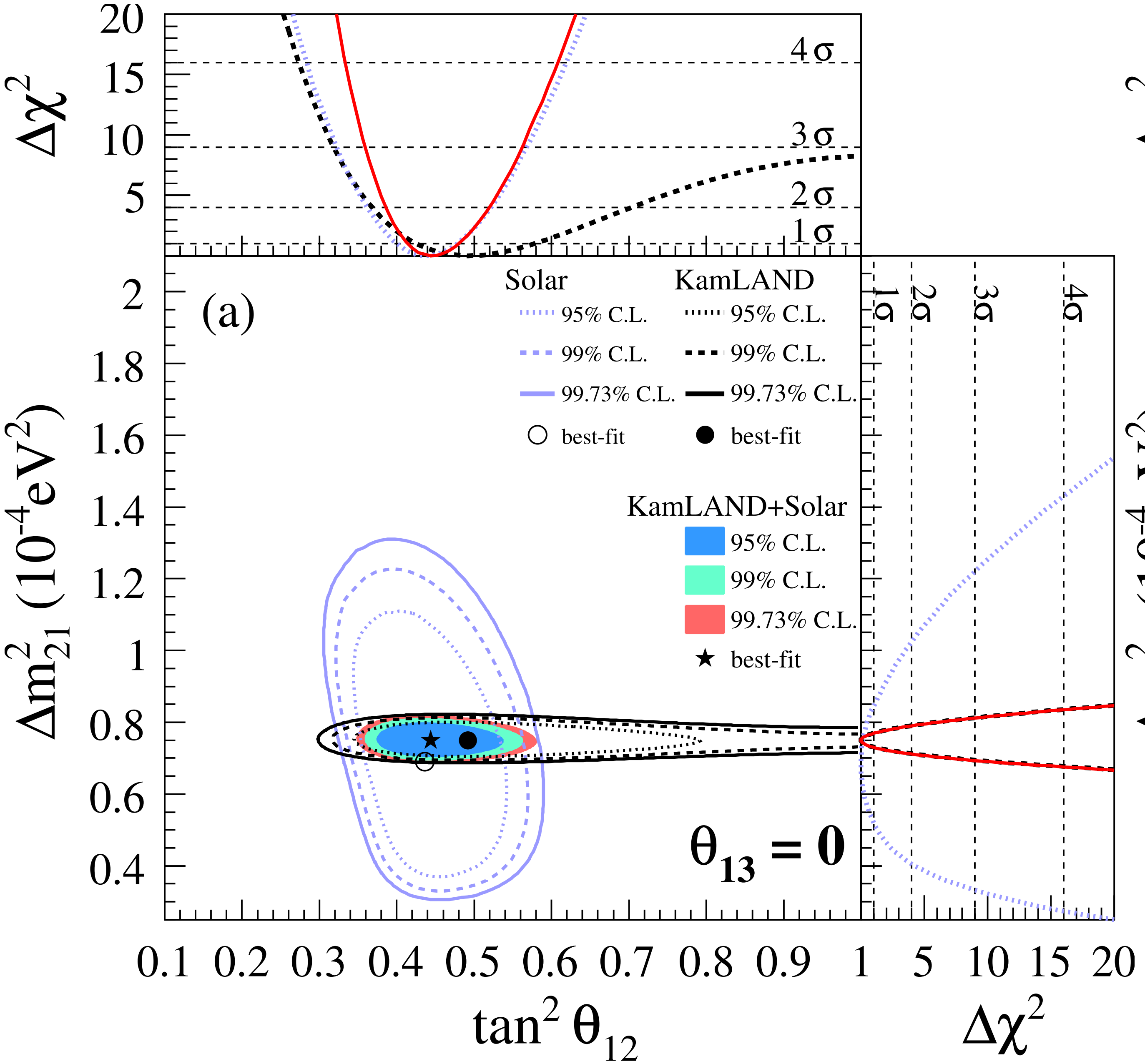
Shape Distortion and Evidence for Neutrino Oscillations



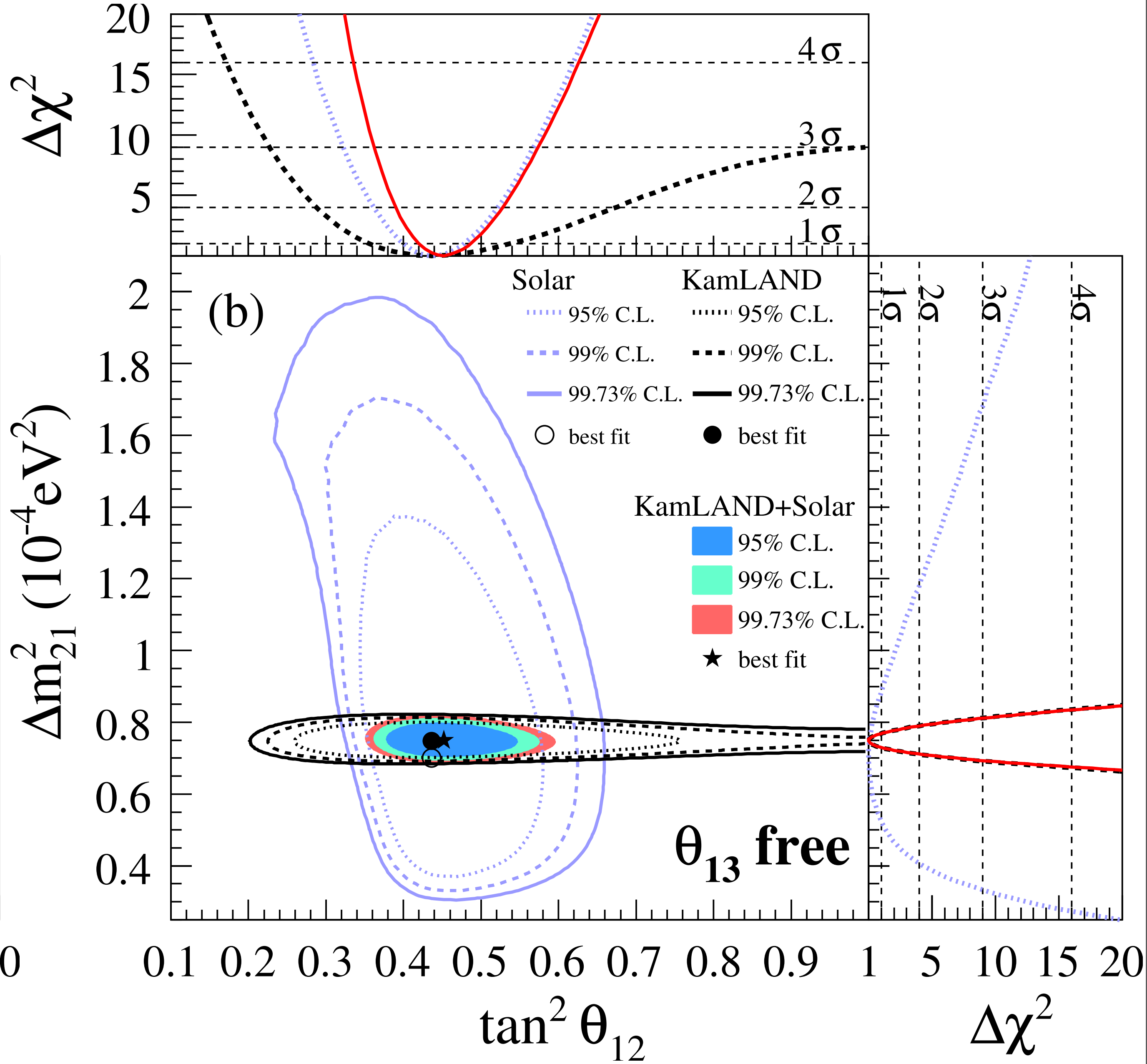
(L_0 = 180 km chosen for scale)

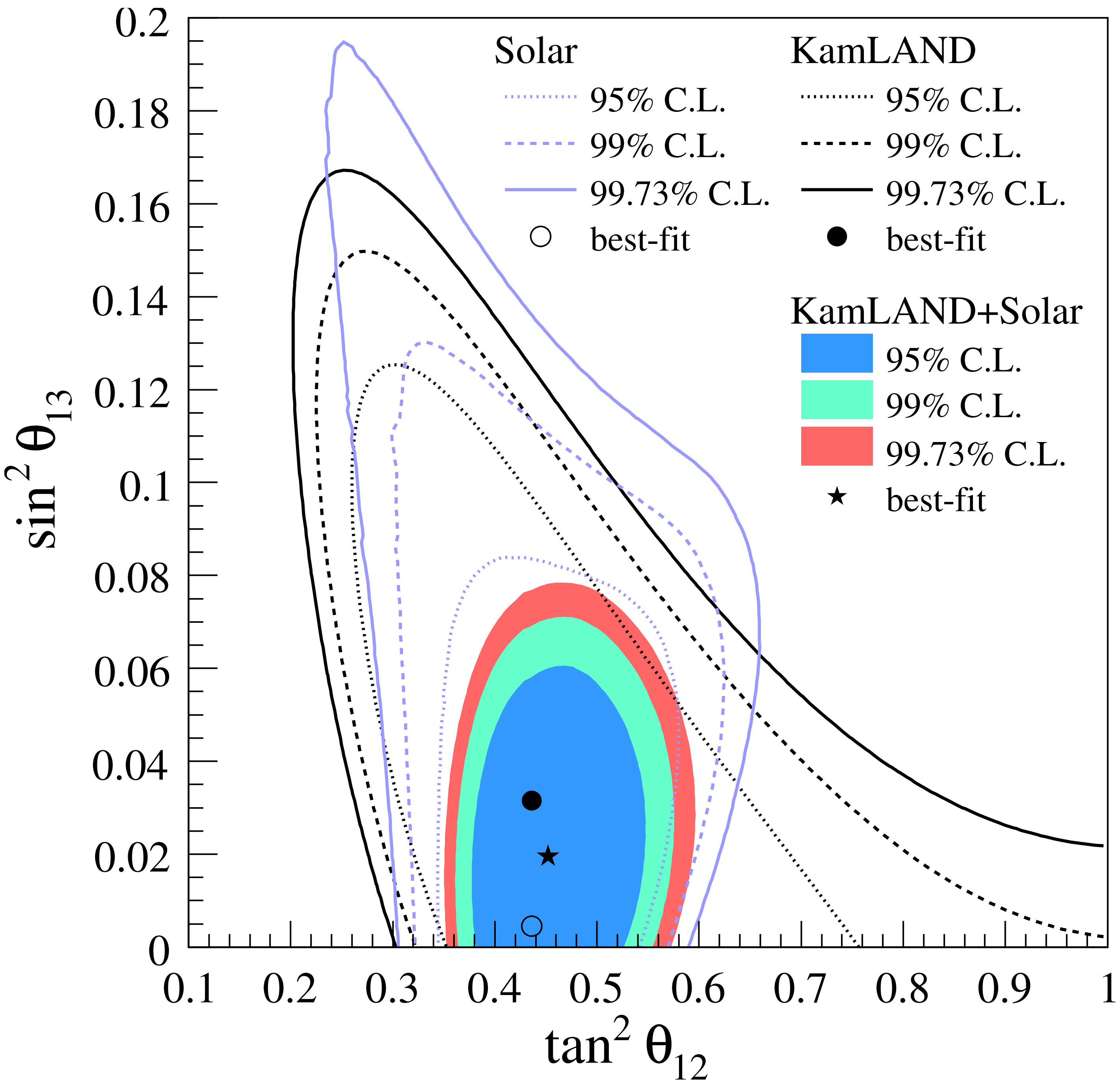
2-Flavor/3-Flavor Analysis Comparison

2-Flavor

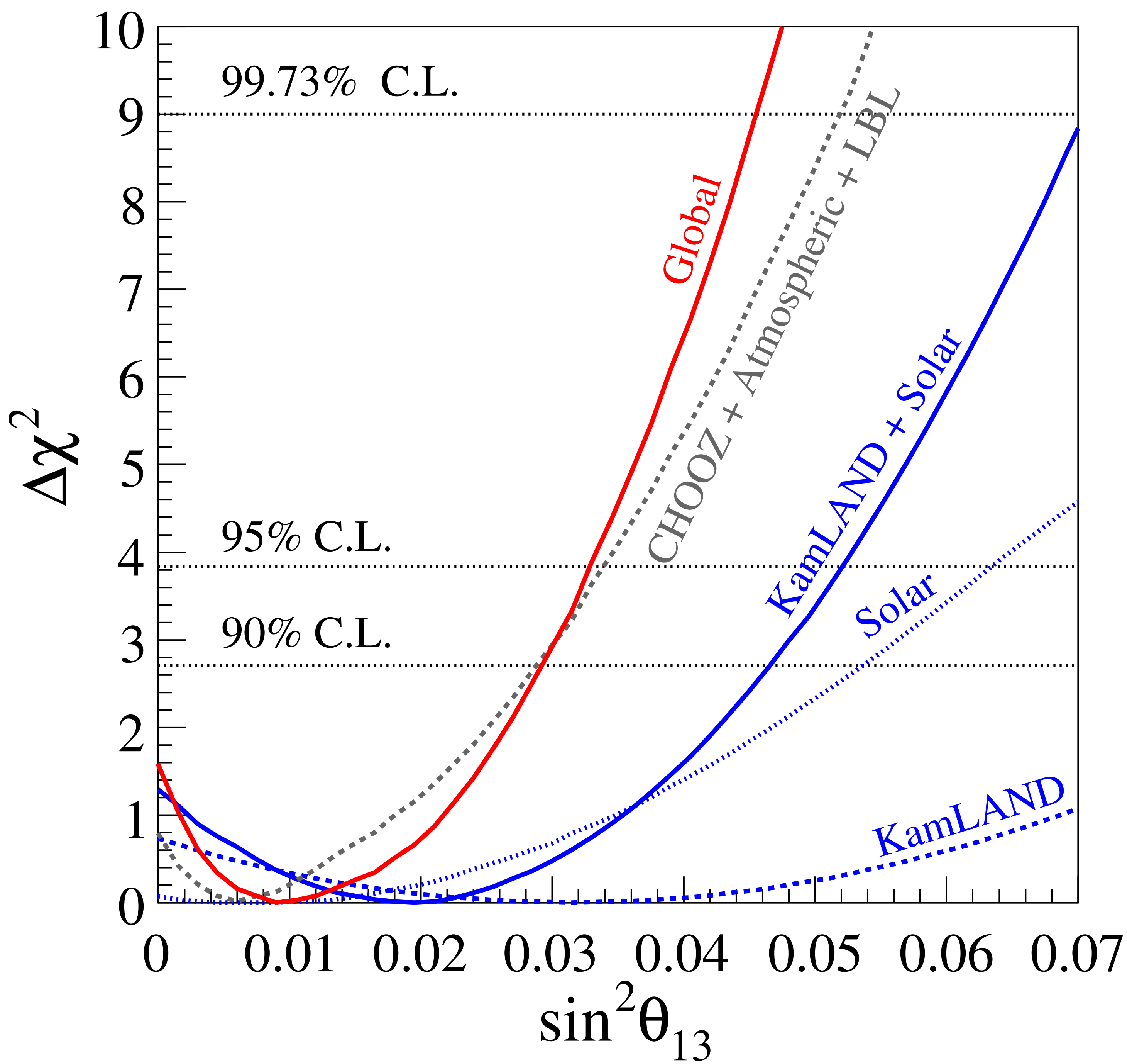


3-Flavor




Solar
95% C.L.
99% C.L.
99.73% C.L.
best-fit
KamLAND
95% C.L.
99% C.L.
99.73% C.L.
best-fit
KamLAND+Solar
95% C.L.
99% C.L.
99.73% C.L.
best-fit
$\sin^2\theta_{13}$
$\tan^2\theta_{12}$
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.18
0.2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Global Analysis



Global:

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

Visualization of KamLAND's Sensitivity to θ13

Survival Probability:

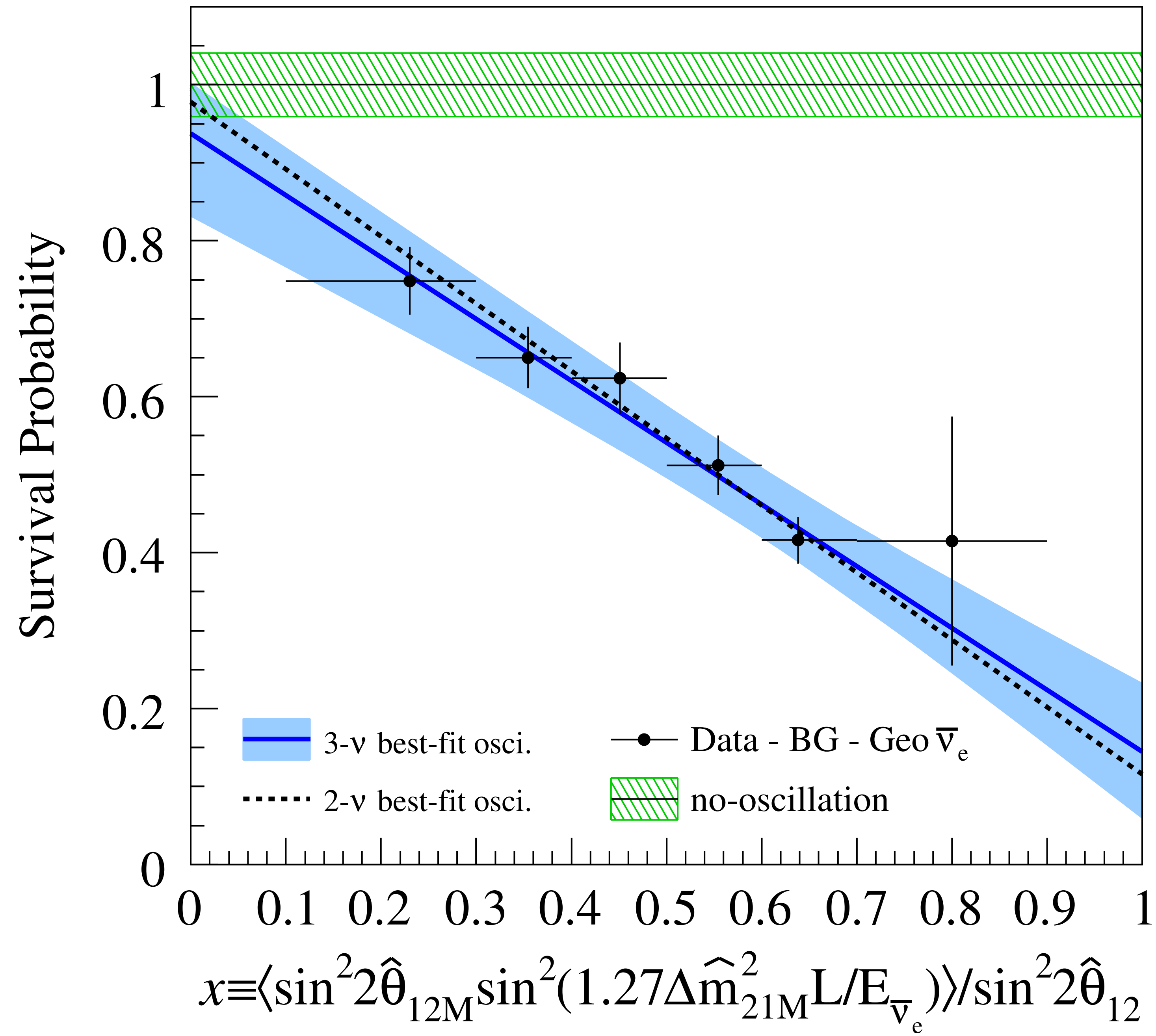
$$P(E_{\rm p}, t) = A - B \cdot x(E_{\rm p}, t)$$

Dependent on θ13:

$$A = (\cos^4\theta_{13} + \sin^4\theta_{13})$$

Mostly Dependent on θ12:

$$B = \cos^4\theta_{13}\sin^2 2\theta_{12}$$

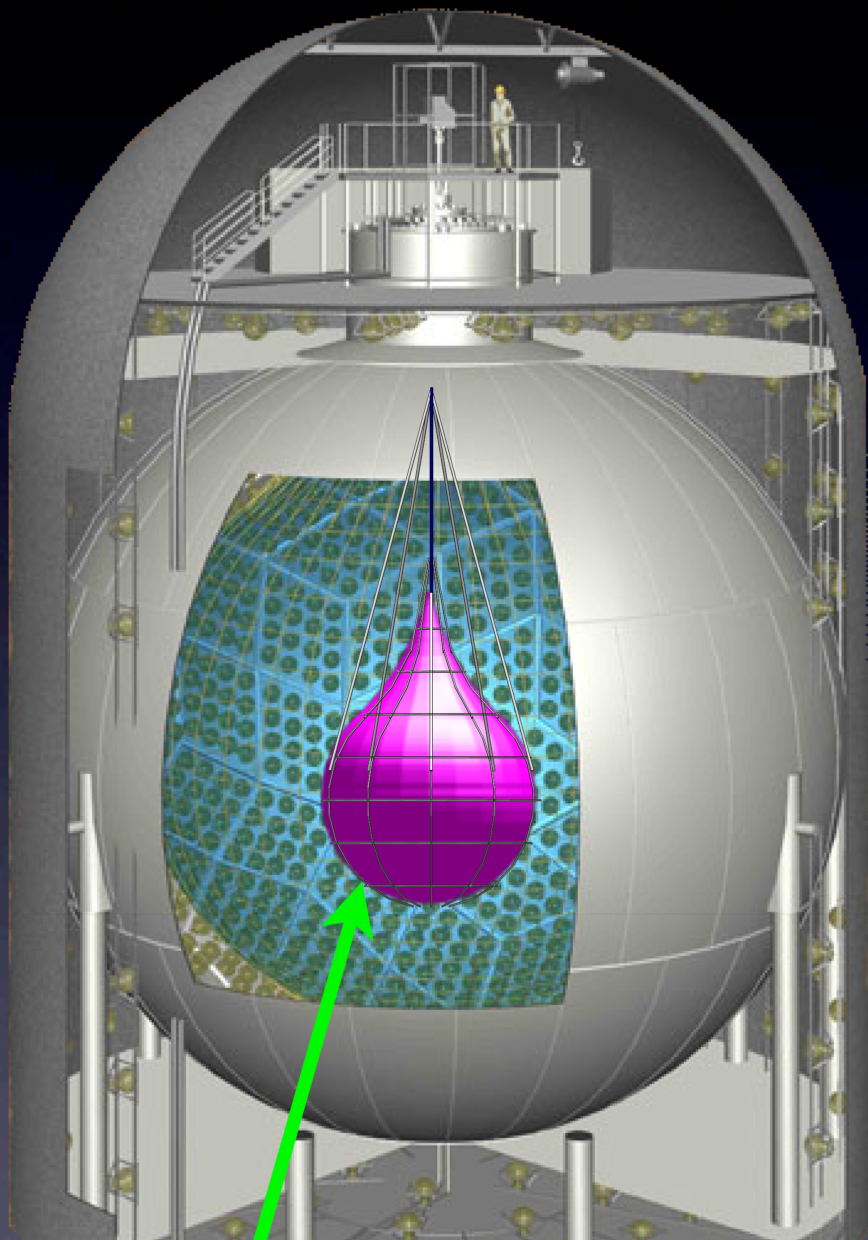


5th KamLAND Reactor Neutrino Result?

- Slightly increased exposure compared to the 4th result.
- Full volume calibration campaign is scheduled for June 2011 which will reduce the fiducial volume uncertainties for the post-purification period.
- Consider the implications of the updated reactor neutrino spectrum predictions.

Future of Long Baseline Reactor Neutrino Experiments

KamLAND-Zen



^{136}Xe 400 kg:

- 2.7 wt% dissolved into LS
- easy handling/ enrichment (90%)
- longer 2ν beta decay life time
- $T^{2\nu} > 10^{22}$ years (cf: $\sim 10^{19\text{-}20}$)

KamLAND exists:

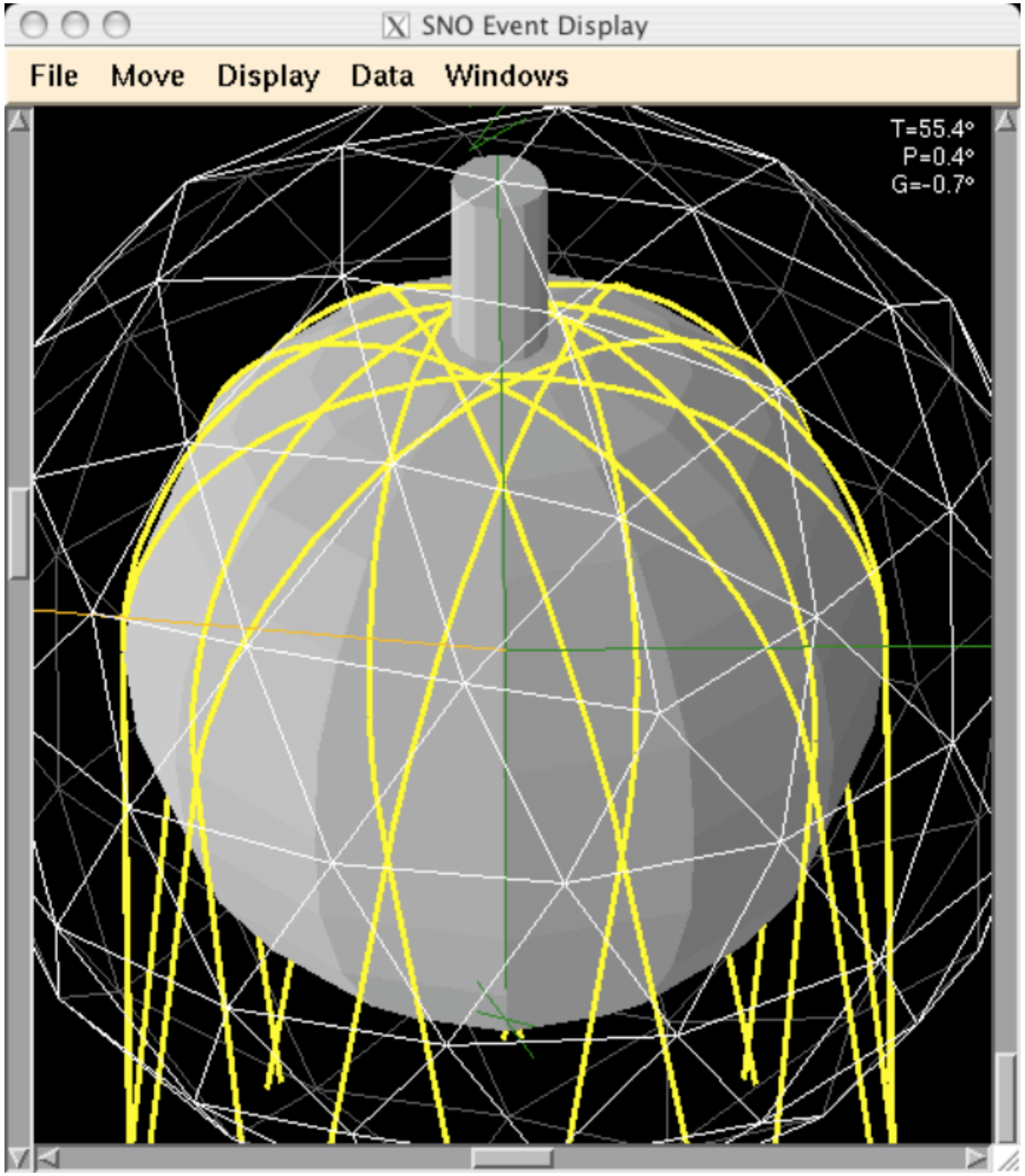
- ultra pure environment (U/Th~10^{-17} g/g)
- LS techniques
- Balloon experience
- LS Density control techniques
- Reactor/Geo neutrino

^{136}Xe 400 kg loaded LS in mini-balloon, R=1.7m

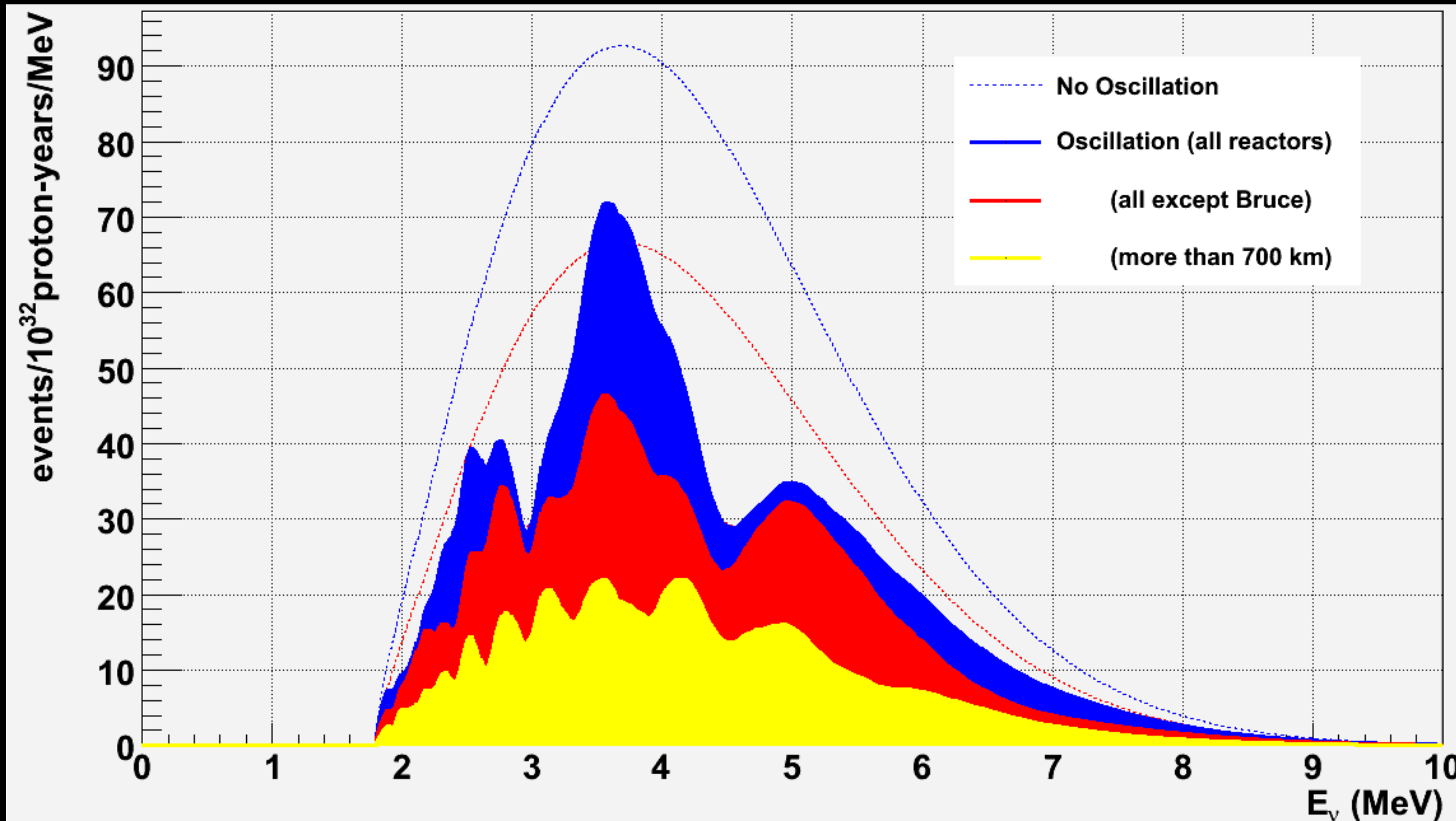
Slide courtesy of
Dr. K Nakamura,
RCNS Tohoku University, Jp
Neutrino 2010

SNO+

Neutrinoless Double Beta Decay Search



Reactors Contribution to the Spectrum

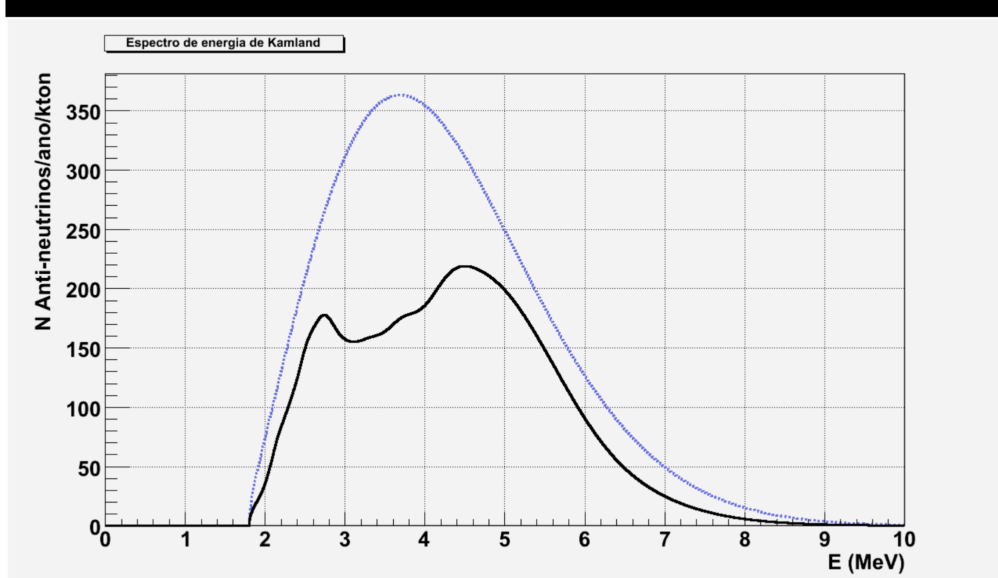


- Bruce reactor will contribute mainly to the central peak.
- We can take advantage from any "shut-off" period

L/E Analysis

Main Reactors (distances smaller than 700km to the detector)

Reactor	d (km)	Th. Power (GW)
Bruce	281	10,32
Pickering	330	6,192
Darlington	340	10,572
R.E. Ginna	455	1,41
James A. Fitzpatrick	488	2,34
Nine Mile Point	488	5,07
Perry	530	3,1615
Enrico Fermi	559	3,255
Kewaunee	568	1,509
Davis-Besse	588	2,531
Point Beach	589	2,91
Palisades	617	2,34
Gentily	648	1,914
Beaver Valley	657	4,929
Donald C. Cook	685	3,06

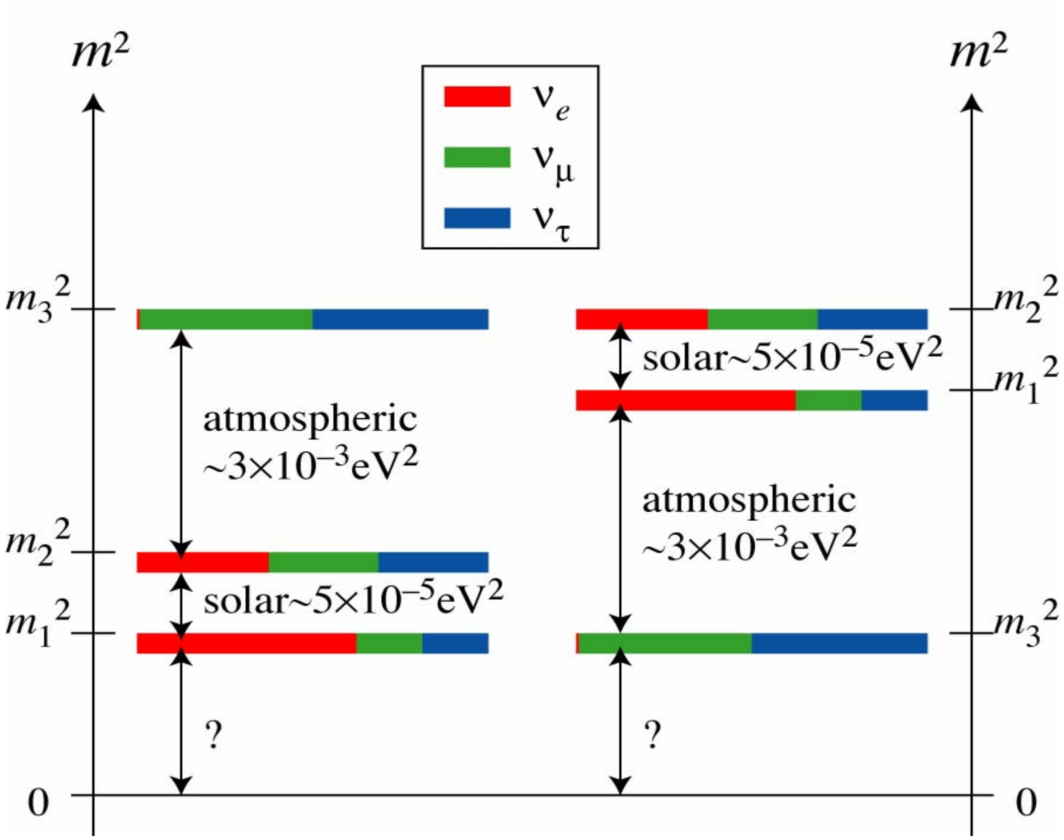


Steve Biller ANT 2011

Intermediate Baseline Reactor Neutrino Experiments

Can the neutrino mass hierarchy be determined by a reactor experiment?

Normal Inverted



Petcov & Piai, PLB **533**, 94 (2002)
Choubey *et al.*, PRD **68**, 113006 (2003)
Learned *et al.*, PRD **78**, 071302 (2008)
Zhan, *et al.*, PRD **78**, 111103 (2008)
Zhan, *et al.*, PRD **79**, 073007 (2009)
Ghosha & Petcov, arXiv:1011.1646

Fourier transformation of L/E spectrum

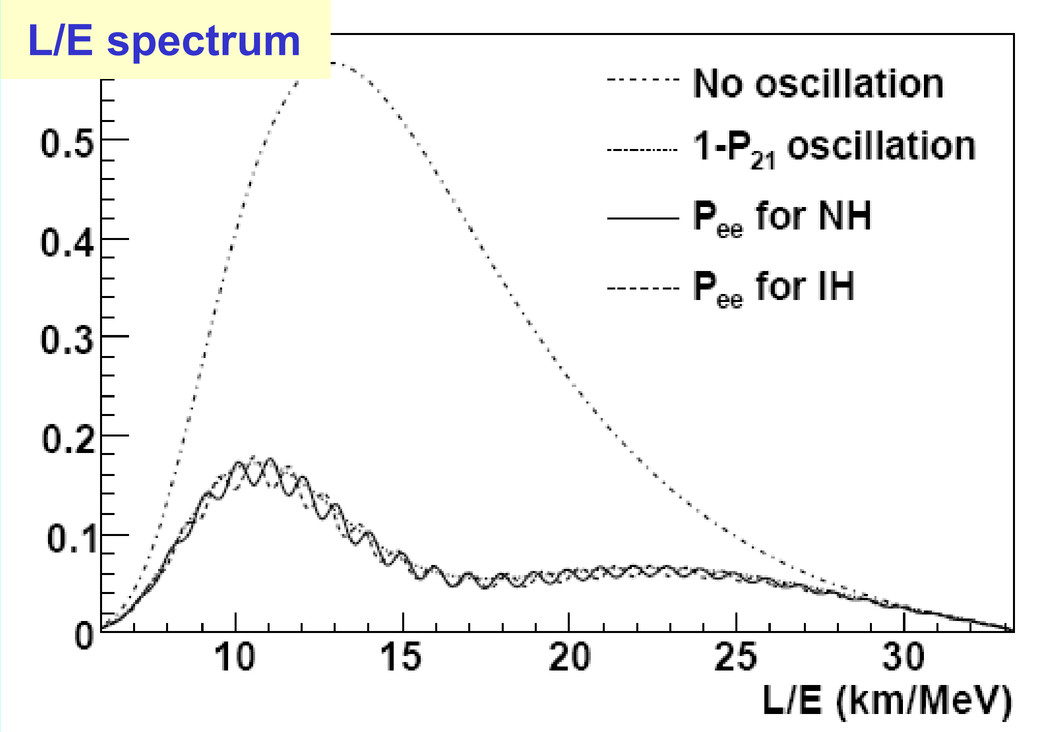
- **Frequency regime is in fact the ΔM^2 regime ➔ enhance the visible features in ΔM^2 regime**
- **Take ΔM^2_{32} as reference**
  - **NH: $\Delta M^2_{31} > \Delta M^2_{32}$, ΔM^2_{31} peak at the right of ΔM^2_{32}**
  - **IH: $\Delta M^2_{31} < \Delta M^2_{32}$, ΔM^2_{31} peak at the left of ΔM^2_{32}**

$$F(L/E) = \phi(E)\sigma(E)P_{ee}(L/E)$$

$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$

$$\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$

$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \mathrm{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\ \mathrm{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \end{aligned}$$



Yifang Wang ANT 2011

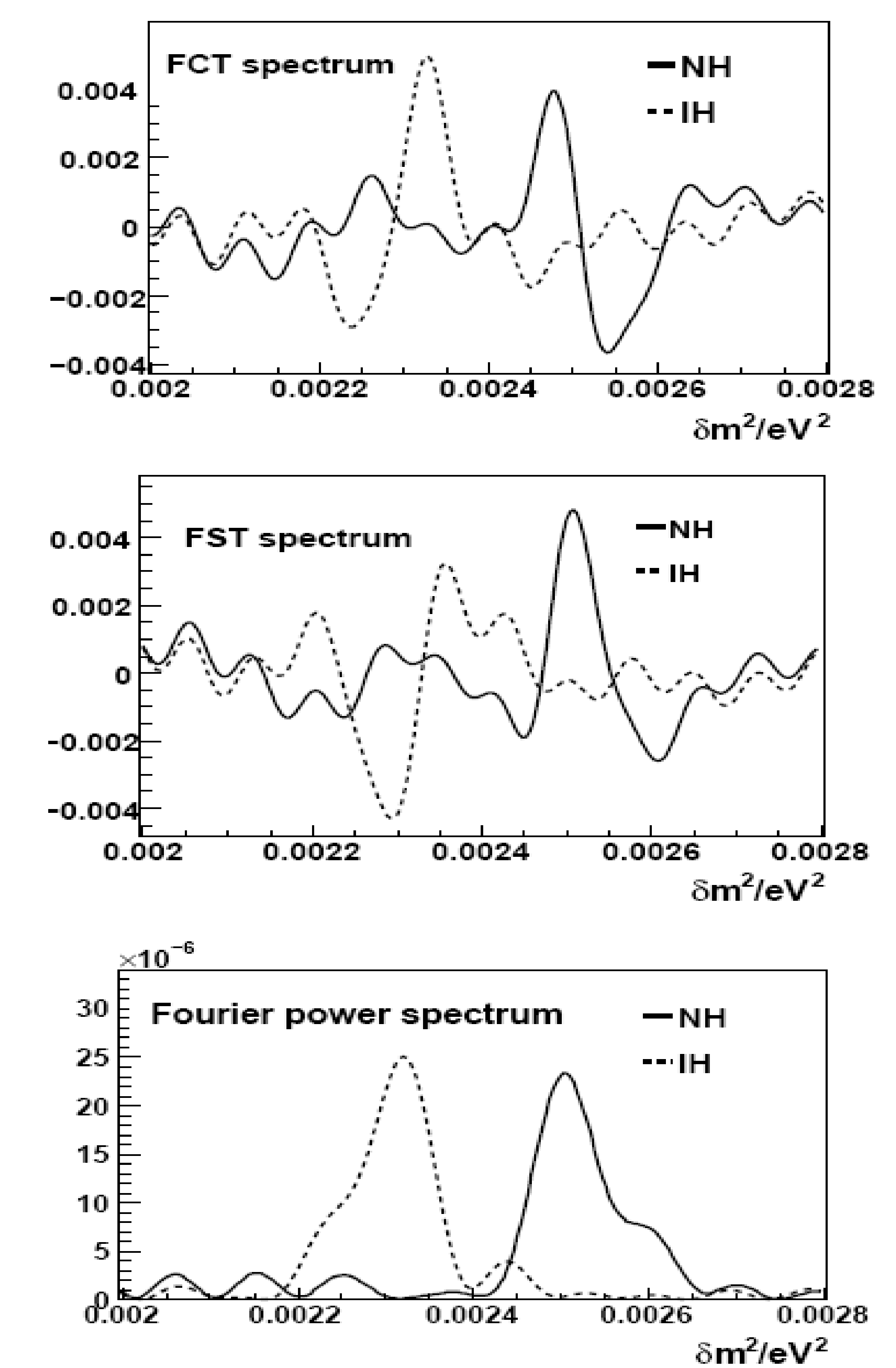
Features of Mass Hierarchy

- **A different Fourier formalism:**

$$FST(\omega) = \int_{t_{min}}^{t_{max}} F(t)\sin(\omega t)\mathrm{d}t$$

$$FCT(\omega) = \int_{t_{min}}^{t_{max}} F(t)\cos(\omega t)\mathrm{d}t$$

- **Clear distinctive features:**
  - **FCT:**
    - **NH: peak before valley**
    - **IH: valley before peak**
  - **FST:**
    - **NH: prominent peak**
    - **IH: prominent valley**
- **Better than power spectrum**
- **No pre-condition of Δm^2_{23}**



L. Zhan et al., PRD78(2008)111103

Quantify Features of FCT and FST

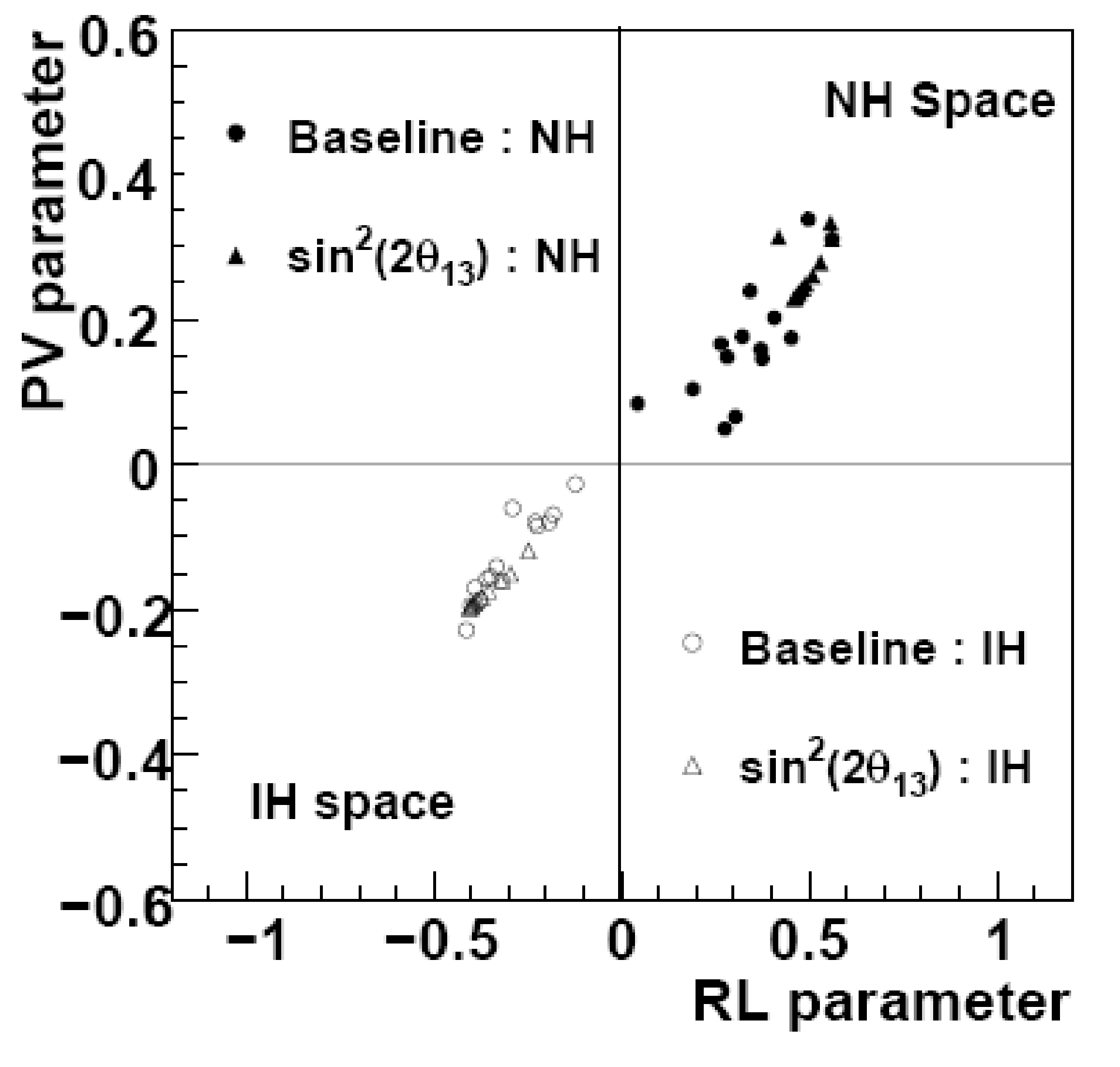
- To quantify the symmetry breaking, we define:

$$RL = \frac{RV - LV}{RV + LV}, \quad PV = \frac{P - V}{P + V}$$

RV/LV: amplitude of the right/left valley in FCT

P/V: amplitude of the peak/valley in FST

- For asymmetric P_{ee}
  - NH: RL>0 and PV>0
  - IH: RL<0 and PV<0

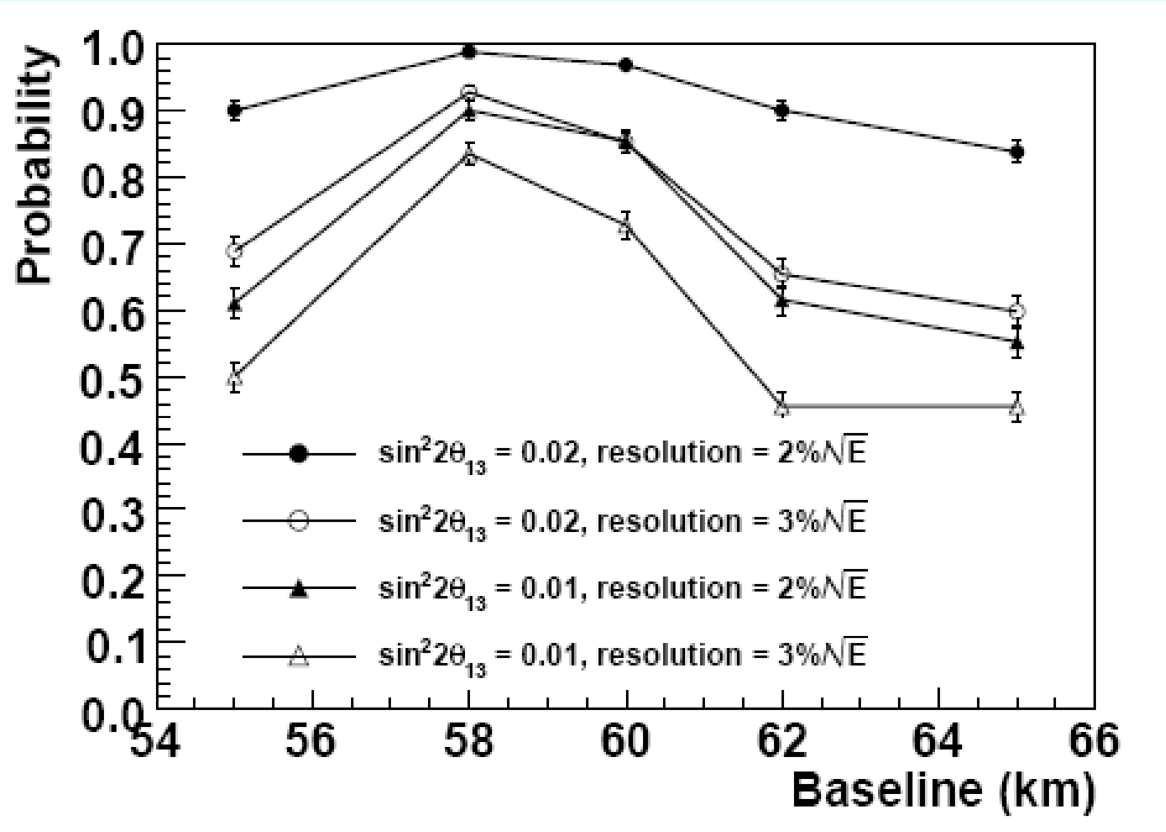


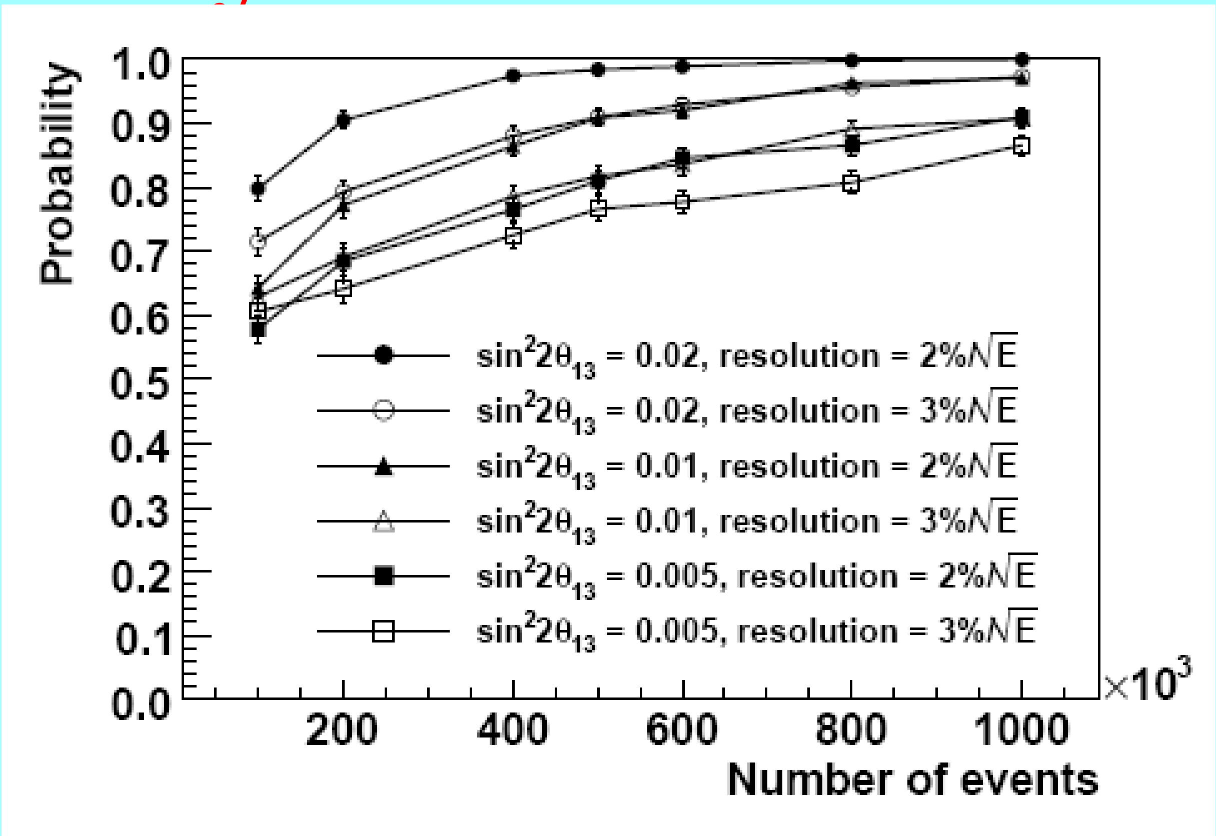
Two clusters of RL and PV values show the sensitivity of mass hierarchy determination

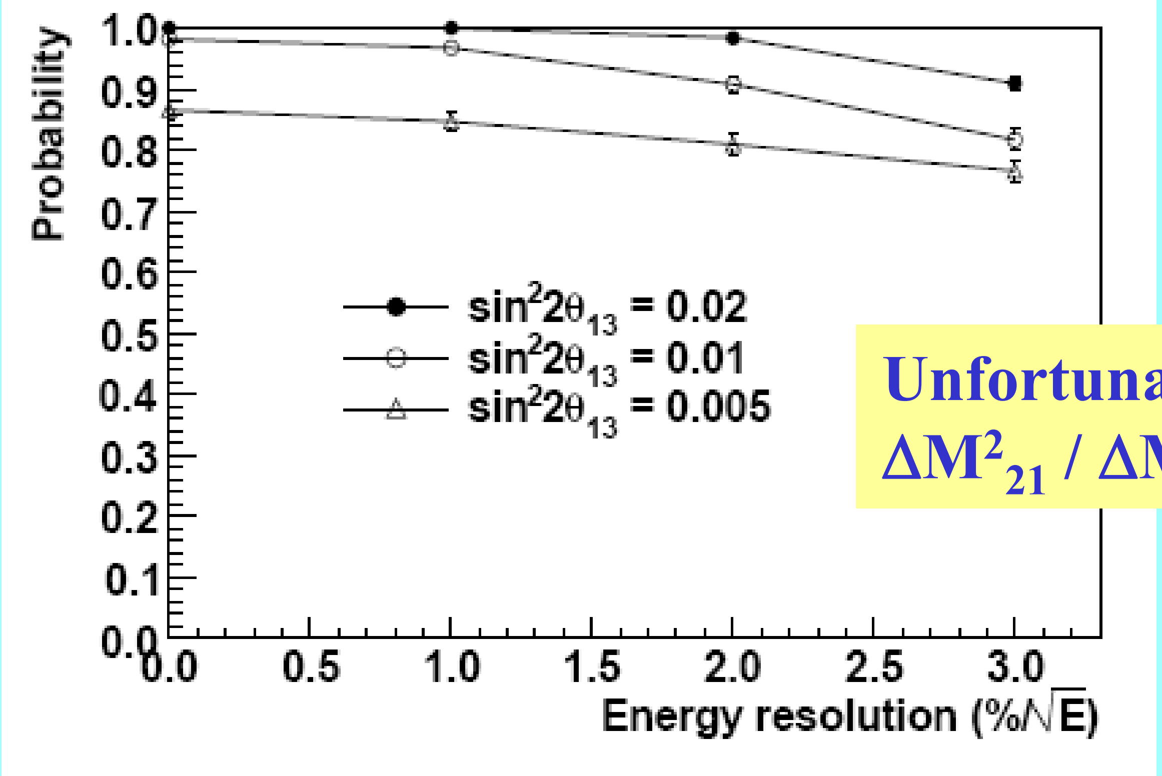
Baseline: 46-72 km
$Sin^2(2\theta_{13})$: 0.005-0.05
Others from global fit

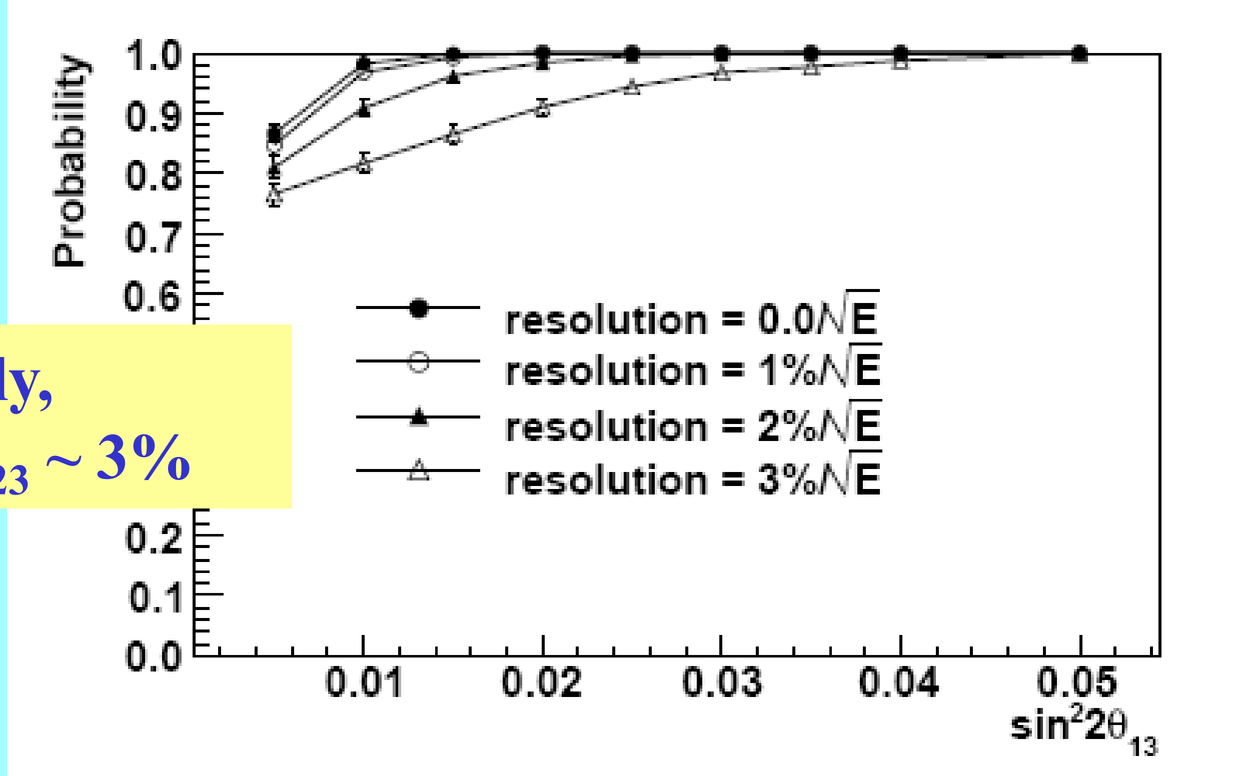
L. Zhan et al., PRD78:111103,2008

In reality









Unfortunately,
$\Delta M^2_{21} / \Delta M^2_{23} \sim 3\%$

L. Zhan, et. al., Phys.Rev.D79:073007,2009

Requirement

- To determine mass hierarchy at > 90% CL:
  - Baseline: ~ 58 km, determined by θ_{12}
  - Reactor power > 24 GW_{th}
  - Flux and detector size: ~ (250-700) kt•year
  - Ideally, $\sin^2 2\theta_{13} > 0.02$ & energy resolution < 2%
    - IF $\sin^2 2\theta_{13}=0.01$, energy resolution < 2% & 700 kt•year
    - For $\sin^2 2\theta_{13}=0.02$, energy resolution < 3% & 700 kt•year
- Overburden > 1000 MWE
- A huge ν_e detector with mass >20kt
  - currently the largest on is 1kt (KamLAND & LVD)

A possible location

60 km from Daya Bay and Haifeng
Thermal power > 40 GW

Technical challenges

- **Requirements:**
  - Large detector: >10 kt LS
  - Energy resolution: 2%/√E ➔ 2500 p.e./MeV
- **Ongoing R&D:**
  - Low cost, high QE "PMT"
    - New type of PMT
  - Highly transparent LS: 15m ➔ >25m
    - Understand better the scintillation mechanism
    - Find out traces which absorb light, remove it from the production

Now:
1kt
250 p.e./MeV

20" UBA/SBA photocathode PMT is also a possibility

Summary

- KamLAND observes a neutrino survival probability that is consistent with the solar LMA solution.
- At the present time, KamLAND has the most precise measurement of Δm^2_{21}.
- Experiments will continue to measure reactor neutrinos at long baselines (parasitically).
- If $\sin^2 2\theta_{13}$ is large enough (>0.02), then intermediate baseline reactor neutrino experiments may have the capability of determining the neutrino mass hierarchy.