Evidence for Neutrino Oscillation in KamLAND

（ KamLANDにおけるニュートリノ振動の証拠 ）

ICEPP Symposium 2005.2.20

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1. Motivation
2. KamLAND Detector and Neutrino Event Selection
3. Significance of Neutrino Oscillation
4. 3 Flavor Oscillation Analysis

Motivation

Primary goal of KamLAND

Search for the neutrino oscillation of $\bar{\nu}_e$ from distant reactors

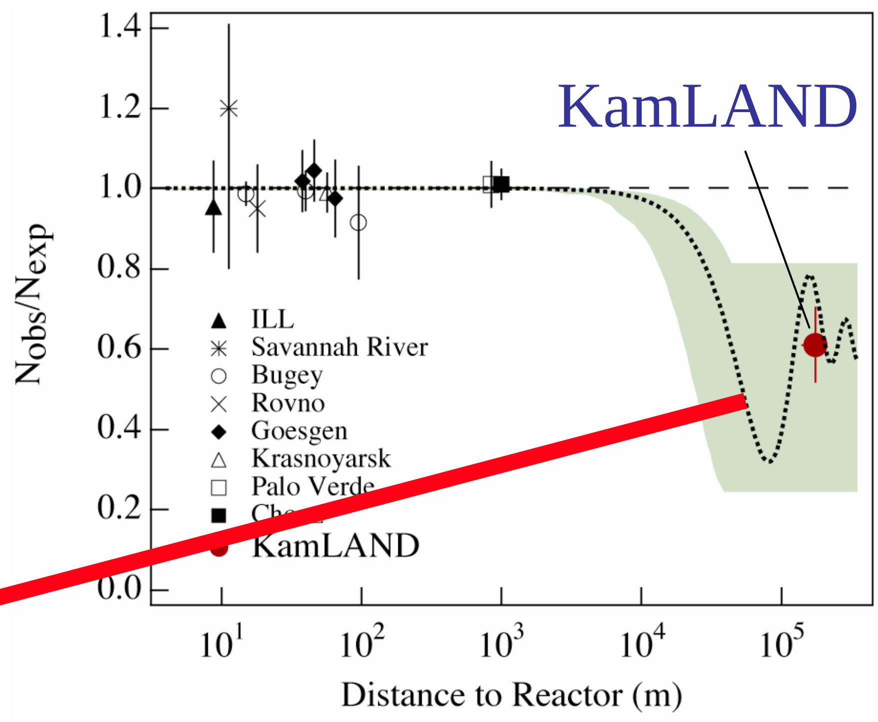
first-result (Dec. 2002)

disappearance of $\bar{\nu}_e$

second-result (Jun. 2004)

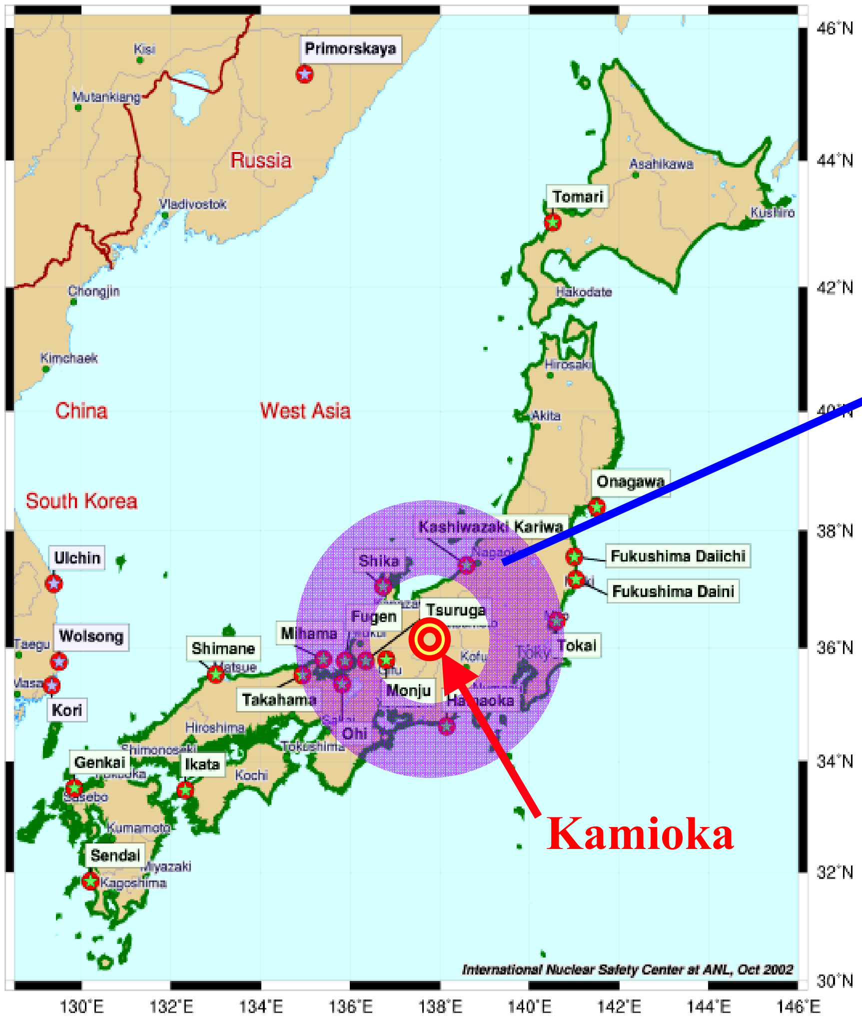
distortion of $\bar{\nu}_e$

reactor experiment

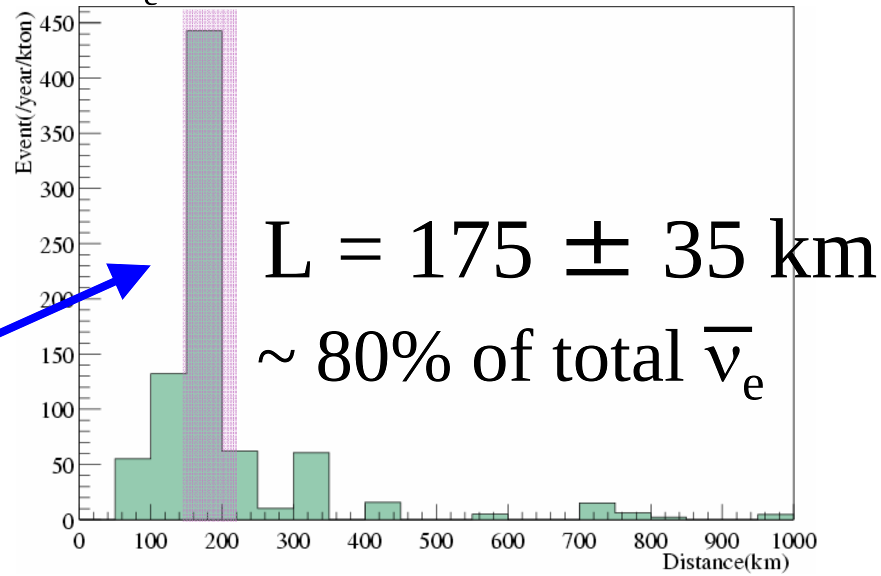


oscillatory shape from neutrino oscillation

KamLAND Experiment



$\overline{\nu}_e$ contribution from reactors



ΔL (distribution of reactors)

175 ± 35 km **~ 20%**

ΔE (energy resolution)

17 inch PMTs **$7.3\% / \sqrt{E(MeV)}$**

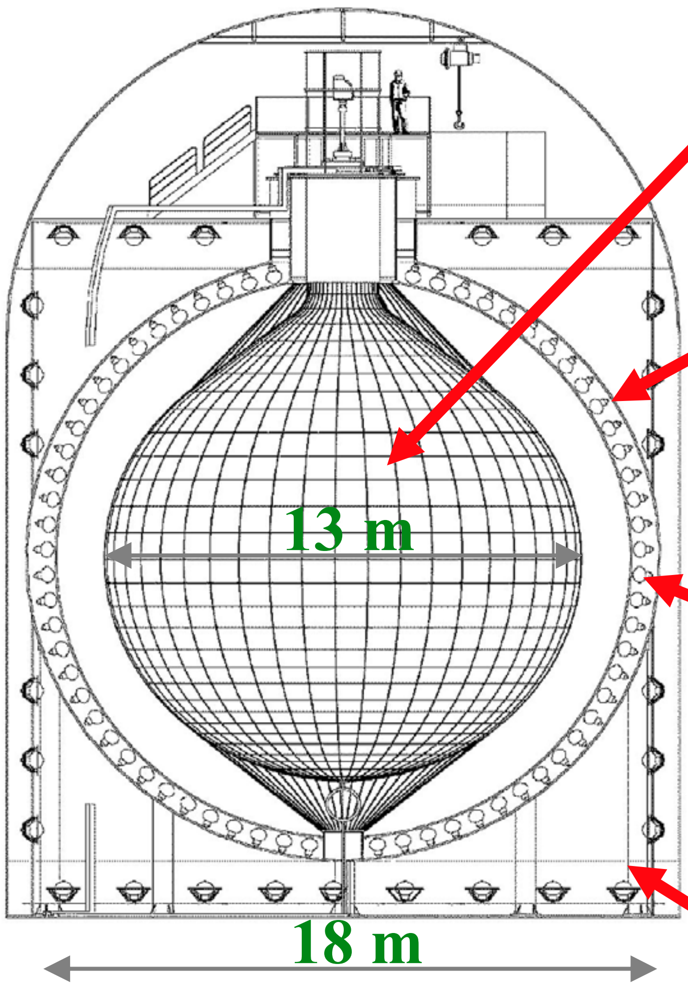
17 inch + 20 inch **$6.2\% / \sqrt{E(MeV)}$**

high L/E resolution to see oscillatory shape

KamLAND Detector and Neutrino Event Selection

KamLAND Detector

Kamioka **L**iquid Scintillator **A**nti-**N**eutrino **D**etector



1,000 ton liquid scintillator

80% (dodecane) + 20% (pseudocumene) + 1.52 g/l PPO

3000 m^3 stainless steel vessel

filled with a mixture of paraffin oil and dodecane

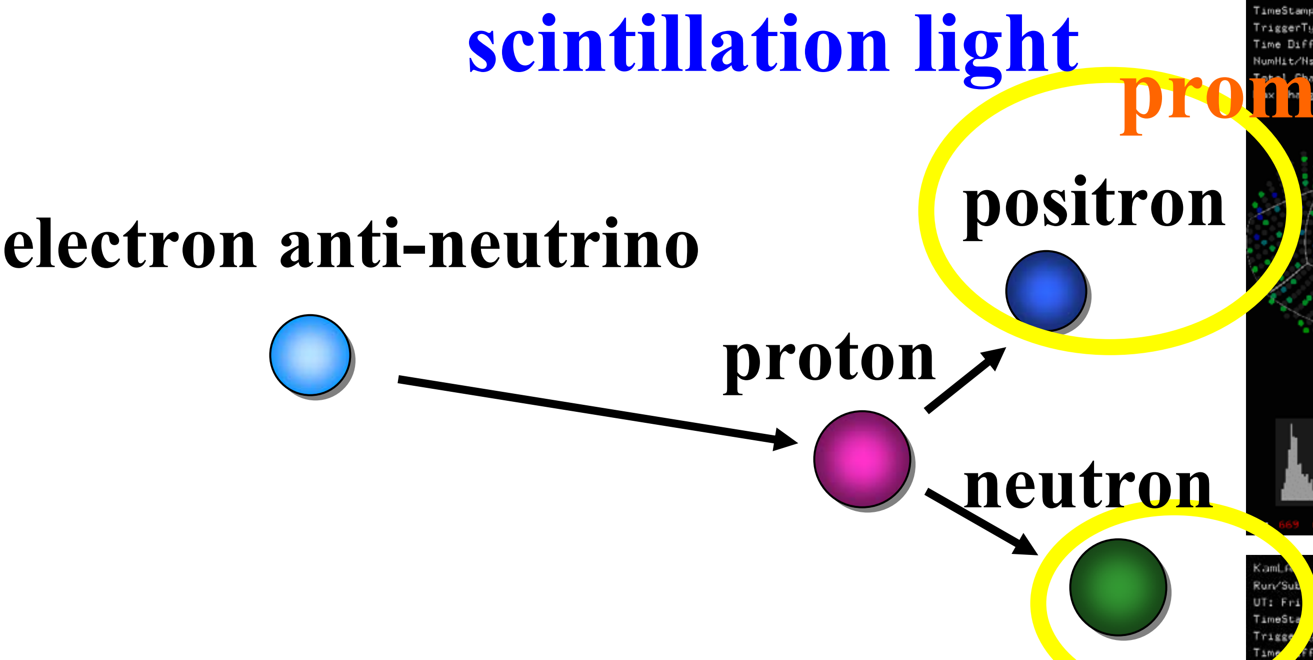
1325 17-inch + 554 20-inch PMTs

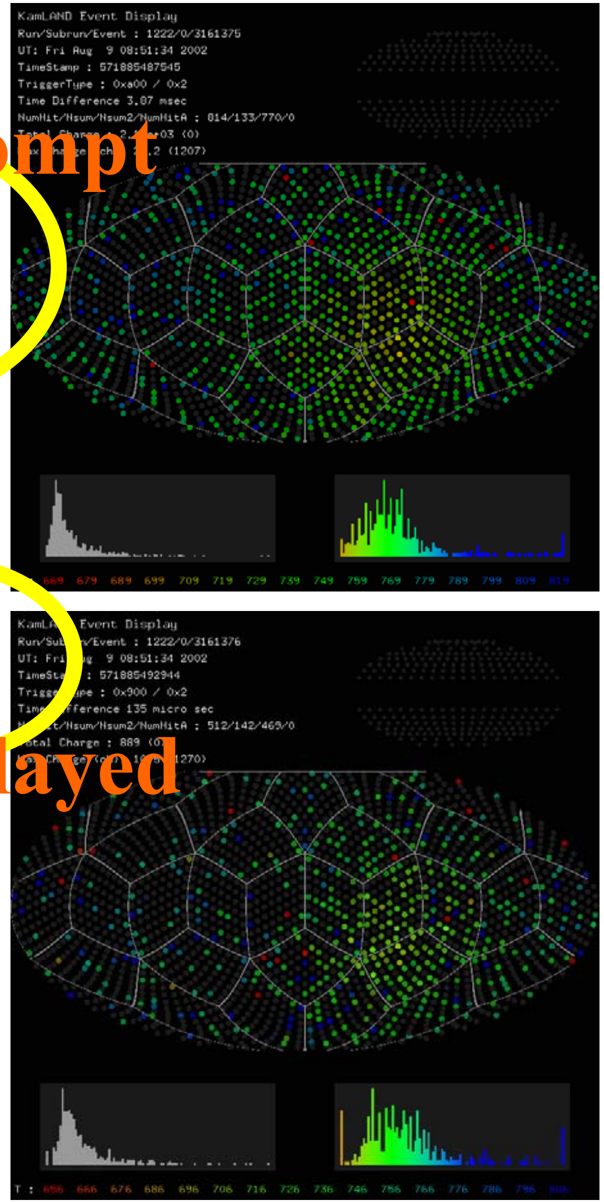
commissioned in February, 2003

photocathode coverage : 22% → 34%

water Cherenkov outer detector

Delayed Coincidence Detection





$\bar{\nu}_e \, p \rightarrow n \, e^+$ (inverse β decay)

$\quad \hookrightarrow n \, p \rightarrow d \, \gamma$ (2.2MeV)

(thermalize and capture)

$\tau \sim 200 \ \mu sec$

Neutrino Event Selection

primary cuts

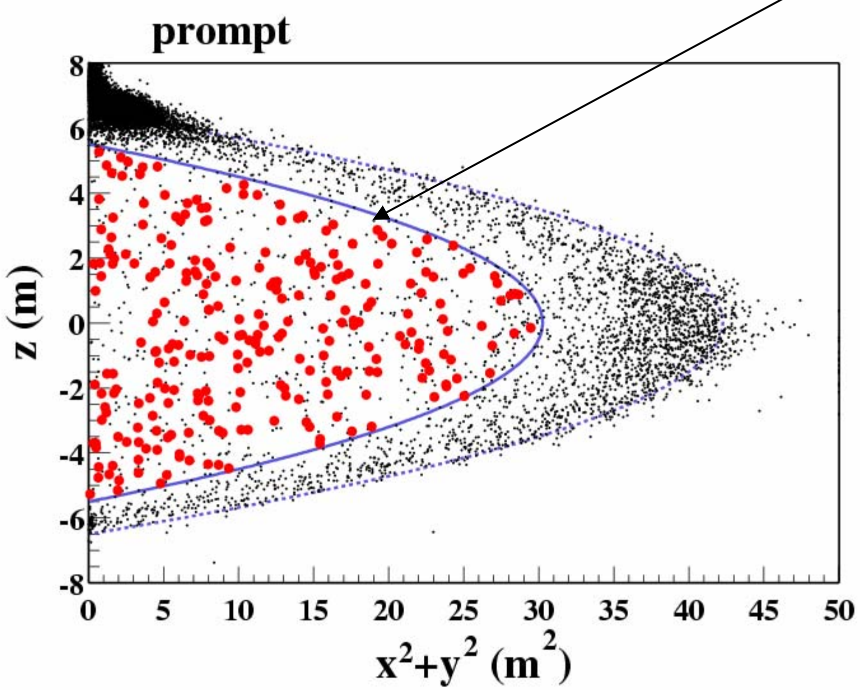
- $0.5\ \mu sec < \Delta T < 1000\ \mu sec$
- $\Delta R < 2m$
- $1.8\ MeV < E_{delayed} < 2.6\ MeV$
- $2.6\ MeV < E_{prompt} < 8.5\ MeV$

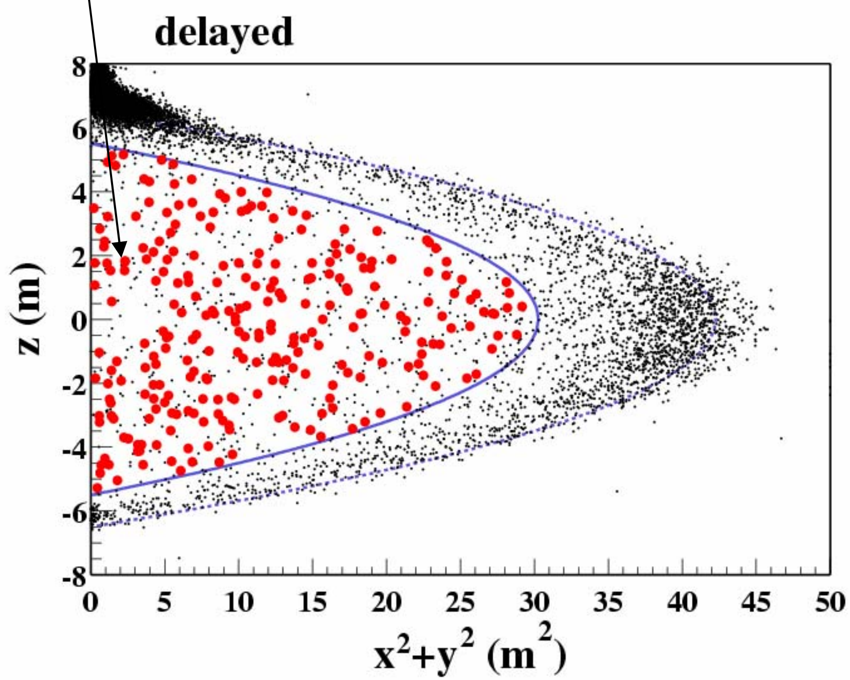
fiducial cut + μspallation cut

- R_{prompt}, $R_{delayed} < 5.5m$
- 2 sec veto after showering μ
- 2 sec veto after non-showering μ in 3m cylinder

efficiency 89.8%

deadtime 9.7%





Systematic Error

Systematic	%
Fiducial volume	4.7
Energy threshold	2.3
Efficiency of cuts	1.6
Livetime	0.06
Reactor power	2.1
Fuel composition	1.0
$\bar{\nu}_e$ spectra	2.5
Cross section	0.2
Total	6.5

Significance of Neutrino Oscillation

Result of Neutrino Disappearance

analyzed data March 9, 2002 ~ January 11, 2004

(livetime : 515.1 days, fiducial mass : 543.3 ton, E_{prompt}>2.6MeV)

33% increase (R 5m → 5.5m)

4.7x the statistics of first result

no osc. expected 365 ± 24

observed 258

background 17.8 ± 7.3

background

Accidental	2.69 ±
0.02	
$^{8}He/^{9}Li$	4.8 ± 0.9
μ induced n	< 0.89
(α, n)	10.3 ± 7.1

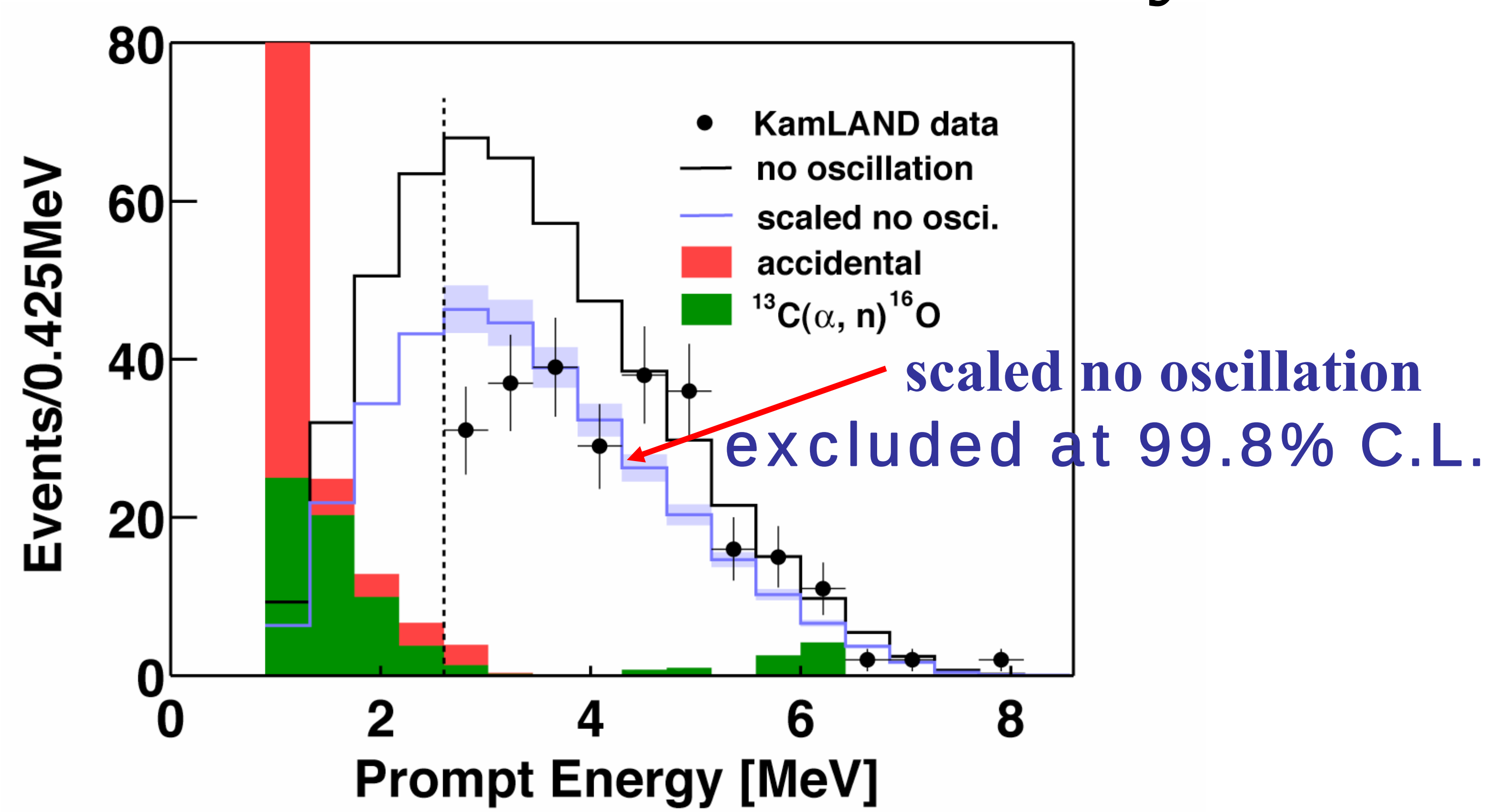
(Observed – Background) / Expected

0.658 ± 0.044(stat) ± 0.047(syst)

inconsistent with no oscillation neutrino propagation

significance of disappearance is 99.998%

Null Oscillation Probability



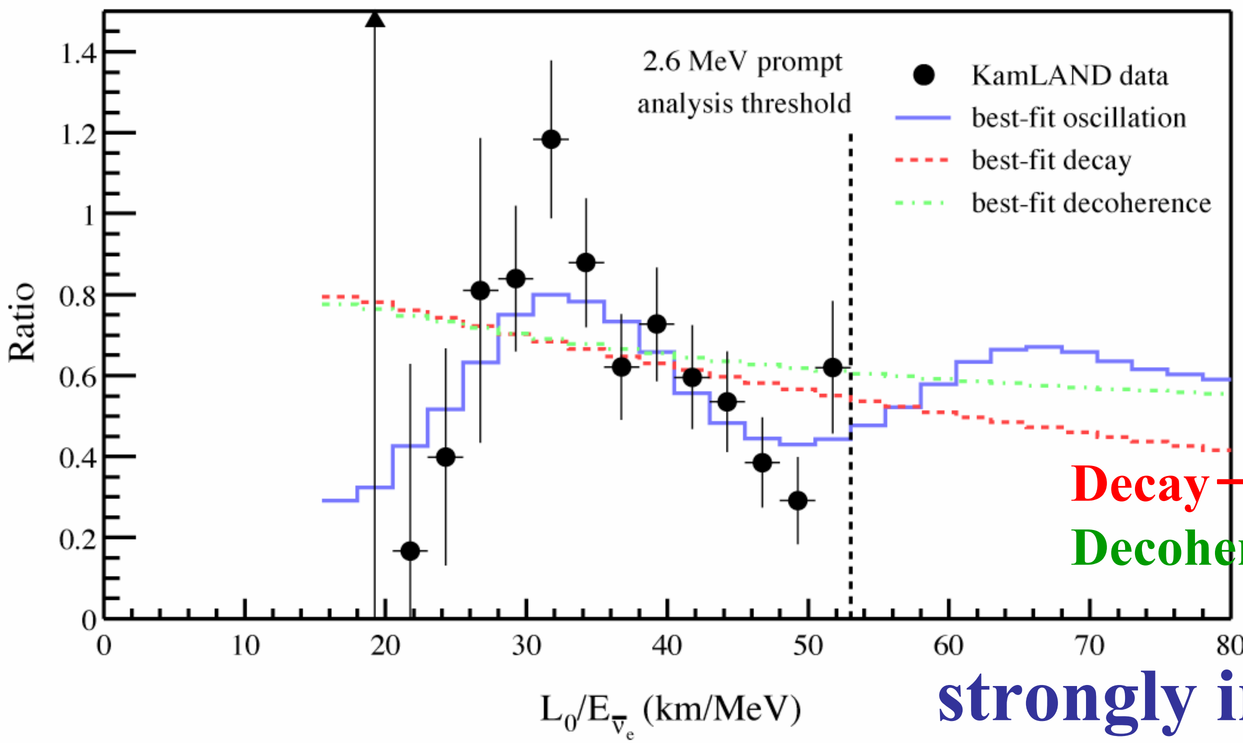
Hypothesis test

Disappearance	99.998%
Shape Distortion	99.8%
Combined	99.999995%

L/E plot

—	Neutrino Oscillation	$1-\sin^2 2\theta \sin^2 \frac{1.27\,\Delta m^2 L}{E}$
—	Neutrino Decay	$(\cos^2\theta + \sin^2\theta \exp(-\frac{m\,L}{2\,\tau\,E}))^2$
—	Neutrino Decoherence	$1-\frac{1}{2}\sin^2 2\theta\,(1-\exp(-\gamma\,\frac{L}{E}))$

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

	$\Delta\chi^2$
Decay − Oscillation	10.7
Decoherence − Oscillation	12.7

↓

strongly indicate Oscillation

L/E plot

—	**Neutrino Oscillation**	$1-\sin^2 2\theta \sin^2 \frac{1.27\,\Delta m^2 L}{E}$
—	**Neutrino Decay**	$(\cos^2\theta + \sin^2\theta \exp(-\frac{m\,L}{2\,\tau\,E}))^2$
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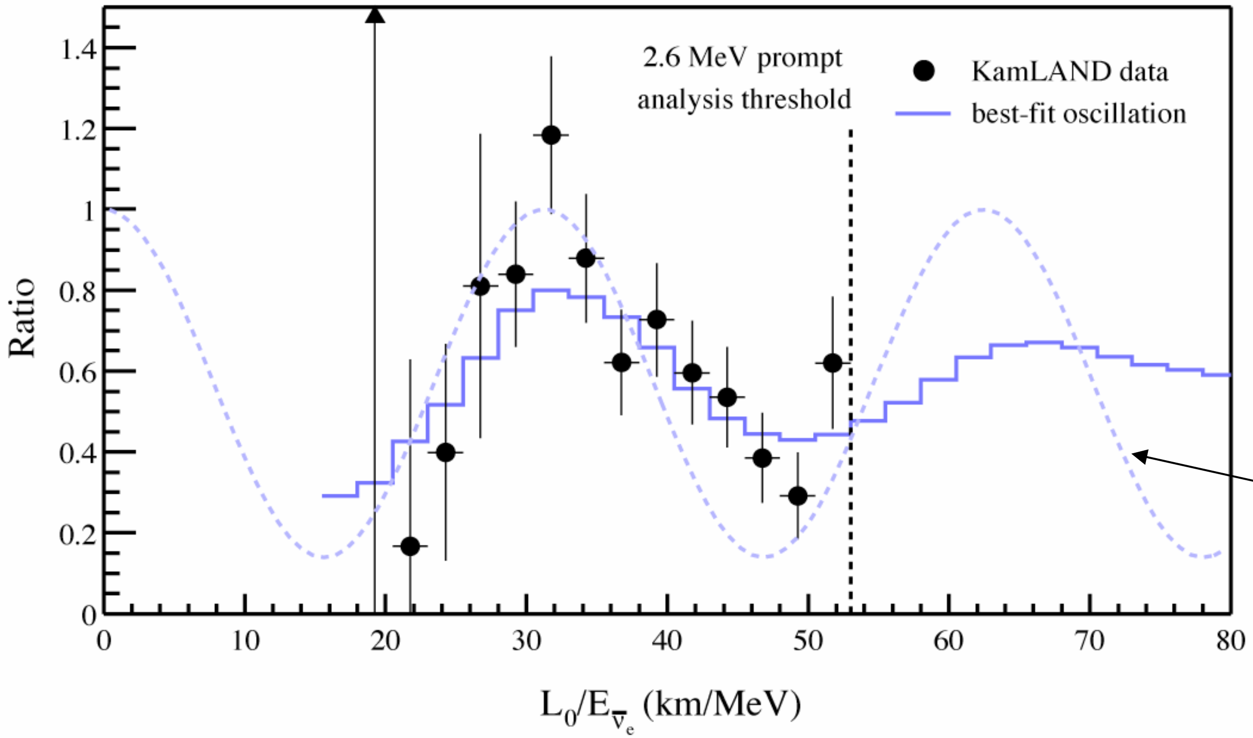
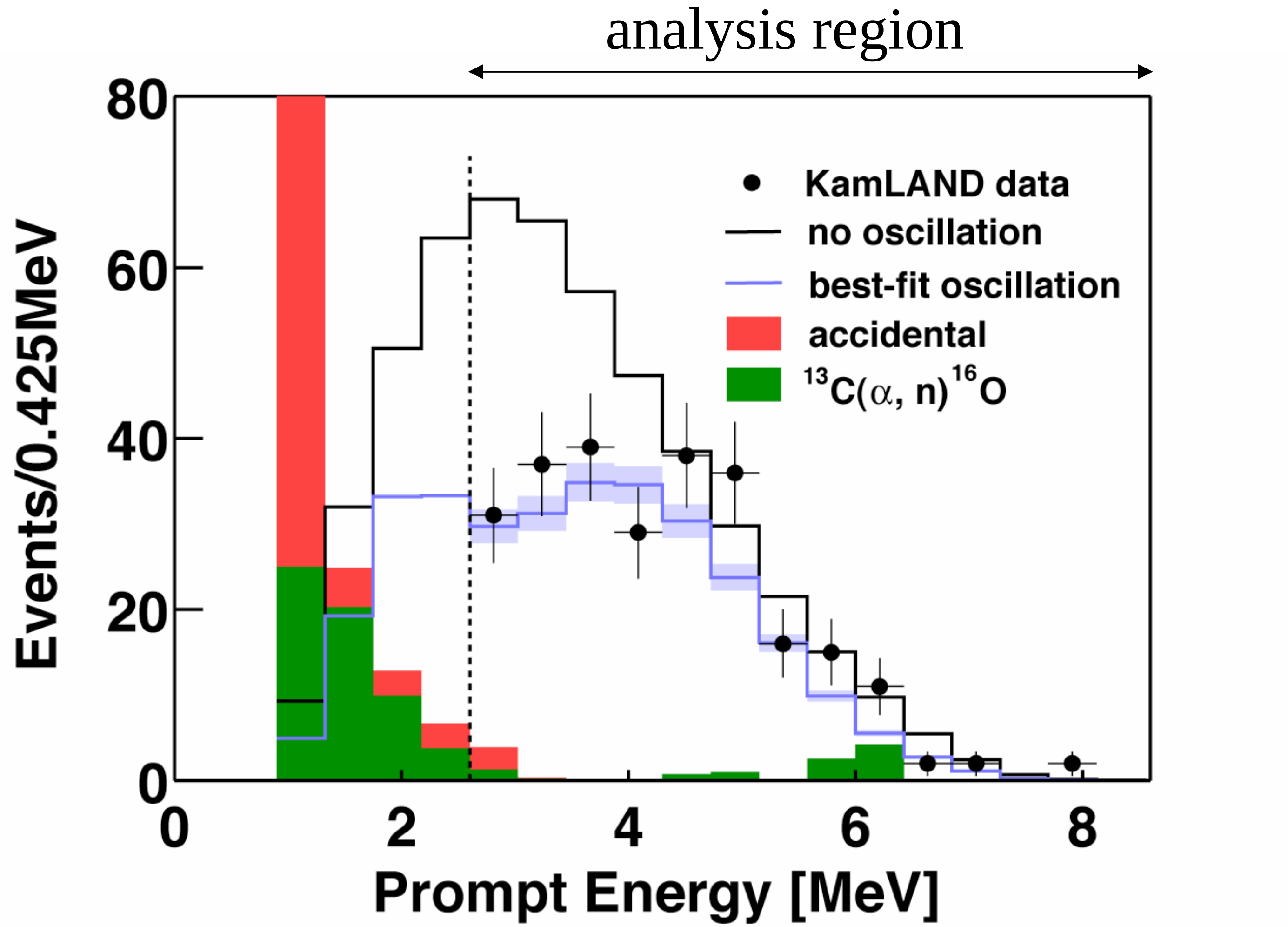


hypothetical single 180 km baseline experiment

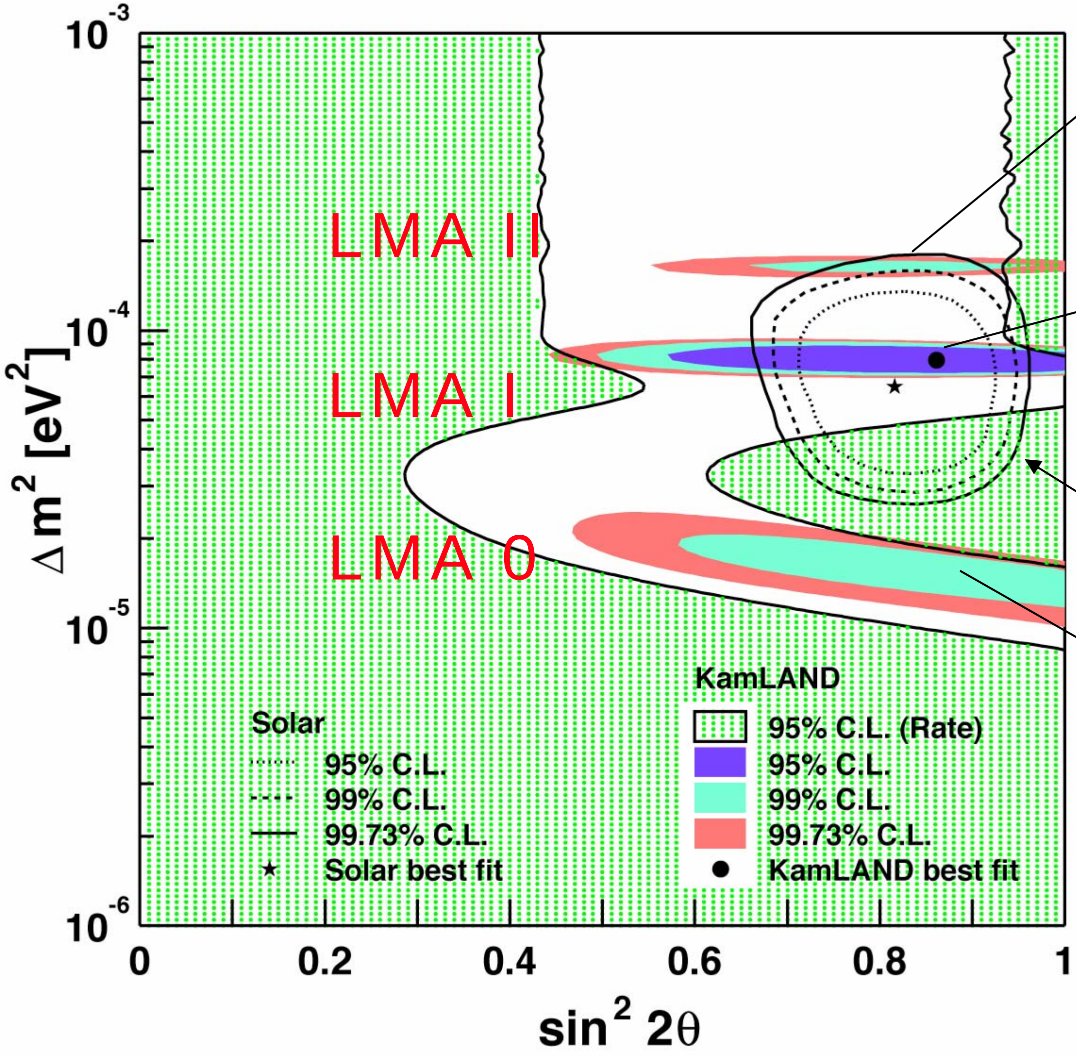
Best-fit to Oscillation



best-fit oscillation

$\sin^2 2\theta = 0.86$ $\Delta m^2 = 7.9 \times 10^{-5}\ eV^2$

Rate + Shape Analysis



LMA II region is disfavored at 98.0% C.L.

KamLAND (2-flavor)

best-fit

$\sin^2 2\theta = 0.86$

$\Delta m^2 = 7.9 \times 10^{-5}\ eV^2$

consistent with solar result

LMA 0 region is disfavored at 97.5% C.L.

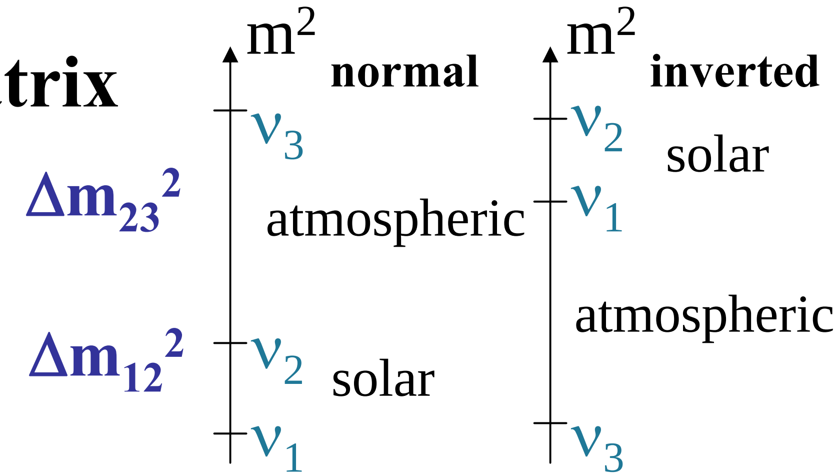
3 Flavor Oscillation Analysis

(from my Ph.D. thesis, not KamLAND official)

Neutrino Oscillation

Maki-Nakagawa-Sakata Matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



θ_{23} | **θ_{13}, CP phase** | **θ_{12}** | **majorana phases**

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

atmospheric | **solar**

6 parameters : 3 angles, 2 mass difference, 1 CP phase

+ 2 majorana phases

↓

measured by neutrino oscillation experiments

Oscillation Experiments

Natural neutrino

- **Solar neutrino** $\nu_e \longrightarrow \nu_x$

Homestake, SAGE, GALLEX, GNO, SNO, Super-Kamiokande

- **Atmospheric neutrino** $\nu_\mu(\overline{\nu_\mu}) \longrightarrow \nu_x(\overline{\nu_x})$

Kamiokande, IMB, Super-Kamiokande, Soudan2 …

Man-made neutrino

- **Accelerator neutrino**

K2K, LSND, KARMEN, MiniBooNE …

- **Reactor neutrino**

Bugey, CHOOZ, Palo Verde, **KamLAND** …

K2K and KamLAND show neutrino disappearance

KamLAND (3-flavor)

survival probability

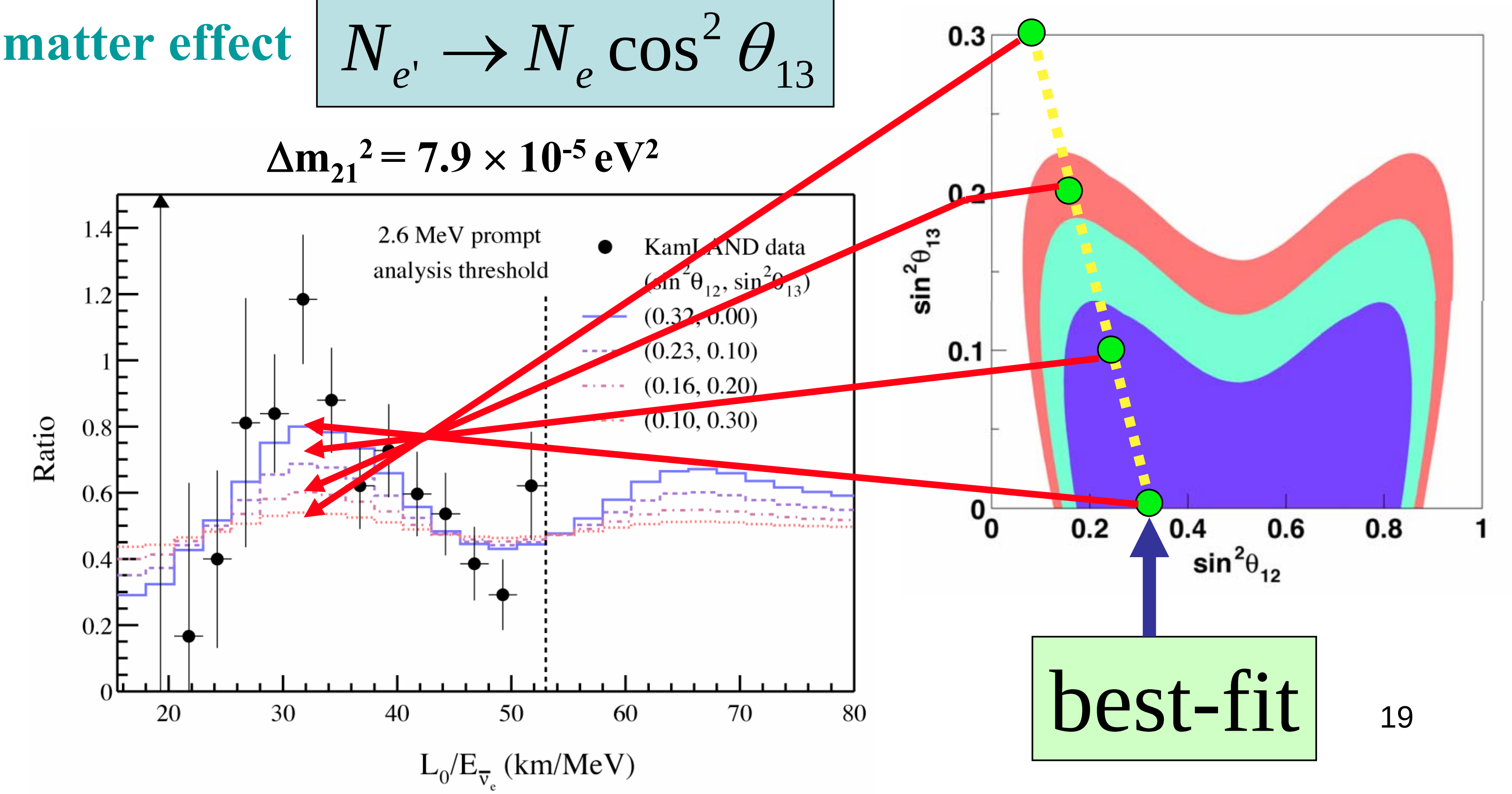
$$P_{ee}^{3\nu} = \cos^4\theta_{13} P_{e'e'}^{2\nu} + \sin^4\theta_{13}$$

atmospheric oscillation length is completely averaged out

~~Δm_{31}^2~~

electron density

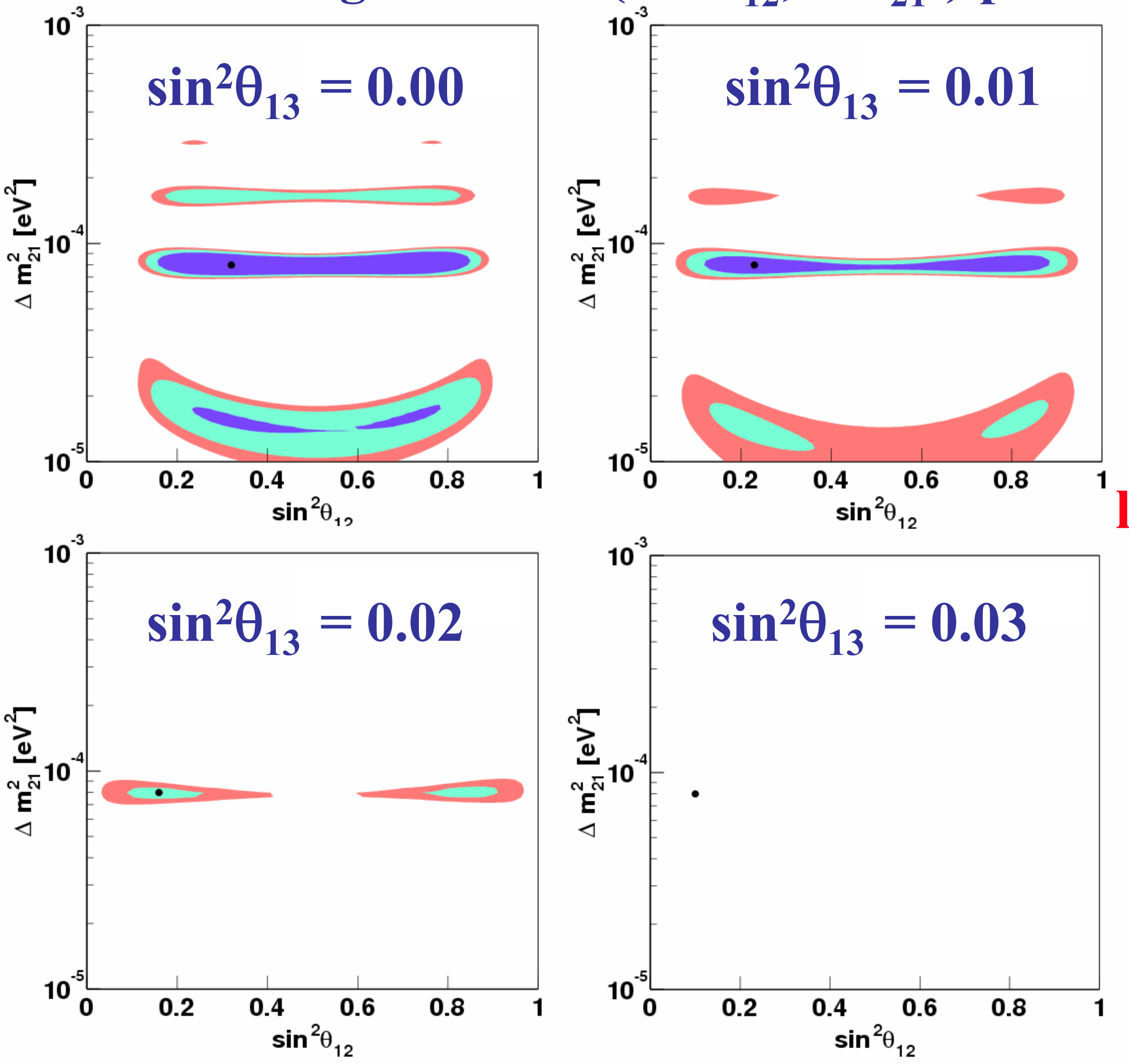
matter effect $N_{e'} \rightarrow N_e \cos^2\theta_{13}$



best-fit

KamLAND

allowed region in the ($\sin^2\theta_{12}$, Δm_{21}^2) plane



best-fit

$\sin^2\theta_{12} = 0.31$

$\sin^2\theta_{13} = 0.00$

$\Delta m_{21}^2 = 7.9 \times 10^{-5}$ eV^2

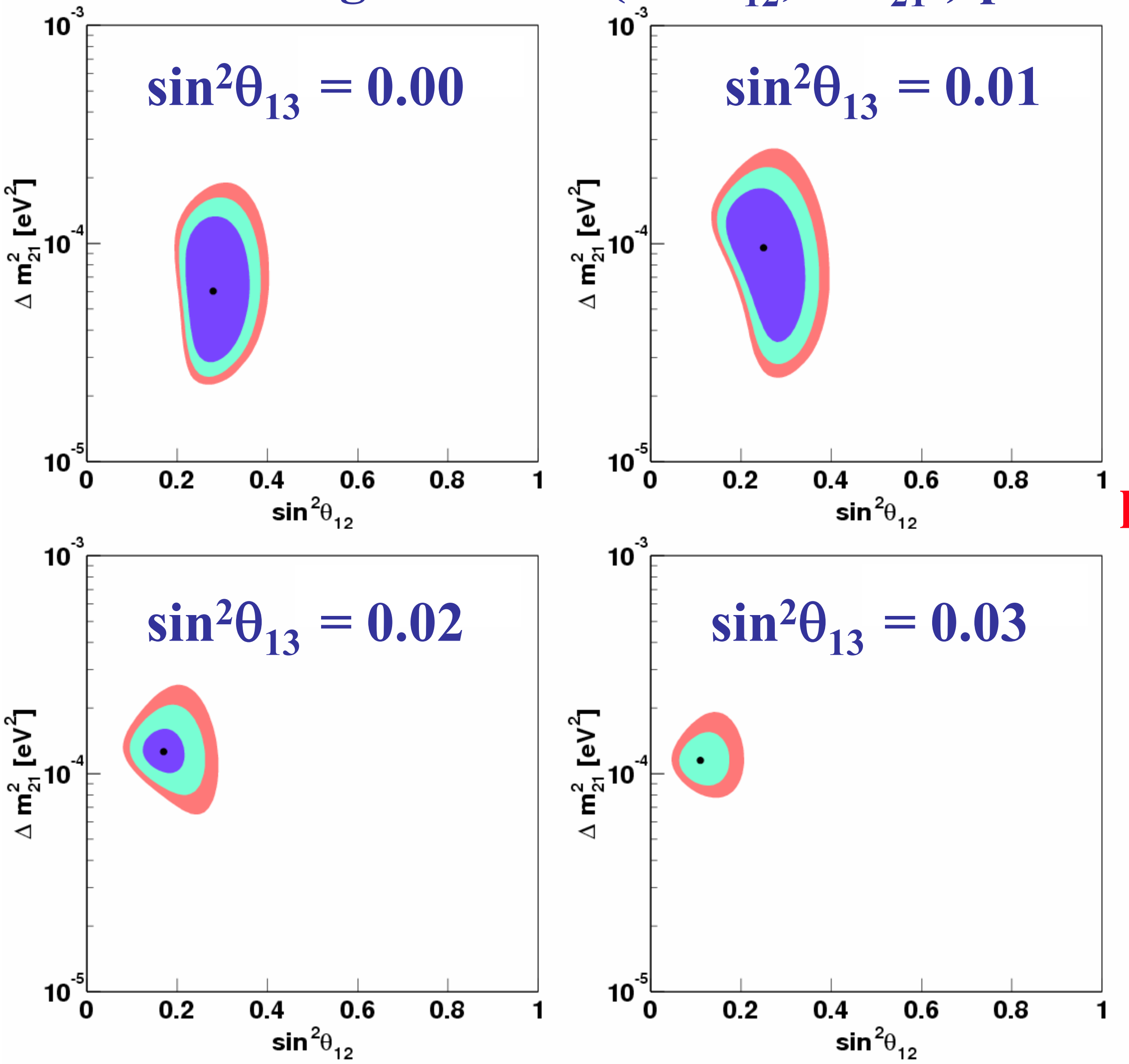
larger θ_{13} is disfavored

$\sin^2\theta_{13} \longleftrightarrow \sin^2\theta_{12}$
negative correlation

$\sin^2\theta_{13} \longleftrightarrow \Delta m_{21}^2$
no correlation

Solar

allowed region in the ($\sin^2\theta_{12}$, Δm_{21}^2) plane



best-fit

$\sin^2\theta_{12} = 0.28$

$\sin^2\theta_{13} = 0.04$

$\Delta m_{21}^2 = 6.6 \times 10^{-5}\ \mathrm{eV}^2$

larger θ_{13} is disfavored

$\sin^2\theta_{13} \longleftrightarrow \sin^2\theta_{12}$
negative correlation

$\sin^2\theta_{13} \longleftrightarrow \Delta m_{21}^2$
positive correlation

Global Analysis

neutrino oscillation experiment

solar, KamLAND $\Delta m^2_{21}, \theta_{12}, \theta_{13}$

solar neutrino oscillation parameter

atmospheric, K2K $\Delta m^2_{31}, \theta_{23}, \theta_{13}$

CHOOZ θ_{13}

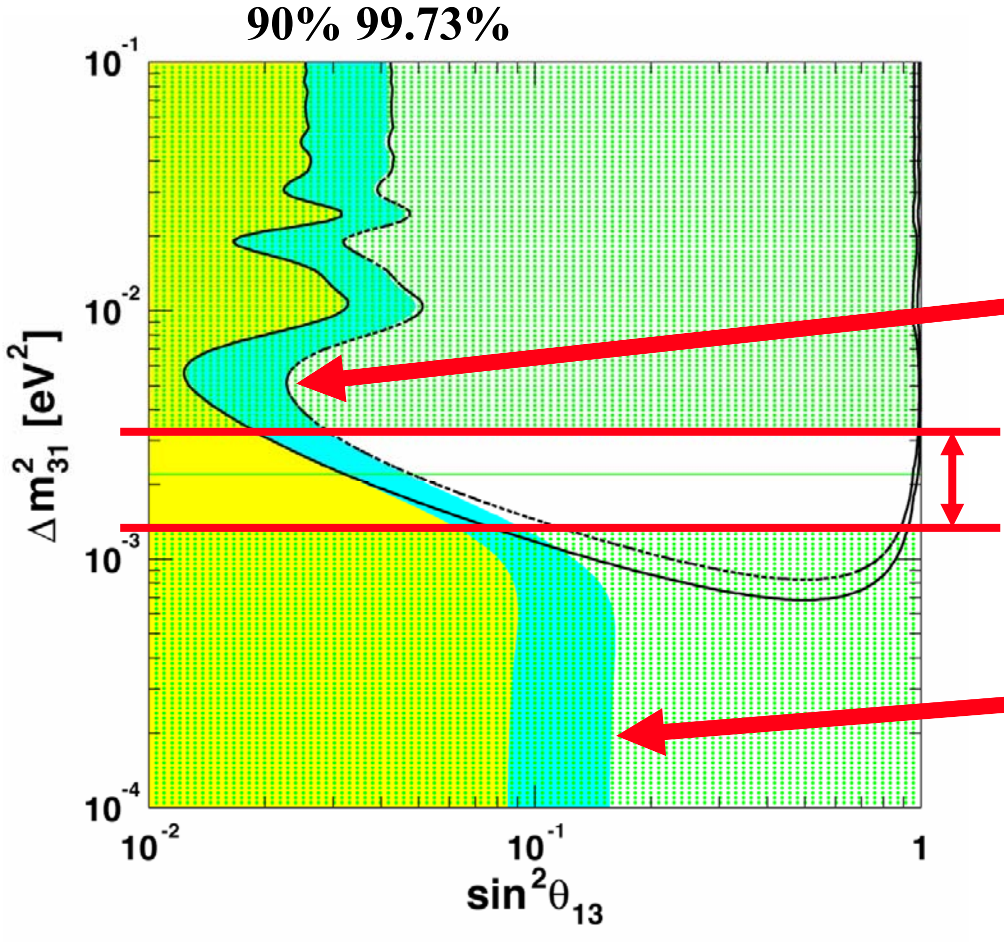
global analysis

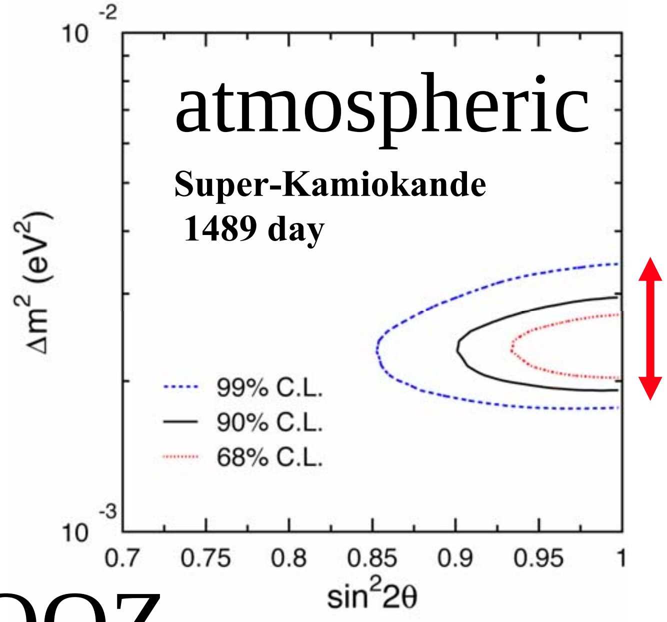
$$\chi^2_{global} = \chi^2_{solar+KamLAND}\left(\Delta m^2_{21}, \theta_{12}, \theta_{13}\right) + \chi^2_{CHOOZ+Atmospheric+K2K}\left(\Delta m^2_{31}, \theta_{23}, \theta_{13}\right)$$
$$= \chi^2_{solar+KamLAND}\left(\Delta m^2_{21}, \theta_{12}, \theta_{13}\right) + \chi^2_{CHOOZ+Atmospheric+K2K|\mathrm{marg}}\left(\theta_{13}\right)$$

θ_{13} is strongly constrained by atmospheric, K2K and CHOOZ

θ_{13} limit

$\Delta m_{31}{}^2$ dependence





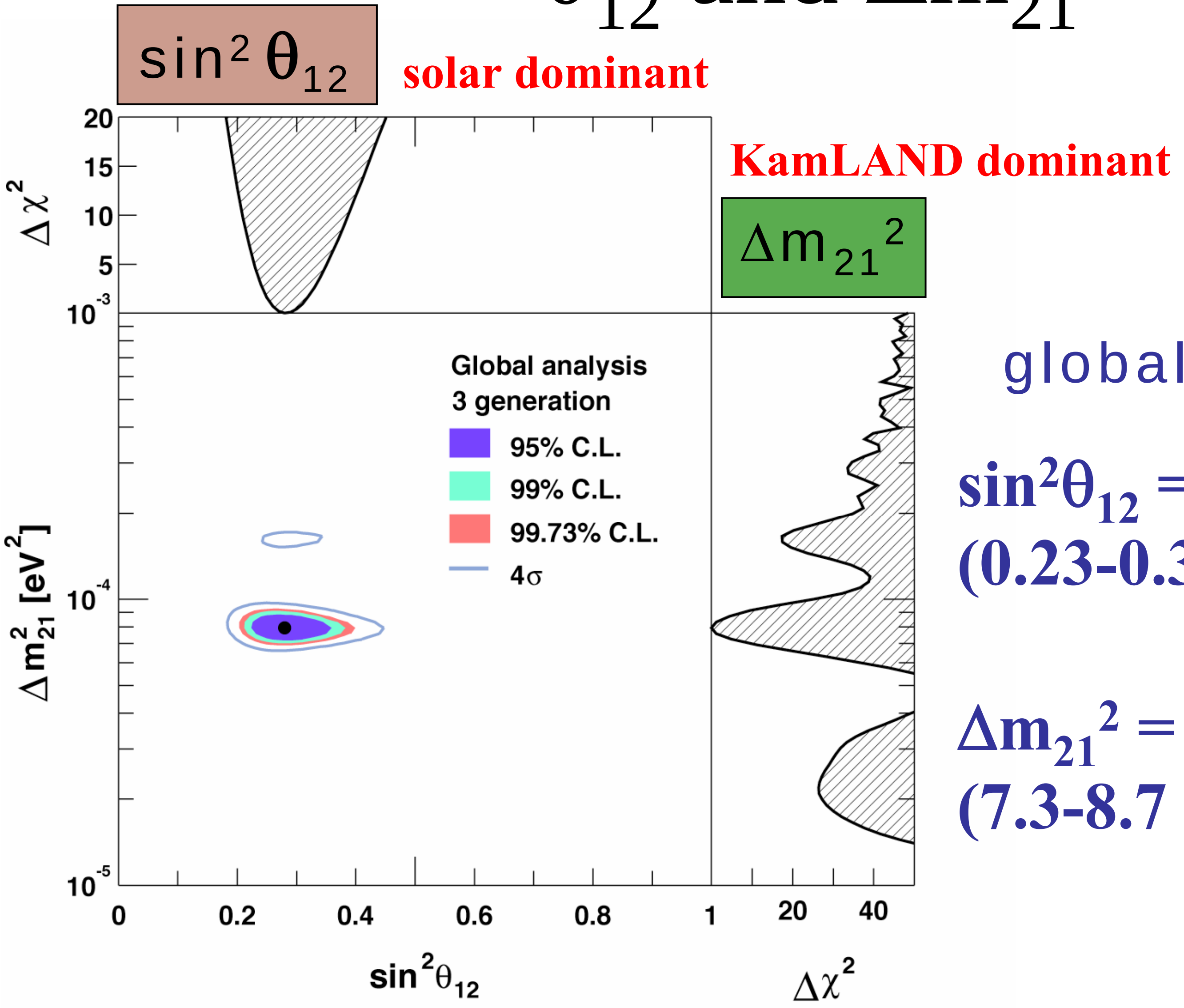
CHOOZ

atmospheric + K2K
at 3σ C.L

CHOOZ +
KamLAND + solar

KamLAND constraint is dominant at lower $\Delta m^{23}_{31}{}^2$

θ_{12} and $\Delta m_{21}{}^2$



global analysis

$\sin^2\theta_{12} = 0.28$
(0.23-0.34 at 95% C.L.)
1 n.d.f.

$\Delta m_{21}{}^2 = 7.9 \times 10^{-5}$ eV^2
(7.3-8.7 at 95% C.L.)
1 n.d.f.

LMA II and LMA 0 are excluded at >3σ and >4σ C.L.

Summary

- Result of KamLAND for the 766.3 ton-year data set are presented.
- The significance of $\bar{\nu}_e$ shape distortion is 99.8% C.L.
- The oscillatory shape of $\bar{\nu}_e$ is observed in KamLAND for the first time.
- Larger θ_{13} is disfavored from the oscillatory data in KamLAND.

- Global analysis (solar + KamLAND + atmospheric + K2K + CHOOZ) gives

$\Delta m_{21}^2 = 7.9 \times 10^{-5}$ eV^2

(7.3 ~ 8.7 $\times 10^{-5}$ eV^2 at 95% C.L.)

$\theta_{12} = 32^\circ$

($29^\circ \sim 36^\circ$ at 95% C.L.)

$\theta_{13} < 11^\circ$ (95% C.L.)

3-flavor oscillation effect is very small for solar and KamLAND experiment.

Web Page for data release

http://www.awa.tohoku.ac.jp/KamLAND/datarelease/2ndresult.html

- Event List
- Background Spectrum
- Number of Fissions
- χ^2 Map
- Other Relevant Constants

Please make use of KamLAND data!