KamLAND and Solar Neutrinos I

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祝！ LMA 観測

1. Introduction

⋆ Status for neutrino parameters before KamLAND Result

"Allowed Regions"

$$\begin{cases} \sin^2 2\theta_{23} \\ |\delta m^2_{31}| \end{cases} \sim \begin{cases} 0.9 - 1 \\ (1-6) \times 10^{-3}\text{eV}^2 \end{cases}$$

Atmospheric neutrino anomaly

$$\begin{cases} \sin^2 2\theta_{12} \\ \delta m^2_{21} \end{cases} \sim \begin{cases} \begin{cases} 0.5 - 1 \\ (1-20) \times 10^{-5}\text{eV}^2 \end{cases} & \text{Large MSW} \\ \begin{cases} O(10^{-3}) \\ (1-10) \times 10^{-6}\text{eV}^2 \end{cases} & \text{Small MSW} \\ \begin{cases} O(1) \\ (1-1000) \times 10^{-10}\text{eV}^2 \end{cases} & \text{Vacuum/ LOW} \end{cases}$$

Solar neutrino deficit

"Upper Limit"

$$\sin^2 2\theta_{13} < 0.1$$

Chooz experiment

⋆Interpretation with hierarchical mass structure

∘ Chooz experiment

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\delta m_{31}^2 L}{4E}$$
$$= \begin{cases} 1 - \frac{1}{2}\sin^2 2\theta_{13} & \text{larger } \delta m_{31}^2 \\ 1 - \sin^2 2\theta_{13} \left(\frac{\delta m_{31}^2 L}{4E}\right)^2 & \text{smaller } \delta m_{31}^2 \end{cases}$$

$\Longrightarrow$

$$\sin^2 2\theta_{13} \sin^2 \frac{\delta m_{31}^2 L}{4E} < 0.05$$

∘ Solar Neutrino Deficit Disappearance $\nu_e \to \nu_e$

$$P(\nu_e \to \nu_e) = \cos^4\theta_{13} \underbrace{P(\nu_e \to \nu_e; \theta_{12}, \delta m_{21}^2)_2}_{\text{2 Generation Oscillation Probability}} + \sin^4\theta_{13}$$

∘ Atmospheric Neutrino Anomaly

Disappearance and Appearance

$\nu_{\mu(e)} \to \nu_{\mu(e)}$ $\qquad$ $\nu_{e(\mu)} \to \nu_{\mu(e)}$

Mainly disappearance mode:: small θ_{13}

$$P(\nu_\mu \to \nu_\mu) = 1 - 4|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) \sin^2 \frac{\delta m_{31}^2 L}{4E}$$
$$\simeq 1 - \sin^2 2\theta_{23} \sin^2 \frac{\delta m_{31}^2 L}{4E}$$

2. Solar Neutrino Parameter Before KamLAND
~ 2 Neutrino Analysis ~

★ Energy Dependence / NC/CC rate — disfavor SMA/VAC

◇$P(\nu_e \rightarrow \nu_e)$ at $E_\nu >$ a few Mev

○ Slight energy dependence of suppression for $^8B\ \nu$

⟹ Small energy dependence

⟹ SMA and some region of VAC disfavored

○ Large NC/CC ratio

⟹ Low survival probability required

⟹ SMA disfavored

Surprising !!

Who said " SMA is most favorable and LMA will go away ?

Solution	Δm^2	$\tan^2(\theta)$	$f_{\mathrm{B,best}}$	χ^2_{min}	g.o.f.
LMA	5.0×10^{-5}	4.2×10^{-1}	1.07	45.5	49%
LOW	7.9×10^{-8}	6.1×10^{-1}	0.91	54.3	19%
VAC	4.6×10^{-10}	1.8×10^{0}	0.77	52.0	25%
SMA	5.0×10^{-6}	1.5×10^{-3}	0.89	62.7	5.1%
Just So^2	5.8×10^{-12}	1.0×10^{0}	0.46	86.3	~ 0%
Sterile VAC	4.6×10^{-10}	2.3×10^{0}	0.81	81.6	~ 0%
Sterile Just So^2	5.8×10^{-12}	1.0×10^{0}	0.46	87.1	~ 0%
Sterile SMA	3.7×10^{-6}	4.7×10^{-4}	0.55	89.3	~ 0%

表 1: **Best-fit global oscillation parameters with all solar neutrino data.** Bahcall et.al JHEP 07 (2002) 205

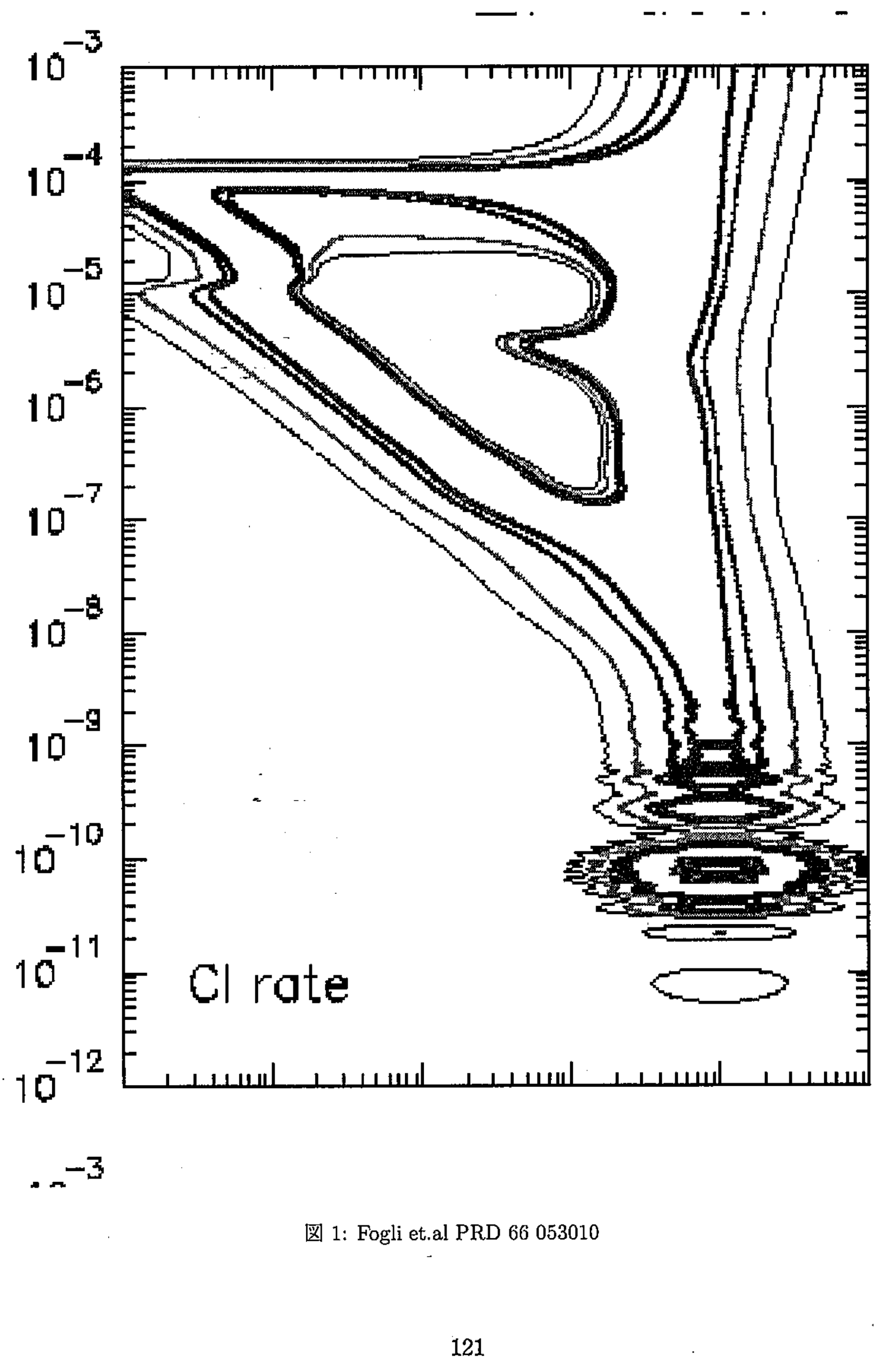

図 1: Fogli et.al PRD 66 053010

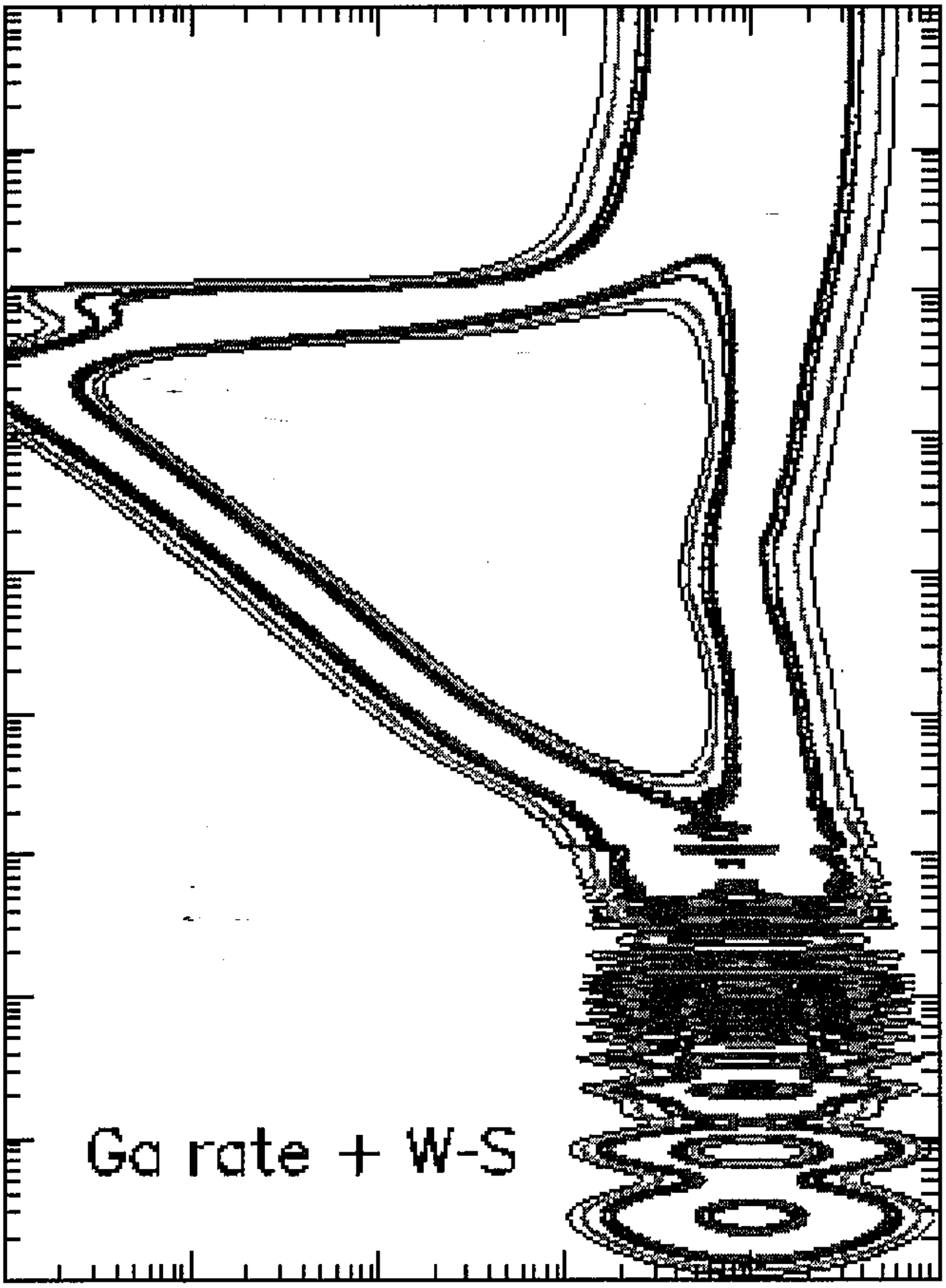

図 2: Fogli et.al PRD 66 053010

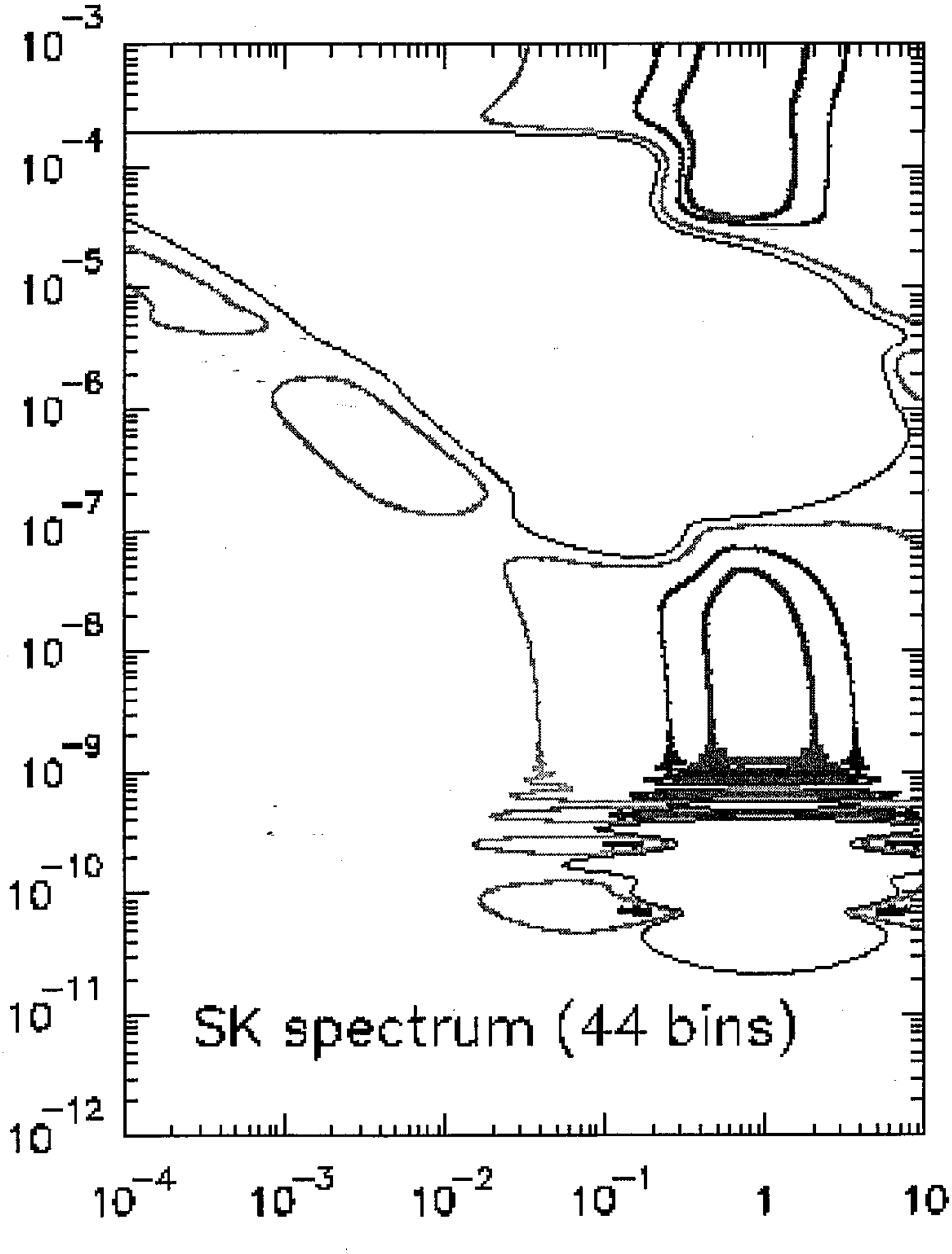

図 3: Fogli et.al PRD 66 053010

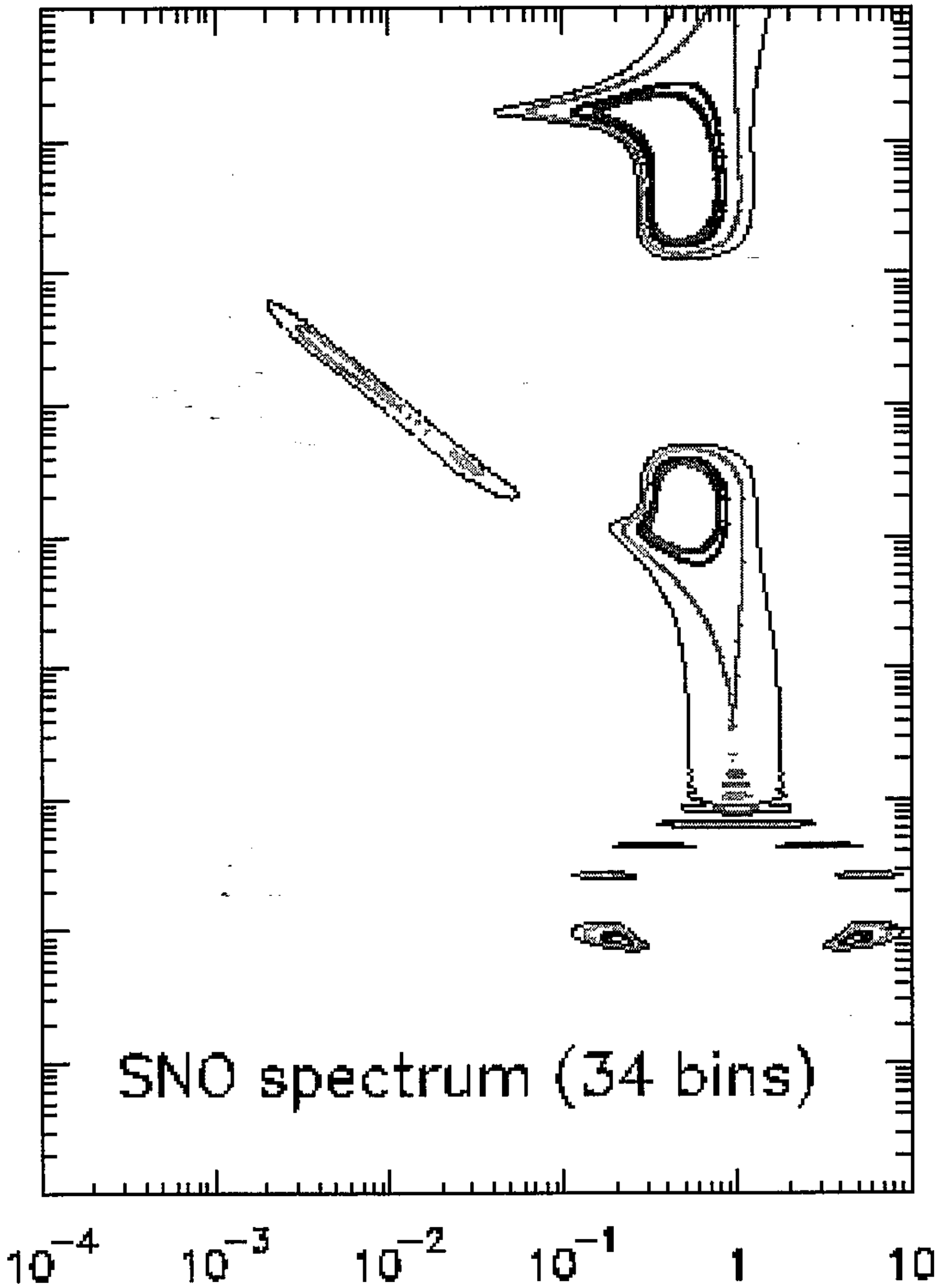

図 4: Fogli et.al PRD 66 053010

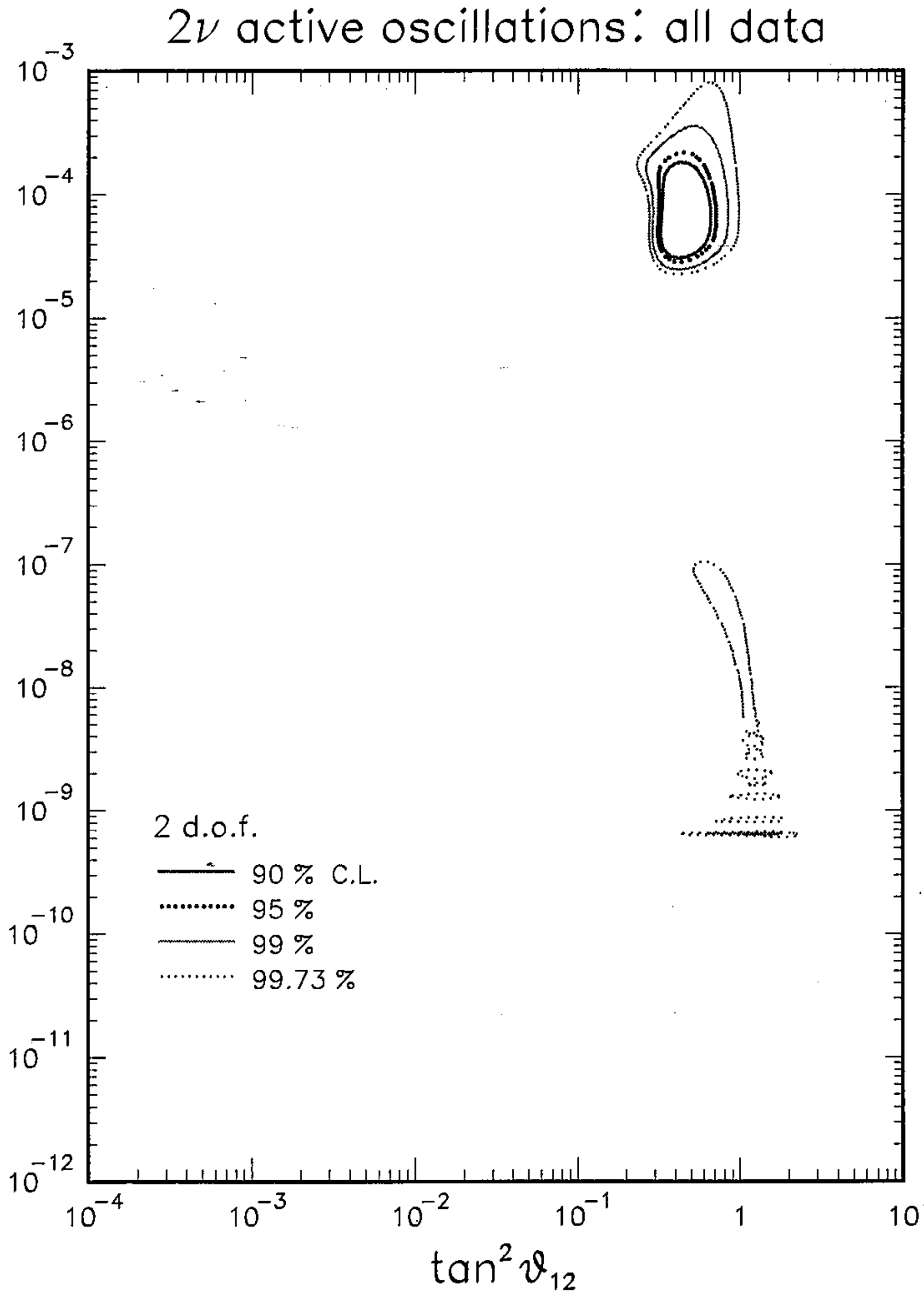

図 5: Fogli et.al PRD 66 053010

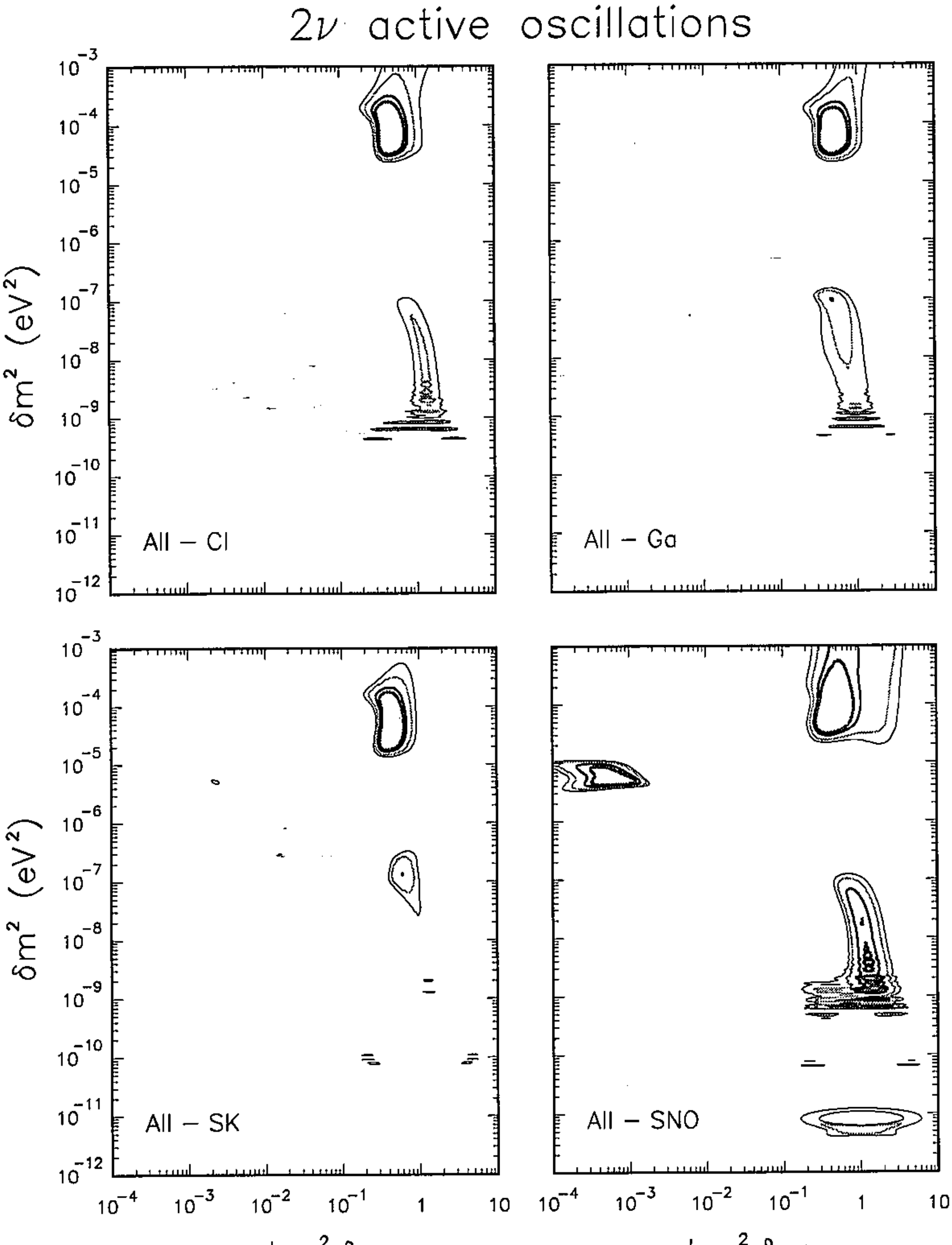

図 6: Fogli et.al PRD 66 053010

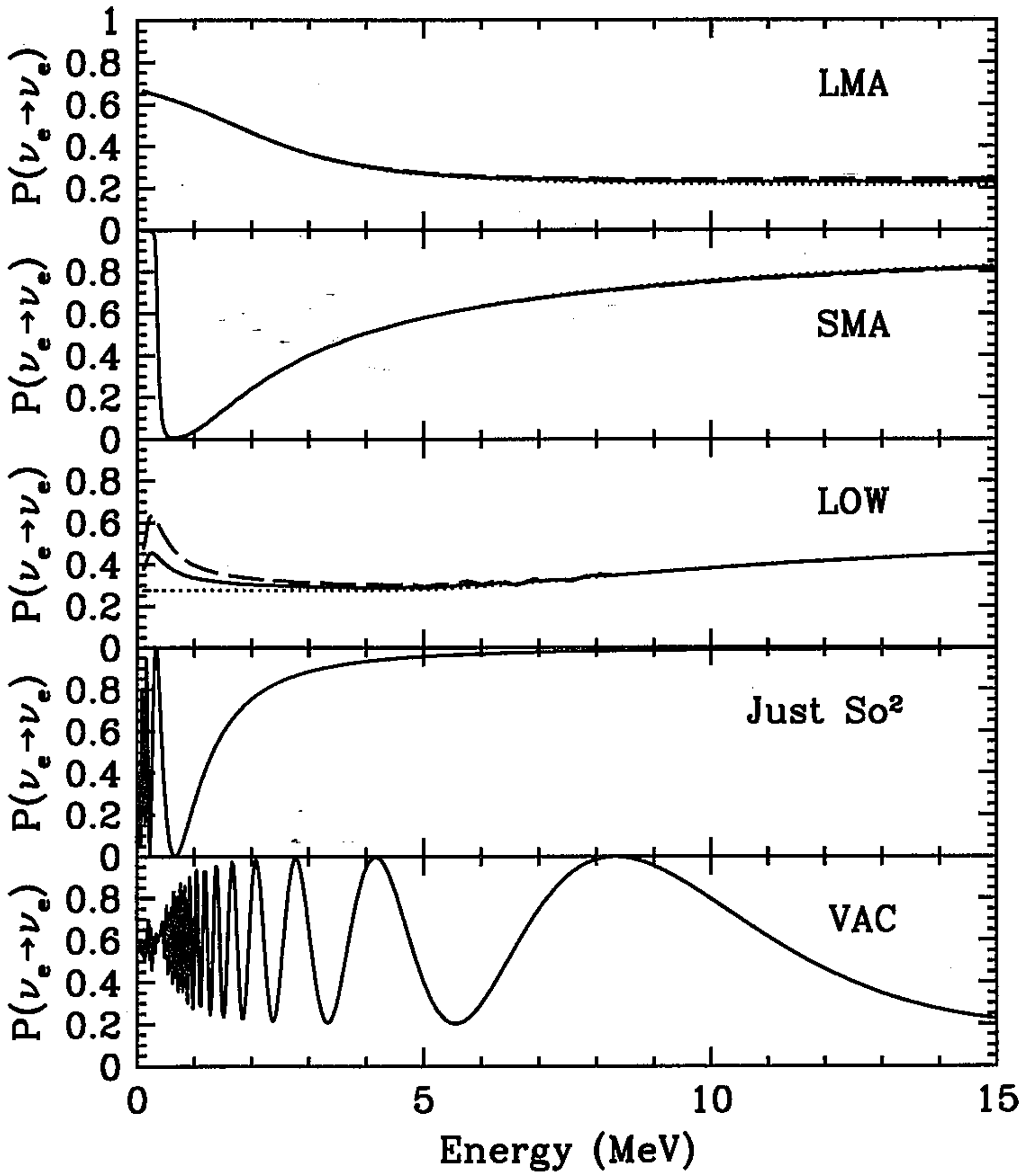

図 7: Bahcall et.al JHEP 0105:015,2001

3. Solar Neutrino Parameter After KamLAND

3.1 Naive Interpretation of KamLAND Result

⋆ KamLAND

∘ Reactor experiment (E_ν = a few MeV)
with $L = 180$ km

∘ Relevant Survival Probability

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_{12} \sin^2(\frac{\delta m^2_{21}}{4E_\nu}L)$$
$$= 1 - 4\frac{\tan^2\theta_{12}}{(1+\tan^2\theta_{12})^2}\sin^2(\frac{\delta m^2_{21}}{4E_\nu}L)$$

$$E_\nu = E_{prompt} + 0.8\text{MeV}$$

∘ Rate $(N_{obs}/N_{exp}) \sim 0.6$

Significant decrease But Sufficiently large observation

$\Longrightarrow P \gg 0$ and $P < 1$

◇ $P < 1 \Longrightarrow$ **LMA Only**

since

$$\frac{\delta m^2_{21}}{4E_\nu}L \ll 10^{-2} \qquad \text{LOW/VAC}$$
$$\sin^2 2\theta_{12} \ll 10^{-2} \qquad \text{SMA}$$

in another word

$$\delta m^2_{21} > O(10^{-5})\ \text{eV}^2$$
$$\sin^2 2\theta_{12} > 0.4 \Longleftrightarrow R \sim 0.6$$

besides $\delta m^2_{21} \sim 3 \times 10^{-5}\text{eV}^2$

◇ $P \gg 0 \Longrightarrow$ excluded region of

$$\delta m^2_{21} \sim 3 \times 10^{-5}\ \text{eV}^2 \quad \text{and} \quad \sin^2 2\theta_{12} \sim 1$$

since $\frac{\delta m^2_{21}}{4E_\nu}L \sim \frac{\pi}{2}$ around $E_\nu = 5\text{MeV}$

○ With Energy Spectrum

◇ Other excluded regions

$$\delta m^2_{21} \sim (2n+1) \times (3 \times 10^{-5})\text{eV}^2 \& \sin^2 2\theta_{12} \sim 1$$

due to mild suppression around $E_\nu \sim 5$ MeV

∘ Then allowed regions are

$$\delta m^2_{21} \sim (1-3) \times 10^{-5}\ \mathrm{eV}^2$$
$$\sin^2 2\theta_{12} > 0.4$$

$$\delta m^2_{21} \sim (5-9) \times 10^{-5}\ \mathrm{eV}^2$$
$$\sin^2 2\theta_{12} > 0.4$$

$$\delta m^2_{21} \sim (10-15) \times 10^{-5}\ \mathrm{eV}^2$$
$$\sin^2 2\theta_{12} > 0.4$$

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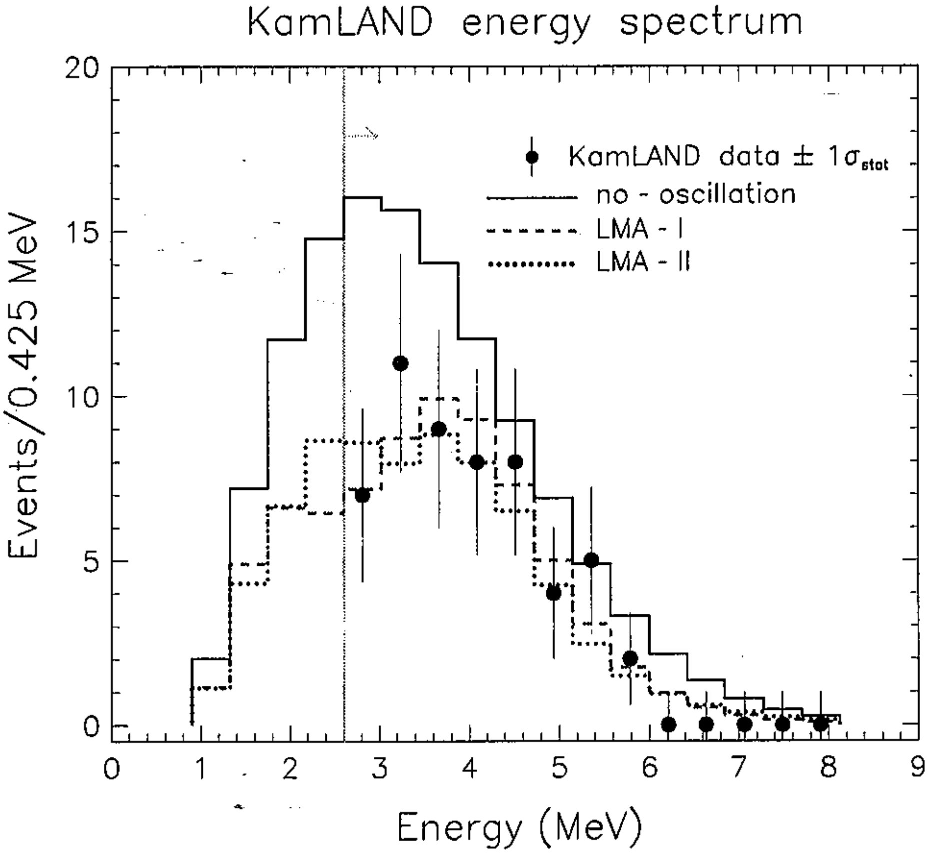

図 8: Fogli et.al hep-ph0212127

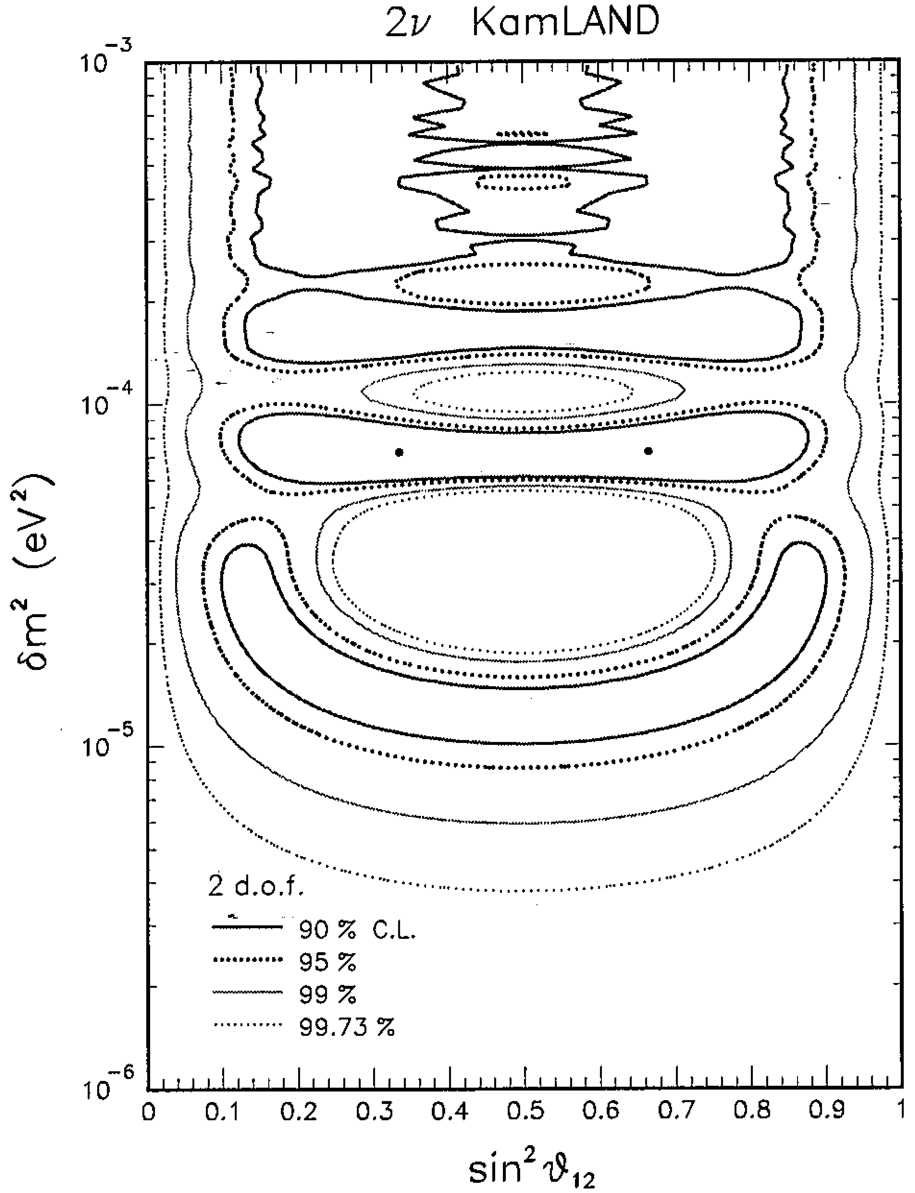

図 9: Fogli et.al hep-ph0212127

3.2 Combination of Solar ν and KamLAND

◇ Allowed region(s)

Intersection of Solar ν result and KamLAND result

$$\delta m^2_{21} \sim (6-9) \times 10^{-5}\ \mathrm{eV}^2$$

$$0.4 < \sin^2 2\theta_{12} < 1$$

$$\delta m^2_{21} \sim (10-13) \times 10^{-5}\ \mathrm{eV}^2$$

$$0.4 < \sin^2 2\theta_{12} < 1$$

◇ Best fit point

$$\delta m^2_{21} \sim 7 \times 10^{-5}\ \mathrm{eV}^2$$

$$\sin^2 2\theta_{12} \sim 0.8$$

$$\tan^2\theta_{12} \sim 0.4 \quad \sin^2\theta_{12} \sim 0.3$$

⋆ Caution

We should be very conservative about "Allowed Region"

◇ "$\Delta\chi^2$'s in analyzes are not well defined mathematically as statistics obeying χ^2 distribution

For them to be $\Delta\chi^2$, there are several requirements, e.g.

$$\Delta\chi^2 \simeq \sum_{ij} \delta x_i (V^{-1})_{ij} \delta x_j \tag{1}$$

δx_i's are deviation of parameters from the minimum and V_{ij} should be the covariance matrix.

However,

(i) apparantly we cannot have such bilinear expression and

(ii) moreover due to Cramer-Rao's inequality, V is always amaller (or at best equalto) the covariance

V's are Fisher information and the covariance for x_i's are always larger (or at best equal to) it.

◇ We can do at best a test of goodness of fit

Or we should consider another way of construcion for confidence level

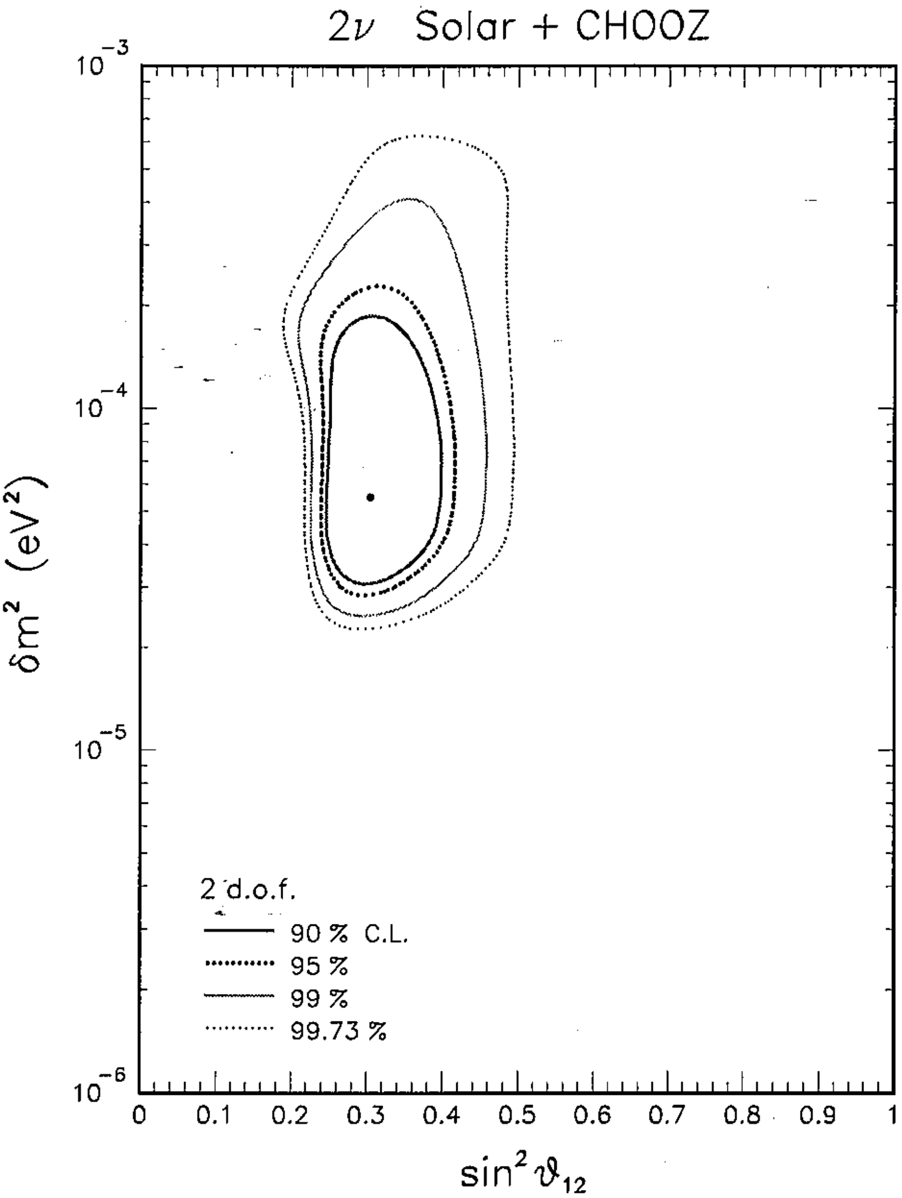

図 10: Fogli et.al hep-ph0212127

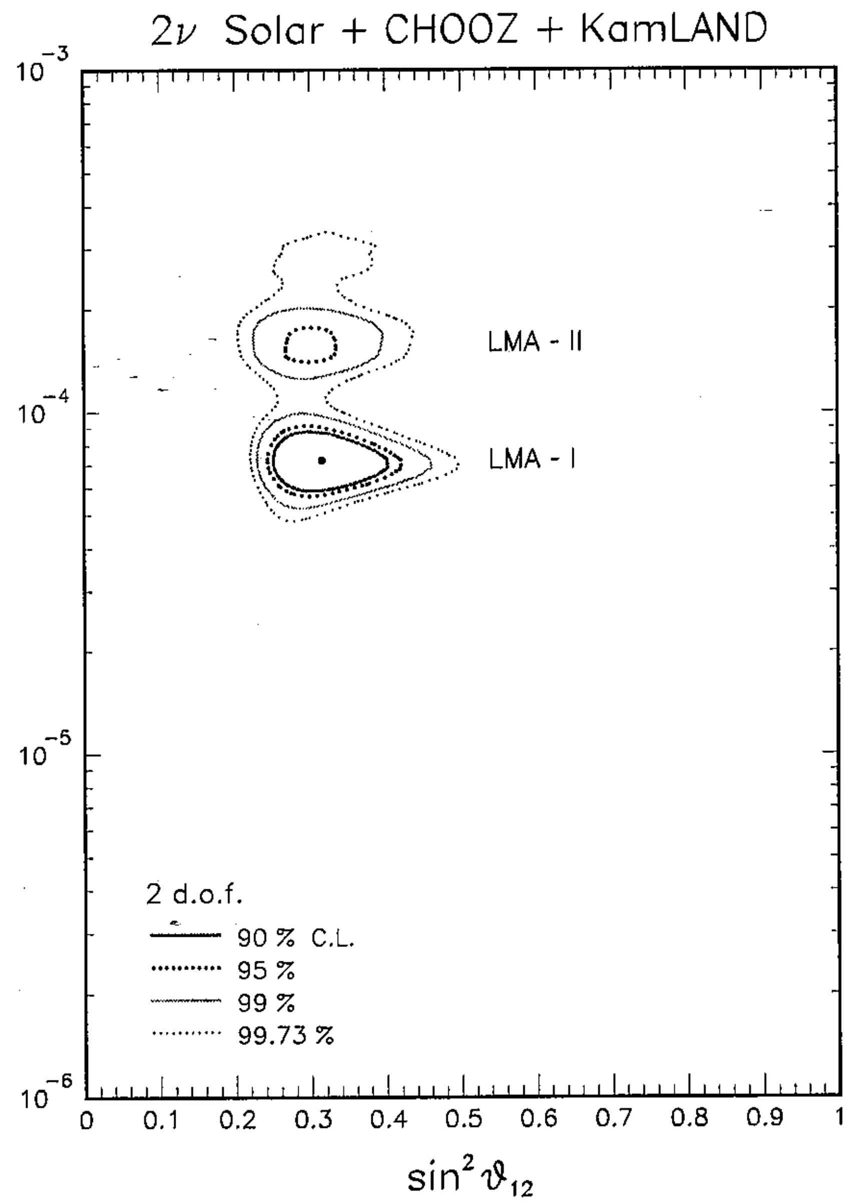

図 11: Fogli et.al hep-ph0212127

4. 3 ν case

⋆ Survival probability (with energy resolution)

$$P = \cos^4\theta_{13}\left\{1 - \sin^2 2\theta_{12}\sin^2\left(\frac{\delta m^2_{21}}{4E_\nu}\right)L\right\} + \sin^4\theta_{13}$$

$\Longrightarrow$ small modification

∘ Larger θ_{13}

stable δm^2_{21}

decreace of θ_{12}

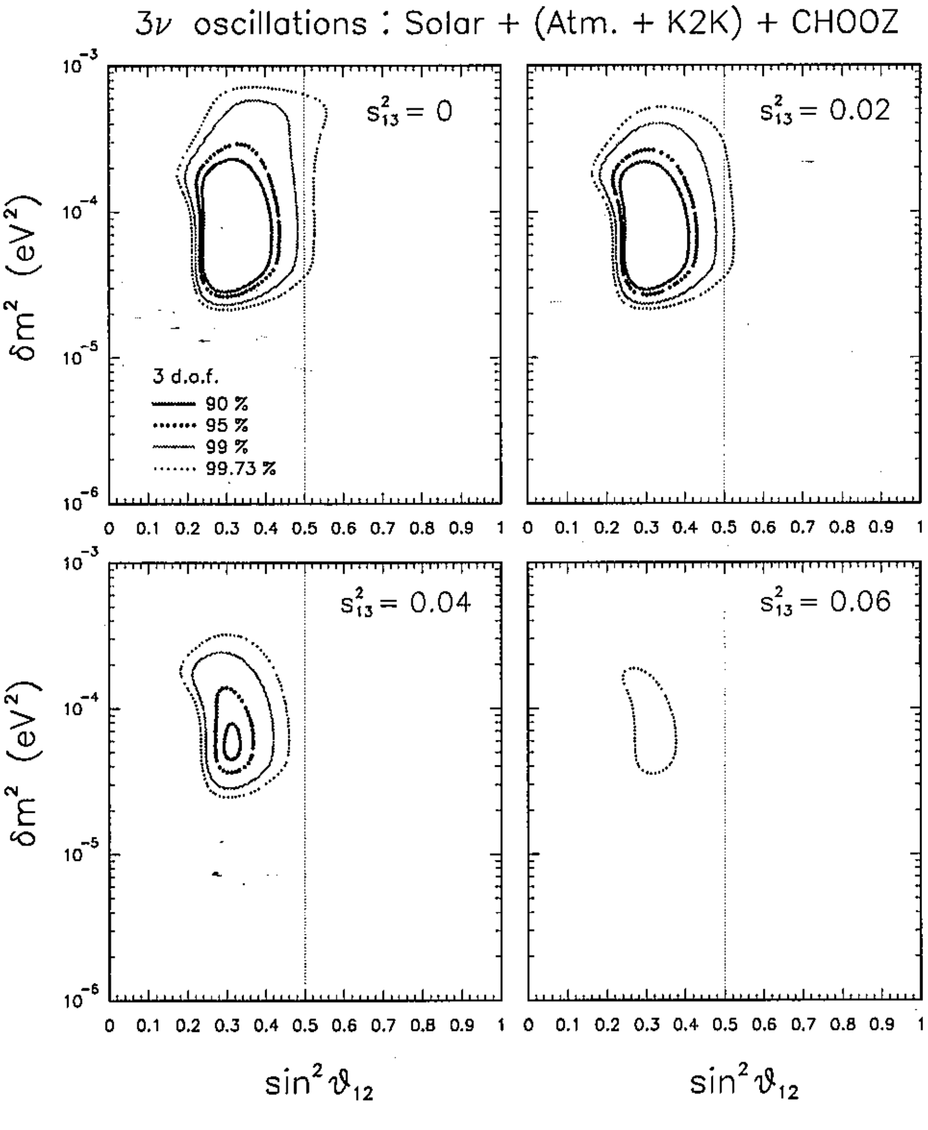

図 12: Fogli et.al hep-ph0212127

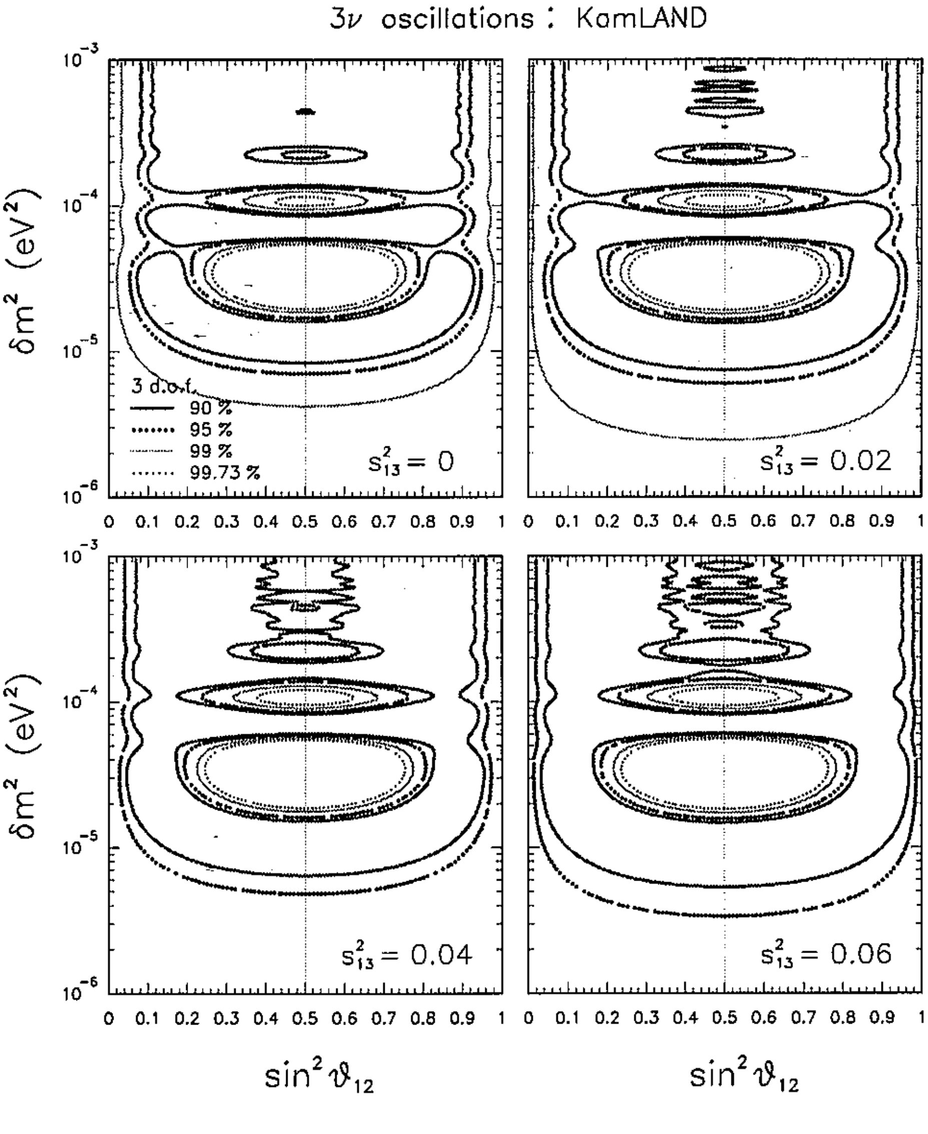

図 13: Fogli et.al hep-ph0212127

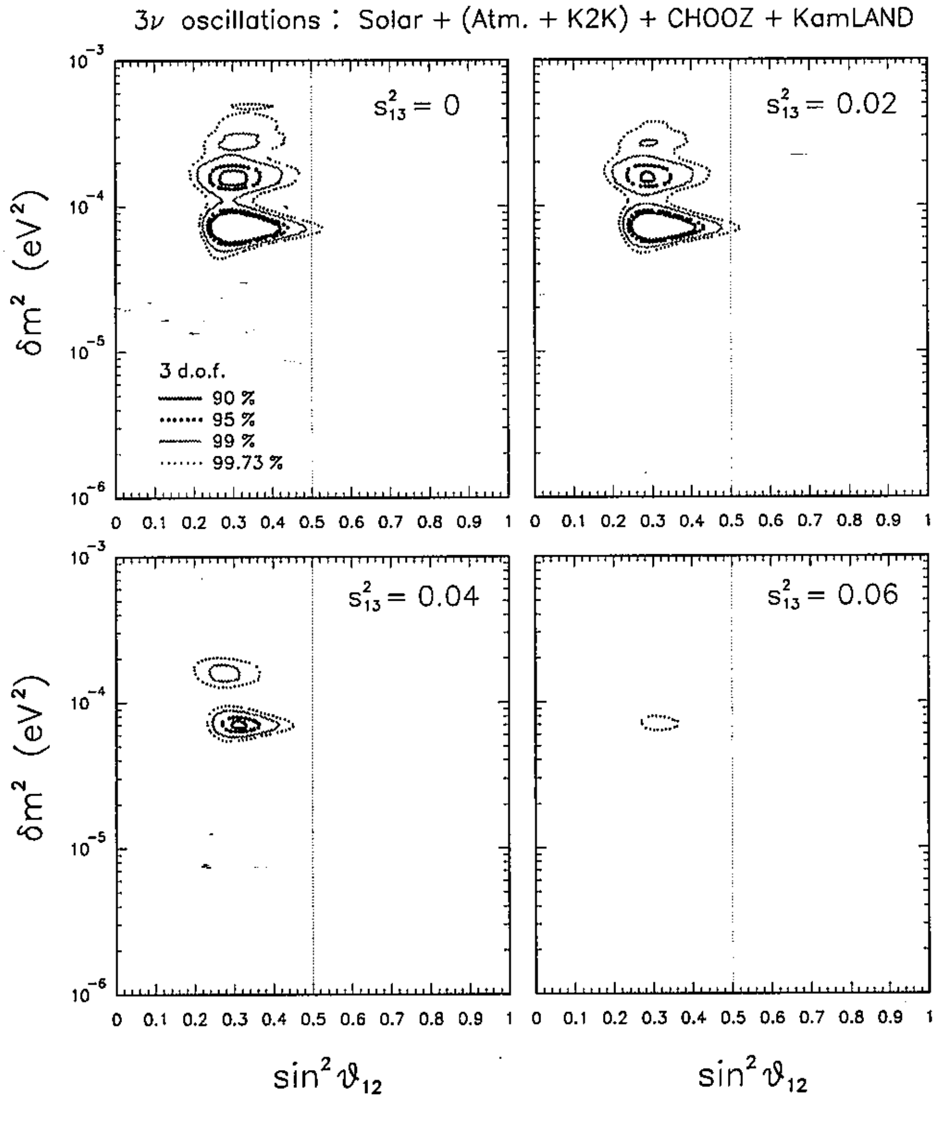

図 14: Fogli et.al hep-ph0212127

5. Discussion

⋆ Confirmation of LMA by KamLAND

⋆ Hope for observation of CP Violation in neutrino oscillation

$$\text{Sensitivity} \propto (\delta m^2_{21})^2 \sin^2 2\theta_{12}$$

Larger δm^2_{21} is preferable

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J2K and Leptonic CP Violation

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祝！ CP Violation 観測

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