Solar Neutrinos: Before and After KamLAND

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2002: The Year of the Solar Neutrino

– April 20 : Direct Evidence of ν_e flavour conversion from the SNO NC data

–December 6: Evidence in favour of the LMA solution to the solar neutrino problem from KamLAND

The results represent the culmination of a focussed and outstanding experimental program with seminal contributions by the Homestake, Kamiokande, Gallium, SAGE, and SuperK collaborations, buttressed by increasingly refined and accurate solar model calculations and theoretical understanding of the passage of neutrinos in matter (MSW effect)

Solar Neutrino Experiments

- Radiochemical Experiments

–Homestake (South Dakota, USA) $E_{th} = 0.81 MeV$

$\star\ ^{37}Cl + \nu_e \rightarrow ^{37} Ar + e^-$ $^8B, ^7Be$

–SAGE(Baksan,Russia) and
GALLEX, GNO (Gran Sasso, Italy) $E_{th} = 0.23 MeV$

$\star\ ^{71}Ga + \nu_e \rightarrow ^{71} Ge + e^-$ pp, ^7Be, ^8B

- Real-Time Experiments

–Kamiokande, SuperK. (Kamioka,Japan) $E_{e,th} = 5.0 MeV$

$e^- + \nu_x \rightarrow e^- + \nu_x,$ ^8B,hep

–SNO (Sudbury,Canada) $T_{e,th} = 5.0 MeV$

CC $\star\ d + \nu_e \rightarrow p + p + e^-,$ ^8B,hep

NC $d + \nu_x \rightarrow p + n + \nu_x$

ES $e^- + \nu_x \rightarrow e^- + \nu_x$

– $\star$ sensitive to only ν_e.

– ES and NC sensitive to all neutrino flavours.

– NC provides a direct measurement of the ^8B flux.

Evidence for Flavour Conversion from Rate Observations

- The ratio of the observed solar neutrino rates to the SSM predictions.

experiment	$\frac{obsvd}{BPB00}$
Cl	0.337 ± 0.029
Ga	0.553 ± 0.034
SK	0.465 ± 0.014
SNO(CC)	0.349 ± 0.021 ⋆
SNO(ES)	0.473 ± 0.074 ⋆
SNO(NC)	1.008 ± 0.123 ⋆

⋆ Assuming undistorted ^8B spectrum

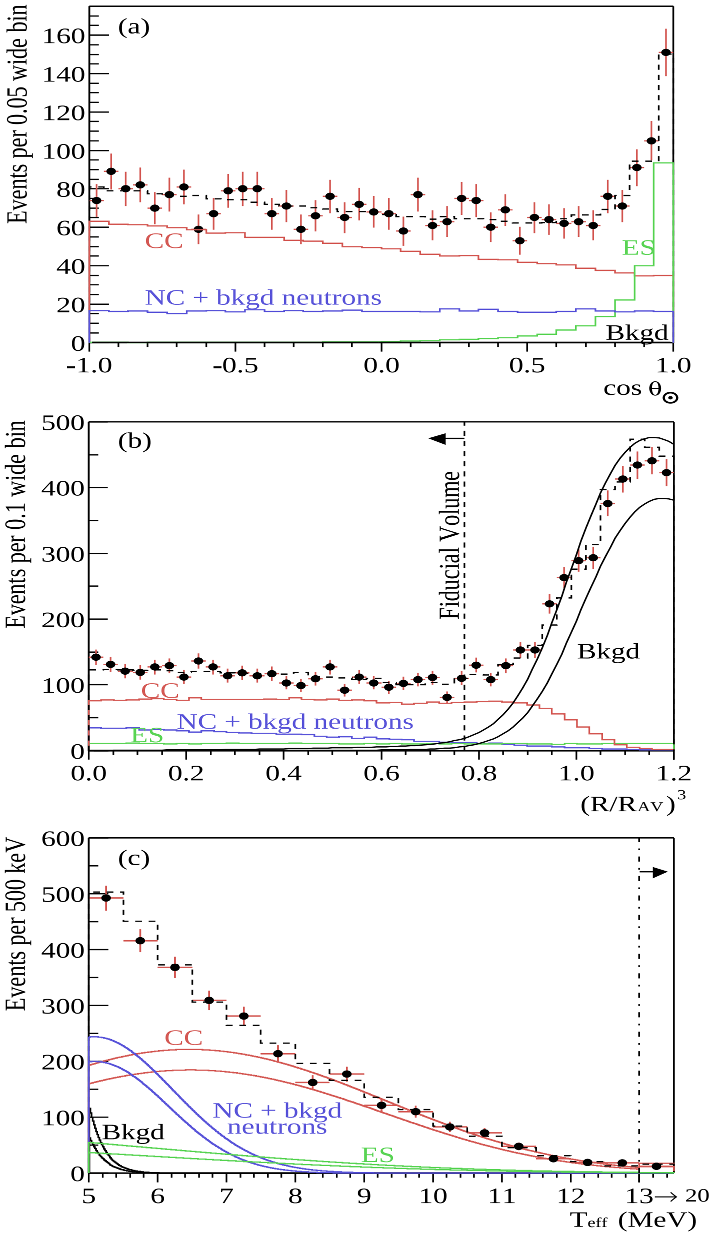
- $$\frac{CC}{NC} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} < 1$$

→ signals flavour conversion

- $$\frac{CC}{ES} = \frac{\nu_e}{\nu_e + 0.15(\nu_\mu + \nu_\tau)} < 1$$

→ signals flavour conversion

Results from SNO



NC signal entangled with ES and CC signal. Hence extraction of the separate components requires assuming that the Boron flux is undistorted

Time Variations

– Day/Night Effect (Zenith Angle Dependence)

$$A_{SK} = \frac{2(\phi_N - \phi_D)}{(\phi_N + \phi_D)} = 2.1 \pm 2.0 \pm 1.3\ \%(0.9\sigma\ \text{effect})$$

$$A_{SNO} = \frac{2(\phi_N - \phi_D)}{(\phi_N + \phi_D)} = 7.1 \pm 4.9 \pm 1.3\ \%(1.4\sigma\ \text{effect})$$

–Seasonal Variation: (SK)

- Consistent with that due to Earth's eccentricity

Evolution of the Solar Neutrino Problem

- I: Before SNO

– The Observed flux < SSM prediction

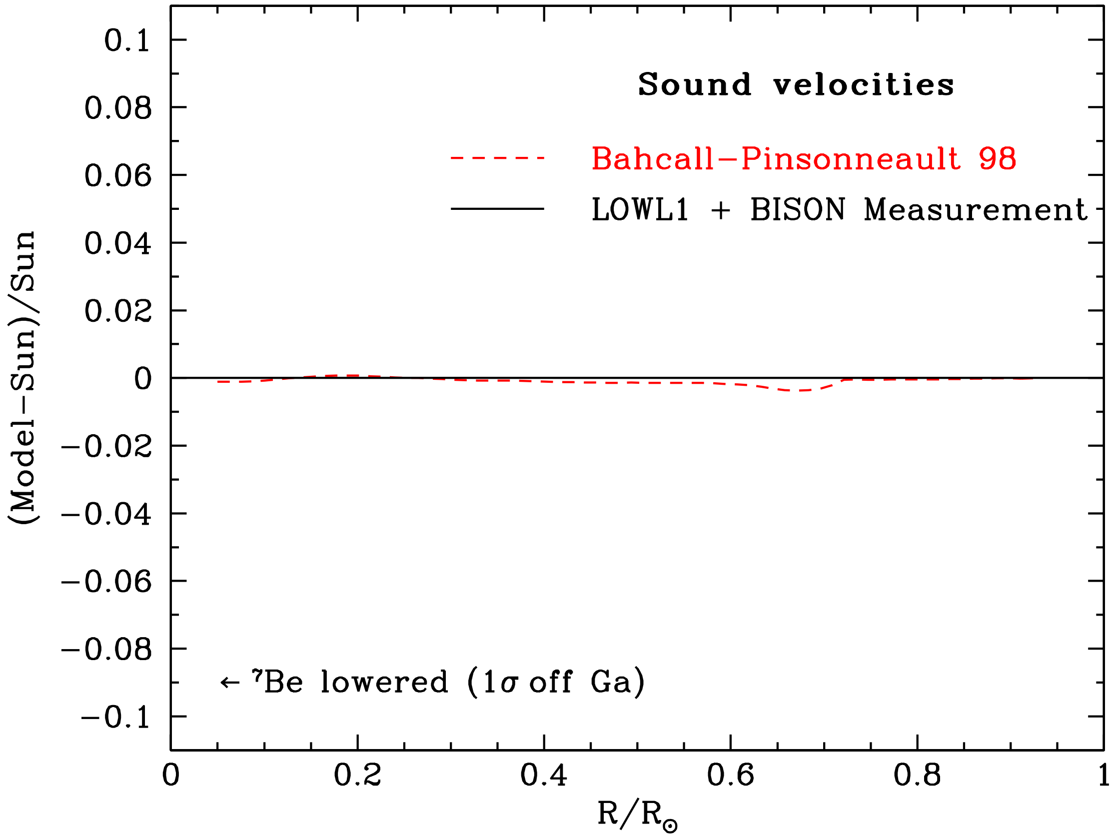
–^7Be neutrino problem

$$\text{Cl} \longrightarrow {}^8B + {}^7Be$$
$$\text{Ga} \longrightarrow \text{pp} + {}^8B + {}^7Be \Longrightarrow \Phi^7Be \text{ negative}$$
$$\text{SK} \longrightarrow {}^8B$$

– Astrophysical explanations highly disfavoured by helioseimological data

–Neutrino Flavour conversion ?

———SMA favoured until SK results on flatness of spectrum and absence of peak in zenith angle distribution in earth-core bin.



- Standard Solar Model is in excellent agreement with helio-seismological measurements

- All the Standard Solar Models agree to one another to an accuracy of better than 10% with same input parameters.

• II: After SNO CC

SNO CC: $\nu_e d \rightarrow \nu_e pp \rightarrow \Phi_e$

SK ES : $\nu_x d \rightarrow \nu_x e \rightarrow \Phi_e + 0.15\phi_{\mu\tau}$

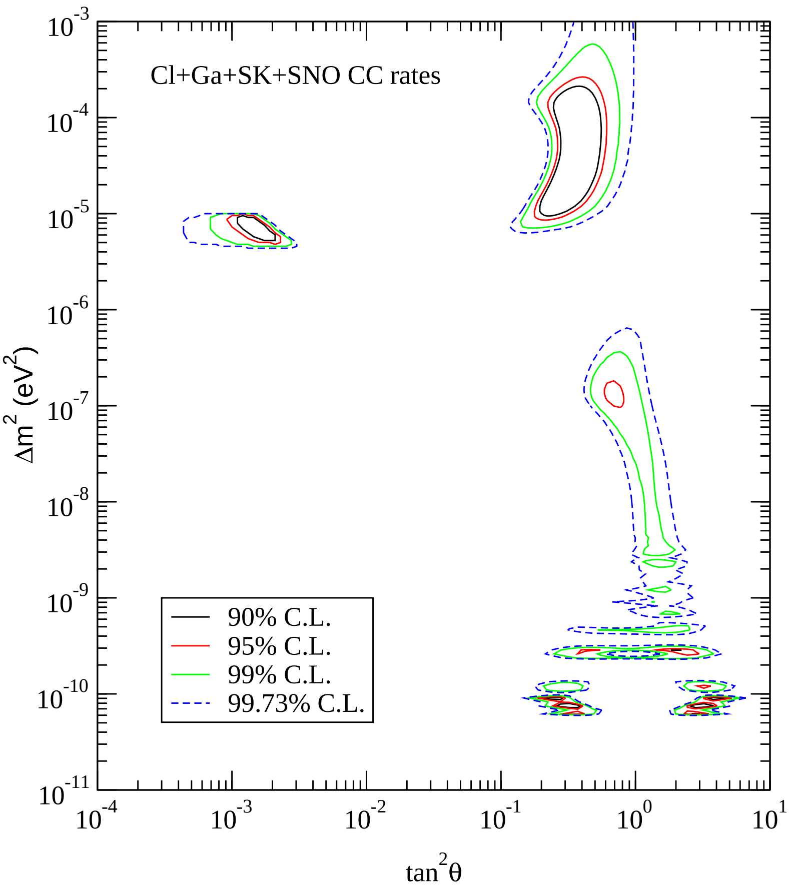
• $\phi_{ES}^{SK} - \phi_{ES}^{SNO} = 0.57 \pm 0.17 \times 10^6/cm^2/sec$

$\longrightarrow$ Presence of ν_μ/ν_τ at 3.3 σ

SNO CC rate by itself does not alter constraints on SMA significantly

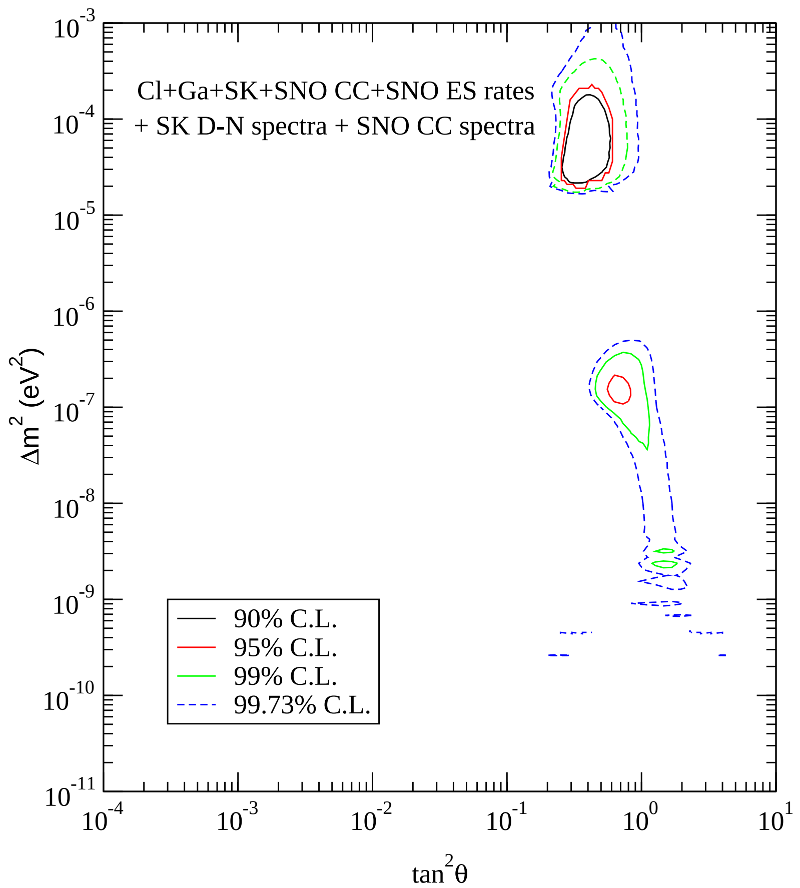
The SNO Collab. PRL **87, 2001**

Allowed Area from total flux measurement
(2001)



A. Bandyopadhyay,S.Choubey,S.Goswami,K.Kar,PLB **519**,2001

SK spectrum + SNO CC spectrum + Rates
(2001)



- Flatness of SK/SNO CC spectra practically eliminate SMA

(A. Bandyopadhyay,S.Choubey,S.Goswami,K.Kar,PLB **519**,2001)

- After SNO NC

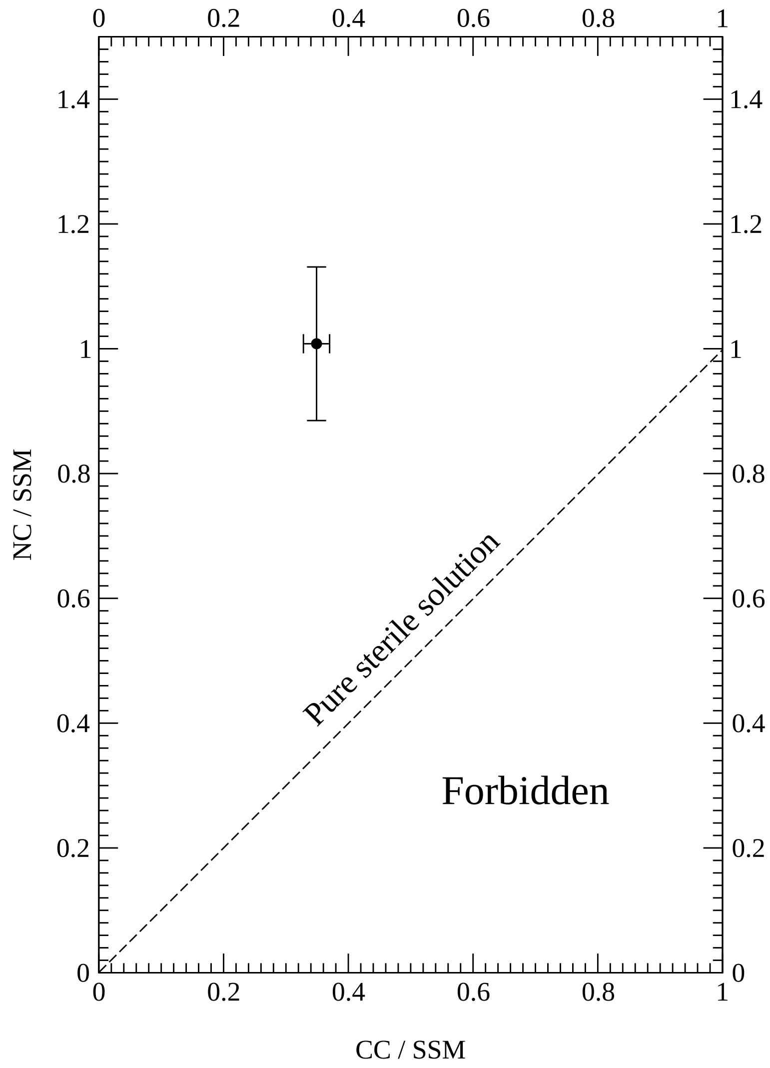
SNO CC: $\nu_e d \to \nu_e pp \to \Phi_e$

SNO NC : $\nu_x d \to \nu_x np \to \Phi_e + \phi_{\mu\tau}$

- $\phi_{NC}^{SNO} - \phi_{CC}^{SNO} = 3.41 \pm 0.65 \times 10^6/cm^2/sec$

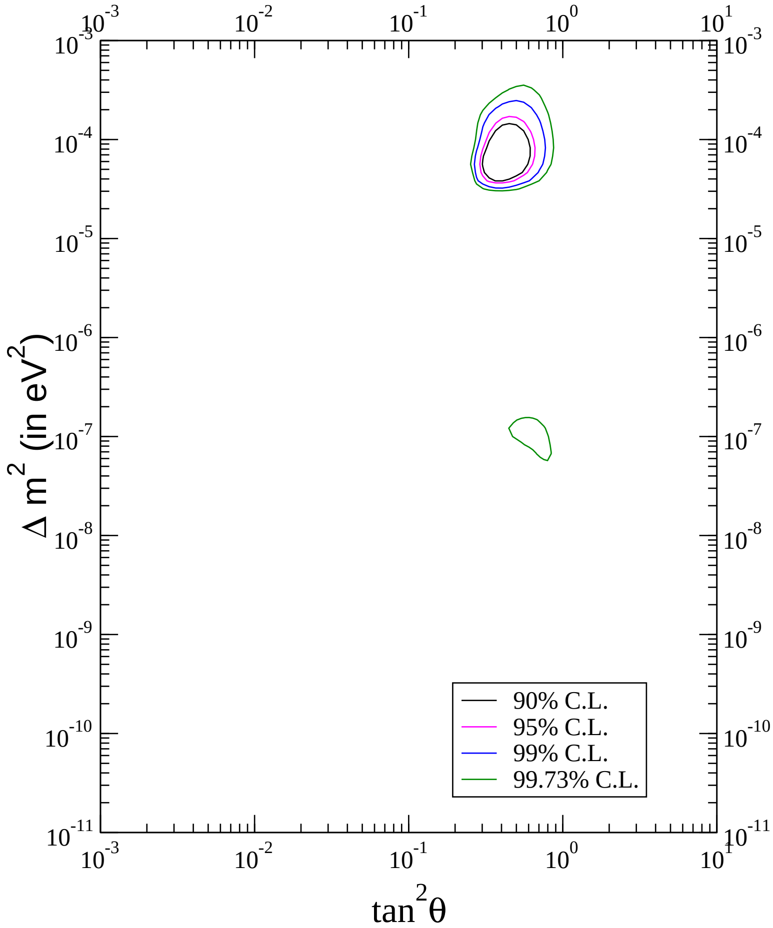
$\longrightarrow$ Presence of ν_μ/ν_τ at 5.3 σ

The SNO Collab.
PRL **89, 2002**



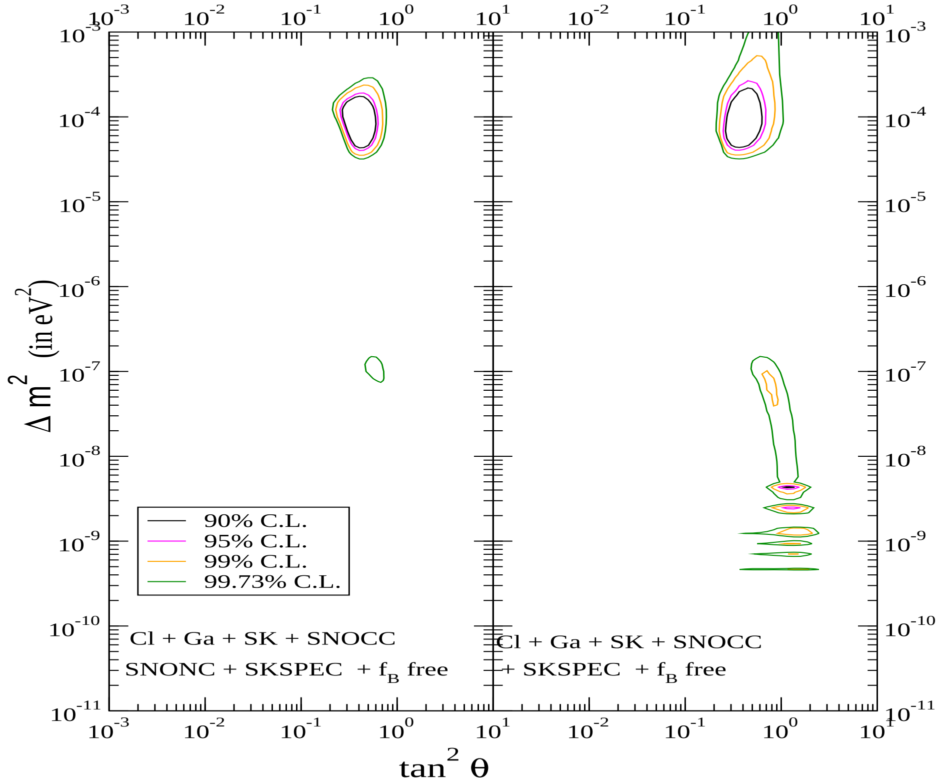
(A.Bandyopadhyay, S. Choubey, S.Goswami, D.P.Roy PLB,**540**,2002.)

- Pure $\nu_e - \nu_s$ /No oscillation disfavoured at 5.3σ.



10^-3
10^-2
10^-1
10^0
10^1
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
10^-11
Δ m^2 (in eV^2)
tan^2θ
90% C.L.
95% C.L.
99% C.L.
99.73% C.L.

Impact of SNO NC



- LMA is the favoured solution
- LOW appears only at 3σ
- Values of Δm^2 above 3×10^{-4} eV^2 disfavored since low f_B needed
- VO not allowed at 3σ
- Maximal Mixing ($\theta = \pi/4$)is disfavored at 3.4σ
- SMA disfavored at 3.7σ.
- Dark Side ($\theta > \pi/4$) solutions are gone

(A.Bandyopadhyay, S. Choubey, S.Goswami, D.P.Roy PLB,**540**,2002.)

Why is maximal mixing disfavoured?

$$P_{ee}^{maxmix} \approx 1/2 + f_{reg}$$

- Only observed rate $> 1/2$ is in Ga Experiments
- SNO NC $\Longrightarrow f_B \approx 1.0$
- Pre-SNO NC uncertainty about f_B allowed max mixing for SK

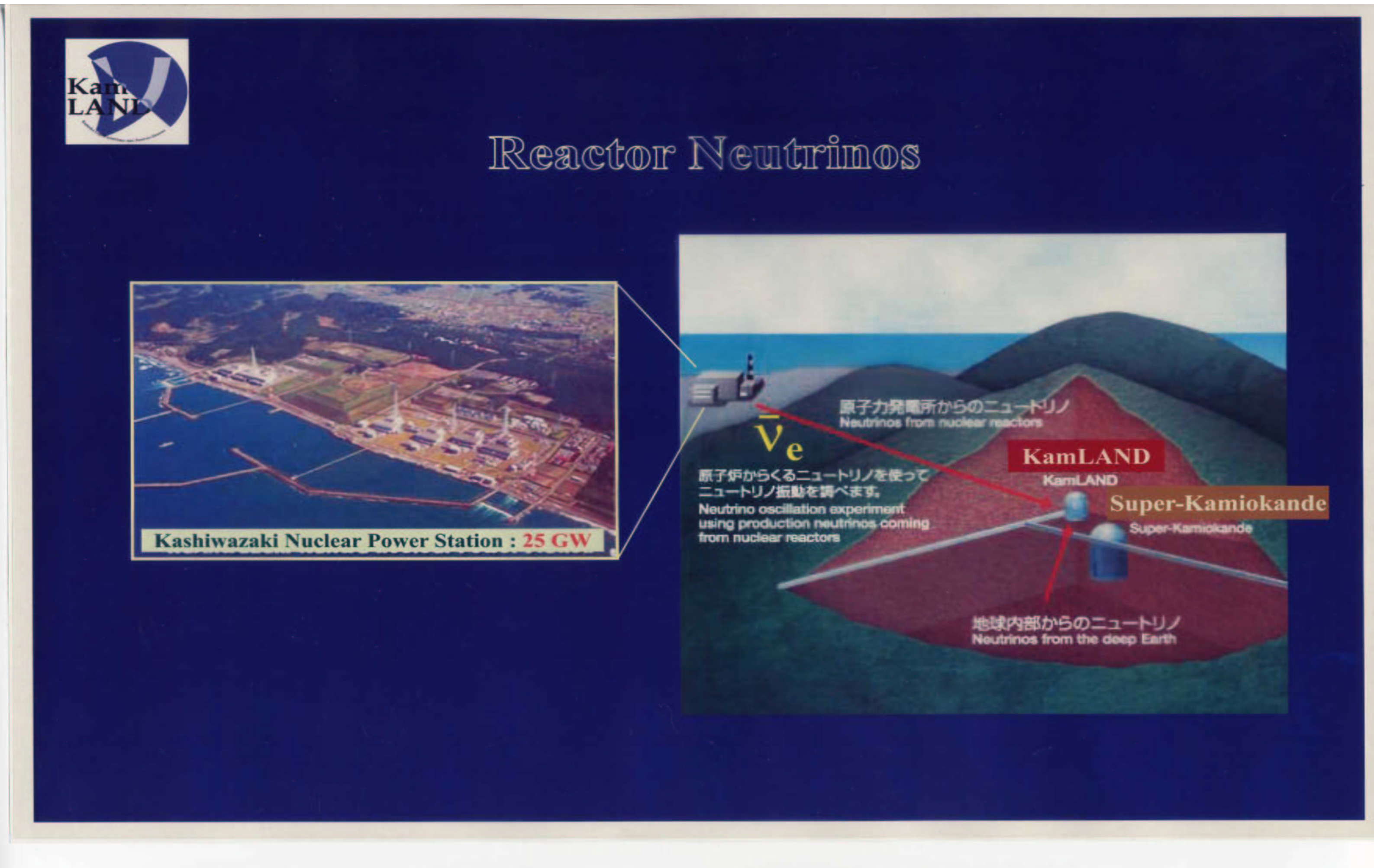
Why is the LOW solution disfavoured

$$R_{Ga} \approx \sin^2\theta + f_{reg}$$
$$R_{SK} \approx R_{CC} \approx f_B \sin^2\theta$$

- SNO NC $\Longrightarrow f_B \approx 1.0$
- Large f_{reg} to reconcile the Ga and SK/CC rates
- No peaks observed in the zenith angle spectrum of SK
- SK+SNO+Ga disfavours LOW

KamLAND experiment

•1000 ton liquid scintillator neutrino detector situated at the former site of Kamiokande.



•$\bar{\nu}_e$ source: 16 reactors at distances 81 - 824 km

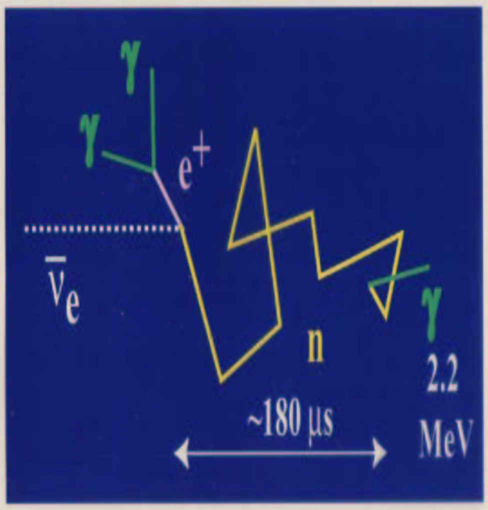
•Most powerful reactors are at distance $\sim$ 180 km

Reactor $\bar{\nu}_e$ Detection in Liquid Scintillator

reaction process : inverse- β decay ($\bar{\nu}_e + p \longrightarrow e^+ + n$)

$$n + p \longrightarrow d + \gamma$$

distinctive two-step signature



$$E_{th} = \frac{(M_n + m_e)^2 - M_p^2}{2M_p} = 1.806\ MeV$$

- **prompt part : e^+**

  $\bar{\nu}_e$ energy measurement

  $$E_\nu \sim (E_e + \Delta)[1 + \frac{E_e}{M_p}] + \frac{\Delta^2 - m_e^2}{M_p}$$

  $$\Delta = M_n - M_p$$

- **delayed part : γ (2.2 MeV)**

- **tagging : correlation of time, position and energy between prompt and delayed signal**

KamLAND experiment

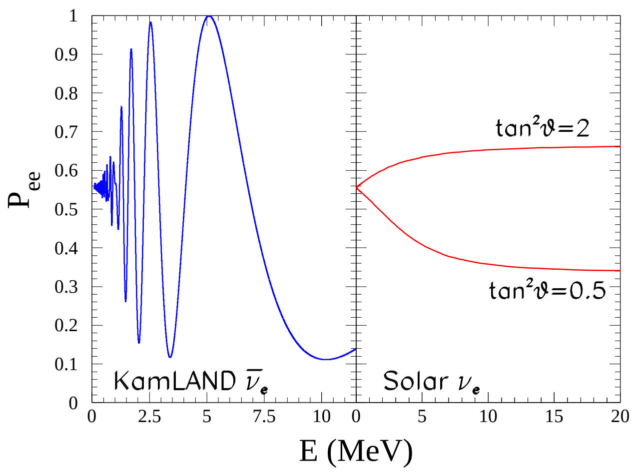
- 1 kTon Liquid Scintialltor detector situated at the old Kamioka site.
- Looks for $\bar{\nu}_e$ oscillation coming from 16 reactors at distances 81 - 824 km.
- Most powerful reactors are at a distance $\sim$ 180 km.
- Detection process :$\bar{\nu}_e p \rightarrow e^+ n$
- Survival Probability

$$P_i(\bar{\nu}_e \leftrightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 d_i}{E_\nu}\right)$$

- $E_\nu \sim 3$ MeV, L $\sim 1.8 \times 10^5$ m , $\Delta m^2 \sim 1.6 \times 10^{-5}$ eV^2

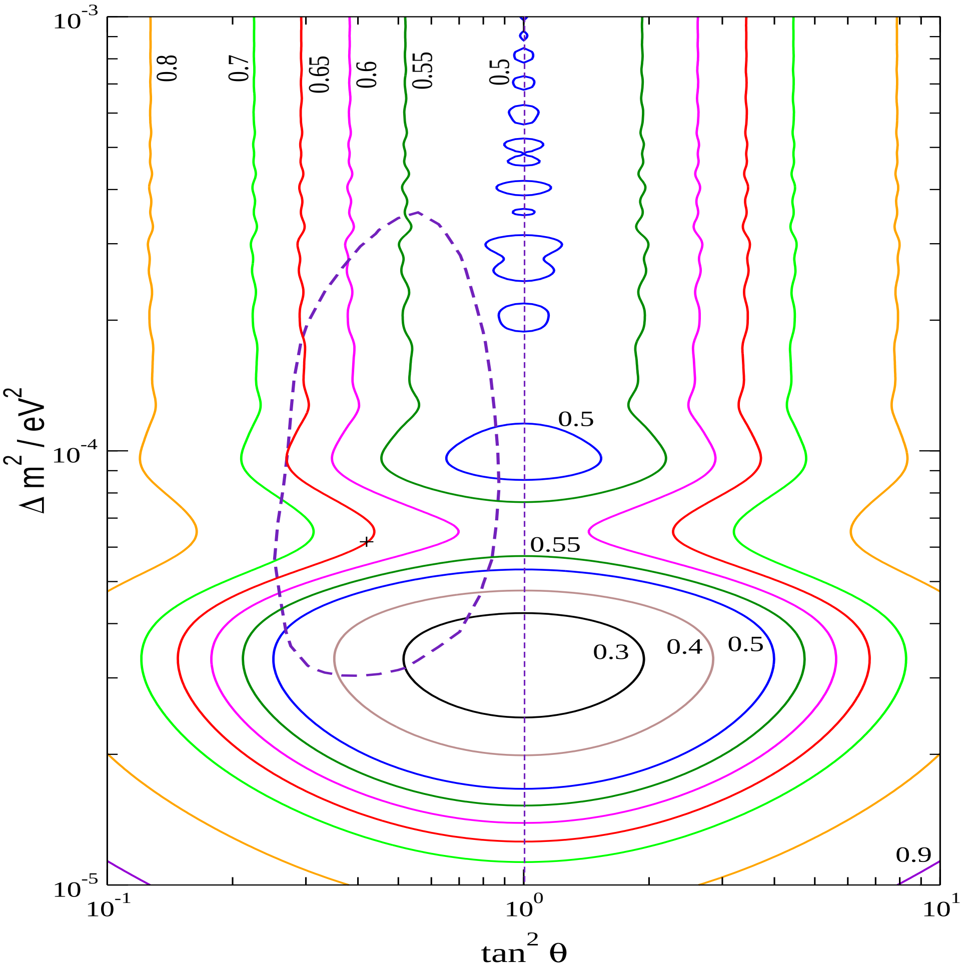
– sensitive to LMA region

- No matter effects: $\theta \equiv= \frac{\pi}{2} - \theta$



J.N.Bahcall et al.,hep-ph/0212247

Can probe the L/E dependence of the oscillations in the LMA region —unprecedented sensitivity to Δm^2



A.Bandyopadhyay et al., hep-ph/0211266

- Solar best fit predicts $R_{KL} = 0.65^{+0.08}_{-0.39}$ (3σ)

- LOW predicts $R_{KL} > 0.9$

- First KamLAND results (KamLAND Collab. hep-ex/0212021)

$$R_{KL} = 0.611 \pm 0.094 \text{ (145 days)}$$

⋆ KamLAND confirms LMA ⋆

Combined Solar+KamLAND analysis

• V. Barger and D. Marfatia, hep-ph/0212126.

• G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo and A. M. Rotunno, hep-ph/0212127.

• M. Maltoni, T. Schwetz and J. W. Valle, hep-ph/0212129.

• P. Creminelli, G. Signorelli and A. Strumia, hep-ph/0102234, v4, 9 Dec. (2002).

• A. Bandyopadhyay, S. Choubey, R. Gandhi, S. Goswami and D. P. Roy, hep-ph/0212146.

• J. N. Bahcall, M. C. Gonzalez-Garcia and C. Pena-Garay, hep-ph/0212147.

• H. Nunokawa, W. J. Teves and R. Z. Funchal, hep-ph/0212202.

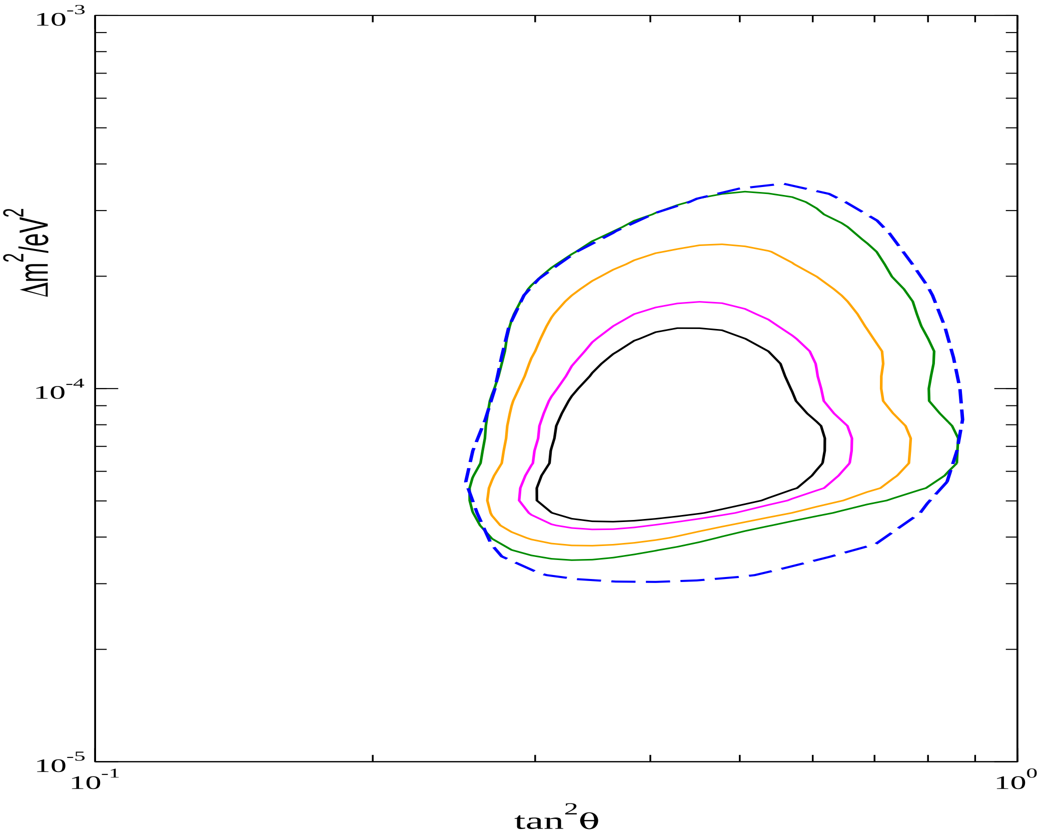
• P. Aliani, V. Antonelli, M. Picariello and E. Torrente-Lujan hep-ph/0212212.

• P. C. de Holanda and A. Yu. Smirnov, hep-ph/0212270.

• W. l. Guo and Z. z. Xing, hep-ph/0212142

• A. B. Balantekin and H. Yuksel, hep-ph/0301072

Impact of KamLAND rate on Allowed LMA Zone

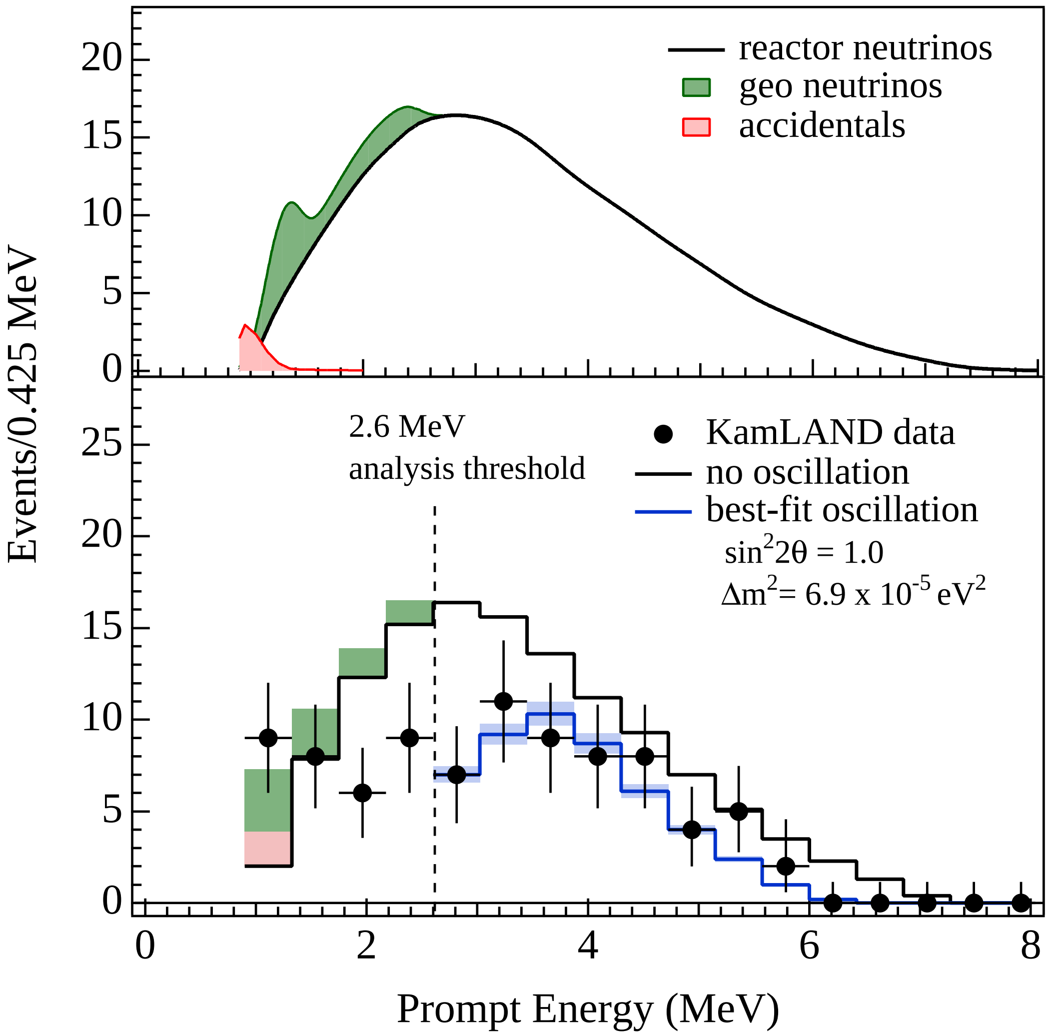


- Lower bound: $\Delta m^2 > 4 \times 10^{-5}$ eV^2

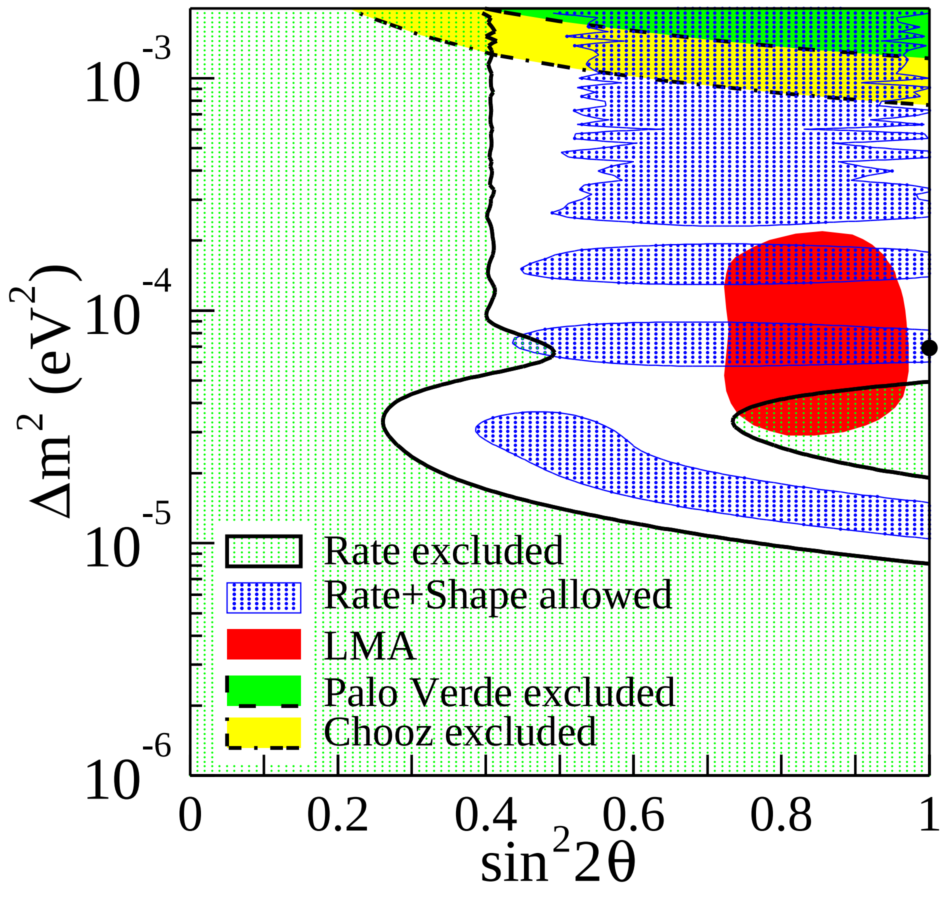
- Only a moderately tighter constraint on Δm^2, practically no other changes

A. Bandyopadhyay et al. hep-ph/0212146

KamLAND spectrum

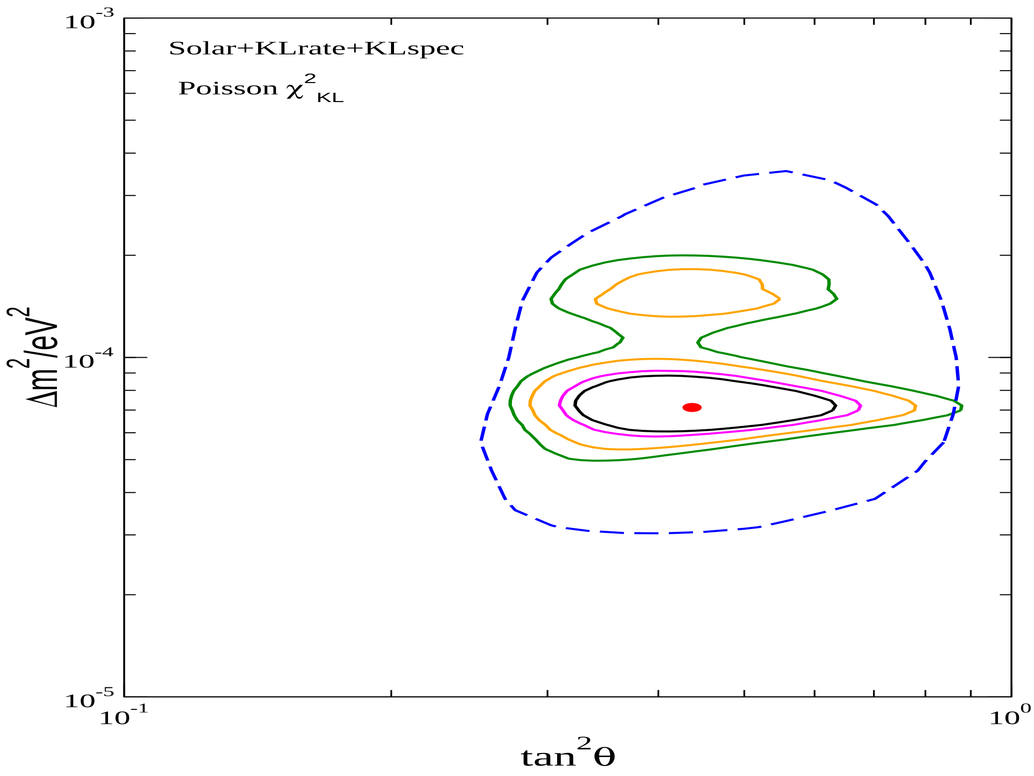


KamLAND Collaboration, hep-ex/0212021



KamLAND Collaboration, hep-ex/0212021

Impact of KamLAND spectrum on Allowed LMA Zone



- Stronger bound on Δm^2
- Splits the allowed region into two zones at 99% C.L.

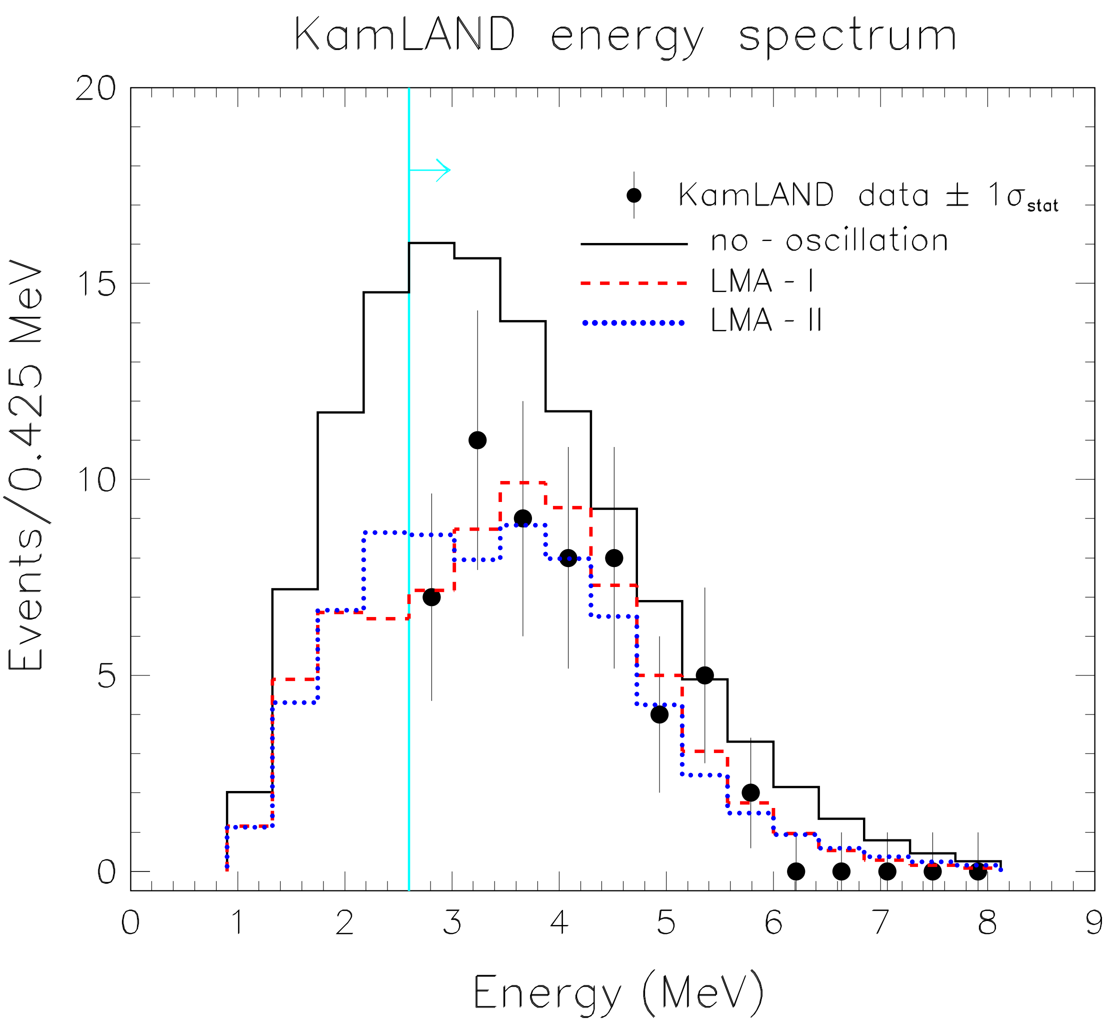
low-LMA (LMA1) and high-LMA (LMA2)

- LMA2 has less statistical significance (by $\approx 2\sigma$)
- The global best-fit $\Delta m^2 = 7.17 \times 10^{-5}$ eV^2, $\tan^2\theta = 0.44$

in low-LMA

- LOW disfavoured at 5σ
- Maximal Mixing disfavoured at 3.4 σ

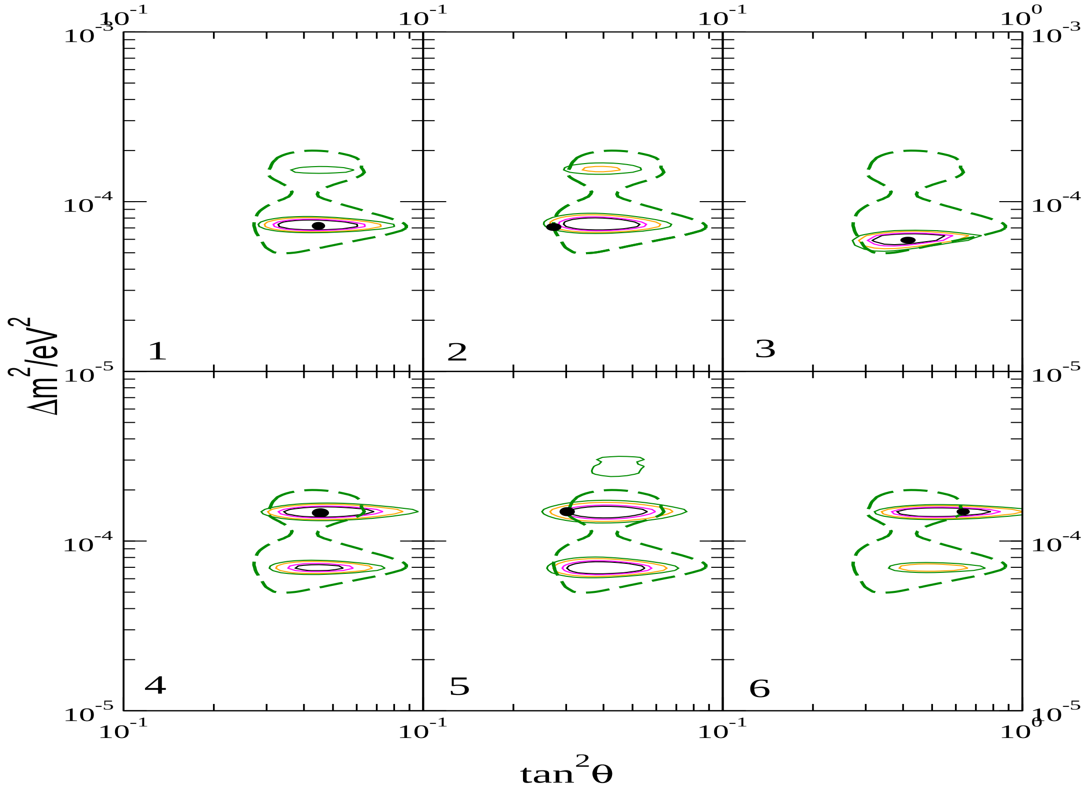
A. Bandyopadhyay et al. hep-ph/0212146



G.L. Fogli et al.

hep-ph/0212127.

Projected Analysis: 1 kiloTon year (2.5 year)



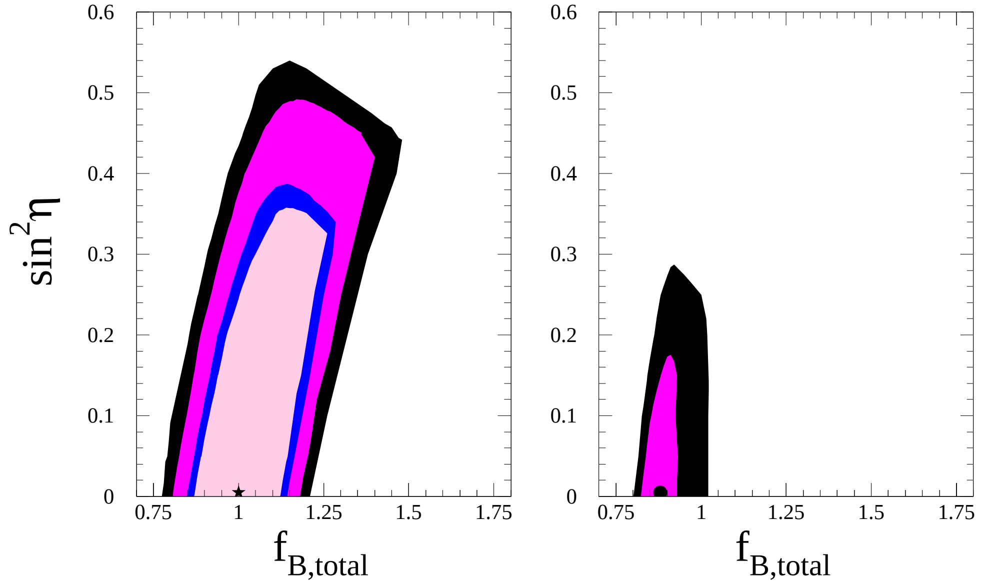
- For spectra simulated at lower Δm^2 values the high-LMA region is more disfavoured
- For spectra generated at solar best-fit no high-LMA region found
- For spectrum simulated at high-LMA region the ambiguity remains.

— More statistics

— Data below 2.6 MeV

A. bandyopadhyay et al. hep-ph/0212146

Transitions to Active+Sterile Species



- $P_{ea} = \cos^2\eta(1 - P_{ee})$
- At $1\sigma(3\sigma) \Rightarrow \sin^2\eta < 0.13(0.52)$

J.N.Bahcall et al.,hep-ph/0212247

Three Flavour Oscillation

- $\Delta m^2_{21} = \Delta m^2_{\odot}$
- $\Delta m^2_{31} = \Delta m^2_{CHOOZ} \simeq \Delta m^2_{atm} = \Delta m^2_{32}$
-

$$
\begin{aligned}
U &= R_{23} R_{13} R_{12} \\
&= \begin{pmatrix} c_{13}c_{12} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - s_{23}s_{13}c_{12} & c_{23}c_{12} - s_{23}s_{13}s_{12} & s_{23}c_{13} \\ s_{23}s_{12} - s_{13}c_{23}c_{12} & -s_{23}c_{12} - s_{13}s_{12}c_{23} & c_{23}c_{13} \end{pmatrix}
\end{aligned}
$$

- $\theta_{13} = 0$ solar and atmospheric neutrinos decouple

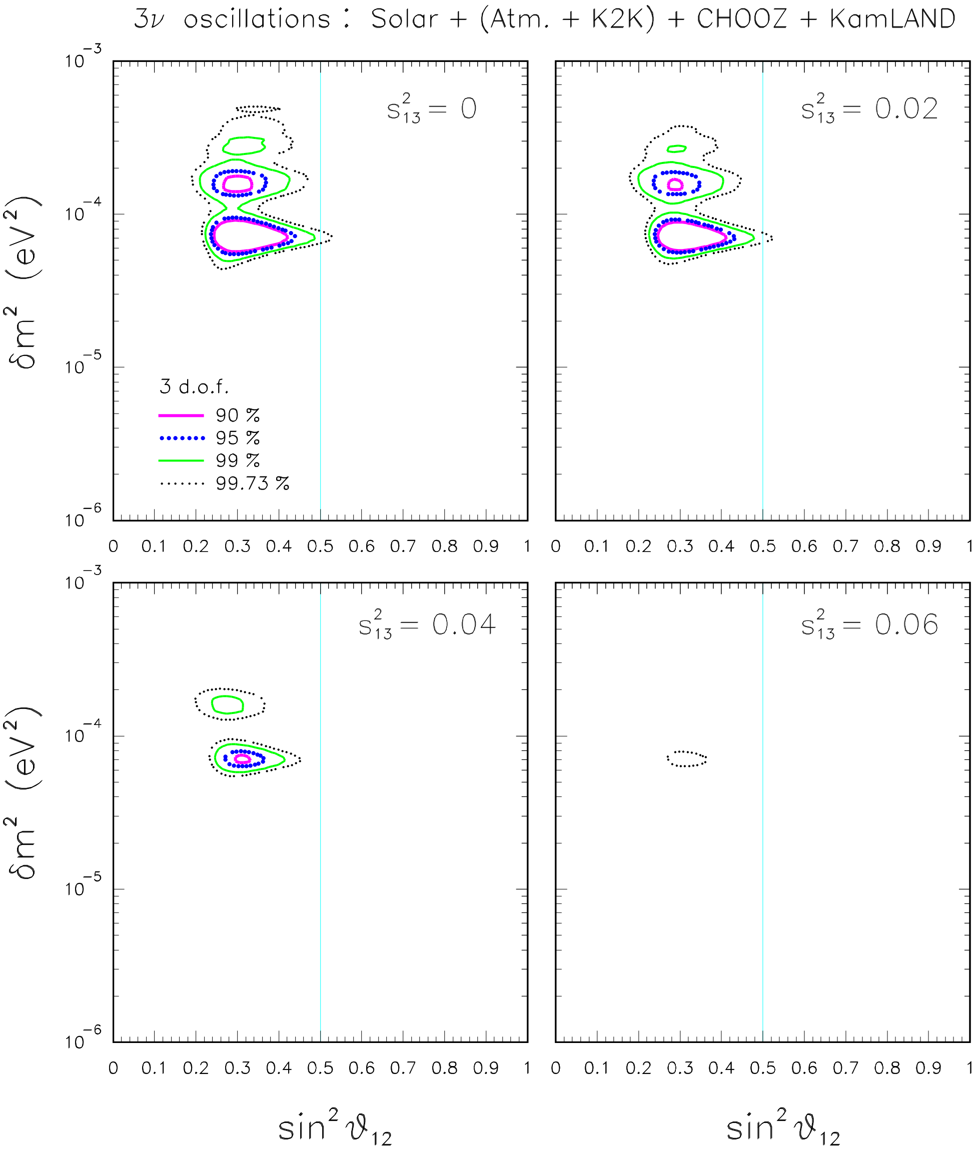
- For $\theta_{13} \neq 0$ and $\Delta \mathrm{m}^2_{31} >> \Delta \mathrm{m}^2_{21}$
-

$$P_{ee} = c^4_{13} P^{2gen}_{ee} + s^4_{13}$$

$\rightarrow$ Independent of $\theta_{23}, \Delta m^2_{31}$

- θ_{13} is constrained mainly from CHOOZ data to $\sin^2\theta_{13} < 0.04$ (3σ)

- Non zero θ_{13} modifies the allowed area in $\Delta m^2_{12} - \sin^2\theta_{12}$ parameter space.



- A third solution (LMA-III) marginally allowed
- LMA-I most stable against increasing θ_{13}

G.L. Fogli et al., hep-ph/0212127

Summary (2002)

- Comparison of SNO CC and SNO NC signifies neutrino flavour conversion at 5.3σ

- Rules out transitions to pure sterile states at 5.3σ

- LMA is the favoured solution to the solar neutrino problem with 3×10^{-5} eV$^2 \leq \Delta m^2 \leq 3 \times 10^{-4}$ eV^2 and $0.25 \leq \tan^2\theta \leq 0.87$ at 3σ

- KamLAND confirms LMA

- Best-fit Δm^2:
6×10^{-5} eV$^2 \rightarrow 7.2 \times 10^{-5}$ eV^2

- No significant change in best-fit θ ($\tan^2\theta = 0.4$)

- LMA region splits into two parts at 99% C.L.

- 3σ allowed range after the first KamLAND data 4.96×10^{-5} eV$^2 < \Delta m^2 < 2 \times 10^{-4}$ eV^2 and $0.27 < \tan^2\theta < 0.88$

- Transitions to mixed state still allowed with $< 13\%(52\%)$ sterile mixture at $1\sigma(3\sigma)$.

- Alternative solutions to solar neutrino problem predicting undiminished KamLAND rate e.g spin flip precession ruled out at $> 3.5\sigma$.

Future

- Discrimination between the two LMA regions

–• More statistics from KamLAND

–• Reducing the threshold below 2.6 MeV

–• Precise measurment of CC/NC at SNO

–• Day-night asymmetry $> 1\%$ in SNO can exclude LMA2 .

–• Borexino should see a rate 0.64 ± 0.03 (1σ) and no day-night asymmetry. It cannot differentiate between the two LMA regions.

•Measurement of the low energy neutrino flux and spectrum

– • "LowNu" experiments

XMASS, CLEAN, GENIUS, MOON,LENS,HELLAZ,HERON...

R & D in progress.

J.N.Bahcall et al.,hep-ph/0212247

A. de Holanda and A. Yu. Smirnov, hep-ph/0212270.

G.L. Fogli et al., hep-ph/0212127

A. Bandopadhyaya et al., hep-ph/0212146