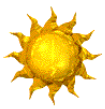


Solar Neutrino Oscillation Phenomenology

Srubabati Goswami

Harish-Chandra Research Institute
Allahabad, India

PASCOS'03

Tata Institute of Fundamental Research

Mumbai, India

– Aprill 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

Plan of Talk

I. Solar Neutrinos and SSM

II. Solar Neutrino Experiments and Data

III. Two Flavour Oscillation Analysis

- Impact of SNO
- Impact of KamLAND

IV. Sterile Neutrinos, Three Flavours

V. Summary and Prospects

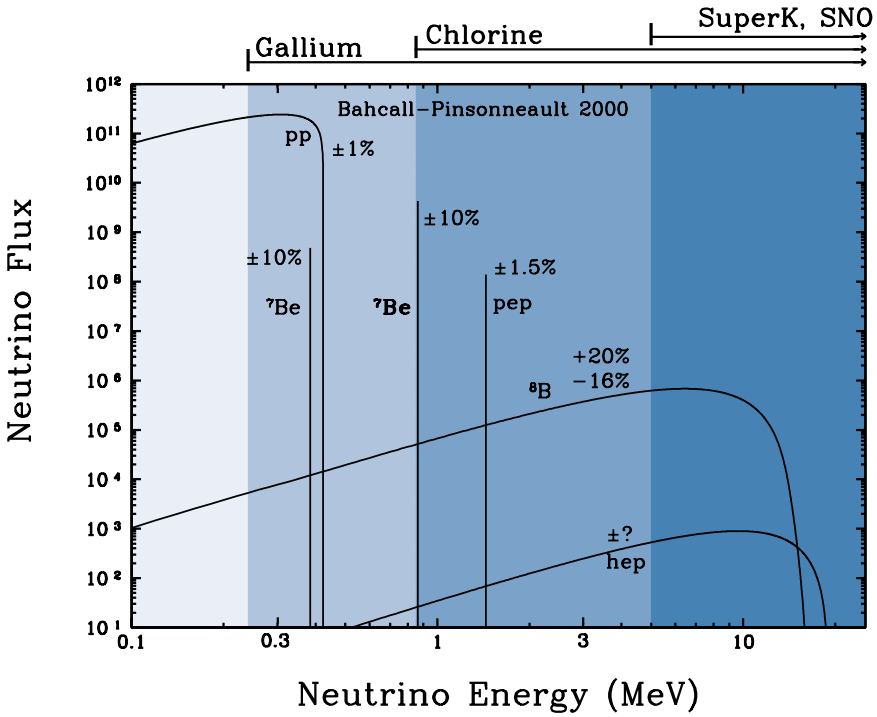
Solar Neutrinos

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e + 28\text{MeV}$$

- Two main cycles of nuclear reactions

  pp chain: responsible for 98.5% of the energy

  CNO cycle: responsible for 1.5% of the energy

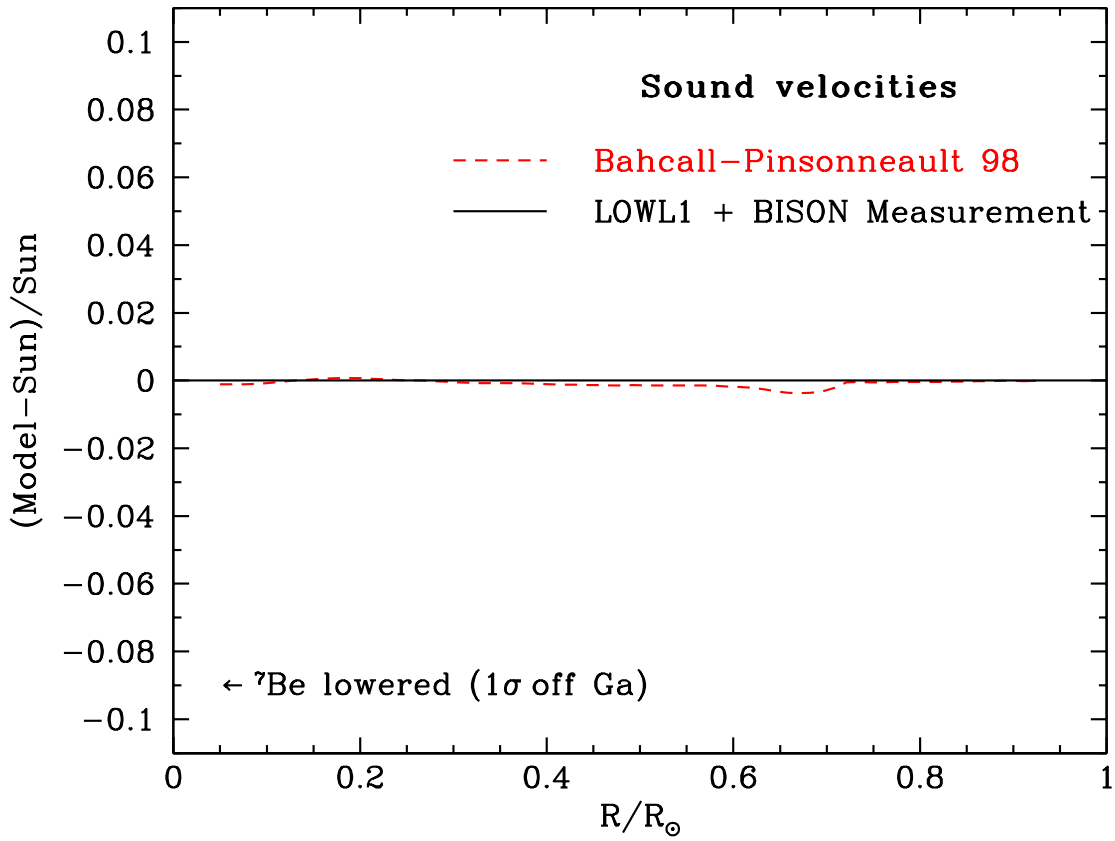


(http://www.sns.ias.edu/ jnb/)

•Eight different types of neutrino flux
pp,pep,hep,^7Be,^8B, ^{13}N, ^{15}O,^{17}F

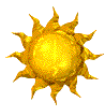
- pp $\rightarrow$ responsible mainly for solar luminosity, least uncertain

- ^8B flux is most uncertain



- Standard Solar Model is in excellent agreement with helioseismological measurements

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



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

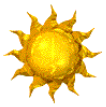
NC $d + \nu_x \rightarrow p + n + \nu_x$

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.



Total Solar Neutrino Flux

- 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 $\star$
SNO(ES)	0.473 ± 0.074 $\star$
SNO(NC)	1.008 ± 0.123 $\star$

$\star$ Assuming undistorted ^8B spectrum

- Observed ν_e flux $<$ Theoretical Prediction

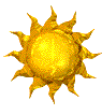
$\rightarrow$ solar Neutrino Problem

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

$\rightarrow$ indicative of flavour conversion

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

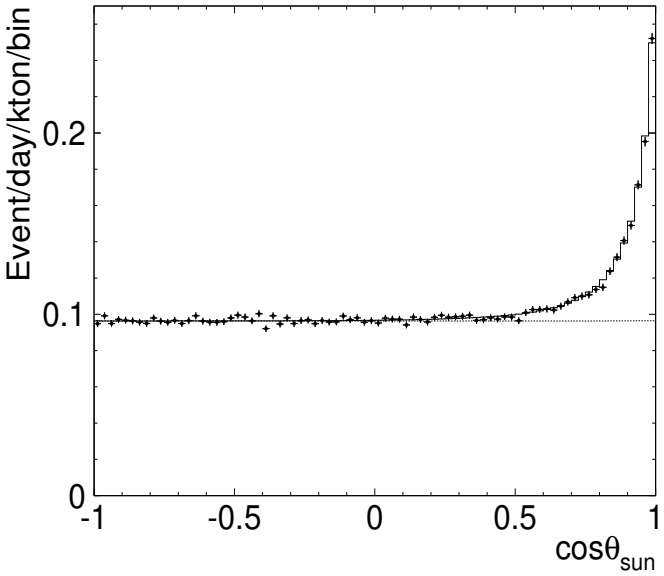
$\rightarrow$ indicative of flavour conversion



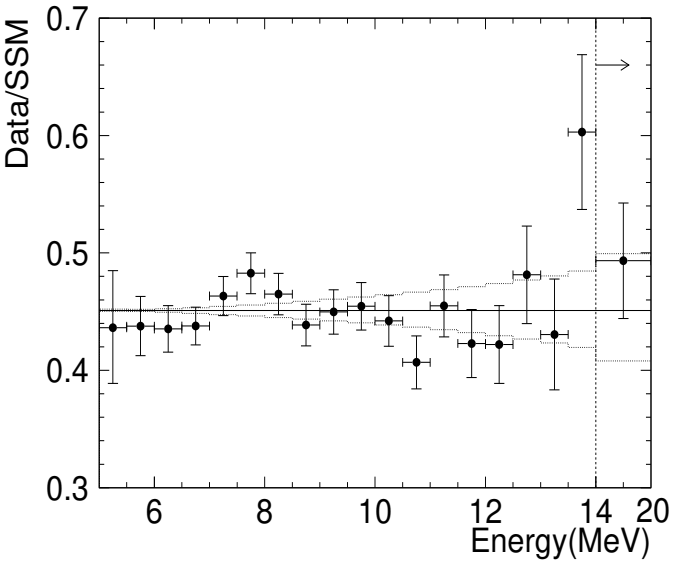
Information on Direction and Energy

- Results from SuperKamiokande $(e^- + \nu_x \rightarrow e^- + \nu_x)$

– Neutrinos coming from Sun

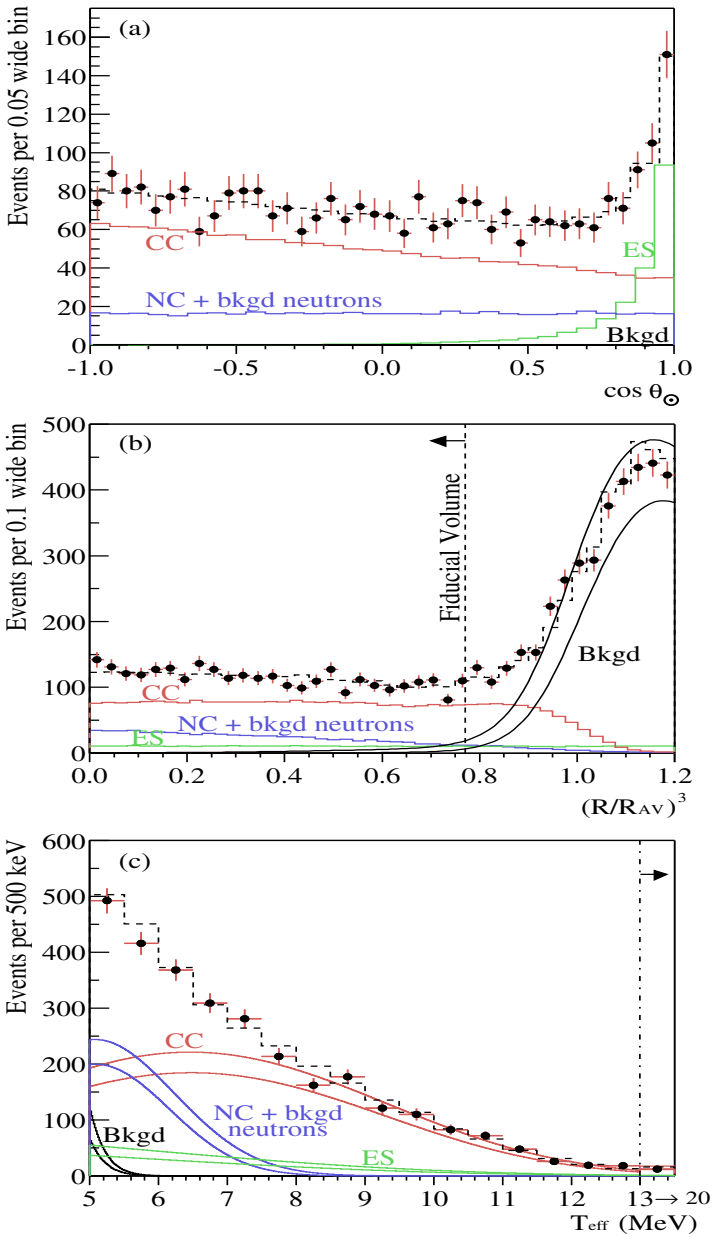


– Flat recoil electron energy spectrum



Information on Direction and Energy

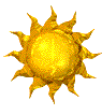
- Results from SNO



NC signal entangled with ES and CC signal

– NaCl added to increase neutron capture efficiency

– ^3He proportional counter for direct detection of neutron



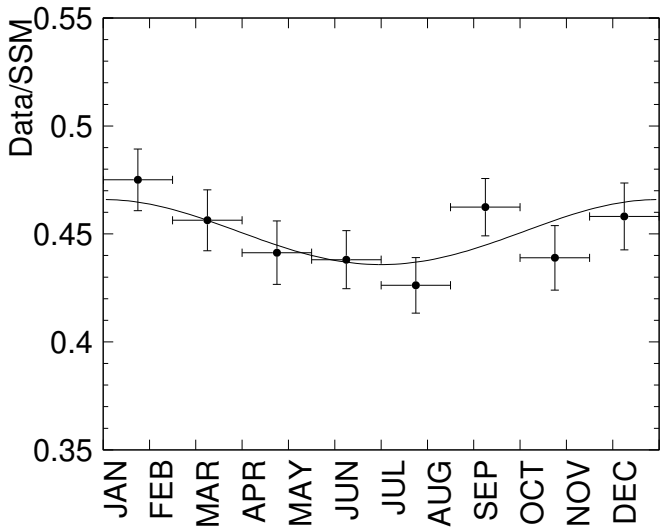
Time Variations

– 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

- Before SNO

– The Observed flux $<$ SSM prediction

– ^7Be neutrino problem

$$\text{Cl} \longrightarrow {}^8B + {}^7Be$$

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

$$\text{SK} \longrightarrow {}^8B$$

– No astrophysical explanation

–Neutrino Flavour conversion ?

- After SNO CC

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

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

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

$\longrightarrow$ Presence of ν_μ/ν_τ at 3.3 σ The SNO Collab.

PRL **87, 2001**

- After SNO NC

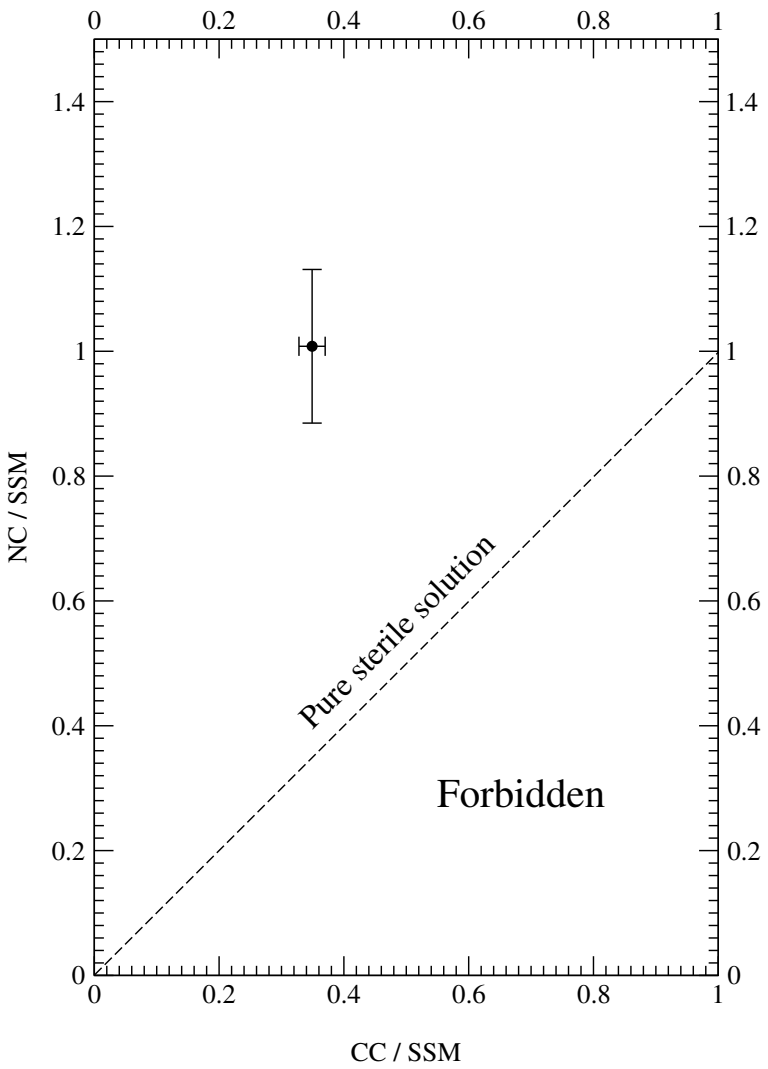
SNO CC: $\nu_e d \rightarrow \nu_e pp \rightarrow \Phi_e$

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

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

$\longrightarrow$ Presence of ν_μ/ν_τ at 5.3 σ The SNO Collab.

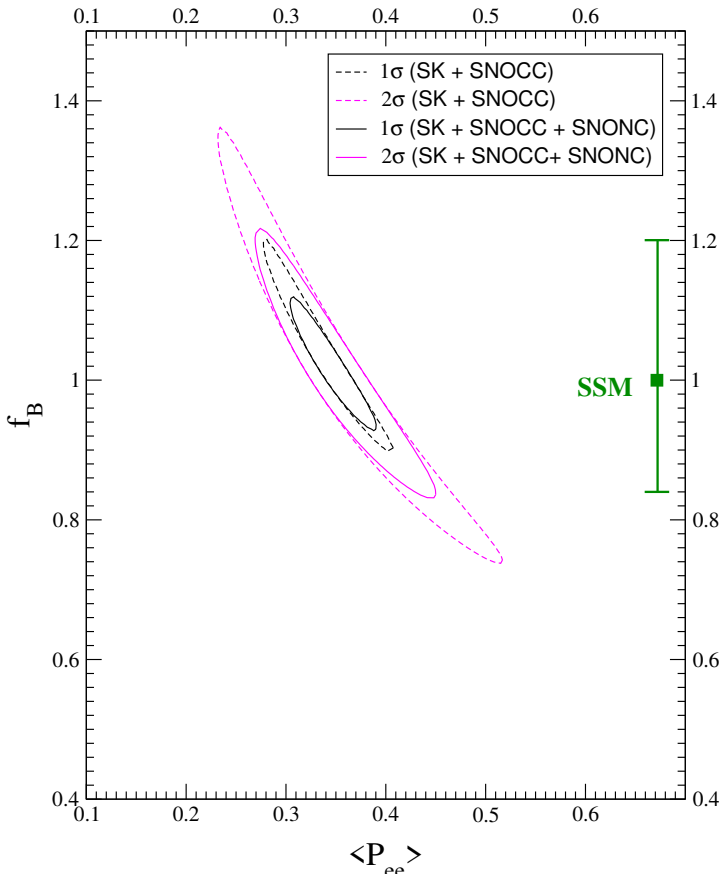
PRL **89, 2002**



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

- ν_s does not interact at the detector
- Pure $\nu_e - \nu_s$ /No oscillation disfavoured at 5.3σ.

Model Independent Analysis



$$
\begin{aligned}
R_{SK}^{el} &= f_B P_{ee} + f_B r(1 - P_{ee}) \\
R_{SNO}^{CC} &= f_B P_{ee} \\
R_{SNO}^{NC} &= f_B
\end{aligned}
$$

- ^8B survival probability independent of energy above 5 MeV
- Inclusion of SNO NC reduces the error
- Absolutly consistent with BPB2000 SSM

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

Two Flavour Oscillation

- Vacuum Mixing
  - If Neutrinos have mass

$$\begin{pmatrix} \nu_e \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$\theta \rightarrow$ vacuum mixing angle

  - Survival Probability (in vacuum)

$$P_{\nu_e\nu_e} = 1 - \sin^2 2\theta \sin^2(1.27\Delta m^2 L/E)$$

$$\Delta m^2 = m_2^2 - m_1^2$$

$\rightarrow$ coherent propagation of the mass eigenstates

- Matter Mixing
  - In matter, only ν_e's undergoes Charged current interaction $\rightarrow$ an effective potential of $\sqrt{2}G_F N_e$
- $\theta \rightarrow \theta_m$

$$tan2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta \cos 2\theta - 2\sqrt{2}G_F n_e E}$$

- $n_e \rightarrow 0, \theta_M \rightarrow \theta,$

$n_e \rightarrow \infty, \theta_M \rightarrow \pi/2$

$\Delta m^2 cos2\theta = 2\sqrt{2}G_F n_e, \theta_M \rightarrow \pi/4 \longrightarrow$ MSW Matter Enhanced Resonance

L. Wolfenstein, PRD **17**, 1978

S.P. Mikhyev, A.Yu. Smirnov, SJNP **42**, 1985

- Intrinsic Neutrino Properties: Δm^2, θ

Survival Probability of Solar Neutrinos

The ν_e survival amplitude for propagation from Sun to earth:

$$A_{ee} = A^{\odot}_{e1} A^{vac}_{11} A^{\oplus}_{1e} + A^{\odot}_{e2} A^{vac}_{22} A^{\oplus}_{2e}$$

$$\begin{aligned} P_{ee} &= P_{\odot}P_{\oplus} + (1-P_{\odot})(1-P_{\oplus}) \\ &\quad +2\sqrt{P_{\odot}(1-P_{\odot})P_{\oplus}(1-P_{\oplus})}\cos\xi \end{aligned}$$

- $\Delta \leq 5 \times 10^{-10}$ eV$^2 \Longrightarrow P_{\odot} = \cos^2\theta,\ P_{\oplus} = \cos^2\theta$

$$\boxed{P_{ee} = 1 - \sin^2 2\theta \sin^2\xi} \qquad \text{(vac. osc)}$$

- $\Delta \geq 10^{-8}$ eV$^2 \Longrightarrow$, $\cos\xi = 0$ (incoherent propagation)

- Day time Probability

– No earth effect $\Longrightarrow P_{\oplus} = \cos^2\theta$

- Adiabatic Propagation: (slowly varying density)

$$\boxed{P^{Day}_{ee} == \cos^2\theta_M \cos^2\theta + \sin^2\theta_M \sin^2\theta}$$

- Non-Adiabatic Effect:

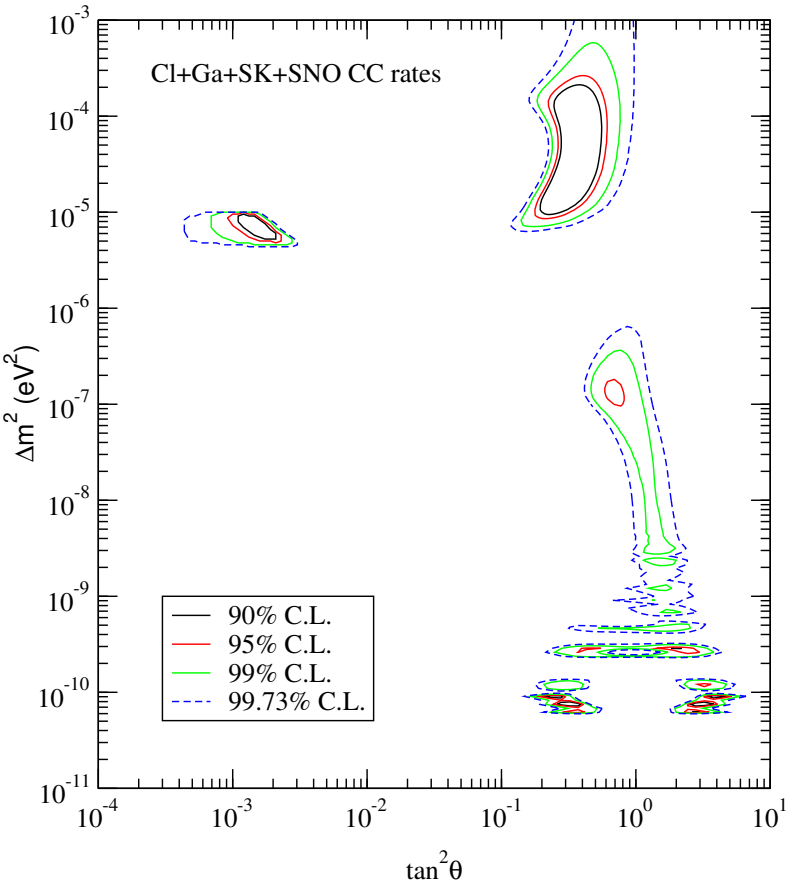
$$\boxed{P^{Day}_{ee} = 0.5 + (0.5 - P_J)\cos 2\theta \cos 2\theta_M}$$

- Night time probability

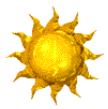
– (including earth effect)

$$P_{ee} = P^{Day}_{ee} + \frac{(2P^{Day}_{ee} - 1)(\sin^2\theta - P^{\oplus}_{2e})}{\cos 2\theta}$$

Allowed Area from total flux measurement (2001)

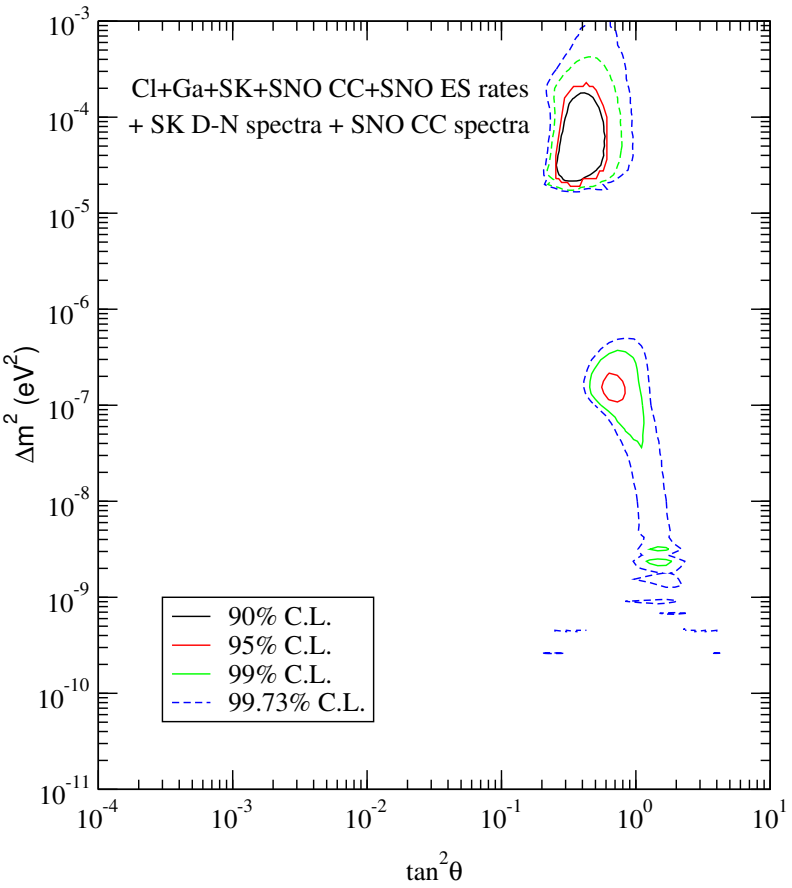


A. Bandyopadhyay,S.Choubey,S.G,K.Kar,PLB **519**,2001



SK spectrum + total flux

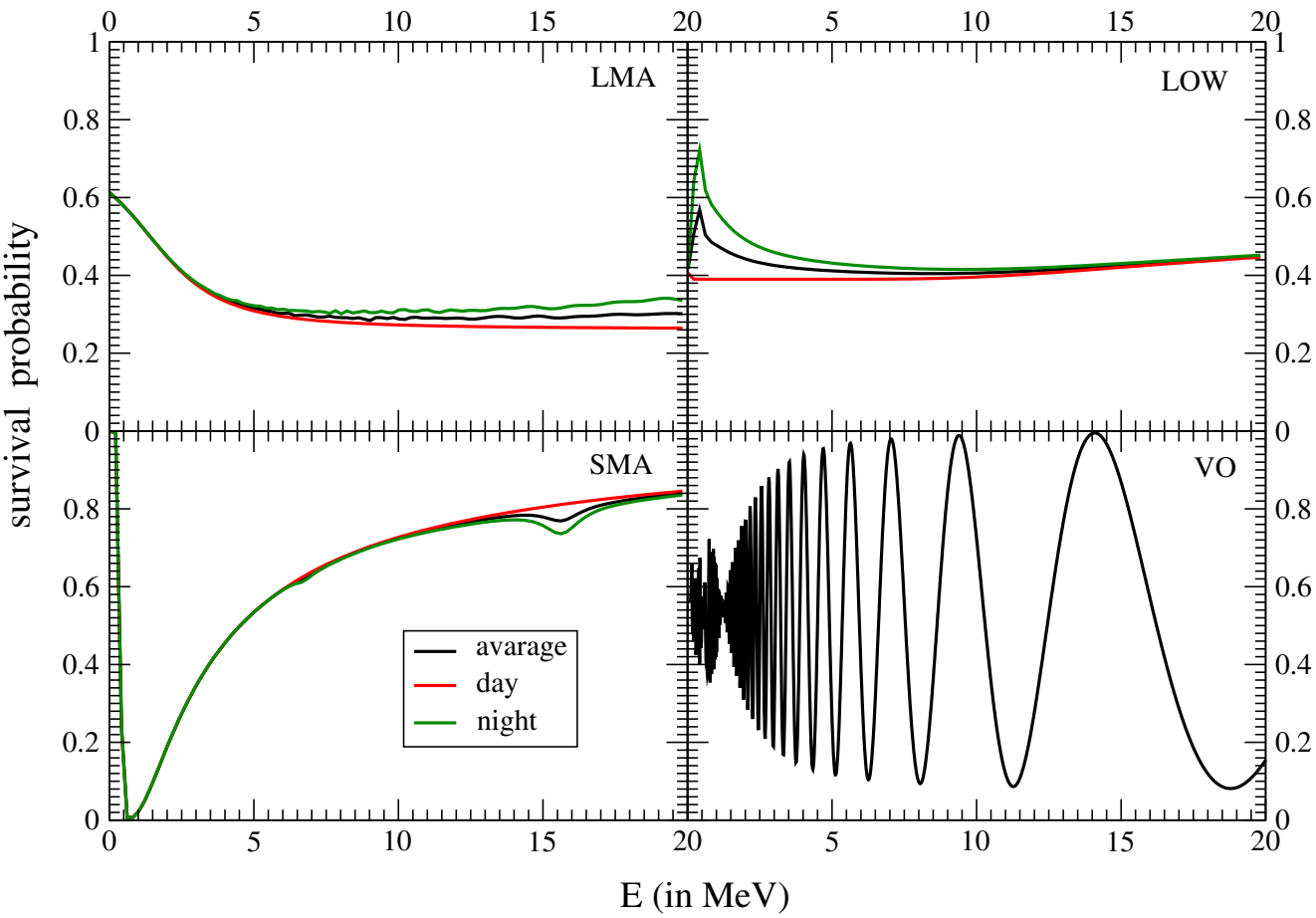
(2001)



- Flat SK spectrum +SNO CC disfavours SMA

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

The dependence of Probability on Energy

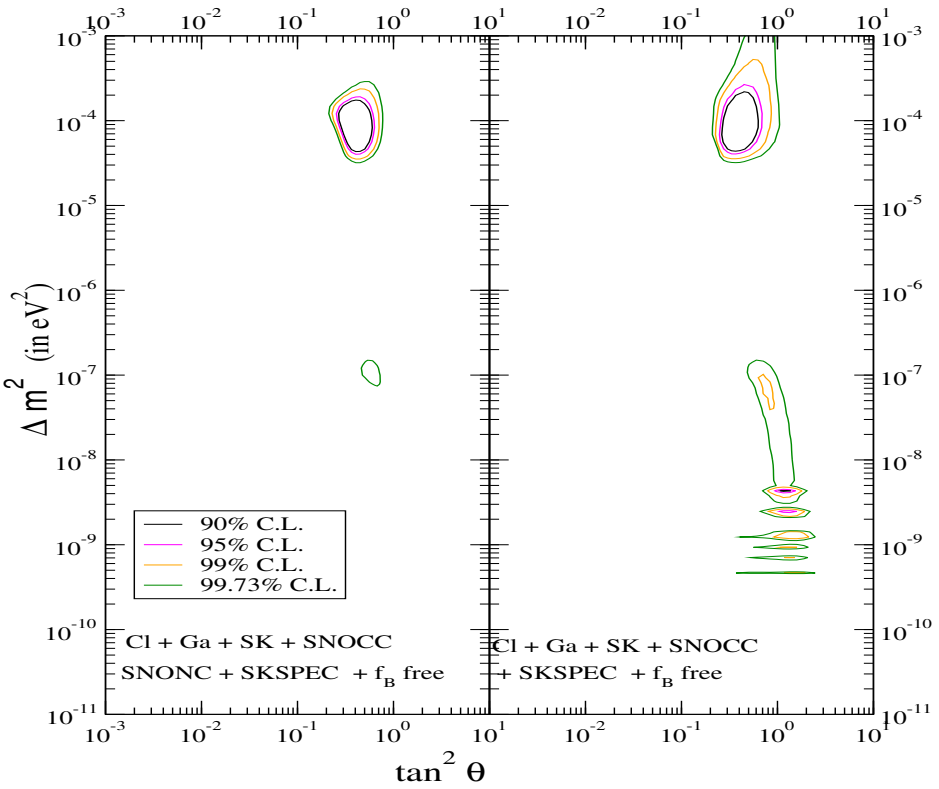


Implications of the NC Data

- SNO Collaboration,
  nucl-ex/0204009
- V.Barger, D.Marfatia, K.Whisnant, B.P.Wood,
  hep-ph/0204253
- P.Creminelli, G.Signorelli, A.Strumia,
  hep-ph/0102234 (V3)
- A.Bandyopadhyay, S.Choubey, S.Goswami, D.P.Roy,
  hep-ph/0204286, hep-ph/0209222
- J.N.Bahcall, M.C.Gonzalez-Garcia, C.Pena-Garay,
  hep-ph/0204314
- P.Aliani, V.Antonelli, M.Picariello, E.Torrente-Lujan,
  hep-ph/0205053
- A.Strumia, C.Cattadori, N.Ferrari, F.Vissani
  hep-ph/0205261
- P.C. de Holanda, A.Yu.Smrinov
  hep-ph/0205241
- Super-Kamiokande Collaboration,
  hep-ex/0205075
- G.L.Fogli,E.Lisi,A.Marrone,D.Montanino,A.Palazzo
  hep-ph/0206162

Impact of SNO NC

•Use ^8B flux and uncertainty from the SNO NC data, thereby reducing the error from (16-20%) as in SSM to 12%



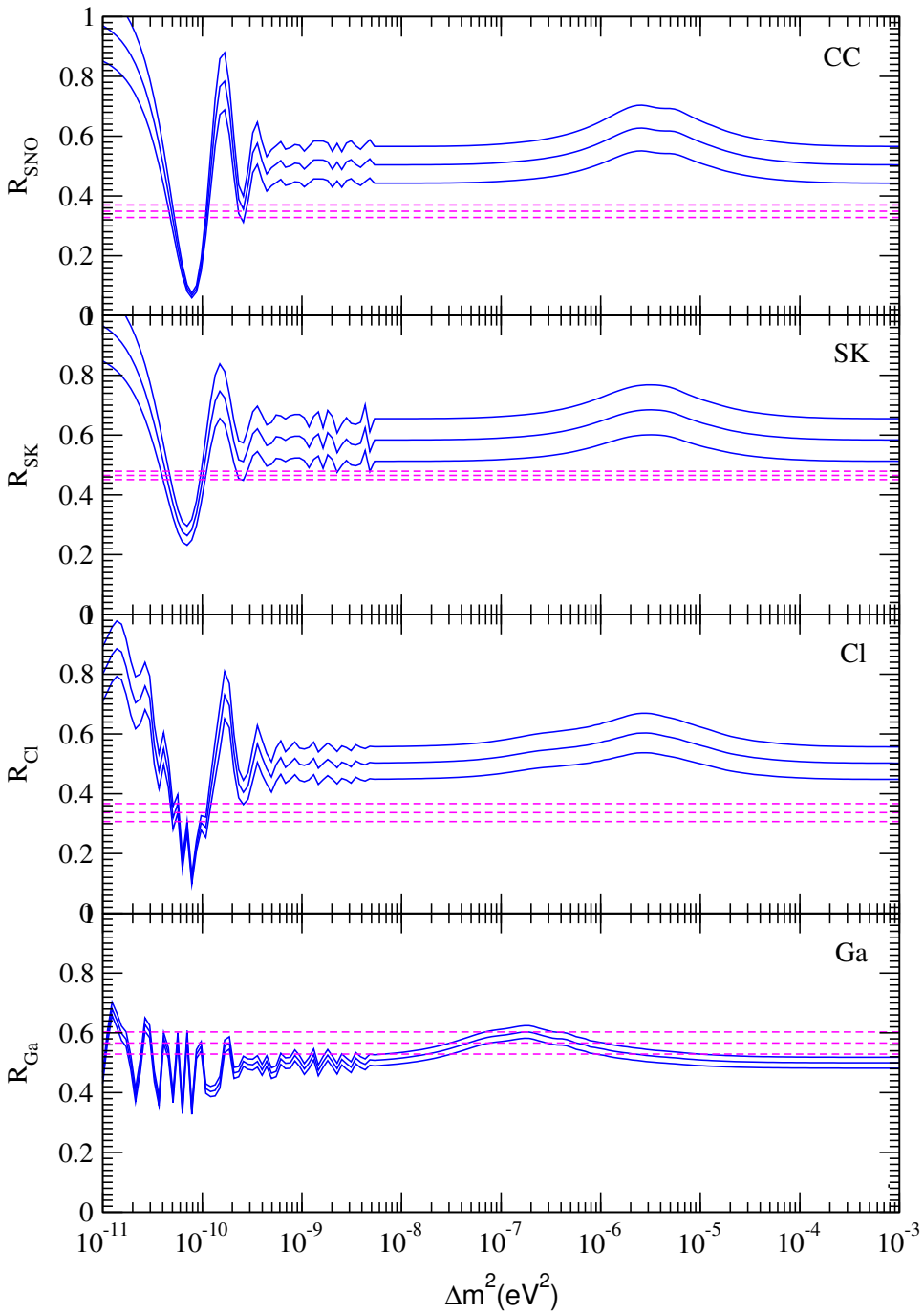
- LMA is the favoured solution
- LOW appears only at 3σ
- Values of Δm^2 above 3×10^{-4} eV^2 disfavored
- VO not allowed at 3σ
- Maximal Mixing ($\theta = \pi/4$)is disfavored at 3.4σ
- SMA disfavored at 3.7σ.
- Dark Side ($\theta > \pi/4$) solutions are gone

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

Why LOW is 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

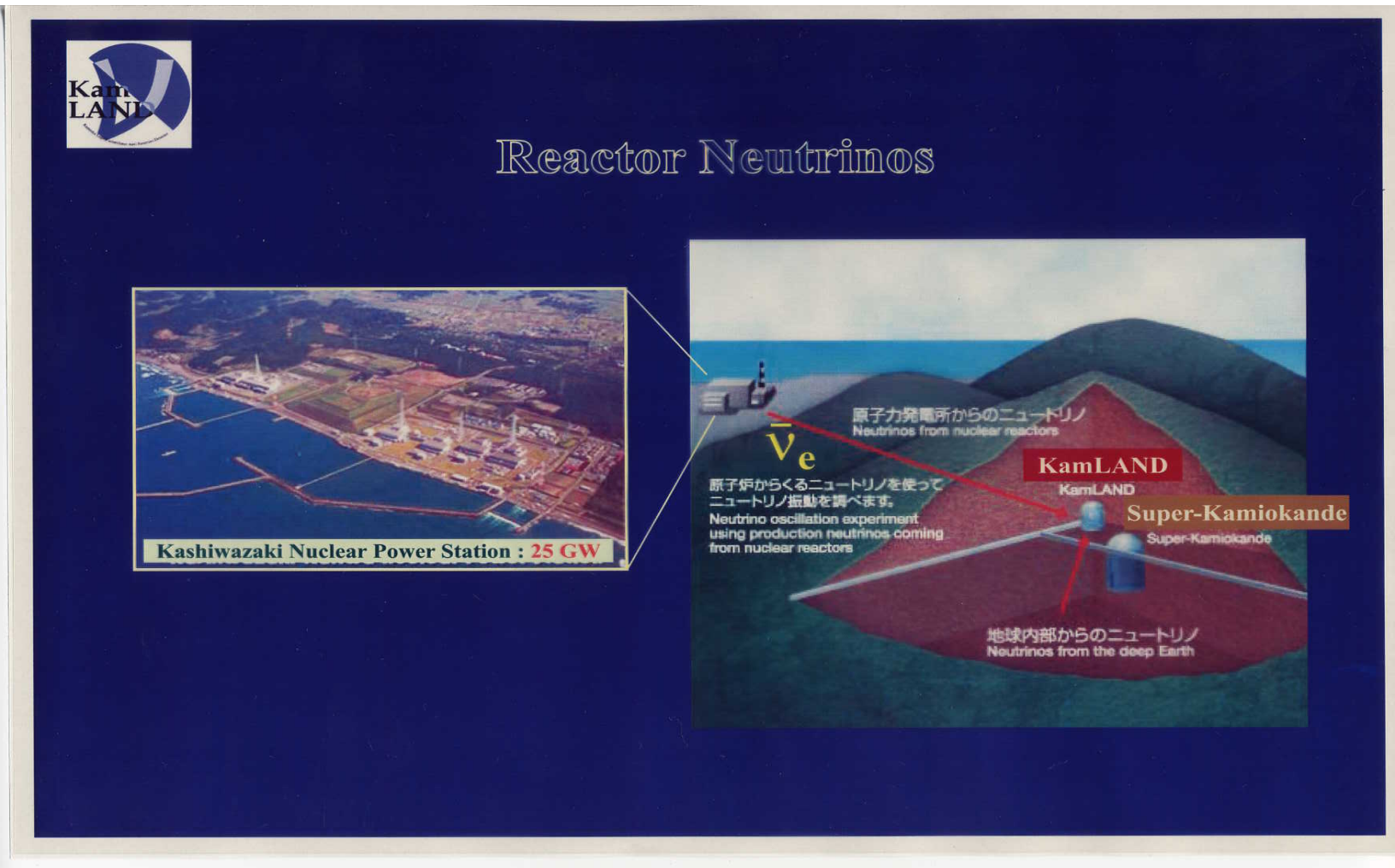


- Predicted Rates at Maximal Mixing with ^8B flux error is taken from NC data.

A. Bandyopadhyay et al. hep-ph/0209222

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

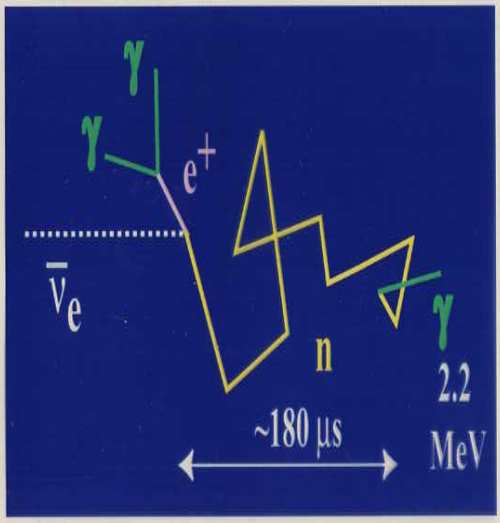
• Most powerful reactors are at distance $\sim$ 180 km

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

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

$+ p \longrightarrow d + \gamma$

distinctive two-step signature



- 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

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

KamLAND experiment

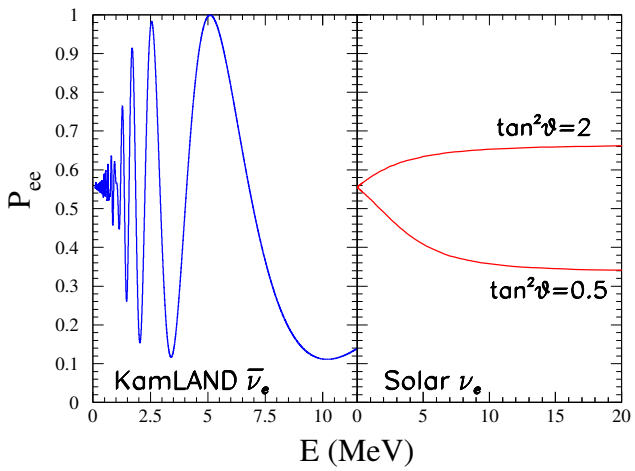
- 1 kTon Liquid Scintialltor detector situated at the old Kamioka site.
- Looks for $\bar{\nu_e}$ oscillation coming from 16 reactors at distances 81 - 824 km.
- Most powerful reactors are at a distance $\sim$ 180 km.
- Detection process :$\bar{\nu_e} p \rightarrow e^+ n$
- Survival Probability

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

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

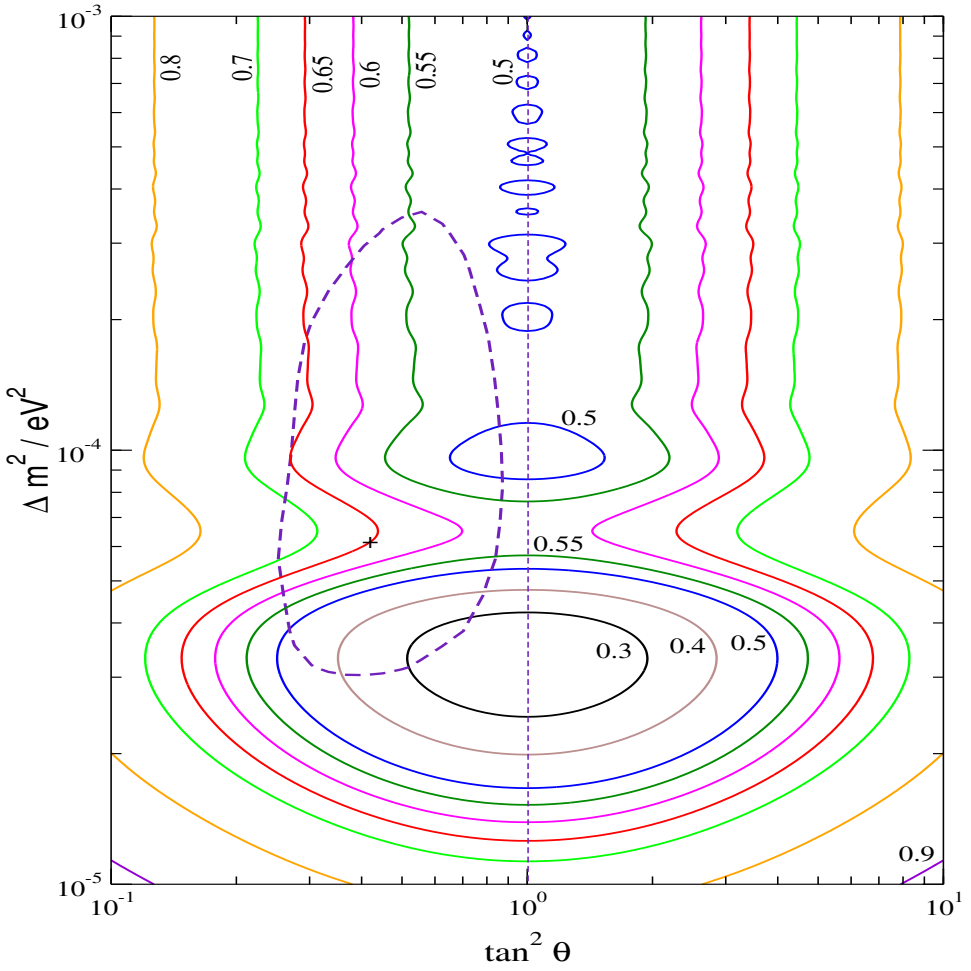
– sensitive to LMA region

- 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)

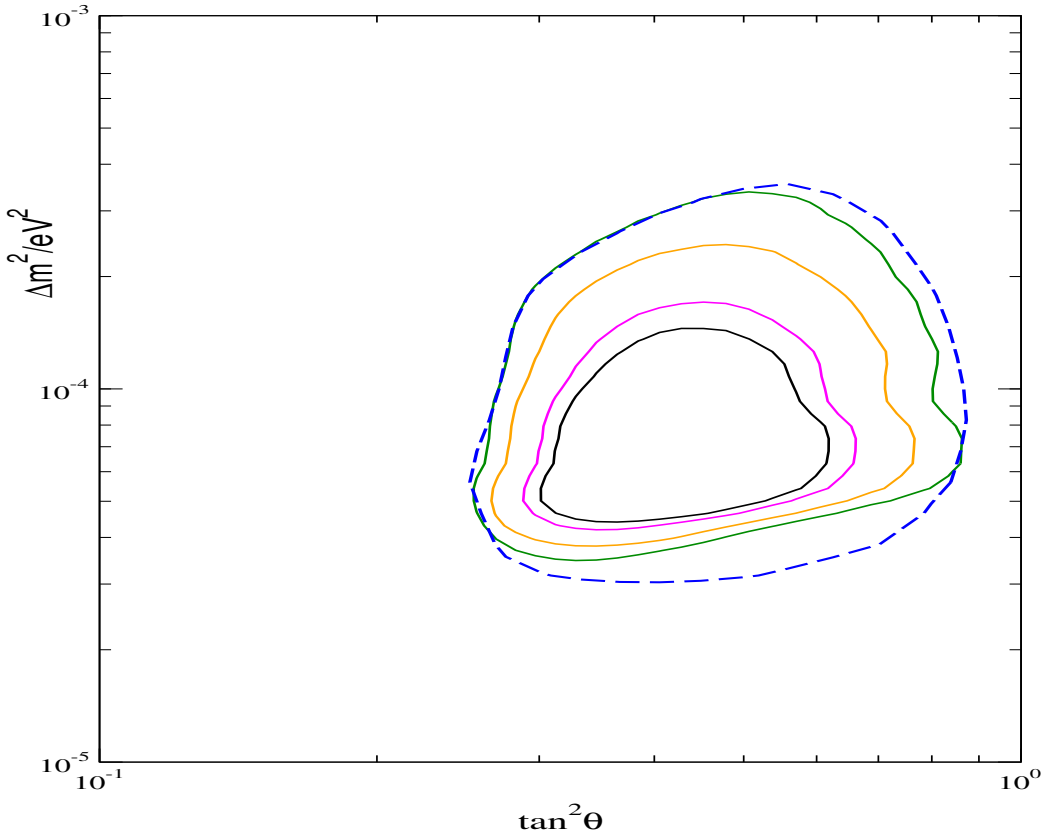
$$R_{KL} = 0.611 \pm 0.094 \text{ (145 days)}$$

⋆ 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.

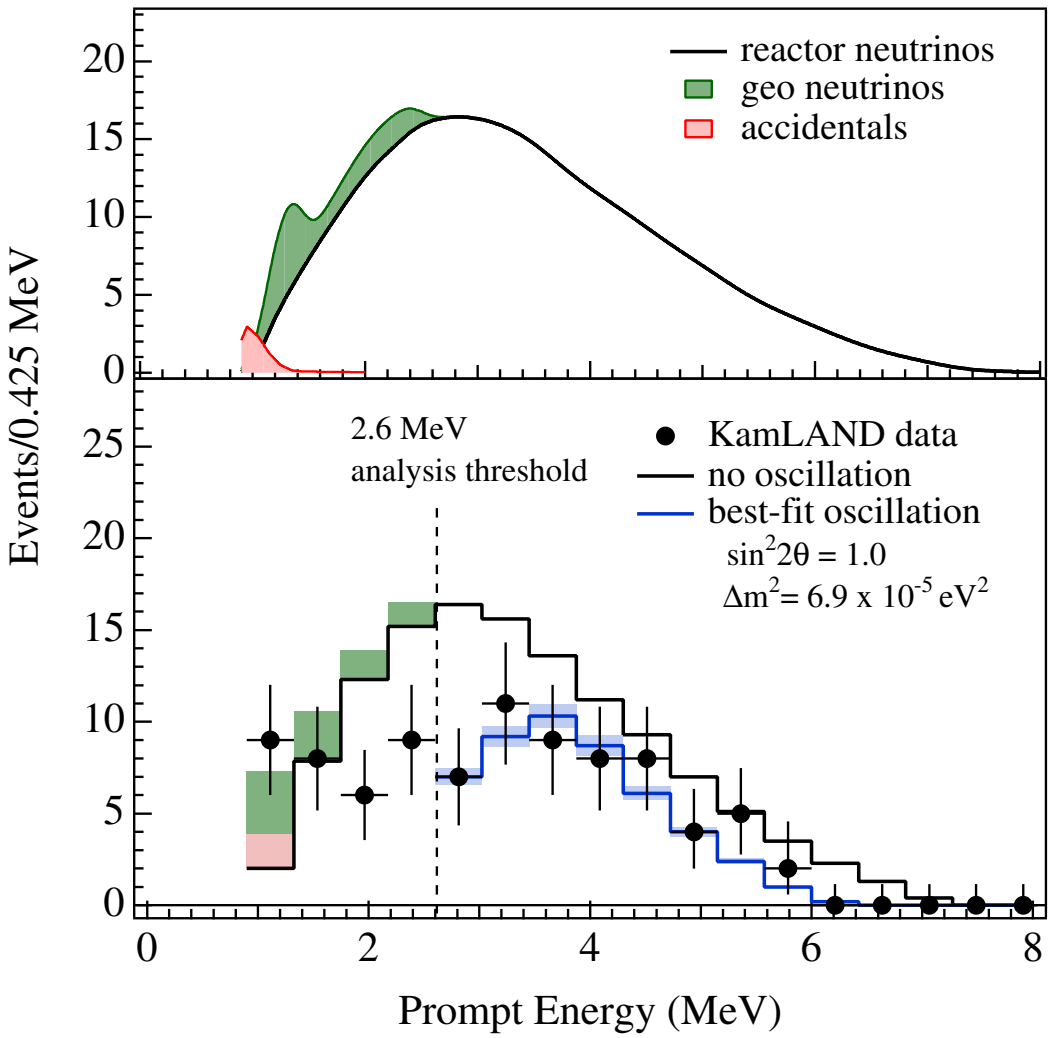
Impact of KamLAND rate on Allowed LMA Zone



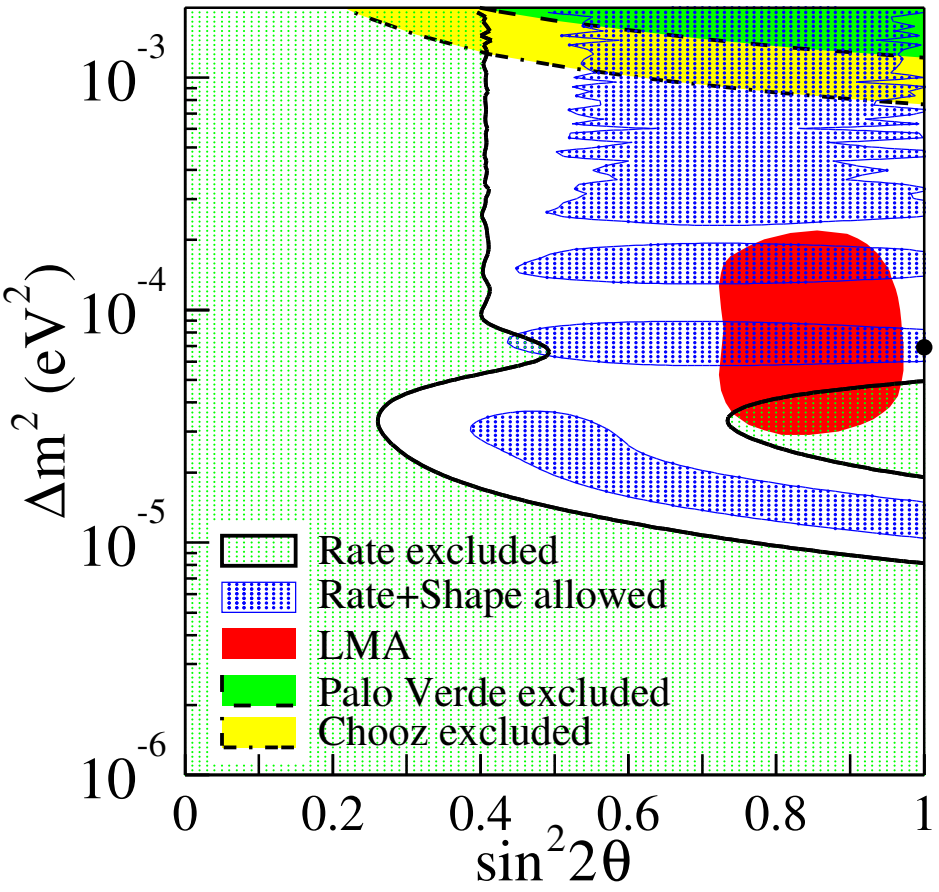
- Lower bound: $\Delta m^2 > 4 \times 10^{-5}$ eV^2
- The other parts are not constrained much.

A. bandyopadhyay et al. hep-ph/0212146

KamLAND spectrum



KamLAND Collaboration, hep-ex/0212021



KamLAND Collaboration, hep-ex/0212021

$$P_{\nu_e\nu_e} = 1 - \sin^2 2\theta \sin^2(\pi L/\lambda)$$

$$\lambda = 2.5m \frac{E_\nu}{MeV} \frac{eV^2}{\Delta m^2}$$

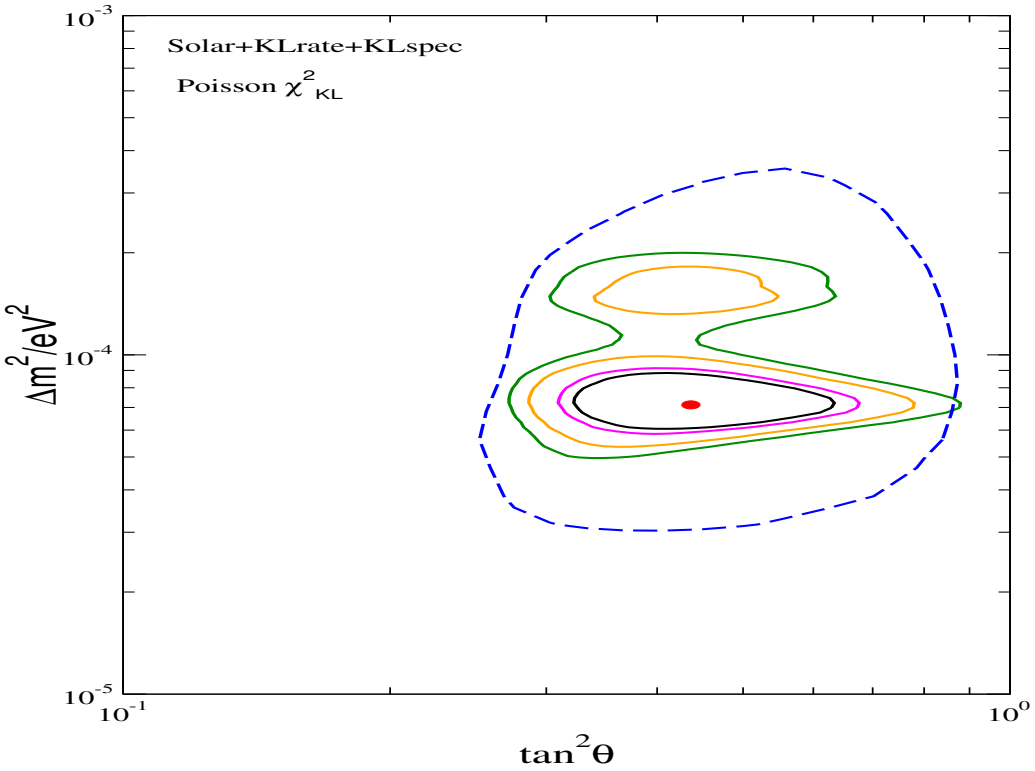
- $E \sim 5MeV$, $L \sim 180km$

– $\Delta m^2 = 7 \times 10^{-5}$ eV^2 , $\lambda = L$, $P_{ee} = 1$

– $\Delta m^2 = 3.5 \times 10^{-5}$ eV^2 , $\lambda = 2L$, $P_{ee} = 0$

– $\Delta m^2 = 1.4 \times 10^{-4}$ eV^2 , $\lambda = L/2$, $P_{ee} = 1$

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

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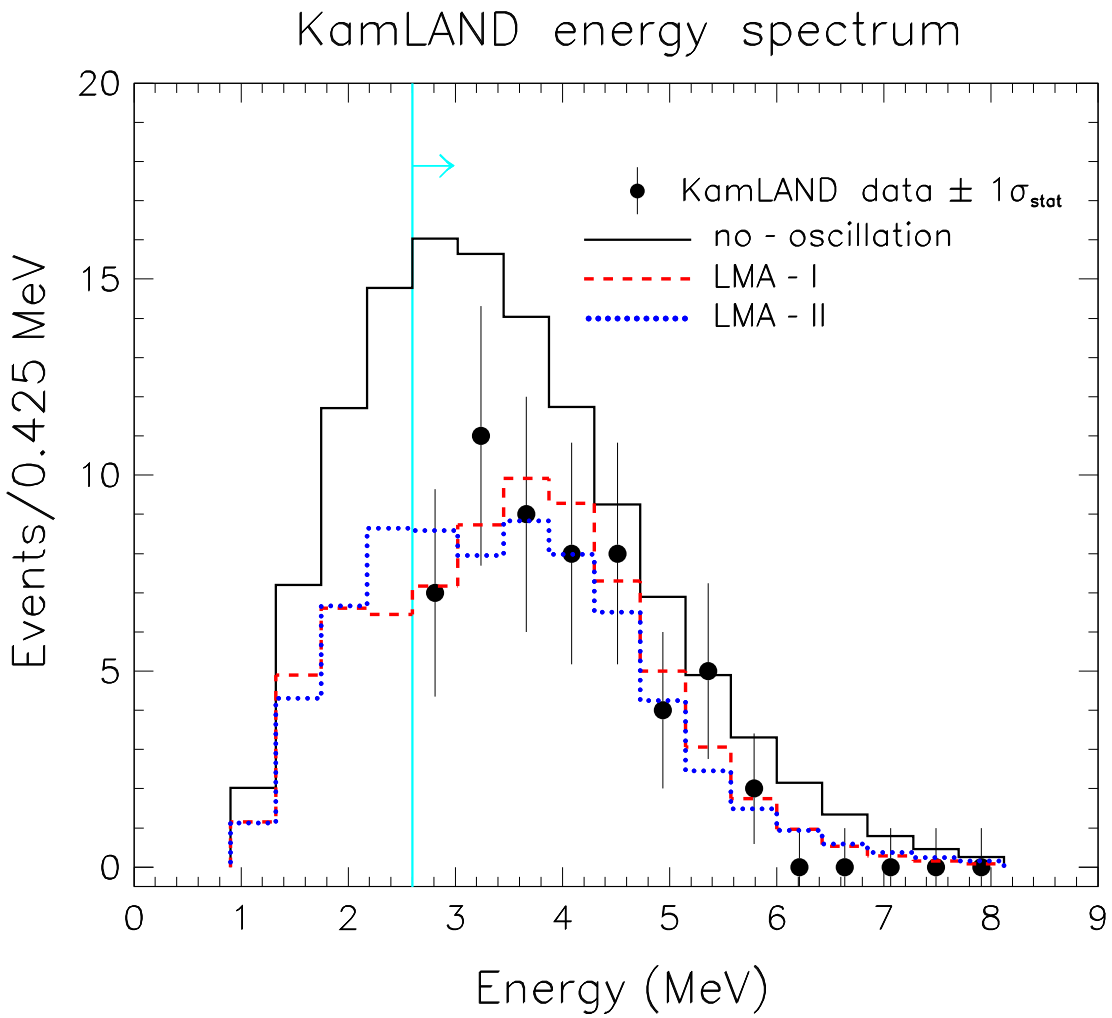
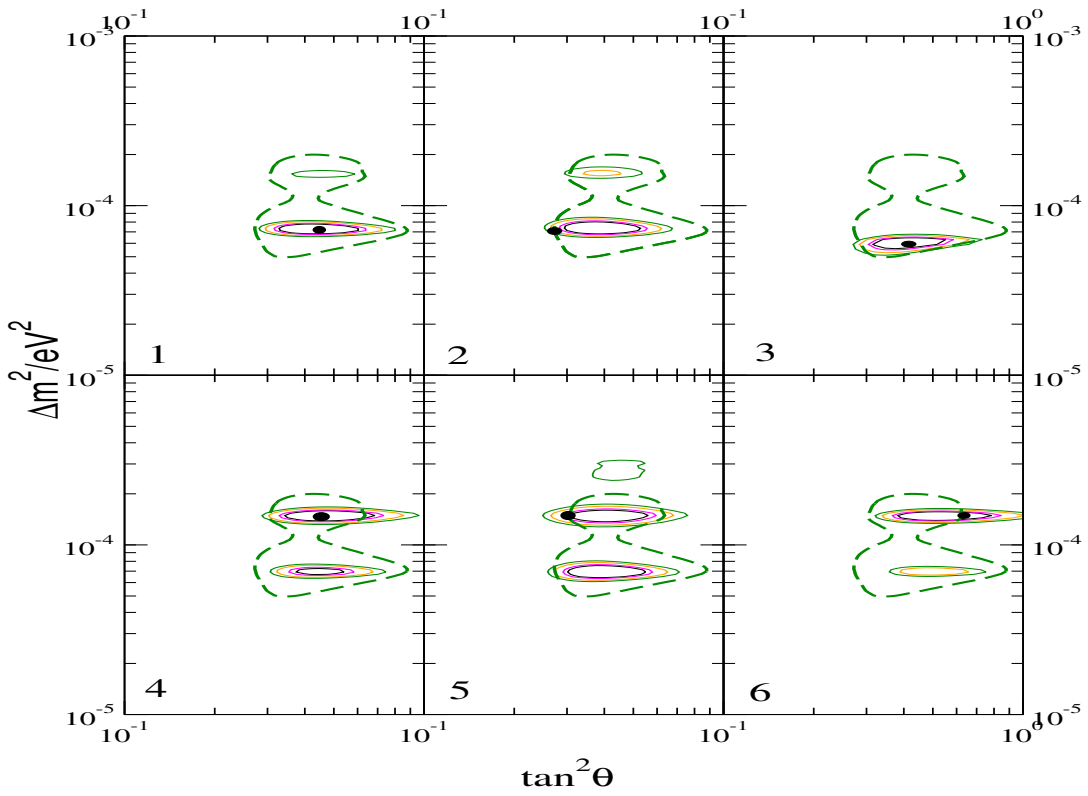


G.L.

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

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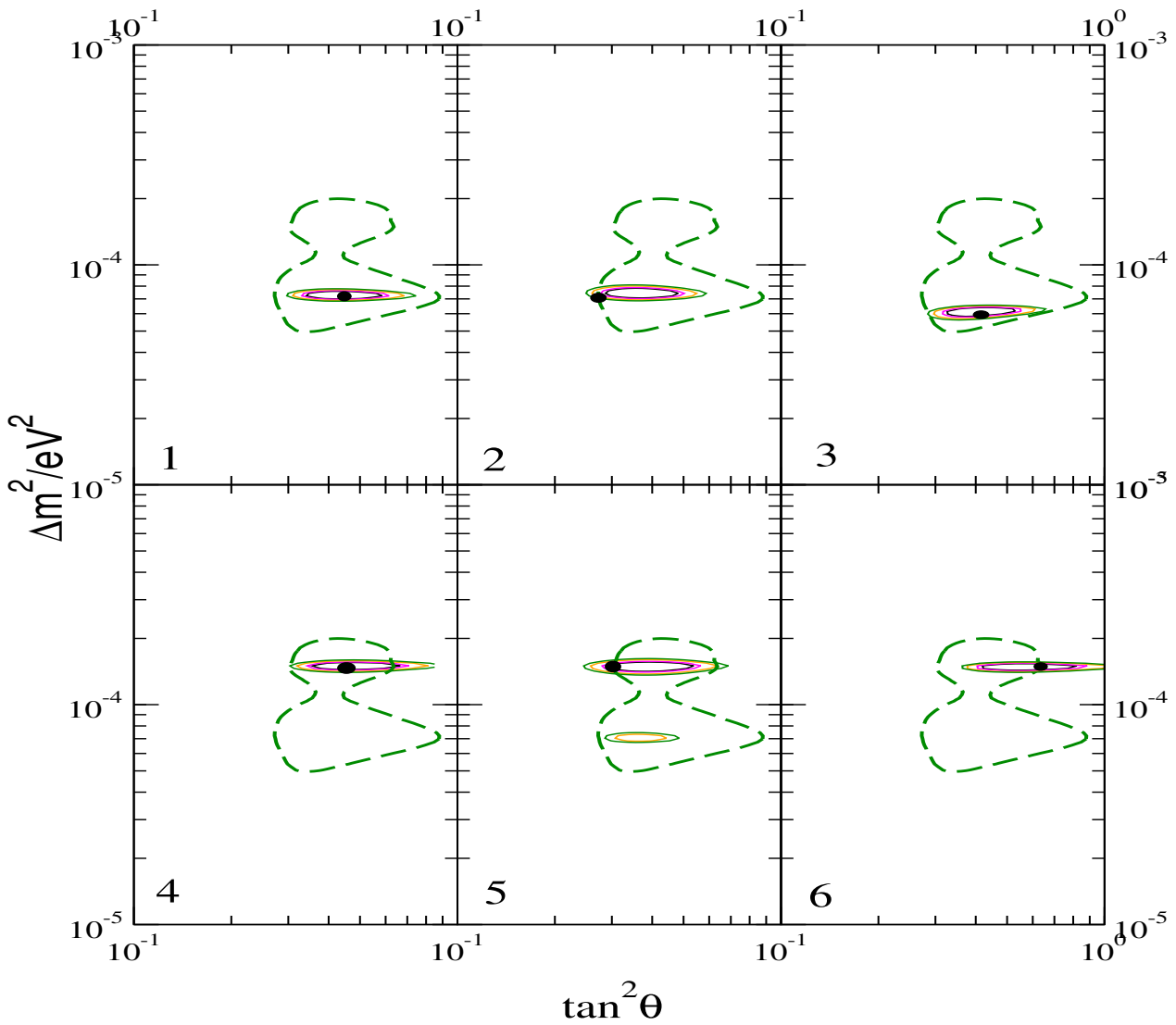
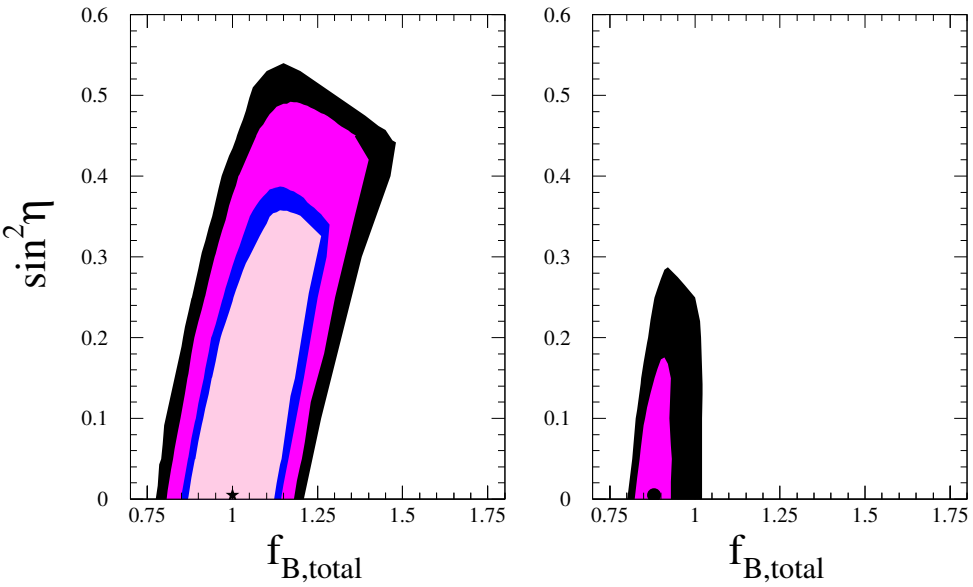
Projected Analysis: 3 kiloTon year



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

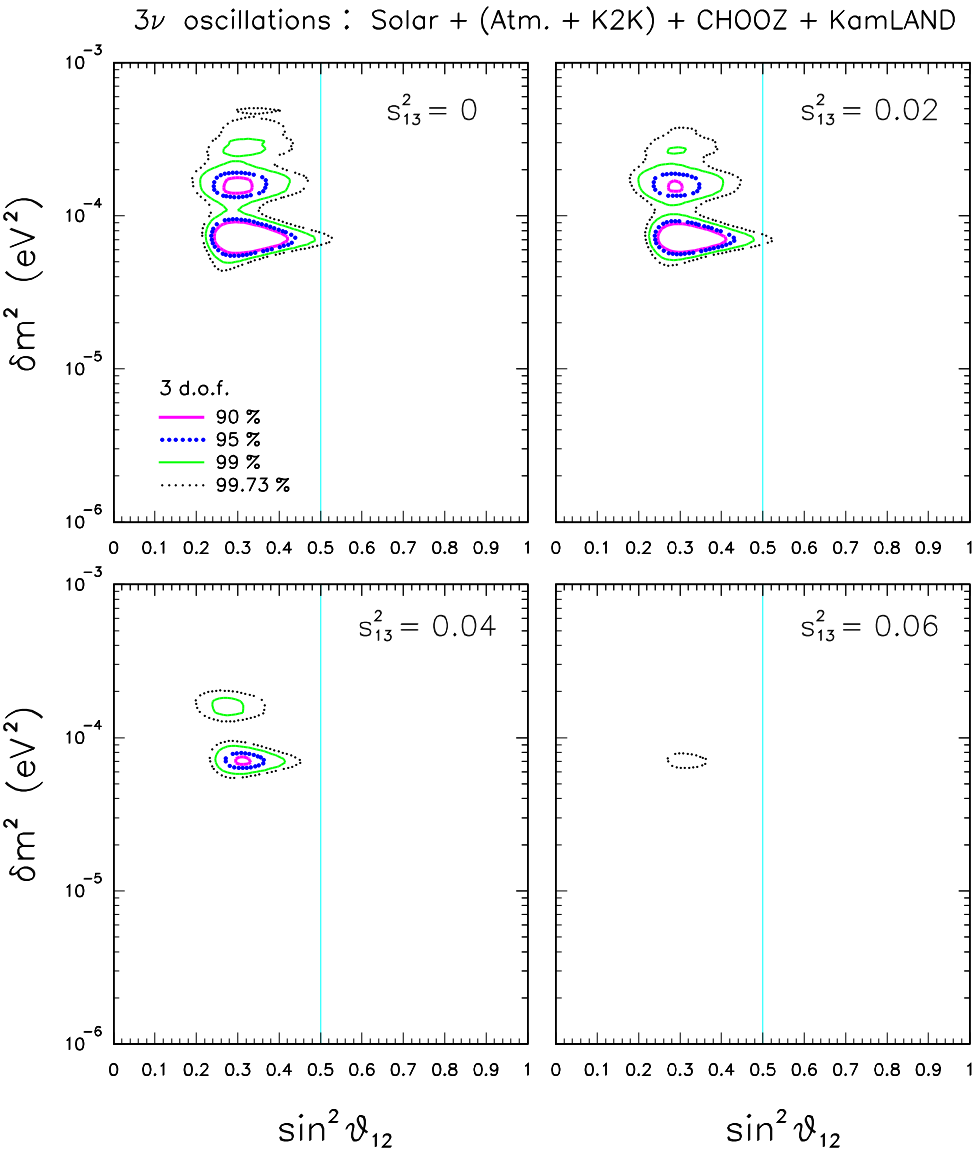
- For $\theta_{13} \neq 0$ and $\Delta m^2_{31} >> \Delta m^2_{21}$
-

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

$\rightarrow$ 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 $1\sigma(3\sigma)$.

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.

- More precise determination of neutrino oscillation parameters.
  - More statistics from KamLAND
  - Improvement in CC/NC precision from SNO

- 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.