Precision Measurement of Oscillation Parameters with Reactors

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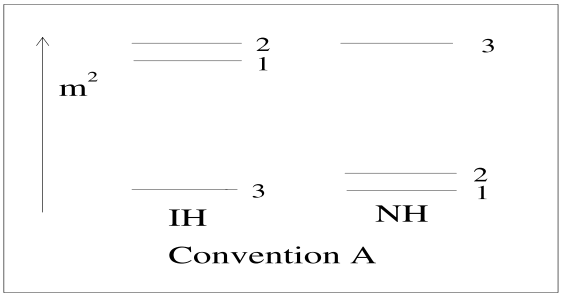
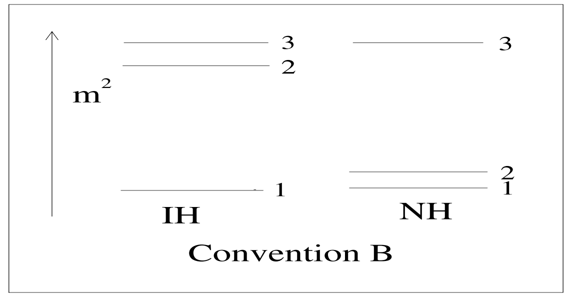
Three-Generation Survival Probability

- Two possible neutrino mass hierarchies





$$
\begin{aligned}
P_{NH}(\bar{\nu}_e \to \bar{\nu}_e) & \\
= \quad & 1 - 2\sin^2\theta\cos^2\theta\left(1-\cos\frac{\Delta m^2_{\text{atm}}\,L}{2\,E_\nu}\right) \\
- \quad & \frac{1}{2}\cos^4\theta\,\sin^2 2\theta_\odot\left(1-\cos\frac{\Delta m^2_\odot\,L}{2\,E_\nu}\right) \\
+ & 2\sin^2\theta\,\cos^2\theta\,\sin^2\theta_\odot\left(\cos\left(\frac{\Delta m^2_{\text{atm}}L}{2E_\nu}-\frac{\Delta m^2_\odot L}{2E_\nu}\right)-\cos\frac{\Delta m^2_{\text{atm}}L}{2E_\nu}\right)
\end{aligned}
$$

$$
\begin{aligned}
P_{IH}(\bar{\nu}_e \to \bar{\nu}_e) & \\
= \quad & 1 - 2\sin^2\theta\cos^2\theta\left(1-\cos\frac{\Delta m^2_{\text{atm}}\,L}{2\,E_\nu}\right) \\
- \quad & \frac{1}{2}\cos^4\theta\,\sin^2 2\theta_\odot\left(1-\cos\frac{\Delta m^2_\odot\,L}{2\,E_\nu}\right) \\
+ & 2\sin^2\theta\,\cos^2\theta\,\cos^2\theta_\odot\left(\cos\left(\frac{\Delta m^2_{\text{atm}}L}{2E_\nu}-\frac{\Delta m^2_\odot L}{2E_\nu}\right)-\cos\frac{\Delta m^2_{\text{atm}}L}{2E_\nu}\right)
\end{aligned}
$$

- Depends on 5 parameters: 4 continuous oscillation parameters $\Delta m^2_\odot$, $\sin^2\theta_\odot$, Δm^2_{atm}, $\sin^2\theta$ and the hierarchy.

- Does not depend on θ_{atm} and δ.

The Baseline

- For Reactors, $E_\nu \sim 3.6$ MeV, $L^* \equiv \frac{2\pi E_\nu}{\Delta m^2}$
- For $\Delta m^2 \equiv \Delta m^2_{\text{atm}} \sim 2.5 \times 10^{-3}$ eV^2, $L^* \equiv 1.1 - 1.7$ km

$$P_{ee} \approx 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2_{\text{atm}} L}{4E_\nu} - \cos^4\theta \sin^2 2\theta_\odot \sin^2 \frac{\Delta m^2_\odot L}{4E_\nu}$$

Short Baseline Experiment

CHOOZ, Palo Verde, Krasnoyarks....
Minakata, et al., hep-ph/0211111
Huber, et al., hep-ph/0303232

- For $\Delta m^2 \equiv \Delta m^2_\odot \sim 7.2 \times 10^{-5}$ eV^2, $L^* \equiv 50 - 70$ km

$$P_{ee} \approx 1 - \cos^4\theta \sin^2 2\theta_\odot \sin^2 \frac{\Delta m^2_\odot L}{4E_\nu} - \frac{1}{2}\sin^2 2\theta$$

Long Baseline Experiment

KamLAND, Eguchi et al.,PRL 90,021802,2003
Bandyopadhyay,S.C.,Goswami,hep-ph/0302243 (PRD)

- For $\Delta m^2 \equiv \Delta m^2_\odot \sim 1.5 \times 10^{-4}$ eV^2, $L^* \equiv 20 - 30$ km

$$\begin{aligned} P_{ee} &\approx 1 - \cos^4\theta \sin^2 2\theta_\odot \sin^2 \frac{\Delta m^2_\odot L}{4E_\nu} - \frac{1}{2}\sin^2 2\theta \sin^2 \frac{\Delta m^2_{\text{atm}} L}{4E_\nu} \\ &+ 2\sin^2\theta\cos^2\theta\sin^2\theta_\odot\left(\cos\left(\frac{\Delta m^2_{\text{atm}} L}{2E_\nu} - \frac{\Delta m^2_\odot L}{2E_\nu}\right) - \cos\frac{\Delta m^2_{\text{atm}} L}{2E_\nu}\right)\end{aligned}$$

Intermediate Baseline Experiment

Heilbronn, Schonert et al., hep-ex/0203013
Petcov and Piai,PLB 533,94,2002
S.C.,Petcov and Piai, hep-ph/0306017

Long Baseline Reactor Experiments

KamLAND

- 1 kTon Liquid Scintillator 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 $\sim$ 160 km.
- Detection process :$\bar{\nu}_e p \to e^+ n$

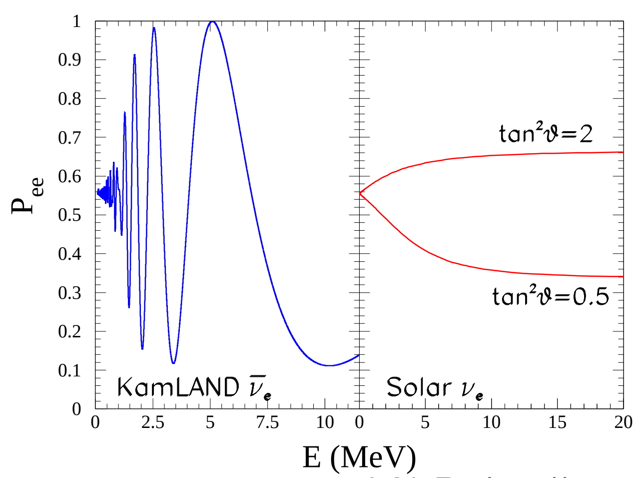
- Survival Probability

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

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

– sensitive to LMA region

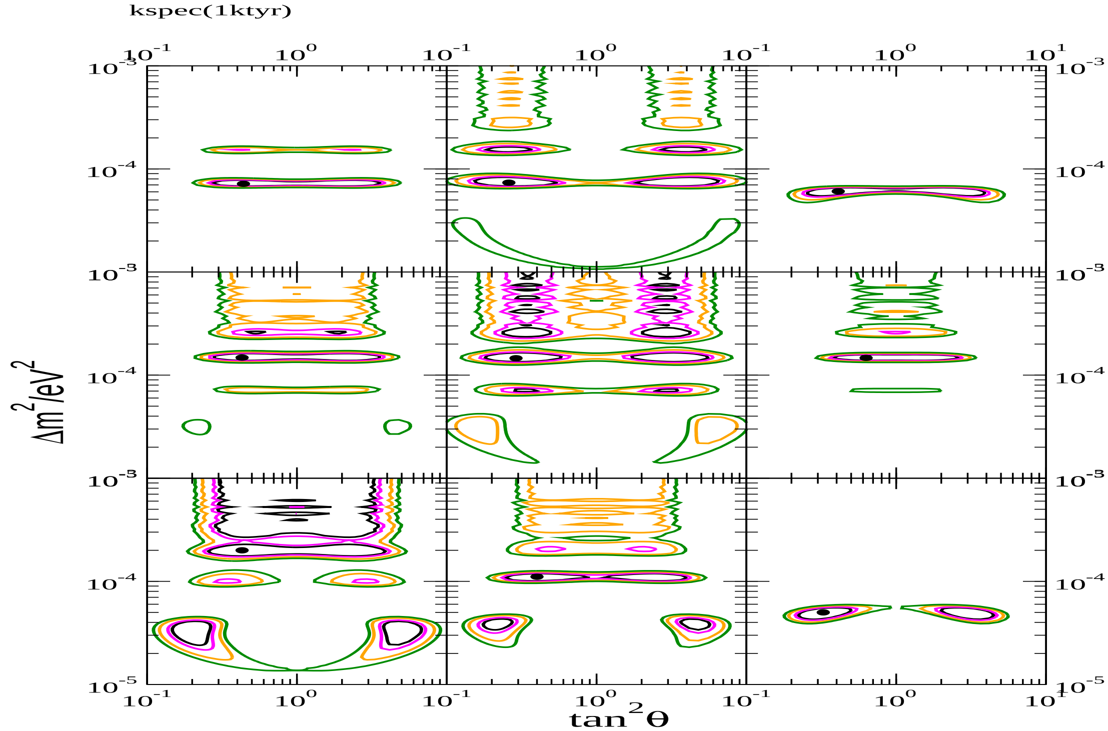
- No matter effects: $\theta \equiv = \frac{\pi}{2} - \theta$

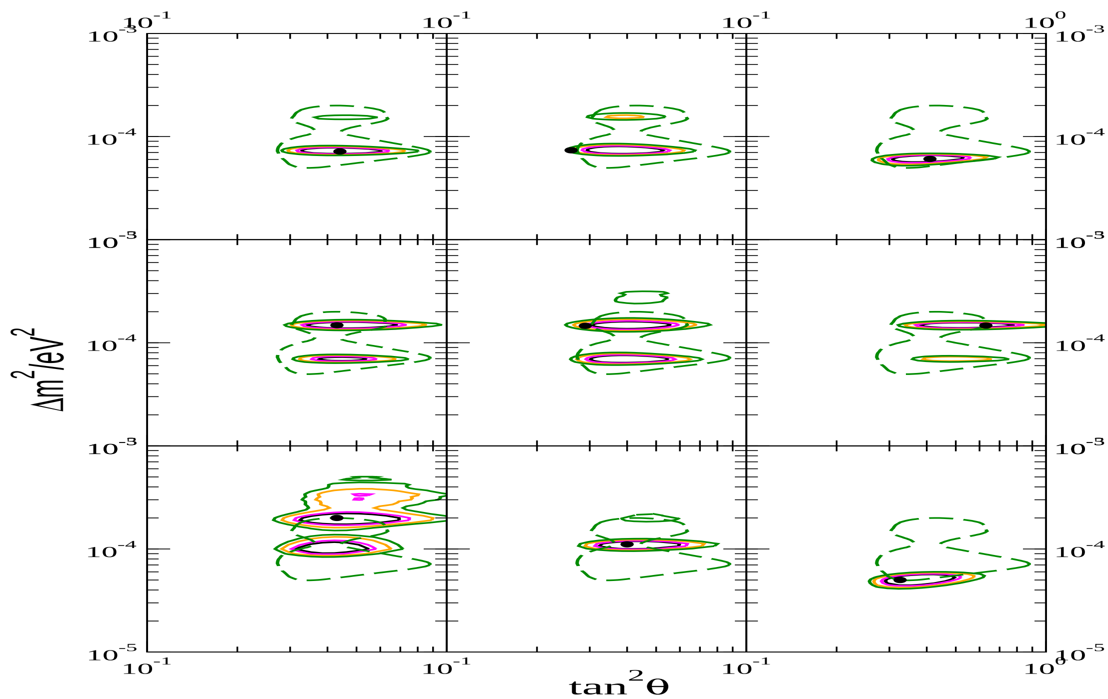


J.N.Bahcall et al.,hep-ph/0212247

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

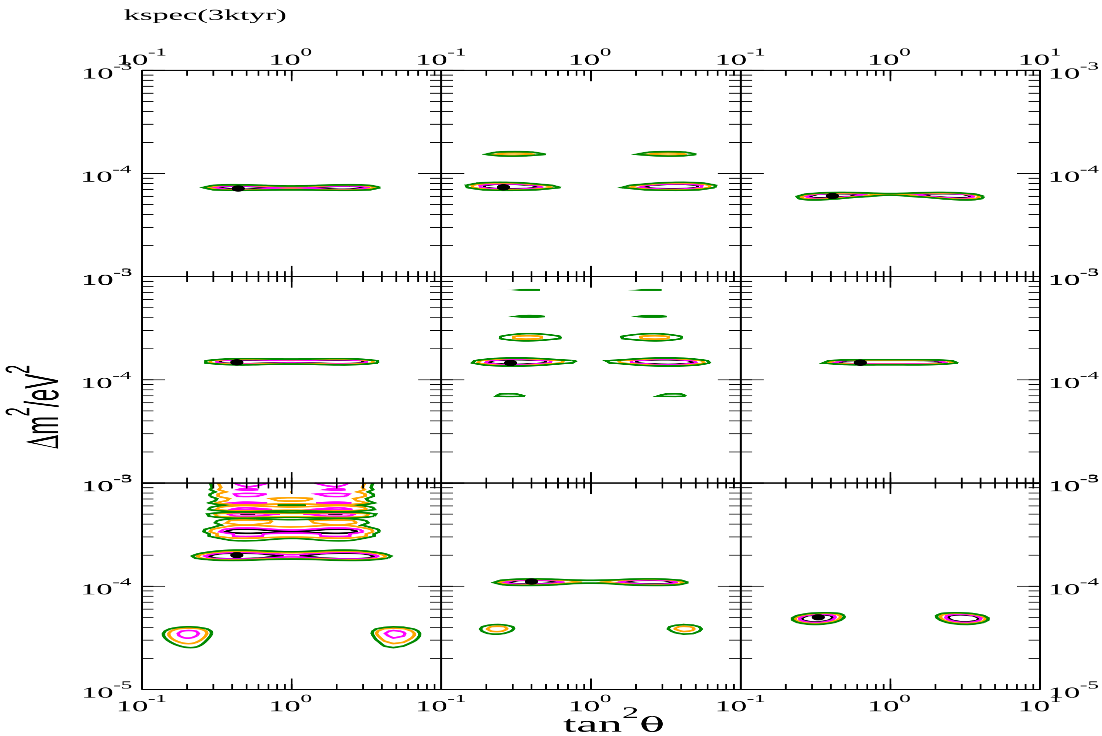
• KamLAND 1 kTy

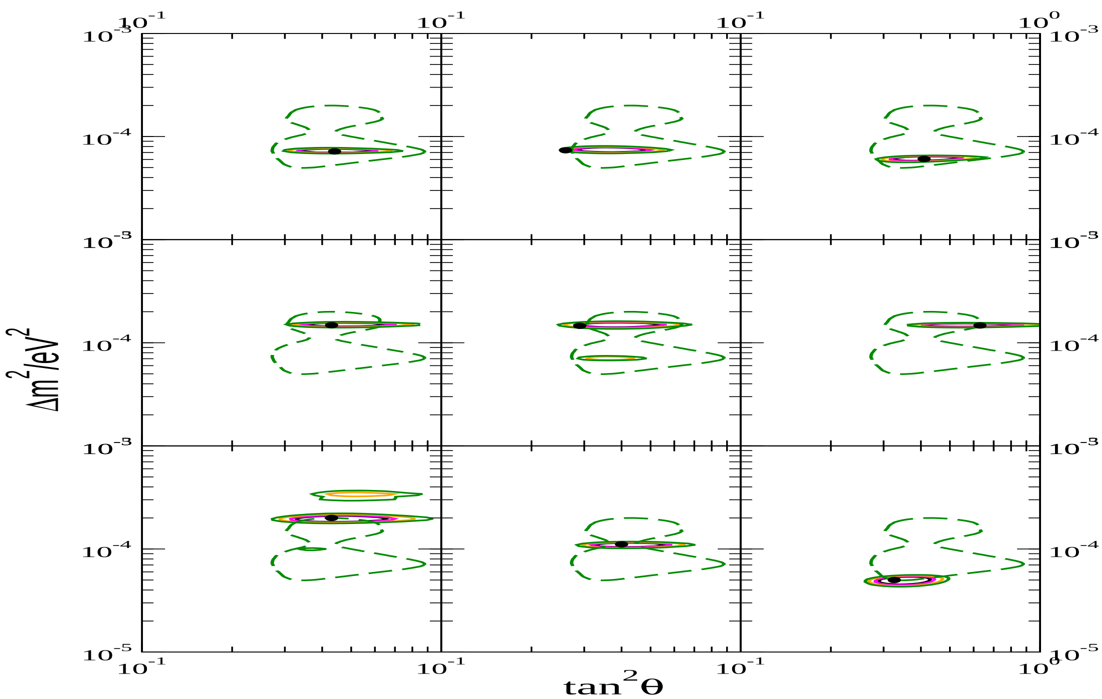




A.Bandyopadhyay et al, hep-ph/0212146

• KamLAND 3 kTy





A.Bandyopadhyay et al, hep-ph/0212146

Closer look at KamLAND sensitivity

- 5% systematic uncertainty for 1 kTy KamLAND
- 3% systematic uncertainty for 3 kTy KamLAND
- 7% total error for future SNO NC data

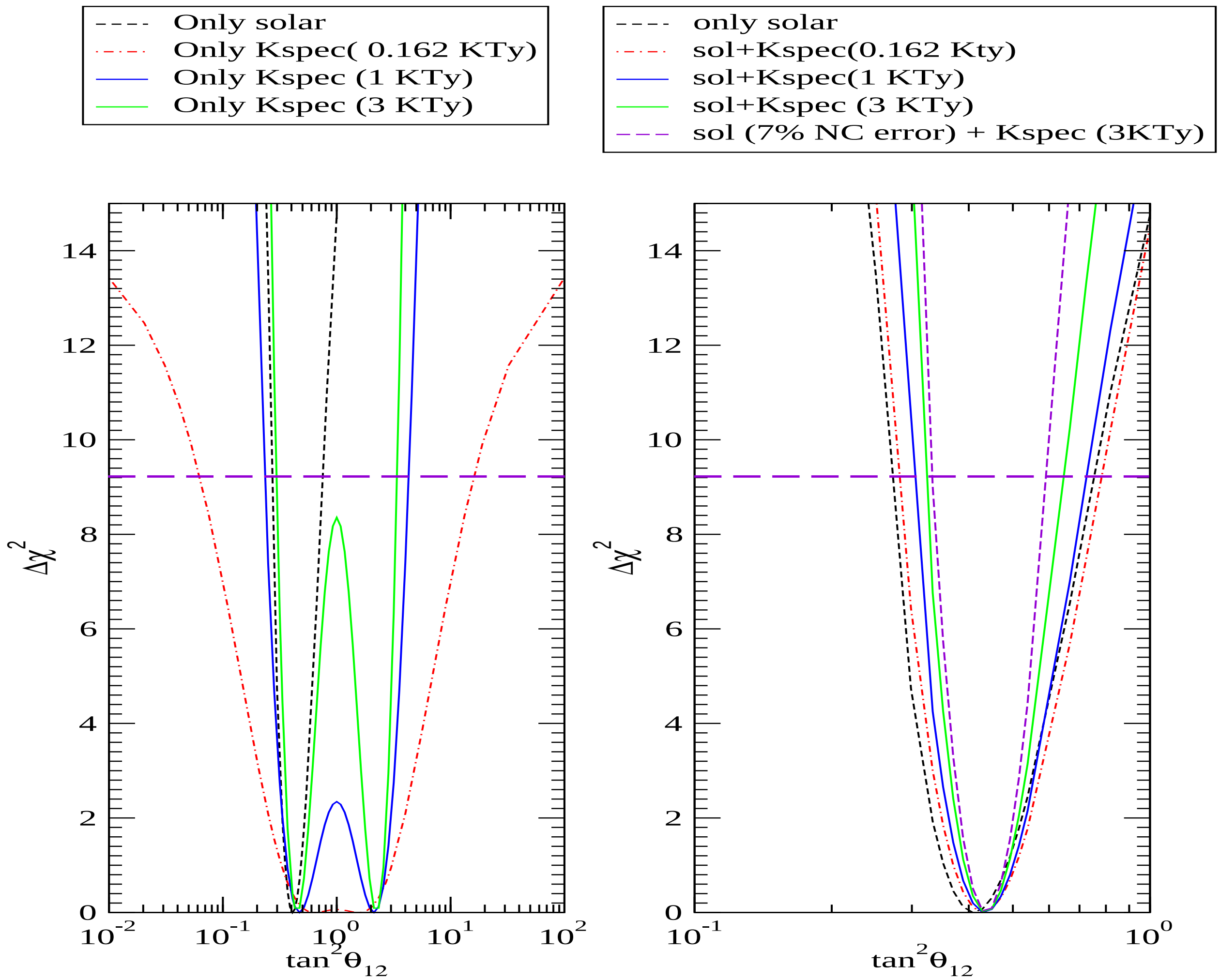
$$\text{spread} = \frac{a_{max} - a_{min}}{a_{max} + a_{min}} \times 100\ \%$$

Data set used	99% CL range of $\Delta m^2_{21} \times 10^{-5}\text{eV}^2$	99% CL spread of Δm^2_{21}	$1\ \sigma$ range of $\tan^2\theta_{12}$	2σ range of $\tan^2\theta_{12}$	99% CL range of $\tan^2\theta_{12}$	$1\ \sigma$ spread in $\tan^2\theta_{12}$	$2\ \sigma$ spread in $\tan^2\theta_{12}$	99% CL spread in $\tan^2\theta_{12}$
only sol	3.2 - 24.0	76%	$.33 - .53$	$.29 - .66$	$.27 - .75$	23%	39%	47%
sol+162 Ty	5.3 - 9.9	30%	$.34 - .55$	$.30 - .68$	$.28 - .78$	23%	39%	47%
sol+1 kTy	6.7 - 8.0	9%	$.36 - .54$	$.33 - .65$	$.30 - .72$	20%	33%	41%
sol+3 kTy	6.8 - 7.7	6%	$.37 - .52$	$.34 - .59$	$.33 - .65$	17%	27%	33%
sol(7%)+3 kTy	6.8 - 7.7	6%	$.38 - .50$	$.35 - .56$	$.33 - .60$	14%	23%	29%

Table 1: The range of parameter values allowed and the corresponding spread. For the current observed solar+KamLAND analysis we show the ranges and the spread only in the low-LMA region. For the 1 kTy and 3 kTy ranges we have simulated the spectrum at the current low-LMA best-fit. We assume 5% systematic error for 1 kTy KamLAND spectrum and 3% systematic error for 3 kTy KamLAND spectrum. The last row of the Table corresponds to a combination of the 3 kTy KamLAND data and the global solar neutrino data where the SNO NC error has been reduced to only 7%.

- Tremendous sensitivity to Δm^2_{21}
- However sensitivity to θ_{12} does not look good

A.Bandyopadhyay, S.C., S.Goswami, hep-ph/0302243



- KamLAND has a θ_{12} and $\pi/2 - \theta_{12}$ ambiguity

- Even with 3 kTy statistics, KamLAND fails to constrain θ_{12} better than the current solar neutrino experiments

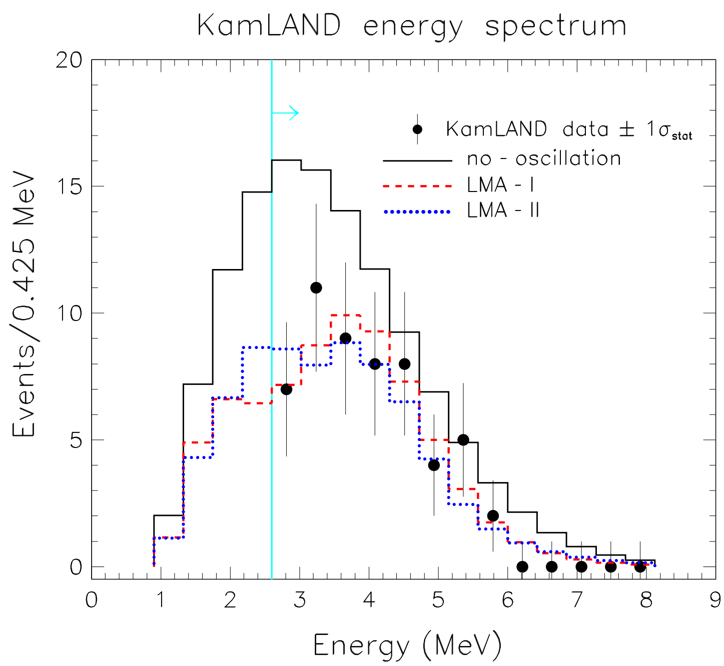
- Even with 3 kTy KamLAND can rule out maximal mixing only at the 2σ level

A.Bandyopadhyay, S.C., S.Goswami, hep-ph/0302243

Still closer look at KamLAND

- The survival probability at KamLAND

$$P_{ee} = 1 - \sum_i \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L_i}{4E}\right)$$



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

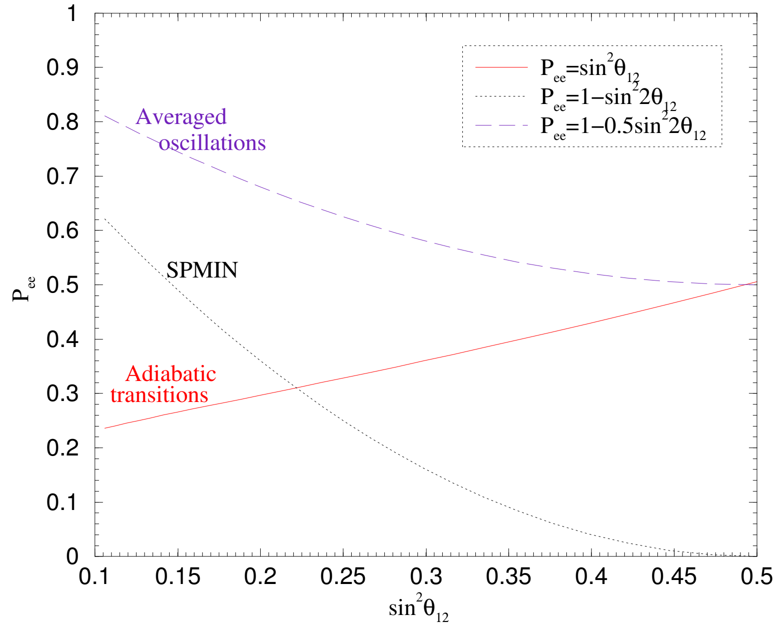
- KamLAND has a peak in its survival probability

$$\Downarrow$$

$$\sin^2\left(\frac{\Delta m^2_{21} L_i}{4E}\right) \sim 0$$

- The θ_{12} term gets smothered!

Measurement of $\sin^2\theta_\odot$



For ^8B neutrinos undergoing matter enhanced resonance

$$
\begin{aligned}
P_{ee}^{AD} &= \frac{1}{2} + \frac{1}{2}(1 - P_J)\cos 2\theta_m \cos 2\theta_\odot \\
&\approx \sin^2\theta_\odot \quad \text{LMA(AD)}
\end{aligned}
$$

For pp neutrinos do not encounter resonance,

$$P_{ee}^{AV} = 1 - \frac{1}{2}\sin^2 2\theta_\odot \quad \text{Averaged Oscillations(AV)}$$

For VO such that $\sin^2(\Delta m^2_\odot L/E) = 1$

$$P_{ee}^{SPMIN} = 1 - \sin^2 2\theta_\odot \text{Survival Probability MINima(SPMIN)}$$

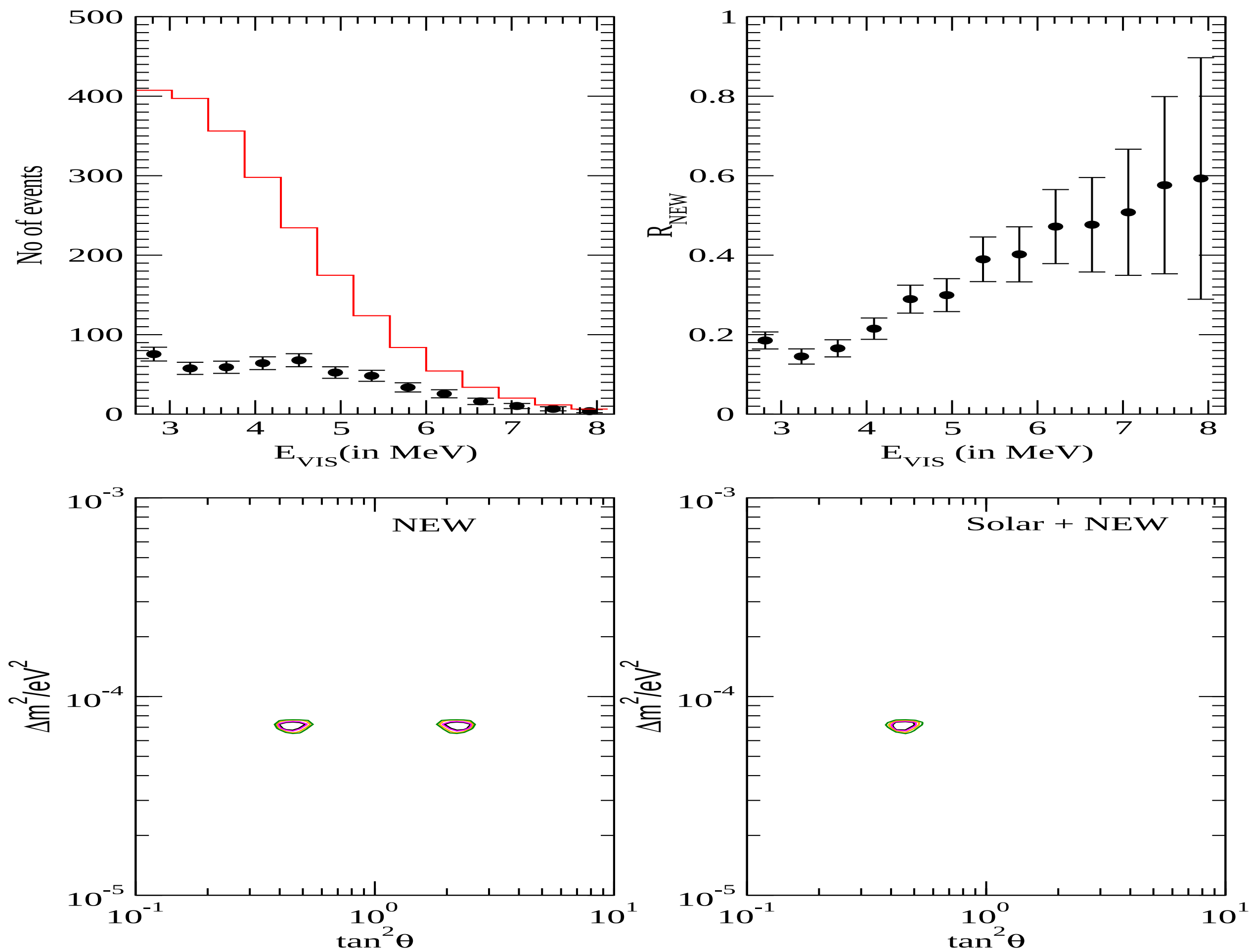
$(\Delta\sin^2\theta_\odot)_{AD} \sim \Delta P_{ee}$; good if $\sin^2\theta_\odot \sim 0.5$

$(\Delta\sin^2\theta_\odot)_{AV} \sim \frac{\Delta P_{ee}}{-2\cos 2\theta_\odot}$; better if $\cos 2\theta \gtrsim 0.5 (\sin^2\theta_\odot \lesssim 0.25)$

$(\Delta\sin^2\theta_\odot)_{spmin} \sim \frac{\Delta P_{ee}}{-4\cos 2\theta_\odot}$; best if $\cos 2\theta_\odot \gtrsim 0.25 (\sin^2\theta_\odot \lesssim 0.375)$

- Best-Fit: $\sin^2\theta_\odot = 0.3$, Range: $0.21 < \sin^2\theta_\odot < 0.47$

New Reactor Experiment for $\theta_\odot$



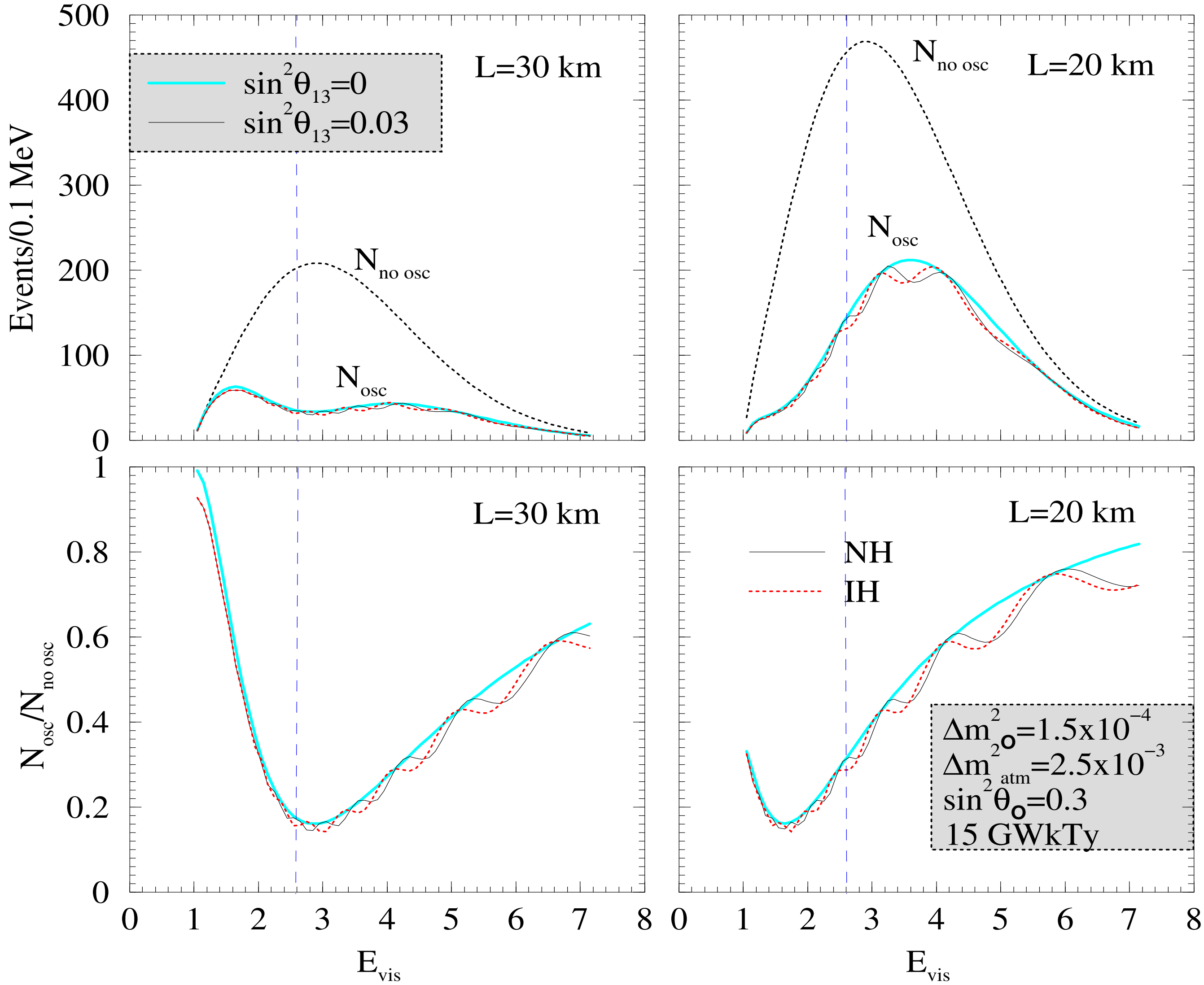
- Take a powerful reactor source: Kashiwazaki
- Take a baseline of $L \sim 70$ km
- This corresponds to an SPMIN at $\sim 3-4$ MeV
- Reduce systematic uncertainty to 2%
- Spread in $\tan^2\theta_\odot$($\sin^2\theta_\odot$) at 99% 14%(9.6%)!!

A.Bandyopadhyay, S.C., S.Goswami, hep-ph/0302243

- Check out 70 km baseline sites along the Rhone Valley

C.Bouchiat, hep-ph/0304253

Intermediate Baseline Reactor Experiments

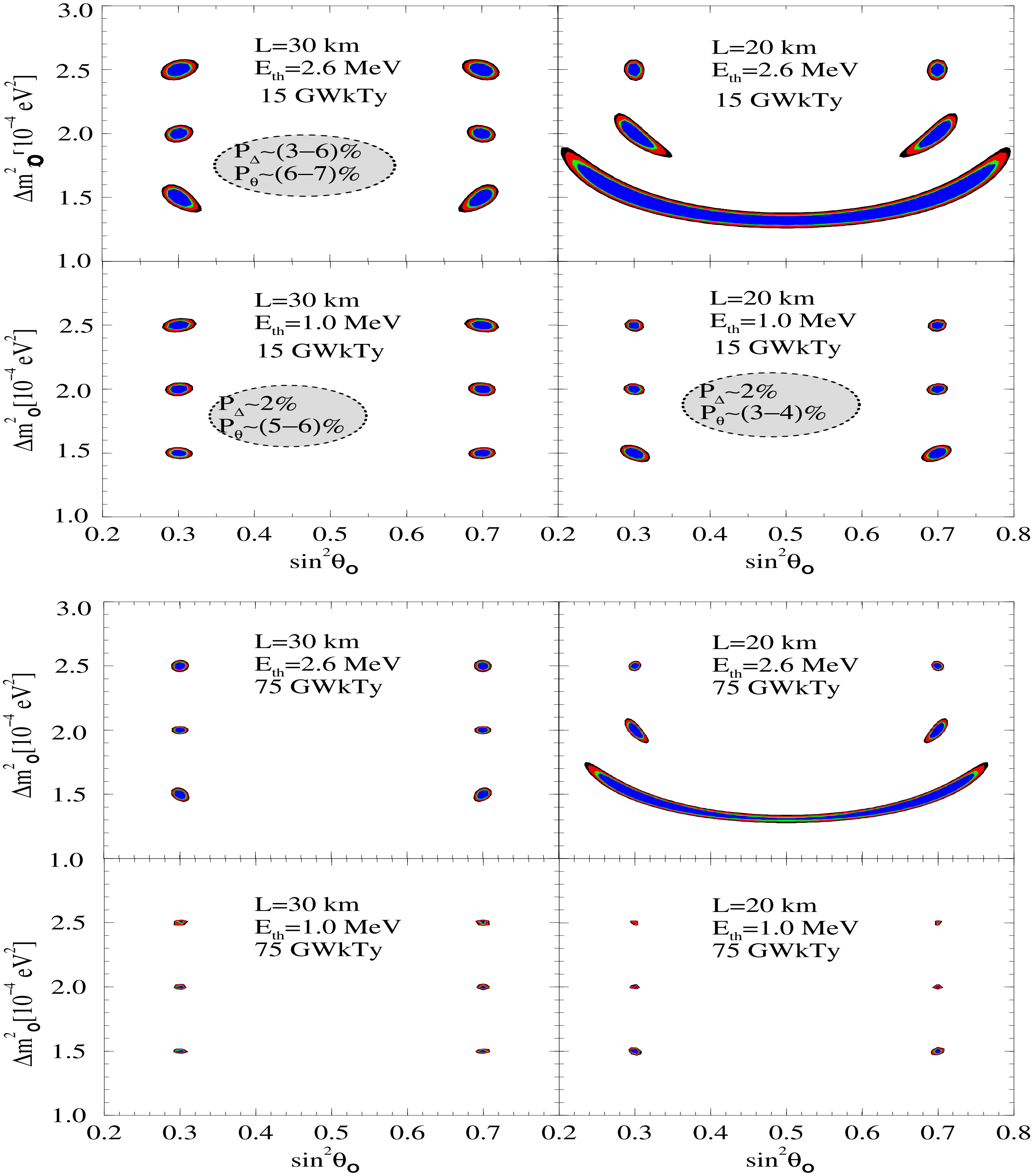


- Has the potential to measure all the 5 parameters if:
  - ⋆⋆ $\Delta m^2_{\odot}$ is in high-LMA
  - ⋆⋆ E_{th} and L allow $\Delta m^2_{\odot}$ driven SPMIN
  - ⋆⋆ Energy resolution of the detector is good enough
  - ⋆⋆⋆ Statistics are high enough
  - ⋆⋆⋆ Systematics are low enough

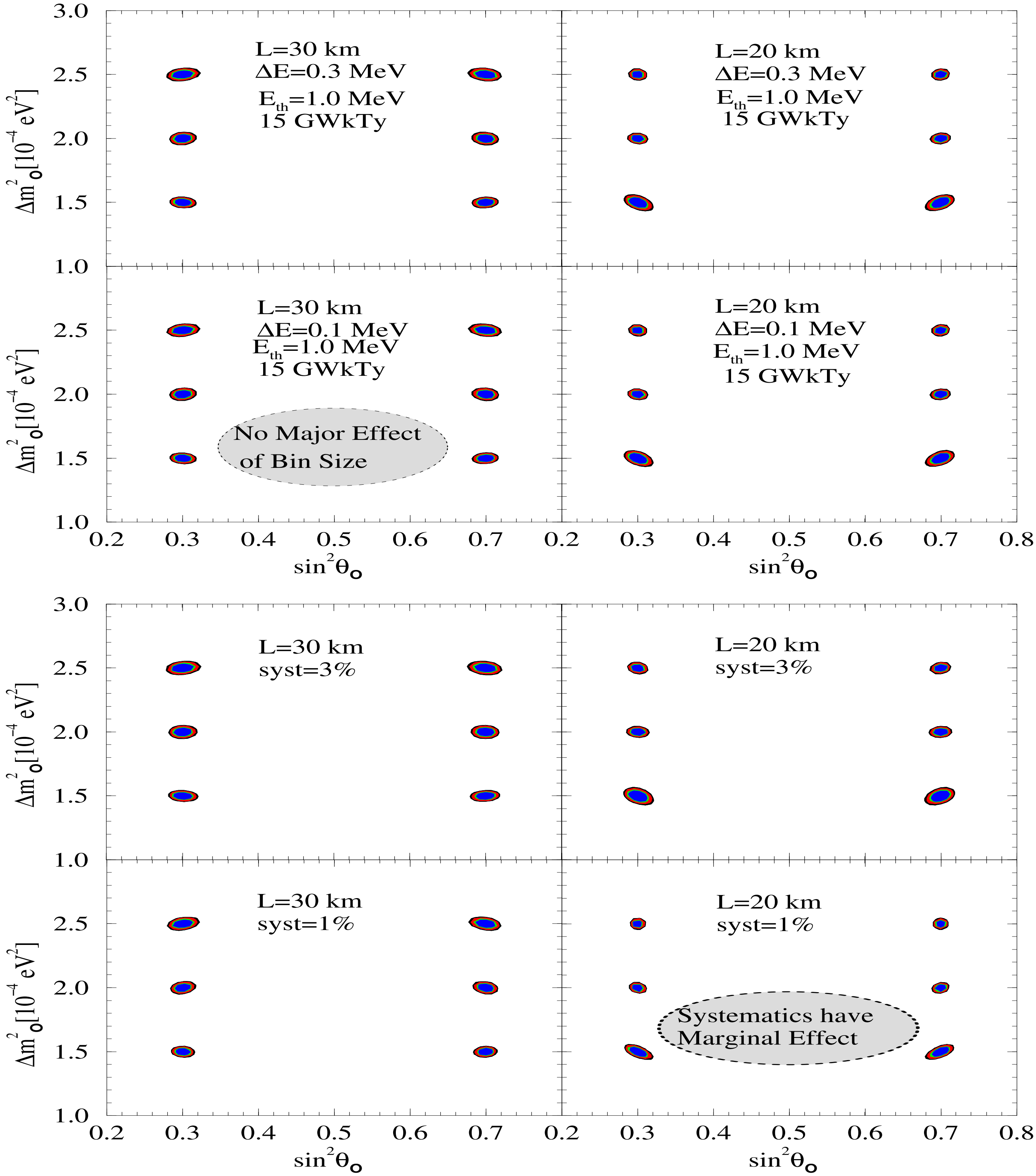
($\Delta m^2_{\odot}$, $\sin^2\theta_{\odot}$, $\sin^2\theta$, Δm^2_{atm}, Hierarchy)

S.C., S.T.Petcov, M.Piai, hep-ph/0306017

Precision Measurement of $\Delta m^2_\odot$ and $\sin^2\theta_\odot$



Precision Measurement of $\Delta m^2_\odot$ and $\sin^2\theta_\odot$



Effect of $\sin^2\theta$ on Solar Parameters

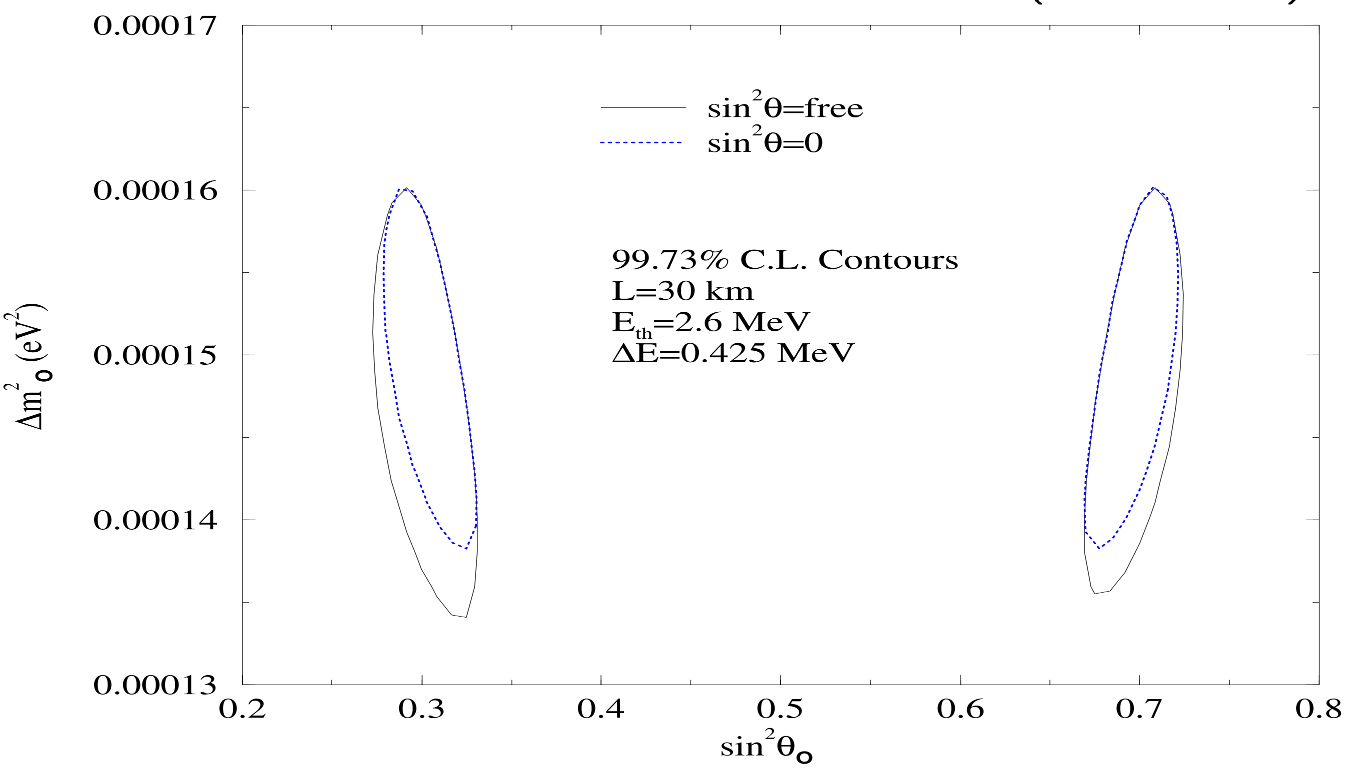
$$P_{ee} \approx \cos^4\theta \left(1 - \sin^2 2\theta_\odot \sin^2 \frac{\Delta m^2_\odot L}{4\,E_\nu}\right)$$

- The factor $\cos^4\theta$ brings a $\sim 10\%$ effect in P_{ee}

$$\delta(\sin^2 2\theta_\odot) \approx \frac{2\Delta P_{ee}\sin^2\theta}{\sin^2\frac{\Delta m^2_\odot L}{4\,E_\nu}} + 2\frac{(1-\sin^2 2\theta_\odot \sin^2\frac{\Delta m^2_\odot L}{4E_\nu})\Delta(\sin^2\theta)}{\sin^2\frac{\Delta m^2_\odot L}{4\,E_\nu}}$$

$\Downarrow$ $\qquad\qquad$ $\Downarrow$

$\lesssim 0.01$ $\qquad\qquad$ ~ 0.017 (for SPMIN)

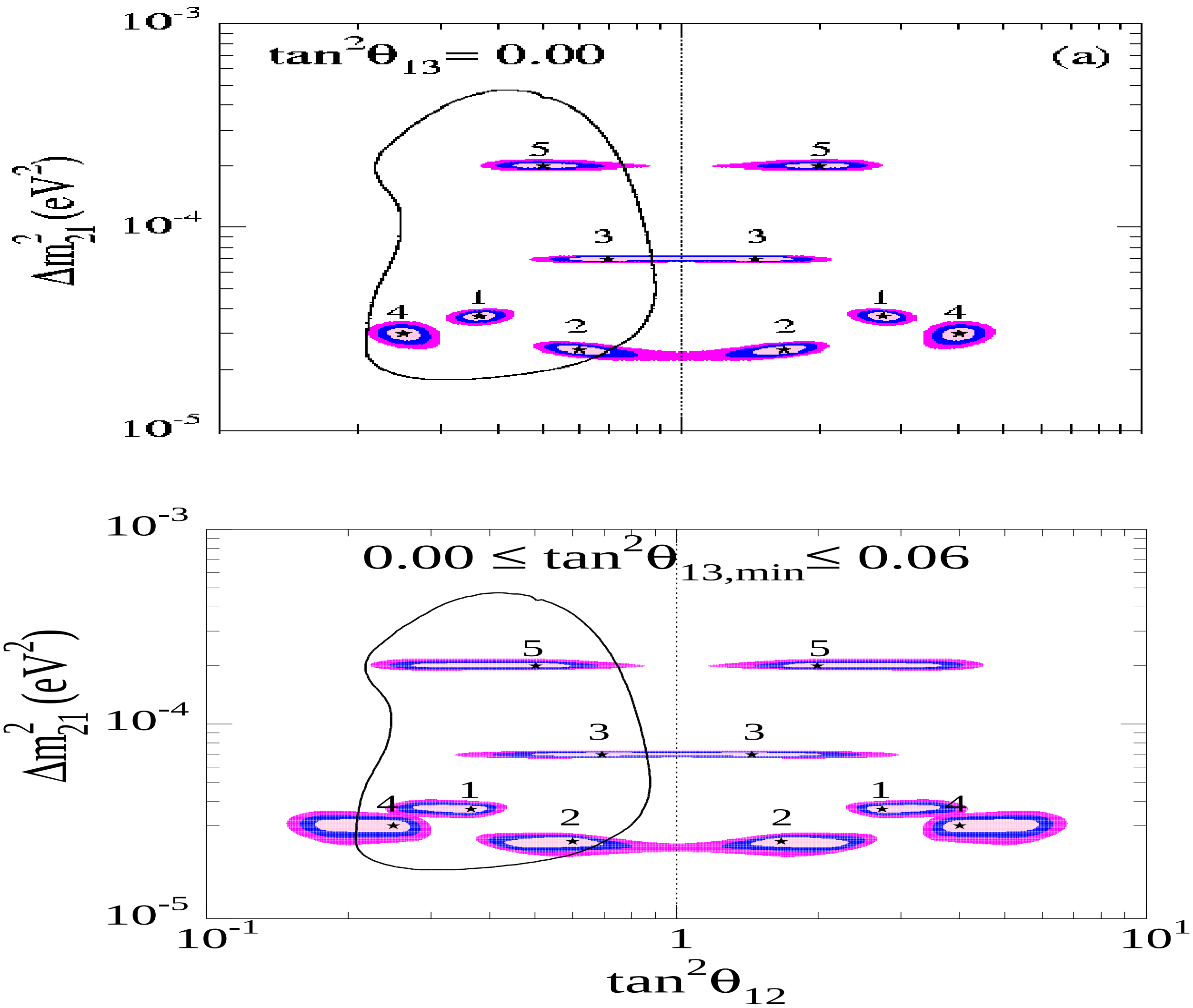


- Effect is very small on the $\sin^2 2\theta_\odot$ precision: $\lesssim 2-3\%$

Effect of $\sin^2\theta$ on Solar Parameters

KamLAND

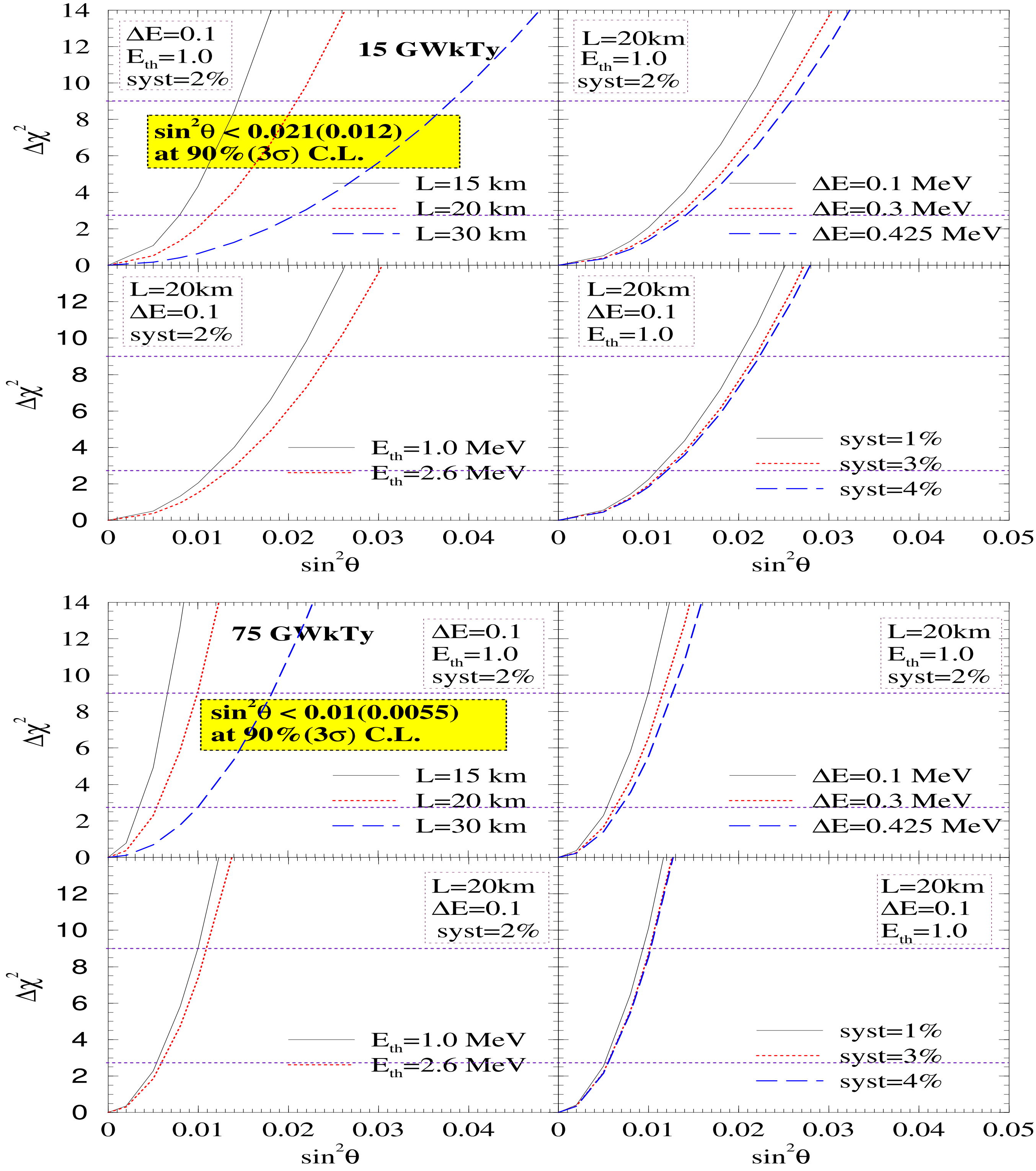
$$\delta(\sin^2 2\theta_\odot) \approx \frac{2\Delta P_{ee}\sin^2\theta}{\sin^2\frac{\Delta m^2_\odot L}{4E_\nu}} + 2\frac{(1-\sin^2 2\theta_\odot \sin^2\frac{\Delta m^2_\odot L}{4E_\nu})\Delta(\sin^2\theta)}{\sin^2\frac{\Delta m^2_\odot L}{4E_\nu}}$$



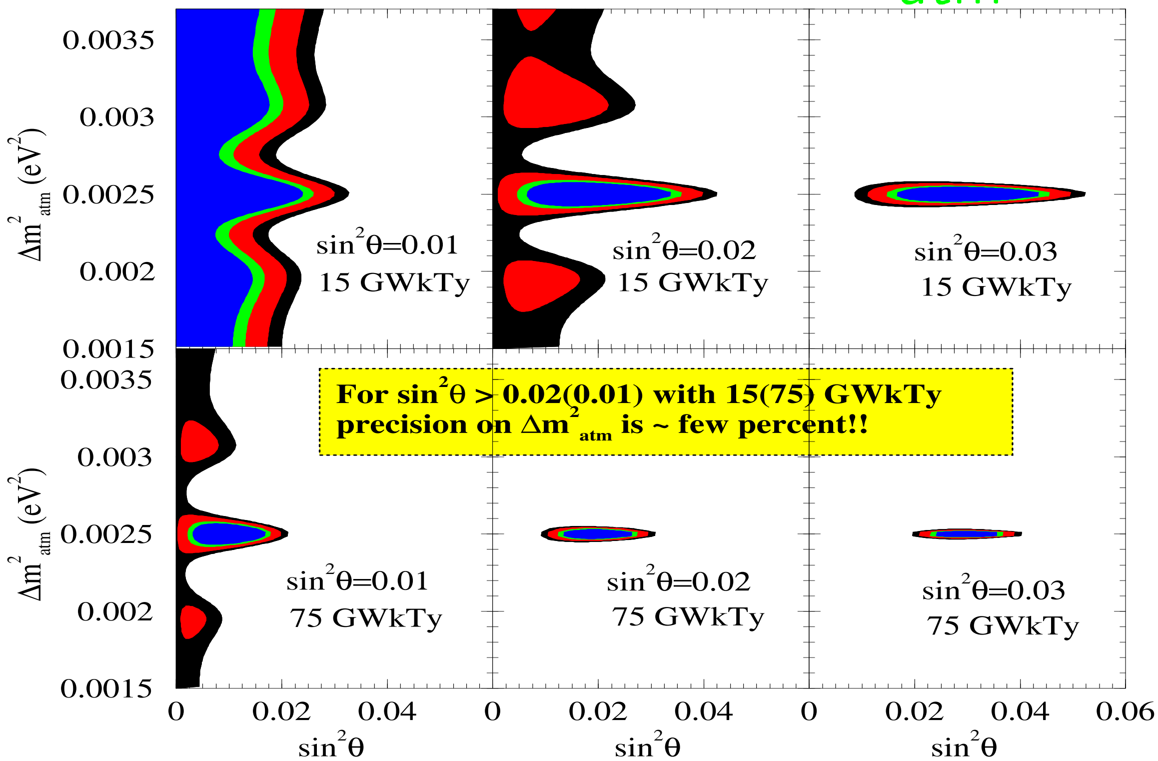
M.C.Gonzalez-Garcia,C.Pena-Garay, hep-ph/0111432

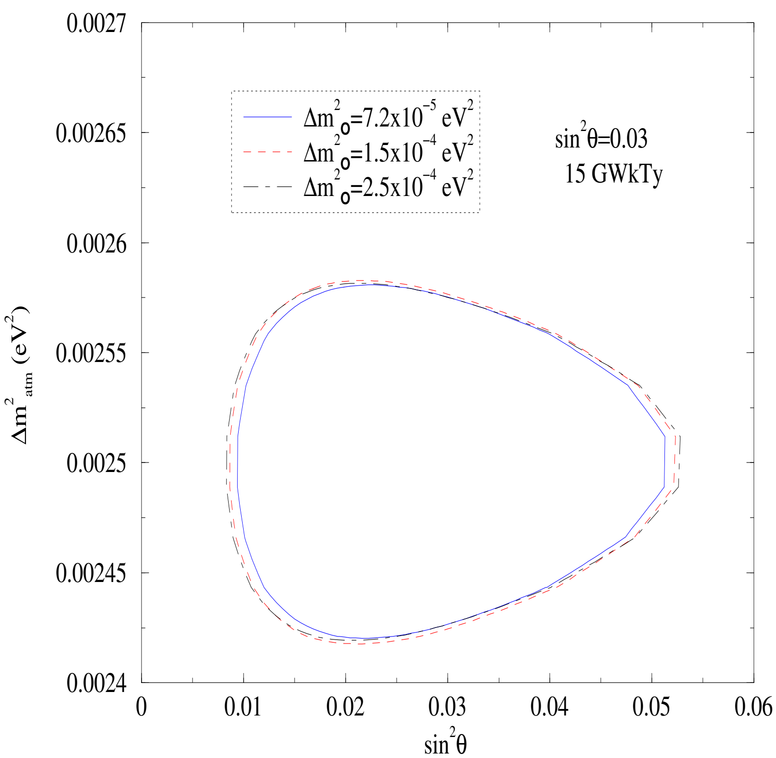
- KamLAND has a problem with $\theta_\odot$ here as well
- Experiments sensitive to SPMIN are required

Limit on $\sin^2\theta$



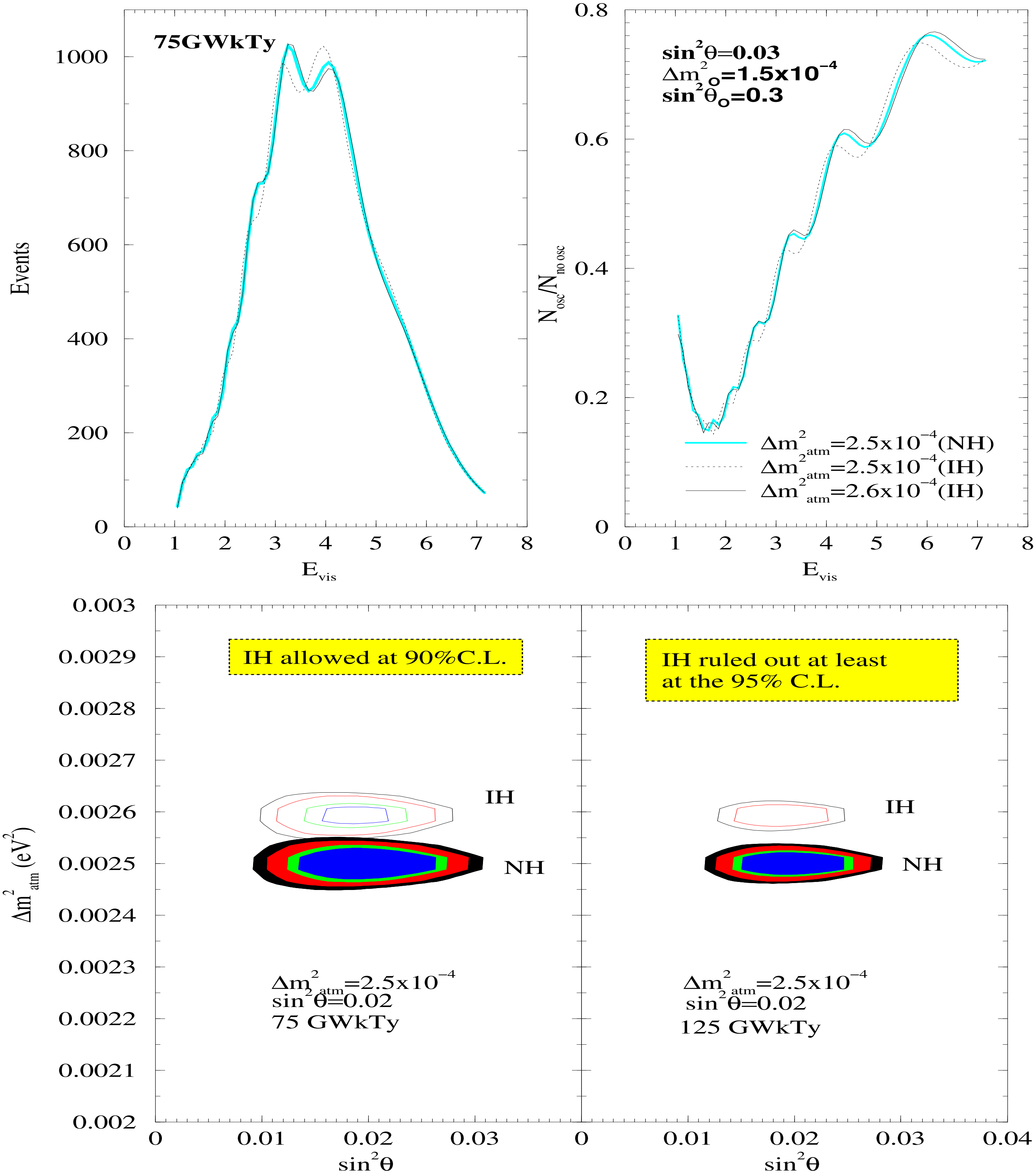
Precision Measurement of Δm^2_{atm} & $\sin^2\theta$





- $\sin^2\theta \Rightarrow$ large
- Statistics $\Rightarrow$ large
- $\Delta m^2_{\odot} \Rightarrow$ any
- $\Delta E \Rightarrow$ small
- Possible for low-LMA
- high-LMA $\Rightarrow$ hierarchy

Determination of the Mass Hierarchy



Closer look at hierarchy dependence

- NH "data" $\Rightarrow \Delta m^2_{\rm atm}$
- IH "fits" this "data" with $\Rightarrow \Delta m^2_{\rm atm} + \Delta m^2$

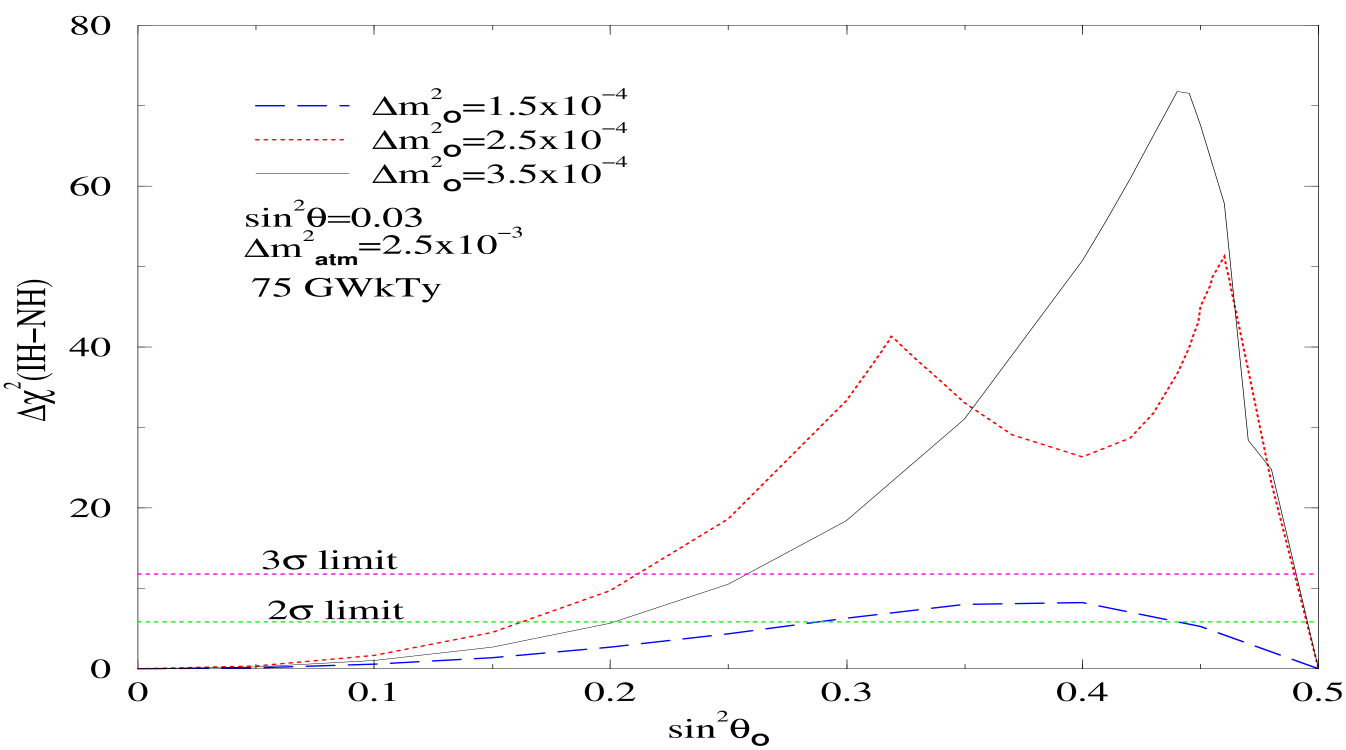
$$P_{IH} - P_{NH} \approx 4\sin^2\theta\cos^2\theta\Big[-\sin\frac{\Delta m^2_{atm}L}{2E}\sin\frac{\Delta m^2 L}{4E} + \cos 2\theta_\odot \sin\frac{\Delta m^2_{atm}L}{2E}\sin\frac{\Delta m^2_\odot L}{4E}\Big]$$

$$\Downarrow$$

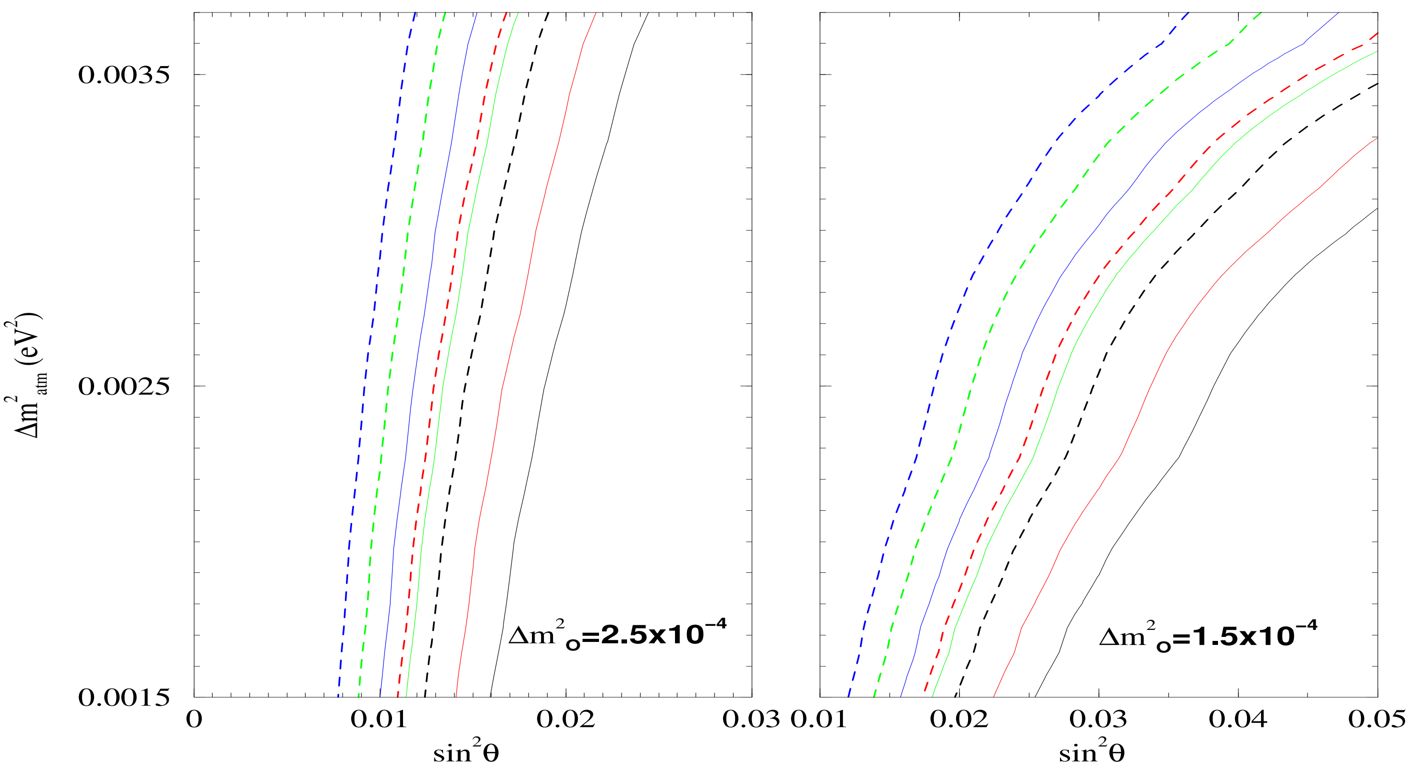
$$P_{IH} - P_{NH} = 0, \text{ when } \sin\frac{\Delta m^2 L}{4E} = \cos 2\theta_\odot \sin\frac{\Delta m^2_\odot L}{4E}$$

$$\Downarrow$$

- $\Delta m^2 \le \Delta m^2_\odot$
- Satisfied identically only for $\cos 2\theta_\odot = 0, 1$



Determination of the Mass Hierarchy



$\boxed{\text{Hierarchy determination certainly possible}}$

$\Downarrow$

With a single intermediate baseline detector? YES

But more easily with the intermediate baseline reactor experiment + precise information on $\Delta m^2_{\rm atm}$ from Superbeam experiments

Conclusions

• Reactor neutrino experiments have huge potential for precision measurement of oscillation parameters

• Baseline is crucial to identify which parameters would be best determined $\Rightarrow$ SPMIN is important

• The long baseline KamLAND experiment can measure $\Delta m^2_\odot$ with very high accuracy $\Rightarrow$ SPMAX

• However the sensitivity of KamLAND to $\sin^2\theta_\odot$ is not good

• If low-LMA is true, then a 70 km baseline reactor experiment can measure $\sin^2\theta_\odot$ down to $\sim$ 10% accuracy

• Short baseline experiments like CHOOZ/Palo Verde but with one reactor two detector technique can measure $\sin^2\theta$ to a very high accuracy (talks by O.Yasuda and P.Huber)

• The Intermediate baseline reactor experiment with $L \sim 20 - 30$ km can measure $\Delta m^2_\odot$ and $\sin^2\theta_\odot$ to a few percent accuracy if the high-LMA is the true solution.

• It can also improve the limit on $\sin^2\theta$

• If $\sin^2\theta$ is large, under favorable experimental conditions it can put very precise limits on the value of $\Delta m^2_{\rm atm}$

• Finally under ideal conditions and/or input on $\Delta m^2_{\rm atm}$ from the superbeam experiments, it can lead to some insight on the type of Neutrino Mass Hierarchy