Current limits on Neutrino Masses and mixings

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Physics with Atmospheric Neutrinos and Neutrinos from Muon Storage Rings

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Plan of Talk

- The Observational Evidence
- Current status of the neutrino oscillation parameters
  - Solar Neutrinos
  - Reactor Neutrinos
  - Atmospheric Neutrinos
  - Accelerator Neutrinos
- Accommodating LSND
- Constraints on Absolute Masses
- Summary
- Conclusions and Outlook

ν Oscillation: experimental evidences . . .

- Atmospheric Neutrino data from SuperKamiokande
- Solar Neutrino Data from Homestake,SAGE, Gallex, GNO, Kamiokande, SuperKamiokande, SNO (Phase-I,Phase-II)
- Data from Long baseline accelerator based experiment K2K
- Long baseline reactor experiment KamLAND
- Accelerator based oscillation experiment LSND

  –not confirmed by Karmen

  —Miniboone will provide independent check

Parameters of Neutrino Mass Matrix

- Assume three neutrino flavours
- 9 unknown parameters in the light neutrino mass matrix
  - 3 masses, m_1, m_2 and m_3
  - 3 mixing angles
  - 1 Dirac CP phase
  - 2 Majorana CP phases
- Oscillation experiments sensitive to
  - 2 mass squared differences ($\Delta m^2{}_{21}$, $\Delta m^2{}_{31} \approx \Delta m^2{}_{32}$)
  - 3 mixing angles (θ_{12}, θ_{13},θ_{23})
  - 1 Dirac CP phase
- Majorana CP phases observable only in $\Delta L = 2$ processes
- Absolute neutrino mass scale comes from
  - Tritium beta decay
  - Neutrino-less double beta decay
  - Cosmology

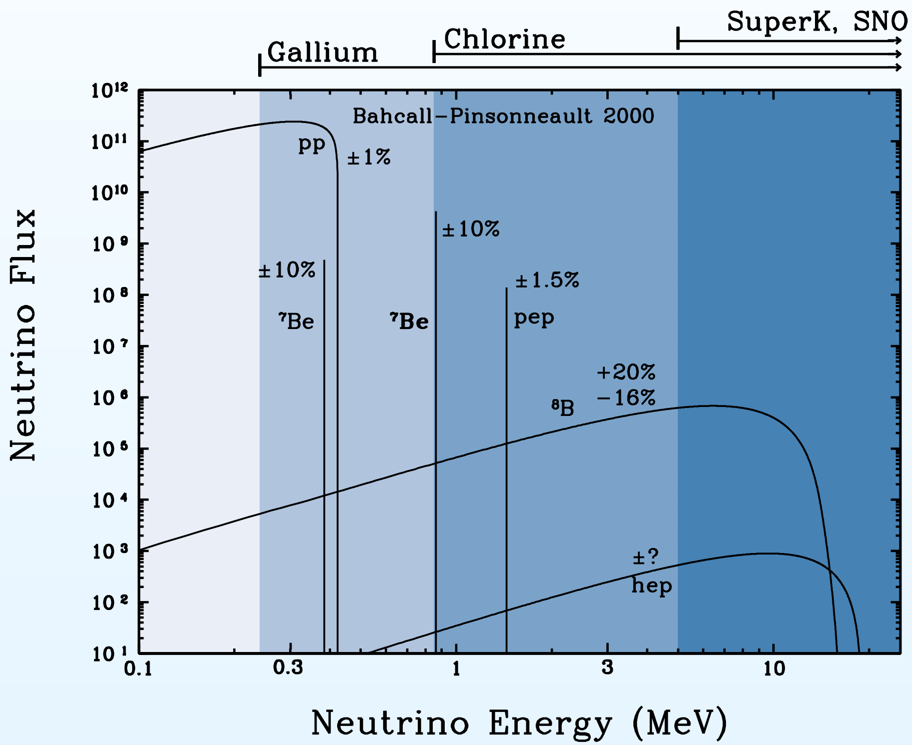
Solar Neutrinos

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

- Two main cycles of nuclear reactions

  pp chain: responsible for 98.5% of the energy

  CNO cycle: responsible for 1.5% of the energy



Eight different types of neutrino flux

- pp,pep,hep,^7Be,^8B,
- ^{13}N, ^{15}O,^{17}F

pp $\rightarrow$ solar luminosity
least uncertain

^8B flux is most uncertain

Solar Neutrinos: Summary of experimental results

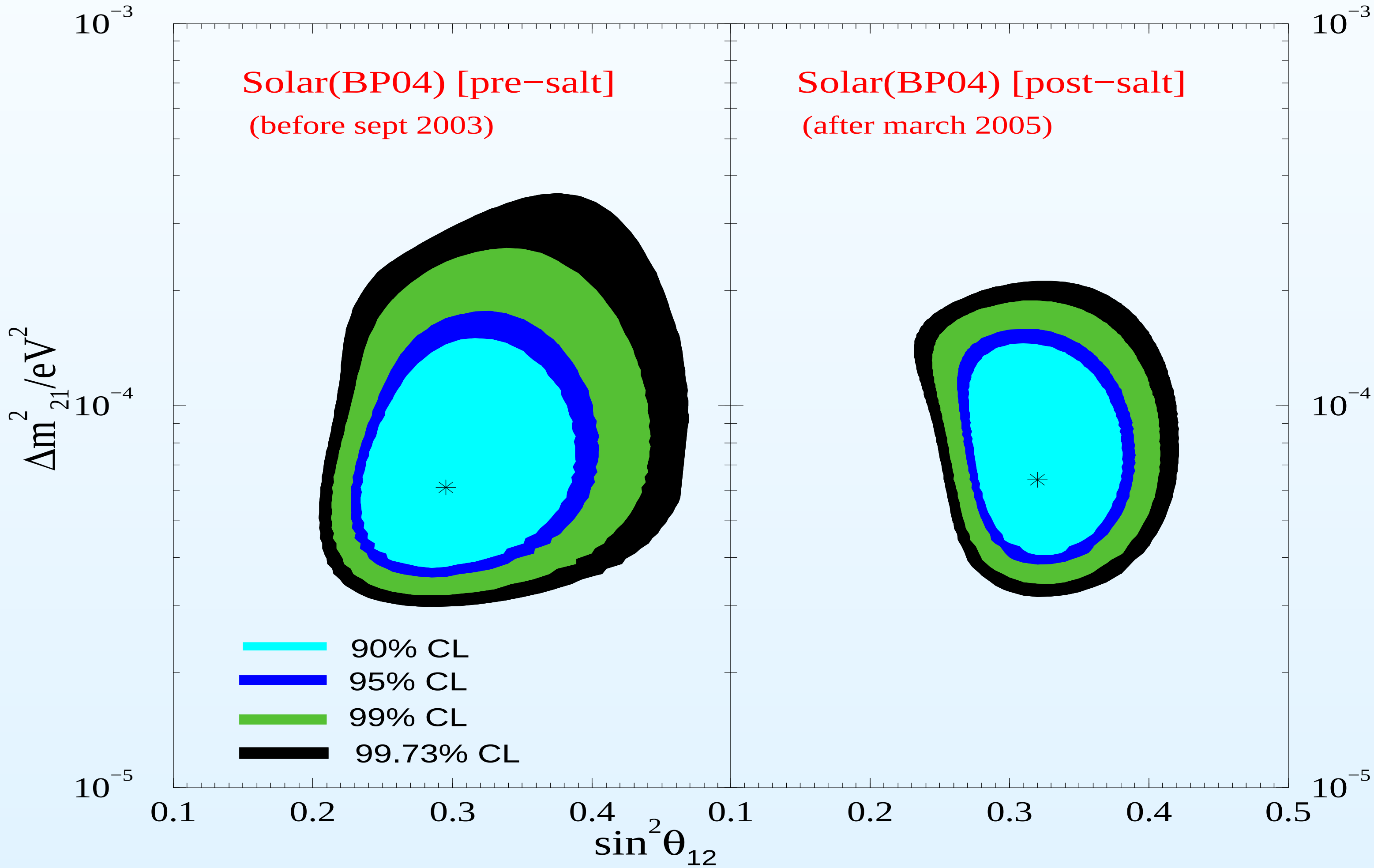
- The ratio of the observed solar neutrino rates to the SSM predictions.

Homestake	$^{37}Cl + \nu_e \rightarrow^{37} Ar + e^-$	0.337 ± 0.029
	0.81 MeV, ^8B,^7Be	
Gallex/GNO/SAGE	$^{71}Ga + \nu_e \rightarrow^{71} Ge + e^-$	0.553 ± 0.034
	0.23 MeV, pp, ^8B,^7Be	
SK	$e^- + \nu_x \rightarrow e^- + \nu_x$	0.465 ± 0.014
	5 MeV, ^8B	
SNO CC	$d + \nu_e \rightarrow p + p + e^-$	0.309 ± 0.19
SNO ES	$e^- + \nu_x \rightarrow e^- + \nu_x$	0.429 ± 0.058
SNO NC	$d + \nu_x \rightarrow p + n + \nu_x$	1.012 ± 0.09
	5 MeV, ^8B	

- 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

Solar Neutrinos: Status of Oscillation Parameters

- $\Delta m^2_{\odot} \equiv \Delta m^2{}_{21}$, $\theta_{\odot} \equiv \theta_{12}$ from Global Solar Data
- BP04 fluxes, ^8B flux normalisation free
- Including the full salt data from SNO



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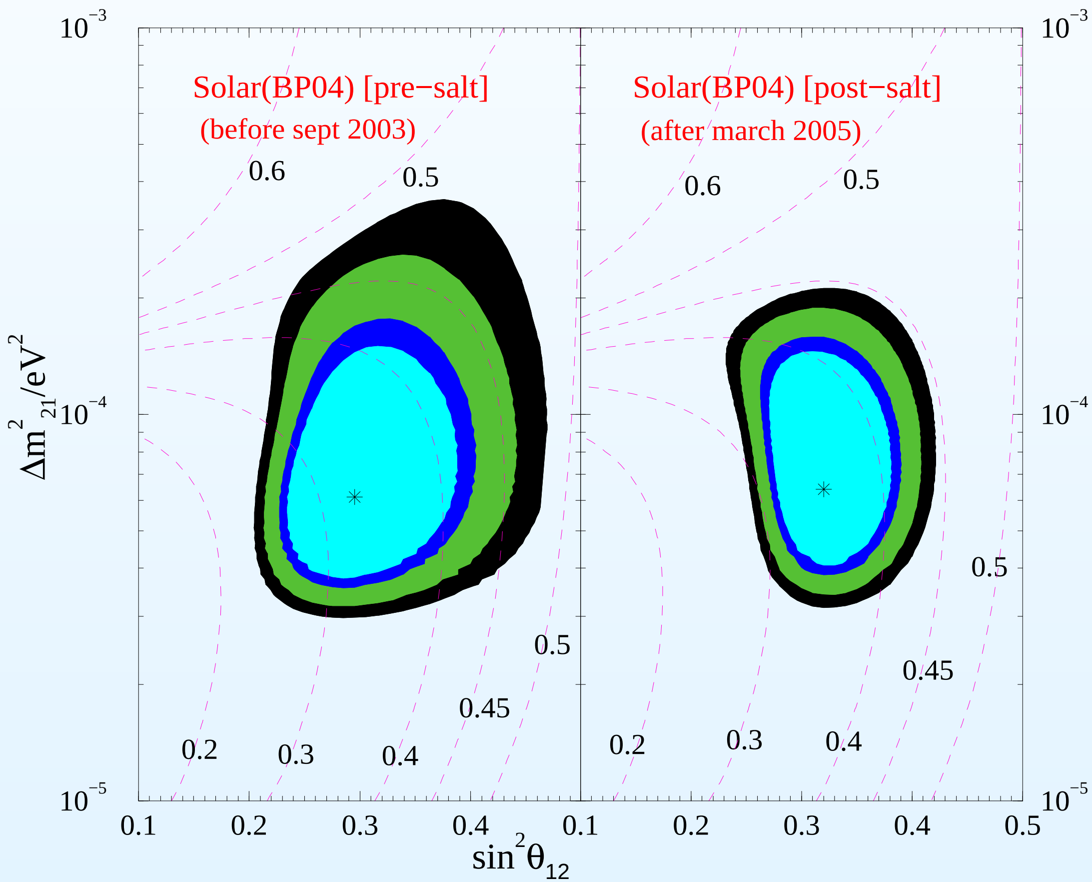

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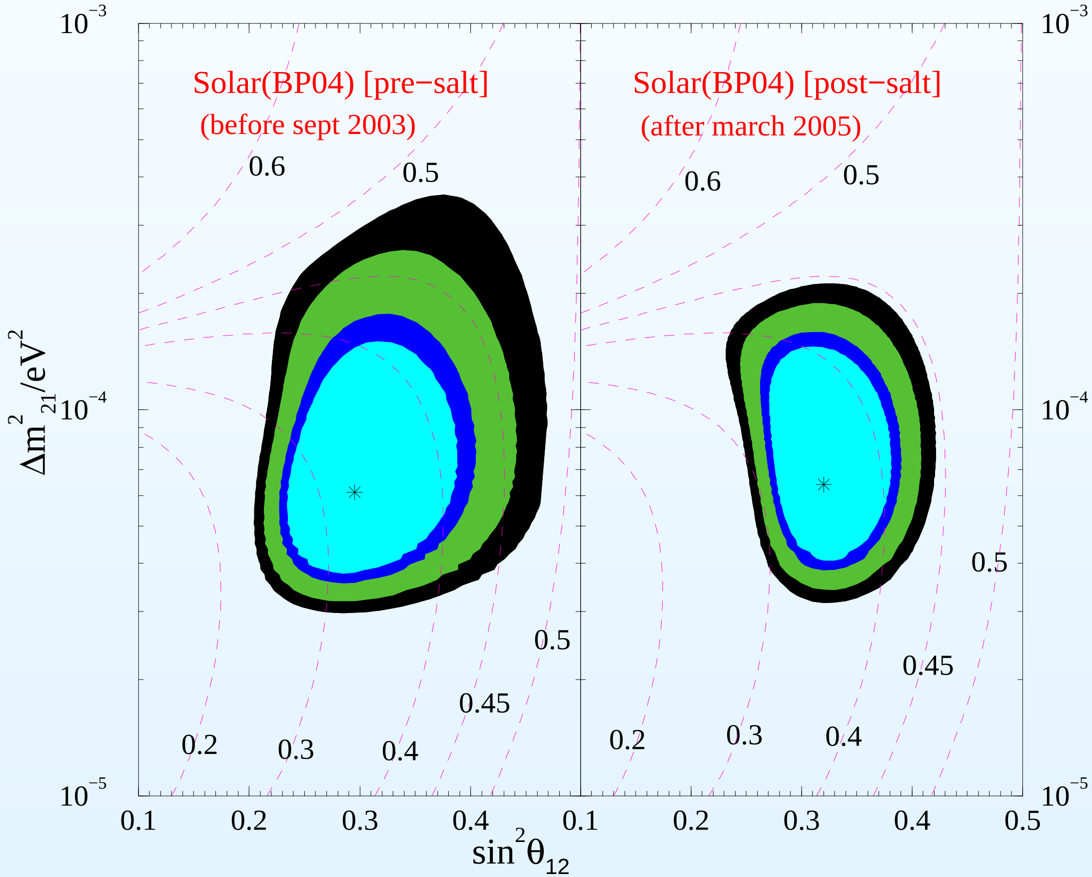

- **Best fit**

$\Delta m^2{}_{21}$ =6.4 $\times 10^{-5}$eV^2

$\sin^2\theta_{12}$ = 0.33 f_B=0.84

Solar Neutrinos: Status of Oscillation Parameters

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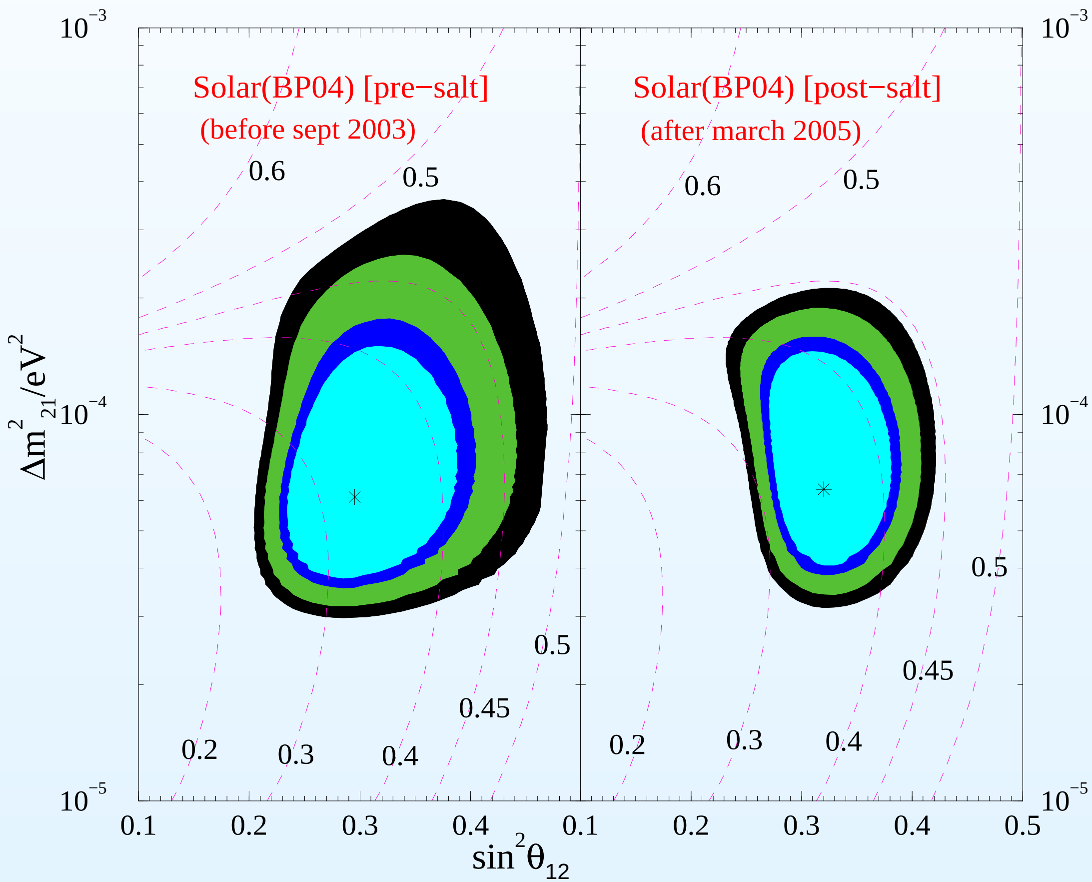

- 99% range$(\Delta\chi^2 = 9.21)$

$\Delta m^2{}_{21}$ =(3.1-25.7) $\times 10^{-5}$eV^2
$\sin^2\theta_{12}$ = 0.21 -0.44
....(before salt)

$\Delta m^2{}_{21}$ =(3.3-18.4) $\times 10^{-5}$eV^2
$\sin^2\theta_{12}$ = 0.24 -0.41
.... (after salt)

Solar Neutrinos: Status of Oscillation Parameters

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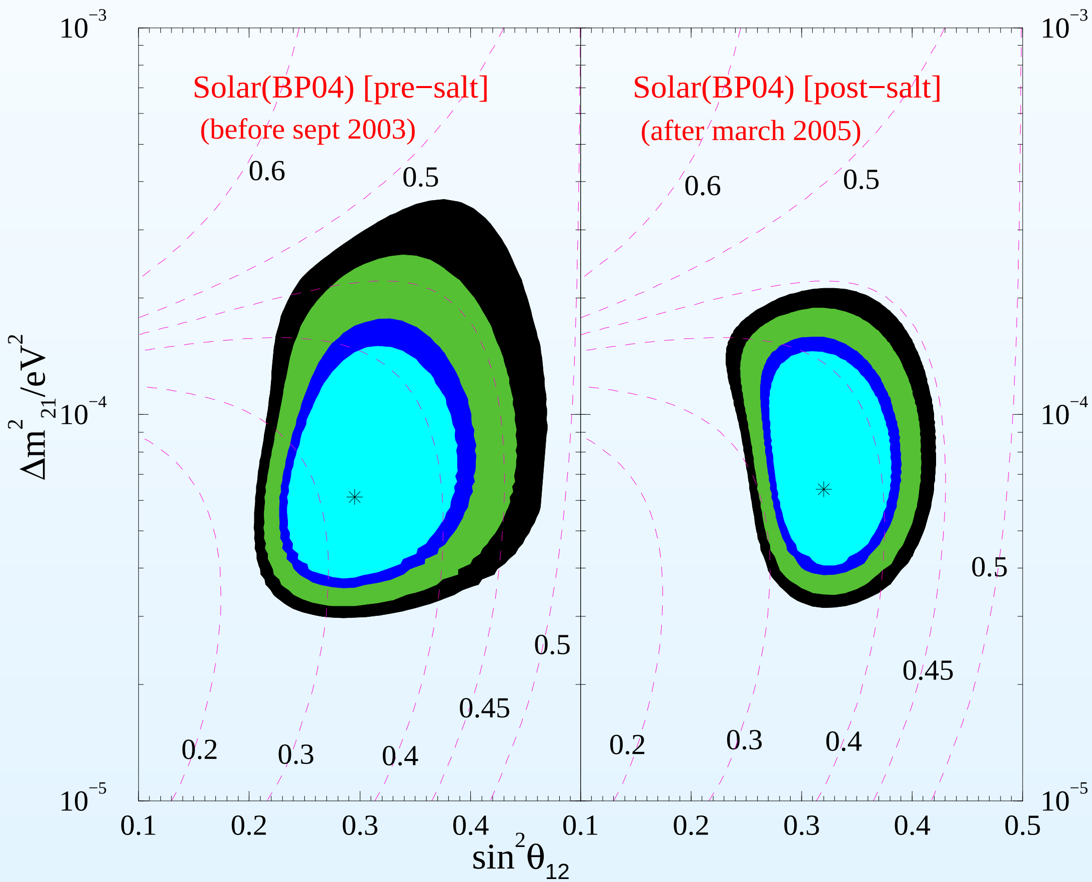

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....(before salt)

$\Delta m^2{}_{21}$ =(3.3-18.4) $\times 10^{-5}$eV^2
$\sin^2\theta_{12}$ = 0.24 -0.41
.... (after salt)

- Upper limit on $\Delta m^2{}_{21}$ and $\sin^2\theta_{12}$ tightens with salt data

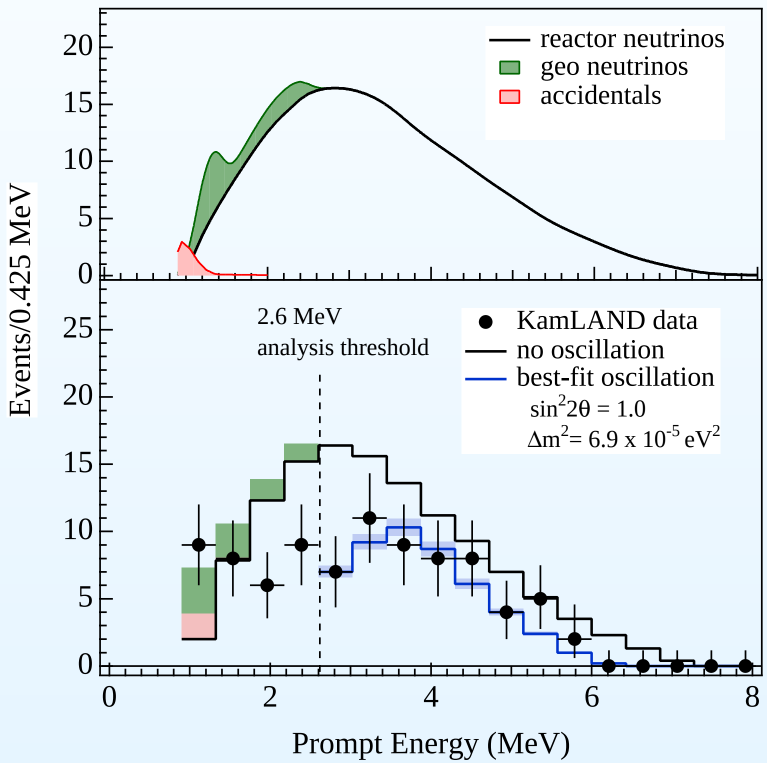
Impact of KamLAND on Oscillation Parameters

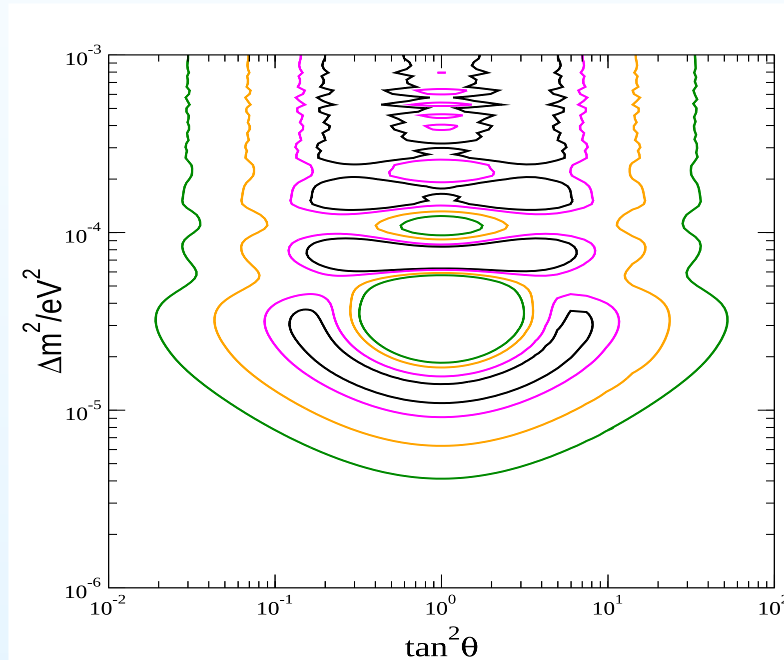
- 1 kton liquid scintillator neutrino detector at Kamioka
- $\bar{\nu}_e$ source: 16 main reactors at distances 81-824 km
- most powerful reactors are at 160 km
- detects reactor antineutrinos through: $\bar{\nu}_e + p \rightarrow n + e^+$

Impact of KamLAND on Oscillation Parameters

First KamLAND results

- Evidence of $\bar{\nu_e}$ disappaerance





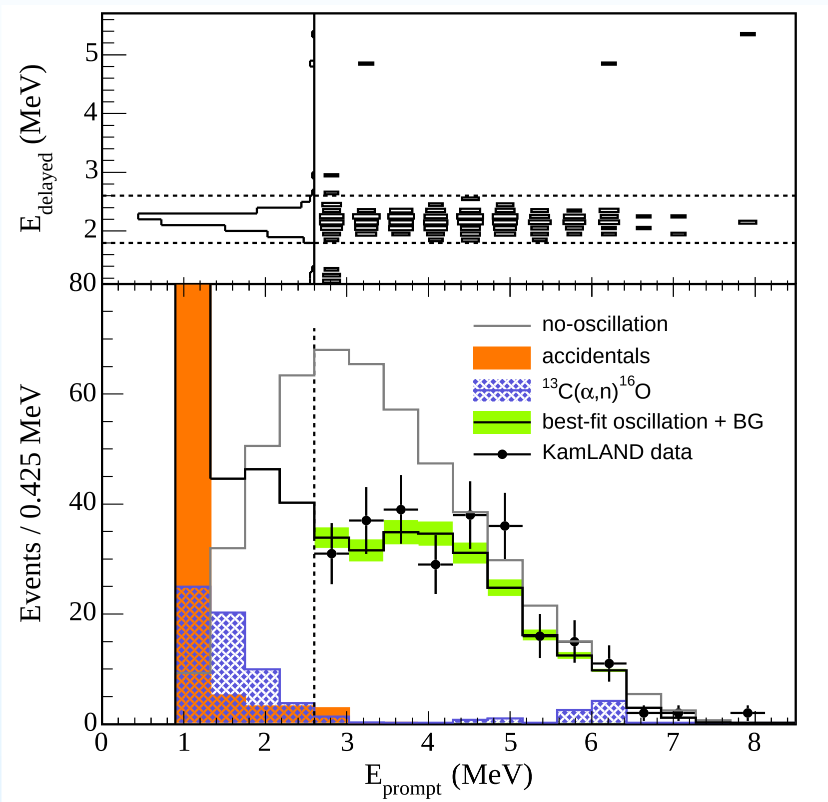
Bandyopadhyay et al,PLB,2003

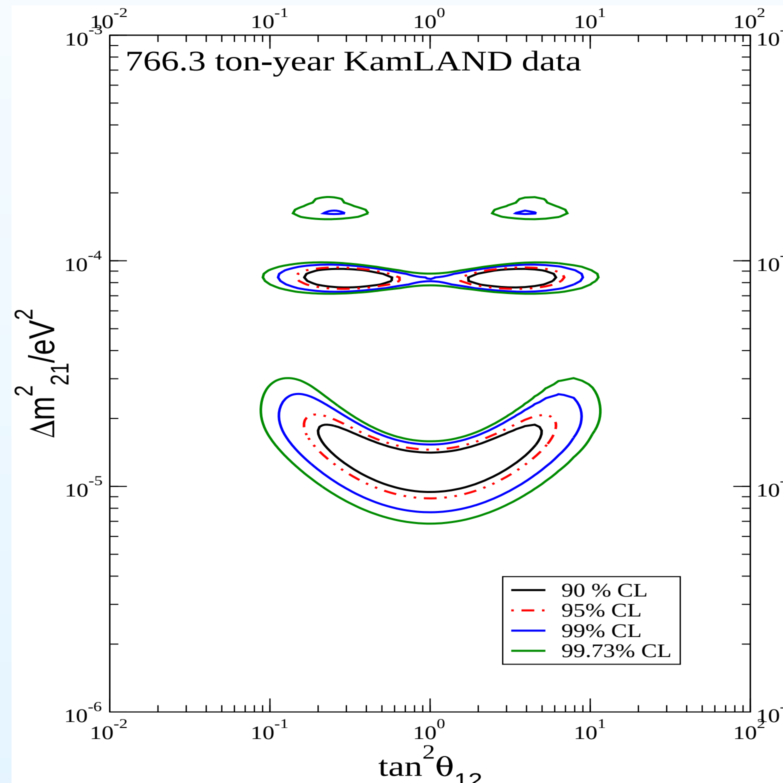
KamLAND Collaboration, PRL 2003

Impact of KamLAND on Oscillation Parameters

Second KamLAND results

- Evidence for spectral distortion at 99.6% significance



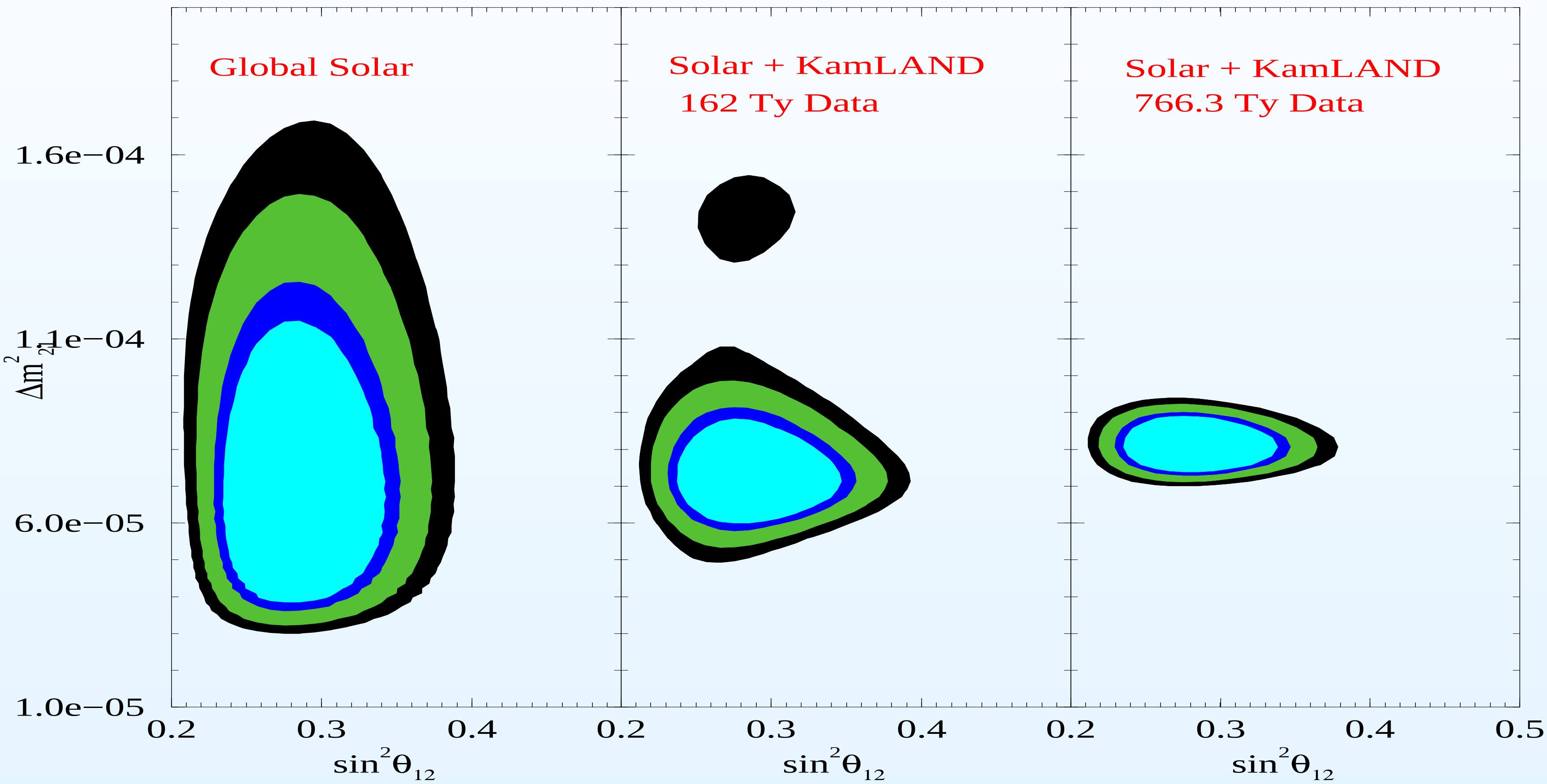


KamLAND Collaboration, PRL 2005

Bandyopadhyay et al,PLB 2005

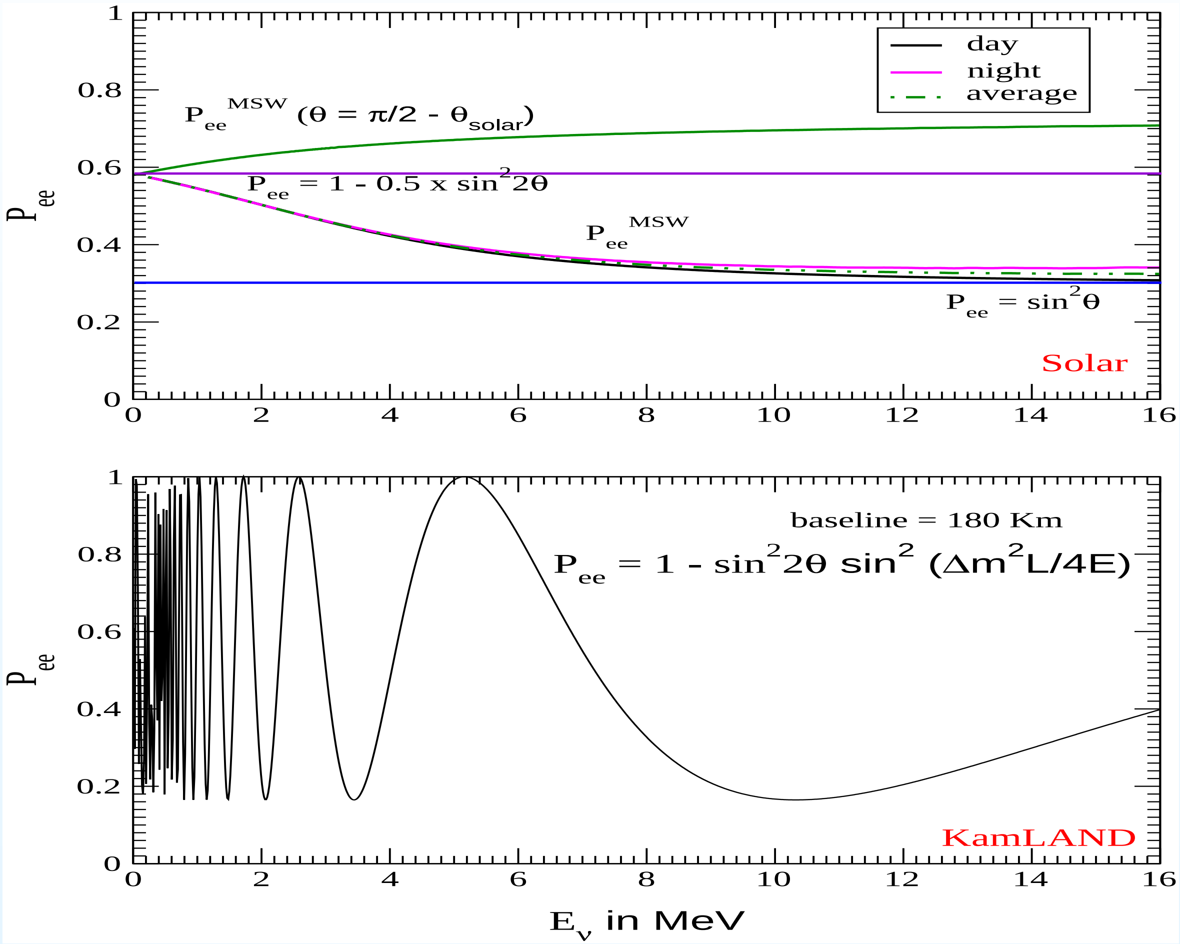
Impact of KamLAND on Oscillation Parameters

- Survival Probability : $P(\bar{\nu}_e \leftrightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E_\nu} \right)$
- Sensitive to LMA region (assuming CPT conservation)

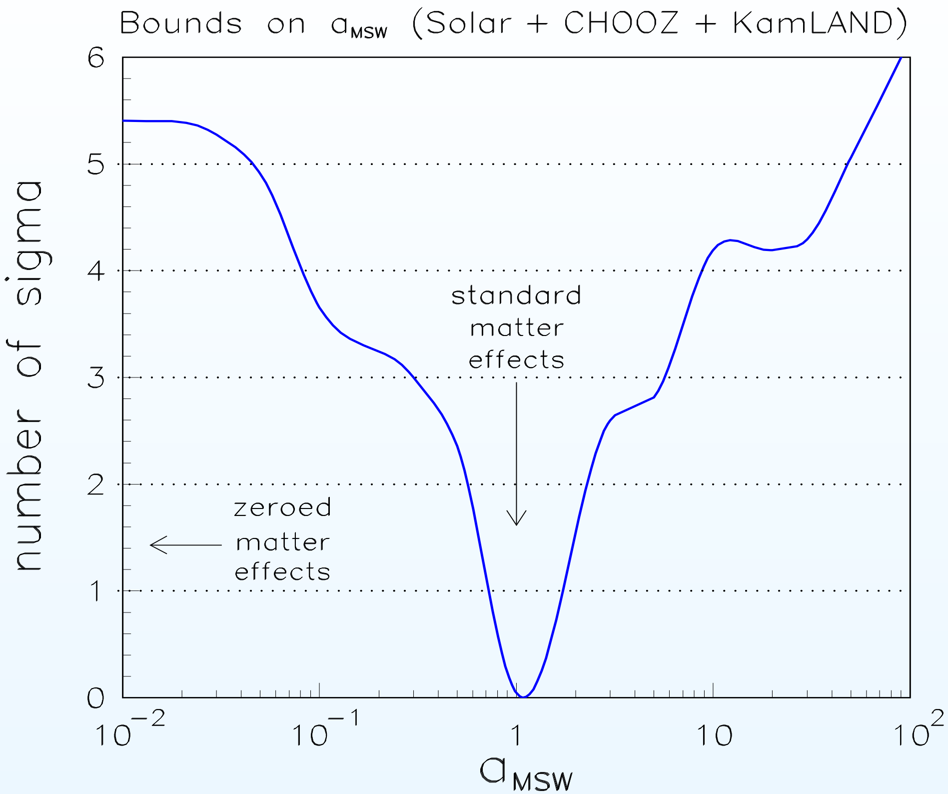


- Solar data disallows $\theta > \pi/4$ (Dark-Side) solutions

Survival Probabilites for solar and KamLAND



Evidence for MSW effect in Sun



$$V_{MSW} = \sqrt{2} G_F n_e$$
$$V_{MSW} \to \alpha_{MSW} . V$$

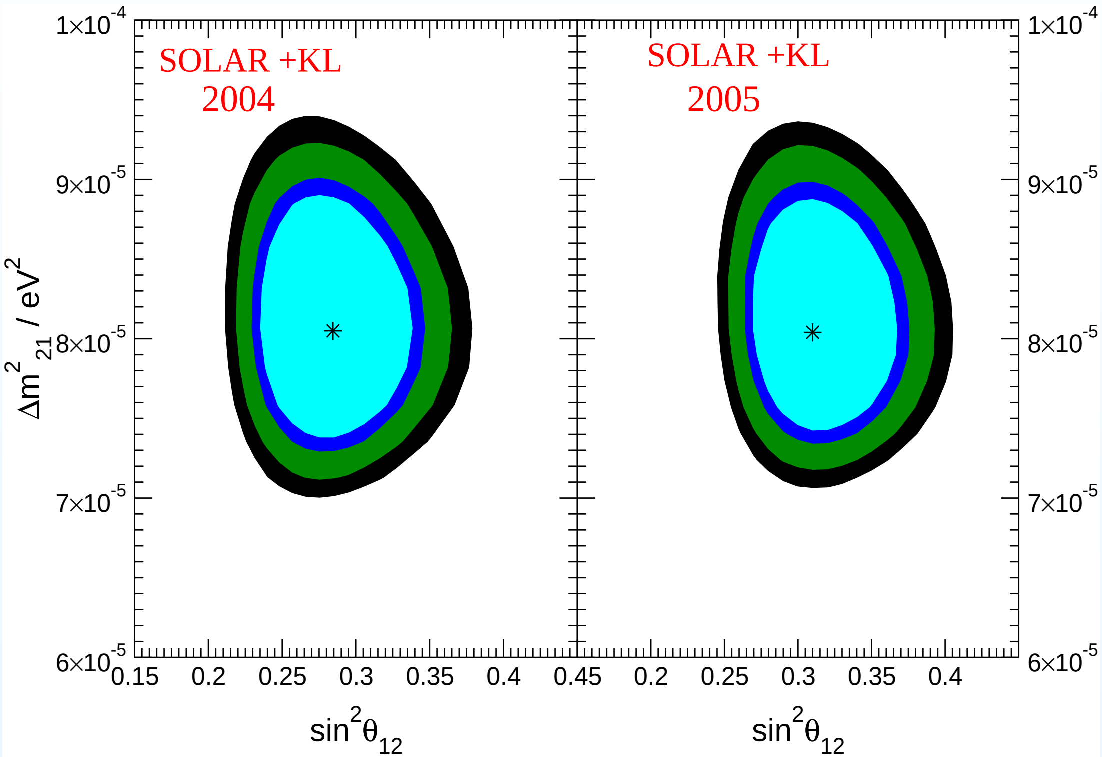
- "No MSW" rejected at several σ

Fogli et al. 2005

- $\tan 2\theta^m_{12} = \frac{\Delta m^2{}_{21} \sin 2\theta_{12}}{\Delta m^2{}_{21} \cos 2\theta_{12} - 2\sqrt{2} G_F n_e}$

- For Resonance $\Delta m^2{}_{21} \cos 2\theta_{12} > 0$
- $P_{ee}^{solar}(^8B) = 0.5\ \ (1 - cos2\theta_{12})$
- Solar data ⇨ $P_{ee}^{solar}(^8B) < 0.5$
- ⇨ $\cos 2\theta_{12} > 0$ (Dark-Side gone)
- ⇨ $\Delta m^2{}_{21} > 0$

Status of Solar Neutrino Oscillation Parameters



Best-fit (Solar+KamLAND)

$\Delta m^2{}_{21}$ =8.0$\times 10^{-5}$eV^2
$\sin^2\theta_{12}$ = 0.31

3σ range (Solar+KamLAND)

$\Delta m^2{}_{21}$ =(7.0-9.3) $\times 10^{-5}$eV^2
$\sin^2\theta_{12}$ = 0.24 -0.41

Bandyopadhyay et al, 2005

Also Vissani and Strumia, Fogli et. al

- Maximal mixing ruled at almost 6σ

On the precision of $\nu_\odot$ oscillation parameters

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

Data set used	Range* of $\Delta m^2{}_{21} \times 10^{-5}$ eV^2	spread in $\Delta m^2{}_{21}$	Range* of $\sin^2\theta_{12}$	spread in $\sin^2\theta_{12}$
only sol	3.2 - 14.9	65%	$0.22 - 0.37$	25%
sol+162 Ty KL	5.2 - 9.8	31%	$0.22 - 0.37$	25%
sol+ 766.3 Ty KL	7.3 - 9.4	13%	$0.22 - 0.36$	24%
sol2005+766.3 Ty KL	7.2 - 9.2	12%	$0.25 - 0.39$	22%

* 99% C.L. ($\Delta\chi^2 = 9.21$, 2 parameters)

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

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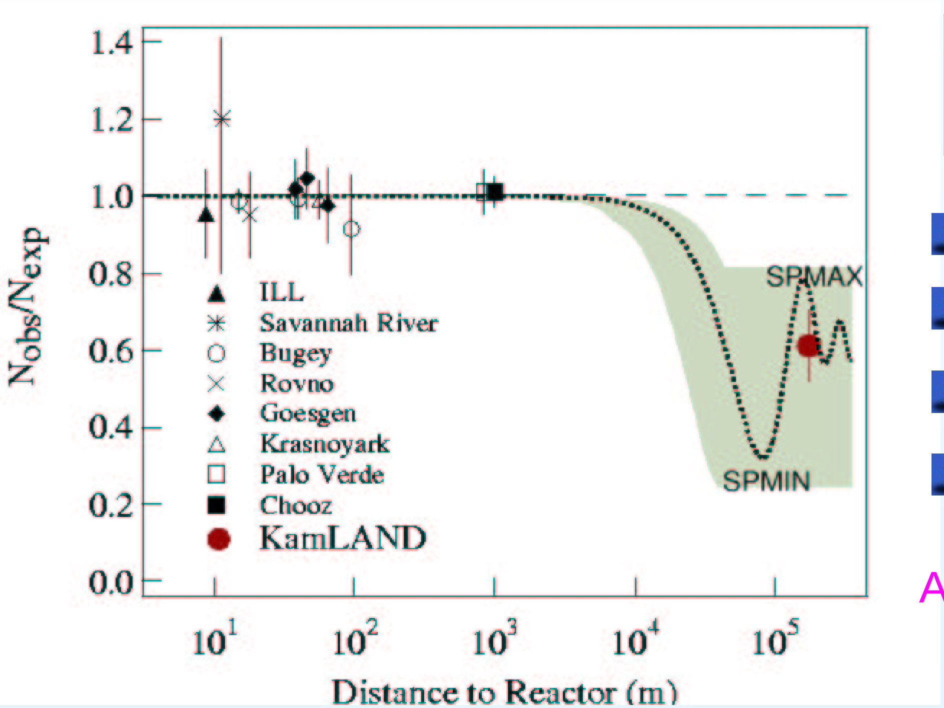
* **99% C.L. ($\Delta\chi^2 = 9.21$, 2 parameters)**

- KamLAND has tremendous sensitivity to $\Delta m^2{}_{21}$
- Does not constrain θ_{12} much better than the current set of solar experiments

Sensitivity of KamLAND for θ_{12}

- $P_{ee}{}^{vac} = 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2{}_{21} L}{4E}\right)$
- $\sin^2\left(\frac{\Delta m^2{}_{21} L}{4E}\right) \to 1 \Rightarrow$ SPMIN, $\sin^2\left(\frac{\Delta m^2{}_{21} L}{4E}\right) \to 0 \Rightarrow$ SPMAX
- SPMIN best for $\sin^2\theta_{12}$ for $\sin^2\theta_\odot \lesssim 0.4$



(KamLAND Collaboration, hep-ex/0212021)

Best-Fit: $\sin^2\theta_{12} = 0.3$
Range: $0.25 < \sin^2\theta_\odot < 0.39$

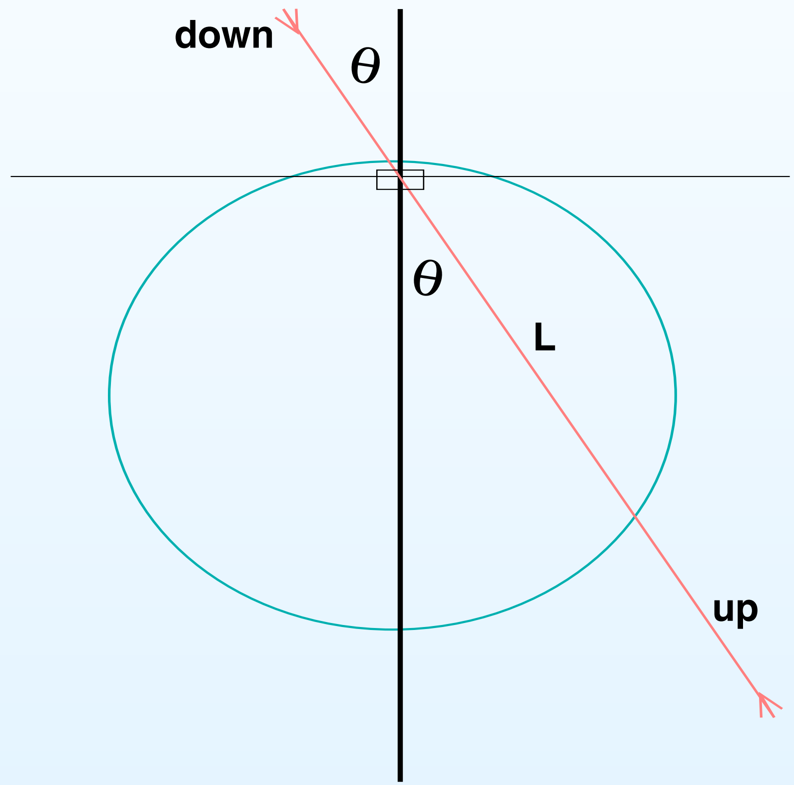
- KamLAND is at SPMAX
- The θ_{12} sensitivity gets smothered
- KamLAND is not at best position for θ_{12}
- SPMIN at $L \sim 60$ km for present best-fit $\Delta m^2{}_{21}$

A. Bandyopadhyay , S.Choubey, S.G. PRD, 2003

Atmospheric neutrinos

➢ Advantage: single detector and 2 equal sources.

➢ Main goal: Study oscillation pattern in atmospheric neutrino events.



$$A_c{}^r + A_{air} \rightarrow \pi^+ + \ldots$$

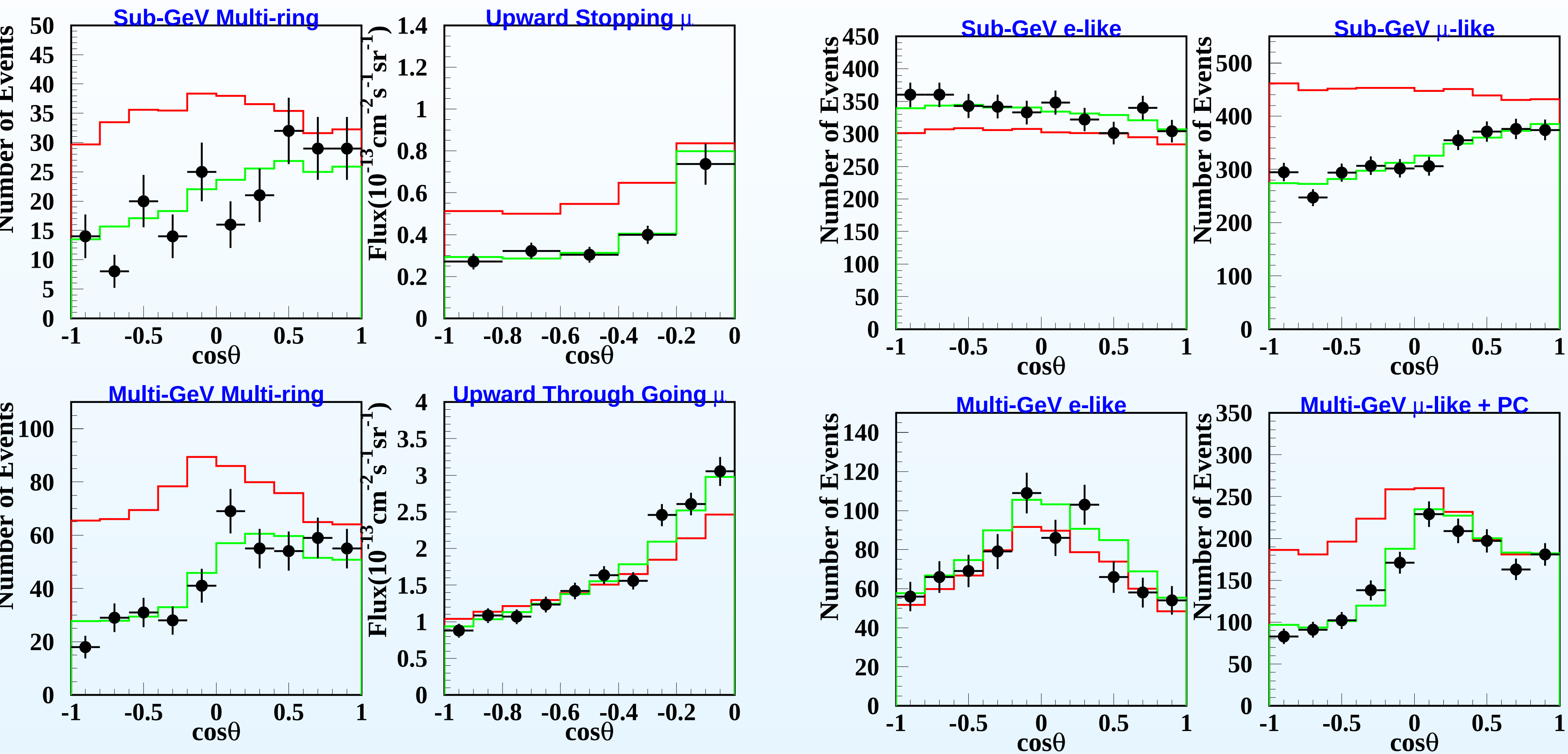
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\frac{N_{up}(L/E)}{N_{down}(L/E)} \simeq P_{\mu\mu}$$

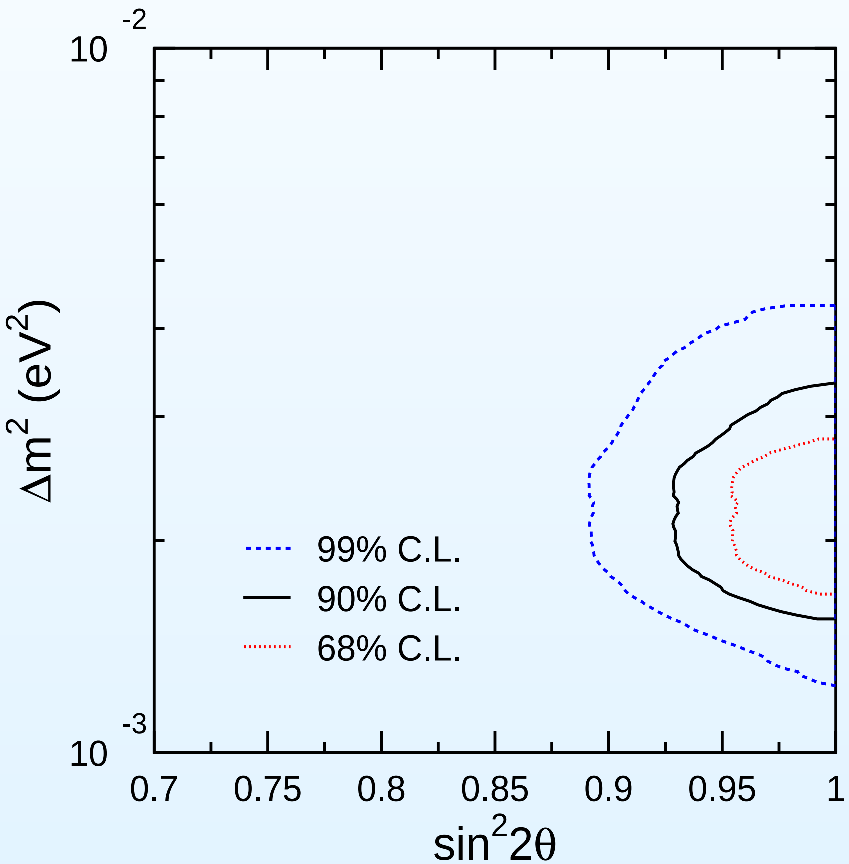
Atmospheric Neutrinos:Experimental Results

- SK-I 1489 days zenith angle spectrum



Atmospheric Neutrino Oscillation Parameters . . .

- Two generation $\nu_\mu - \nu_\tau$ oscillation $(\theta_{atm} \equiv \theta_{23}, \Delta m^2_{atm} \equiv \Delta m^2{}_{32})$
- $P_{\mu\mu} = 1 - \sin^2 2\theta_{atm} \sin^2 \left(\frac{\Delta m^2_{atm} L}{4E} \right)$
- $\theta_{23} - (\pi/2 - \theta_{23})$ symmetry



Y. Ashie et al. hep-ex/05404034

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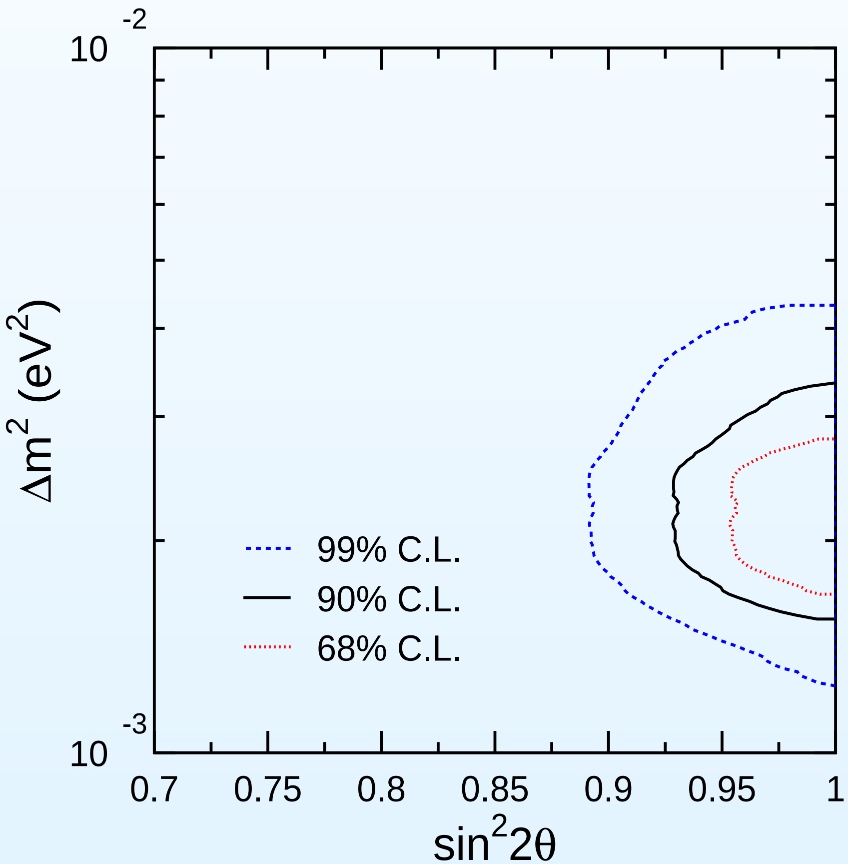

- Best-fit

Δm^2_{atm} = 2.1 $\times 10^{-3}$ eV^2, $\sin^2 2\theta_{atm} = 1.0$

Y. Ashie et al. hep-ex/05404034

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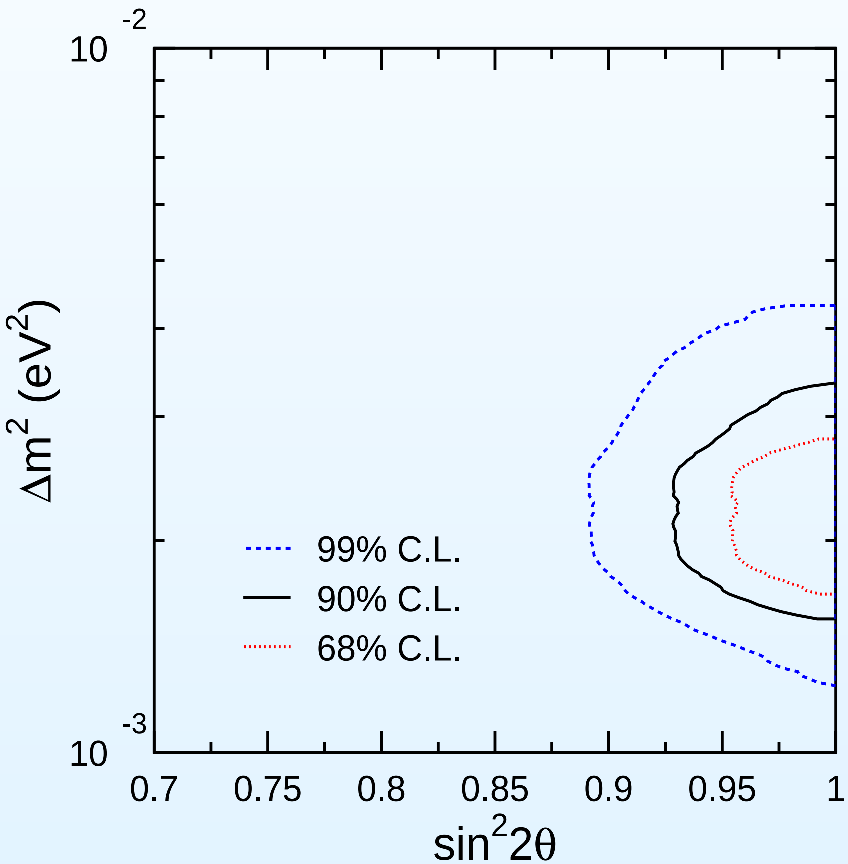


- 3σ range ($\Delta\chi^2 = 9$, 1 parameter)

Δm^2_{atm} = 1.3 - 4.2 $\times 10^{-3}$ eV^2,
$\sin^2 2\theta_{atm} > 0.9$ (SK Zenith)

spread in Δm^2_{atm} = 53%
spread in $\sin^2 2\theta_{23}$ = 5%

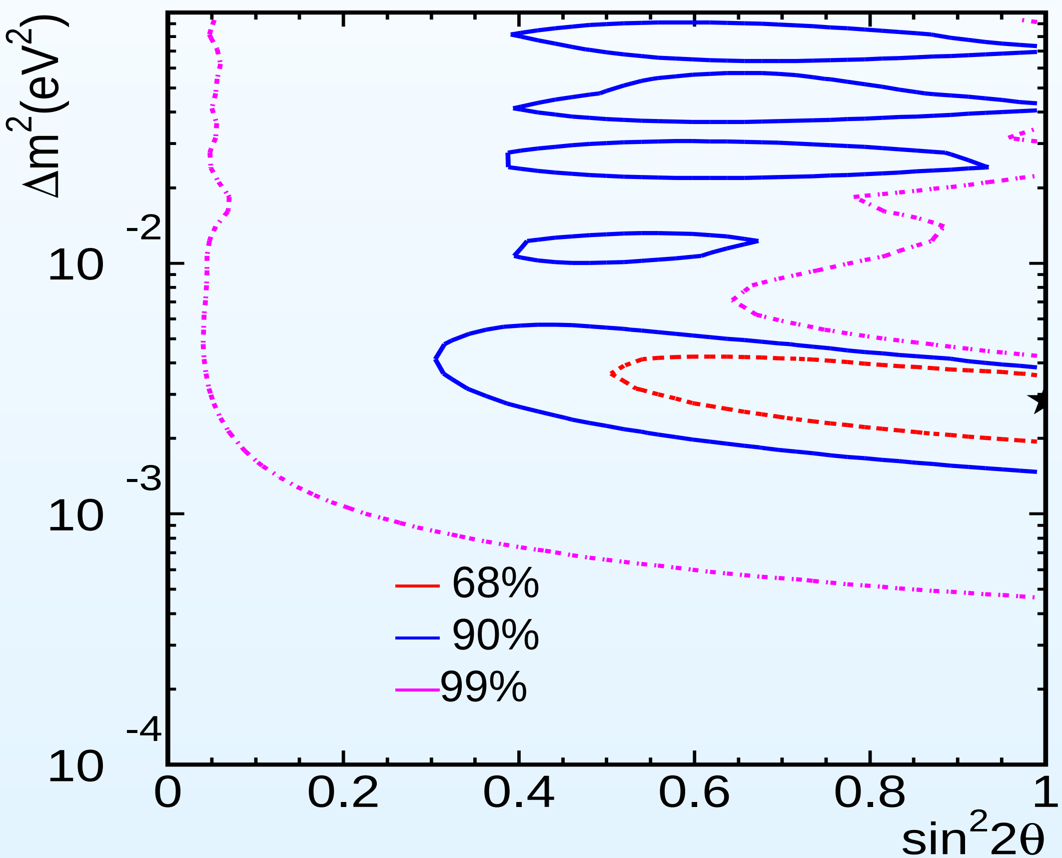
- $\delta(\sin^2\theta_{23}) \sim 32\%$ ⇨ $\sin^2\theta_{23}$ precision is worse than $\sin^2 2\theta_{23}$ precision near maximal mixing

$$\delta(\sin^2\theta) = \frac{\delta(\sin^2 2\theta)}{\cos 2\theta}$$

Y. Ashie et al. hep-ex/05404034

Allowed area from K2K Experiment

- $P_{\mu}\mu \; = 1 - \sin^2 2\theta_{atm} \sin^2 \left(\frac{\Delta m^2_{atm} L}{4E} \right)$
- L $\sim$ 250 km, $E_\nu \sim$ 1.3 GeV



- **Best-fit**

Δm^2_{atm} = 2.8 $\times 10^{-3}$ eV^2

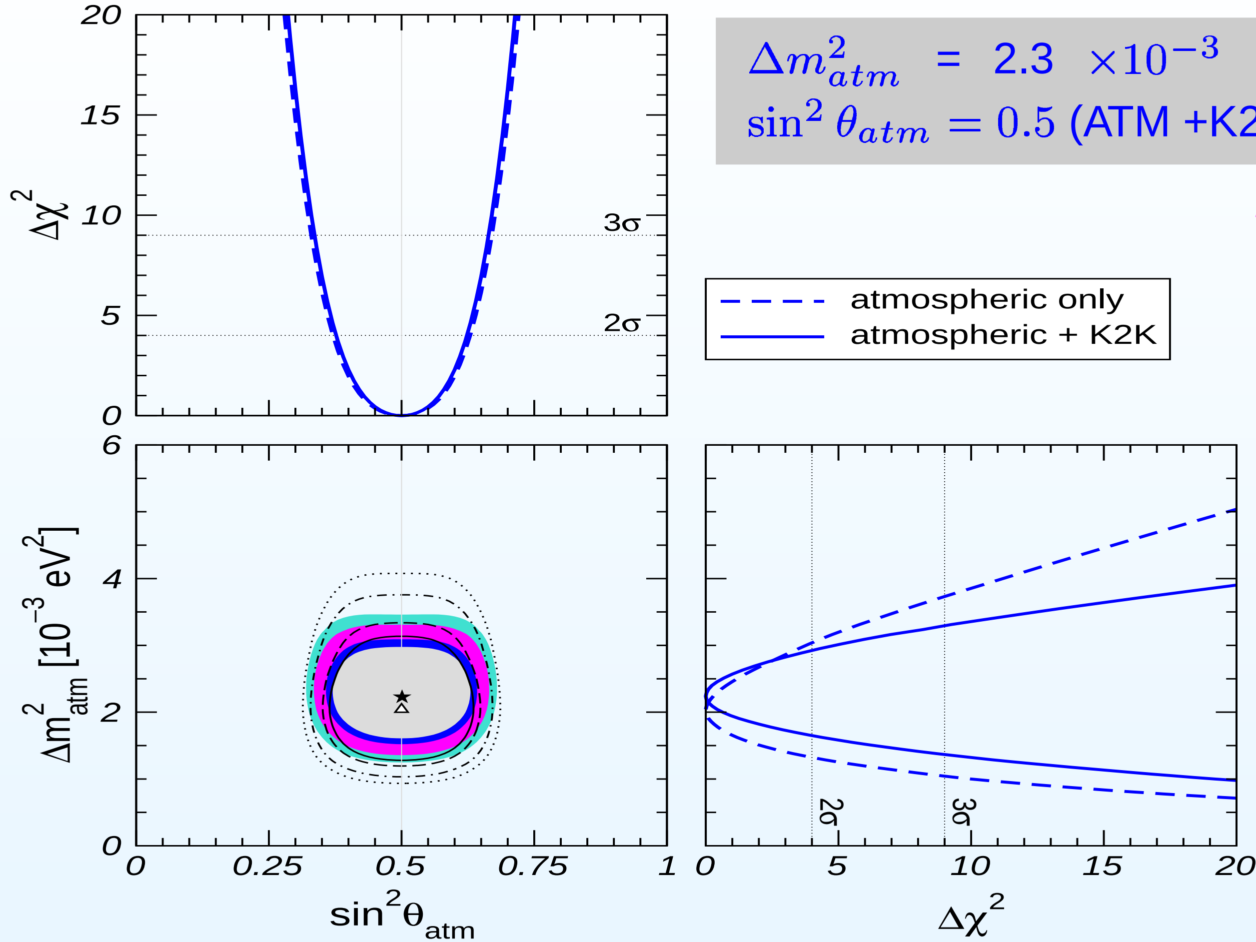
$\sin^2 2\theta_{atm} = 1.0$

K2K collaboration, 2003

Allowed parameters from SK+K2K analysis

Δm^2_{atm} = 2.3 $\times 10^{-3}$ eV^2,
$\sin^2\theta_{atm} = 0.5$ (ATM +K2K)

Maltoni et al.,hep-ph/0405172

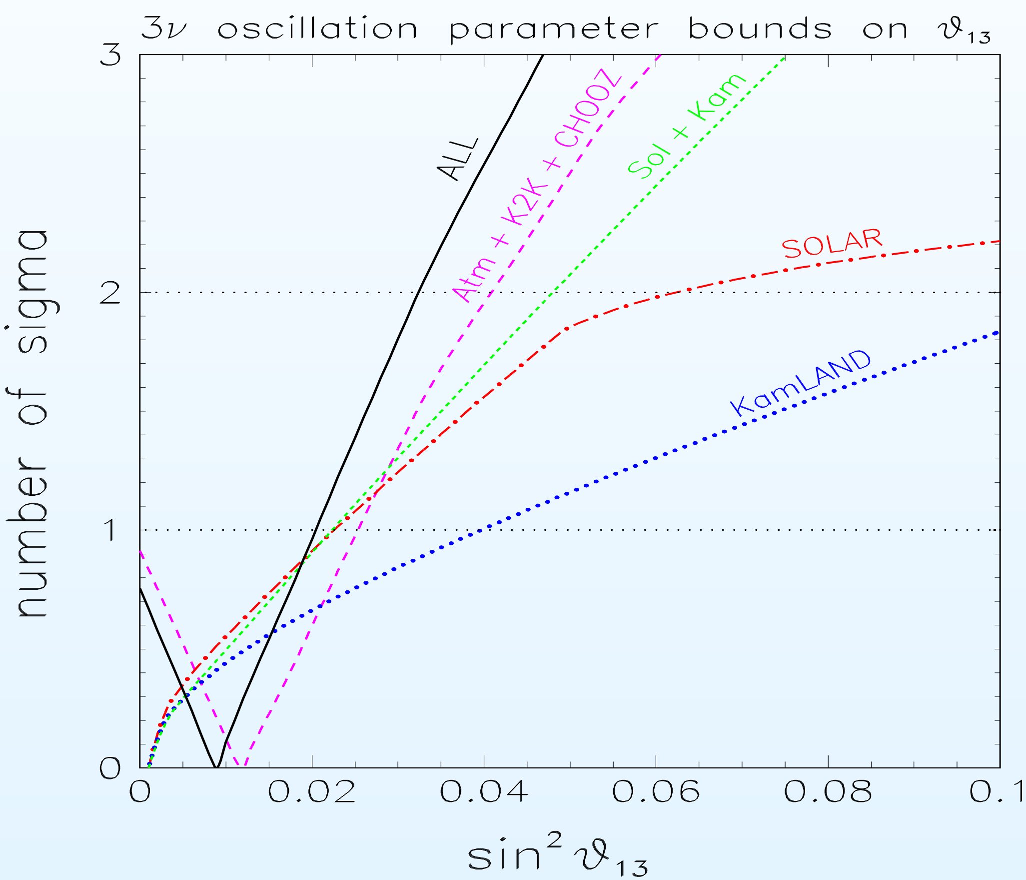


- Higher Δm^2 values are constrained by K2K
- K2K data does not constrain θ_{atm} any better

Three Generation Analysis

- Non-zero θ_{13} couples solar and atmospheric

- **Status of θ_{13}**

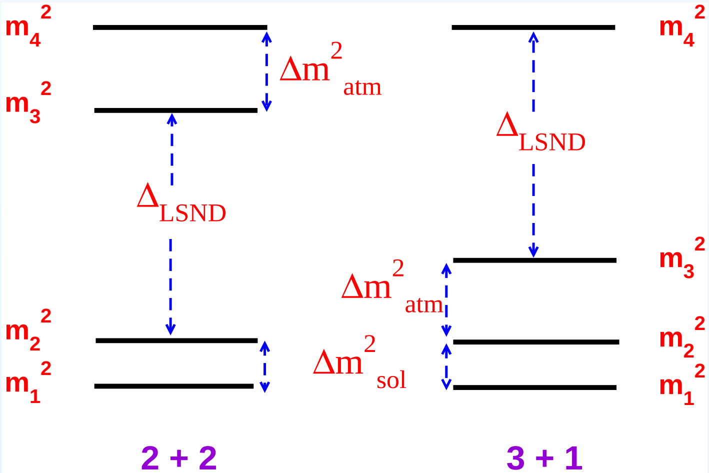


- Combined analysis : $\sin^2\theta_{13} \lesssim 0.04$ (3σ)
- Bound sensitive to value of $\Delta m^2{}_{31}$
- Two generation allowed areas stable

G. L. Fogli et al. ,hep-ph/0506083

Accommodating the LSND Signal

- Evidence for oscillations for $\Rightarrow \Delta m^2 \sim \mathrm{eV}^2$
- Adding extra sterile neutrinos
- CPT violation

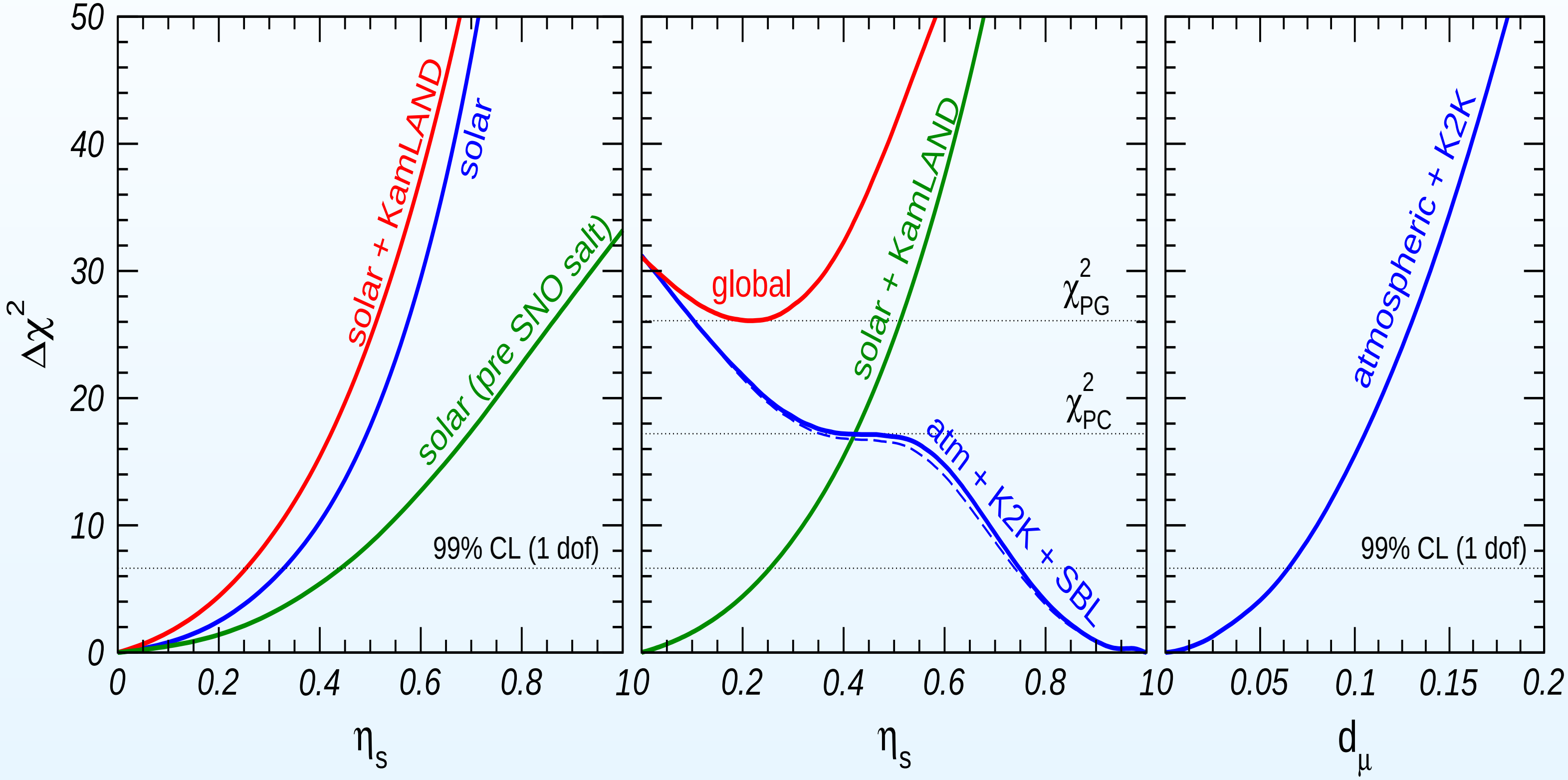


One additional sterile neutrino

2+2 and 3+1 mass schemes

Accommodating the LSND Signal

- The 2+2 scheme is ruled out by the solar and atm data

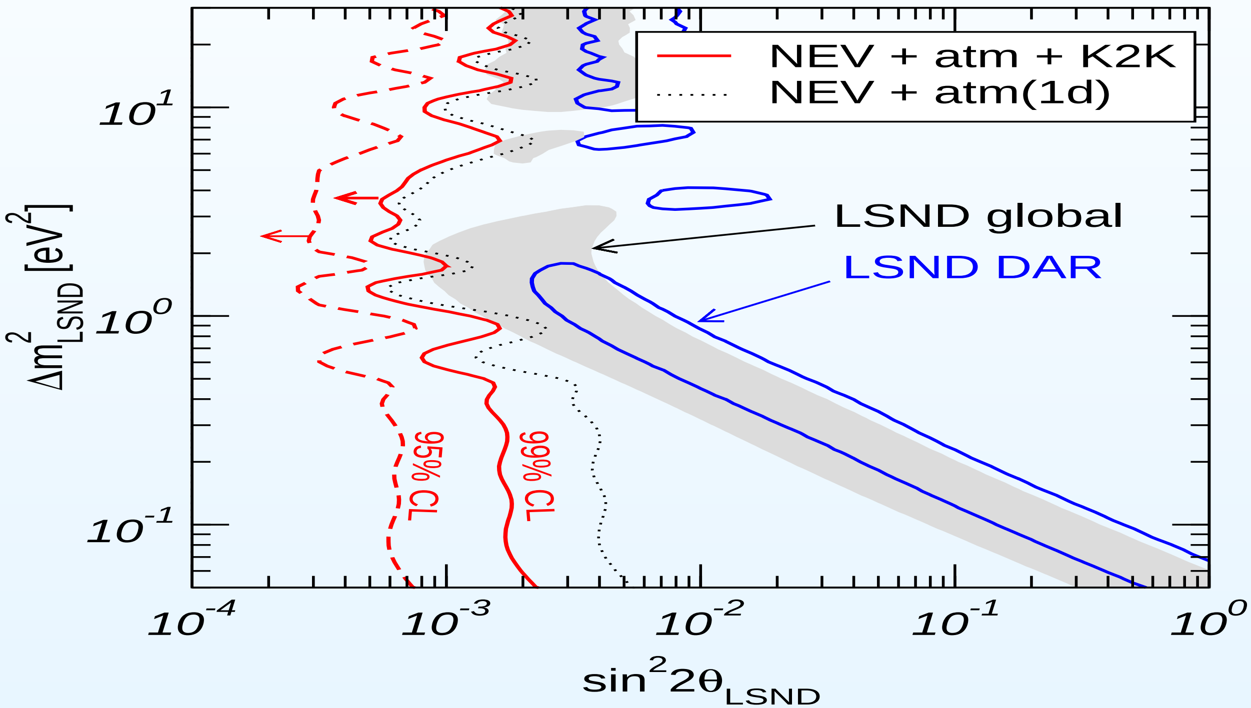


Maltoni et al, hep-ph/0405172

- Oscillations to pure sterile states is strongly disfavored by both the solar and atmospheric data

Accommodating the LSND Signal

- The 3+1 scheme is strongly disfavored by the SBL data



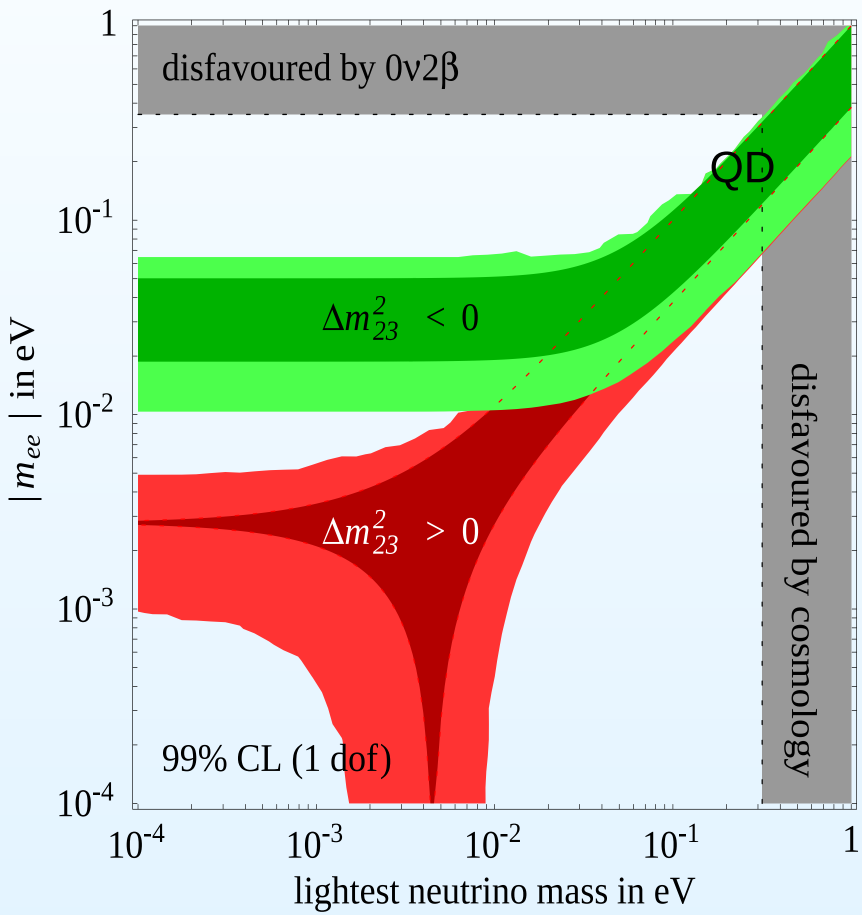
Maltoni et al, hep-ph/0405172

- Very small area allowed at the 99% C.L.
- What if LSND is confirmed by MiniBOONE ??

Neutrino Less Double Beta Decay

$$\langle m \rangle = |m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\phi_1} + m_3|U_{e3}|^2 e^{i\phi_2}|$$

- Neutrino Mass Spectrum
- Absolute Neutrino Mass Scale
- CPV phases



NH: $m_1 << m_2 << m_3$

IH: $m_3 << m_1 \approx m_2$

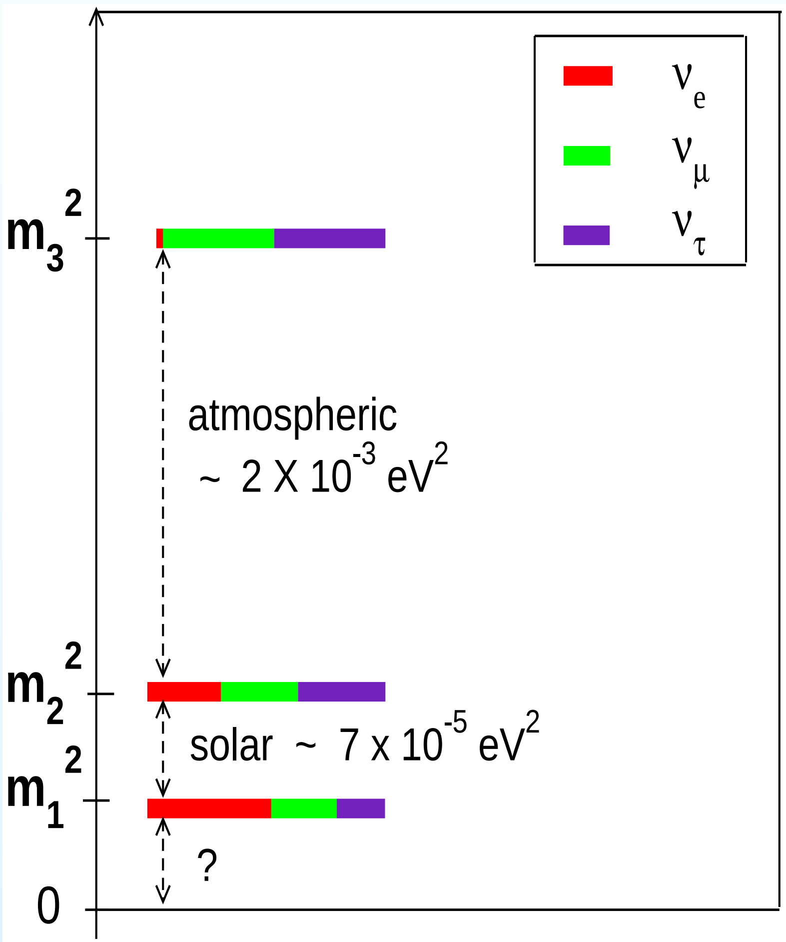
QD: $m_1 \approx m_2 \approx m_3$

- $\langle < m > \rangle$ is in the range of sensitivity of upcoming $0\nu\beta\beta$ experiments for IH and QD
- Uncertainties coming from Nuclear matrix elements

Vissani and Strumia,hep-ph/0503246

Summary-I: What we know

- Atleast 3 flavors involved in oscillation



- Best-fit

$\Delta m^2{}_{21}$ =8.0 $\times 10^{-5}$ eV^2, $\sin^2\theta_{12} = 0.3$
Δm^2_{32} = 2.1 $\times 10^{-3}$ eV^2, $\sin^2\theta_{23} = 0.5$,
$\sin^2\theta_{13} = 0.01$

$$U = \begin{pmatrix} 0.84 & 0.54 & 0.1 \\ -0.44 & 0.56 & 0.71 \\ 0.32 & -0.63 & 0.71 \end{pmatrix}$$

- $\Delta m^2{}_{21} > 0$ (from solar data)

Summary-II:What we don't know

- What are the precise values of $\Delta m^2{}_{21}$ and $\sin^2\theta_{12}$?
- What are the precise values of Δm^2_{32} and $\sin^2\theta_{23}$?
- Is $\sin^2 2\theta_{23}$ exactly maximal?
- What is the sign of Δm^2_{32} (Nature of mass spectrum)?
- How small is $\sin^2\theta_{13}$? Is it zero?
- Are 3 flavor oscillations enough?
- Is the CP phase non-zero?
- Are Neutrinos Dirac or Majorana?
- What is the absolute neutrino mass scale?
- Is there a link between low energy CPV in the lepton sector and Baryogenesis via Leptogenesis?
- Origin of Neutrino masses at a fundamental level

Summary-II:What we don't know

- What are the precise values of $\Delta m^2{}_{21}$ and $\sin^2\theta_{12}$?
- What are the precise values of Δm^2_{32} and $\sin^2\theta_{23}$?
- Is $\sin^2 2\theta_{23}$ exactly maximal?
- What is the sign of Δm^2_{32} (Nature of mass spectrum)?
- How small is $\sin^2\theta_{13}$? Is it zero?
- Are 3 flavor oscillations enough?
- Is the CP phase non-zero?
- Are Neutrinos Dirac or Majorana?
- What is the absolute neutrino mass scale?
- Is there a link between low energy CPV in the lepton sector and Baryogenesis via Leptogenesis?
- Origin of Neutrino masses at a fundamental level

• Next Generation Experiments •

Summary-III: Future RoadMap

- Future Solar Neutrino Data
  - SNO - Phase 3
  - Borexino
  - LowNu
- Future Reactor Neutrino Data
  - More Statistics from KamLAND
  - New Reactor experiment for θ_{12}
  - Θ_{13} Projects : Clean Determination of θ_{13}
- Future Atmospheric Neutrino Data
  - More statistics from SuperK
  - Megaton water cerencov detectors, HyperK,UNO
  - Magnetised Iron Calorimeter detectors, INO
- Future Accelerator Neutrino Data
  - Longbaseline Projects, MINOS,CNGS
  - Longbaseline with Superbeams, Nova,T2K
  - Beta Beams
  - Neutrino Factories
- Three or More
  - MiniBOONE
- Absolute Neutrino Mass scale
  - Beta Decay experiment with increased sensitivity, Katrin
  - $0\nu\beta\beta$ experiments increased sensitivity

Conclusion and Outlook

- The small observed neutrino masses cannot be explained by Standard Model
- The only observational signal of physics Beyond the Standard Model
- Theoretical challenges
  - Why $m_{\nu_i} \ll m_l, m_u, m_d$
  - Why two large and one small angle in neutrino sector while all the angles in quark sector are small
  - Hierarchy for neutrino masses not strong
    Can even be degenerate!
- Hierarchy, θ_{13}, deviation from maximality ⇨ good discriminator of mass Models
- Precision neutrino measurements can help in choosing between various alternatives