The Jigsaw of Neutrino Mass and Mixing
Current Status

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Parameters of Neutrino Mass Matrix

- 9 unknown parameters in the light 3-neutrino mass matrix
  - 3 masses, m_1, m_2 and m_3
  - 3 mixing angles, 1 Dirac CP phase, 2 Majorana CP phases

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- Oscillation experiments sensitive to
  - 2 mass squared differences $(\Delta m^2{}_{21}, \Delta m^2{}_{31} \approx \Delta m^2{}_{32})$
  - 3 mixing angles $(\theta_{12}, \theta_{13}, \theta_{23})$
  - 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

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
- Data from long baseline accelerator based experiment MINOS
- Accelerator based oscillation experiment LSND
  –not confirmed by Karmen
  —Miniboone will provide independent check

Plan of Talk

- Determination of Δm^2_{21} and θ_{12}
  Global Solar SNO,SK,GNO,SAGE,Homestake and KamLAND data
- Determination of Δm^2_{32} and θ_{23}
  SK atmospheric Neutrino data, K2K, first results from MINOS
- Determination of θ_{13}
  Bounded by Global data
- Absolute Neutrino Masses
  Constrained by Tritium Beta decay, Neutrino less double beta decay, Cosmology
- Three or more Neutrinos
  LSND, MiniBoone
- Status of Mass Models

Oscillation Analysis – Ingredients

- Experimental Data
  –statistical error
  –systematic errors and their correlations
- Theoretical Predictions
  –the fluxes and their uncertainties $\leftarrow$ input from Astro Physics
  –the interaction cross-sections and their uncertainties $\leftarrow$ input from Nuclear Physics
  –the oscillation probabilities (depends on the density profile of the propagating medium, Δm^2 , θ, E_ν ....) $\leftarrow$ Input from Particle Physics
- $\text{rate} = \text{flux} \times \text{cross} - \text{section} \times \text{probability}$
- Minimisation of χ^2_{global}

Best-fit values of parameters Δm^2, $\sin^2\theta \ldots$

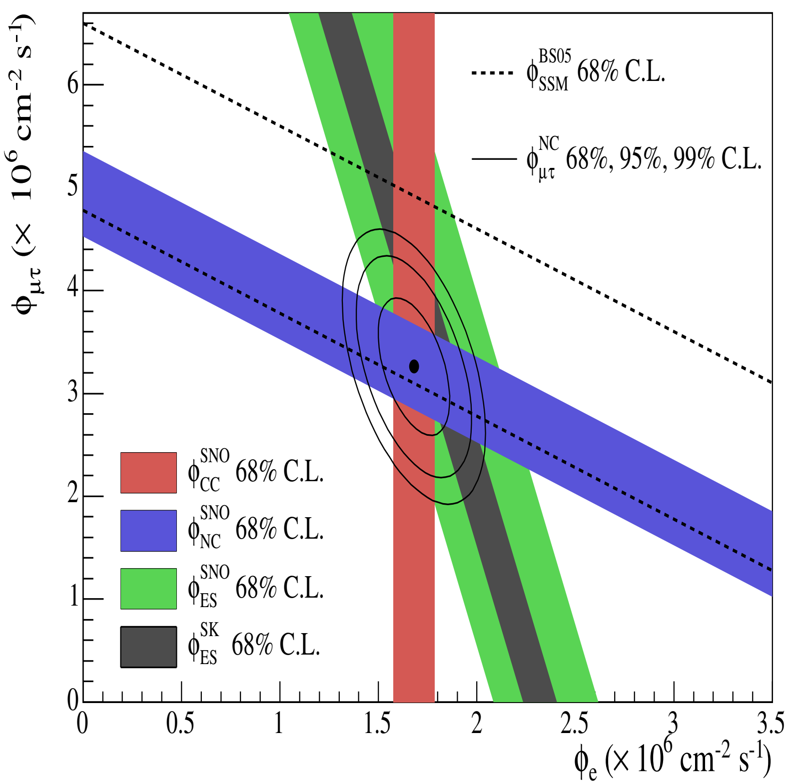
Solar Neutrinos: Experimental Results

- 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
Gallex/GNO/SAGE	${}^{71}Ga + \nu_e \rightarrow {}^{71}\ Ge + e^-$	0.553 ± 0.034
SK	$e^- + \nu_x \rightarrow e^- + \nu_x$	0.465 ± 0.014
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

- 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
- "Neutrino Oscillation" $\rightarrow$ Neutrino Mass and Mixing
- Standard Solar Model is correct

The Solar ^8B flux measured in SNO and SK



- SK:
  - $\phi_{ES} = 2.35 \pm 0.09[\times 10^6/cm^2/s]$
- SNO
  - $\phi_{CC} = 1.68 \pm 0.01[\times 10^6/cm^2/s]$
- SNO
  - $\phi_{NC} = 4.94 \pm 0.43[\times 10^6/cm^2/s]$
- SSM (BP04)
  - $\phi_{SSM} = 5.82 \pm 1.33[\times 10^6/cm^2/s]$

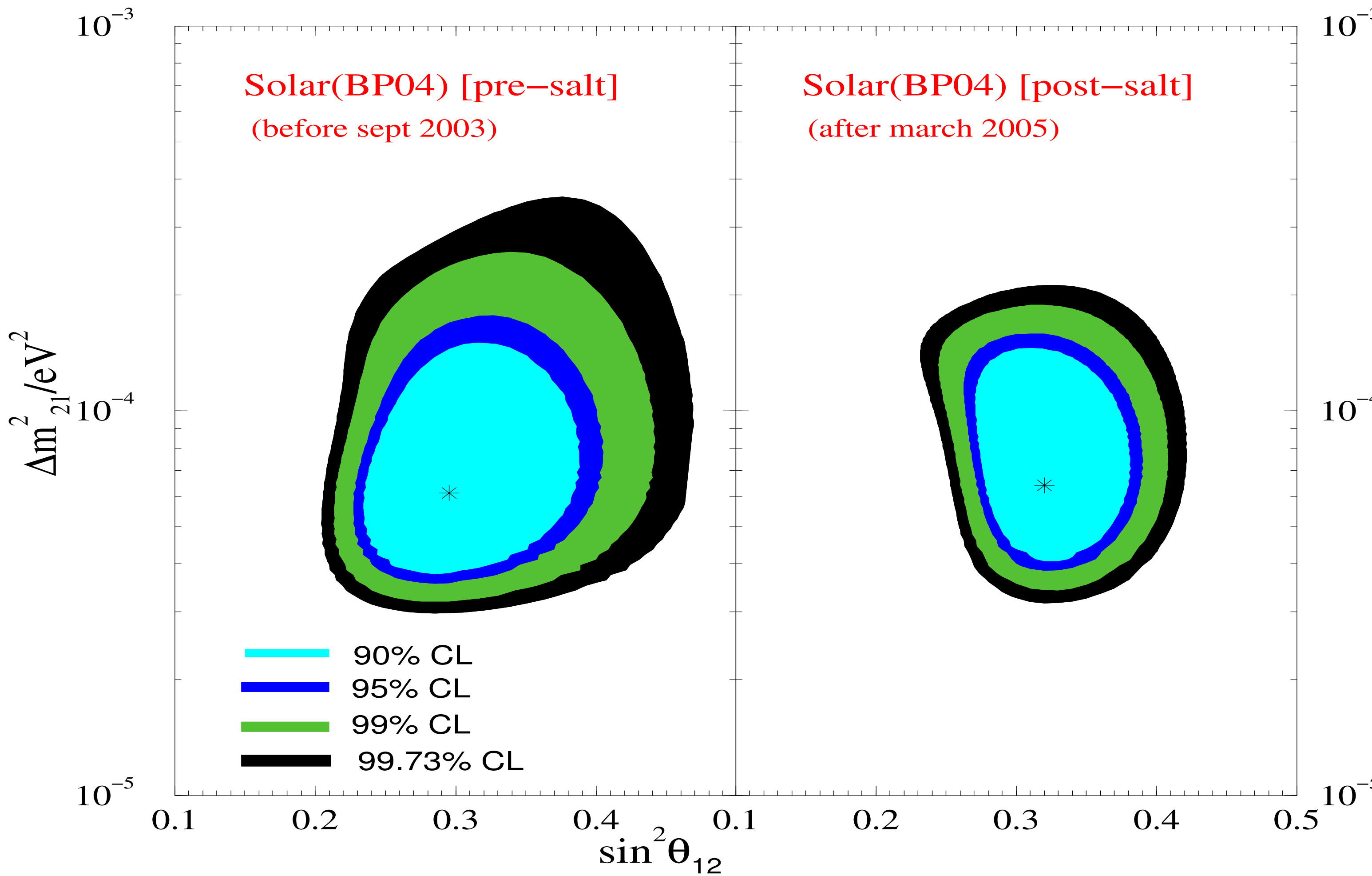
SNO-II 391d, nucl-ex/0502021

$\frac{CC}{NC} = 0.340 \pm 0.023 \pm 0.030$

7σ evidence for a non-zero $\nu_{\mu,\tau}$ flux from SUN

Solar Neutrinos: Status of Oscillation Parameters

- $\Delta m^2_\odot \equiv \Delta m^2{}_{21}$, $\theta_\odot \equiv \theta_{12}$ from Global Solar Data
- Including the Spectral data from SNO and SK



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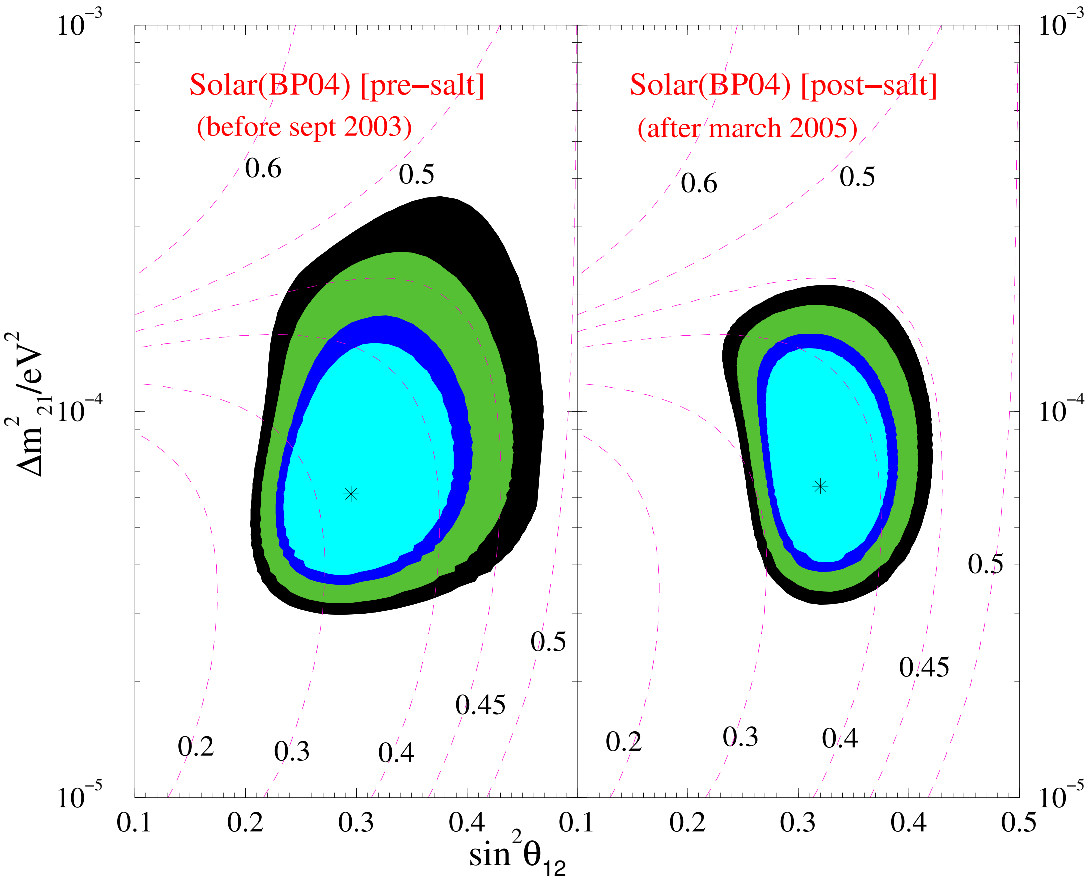

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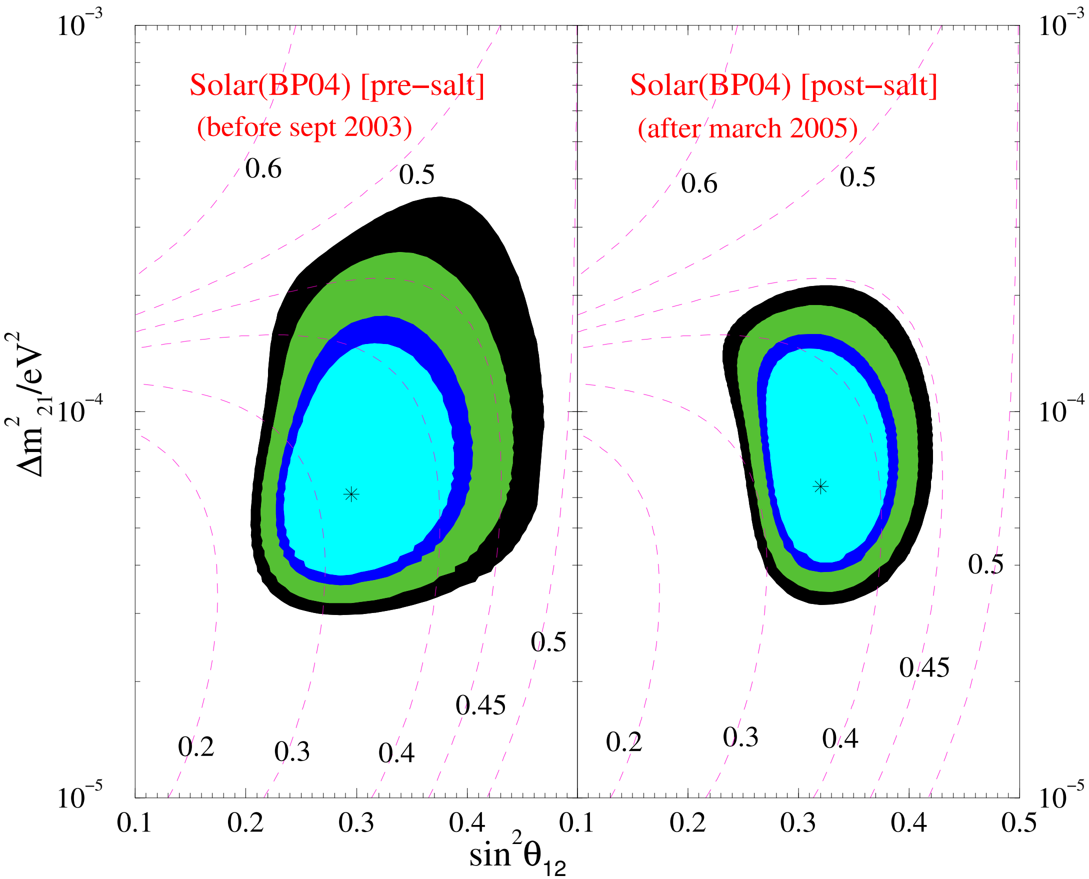

•Best fit

Δm^2_{21} =6.4 $\times 10^{-5}$eV^2
$\sin^2\theta_{12}$ = 0.33 f_B=0.84

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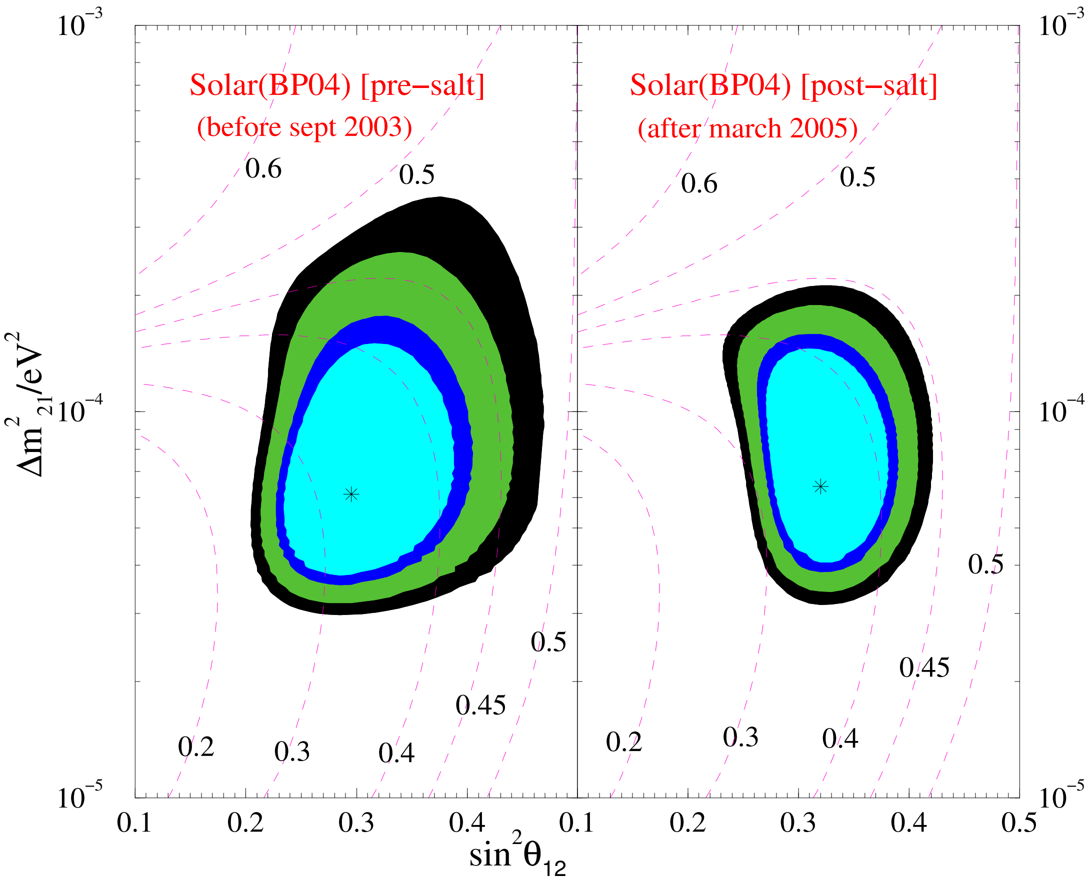


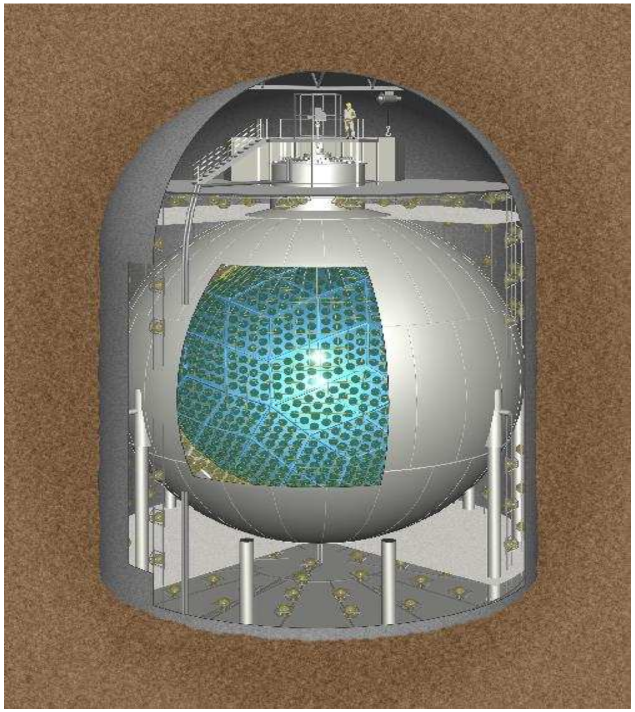
- Best fit

Δm^2_{21} $=6.4 \times 10^{-5}$eV^2
$\sin^2\theta_{12}$ = 0.33 f_B=0.84

- 3 σ range($\Delta\chi^2 = 11.83$)

Δm^2_{21} =(3.0-17) $\times 10^{-5}$eV^2
$\sin^2\theta_{12}$ = 0.21 -0.39

KamLAND

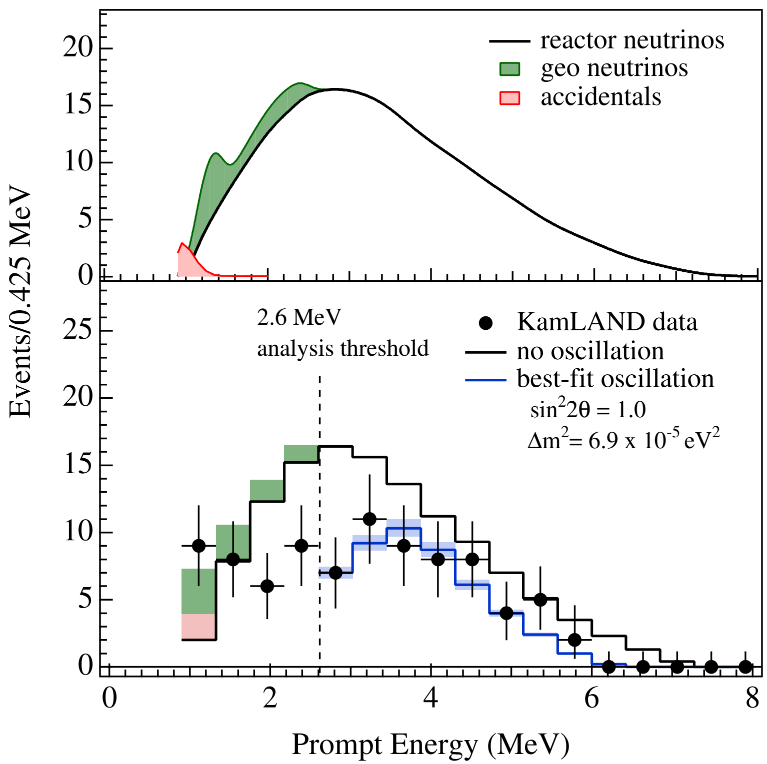


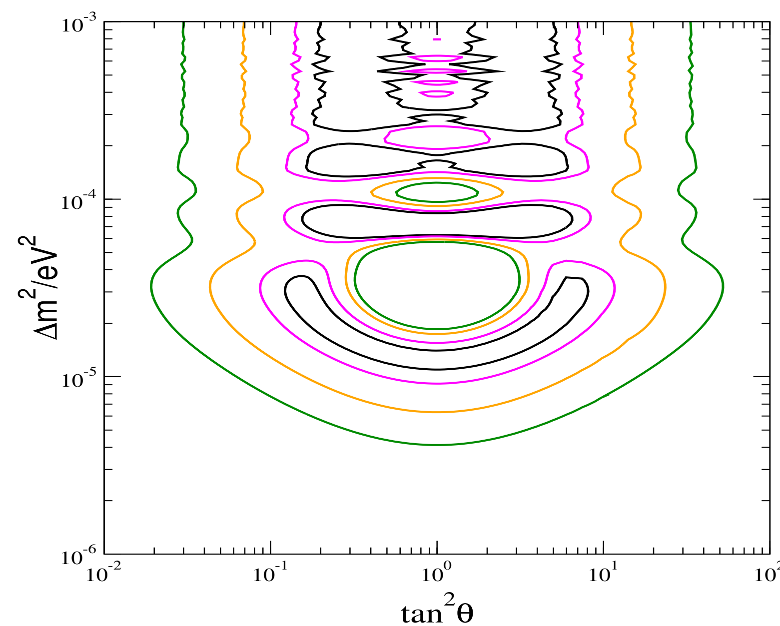
- 1 kton liquid scintillator neutrino detector at Kamioka
- $\bar{\nu}_e$ source: 16 main reactors at distances 81-824 km
- most powerful reactors are at 160 km
- detects reactor antineutrinos through: $\bar{\nu}_e + p \rightarrow n + e^+$
- $E_\nu \sim$ 3 MeV, L $\sim$ 1.8 $\times 10^5$ m , $\Delta m^2 \sim 1.6 \times 10^{-5}$ eV^2

Impact of KamLAND on Oscillation Parameters

First KamLAND results

- Evidence of $\bar{\nu}_e$ disappearance





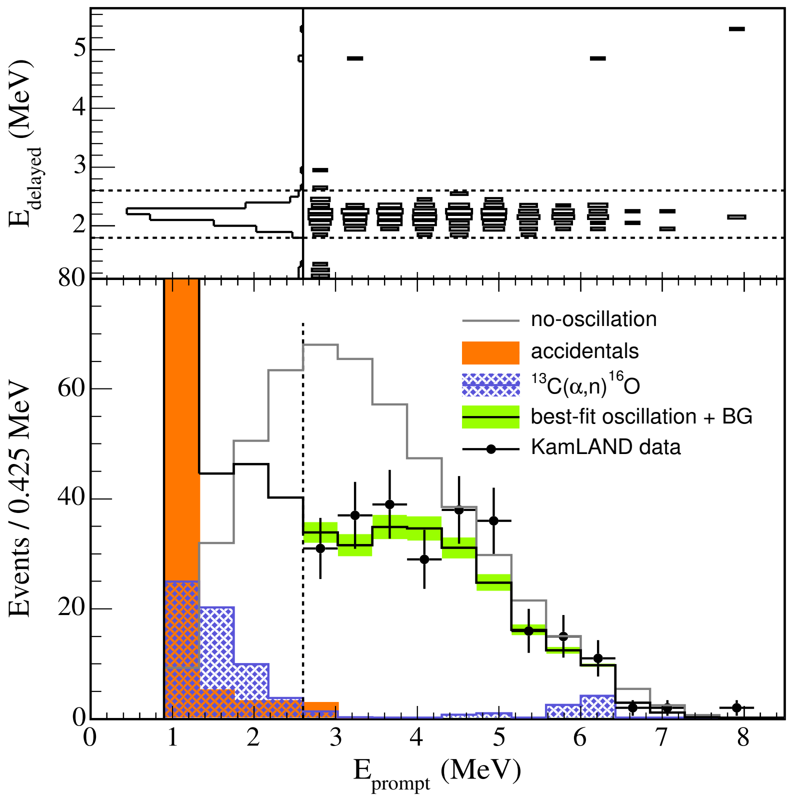
KamLAND Collaboration, PRL 2003

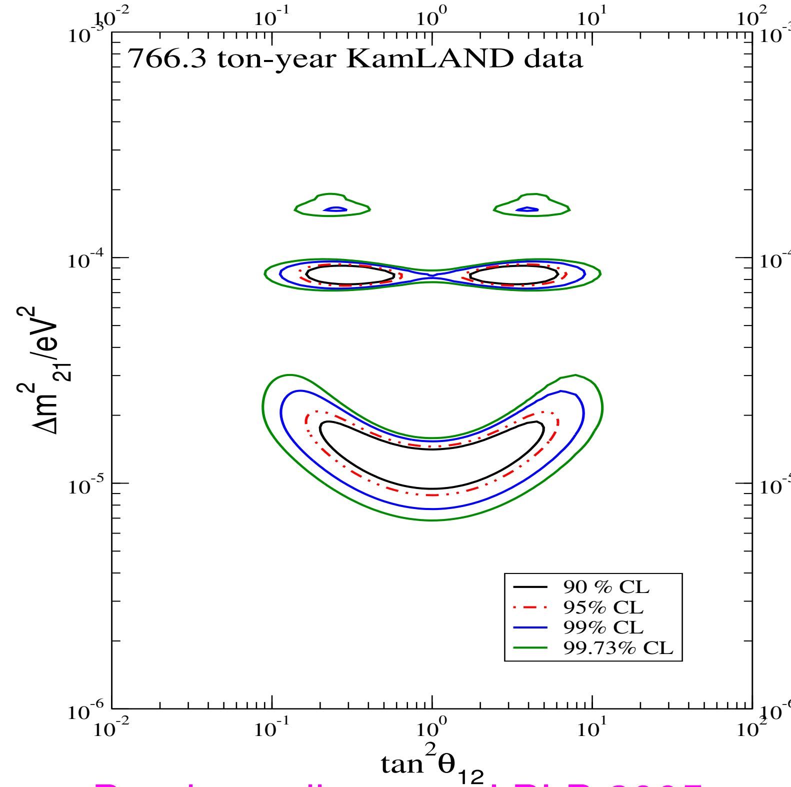
Bandyopadhyay et al,PLB,2003

Impact of KamLAND on Oscillation Parameters

Second KamLAND results

- Evidence for spectral distortion at 99.6% significance



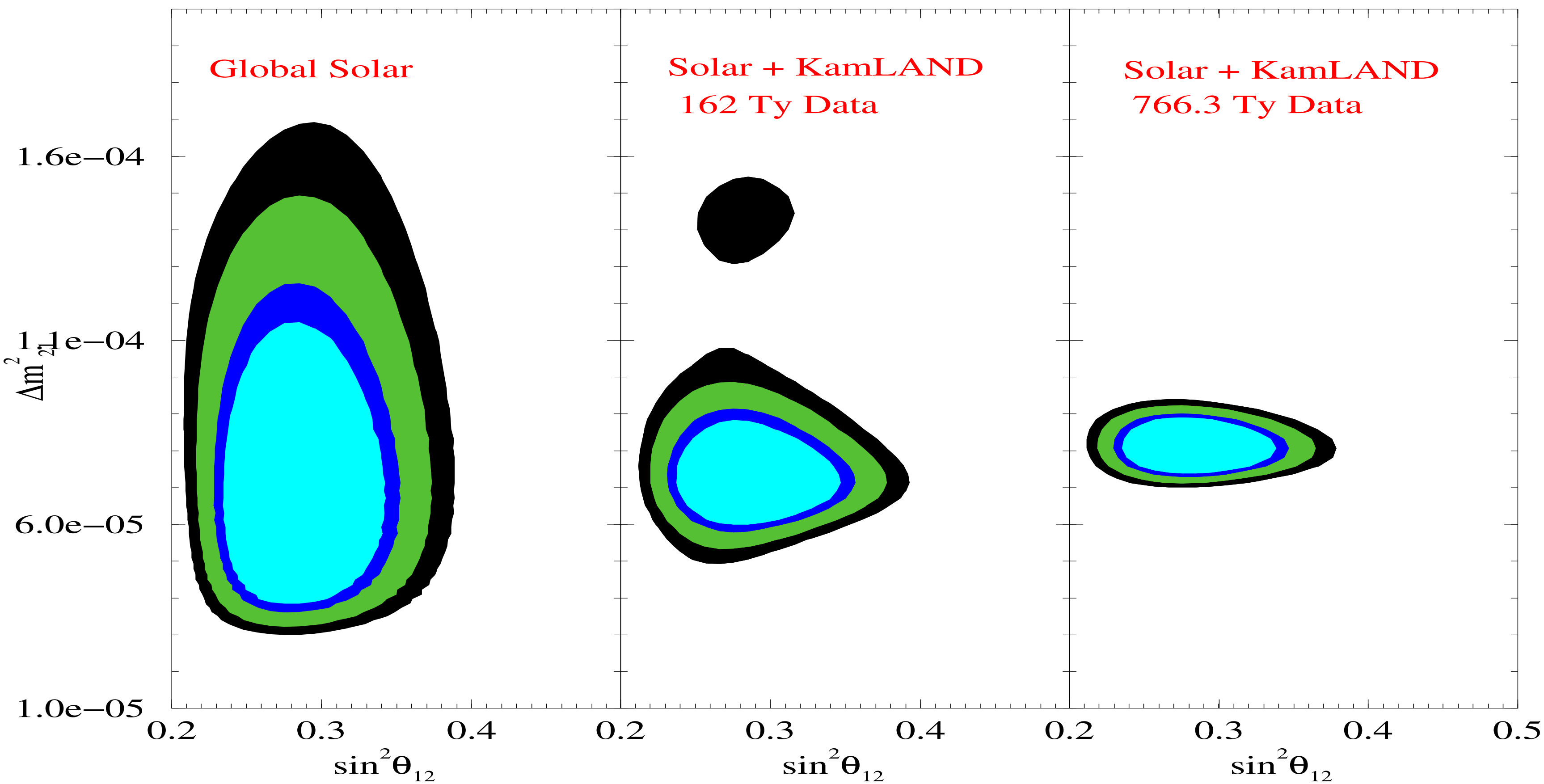


KamLAND Collaboration, PRL 2005

Bandyopadhyay et al,PLB 2005

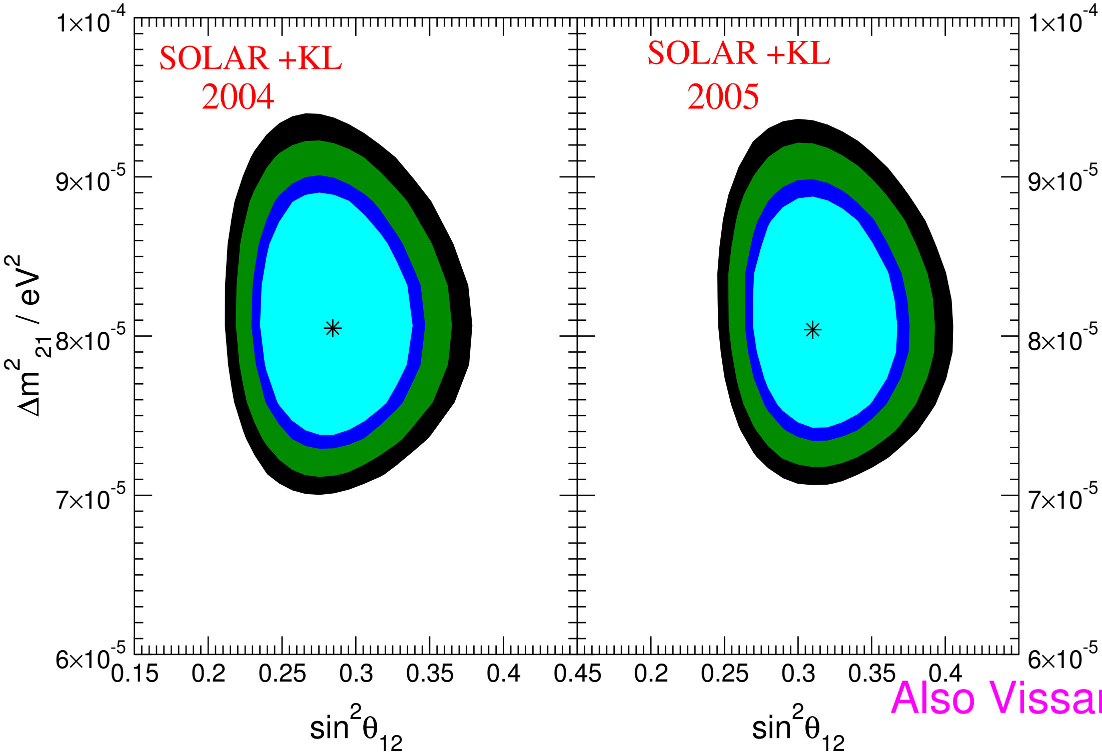
Impact of KamLAND on Oscillation Parameters

- 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

Status of Solar Neutrino Oscillation Parameters



Best-fit (Solar+KamLAND)

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

3σ range (Solar+KamLAND)

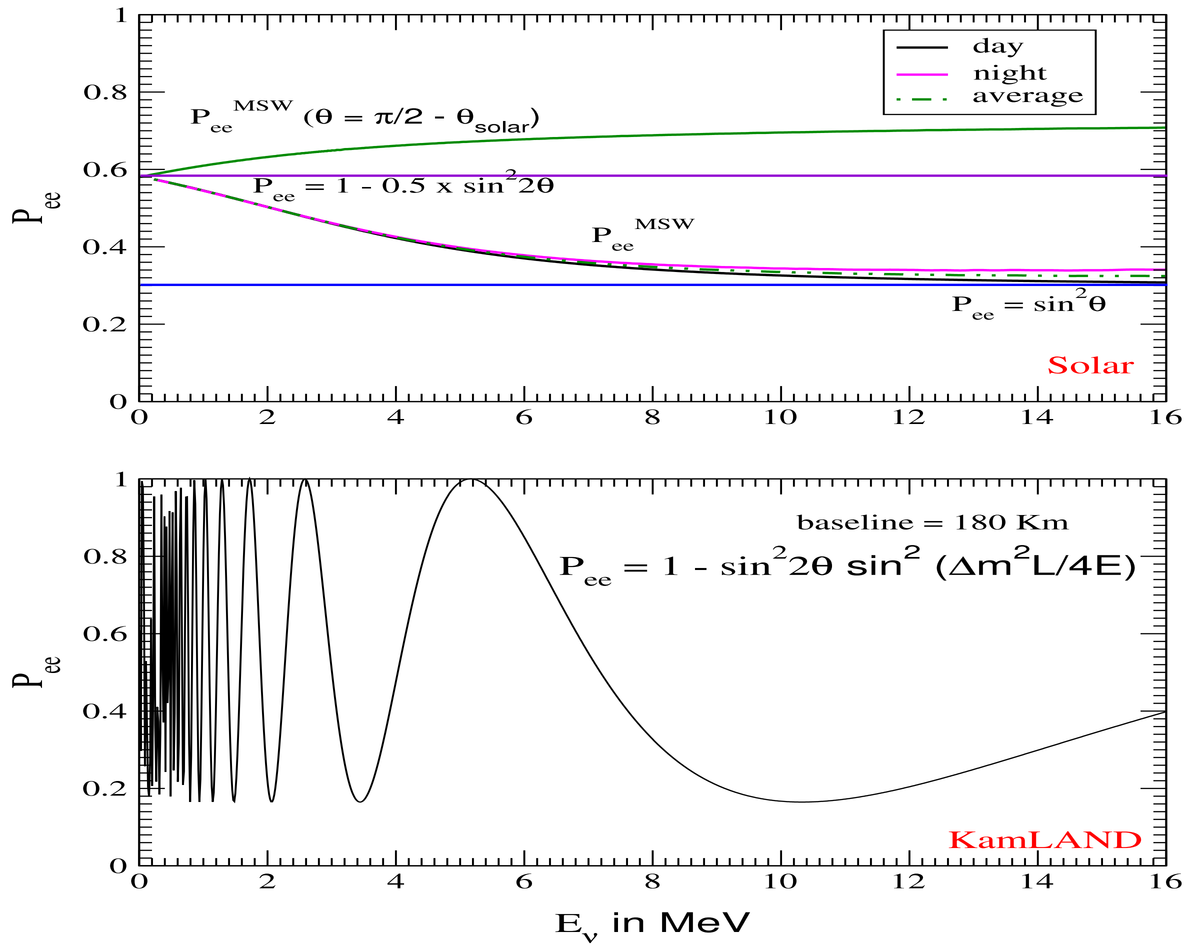
Δm^2_{21} =(7.0-9.3) $\times 10^{-5}$eV^2
$\sin^2\theta_{12}$ = 0.24 -0.41

Bandyopadhyay et al, 2005

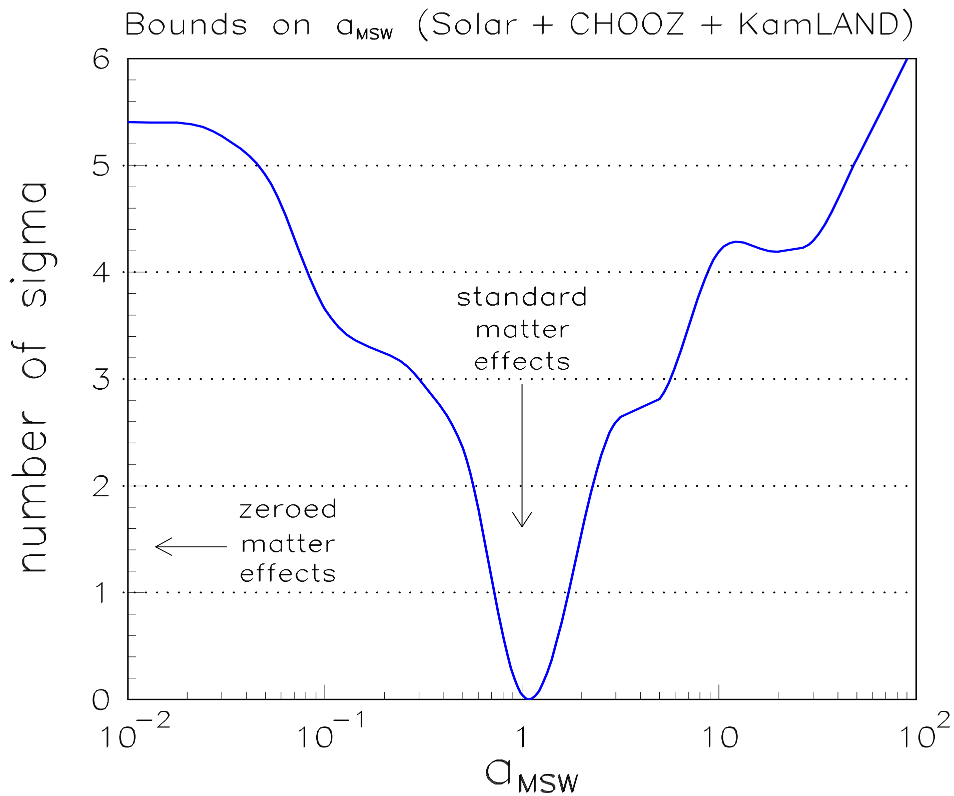
Also Vissani and Strumia, Fogli et. al, Maltoni et al.

- Maximal mixing ruled at almost 6σ

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

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

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

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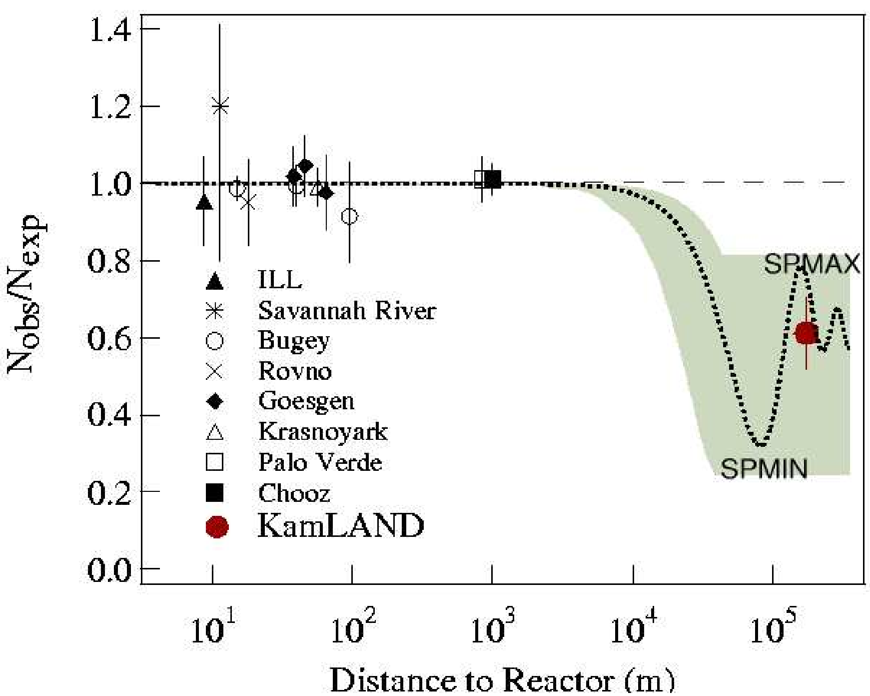
- KamLAND has tremendous sensitivity to $\Delta m^2{}_{21}$
- Does not constrain θ_{12} much better than the current set of solar experiments

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 . . .

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

Cosmic Ray + $A_{air} \longrightarrow \pi^+ + \ldots$

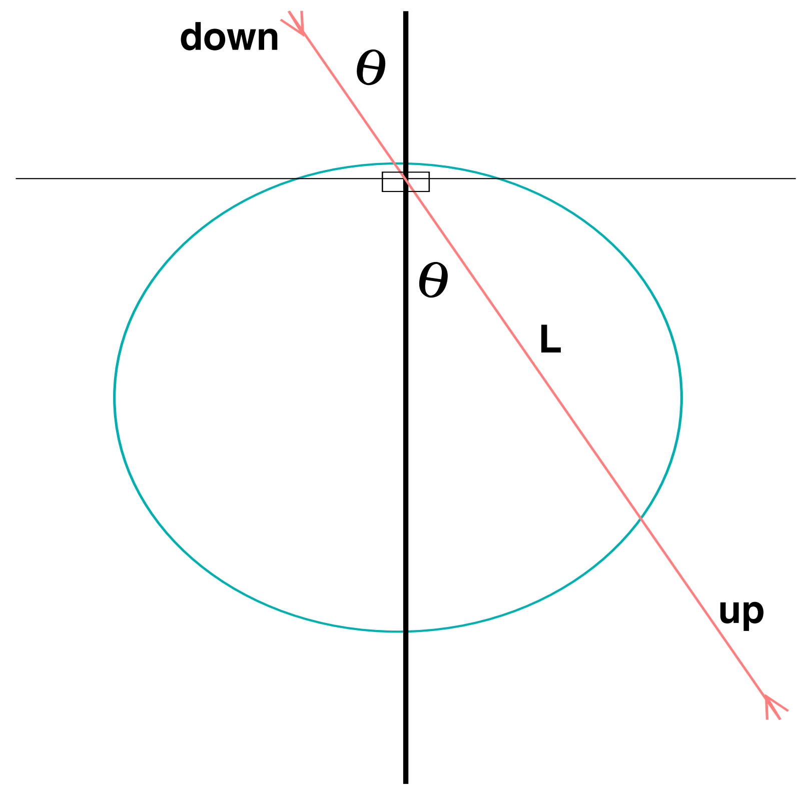
$\pi^+ \longrightarrow \mu^+ + \nu_\mu$

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

$\nu_\mu : \nu_e$ = 2: 1 (expected)

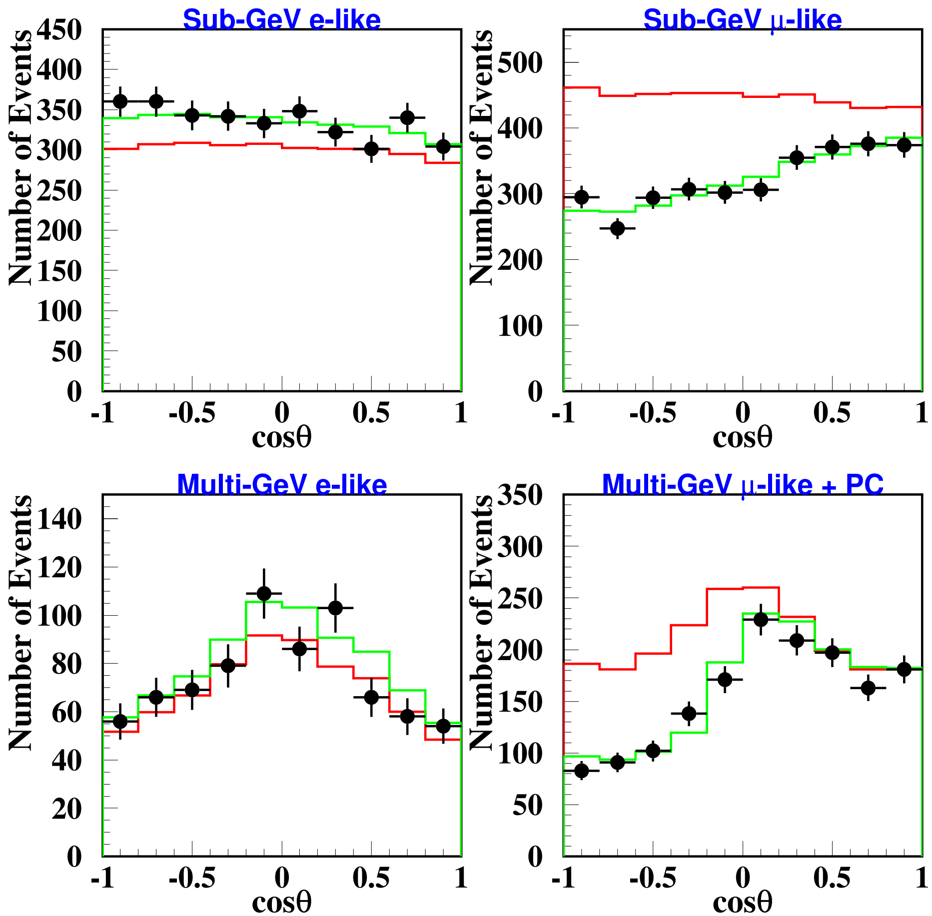
$\nu_\mu / \nu_e \sim$ 0.9 – 1 (observed)

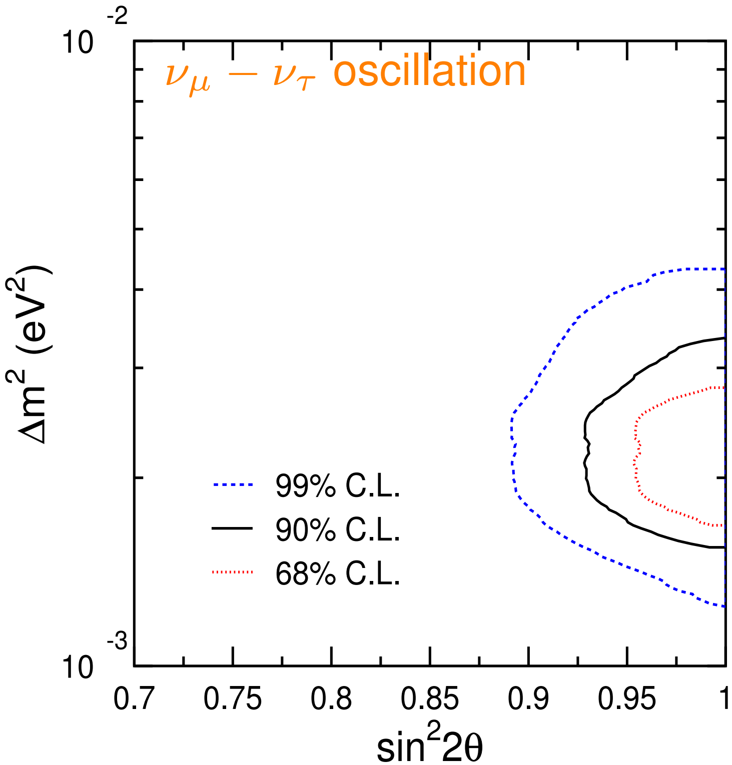
Up-Down asymmetry



Oscillation Parameters from Atmospheric Neutrinos

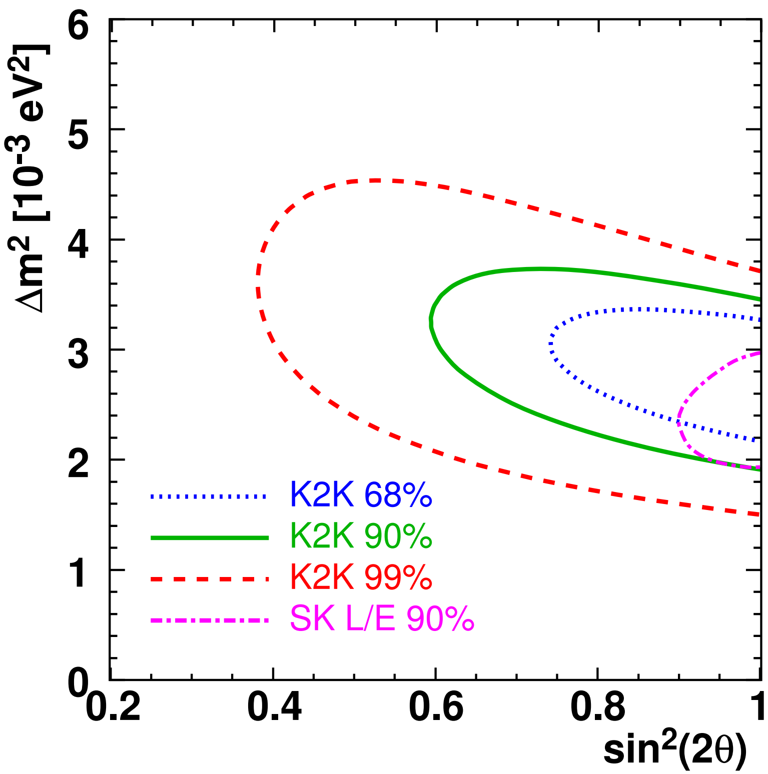
- SK-I 1489 days zenith angle spectrum





Δm^2_{atm} = 2.0 $\times 10^{-3}$ eV^2,
$\sin^2 2\theta_{atm} = 1.0$

K2K



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

•Best-fit

Δm^2_{atm} = 2.8 $\times 10^{-3}$ eV^2
$\sin^2 2\theta_{atm} = 1.0$

MINOS

(Main Injector Neutrino Oscillation Search)

- NuMI beam produced at Fermilab
- 92.9% $\bar{\nu}_\mu$, 1.2% ν_e, 0.1% $\bar{\nu_e}$
- Mean Energy $\sim$ 3 GeV
- Far detector at Soudan Mine (L = 735 km)
- 5.5 kT steel-scintillator tracking calorimeters with toroidal magentic fields $\sim$ 1.3 T
- Oscillation Maximum at $\sim$ 1.5 GeV for $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2

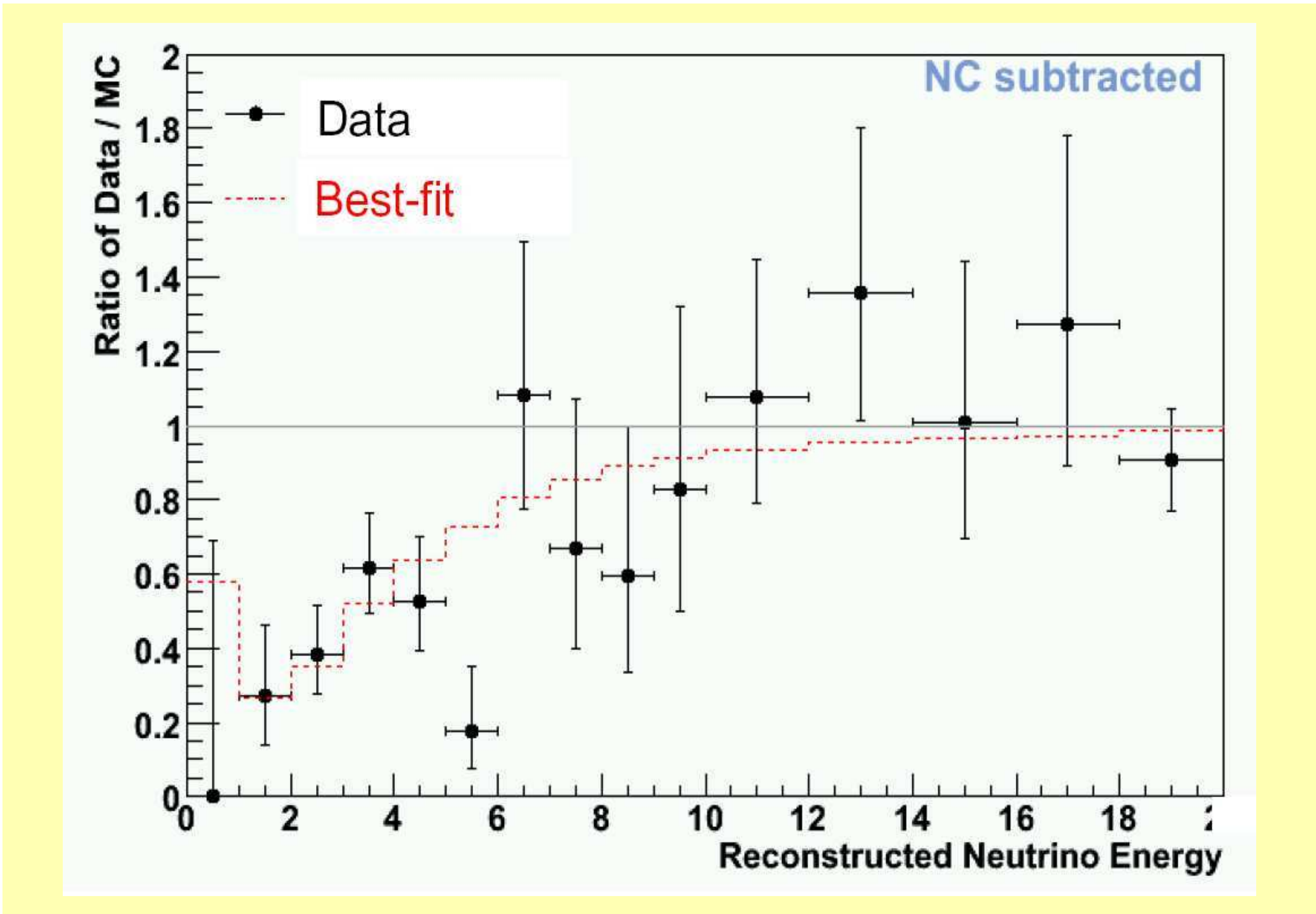
First Results from MINOS

data taken from 20 May to 6 Dec 2005
(0.93×10^{20} p.o.t.)
presented in a talk at Fermilab on 30 March 2006

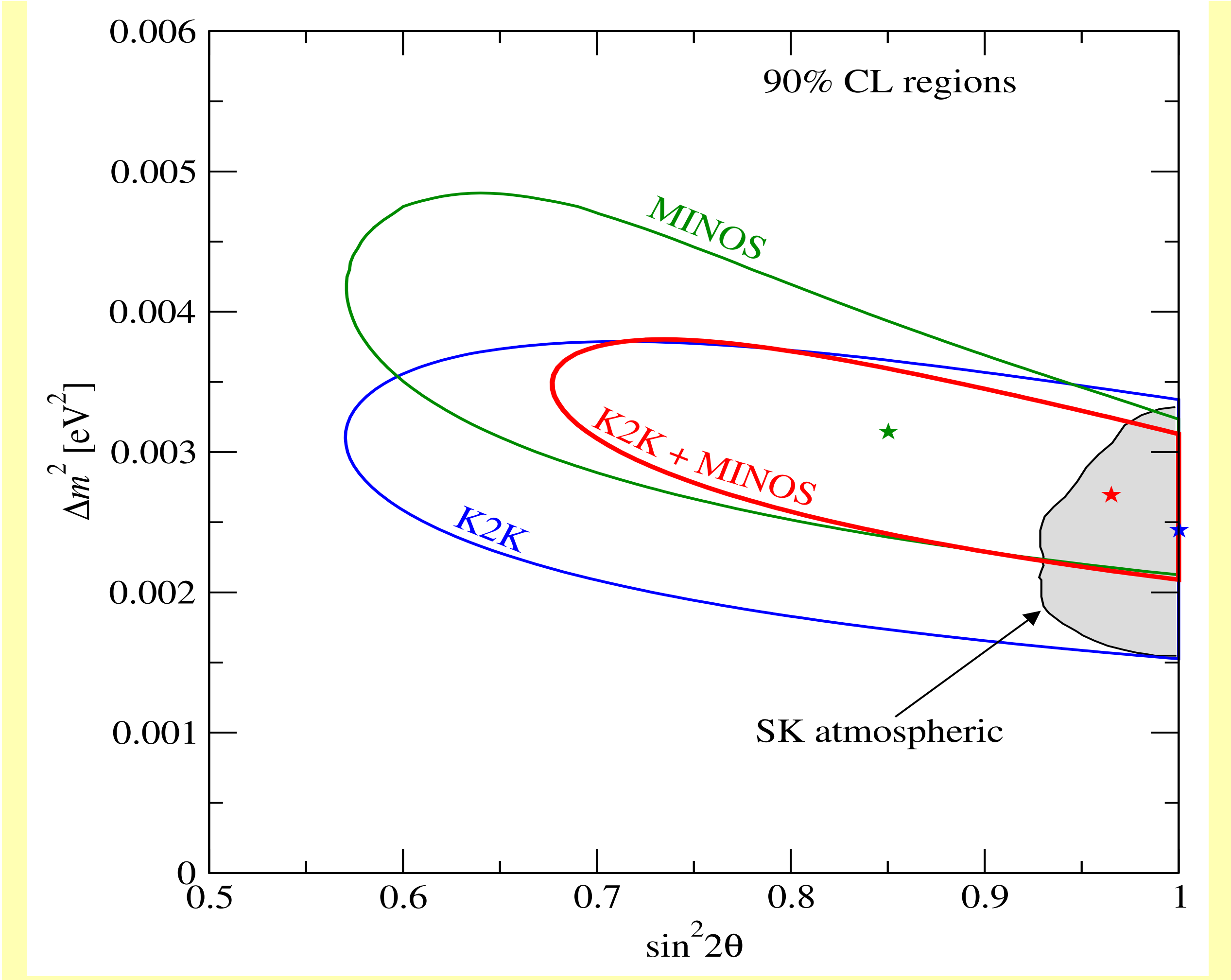
http://www-numi.fnal.gov/talks/results06.html

Data sample	observed	expected	ratio	significance
All CC-like events ($\nu_\mu + \bar{\nu}_\mu$)	204	298±15	0.69	4.1σ
ν_μ only (<30 GeV)	166	249±14	0.67	4.0σ
ν_μ only (<10 GeV)	92	177±11	0.52	5.0σ

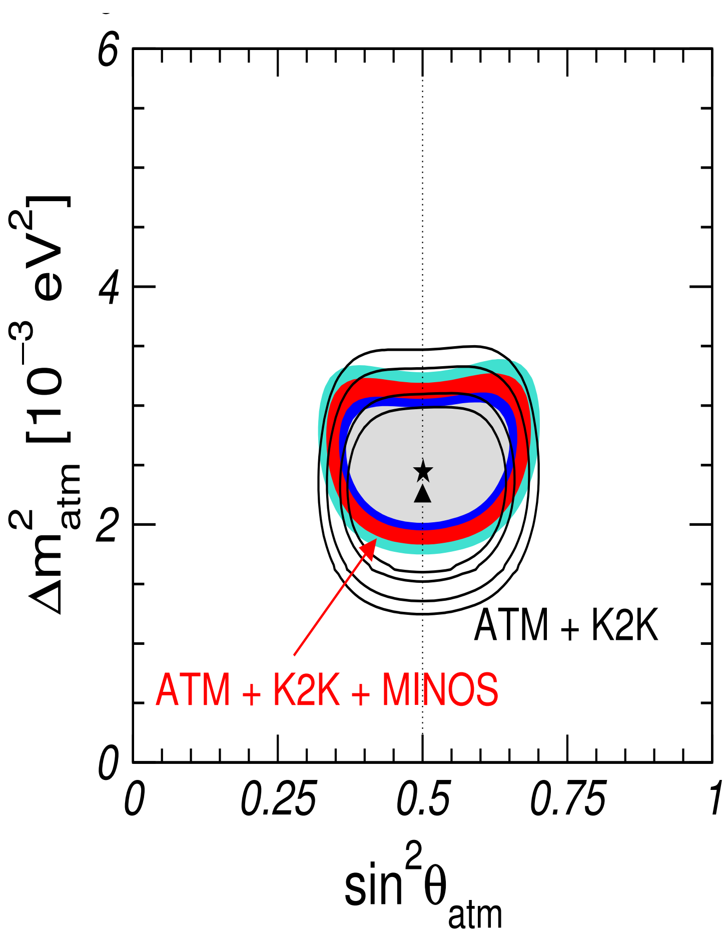
First Results from MINOS



Atmospheric parameters from MINOS



Status of Atmospheric parameters



Exp	bf	3σ range
	Δm^2_{31} [10^{-3} eV^2]	
SK	2.0	$1.0 - 3.8$
$SK + K2K$	2.4	$1.4 - 3.3$
$SK + K2K$ $+MINOS$	2.5	$1.8 - 3.3$
	$\sin^2\theta_{23}$	
SK	0.5	$0.34 - 0.68$

Thomas Schwetz, 2006

- Precision

$\Delta m^2_{31} \sim$ 29% $\sin^2\theta_{23} \sim$ 33 %

Status of θ_{13}

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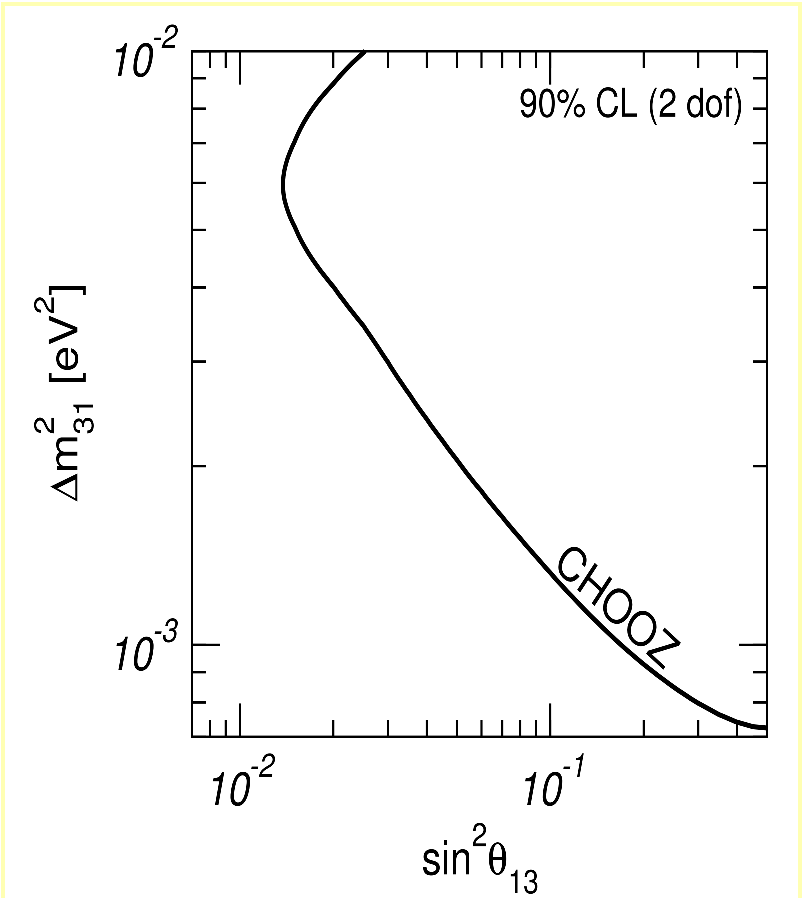

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2 \Delta m^2_{31} L/4E$$

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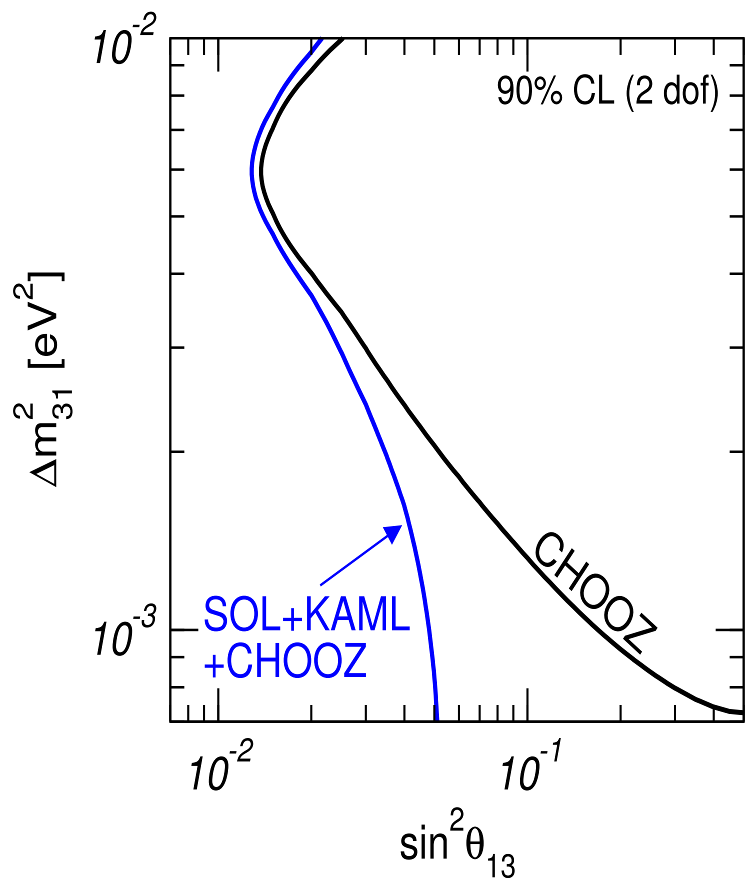

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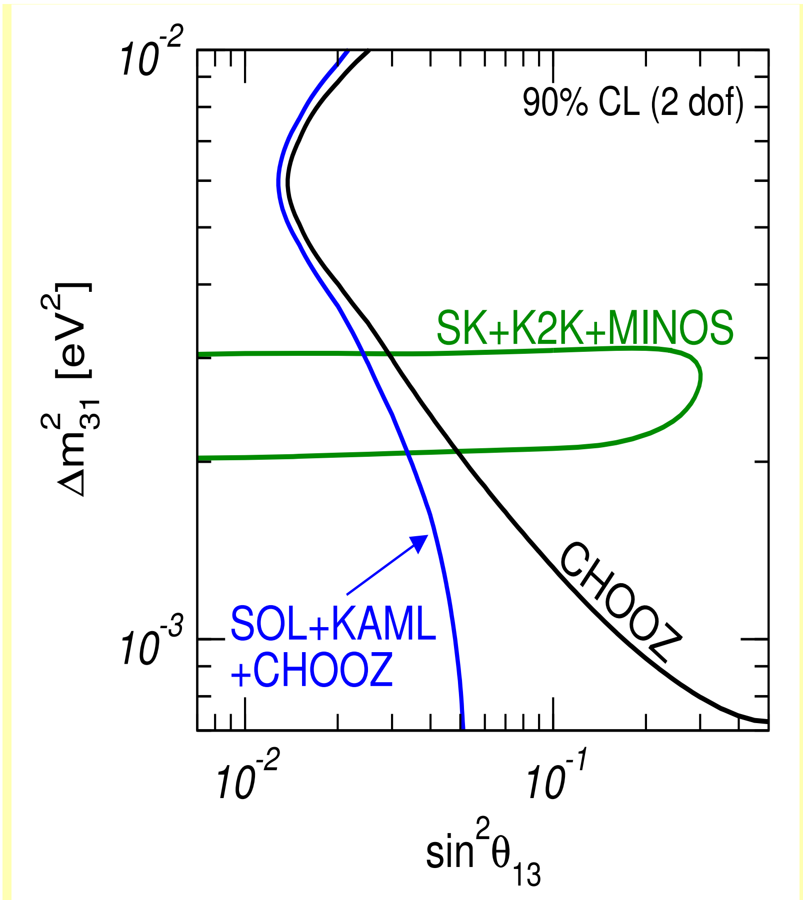

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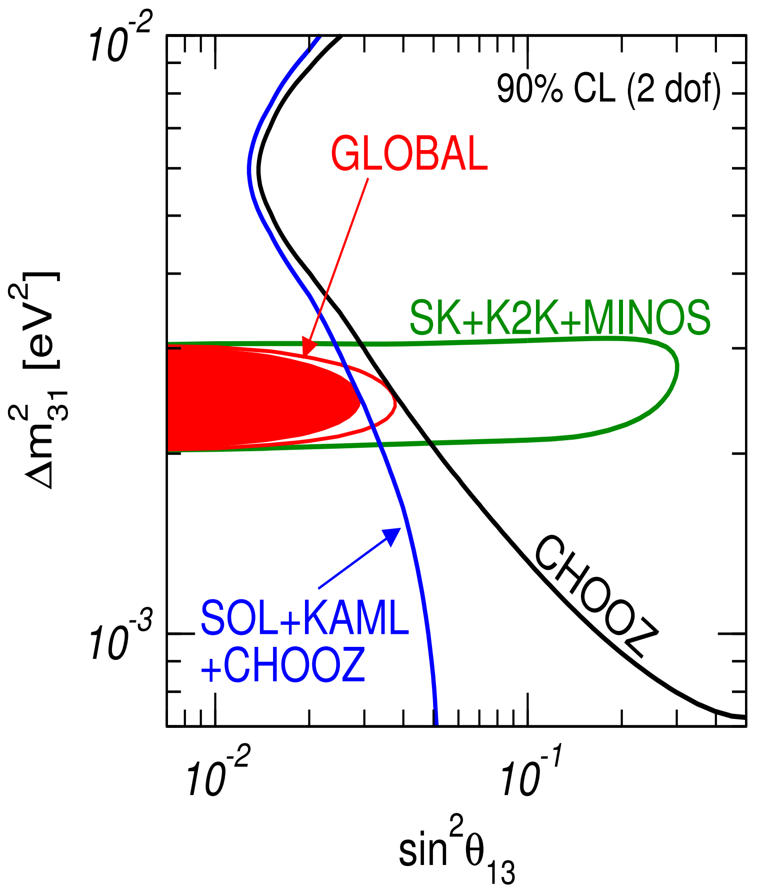

Thomas Schwetz, 2006, Maltoni *et al.* hep-ph/0405172

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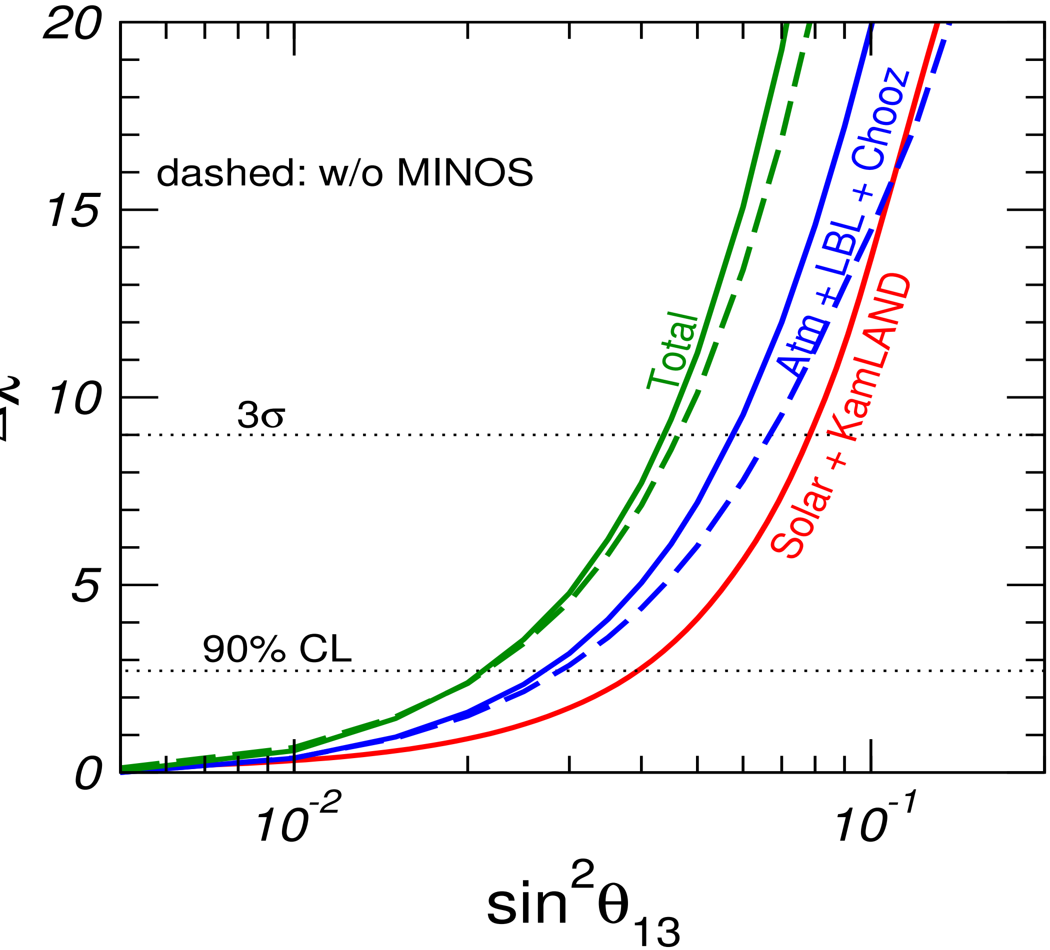


3σ bounds with (w/o) MINOS:

Solar+KamLAND:

$\sin^2\theta_{13} < 0.079$

Atm+Chooz+LBL:

$\sin^2\theta_{13} < 0.058\,(0.067)$

Global:

$\sin^2\theta_{13} < 0.044\,(0.046)$

Thomas Schwetz, 2006, Maltoni *et al.* hep-ph/0405172

Absolute Neutrino Masses

- Tritium β-deay

$$m_{\nu_e} = \left(\Sigma|U_{ei}|^2 m_i^2\right)^{\frac{1}{2}}$$
$$= \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

- Neutrinoless double beta decay

$$m_{ee} = |\ \Sigma U_{ei}^2 m_i\ |$$
$$= |\ c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\ |$$

- Cosmology

$$m_{cosmo} = \Sigma m_i$$

Bound on Neutrino Mass from Cosmology

- Different upper bounds from different groups
  - Some recent bounds (95% C.L.)

Reference	upper bound on m_{cosmo}
Elgaroy $et al.$, 02	1.8 eV
Danchez $et al.$, 05	1.2 eV
Goobar $et al.$, 06	0.62 eV
Fukugita $et al$, 06	2.0 eV
Spergel $et al.$, 06	0.68eV
Seljak $et al.$, 06	0.17eV
Kristiansen $et al.$, 06	1.4eV

Elgaroy et al., 2006

- The bound varies depending on the cosmological model and data sets used

Bound on Neutrino Mass from Cosmology

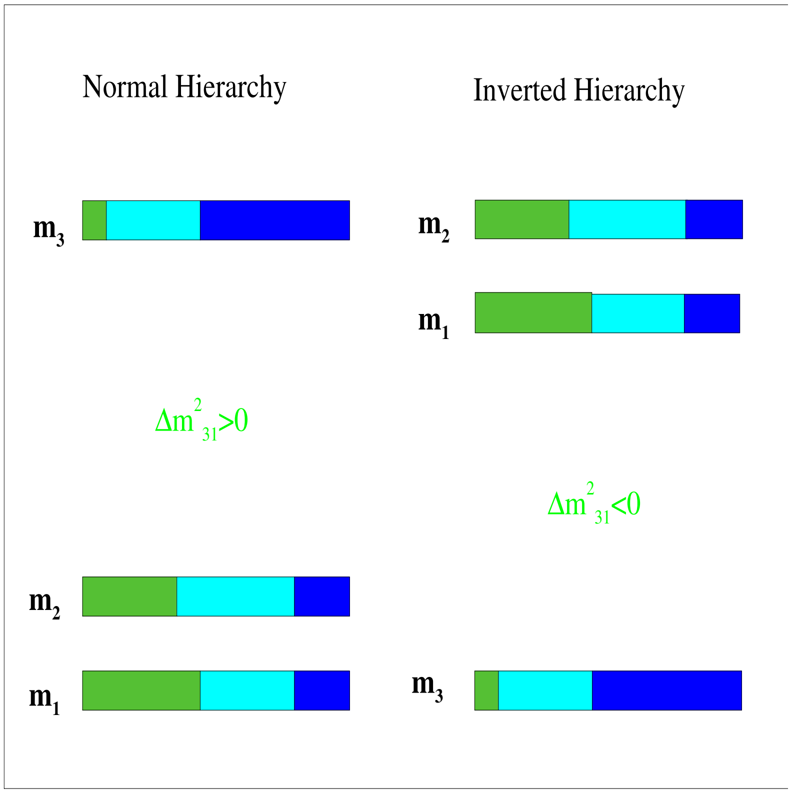
- Dependence of the bound on different combination of data sets used

Fogli *et al.*, 2006

TABLE II: Input cosmological data sets for seven representative cases considered in this work, together with their 2σ (95% C.L.) constraints on the sum of neutrino masses Σ.

Case	Cosmological data set	Σ bound (2σ)
1	WMAP	< 2.3 eV
2	WMAP + SDSS	< 1.2 eV
3	WMAP + SDSS + SN_{Riess} + HST + BBN	< 0.78 eV
4	CMB + LSS + SN_{Astier}	< 0.75 eV
5	CMB + LSS + SN_{Astier} + BAO	< 0.58 eV
6	CMB + LSS + SN_{Astier} + Ly-α	< 0.21 eV
7	CMB + LSS + SN_{Astier} + BAO + Ly-α	< 0.17 eV

Mass Squared Differences and Absolute Masses



- **Normal Hierarchy :**

$$m_3^2 = m_1^2 + \Delta m_{21}^2 + \Delta m_{32}^2$$
$$m_2^2 = m_1^2 + \Delta m_{21}^2$$

$$m_3^2 \approx \Delta m_{atm}^2 >> m_2^2 \approx \Delta m_{\odot}^2 >> m_1^2$$

- **Inverted Hierarchy :**

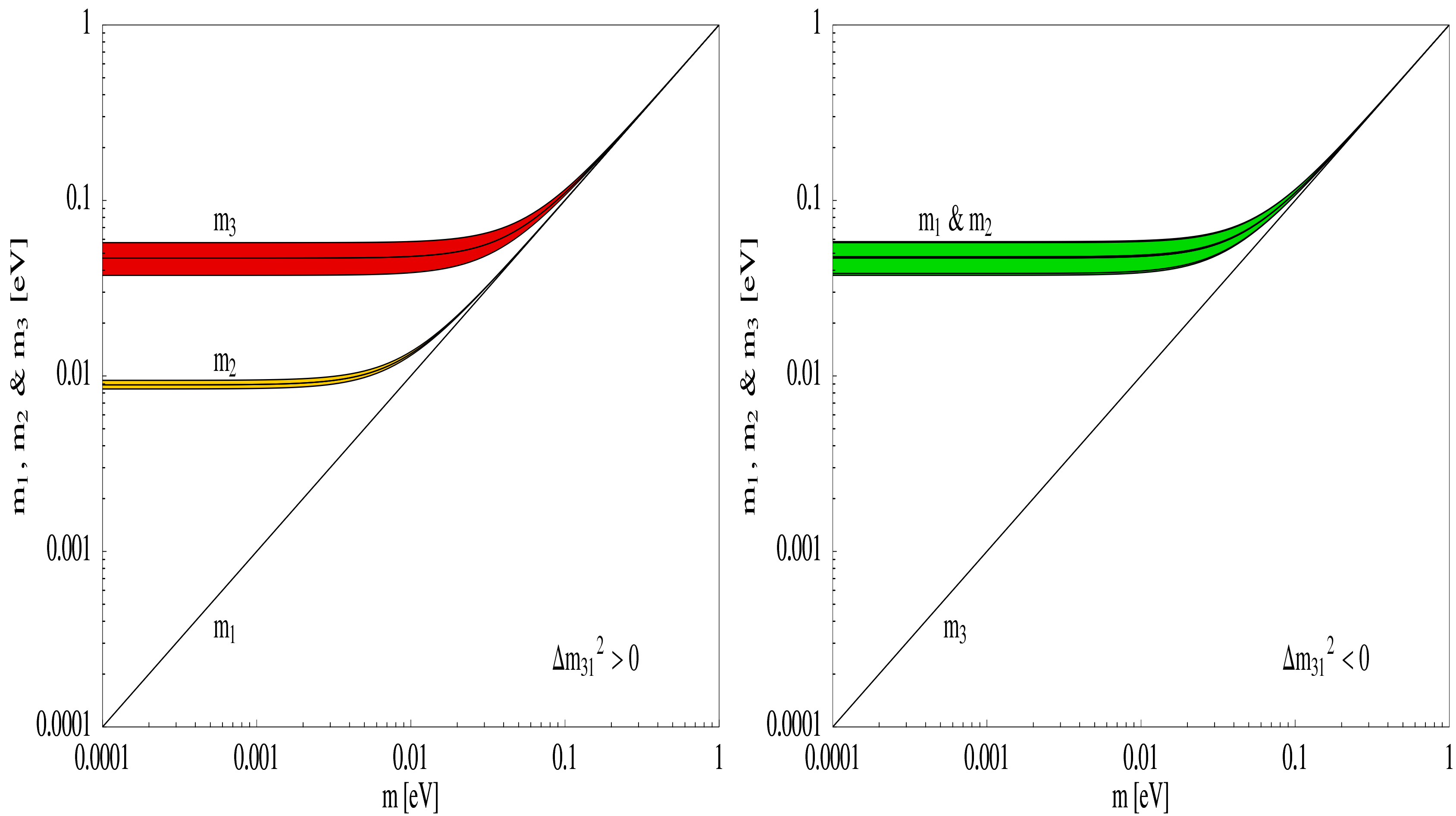
$$m_2^2 = m_3^2 + \Delta m_{23}^2$$
$$m_1^2 = m_3^2 + \Delta m_{23}^2 - \Delta m_{21}^2$$

$$m_2^2 \approx \Delta m_{atm}^2 \approx m_2^2 >> m_3^2$$

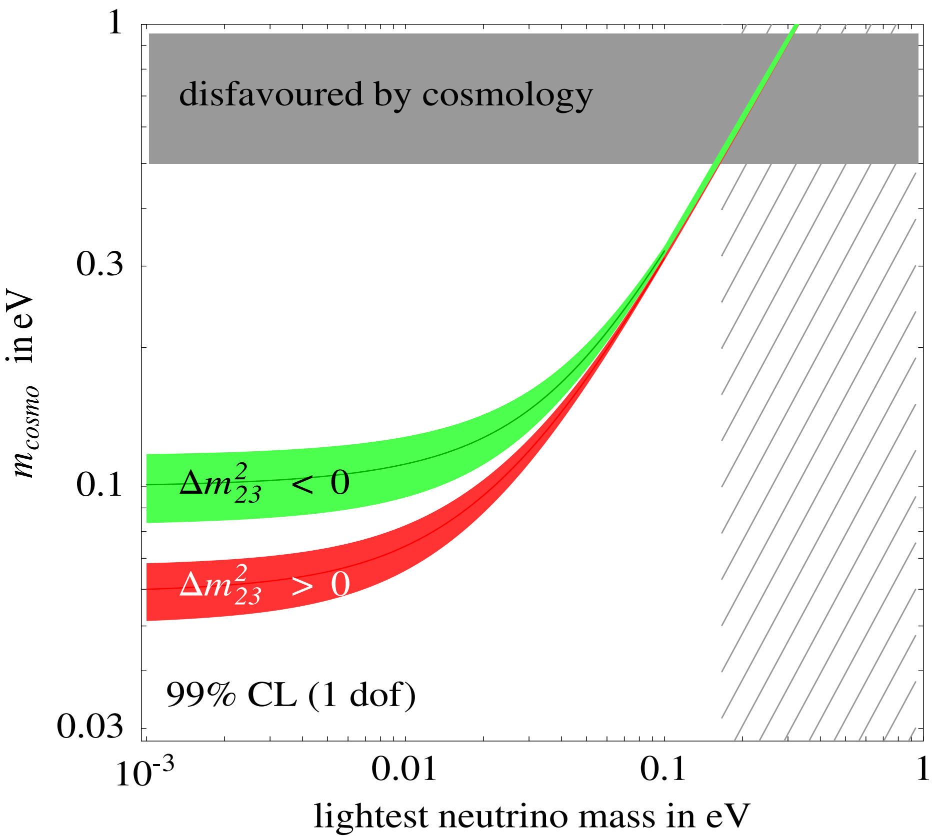
- **Quasi-Degenerate**

$$m_3 \approx m_2 \approx m_1 >> \sqrt{\Delta m_{atm}^2}$$

Mass Squared Differences and Absolute Masses

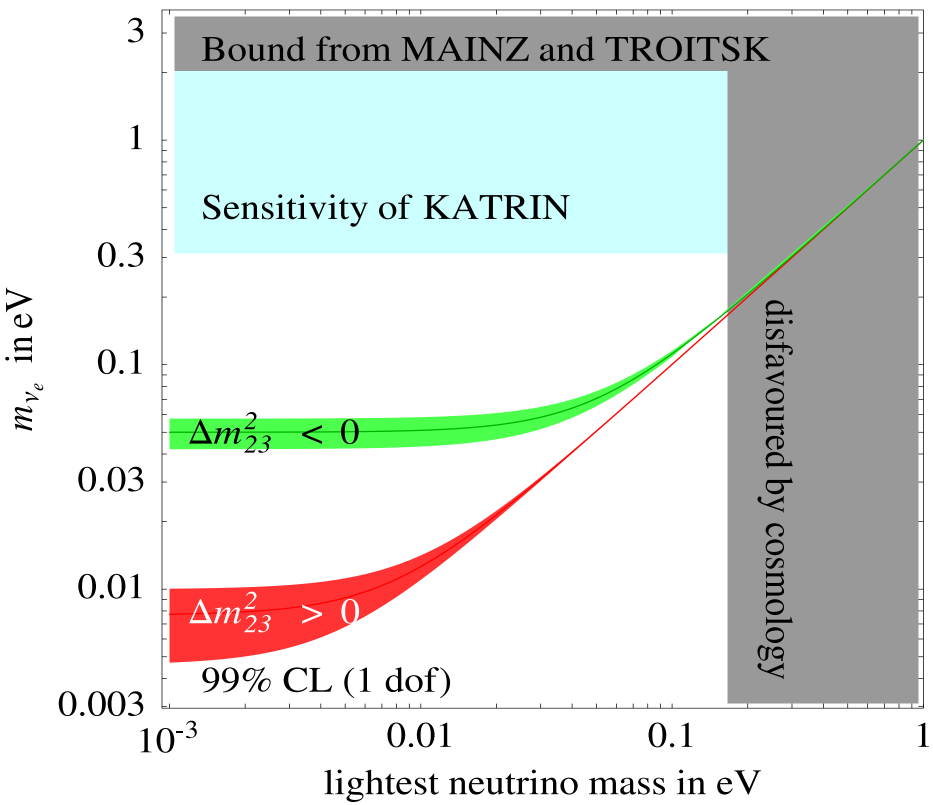


Sum of 3-neutrino masses vs the lightest mass



Vissani and Strumia, 2005

Tritium -decay and 3-neutrino masses



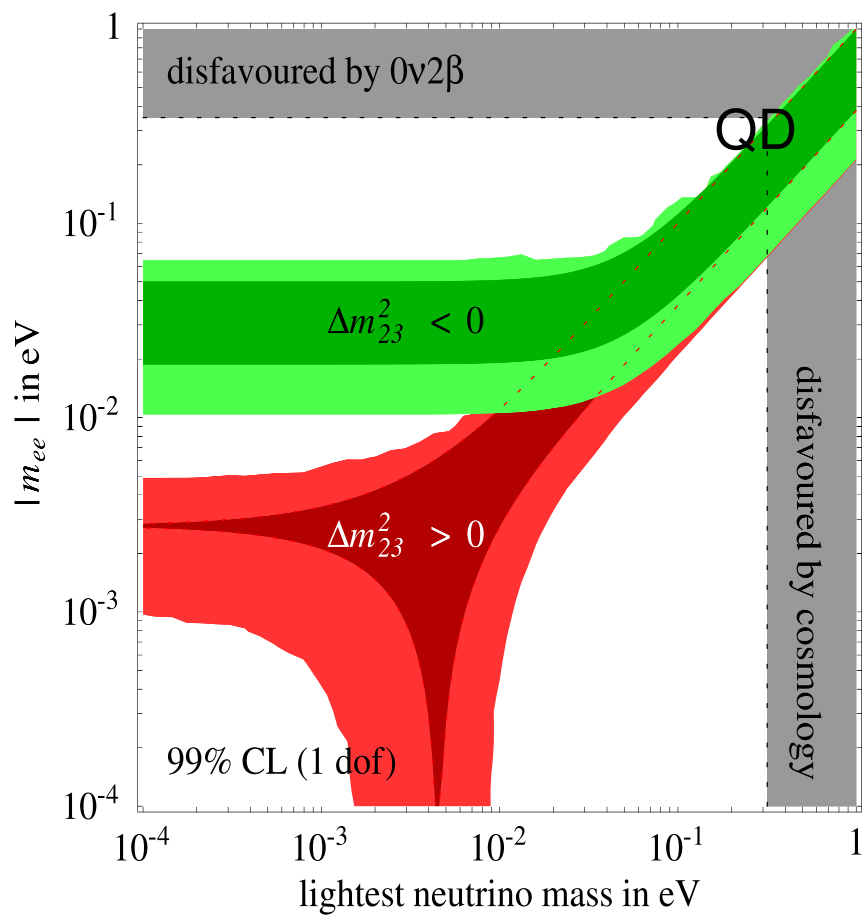
Vissani and Strumia, 2005

Neutrino Less Double Beta Decay

- Can establish Majorana nature of Neutrinos

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

- ν Mass Spectrum • Absolute ν Mass Scale • CP phases



Vissani and Strumia, 2005

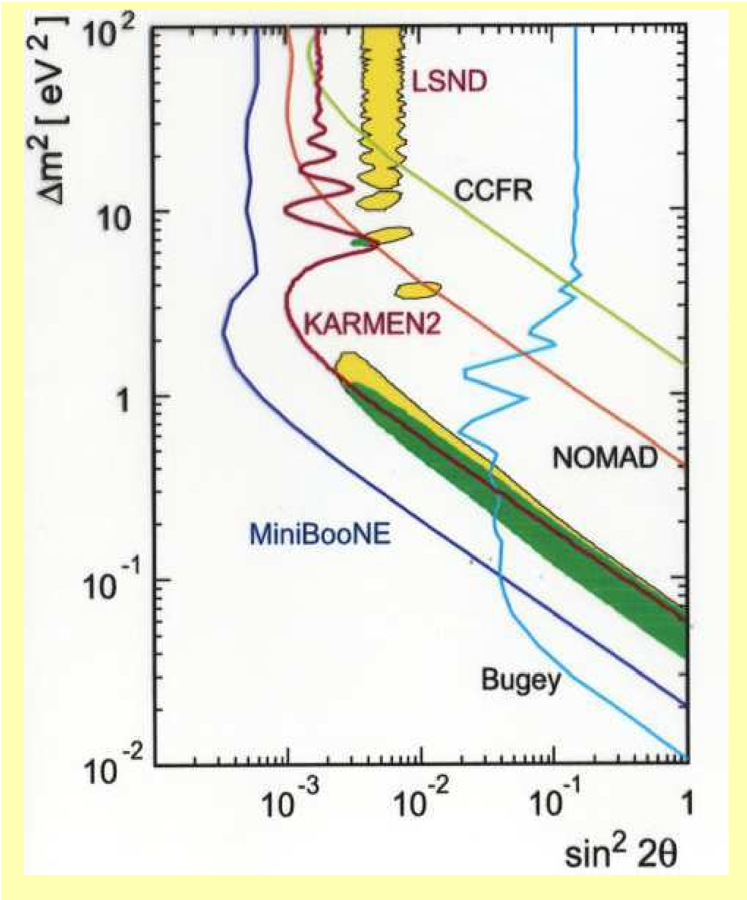
NH: $m_1 << m_2 << m_3$

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

The LSND Puzzle



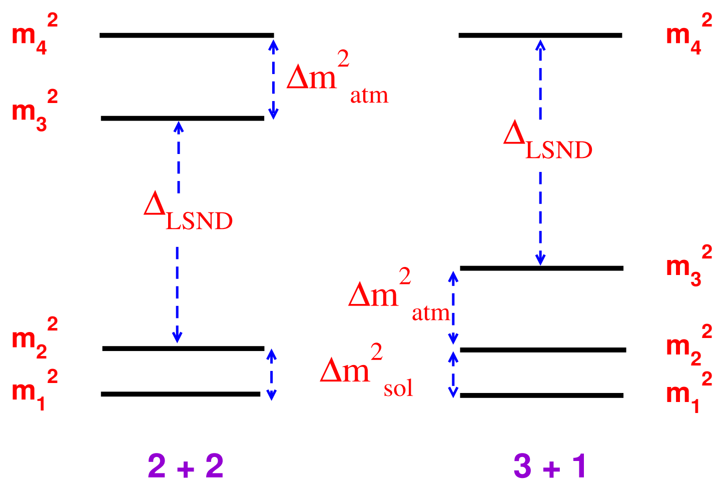
- LSND : Liquid Scintillator Neutrino Detector
- $\pi^+ \rightarrow \mu^+ \nu_\mu$
  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \rightarrow$ decay at rest
- $E \sim 36 - 60$ MeV, $L \sim 30m$
- $\bar{\nu_e}$ is detected by correlating in position and time with a γ produced by $\bar{\nu}_e + p \rightarrow e^+ + n$
  $np \rightarrow d\gamma$ (2.2 MeV)
- Positive evidence of $\bar{\nu}_\mu - \bar{\nu}_e$ oscillation

$87.9 \pm 22.4 \pm 6.0$ excess $\bar{\nu}_e$ events

$P(\bar{\nu}_\mu - > \bar{\nu}_e)$ = $0.264 \pm 0.067 \pm 0.045$

Accommodating the LSND Signal

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



One additional sterile neutrino

2+2 and 3+1 mass schemes

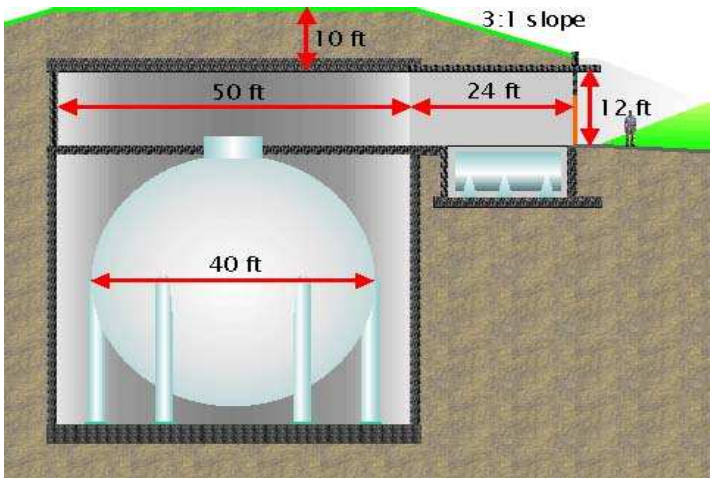
2+2 ruled out by solar and atmosph
data

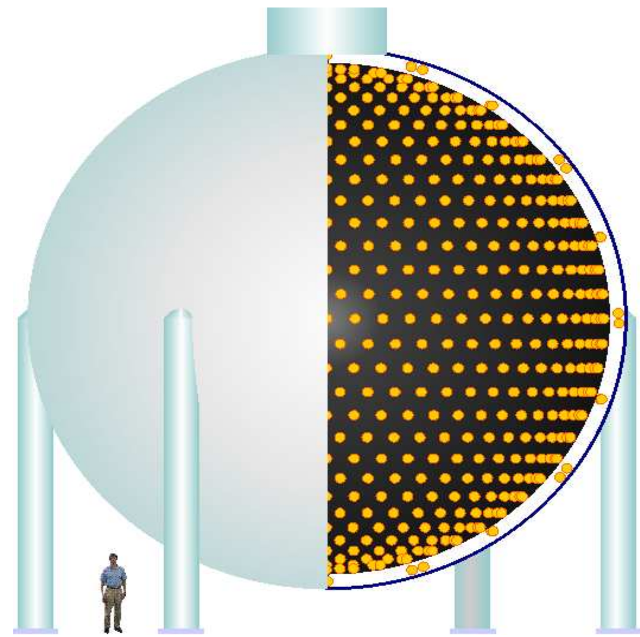
3+1 disfavoured by SBL experiment

Confirmation of LSND by Miniboone
need new ideas

MiniBoone

- Look for ν_e events in a pure ν_μ beam
- Confirm or refute the LSND evidence with higher statistics and different systematics





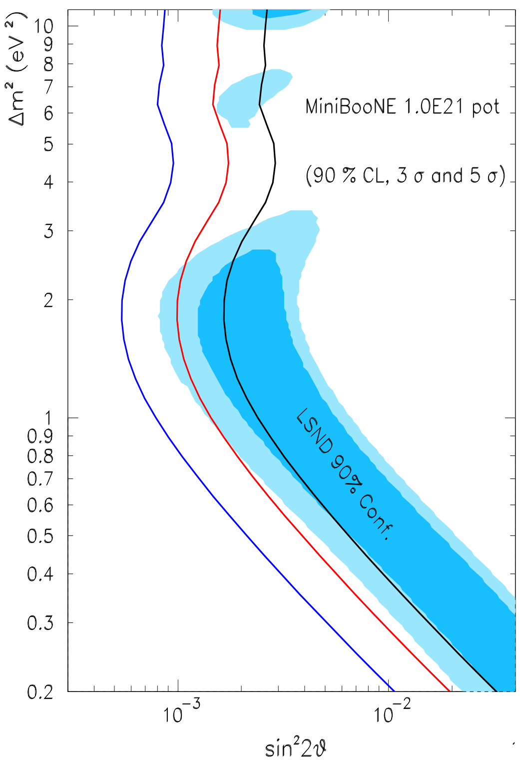
- Use protons from the 8 GeV booster, $\langle E_\nu \rangle \sim 1 GeV$

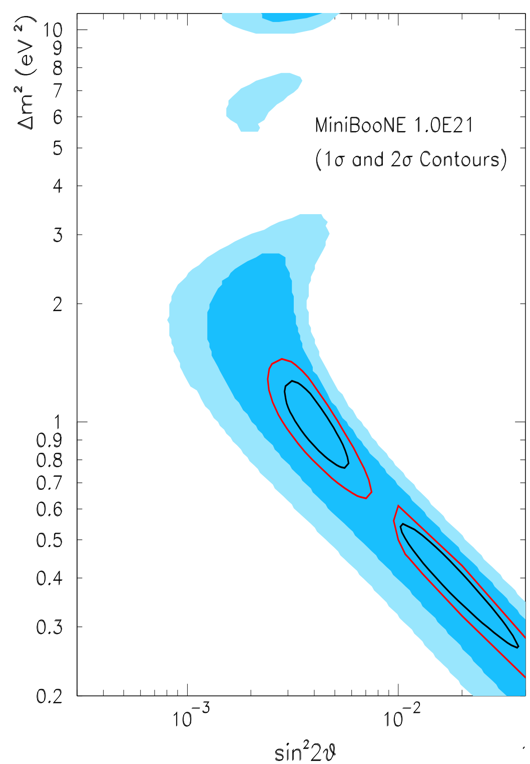
Detector: 12m Diameter Sphere filled with mineral oils and PMTs and 500m from source

MiniBoone

- 10^{21} p.o.t to reach coverage of LSND signal ($\sim$ July 2005)
- L/E $\sim$ 1 MeV/m – same as LSND by increasing both L and E
- This changes signature of signal and major backgrounds in the detector
- MiniBoone detects neutrinos through
  - QE scattering (CCQE)
  - 1 Pion reactions (CCPiP)
- Miniboone collaboration has presented preliminary results for CCPiP/CCQE ratio
- Check the possibility of ν_μ disappearance
- $\nu_\mu - \nu_e$ oscillation analysis –Results ??

MiniBoone Sensitivity





Tri-BiMaximal Mixing

- Present data implies tri-bimaximal mixing
  (Harrison, Perkins and Scott)

$$U = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix} \mathrm{diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, e^{i\alpha_3/2}) \ ,$$

- $\sin^2\theta_{23} = 0.5$, $\sin^2\theta_{12} = 0.33$, $\sin^2\theta_{13} = 0$ Two large and one small mixing
- Key Question : Is there some underlying Symmetry or accidental ?
- Hierarchy of neutrino masses not strong : $m_3/m_2 \leq 6$
- completely different from quark sector

Quark-Lepton Complimentarity

Present data also imply

$$\theta_{12} + \theta_c \approx \pi/4$$

$\theta_c \rightarrow$ Cabbibo Angle

$\rightarrow$ Quark-Lepton Complimentarity

- QLC1

  $U = U_l^\dagger U_\nu$

  $U_l = V_{CKM}$

  $U_\nu = U_{bimax}$

  $\theta_{12} \approx 35.4^o$

  $\theta_{23} \approx 42.5^o$

  $\theta_{13} \approx 8.9^o$

- QLC2 Rajdal, Minakata and Smirnov

  $U = U_l^\dagger U_\nu$

  $U_l = U_{bimax}^T$

  $U_\nu = V_{CKM}^\dagger$

  $\theta_{12} \approx 32.4^o$

  $\theta_{12} \approx 32.4^o$

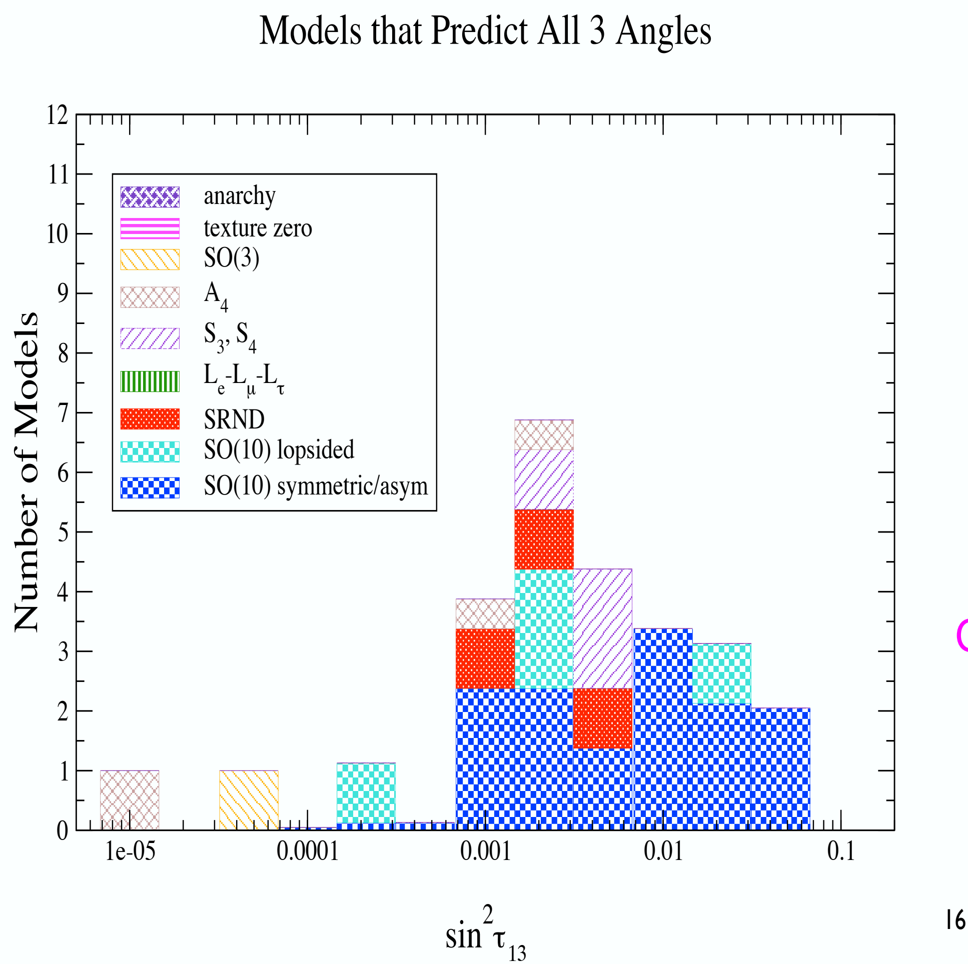
  $\theta_{23} \approx 42.7^o$

  $\theta_{13} \approx 0$

Different Mechanisms to generate Neutrino Mass

- Anarchy – No flavour symnmetry
- Flavour Symmtry
  - $\mu - \tau$ exchange symmetry
  - $L_e - L_\mu - L_\tau$ symmetry
  - $L_\mu - L_\tau$ symmetry
  - S_3, A_4, S_4, D_5
    $A_4 \rightarrow$ Can give tri-bimaximal mixing
  - SO(3) and SU(3) Flavour Symmetries
- SRND
- GUTS : natural framework for Seesaw
  Most Popular candidate : SO(10)

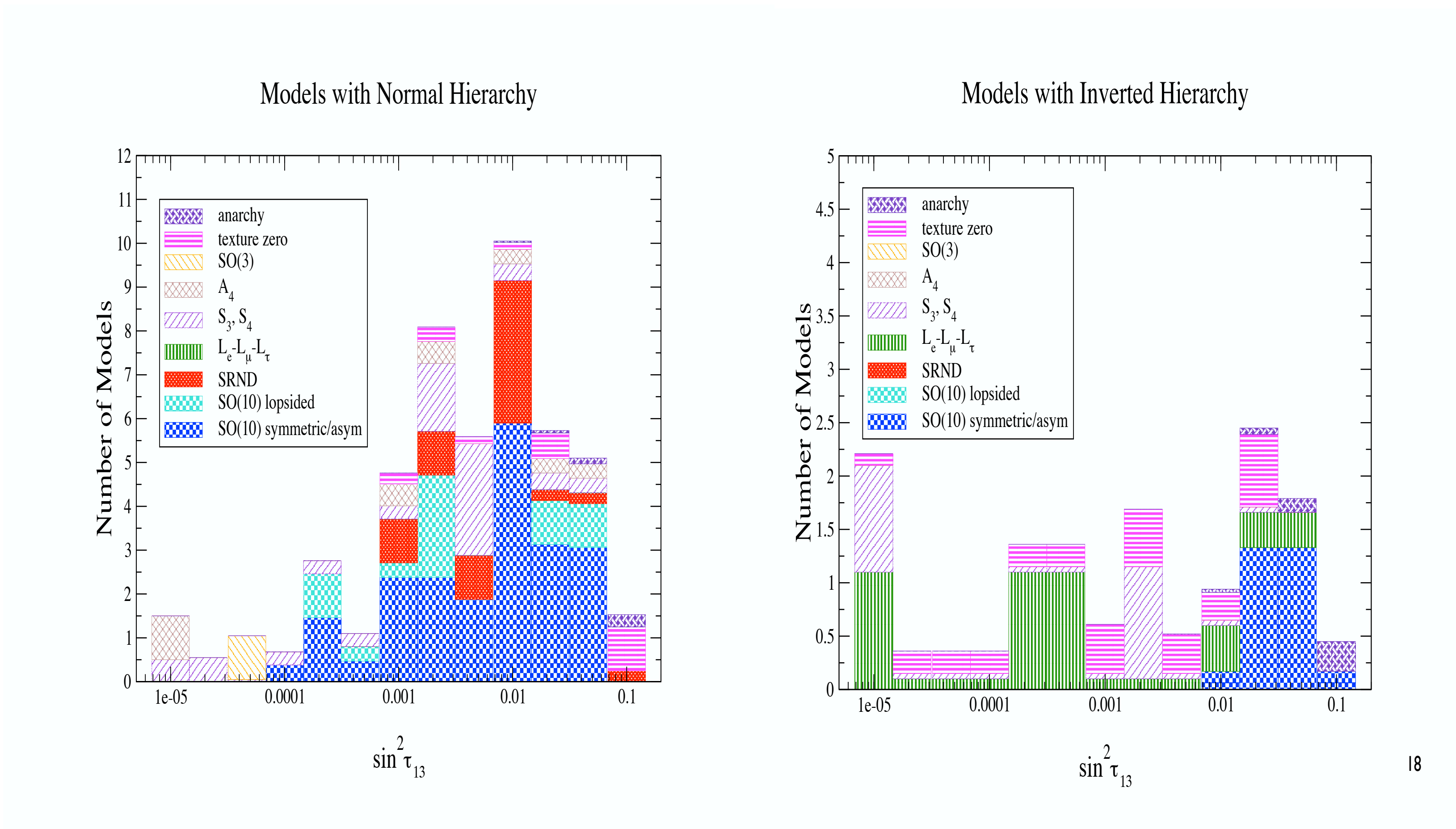
Theoretical Models and their Predictions



27 models predict all 3 mixing angles correctly $\sin^2\theta_{13} = 0.001 - 0.04$

C. Albright *et al.*, hep-ph/0608137

Theoretical Models and their Predictions



Three times more models predict Normal Hierarchy and $\sin^2\theta_{13} = 0.001 - 0.04$

C. Albright *et al.*, hep-ph/0608137

Summary

- Known Parameters

Parameters	Best – fit	3σ range
Δm^2_{21}	8 $\times 10^{-5}$ eV^2	(7.0-9.3) $\times 10^{-5}$ eV^2
Δm^2_{31}	2.5 $\times 10^{-3}$ eV^2	(1.8-3.3) $\times 10^{-3}$ eV^2
$\sin^2\theta_{23}$	0.5	$0.34 - 0.68$
$\sin^2\theta_{12}$	0.31	$0.24 - 0.41$
$\sin^2\theta_{23}$	0.5	$0.34 - 0.68$

- Bounded Parameters

  $\sin^2\theta_{13} \leq 0.044$, $\Sigma m_i \leq (0.17 - 2.0)$ eV

- No information on

  $sgn(\Delta m^2_{31})$ (nature of mass spectrum), Octant of θ_{23}, CP phases

- LSND

  (2+2) ruled out, 3+1 strongly disfavoured

  Confirmation of LSND results by Miniboone will need new ideas

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
- Future neutrino experiments can help in choosing between various alternatives