NEUTRINO MASSES AND MIXING

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SUSY02, DESY June 2002

I. Introduction

- If neutrinos have a mass, the weak eigenstates $|\nu_\alpha\rangle$ are linear combinations of the mass eigenstates $|\nu_i\rangle$

  $|\nu_\alpha\rangle = \sum_{i=1}^{n} U_{\alpha i}\,|\nu_i\rangle$ U is a unitary mixing matrix.

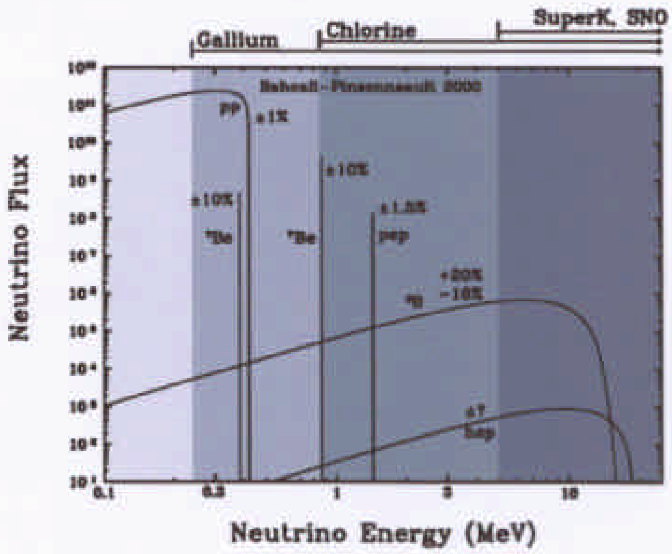
- To fully determine the lepton flavour structure we want to know:
  * How many neutral states: N
  * Their nature: Dirac $\nu^C \neq \nu$
    Majorana $\nu^C = \eta\nu$ (η=phase)
  * Their masses: m_i
  * Their mixings: $\frac{N(N-1)}{2}$ mixing angles
  * Their CP properties:
    $\frac{(N-1)(N-2)}{2}$ (Dirac Phases)+ $N-1$ (Majorana Phases)

- We have information from:
  * The line shape of the Z: $N_{\rm weak} = 3$
  * Neutrino Oscillations: Best at present but only mass differences
  * Direct kinematic measurements of the masses:
    for instance $^3H \rightarrow ^3He + e^- + \bar{\nu}_e \Rightarrow m_e < 2.2$ eV
    but what is $m_e = f(m_i, U)$?
  * ν-less double-β decay: $|\langle m_{\beta\beta}\rangle| = |\sum_{i=1}^{N} U_{ei}^2 m_i|$ if ν_i Majorana
  * Also from Astrophysics and Cosmology:
    BBN, Structure formation, Dark matter ...

II. Solar Neutrinos

- The sun emits $\nu_e's$.

Standard Solar Model fluxes



- Radiochemical experiments: (SNU $\equiv 10^{-36}$ absorptions/atom/sec)
  - Homestake (South Dakota,USA) $E_\nu > 0.81$ MeV

    $\nu_e +^{37} Cl \rightarrow^{37} Ar + e^-$ 2.56 ± 0.23 SNU
  - SAGE (Russia) and GALLEX, GNO (Gran Sasso) $E_\nu > 0.23$ MeV

    $\nu_e +^{71} Ga \rightarrow^{71} Ge + e^-$ 70.8 ± 4.4 SNU

- Real–Time experiments:
  - Kamiokande and SuperK. (Kamioka,Japan) $E_e > 5$ MeV

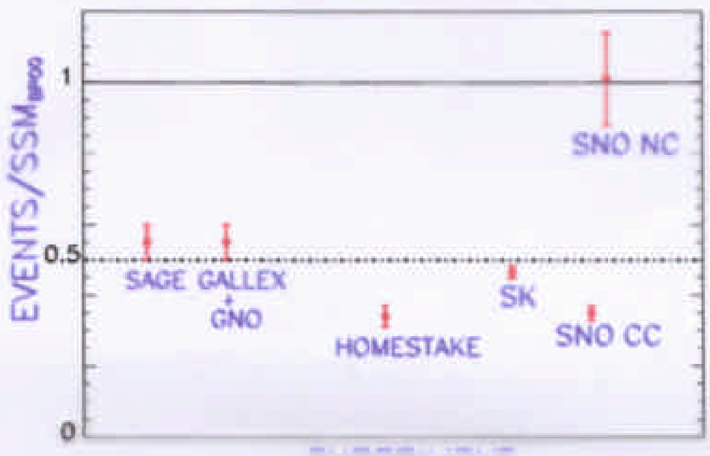
    ES $\nu_x + e^- \rightarrow \nu_x + e^-$ $\frac{\phi}{10^6} = 2.35 \pm 0.02 \pm 0.08\ cm^{-2}s^{-1}$
  - SNO (Sudbury,Canada) $T_e > 5$ MeV

    CC $\nu_e + d \rightarrow p + p + e^-$ $1.76 \pm 0.05 \pm 0.09\ cm^{-2}s^{-1}$ *

    NC $\nu_x + d \rightarrow \nu_x + p + n$ $5.09^{+0.44}_{-0.43}\ ^{+0.46}_{-0.43}\ cm^{-2}s^{-1}$ *

    ES $\nu_x + e^- \rightarrow \nu_x + e^-$ $2.39^{+0.24}_{-0.23} \pm 0.12\ cm^{-2}s^{-1}$ *

(* For undistorted ^{8}B spectrum)



SSM Independent Tests

- For the Chlorine+Gallium+SK+SNO_{CC} rates:

$$\chi^2_{BP00} = 60/4\text{dof} \;\Rightarrow\; \text{GOF} \lesssim 10^{-10}\%$$

- Model Independent Tests Before SNO:
  - Treat Dominant Fluxes ^{7}Be, ^{8}B, pp as free
  - Impose Luminosity Constraint: $\sum \alpha_j \Phi_j = \frac{L_\odot}{4\pi r^2}$

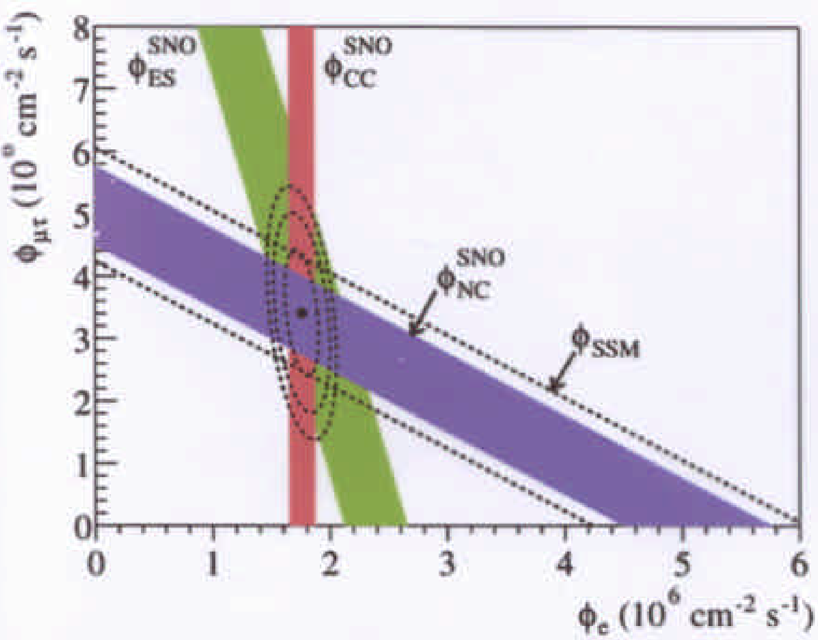
  Best Fit $\Rightarrow$ negative ^{7}Be

  Best Fit with fluxes ≥ 0: $\frac{\alpha_{pp}}{\alpha_{pp}^{SSM}} = 1.08$, $\frac{\alpha_{Be}}{\alpha_{Be}^{SSM}} = 0$, $\frac{\alpha_{8_B}}{\alpha_{8_B}^{SSM}} = 0.45$

$$\chi^2_{min} = 19/1dof \;\Rightarrow\; \text{GOF} = 10^{-3}\%$$

- Model Independent Tests With SK and SNO:
  - $*$ SK and SNO measure $\Phi_{^8B}$:
  - $*$ If flavour conversion:

$$\Phi^{\rm CC} = \Phi_e$$
$$\Phi^{\rm ES} = \Phi_e + r\,\Phi_{\mu\tau} \qquad r = \frac{\sigma_{\rm ES}(\nu_e)}{\sigma_{\rm ES}(\nu_\mu)} \simeq \frac{1}{6}$$
$$\Phi^{\rm NC} = \Phi_e + \Phi_{\mu\tau}$$



$*$ No-oscillation $\Rightarrow$

$\Phi^{\rm ES}_{\rm SK} = \Phi^{\rm CC}_{\rm SNO} \Rightarrow 3.2\sigma$ out

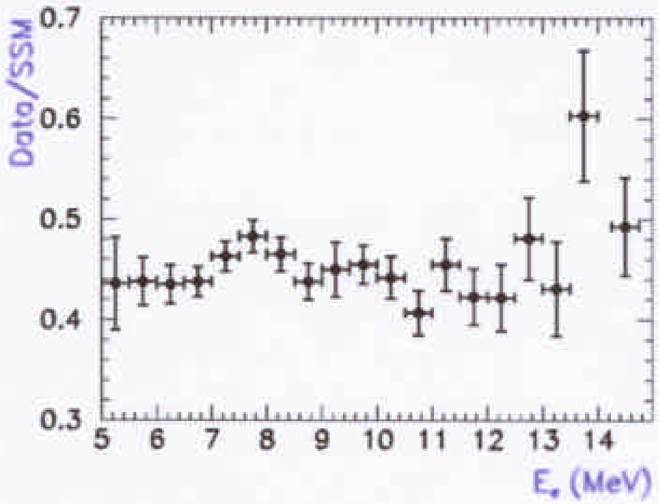
$\Phi^{\rm NC}_{\rm SNO} = \Phi^{\rm CC}_{\rm SNO} \Rightarrow 5.3\sigma$ out

$*$ $\nu_e \rightarrow \nu_{sterile}$ conversion $\Rightarrow$

$\Phi^{\rm NC}_{\rm SNO} \simeq \Phi^{\rm CC}_{\rm SNO} \sim 5\sigma$ out

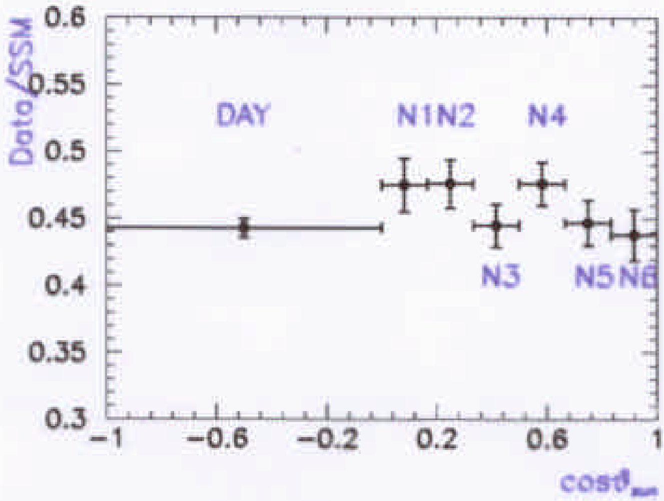
Other Super–Kamiokande Measurements

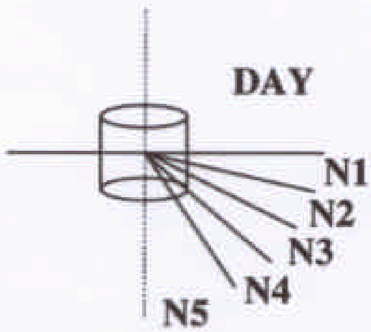
- Recoil Electron Energy Spectrum → no distortion $\chi^2_{flat} = 19/(18dof)$



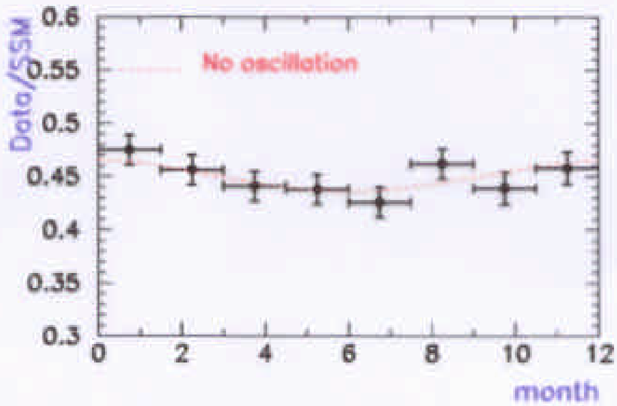
- Zenith Angle Distribution (Day/Night Effect): Effect of Earth Matter

→ Few more events at N than D $2\frac{D-N}{D+N} = -0.021 \pm 0.02 \pm 0.013\,(0.8\sigma)$



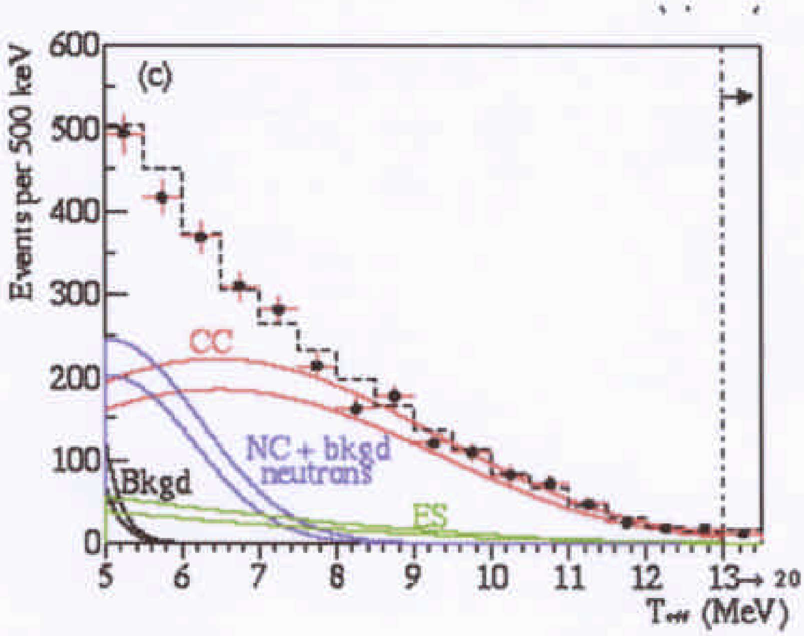


- Seasonal Variation → Small Beyond Earth Orbit Eccentricity

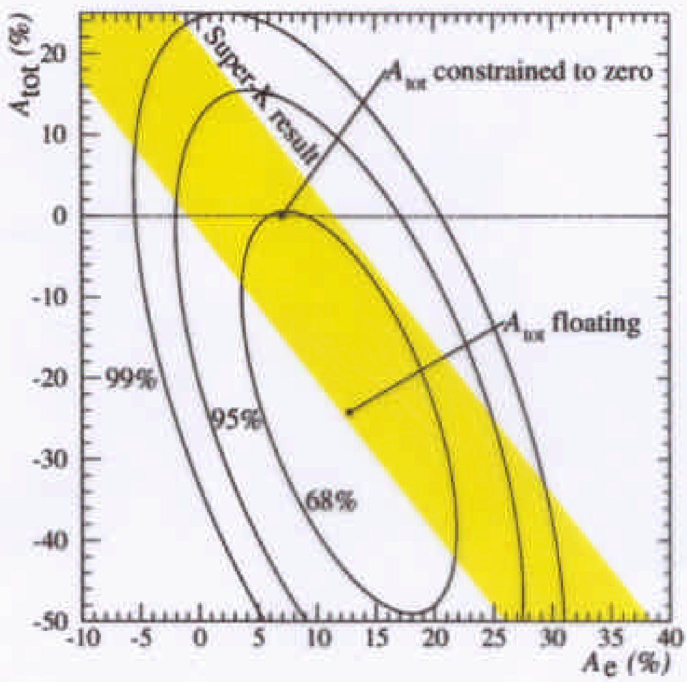


SNO Measurements

- Electron Energy Spectrum → no large distortions
  (Includes CC+NC+ES contributions)



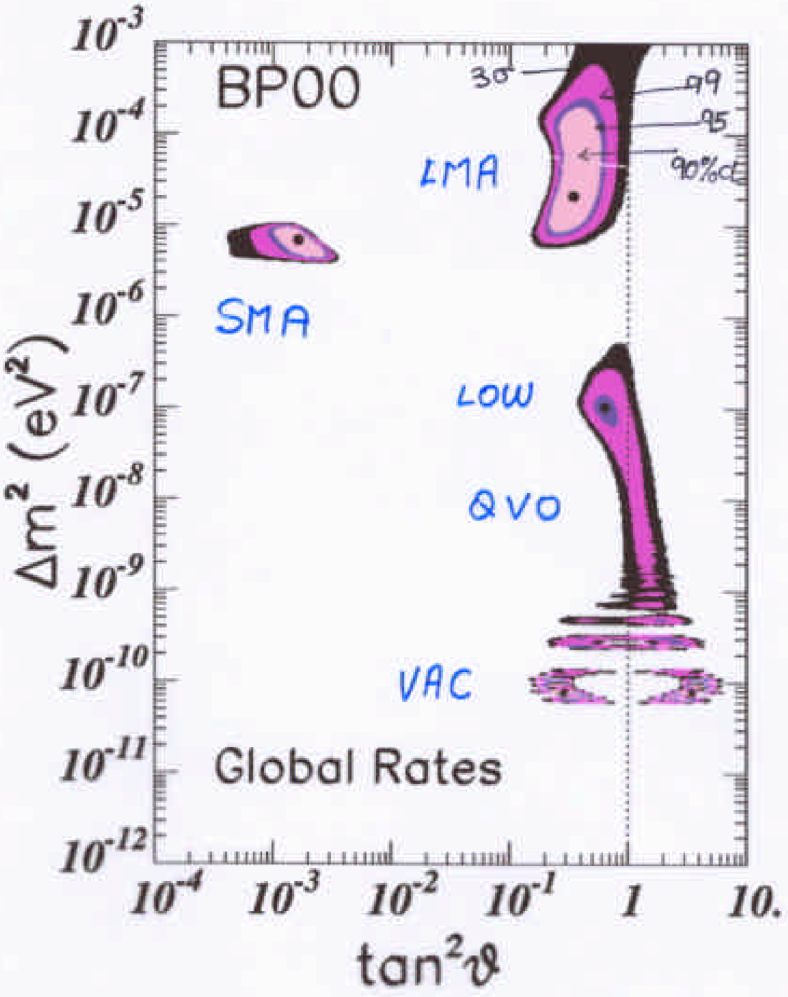
- Day-Night variation
  → Few more events at N than D $2\frac{D-N}{D+N} = 0.07 \pm 0.05 \pm 0.02$
  → agreement with SK



Solutions for $\nu_e \rightarrow \nu_{active}$

Super–Kamiokande 1498 days, SNO CC, BP00 (Before April 20, 2002)

Allowed regions from Rates :



Different regimes could explain the Global Rates

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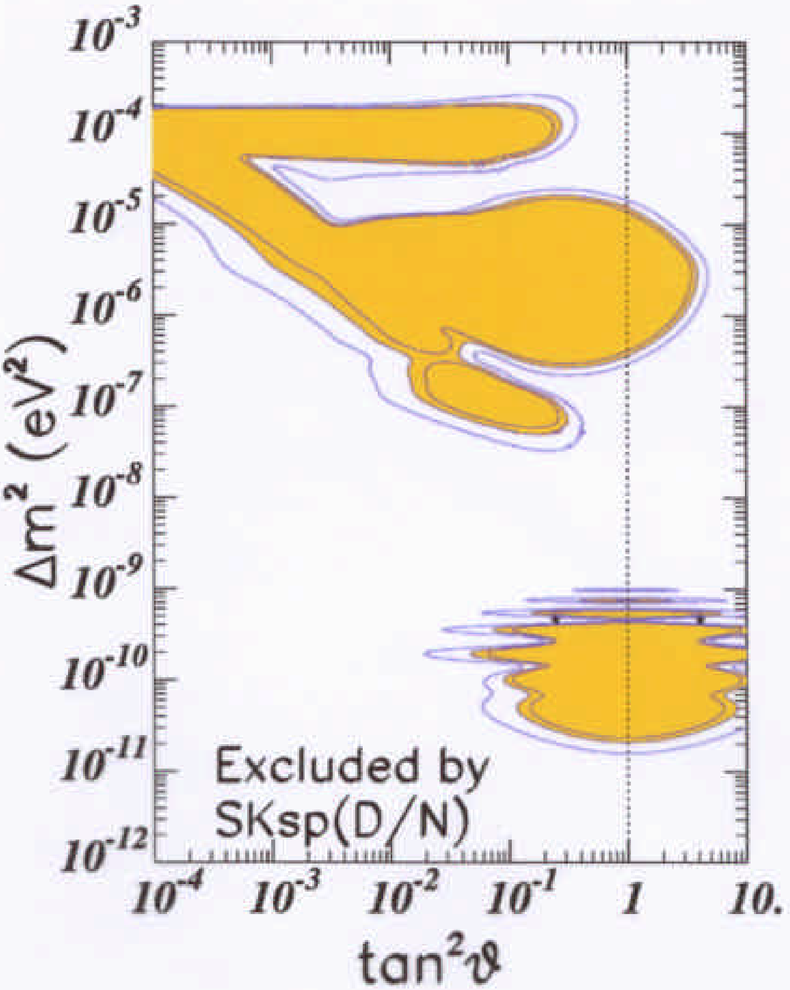
Excluded from SK D/N Spectra:

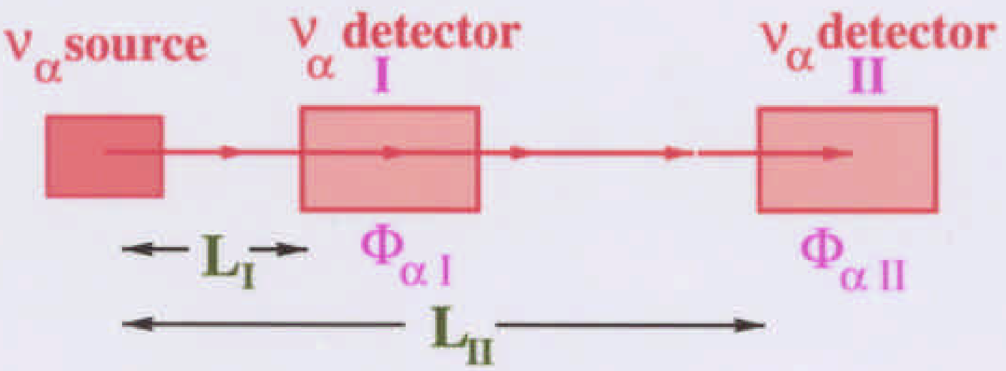


SMA, LOW and VAC were disfavoured

Chooz Experiment

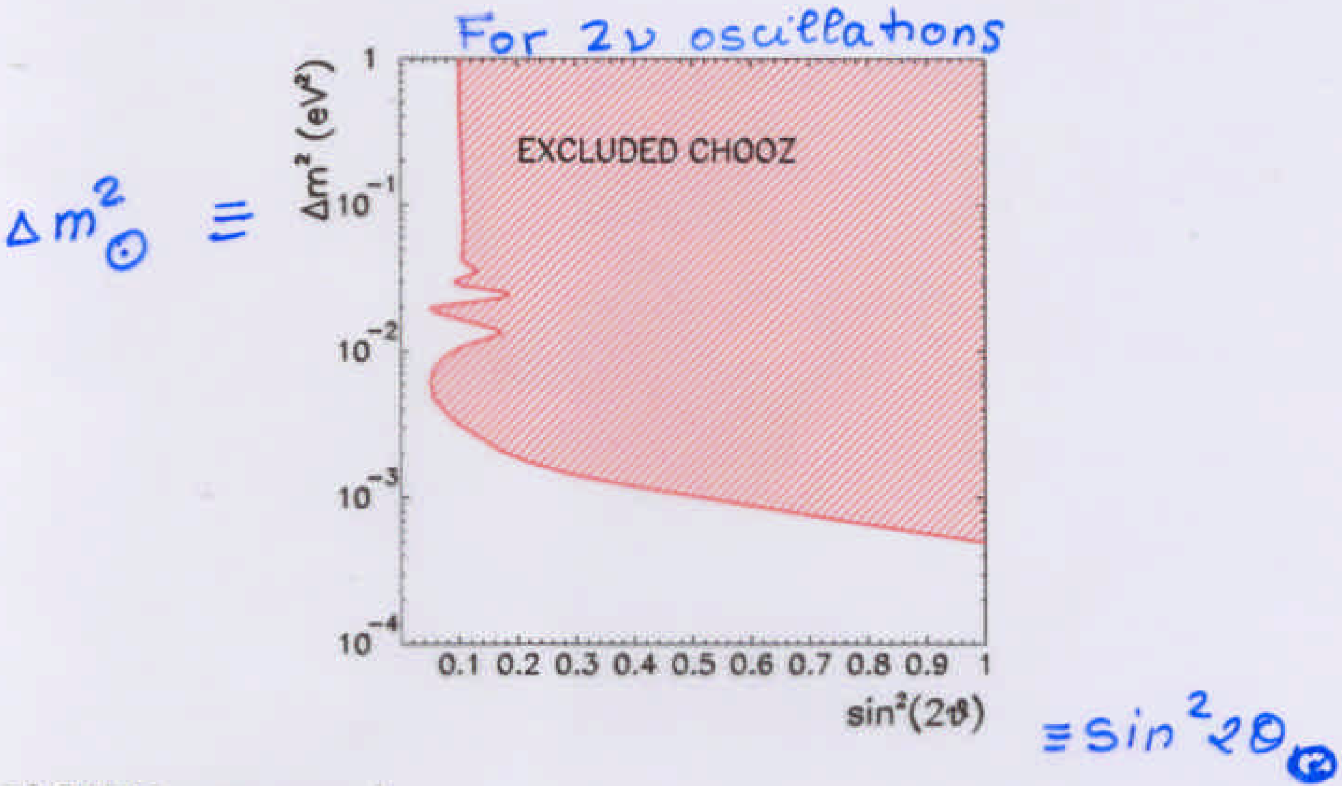
- Negative Lab experiment with ν source: Nuclear Reactor

– Disappearance Experiment



Compares $\Phi_{\alpha\,I}$ and $\Phi_{\alpha\,II}$ to look for loss

Experiment	$\sim \langle L/E \rangle$(m/MeV)		α
Chooz	200	Reactor (France)	$\bar{\nu}_e$



If CPT is conserved:

– Constraints solar oscillations for $\Delta m^2_\odot \gtrsim 8 \times 10^{-4}$ eV^2.

– Constraints $\nu_\mu \to \nu_e$ component of atmospheric oscillations

Impact of SNO April 2002 results:

– SNO collaboration, nucl-ex/0204009

– Barger, Marfatia, Whisnant and Wood, hep-ph/0204253

– Bandyopadhysy, Choubey, Goswami, Roy, hep-ph/0204286

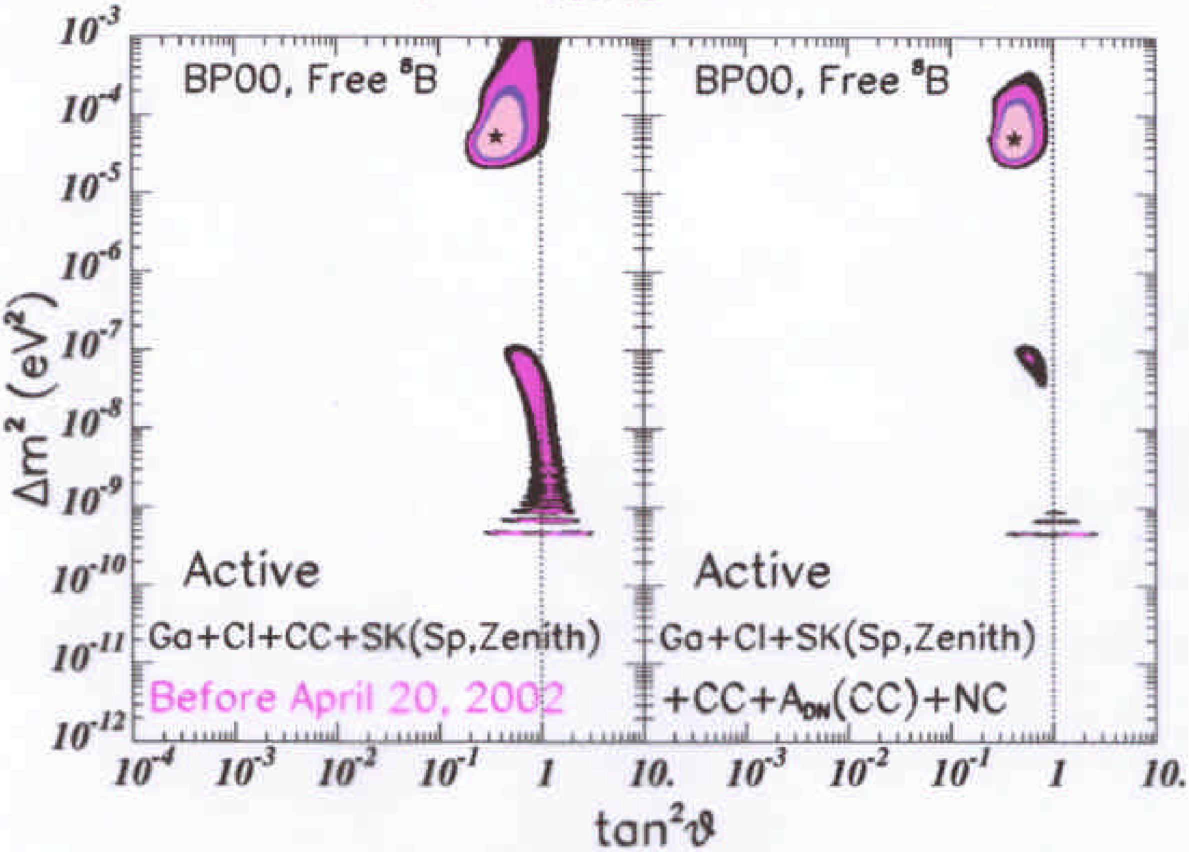
– Creminelli, Signorelli, Strumia addendum to hep-ph/0102234

– Aliani, Antonelli, Picariello, Torrente-Lujan hep-ph/0205053

– de Holanda, Smirnov, hep-ph/0205241

– Strumia, Cattadori, Ferrari, Vissani, hep-ph/0205262

Solutions for $\nu_e \to \nu_{active}$ Where we are now?

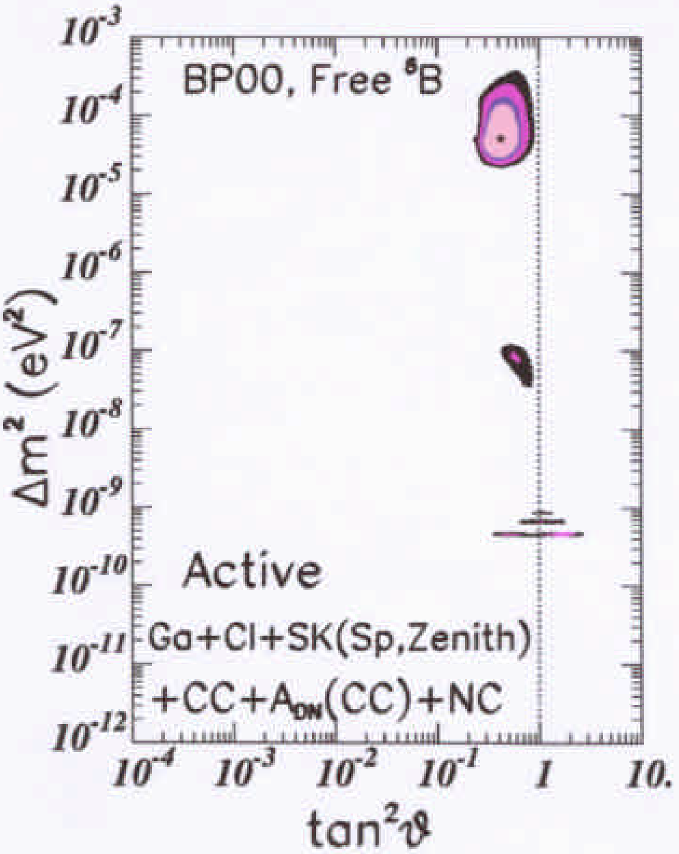


(J.N. Bahcall, M.C.G-G, C. Peña Garay (BGP), hep-ph/0204314)

- LMA best fit:
  – $\Delta m^2 = 5 \times 10^{-5}$eV^2 $\tan^2\theta = 0.42$
  – Maximal mixing is "out" in LMA: $0.24 < \tan^2\theta < 0.89$ at 3σ
  – Δm^2 below CHOOZ: $\Delta m^2 = (0.25 - 3.7) \times 10^{-4}$ eV^2 at 3σ
- LOW and QVAC-VAC further disfavoured
- SMA "out" at 3.7 σ and Pure sterile is "way out" at 5.4σ

Solutions for $\nu_e \to \nu_{active}$ Where we are now?

(J.N. Bahcall, M.C.G-G, C. Peña Garay, hep-ph/0204314)



- LMA best fit in all analysis:
  - Maximal mixing excluded at 3.2 in LMA: $\tan^2\theta \leq 0.89$ at 3σ
  - LMA below CHOOZ bound: $\Delta m^2 \leq 3.7 \times 10^{-4}$ eV^2 at 3σ

Other analysis $\tan^2\theta \leq \begin{cases} 0.55 \\ 0.64 \\ 0.79 \\ 1 \end{cases}$ $\Delta m^2 \leq \begin{cases} 1.9 \times 10^{-4} \text{ SNO} \\ 2.3 \times 10^{-4} \text{ Barger } et\ al \\ 3.4 \times 10^{-4} \text{ de Holanda } et\ al \\ 5.0 \times 10^{-4} \text{ Strumia } et\ al \end{cases}$

- LOW solution: allowed only at 2.5σ
- (Q)VAC allowed, but not robustly, at 2.1σ.

Other analysis LOW at $\begin{cases} 2.8\,\sigma \\ 2.5\,\sigma \\ 3.2\,\sigma \\ 2.2\ \sigma \end{cases}$ (Q)VAC at $\begin{cases} > 3\,\sigma \text{ SNO} \\ > 3\,\sigma \text{ Barger } et\ al \\ 2.7\,\sigma \text{ de Holanda } et\ al \\ 2.5\ \sigma \text{ Strumia } et\ al \end{cases}$

- Small mixing angles are “out” at more than 3.5σ in all analysis .
- Pure sterile is “way out” at more than 5σ in all analysis

Near Future Experiments:

- Reactor neutrino experiments: KamLAND

  ⋆ Search on $\overline{\nu_e}$ for L~ 200 km (17 reactors), $E_\nu \sim$ few MeV

  $$\bar{\nu}_e + p \to n + e^+ \qquad \text{CC in liq. scintillator}$$

  – Sensitive to the LMA region

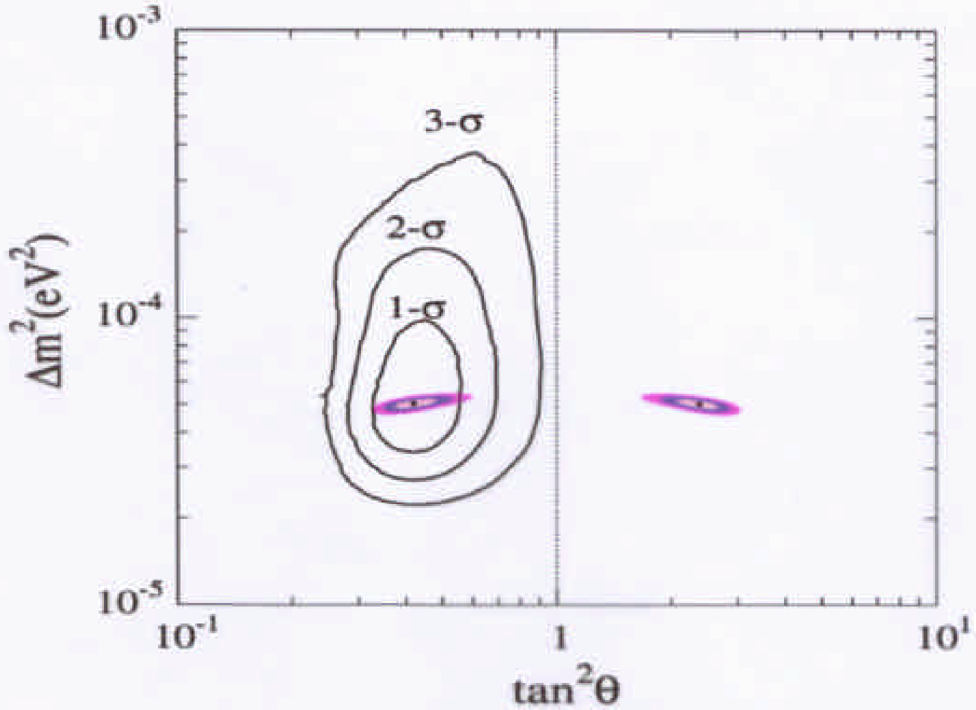
  – No matter effects: $\theta \equiv \frac{\pi}{2} - \theta$ but combined with solar $\Rightarrow \theta < \frac{\pi}{2}$ (deGouvea&Peña-Garay, PLB2001)

  – CC events: No information about active or sterile osc.

  ⋆ Running since January: In May, 11 reported $\overline{\nu}_e$ candidates

  ⋆ Expected Allowed regions from KamLAND data

  (if LMA is the solution to the SNP)



- Solar neutrino experiments: BOREXINO

  ⋆ Search on low energy solar neutrinos

  $$\nu_x + e^- \to \nu_x + e^- \qquad \text{ES in liq. scintillator}$$

  – Measurement of Φ (^{7}Be) ($0.25 < T_e < 0.8$)

  – Sensitive to the LOW region: D/N, Zenith dependence

  – Sensitive to the VAC region: Seasonal dependence

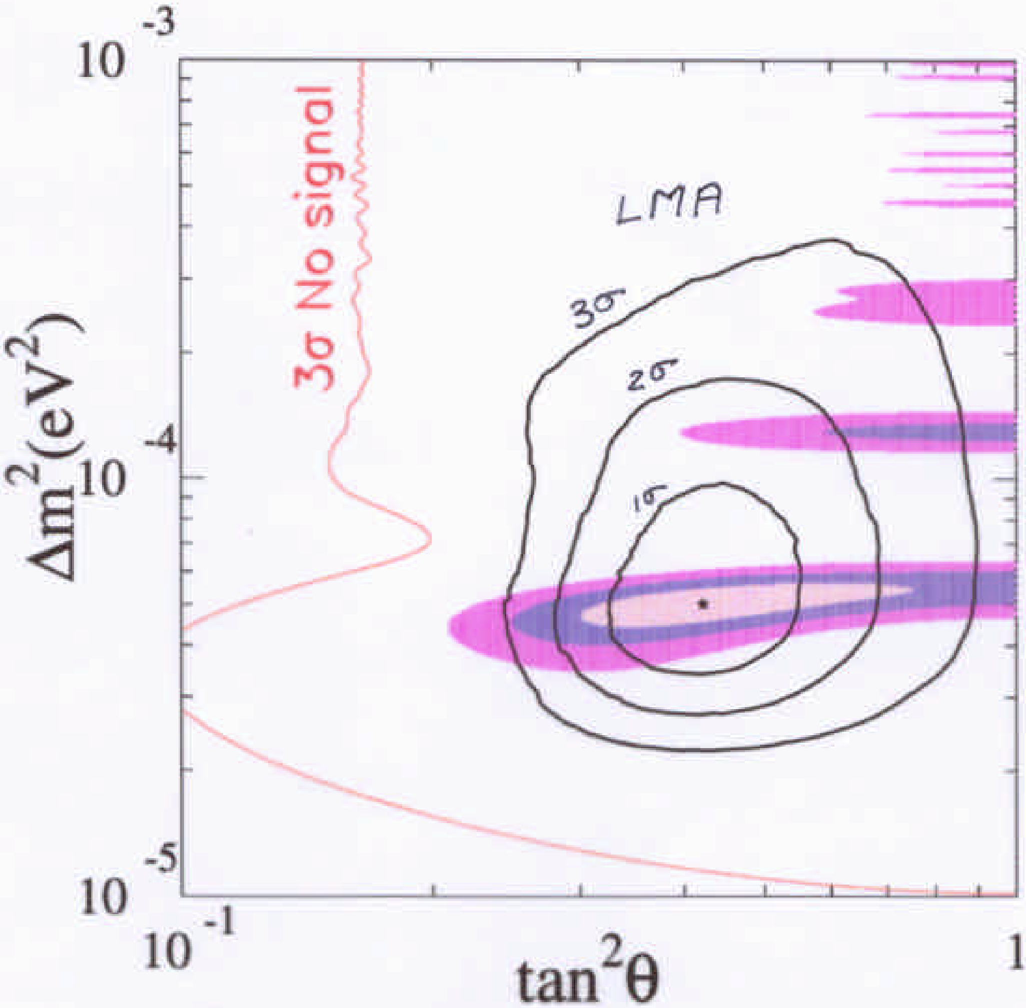
What could KamLAND say this year?

- Lets assume 200 expected events and

  (1) 97 observed (best fit LMA) with best fit LMA spectrum

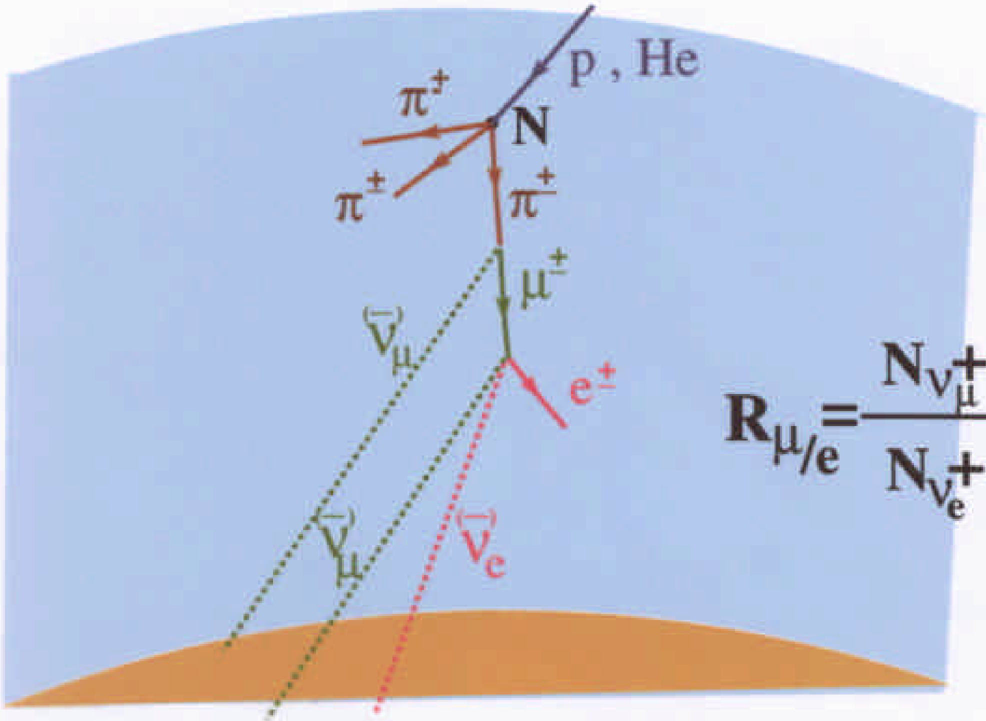
  (2) 200 observed with no distortion in spectrum

  Including only statistical errors



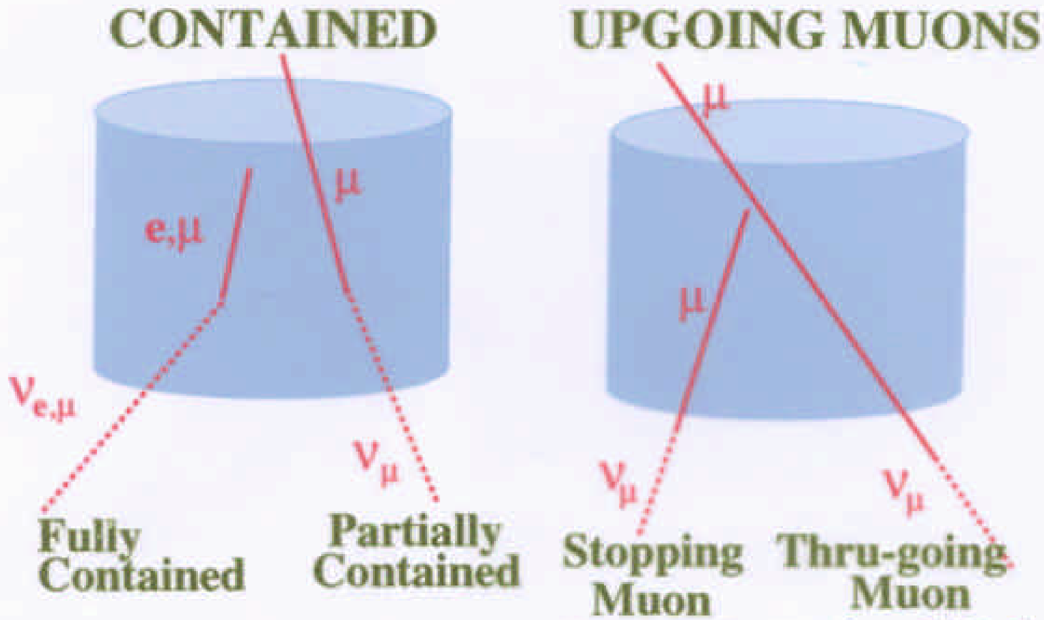
III. Atmospheric Neutrinos

Atmospheric $\nu_{e,\mu}$ are produced by the interaction of cosmic rays (p, He ...) with the atmosphere



$$R_{\mu/e} = \frac{N_{\nu_\mu} + N_{\bar{\nu}_\mu}}{N_{\nu_e} + N_{\bar{\nu}_e}} \sim 2$$

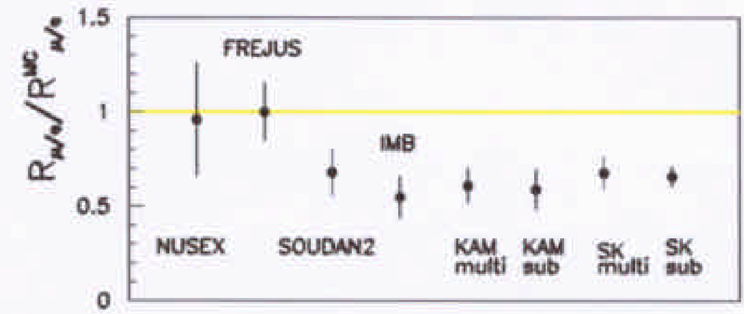
EVENT CLASSIFICATION



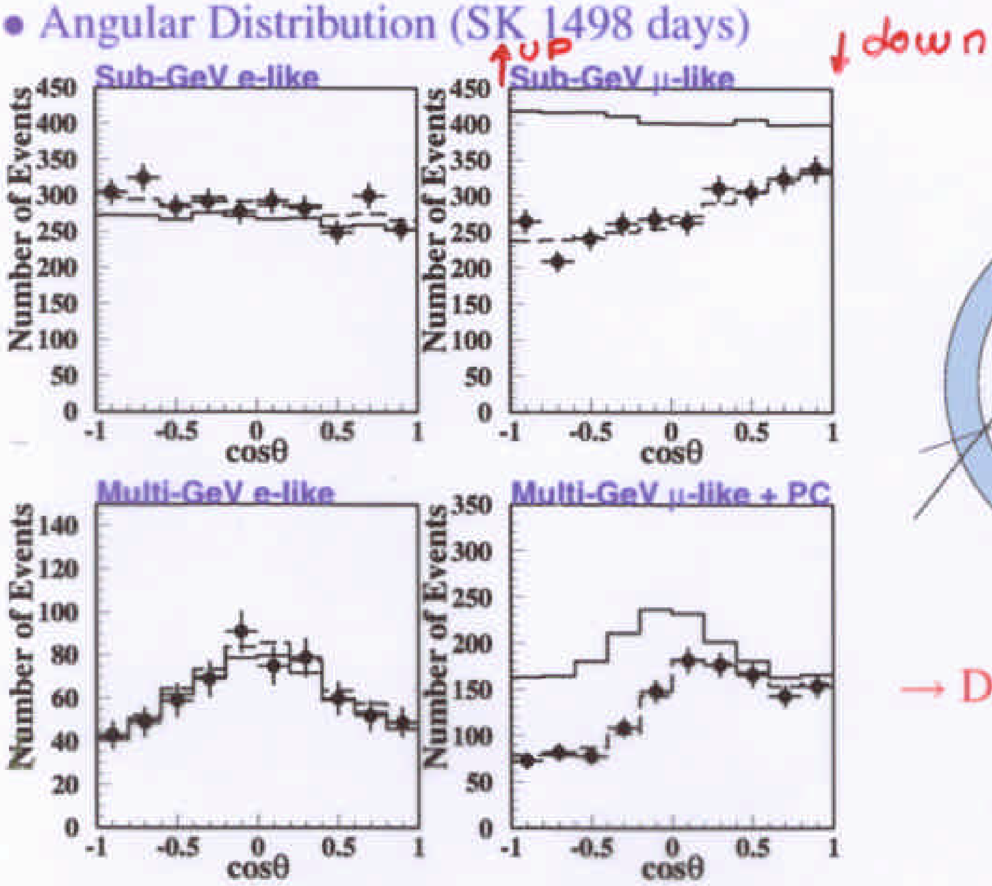
E_ν 0.1 - few GeV few GeV few 10 GeV few 100 GeV

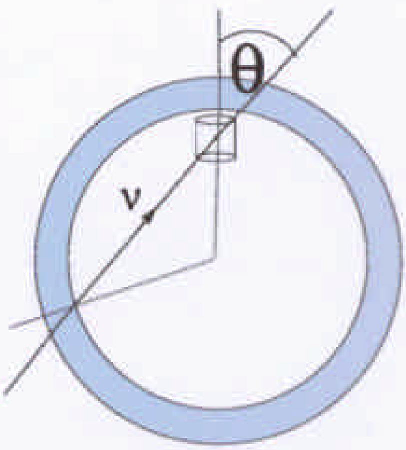
Atmospheric Neutrino Data

- Total Rates for Contained Events

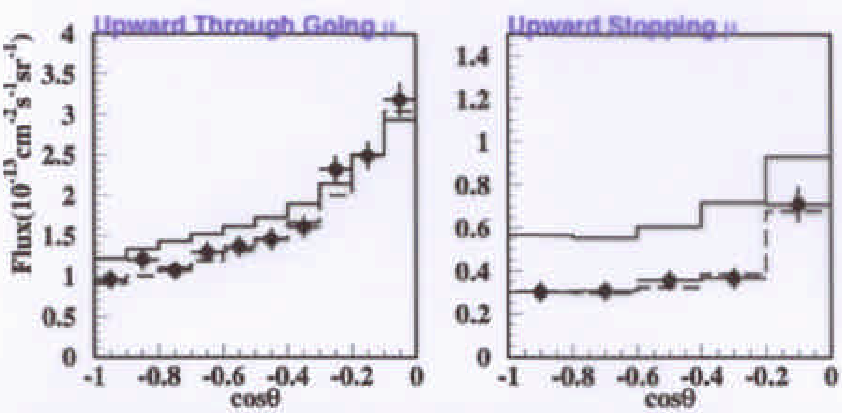


- Angular Distribution (SK 1498 days)



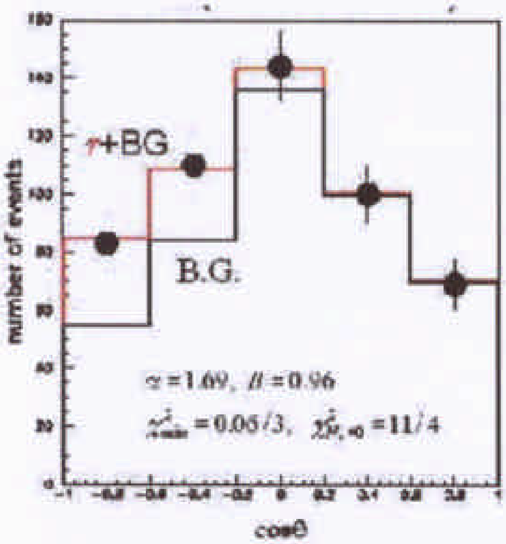


→ Deficit grows with L



→decreases with E

- τ searches in SK: Events with topologies compatible with τ decay.



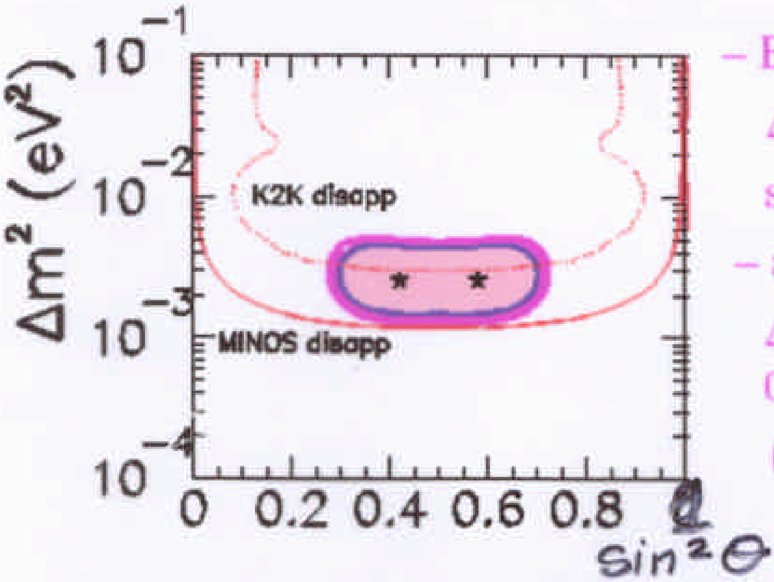
$N_{\rm ev}^{\tau-like} = 145 \pm 44^{+11}_{-16}$

$N_{\rm exp} = 86$

Compatible with $\nu_\mu \to \nu_\tau$

But not very significant yet

- $\nu_\mu \to \nu_\tau$ oscillation regions: Not much to add to SK analysis



– Best fit:

$\Delta m^2 = 2.5 \times 10^{-3}$ eV^2

$\sin^2\theta = 0.42$

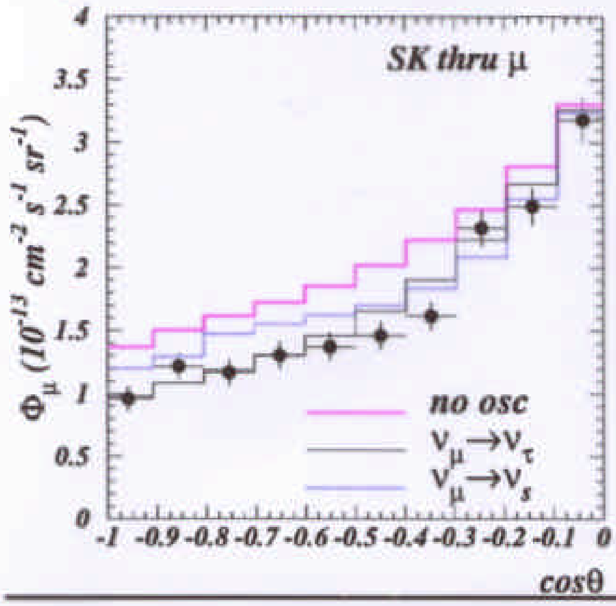
– at 99% CL

$\Delta m^2 = (1-5) \times 10^{-3}$eV^2

$0.26 < \sin^2\theta < 0.74$

$(\sin^2 2\theta > 0.8)$

- $\nu_\mu \to \nu_{\rm sterile}$: Matter effects ⇒ Flatter upgoing-μ distribution



$\nu_\mu \to \nu_{\rm sterile}$

disfavoured are more than 4σ

- For 3-ν mixing U: 3 angles, 1 CP-phase + (2 Majorana phases)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

– The angles $\theta_{ij} \in [0, \pi/2] \Rightarrow \sin^2 2\theta$ does not cover full space

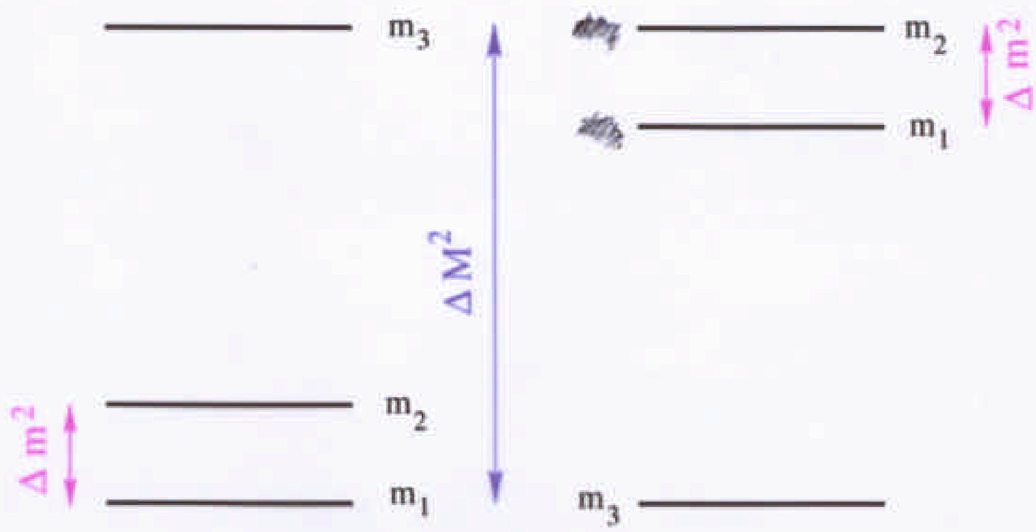
$\sin^2(\theta)$ Better for linear scale

$\tan^2(\theta)$ Better for log scale

– For the CP phase there are two options:

$0 \leq \delta < 2\pi$ and $m_1 \leq m_2 \leq m_3$

$0 \leq \delta \leq \pi$ and two mass ordering



NORMAL

$$\Delta M^2 = \Delta m^2_{31}$$
$$\Delta m^2 = \Delta m^2_{21}$$

INVERTED

$$\Delta M^2 = -\Delta m^2_{32}$$
$$\Delta m^2 = \Delta m^2_{21}$$

– Two *different* CP conserving values $\delta = 0, \pi$, ($\cos\delta = \pm 1$)

– *Hierarchy* parameter: $\alpha = \frac{\Delta m^2}{\Delta M^2}$

– *Hierarchical approximation* $\alpha = 0$

- The Evolution Equation in Matter: ($A = 2\sqrt{2}G_F E N_e$)

$$i\frac{d\nu_\alpha}{dt} = \sum_\beta \left[\sum_j U_{\alpha j} U^*_{\beta j} \frac{m_j^2}{2E} + A\delta_{\alpha e}\delta_{\beta e}\right]\nu_\beta$$

- In the Hierarchical approximation

  $*$ No dependence of CP phase δ

  $*$ For $\theta_{13} = 0$ solar and atmospheric oscillations decouple

  – Normal and Inverted schemes are equivalent

  – solar $\rightarrow \Delta m^2 = \Delta m^2_\odot \quad \theta_{12} = \theta_\odot$

  – atmospheric $\rightarrow \Delta M^2 = \Delta m^2_{atm} \quad \theta_{23} = \theta_{atm}$

  $*$ For $\theta_{13} \neq 0$

  – Solar Oscillations (Hierarchical $\Rightarrow \Delta M^2 \rightarrow \infty$)

  $P^{3\nu,Sun}_{ee} = c^4_{13} P^{2\nu,Sun}_{ee}(\Delta m^2_{12}, \theta_{12}, A = c^2_{13} A_2) + s^4_{13}$

  Independent of θ_{23}

  – Atmospheric Oscillations (Hierarchical $\Rightarrow \Delta m^2 \rightarrow 0$)

  Independent of θ_{12}

  Dependence on scheme due to matter effects

$$\sin 2\theta_{13,m} = \frac{\sin 2\theta_{13}}{\sqrt{(\cos 2\theta_{13} \mp A/\Delta M^2)^2 + (\sin 2\theta_{13})^2}}$$

  For Normal matter enhancement for neutrinos

  For Inverted matter enhancement for antineutrinos

  – CHOOZ: limit on $\overline{\nu_e}$ disappearance

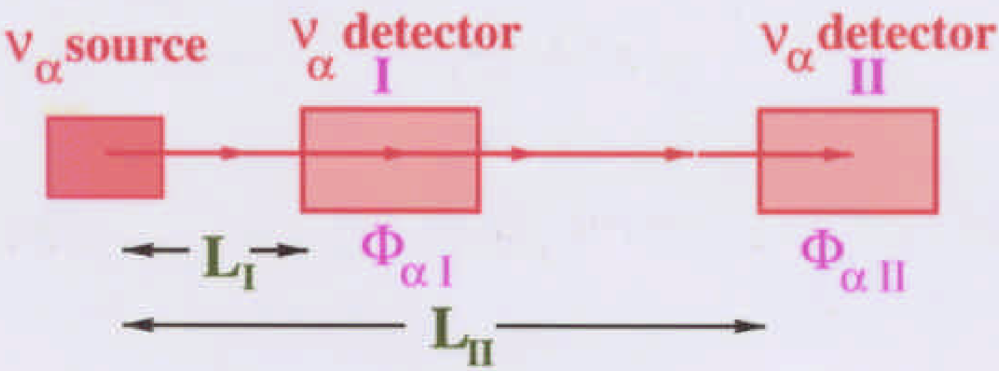
  $P^{CH}_{ee} \simeq 1 - 4c^2_{13}s^2_{13}\sin^2\left(\frac{\Delta M^2 L}{4E}\right)$

  For $\Delta M^2 \gtrsim 8 \times 10^{-4}$ eV^2 $\Rightarrow$ CHOOZ limits θ_{13}

Chooz Experiment

- Negative Lab experiment with ν source: Nuclear Reactor

– **Disappearance Experiment**

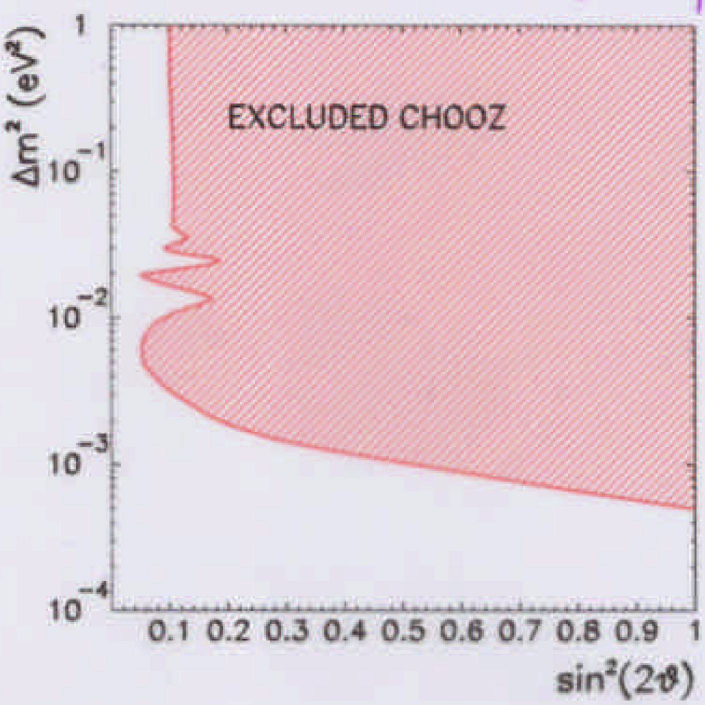


Compares $\Phi_{\alpha I}$ and $\Phi_{\alpha II}$ to look for loss

Experiment	$\sim \langle L/E \rangle$(m/MeV)		α
Chooz	200	Reactor (France)	$\bar{\nu}_e$

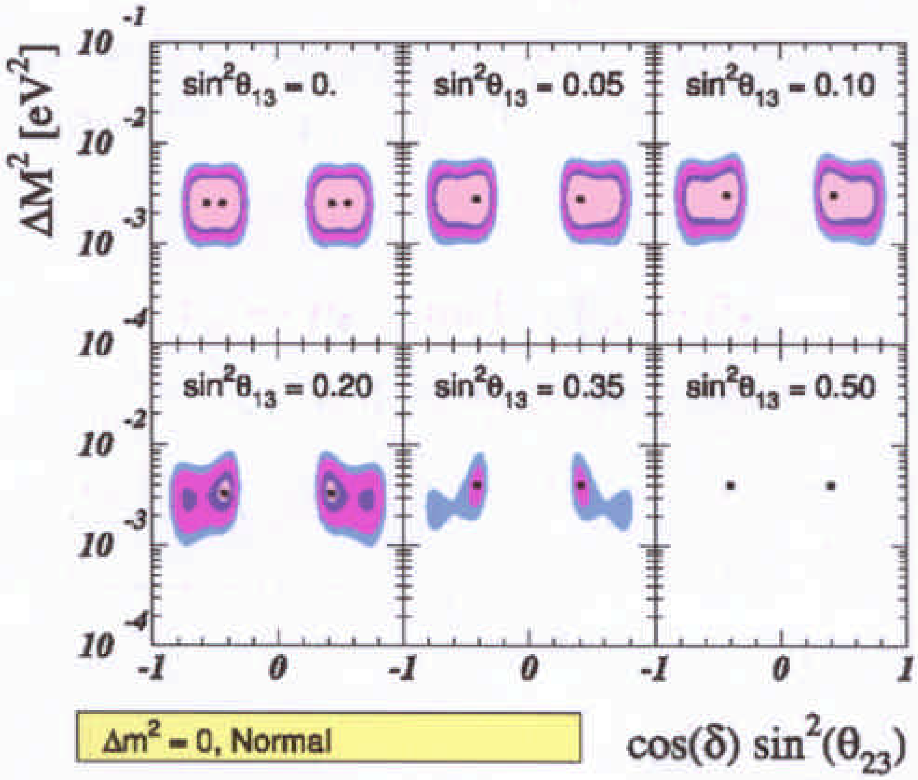
In Hierarchical Approximation and CPT

$\Delta M^2 =$

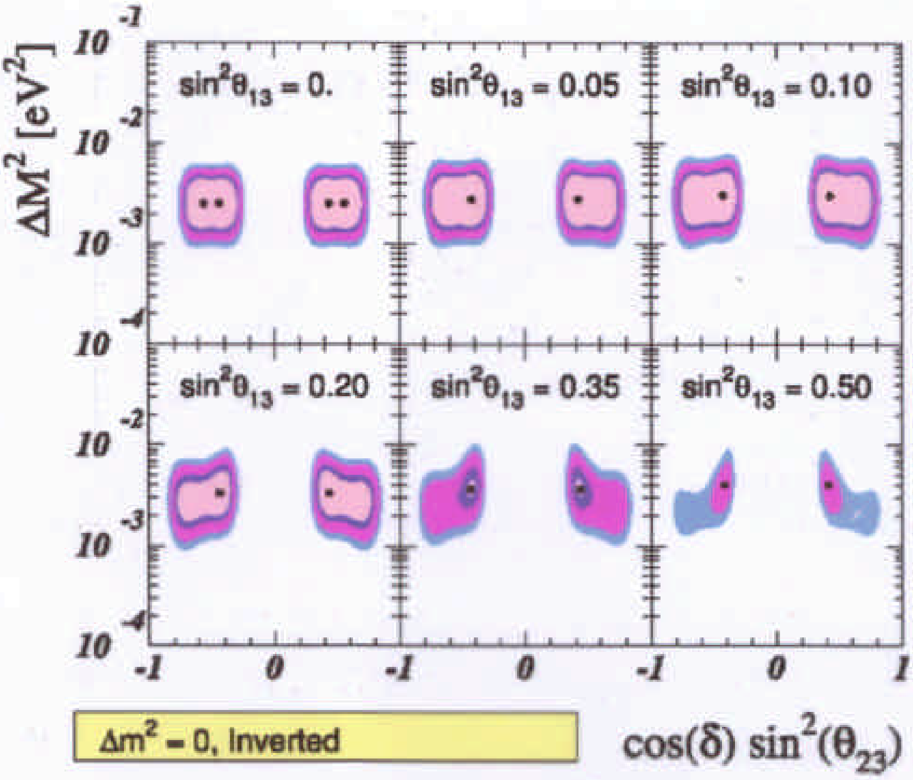


$\equiv \sin^2(2\theta_{13})$

3–ν Atmospheric Neutrino Oscillation Parameters



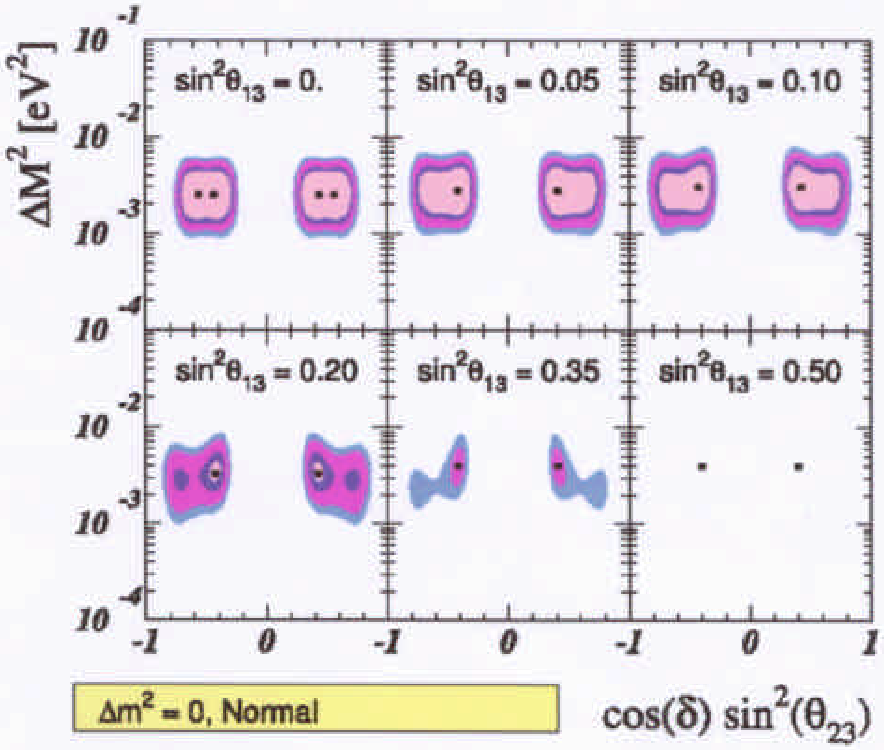
M.C. G-G and M. Maltoni, hep-ph/0202218

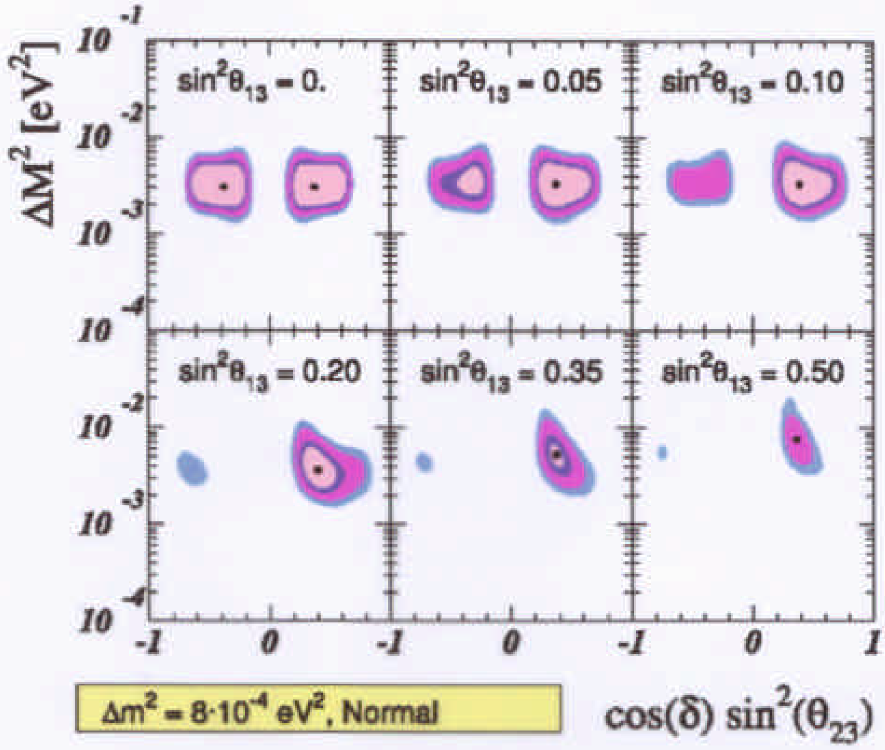


- From ATM data alone $\Rightarrow$ limit on $\sin^2\theta_{13}$
- If $\not{C}PT$ this is the only limit on $\sin^2\theta_{13}$ for ν's
- For CPT since $\Delta M^2 \gtrsim 8\times 10^{-4}$ eV^2 CHOOZ limits also θ_{13}
- But from 2ν 3σ ranges $\Rightarrow$ $\alpha = \frac{\Delta m^2}{\Delta M^2} \lesssim 0.4$

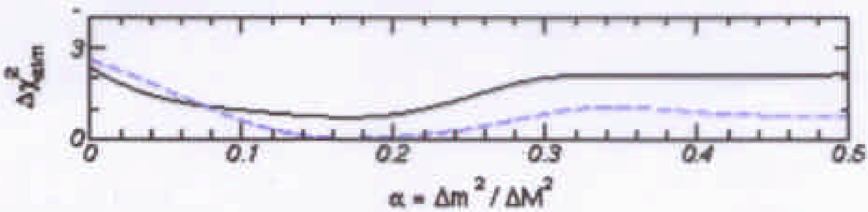
  $\Rightarrow$ *Possible effects beyond hierarchical approximation?*

ATM 3–ν Oscillations Beyond Hierarchical Approximation



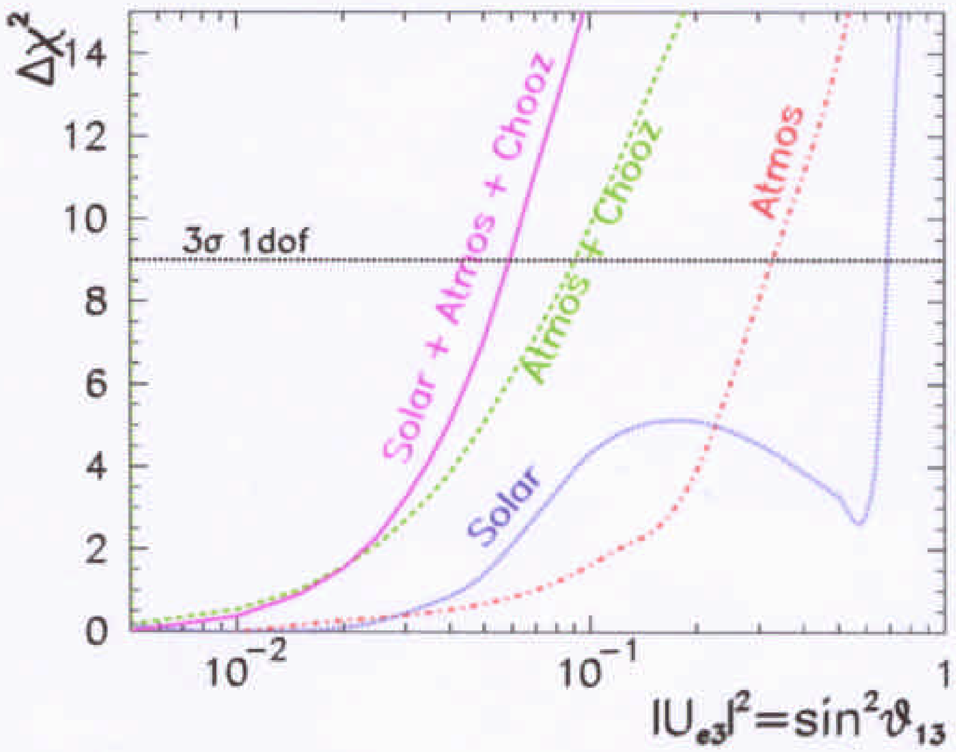


– ATM fit is not sensitive to large α



– But always $\Delta M^2 \gtrsim 10^{-3} \Rightarrow$ CHOOZ bound

3–ν Combined Analysis: Constraints on θ_{13}



- All data favour θ_{13} small
- 3σ (1dof) allowed ranges of parameters

$$
\begin{array}{rccl}
2.4\times10^{-5} < & \Delta m^2/\mathrm{eV}^2 & < 2.4\times10^{-4} & \text{LMA} \\
0.27 < & \tan^2\theta_{12} & < 0.77 & \text{LMA} \\
1.4\times10^{-3} < & \Delta M^2/\mathrm{eV}^2 & < 6.0\times10^{-3} & \\
0.4 < & \tan^2\theta_{23} & < 3.0, & \\
\sin^2\theta_{13} & < 0.06 & &
\end{array}
$$

- Mixing Matrix U

$$
|U| = \begin{pmatrix} 0.73-0.89 & 0.44-0.66 & <0.24 \\ 0.23-0.66 & 0.24-0.75 & 0.51-0.87 \\ 0.06-0.57 & 0.40-0.82 & 0.48-0.85 \end{pmatrix}.
$$

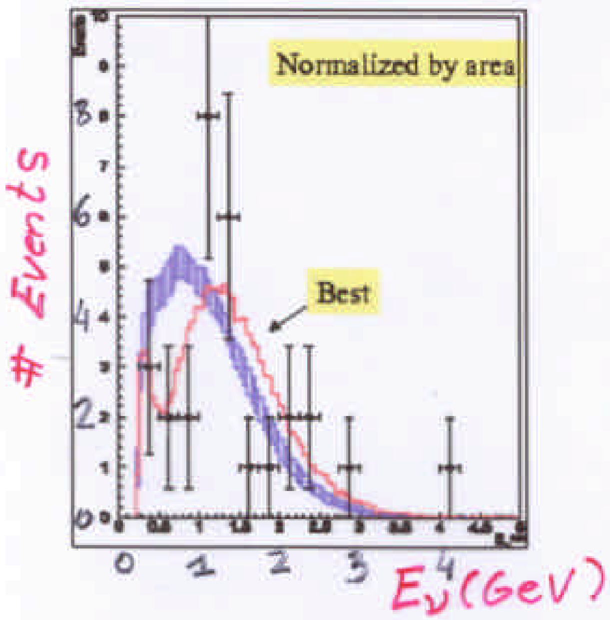
Long Baseline Experiments

- To Test Atmospheric Neutrino Oscillations

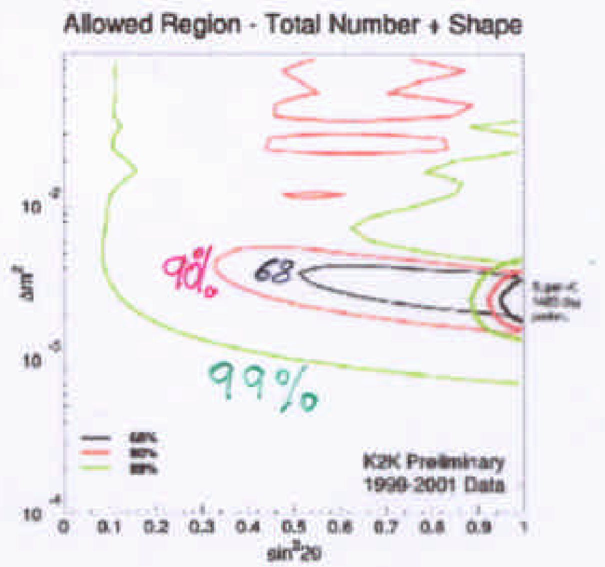
Experiment	Production	Detection	L (Km)
K2K	ν_μ at KEK	Kamiokande	250
MINOS	ν_μ at Fermilab	Soundan	730
Opera/Icarus	ν_μ at CERN	Gran Sasso	740

– K2K Run since June 1999 to July 2001:

(preliminary results presented at ν-2002 conference)



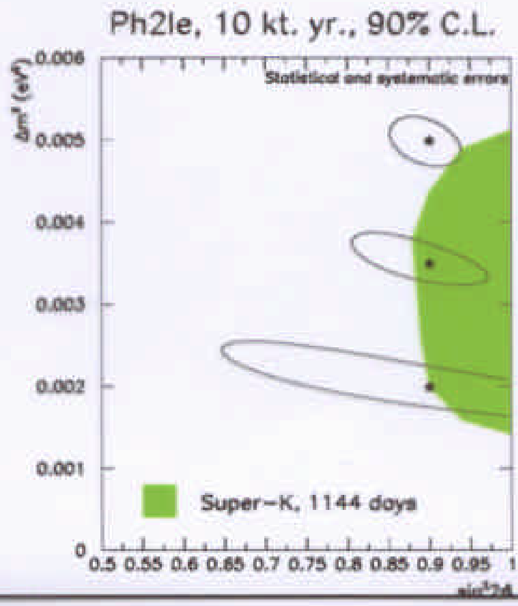
Comparison with SK atm ν observation



Compatible with Atmospheric but not much constraint on parameters

– MINOS

- Expected to start Dec 2004
- Expected Reconstruction of Atmospheric Parameters
- No improvement on θ_{13}



Test of CPT with Atmospheric ν's

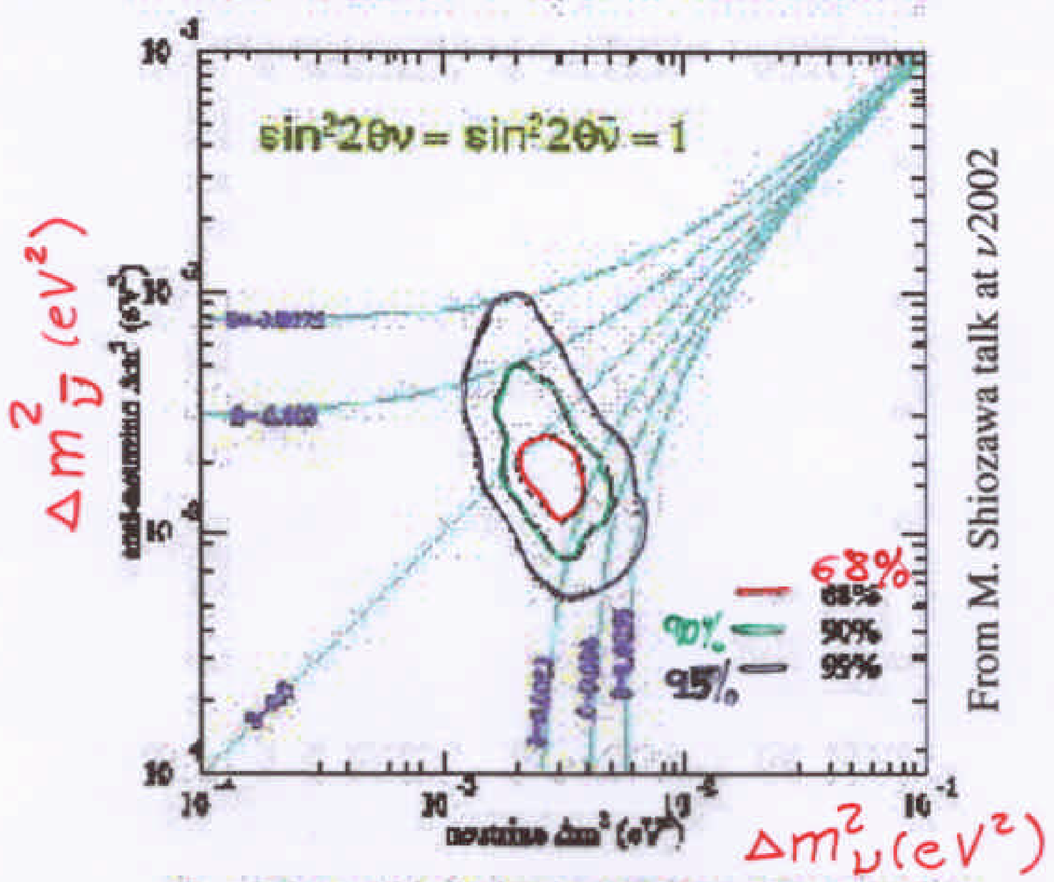
Murayama and Yanaguida PLB (2001), Barenboim etal hep-ph/0108199, hep-ph/0201134, Skadghauge hep-ph/0112189

- Since in Atmospheric Oscillations both:

$$\nu_\mu \to \nu_\tau \quad \text{and} \quad \overline{\nu}_\mu \to \overline{\nu}_\tau$$ but

- SK collaboration fits data with $\Delta m^2_\nu \neq \Delta m^2_{\overline{\nu}}$ $(\sin^2\theta_\nu = \sin^2\theta_{\bar\nu})$

➤ $\Delta m^2 \nu \neq \Delta m^2 \bar\nu$ (CPT violation)



- consistent with 0 CPT asymmetry
- limit on $\delta = \Delta m^2\nu - \Delta m^2\bar\nu$; $-0.0075 < \delta < 0.0055$

$-0.0075 < \delta < 0.0055$

– They find:

Best fit is close to CPT conservation $\Delta m^2_\nu = \Delta m^2_{\overline{\nu}}$

Limit at 95 %CL $-0.0075 < (\Delta m^2_\nu - \Delta m^2_{\overline{\nu}}) < 0.0055$

– Still not very conclusive

– Also not fully general analysis

IV. LSND and Karmen and Sterile Neutrinos

• LSND= the only signal for oscillation from laboratory experiment

• Uses the proton beam of Los Alamos

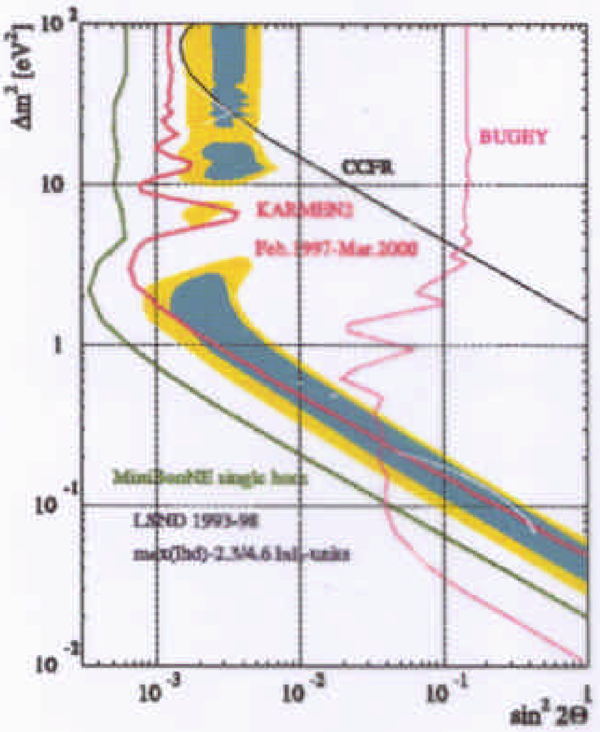
$$p + Target \rightarrow \pi^+ + X$$
$$\pi^+ \rightarrow \nu_\mu \, \mu^+$$
$$\mu^+ \rightarrow e^+ \, \nu_e \, \overline{\nu_\mu}$$

• At $L = 30$ m with $\langle E_\nu \rangle \sim 30$ MeV observes

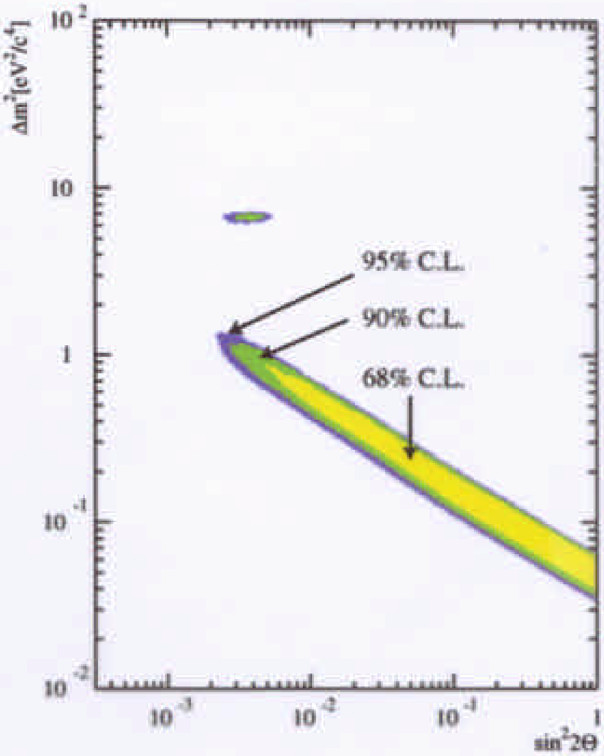
$\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ $\quad (\overline{\nu}_e + p \rightarrow e^+ n$ followed by $n\,p \rightarrow d\,\gamma)$

• with a probability $\langle P_{e\mu} \rangle = (0.264 \pm 0.067 \pm 0.045)\%$

• There is another experiment *Karmen* which searches for the same signal and does not observe oscillations.



LSND+Karmen Combined Analysis



E.D. Church *et. al.*, hep-ex/0203023

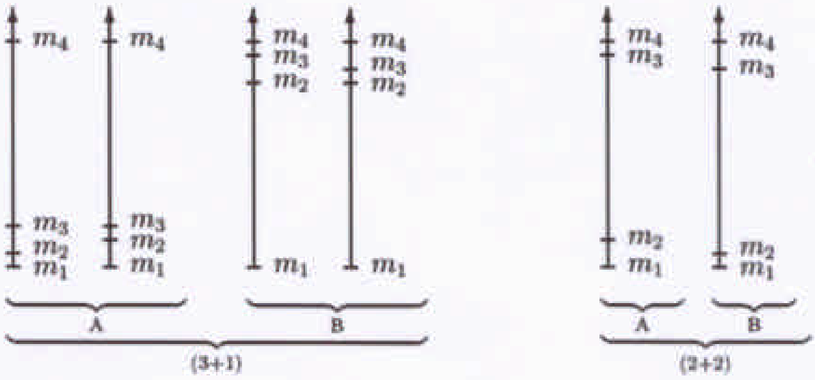
• *MiniBoone* Experiment in Fermilab will solve this.

Four Neutrino Mixing

- To fit solar, atmospheric and LSND

  $\rightarrow 3\ \Delta m^2 : \Delta m^2_{LSND} \ggg \Delta m^2_{atm} \gg \Delta m^2_{sun}$

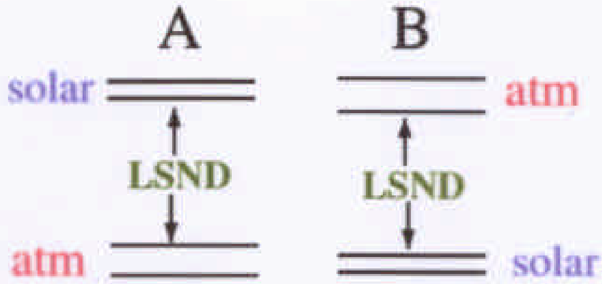
  $\rightarrow 4\ \nu's$ LEP $\Rightarrow$ 4th ν must be sterile
- U: 6 mixing angles and 3 CP phases
- 6 mass spectra:



- Limits from Accelerator and Reactor: $\rightarrow$ 3+1 disfavoured
- Also: – From solar neutrinos: $\nu_e \rightarrow \nu_s$ ruled out ~ 5-σ

  for 2+2 – From atmospheric neutrinos: $\nu_\mu \rightarrow \nu_s$ ruled out $\gtrsim 4$-σ
- But in 4-ν mixing such as:

  Mixed oscillations



Naively: Solar: $\nu_e \rightarrow \nu_+ \quad \nu_+ \simeq s_\eta \nu_s + c_\eta \nu_\tau$ (η = combination of angles in U)

Atm: $\nu_\mu \rightarrow \nu_- \quad \nu_- \simeq c_\eta \nu_s - s_\eta \nu_\tau$

More Precisely: 4 relevant mixing angles

Solar: Oscillations $\nu_e \rightarrow \nu_\alpha$ with $\Delta m^2_\odot$ and osc angle θ_{12}

$$\nu_\alpha = c_{23} c_{24} \nu_s + \sqrt{1 - c^2_{23} c^2_{24}}\, \nu_a \Rightarrow \text{2+1 parameters}$$

ATM: Oscillations $\nu_\beta \rightarrow \nu_\gamma$ with Δm^2_{atm} and osc angle θ_{34}

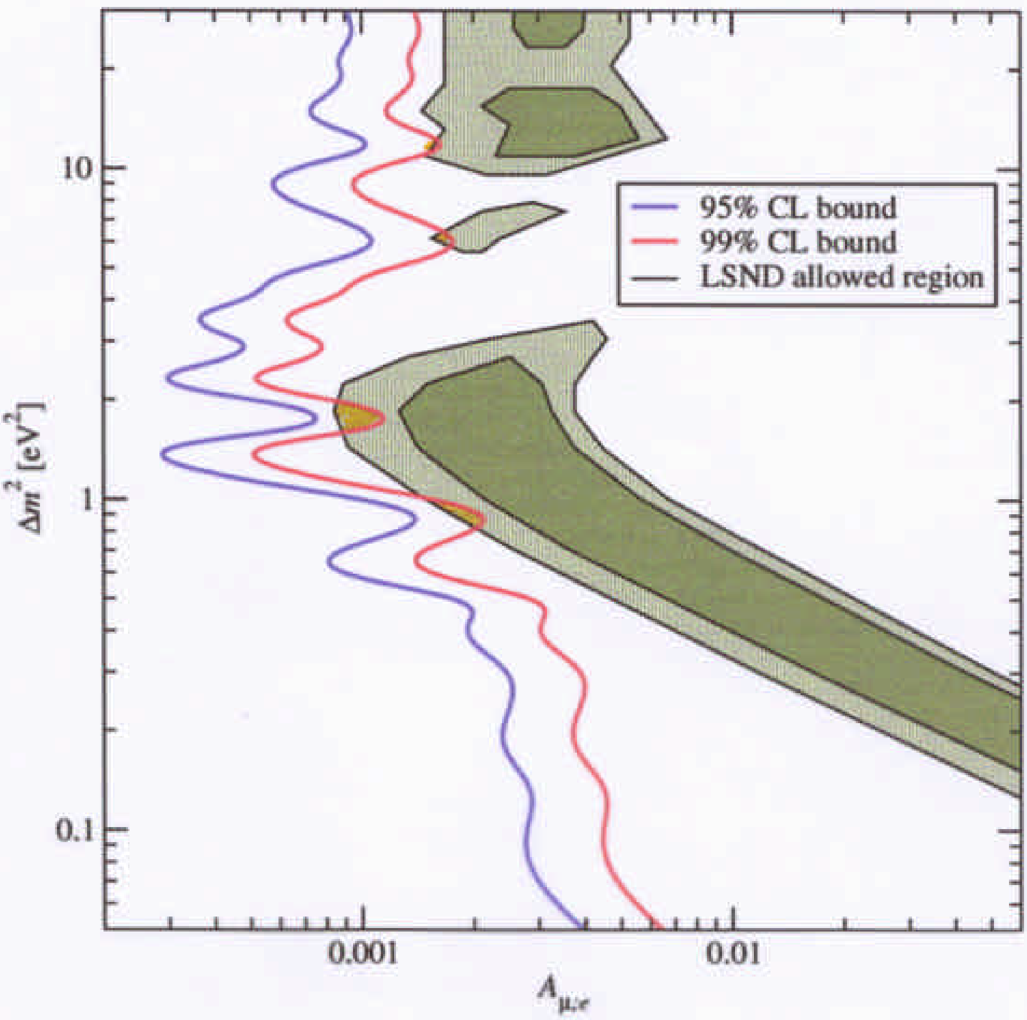
$$\nu_\beta = s_{23} c_{24} \nu_s + c_{23} \nu_\mu - s_{23} s_{24} \nu_\tau \quad \nu_\gamma = s_{24} \nu_s + c_{24} \nu_\tau$$

$\Rightarrow$ 2+2 parameters

Status of 3+1 schemes:

Grimus and Schwetz E.J. Phys (2001)

Valle, Maltoni and Schwetz PRD (2002)



Karmen + Bugey + CDHS +Nomad:

⇒ Only two very small "islands" allowed at 99 %CL

⇒ This is unchanged by the new SNO NC data

Solutions for Solar 4–ν Oscillations

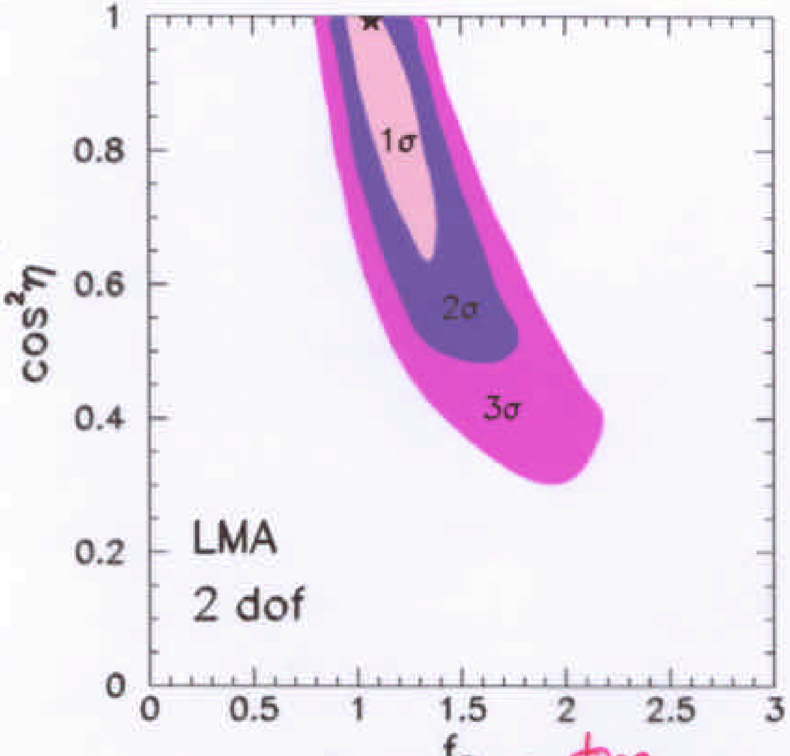
- Sterile limit weaker if free ^{8}B:

$$\Phi(^8B) = \Phi(\nu_e) + \Phi(\nu_{\mu\tau}) + \Phi(\nu_s) = \Phi(\nu_e) + (1 + \tan^2\eta)\Phi(\nu_{\mu\tau})$$

In other way (Barger et al., PRL88, 2002):

$$\Phi(CC) = \Phi(^8B)\cdot < P_{ee} >$$
$$\Phi(NC) = \Phi(^8B)\cdot (< P_{ee} > + \cos^2\eta(1- < P_{ee} >))$$
$$\Phi(ES) = \Phi(^8B)\cdot (< P_{ee} > + 0.17\cdot\cos^2\eta(1- < P_{ee} >))$$

- Allowed region from Global Analysis :



$f_B = \frac{\Phi_{8B}}{\Phi_{SSM}}$

Best fit still $\nu_e \to \nu_a$
But degeneracy in present limit of $\cos^2\eta$ versus f_B
NC data does not solve it

– To determine f_B independently of the sterile admixture
⇒ Combine Solar and terrestial disappearance measurements:

KamLAND and SNO CC ⇒ f_B at ~ 10%

(J.N. Bahcall, M.C.G-G, C. Peña-Garay, hep-ph/0204194)

+SNO NC ⇒ $\cos^2\eta \sim 15\%$

Solutions for Atmospheric 4–ν Oscillations

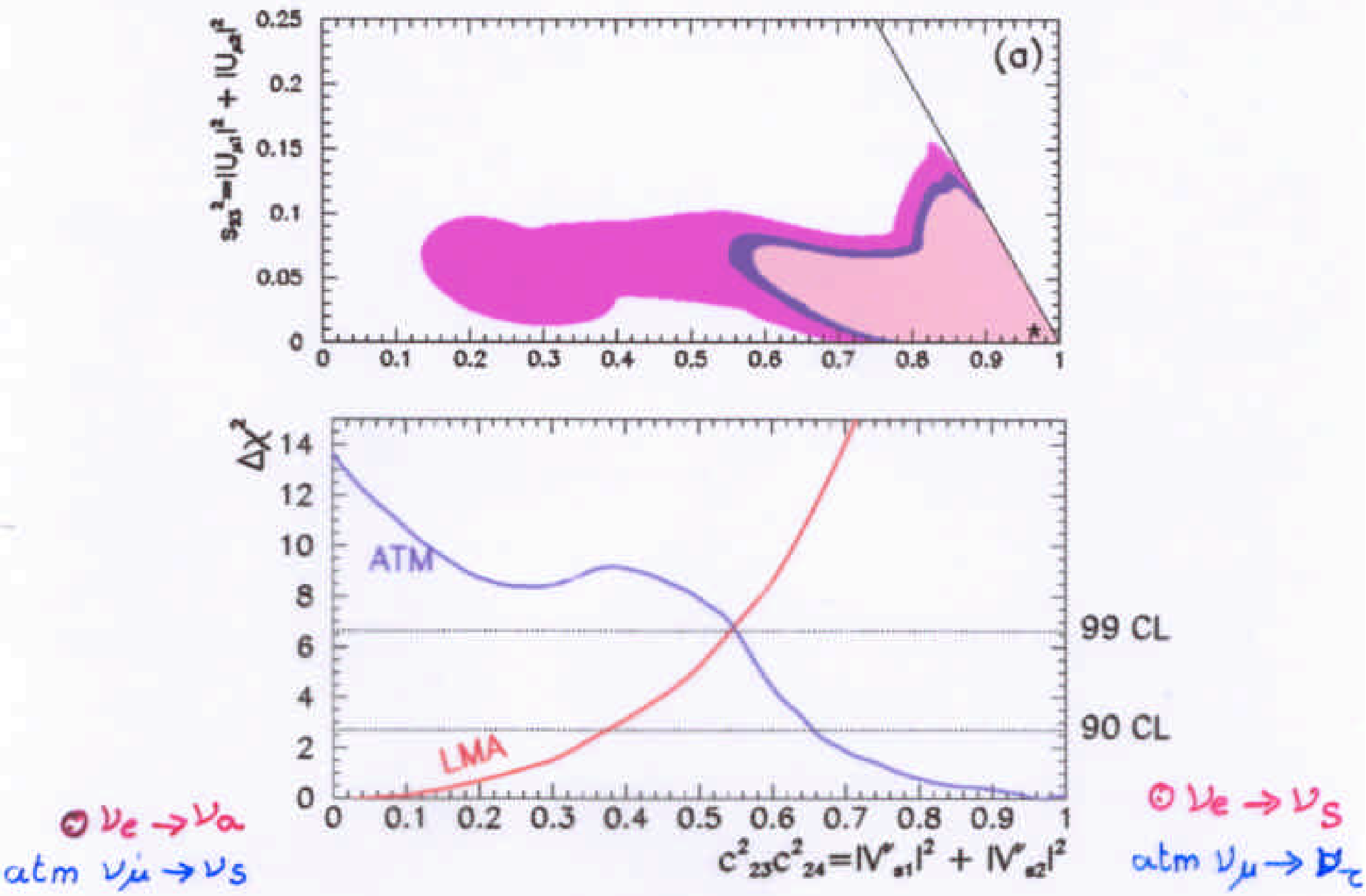
- Oscillations $\nu_\beta \rightarrow \nu_\gamma$ with Δm^2_{atm} and osc angle θ_{34}

$$\nu_\beta = s_{23}c_{24}\nu_s + c_{23}\nu_\mu - s_{23}s_{24}\nu_\tau \quad \nu_\gamma = s_{24}\nu_s + c_{24}\nu_\tau$$

- The analysis constrains two new parameters:

– $c^2_{24} \equiv \tau$–sterile admixture

– $s^2_{23} = |U_{\mu 1}|^2 + |U_{\mu 2}|^2 \equiv$ effect of $\Delta m^2_{\rm LSND}$ on Atm neutrinos



- ν_β =close-to-pure ν_μ ($s^2_{23} \lesssim 0.12(0.16)$ at 90 (99%))

- this oscillates into a state which is preferably composed by ν_τ, but a 48% admixture of sterile still allowed at 99% CL

– Solar $\Rightarrow c^2_{23}c^2_{24} < 0.54$ at 99% CL (weaker if f_B free)

– Atmospheric $\Rightarrow c^2_{23}c^2_{24} > 0.54$ at 99% CL

$\Rightarrow$ 2+2 scenarios still valid at 99% CL

VI. Neutrino Mass Scale

Kinematic Determination

- The strongest limit is (Mainz & Troisk experiments)

$$m_{\nu_e} < 2.2\text{ eV} \quad \text{From } {}^3H \to {}^3He + e + \overline{\nu}_e$$

- What is m_{ν_e} in presence of mixing?:

– Simplification: when m_j are quasi-degenerate

$$\frac{dN}{dE} = R(E)\sqrt{(E_0 - E)^2 - {m^{\beta}_{eff}}^2}\,\Theta(E_0 - E - m^{\beta}_{eff})$$

With $$m_{\nu_e} = m^{\beta}_{eff} = \sum_j m_j |U_{ej}|^2$$

ν-less Double-β decay ($(\beta\beta)_{0\nu}$)

- If ν are Majorana $\Rightarrow$ L is violated $\Rightarrow$ ν-less Double-β decay

$$(A, Z) \to (A, Z+2) + e^- + e^-$$

– $(\beta\beta)_{0\nu}$ amplitude is proportional to effective Majorana mass

$$|\langle m_{\beta\beta}\rangle| = |\sum_i^N U^2_{ei} m_i|$$

– Best limit from ^{75}Ge Heidelberg-Moscow experiment. At 90% CL

* $|\langle m_{\beta\beta}\rangle| < 0.35$ eV +theor. uncert. on nucl. matrix element $\to$ < 1.05 eV

* Sensitive to CP violating phases (unlike m^{β}_{eff})

- How to learn from comparing $|\langle m_{\beta\beta}\rangle|$ and m^{β}_{eff}?

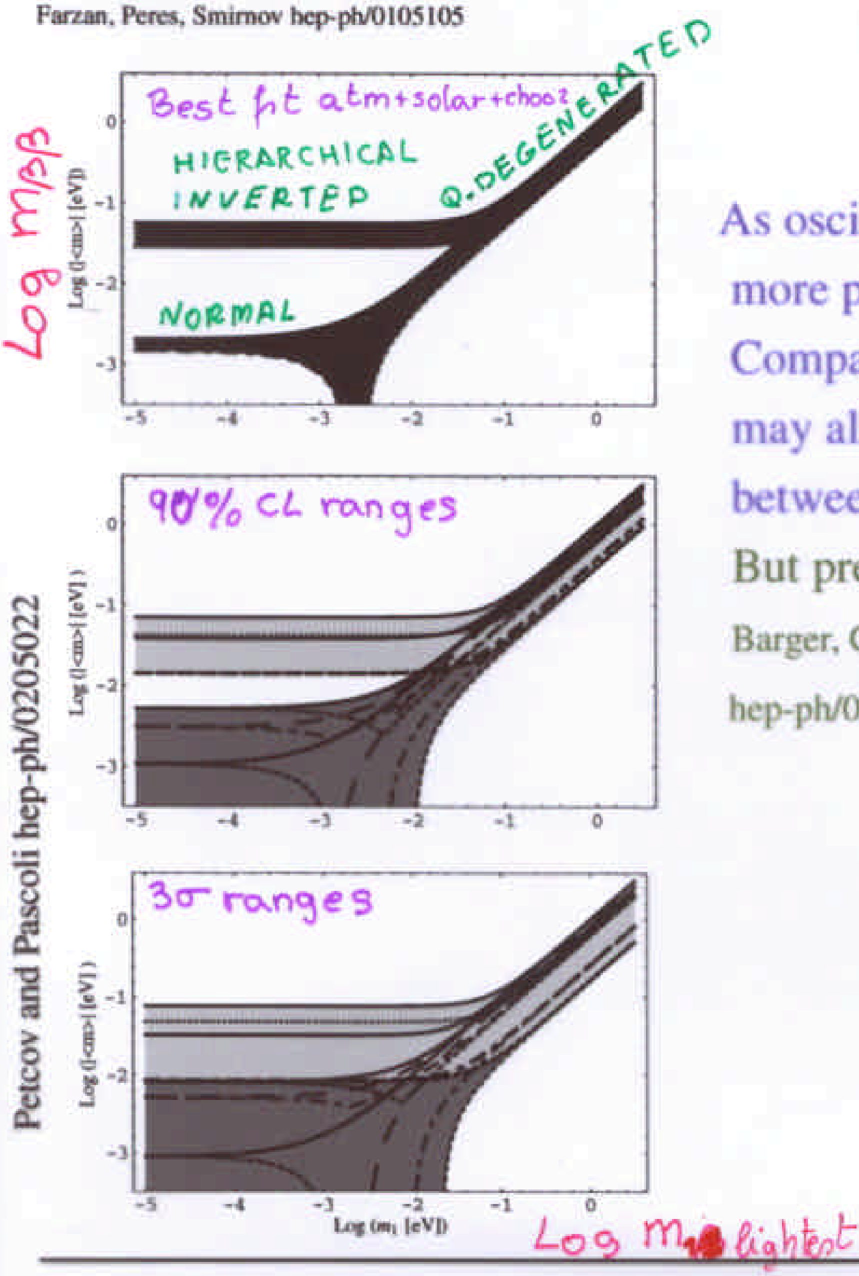
– Choose your favourite mass scheme compatible with $\Delta m^{2\prime}s$ from oscillation data

– Derive bounds and values for $|U_{ei}|$ from oscillation data

– Predict possible values for $|\langle m_{\beta\beta}\rangle|$ and m^{β}_{eff}

– Compare to present/future sensitivity

Bilenky, Giunti, Grimmus, Kayser, Petcov, PLB (1999)
Giunti, PRD (2000)
Bilenky, Giunti, Grimmus, Kayser, Petcov, PLB (1999)
Bilenly, Pascoli, Petcov hep-ph/0102265, hep-ph/0104218
Klapdor, Pas, Smirnov PRD (2001)
Farzan, Peres, Smirnov hep-ph/0105105



Petcov and Pascoli hep-ph/0205022

As oscillation data gets more precise
Comparison of $|\langle m_{\beta\beta}\rangle|$ and m^{β}_{eff} may allow to discriminate between mass schemes

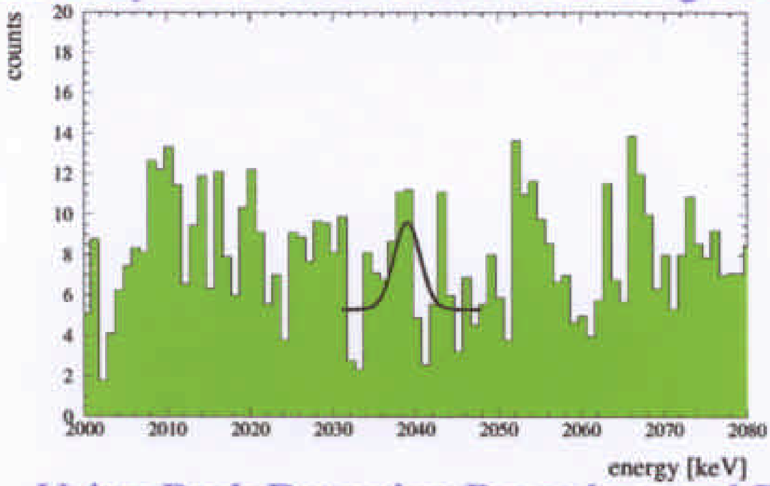
But precision may not be enough

Barger, Glashow, Langacker and Marfatia, hep-ph/0205290

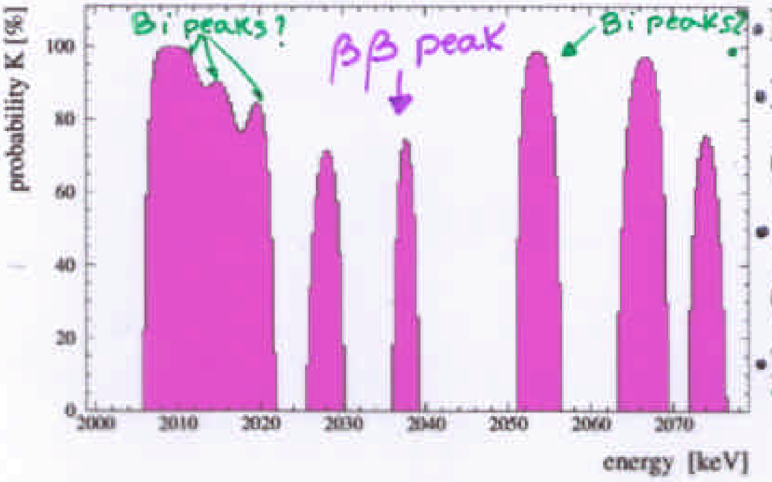
Comment on Evidence of $(\beta\beta)_{0\nu}$

Klapdor-Keingrothaus *et. al.* MPLA (2001)

Reanalysis of 1990-2000 Heidelberg-Moscow data finds evidence



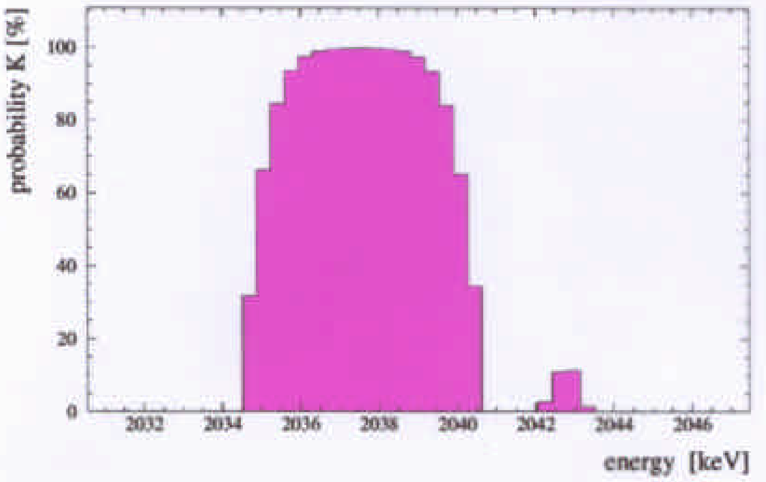
– Using Peak Detection Procedure and Bayesian Approach



- Finds 6 peaks
- 3 recognized 214Bi Peaks (but not fully quantitatively)
- 1 assumed to be $\beta\beta$ peak (because it has the right E)
- 3 peaks are ignored

– Assuming small energy 5σ interval around the $\beta\beta$ Peak

– fits the unique peak to a peak + constant background



finds 2.2 (3.1) σ evidence

$\Rightarrow \langle m_{\beta\beta} \rangle = 0.11 - 0.56\,eV$ (95

Comment on Evidence of $(\beta\beta)_{0\nu}$

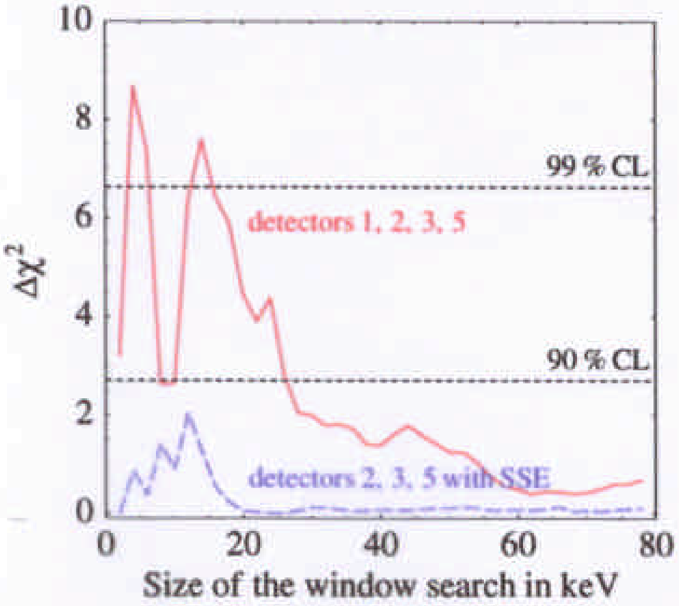
Criticisms:

C. E. Aalseth, *et. al*, hep-ph/0202018, to appear in MPLA

Feruglio, Strumia and Vissani, hep-ph/0201291, to appear in NPB

– How to justify the 5σ window?

If window is larger the significance decreases



From Feruglio et al.

– How well are the 3 recognized 214Bi Peaks understood?

– How about the two non understood Peaks?

Common sense: If some peaks are not fully understood and some peaks are not understood at all the probability of the "signal" peak to be right should be smaller

To quantify this: Fit the full spectrum to flat background + known peaks + signal

Feruglio et al. did it and got at most 1.5σ

VI. Summary

- Solar analysis:

– Full SNO phase-1 data confirms dramatically SSM
– LMA is the only MSW solution at $\sim 99\%$ CL
– KamLAND running and should be giving important results soon

- Solar + atmospheric + reactor in 3-ν

– All data prefers θ_{13} small.
– 3σ (1dof) allowed ranges

$$
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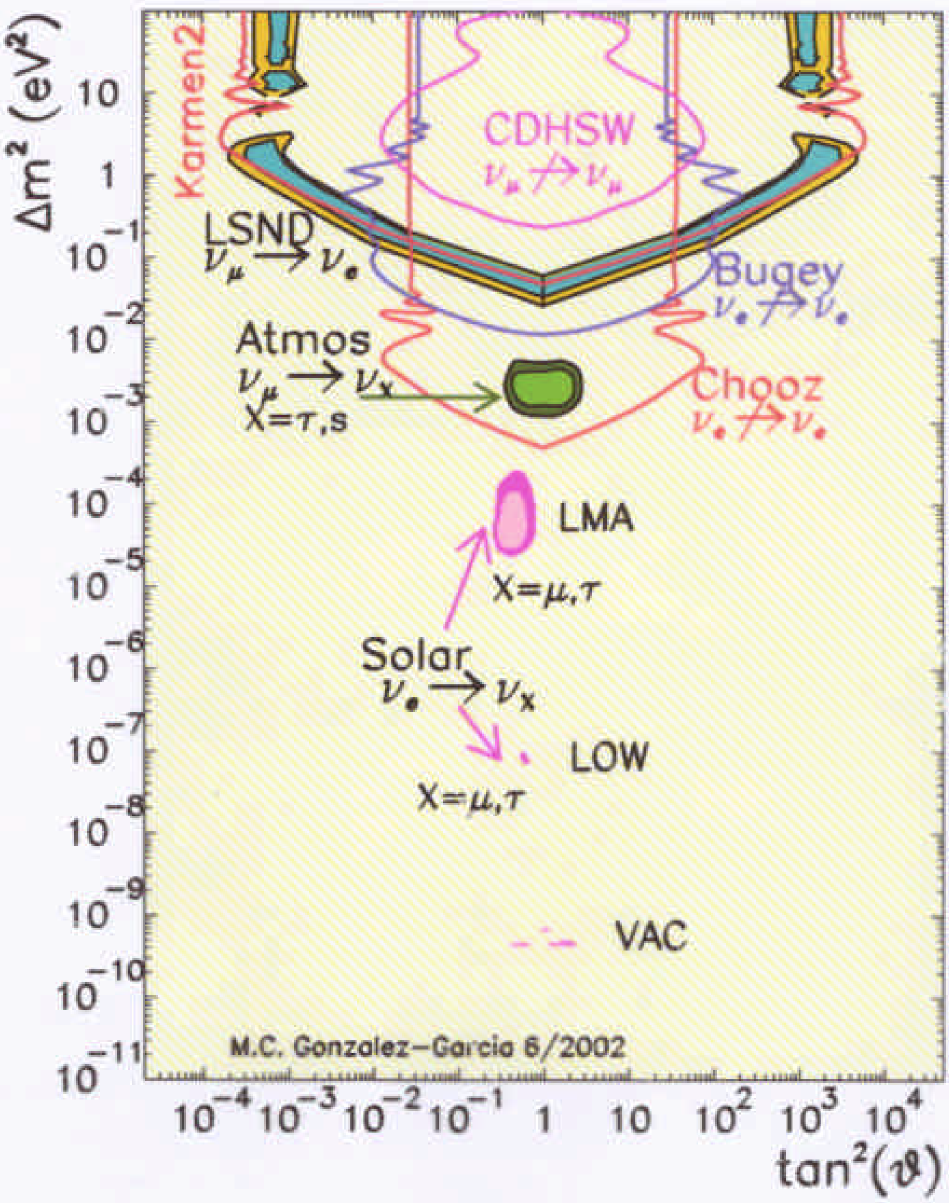
$$

– K2K results compatible with atmospheric oscillations
– KamLAND and MINOS will give important constraints on 12 and 34 parameters
– Still missing an experiment for 13 and CP violation

- 4-ν and sterile neutrinos

– Limit from solar neutrinos relaxed if ^{8}B flux larger than SSM
– Limit from atm relaxed if admixture with $\Delta m^2_{\rm LSND}$ considered
– 2+2 Still compatible at 99% CL

• Summary of Two-Oscillation Searches



My personal summary:

" These have been the hell of very exciting (and very exhausting) years to do neutrino phenomenology"
