Solar and Atmospheric Neutrino Oscillations

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OUTLINE

I. Two–Neutrino Oscillations:

- *"Unified" Analysis of Solar Neutrino Data*
  - *Solutions for* $\nu_e \to \nu_{active}$
  - *Solutions for* $\nu_e \to \nu_{sterile}$
- *Global Analysis of Atmospheric Neutrino Data*
  - *Solutions for* $\nu_e \to \nu_{active}$
  - *Solutions for* $\nu_e \to \nu_{sterile}$

II. Three–Neutrino Mixing

- *Combined Analysis of Solar, Atmospheric and Reactor* ν

III. *Unifying* Active and Sterile Oscillations:

- *Four-neutrino Oscillations*

IV. Summary

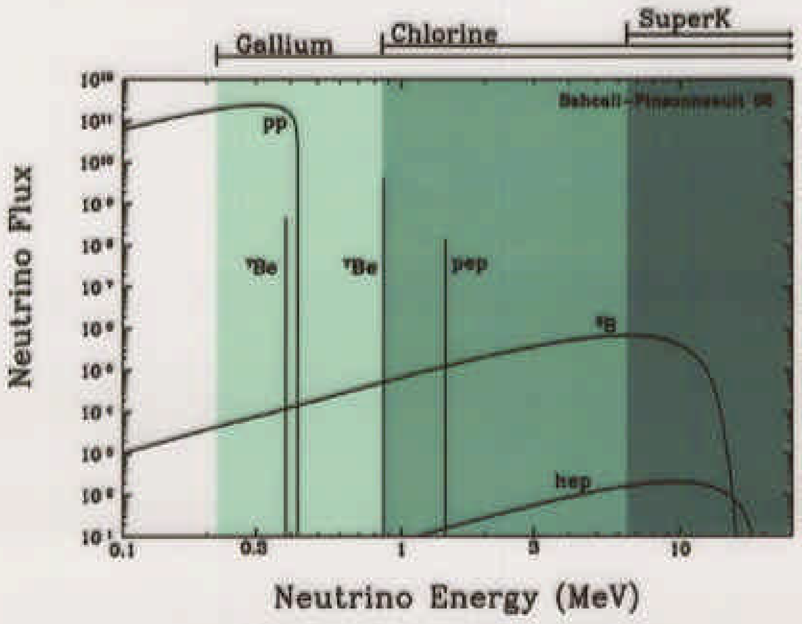
Based on:

M.C.G-G,C. Peña-Garay, ("unified" solar update) in preparation
M.C.G-G,C. Peña-Garay, PRD62 (2000)
M.C.G-G, P.C. de Holanda, C. Peña-Garay, J. Valle, NPB572 (2000)
N. Fornengo, M.C.G-G, J.Valle, NPB580 (2000)
M.C.G-G, M. Maltoni, C. Peña-Garay and J.Valle (3-ν analysis) in prep
C. Giunti, M.C.G-G,C. Peña-Garay, PRD62 (2000)

I. Two–Neutrino Oscillations:

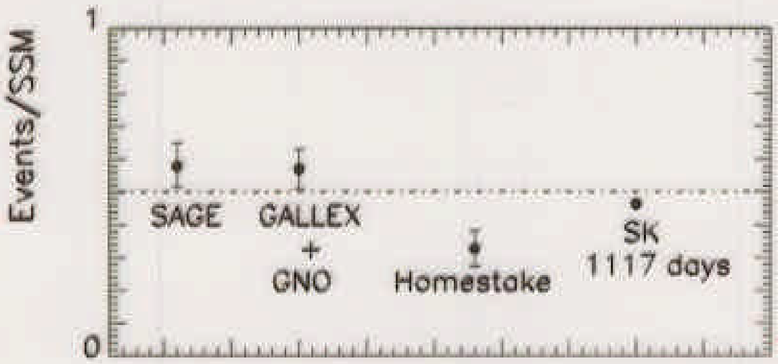
Solar Neutrinos

- The sun emits $\nu_e^\prime s$. The Standard Solar Model fluxes



Solar neutrino energy spectrum

- $\nu_e^\prime s$ are detected on Earth by
  - Homestake ("Clorine") $\nu_e +^{37} Cl \to^{37} Ar + e^-$
  - SAGE and GALLEX+GNO $\nu_e +^{71} Ga \to^{71} Ge + e^-$
  - Kamiokande and SuperK $\nu_e e$ scattering in H_2O Target
- The experiments are sensitive to different E_ν
- All experiments observe a deficit...

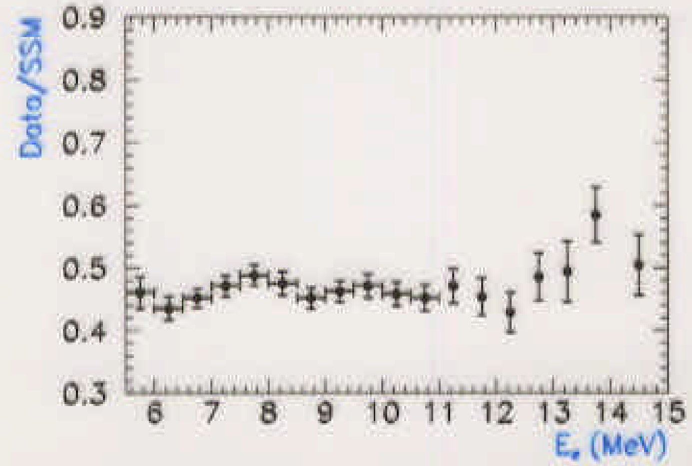


...Of about 30–60 %

Other Super–Kamiokande Measurements

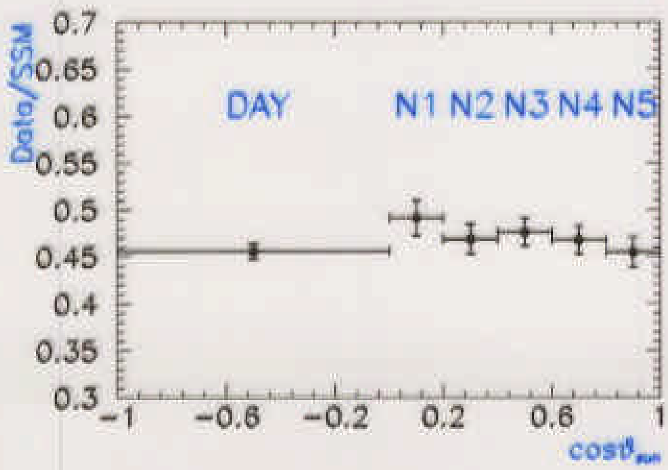
Super–Kamiokande 1117 Days

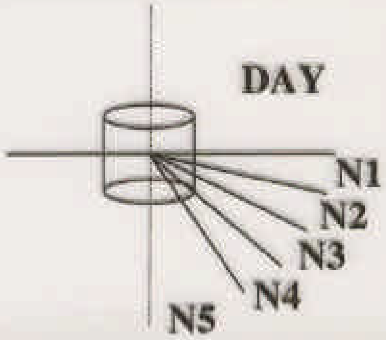
- Recoil Electron Energy Spectrum → no distortion $\chi^2_{flat} = 13/(17dof)$



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

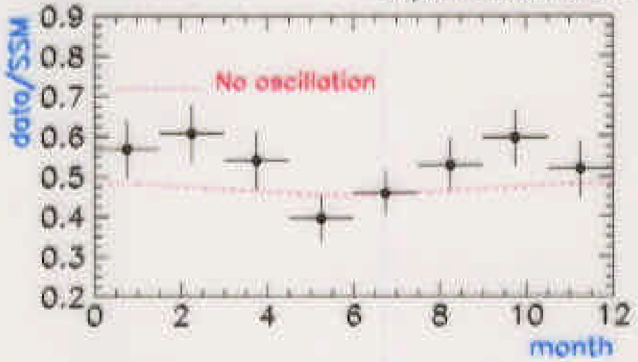
→ Few more events at N than D $2\frac{D-N}{D+N} = -0.034 \pm 0.022 \pm 0.013\,(1.3\sigma)$





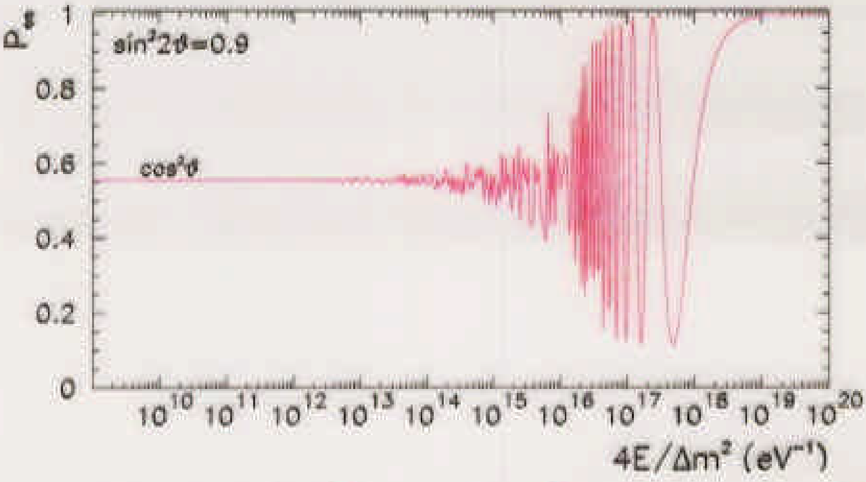
- Seasonal Variation → Small Beyond Earth Orbit Eccentricity

Super–Kamiokande 825 Days



- The *Standard* Interpretation: Oscillation ν_e into ν_μ, ν_τ (active $\nu's$), or ν_s
- Two possible oscillation scenarios:

(a) Vacuum oscillations: $P_{ee}^{vac} = 1. - \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 L/E\right)$



– P_{ee}^{vac} is symmetric under $\Delta m^2 \to -\Delta m^2$ or $\theta \to -\theta + \frac{\pi}{2}$

(b) Resonant Oscillations in Matter (MSW effect):

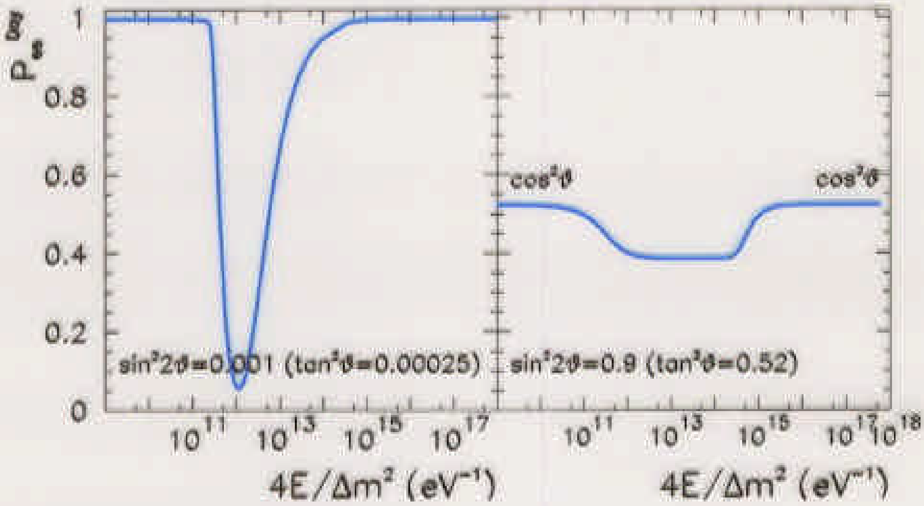
– Neutrinos can interact *coherently* with matter in the sun

– Different flavours have different interactions $\Rightarrow A = 2E(V_e - V_X)$

– Approximate solution: $P_{ee}^{MSW} = \frac{1}{2} + (\frac{1}{2} - P_c)\cos(2\theta_{m,0})\cos(2\theta)$

P_c Level Crossing Probability

$\theta_{m,0}$ mixing in matter: $\sin(2\theta_{m,0}) = \frac{\Delta m^2 \sin(2\theta)}{\sqrt{(\Delta m^2\cos(2\theta) - A)^2 + (\Delta m^2 \sin(2\theta))^2}}$



– Matter $\Rightarrow P_{ee}^{MSW}$ symmetric for *simultaneous* $(\Delta m^2, \theta) \to (-\Delta m^2, \frac{\pi}{2} - \theta)$

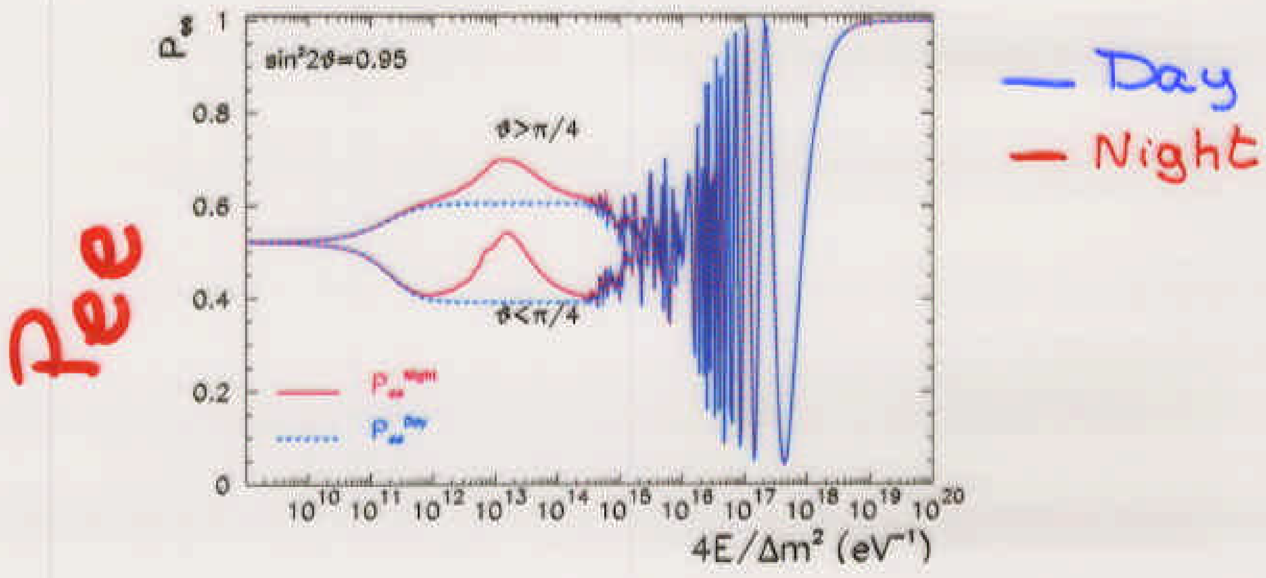
– For $\Delta m^2 > 0$ resonance possible only for $\theta < \frac{\pi}{4}$

– So *Traditionally* MSW solutions are also plotted in $(\Delta m^2, \sin^2(2\theta))$

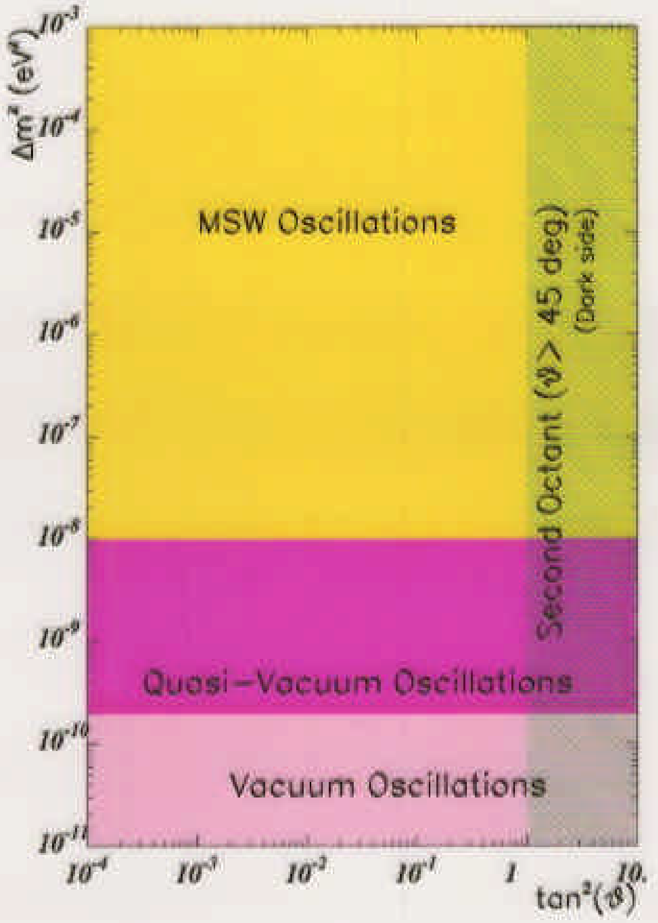
– But solutions are also possible for $\theta > \frac{\pi}{4}$ (Dark Side)

– Comparing P_{ee}^{MSW} with P_{ee}^{vac} : For $10^{13} \lesssim E/\Delta m^2 \lesssim 10^{18}$ both matter and L dependent effects: Quasi-vacuum oscillations.

– In what follows we will use numerical probabilities valid on full parameter space



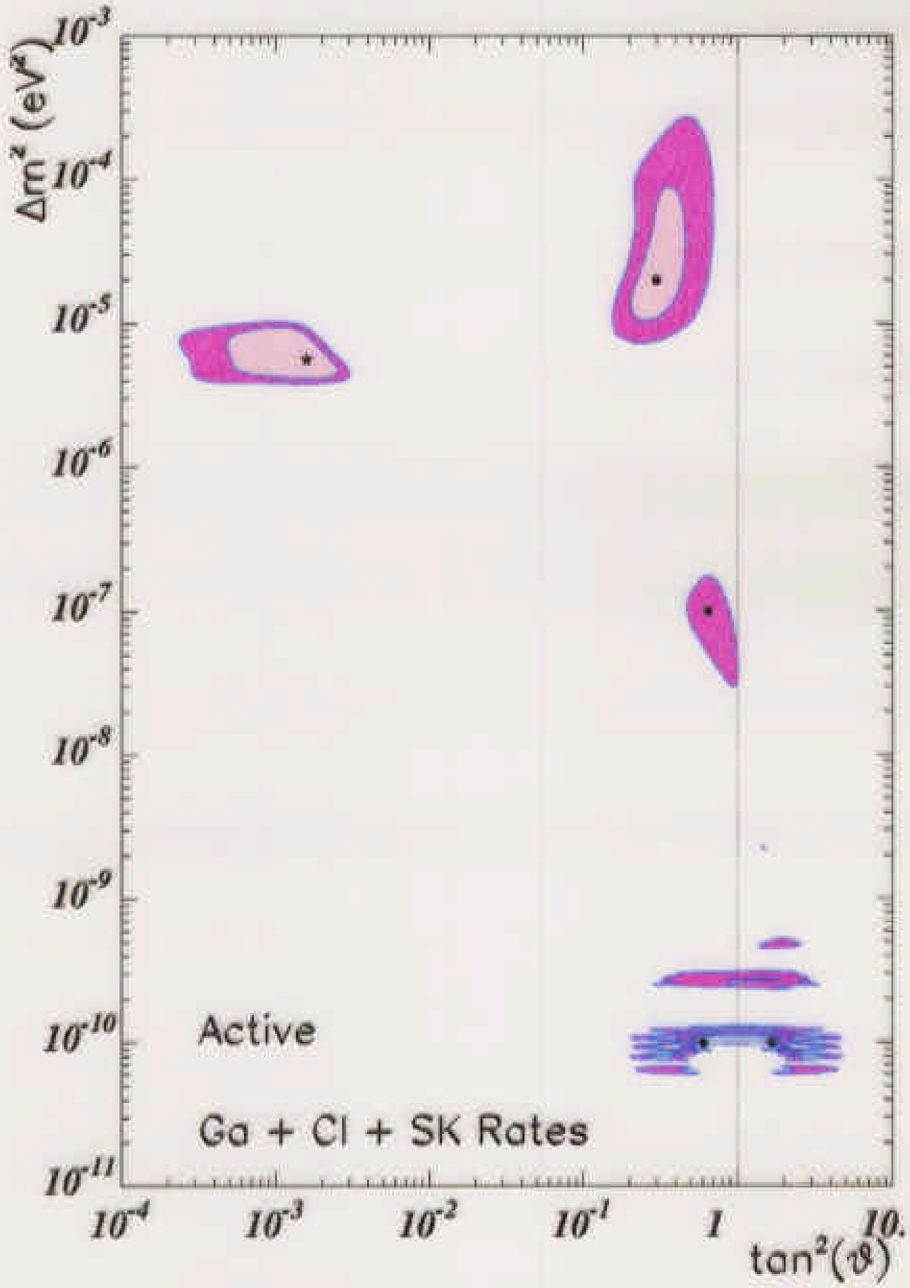
– And plot the allowed regions in the *Unified Oscillation Parameter Plot*:



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

Including new GNO, Sage and Super–Kamiokande 1117 Days

Allowed regions from Rates: M.C.G-G, C. Peña-Garay in preparation



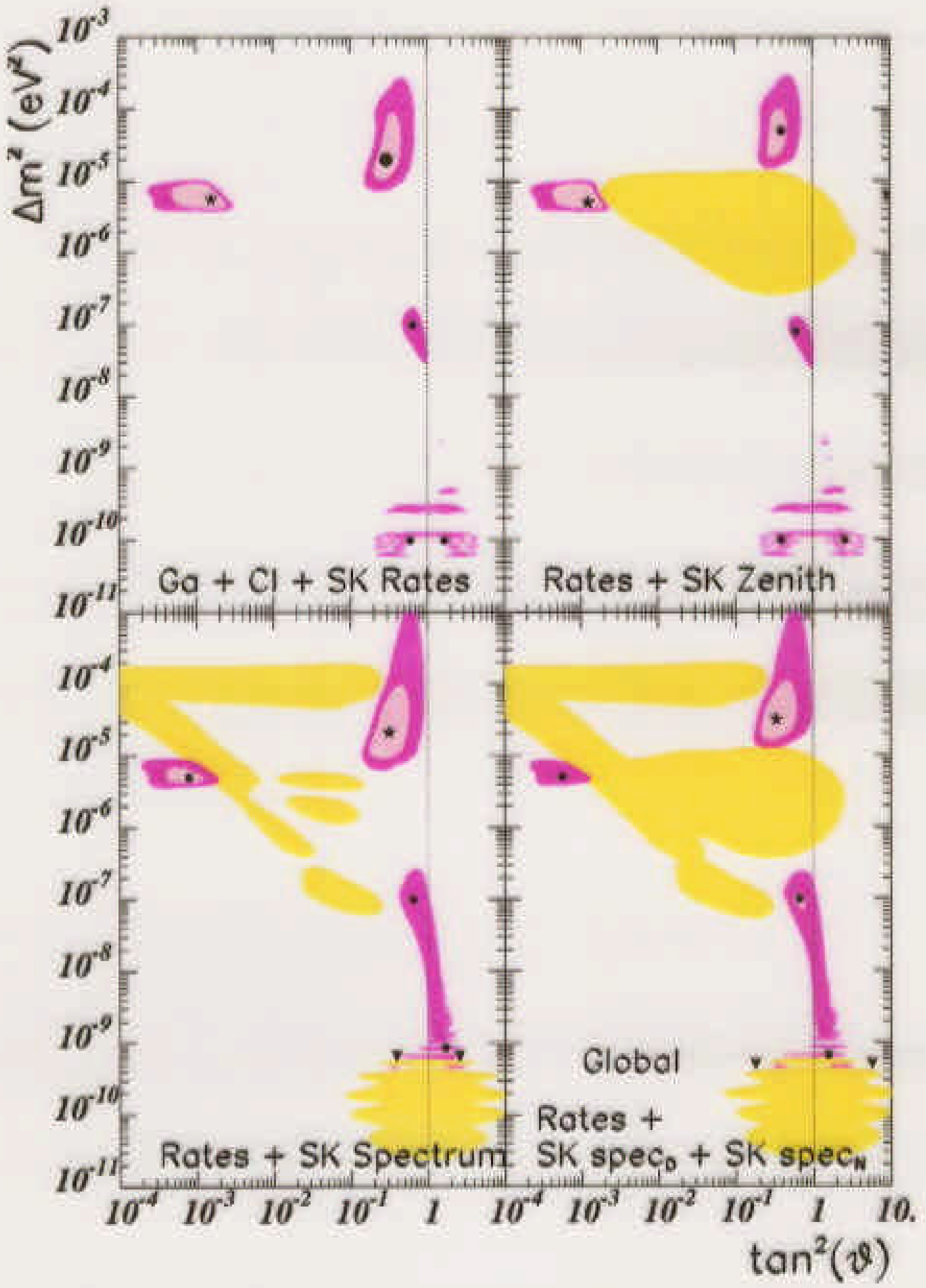
Observable					
Rates		SMA	LMA	LOW	VAC
	Δm^2/eV^2	5.6×10^{-6}	1.9×10^{-5}	$9. \times 10^{-8}$	8×10^{-11}
	$\tan^2 \theta$	0.0014	0.2	0.57	0.51 (1.96)
	Prob (%)	38 %	8 %	0.5 %	4 %

– For higher *Vacuum* solutions matter effects break symmetry

Solutions for $\nu_e \to \nu_{active}$ Including new GNO, Sage and SK 1117 Days

M.C.G-G, C. Peña-Garay in preparation

Effect of Day-Night and Spectrum data:



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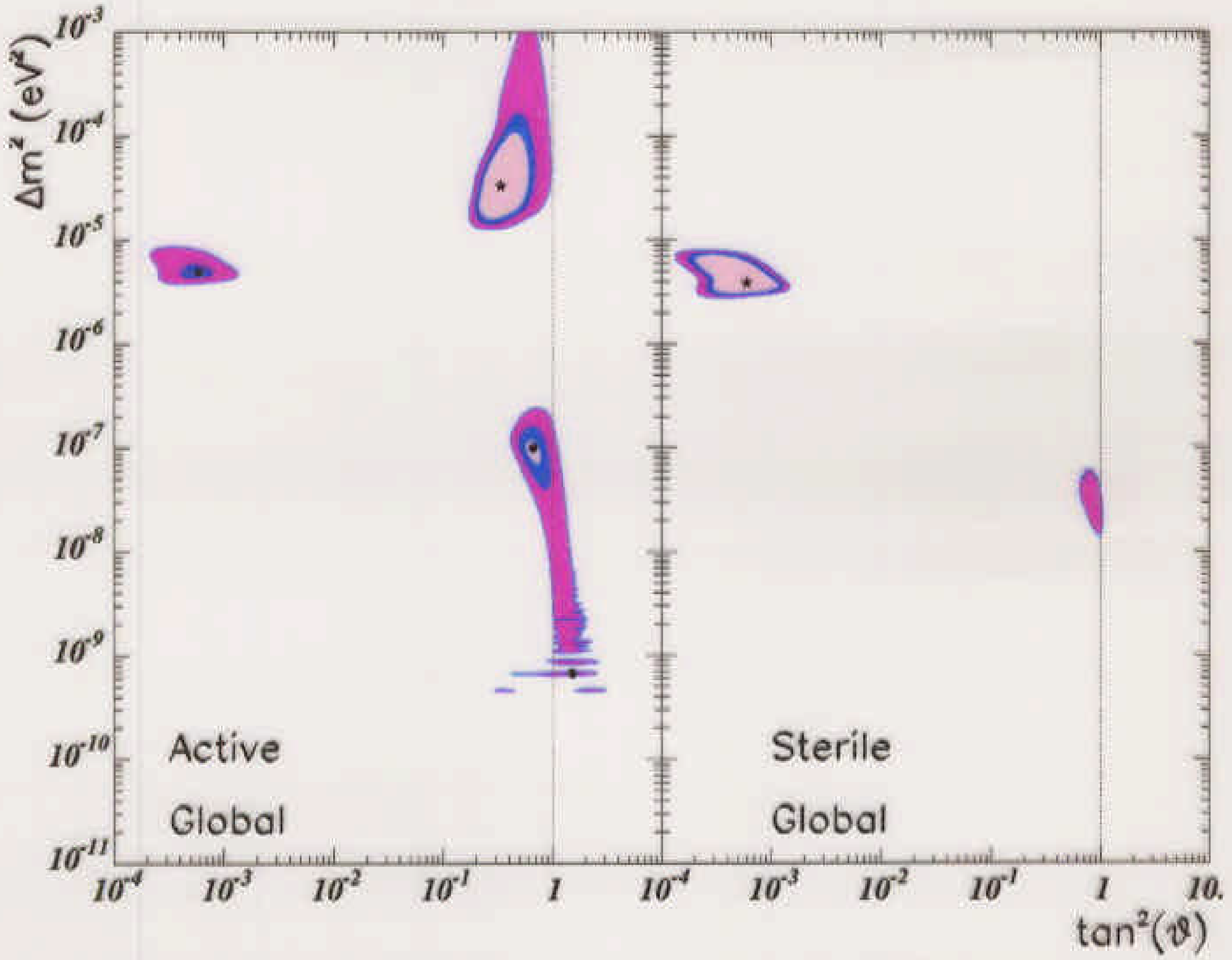
	Prob (%)	38 %	8 %	0.5 %	4 %
Rates+ +Spec$_D$+Spec$_N$	Δm^2/eV^2	5.0×10^{-6}	3.2×10^{-5}	$1. \times 10^{-7}$	6.7×10^{-10}
	$\tan^2\theta$	0.00056	0.33	0.57	1.75 (QVO)
	Prob (%)	34 %	59 %	40 %	32 %

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

Including new GNO, Sage and Super–Kamiokande 1117 Days

M.C.G-G, C. Peña-Garay in preparation



–For Active SMA allowed at 95 % CL but with smaller θ

LOW solution better than SMA after 1117 SK days

–For Sterile SMA: $\Delta m^2 = 3.8 \times 10^{-6}$ $\tan^2\theta = 0.0006$ Prob=31%

– Why differences for oscillations into active or sterile?

Main effect is different contribution to event rates in SuperK

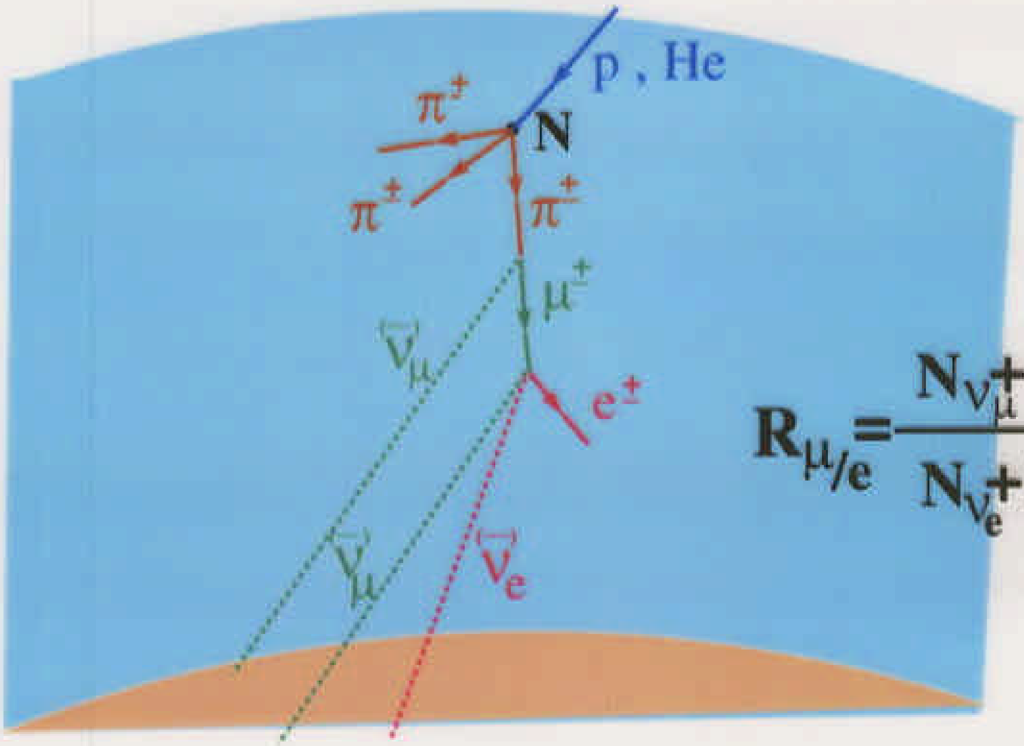
$\nu_{\mu(\tau)} + e \rightarrow \nu_{\mu(\tau)} + e \rightarrow$ NC events in SuperK

$\nu_s + e \not\rightarrow \nu_s + e \rightarrow$ no NC events in SuperK

Also slightly different survival probabilities in the sun

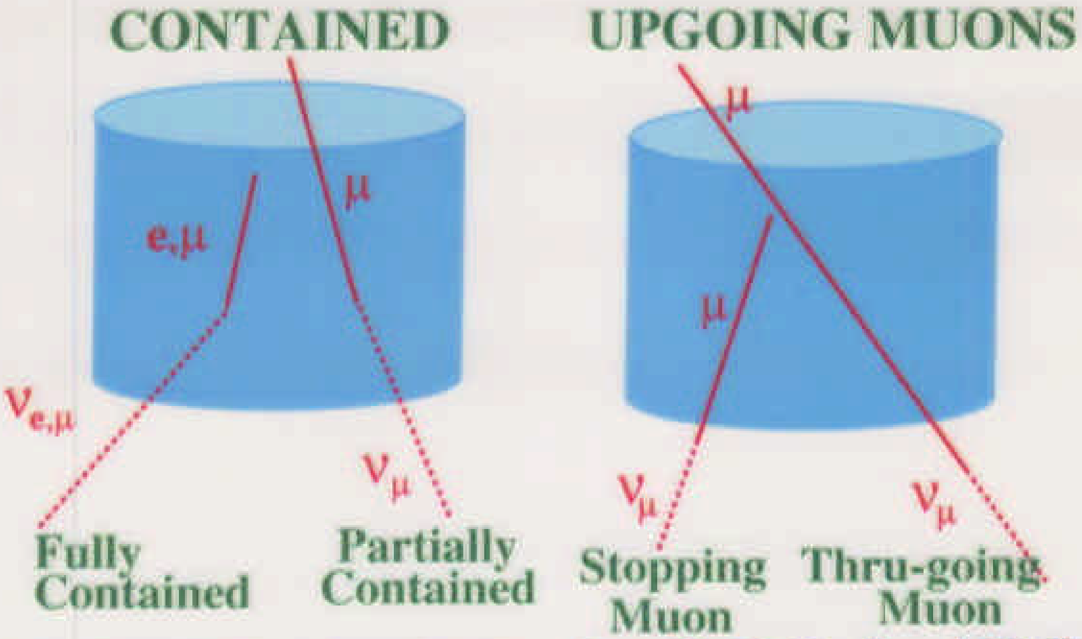
Atmospheric Neutrinos

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



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

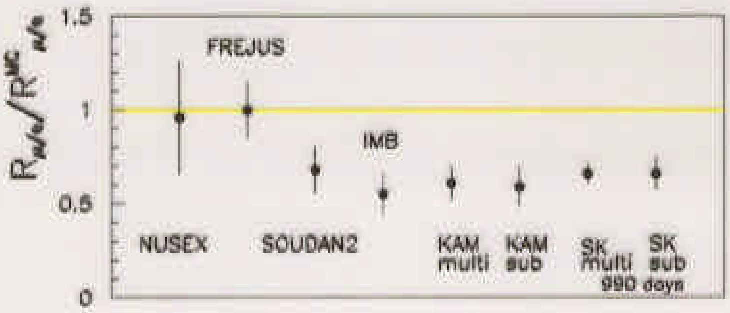
EVENT CLASSIFICATION



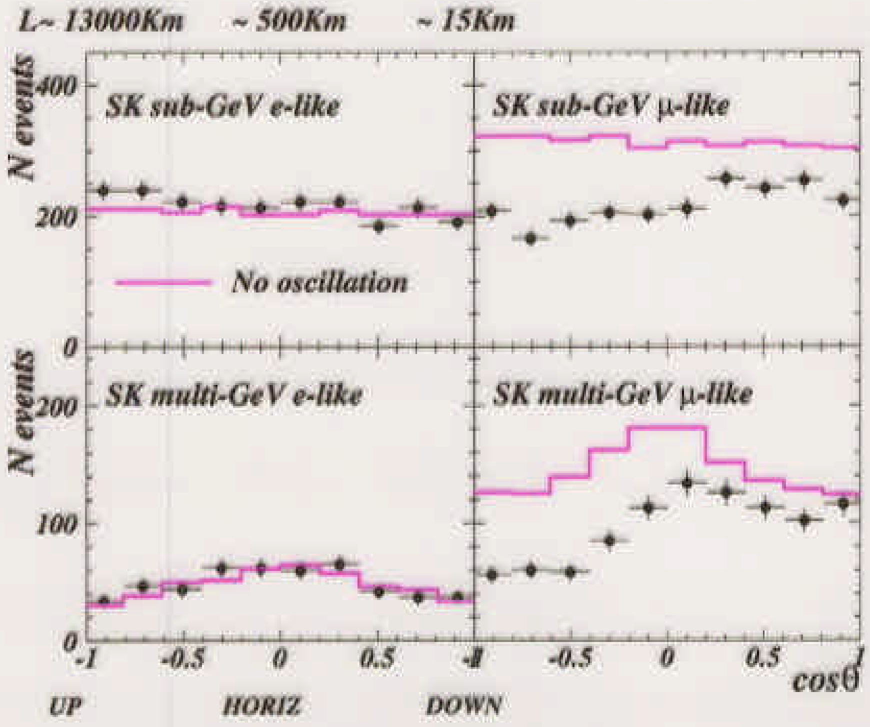
E_ν 0.1 - few GeV   few GeV   few 10 GeV   few 100 GeV

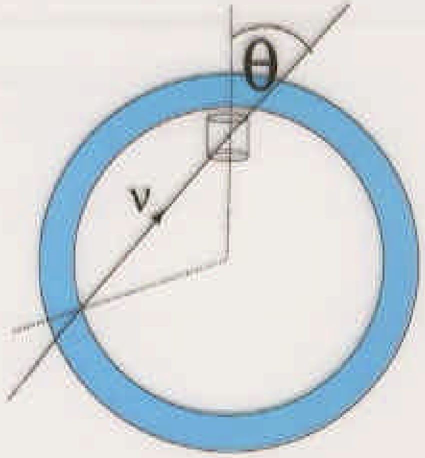
Atmospheric Neutrino Data

- Total Rates for Contained Events



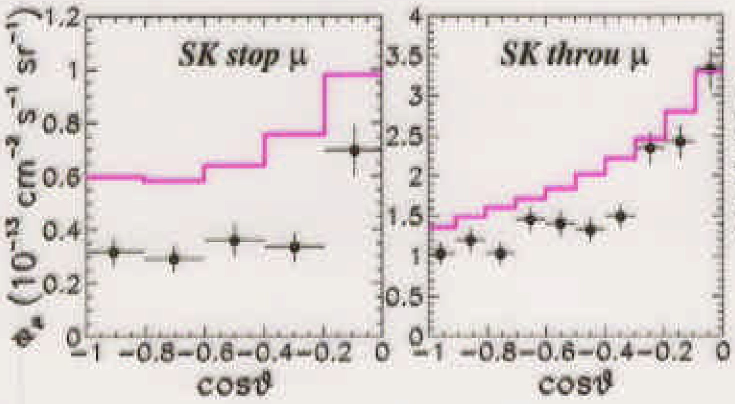
- Angular Distribution of Contained Events → Deficit grows with L





Super-Kamiokande 990 Days Contained

- Upward Going Muon Fluxes → Deficit decreases with E



$$\frac{\left.\frac{STOP}{THROU}\right|_{DATA}}{\left.\frac{STOP}{THROU}\right|_{MC}} = 0.61 \pm 0.1$$

Super-Kamiokande 1050 Days Upgoing

Atmospheric Neutrino Data Oscillation Analysis

- In presence of neutrino oscillations:

– The expected number of contained events

$$N_\mu = N_{\mu\mu} + N_{e\mu} \qquad N_e = N_{ee} + N_{\mu e}$$

$$N_{\alpha\beta} = n_t T \int \frac{d^2\Phi_\alpha}{dE_\nu d\cos\theta_\nu} \kappa_\alpha(h) P_{\alpha\beta} \frac{d\sigma}{dE_\beta} \varepsilon(E_\beta) dE_\nu dE_\beta d\cos\theta_\nu dh$$

– The expected upgoing-μ fluxes:

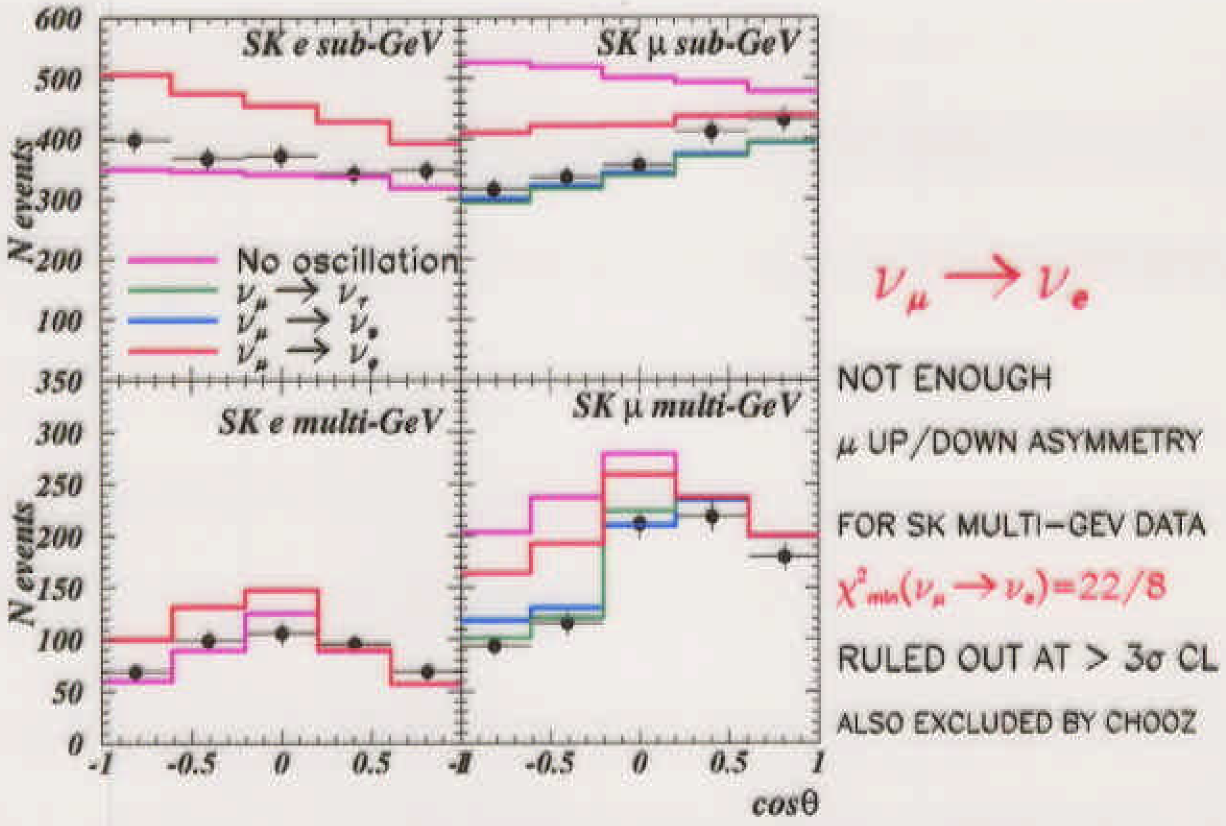
$$\Phi_\mu(\theta)_{S,T} = \frac{1}{A(L_{min},\theta)} \int \frac{d\Phi_\mu(E_\mu,\cos\theta)}{dE_\mu d\cos\theta} A_{S,T}(E_\mu,\theta) dE_\mu$$

$$\frac{d\Phi_\mu}{dE_\mu d\cos\theta} = \int_0^\infty \frac{d\Phi_{\nu_\mu}}{dE_\nu d\cos\theta} P_{\mu\mu} \frac{d\sigma}{dE_{\mu 0}} F_{rock}(E_{\mu 0}, E_\mu, X) N_A dE_\nu dE_{\nu 0} dX$$

- Three possible oscillation channels:

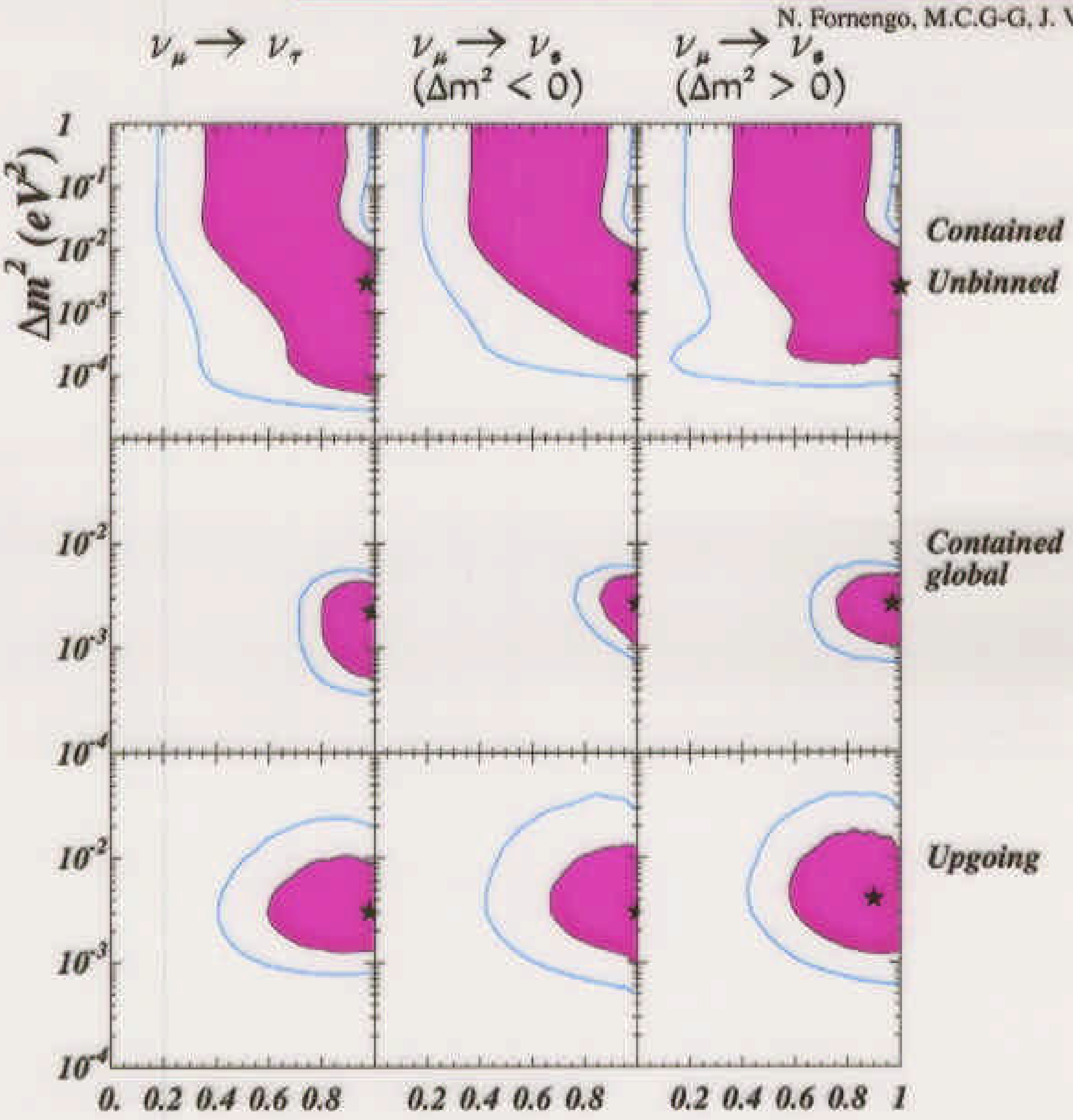
$$\nu_\mu \to \nu_X \quad X = e, \tau, \text{sterile}$$

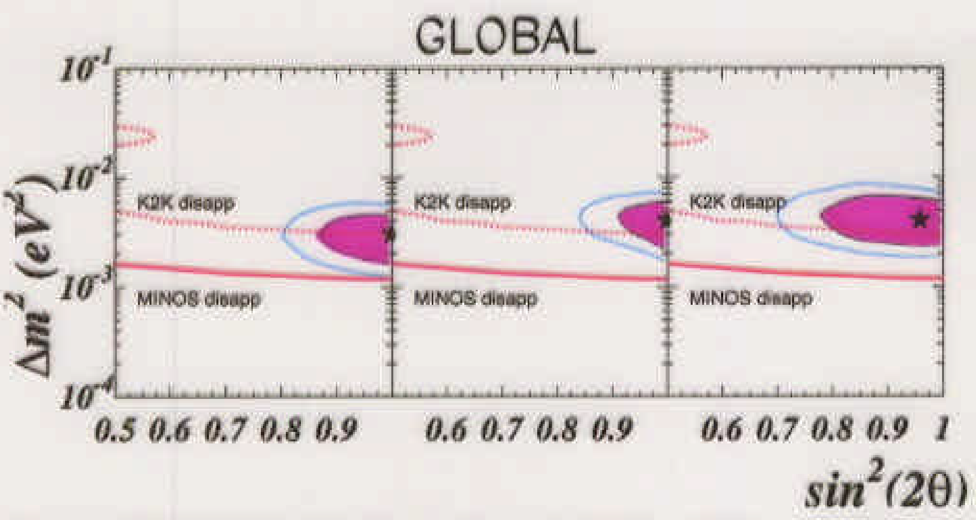
- For $X = e$ and $X = sterile$ Earth matter effects



Atmospheric Neutrino Oscillation Parameters

N. Fornengo, M.C.G-G, J. Valle, NPB680 (2000)





From Global Analysis

χ^2_{min}	
ν_τ	ν_s
58/61	76/61

$\nu_\mu \to \nu_\tau$ Favoured

Prob($\nu_\mu \to \nu_s$) ~ 10%

(not that bad!!)

Super–Kamiokande from the analysis of the zenith angle dependence of high-E PC + thrugoing + NC enriched events:

$\nu_\mu \to \nu_s$ disfavoured with ~ 99 %.

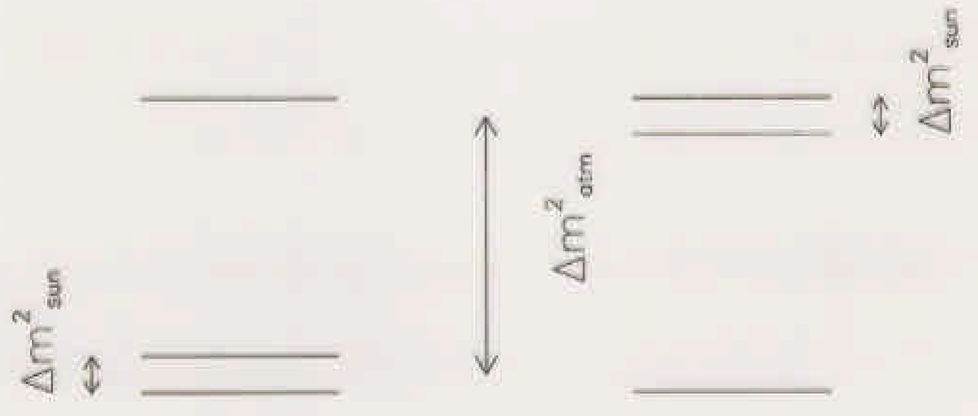
II. Three–Neutrino Oscillations:

- We have 3 oscillation signals with 3 different mass differences
- But 3 neutrinos → 2 mass differences. So:
  - **(a)** Solar or Atmospheric see a combined effect, or
  - **(b)** One experiment is wrong
- **(a)** is not supported by data
  - Solar experiments observe E dependence
  - Atmospheric experiment observe L and E dependence
  - CHOOZ Reactor Limit constraints this possibility
- **(b)** Usually discard LSND (Due to Karmen)

– For 3-ν mixing U: 3 angles and 1 CP-phase

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

– Two possible mass patterns



– The Evolution Equation in Matter:

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

$$= \sum_\beta \left[U_{\alpha 3}U^*_{\beta 3}\frac{\Delta m^2_{32}}{2E} + U_{\alpha 1}U^*_{\beta 1}\frac{\Delta m^2_{12}}{2E} + A\delta_{\alpha e}\delta_{\beta e}\right]$$

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

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

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

- For $\theta_{13} \neq 0$ and $\Delta m^2_{12} \ll \Delta m^2_{23}$

  – solar $\rightarrow$

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

  Independent of θ_{23}

  – atmospheric $\rightarrow$ (in vacuum)

  $P^{3\nu,atm}_{ee} = P^{2\nu,atm}_{ee}(\Delta m^2_{23}, \theta_{13})$

  $P^{3\nu,atm}_{e\mu} = s^2_{23}\, P^{2\nu,atm}_{e\mu}(\Delta m^2_{23}, \theta_{13})$

  $P^{3\nu,atm}_{\mu\mu} = 1 - s^2_{23}\, P^{2\nu,atm}_{e\mu}(\Delta m^2_{23}, \theta_{13}) - c^4_{13}\, P^{2\nu,atm}_{\mu\tau}(\Delta m^2_{23}, \theta_{23})$

  Independent of θ_{12} (also holds in matter)

  – For CHOOZ

  $P^{CHOOZ}_{ee} = 1 - 4c^2_{13}s^2_{13}\sin^2\left(\frac{\Delta m^2_{23}L}{4E}\right)$

  For $\Delta m_{23} > 10^{-3}$ eV^2 CHOOZ limit

  $R = \frac{N_{obs}}{N_{expec}} = 1.01 \pm 0.038 \Rightarrow P^{CHOOZ}_{ee} \gtrsim 0.99$

3–ν Solar Neutrino Oscillation Parameters

M.C.G-G, M. Maltoni, C. Peña-Garay, J. Valle, in preparation

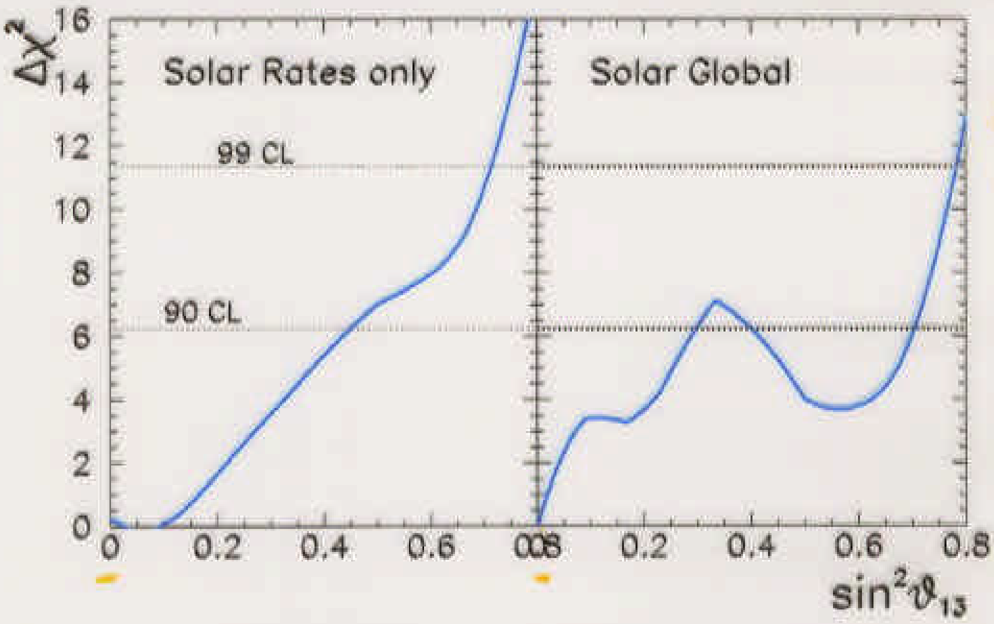
Allowed regions from Global Analysis

$P_{ee}^{3\nu} = c_{13}^4 \, P_{ee}^{2\nu} + s_{13}^4$

3–ν Solar Neutrino Oscillation Analysis

M.C.G-G, M. Maltoni, C. Peña-Garay, J. Valle, in preparation

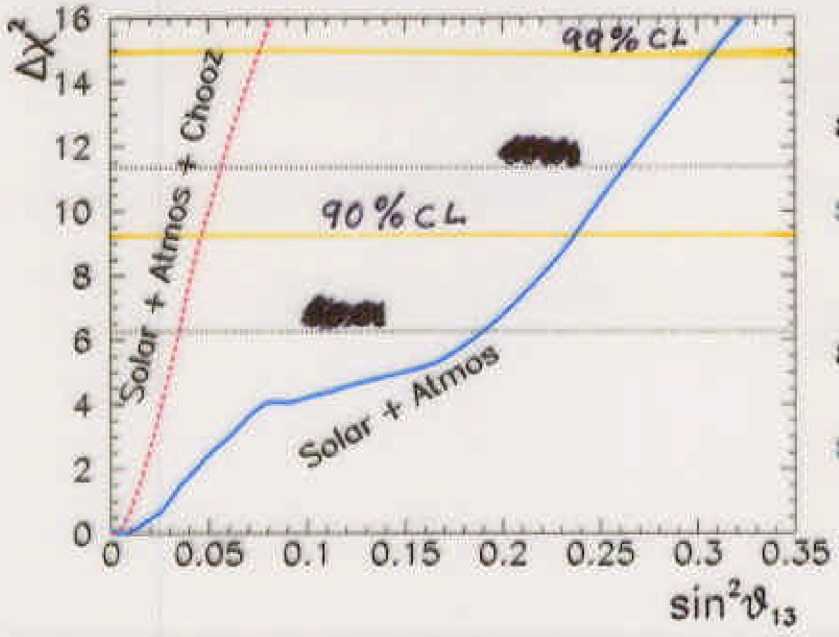
Constraints on θ_{13}



More Quantitatively (Describe)

	$\sin^2\theta_{13}$		θ_{13} deg
Observables	best	limit 90% (99%)	limit 90% (99%)
Rates	0.005	0.45 (0.71)	42° (57.5°)
Global	0.	0.7 (0.78)	57° (62°)

Combining Solar with Atmospheric and Reactor



From Atmospheric + Solar

at 99%CL

$\sin^2\theta_{13} < 0.31$ (34°)

Atm + Solar + Chooz

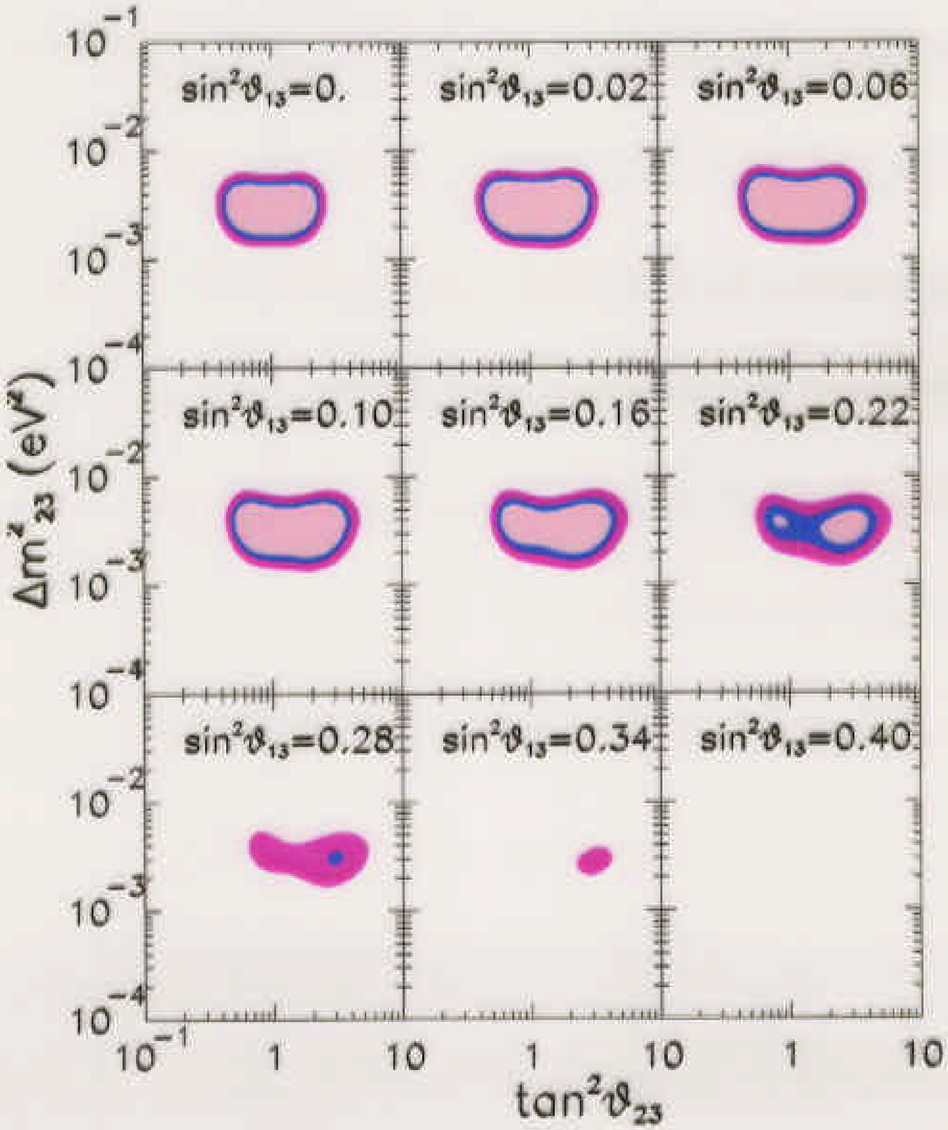
at 99%CL

$\sin^2\theta_{13} < 0.075$ (16.0°)

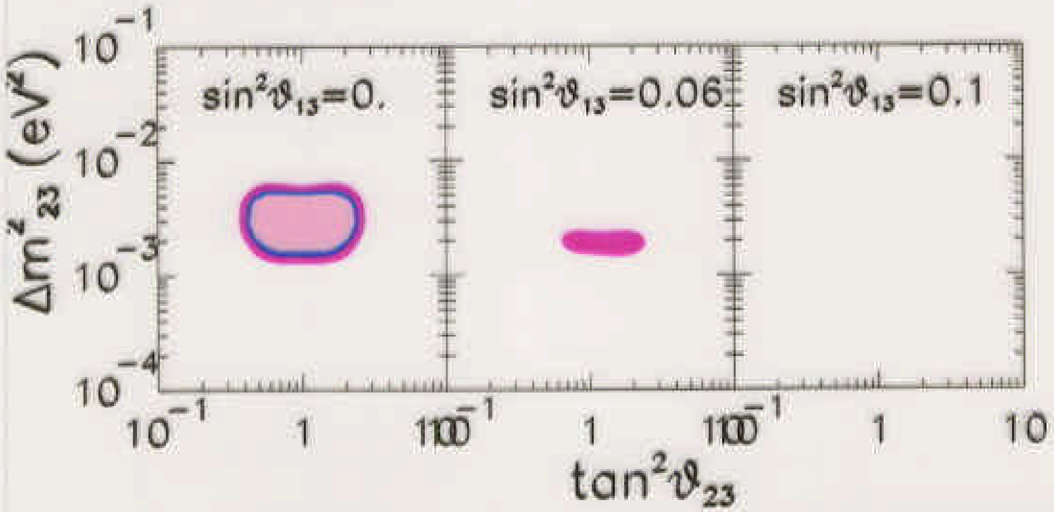
3–ν Atmospheric Neutrino Oscillation Parameters

M.C.G-G, M. Maltoni, C. Peña-Garay, J. Valle, in preparation

From All Atmospheric Neutrino Experiments



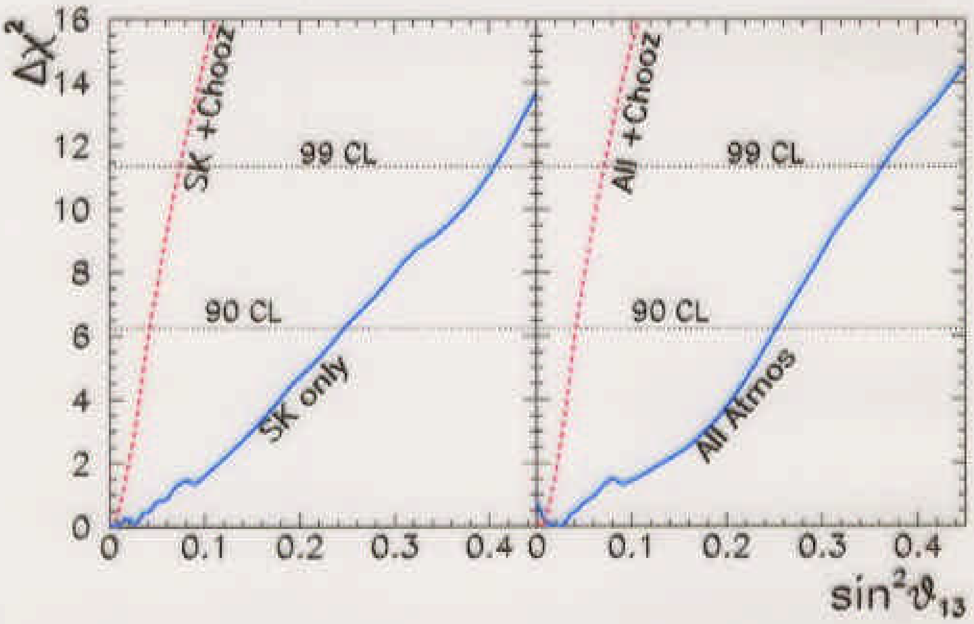
Including Also Chooz



3–ν Atmospheric and Reactor Neutrino Oscillation Analysis

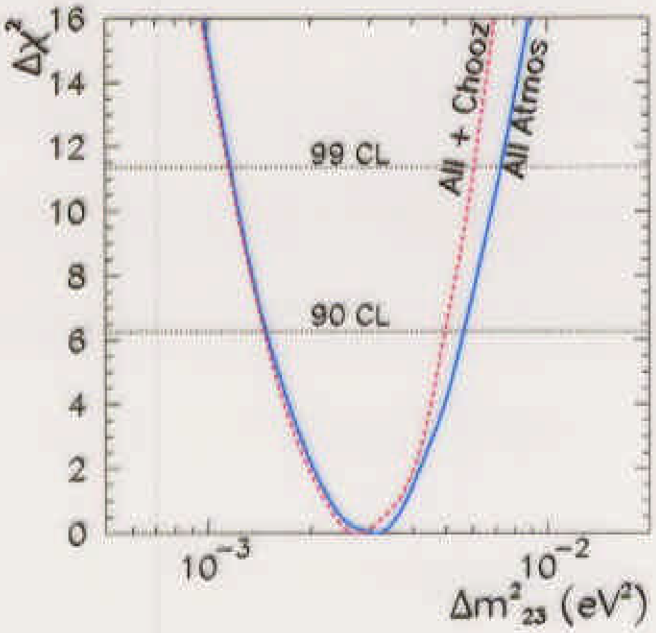
M.C.G-G, M. Maltoni, C. Peña-Garay, J. Valle, in preparation

Constraints on θ_{13}



	$\sin^2\theta_{13}$		θ_{13} deg
Experiment	best	limit 90% (99%)	limit 90% (99%)
All Atmos	0.025	0.25 (0.37)	30° (37.5°)
All+Chooz	0.005	0.04 (0.075)	11.5° (16°)

Constraints on Δm^2_{23}



From Global Atmospheric

$\Delta m^2_{23,best} = 3.3 \times 10^{-3}$ eV^2

at 99%CL

$1.3 \times 10^{-3} \leq \Delta m^2_{23} \leq 8 \times 10^{-3}$

From Global Atmospheric + Chooz

$\Delta m^2_{23,best} = 3.05 \times 10^{-3}$ eV^2

at 99%CL

$1.2\times 10^{-3} \leq \Delta m^2_{23} \leq 6.5\times 10^{-3}$

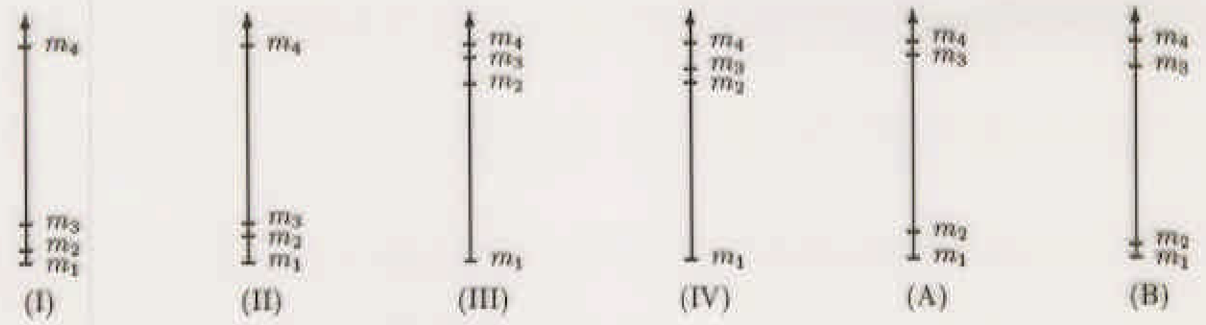
III. *Unifying* Active and Sterile Oscillations: Four-neutrino Oscillations

- To fit solar, atmospheric and LSND

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

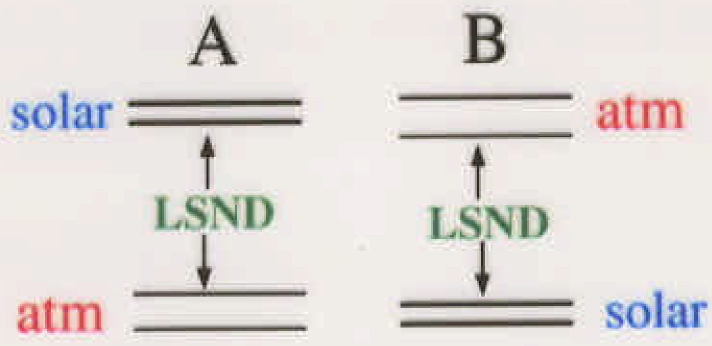
  → 4 $\nu' s$
- But LEP data implies only 3 neutrino flavours

  → 4th ν must be sterile
- U: 6 mixing angles and 3 CP phases
- Possible mass spectra:



- Limits from Accelerator and Reactor:

→ Only two possible mass spectra



→ Mixings between e and heavy states negligible : Only 4 angles

- The mixing matrix U

$$\begin{pmatrix} c_{12} & s_{12} & 0 & 0 \\ -s_{12}c_{23}c_{24} & c_{12}c_{23}c_{24} & s_{23}c_{24} & s_{24} \\ s_{12}(c_{23}s_{24}s_{34}+s_{23}c_{34}) & -c_{12}(s_{23}c_{34}+c_{23}s_{24}s_{34}) & c_{23}c_{34}-s_{23}s_{24}s_{34} & c_{24}s_{34} \\ s_{12}(c_{23}s_{24}c_{34}-s_{23}s_{34}) & c_{12}(s_{23}s_{34}-c_{23}s_{24}c_{34}) & -(c_{23}s_{34}+s_{23}s_{24}c_{34}) & c_{24}c_{34} \end{pmatrix}$$

- <u>For solar neutrinos:</u>

  * $c_{23}c_{24} = 0 \rightarrow$ pure $\nu_e \rightarrow \nu_{active}$ oscillations with mixing θ_{12}
  * $c_{23}c_{24} = 1 \rightarrow$ pure $\nu_e \rightarrow \nu_{sterile}$ oscillations with mixing θ_{12}
  * Intermediate cases $0 < c_{23}c_{24} < 1$ also possible $\nu_e \rightarrow \nu_X$
    ν_X is a combination of $\nu_{sterile}$ and ν_{active}

– In this general case of simultaneous $\nu_e \rightarrow \nu_s$ and $\nu_e \rightarrow \nu_a$

$$P_{ee}^{4\nu,Sun} = P_{ee}^{2\nu,Sun}$$
$$P_{es}^{4\nu,Sun} = c_{23}^2 c_{24}^2 \left(1 - P_{ee}^{Sun}\right)$$

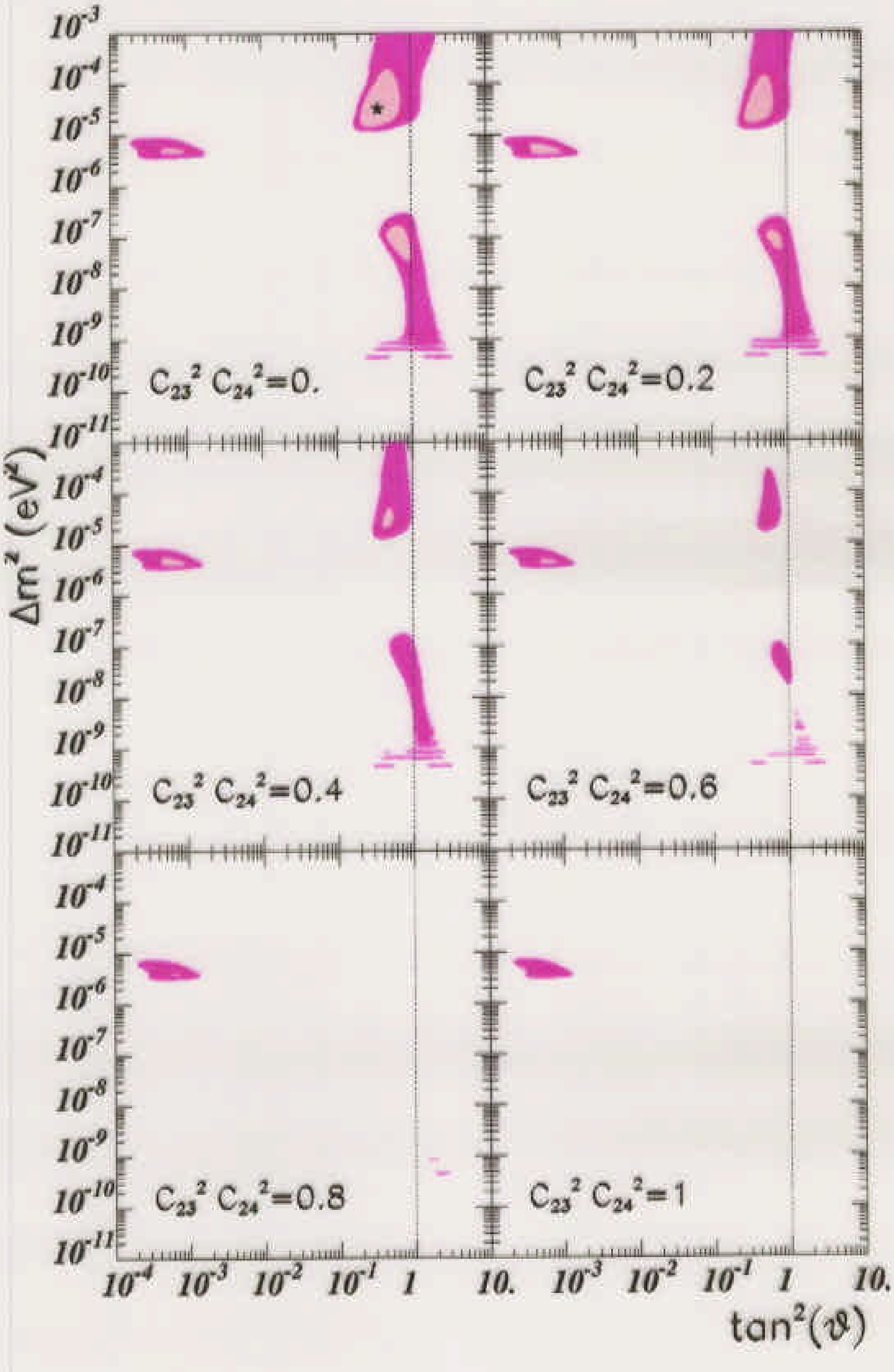
but $P_{ee}^{2\nu,Sun}$ is computed for a matter potential

$$A \equiv A_{CC} + c_{23}^2 c_{24}^2 \, A_{NC}$$

– Same analysis but with 3 parameters: Δm_{12}^2, θ_{12}, and $c_{23}^2 c_{24}^2$

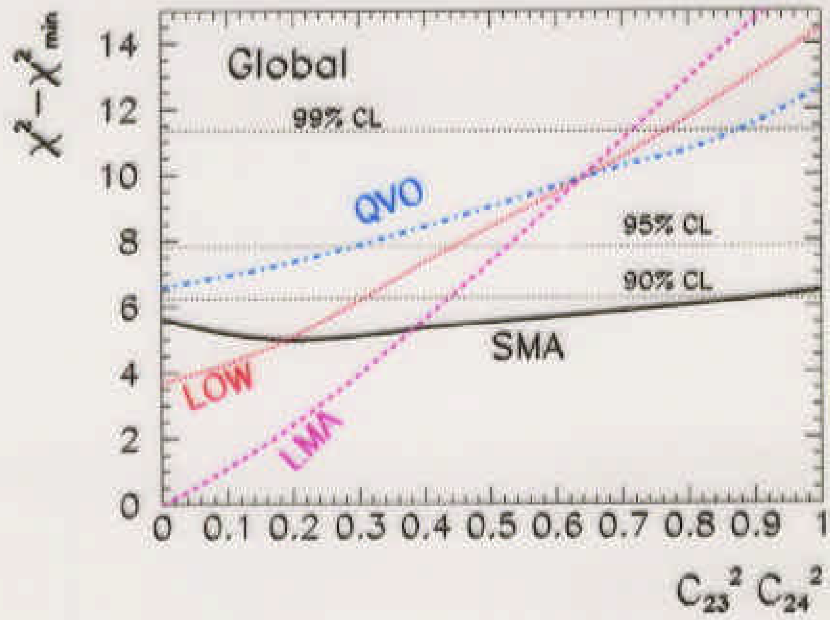
Solutions for Four-neutrino Oscillations

Update of C Giunti, MCG-G, C Peña-Garay PRD62 (2000)



Solutions for Four-neutrino Oscillations

Update of C. Giunti, MCG-G, C. Peña-Garay, PRD 62 (2000)



- LMA, LOW and QVO can have a subdominant $\nu_e \to \nu_s$ component

limit on $c_{23}^2 c_{24}^2$

CL	SMA	LMA	LOW	QVO
90	0.9	0.44	0.3	forbidden
95	all	0.53	0.44	0.28
99	all	0.72	0.77	0.88

- Upgoing-μ atmospheric data can also limit ν_s component for Atmospheric: But limit strongly depends on theoretical uncertainties

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IV. Summary

- Global Analysis of Solar Neutrino Data after ν-2000 in the *Full Parameter Space for Oscillations*:
  - Including Matter Effects in Quasi-Vacuum Oscillation Region
  - Including MSW Transitions for $\theta > \frac{\pi}{4}$

  The best fit points:

	Δm^2	$\tan^2\theta$	g.o.f
LMA	3.2×10^{-5}	0.33	59 %
LOW	1×10^{-7}	0.57	40 %
SMA	5.0×10^{-6}	0.0006	34 %
QVO	6.7×10^{-10}	1.75	32 %
SMA(sterile)	3.8×10^{-6}	0.0006	31 %

  - SMA allowed at 95 % CL but with smaller mixing angle
  - LOW solution better than SMA after 1117 SK days
  - At 99% CL LOW and QVO regions connect and extend to $\theta > \frac{\pi}{4}$:
    Maximal Mixing is Allowed
- Global Analysis of Atmospheric Neutrino Data $\nu_\mu \to \nu_X$:
  - $X = e$ ruled out
  - $X = s$ disfavoured but not ruled out
    For $\Delta m^2 < 0$ $\Delta m^2 \simeq (2\text{–}7) \times 10^{-3}$ eV^2, $\sin^2(2\theta) \simeq 0.85\text{–}1$
    For $\Delta m^2 > 0$ $\Delta m^2 \simeq (2\text{–}9) \times 10^{-3}$ eV^2, $\sin^2(2\theta) \simeq 0.7\text{–}1$
  - $X = \tau$: $\Delta m^2 \simeq (1\text{–}6) \times 10^{-3}$ eV^2, $\sin^2(2\theta) \simeq 0.8\text{–}1$

- In Three-ν mixing
  - Fitting together Solar, Atmospheric and Reactor Data
  - Atmospheric Analysis depends on Δm^2_{23}, θ_{23}, θ_{13}
  - Solar Analysis depends on Δm^2_{12}, θ_{12}, θ_{13}
  - Chooz depends on Δm^2_{23}, θ_{13}
  - Limits on θ_{13} at 90% (99%) CL

	$\sin^2\theta_{13}$	θ_{13} deg
Atmos	0.25 (0.37)	30° (37.5°)
Solar	0.7 (0.78)	57° (62°)
Atmos + Solar	0.24 (0.34)	29° (34°)
Atmos + Solar + Chooz	0.045 (0.075)	12° (16.0°)

- Constraints on Δm^2_{23}

  From Global Atmospheric

  $$\Delta m^2_{23,best} = 3.3 \times 10^{-3}\ \mathrm{eV}^2$$

  at 99%CL: $1.3 \times 10^{-3} \leq \Delta m^2_{23} \leq 8 \times 10^{-3}$

  From Global Atmospheric + Chooz

  $$\Delta m^2_{23,best} = 3.05 \times 10^{-3}\ \mathrm{eV}^2$$

  at 99%CL: $1.2 \times 10^{-3} \leq \Delta m^2_{23} \leq 6.5 \times 10^{-3}$

- In Four-ν mixing:
  - Mixture of Simultaneous $\nu_e \to \nu_{st}$ and $\nu_e \to \nu_{ac}$ oscillations
  - LMA, LOW and QVO can have a subdominant $\nu_e \to \nu_{st}$ component

limit on $c^2_{23}c^2_{24}$

CL	SMA	LMA	LOW	QVO
90	0.9	0.44	0.3	forbidden
95	all	0.53	0.44	0.28
99	all	0.72	0.77	0.88