NEUTRINO OSCILLATIONS
IN VENICE ; July 2001

ATMOSPHERIC ν: STATUS OF SUB-DOMINANT OSCILLATIONS

Eligio LISI
INFN, Bari, Italy

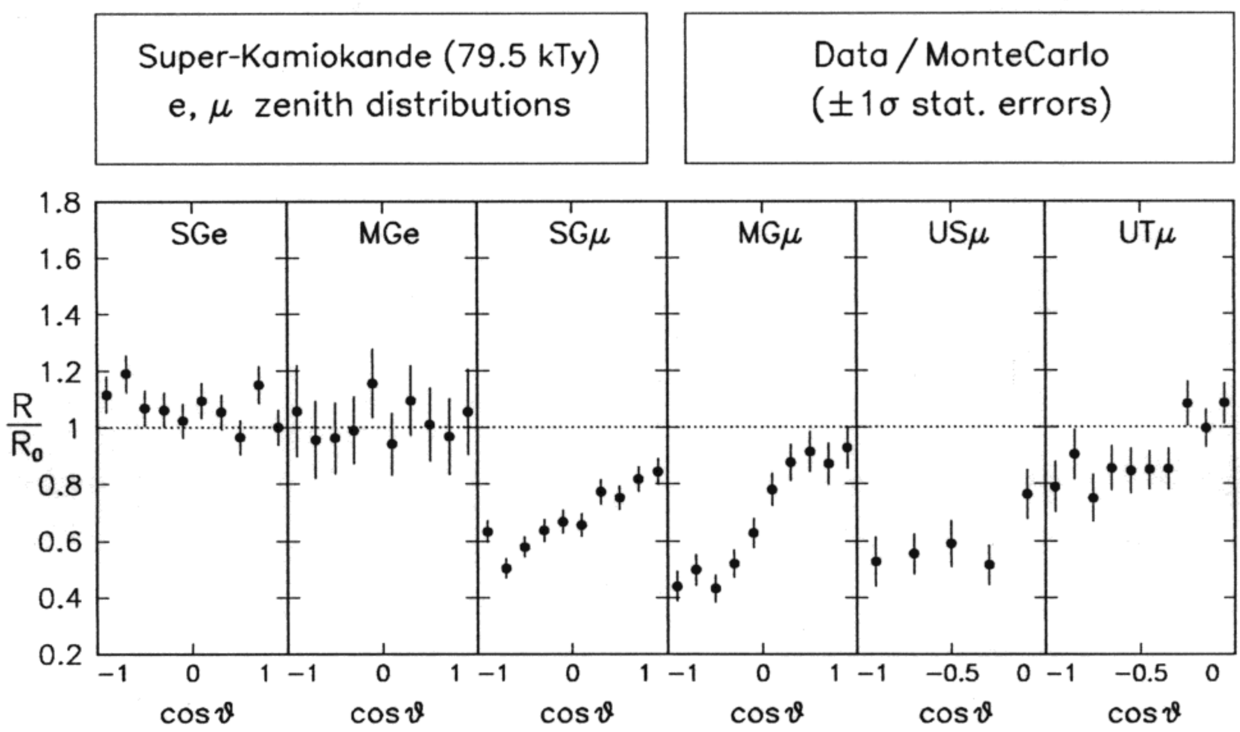
Ref. : hep-ph/0105139 (to appear in PRD)
with G.L. Fogli & A. Marrone

hep-ph/0105080
with G.L. Fogli & A. Palazzo

SK data (79.5 kTy)

DATA (normalized to MC)

..... THEORY (no osc.)

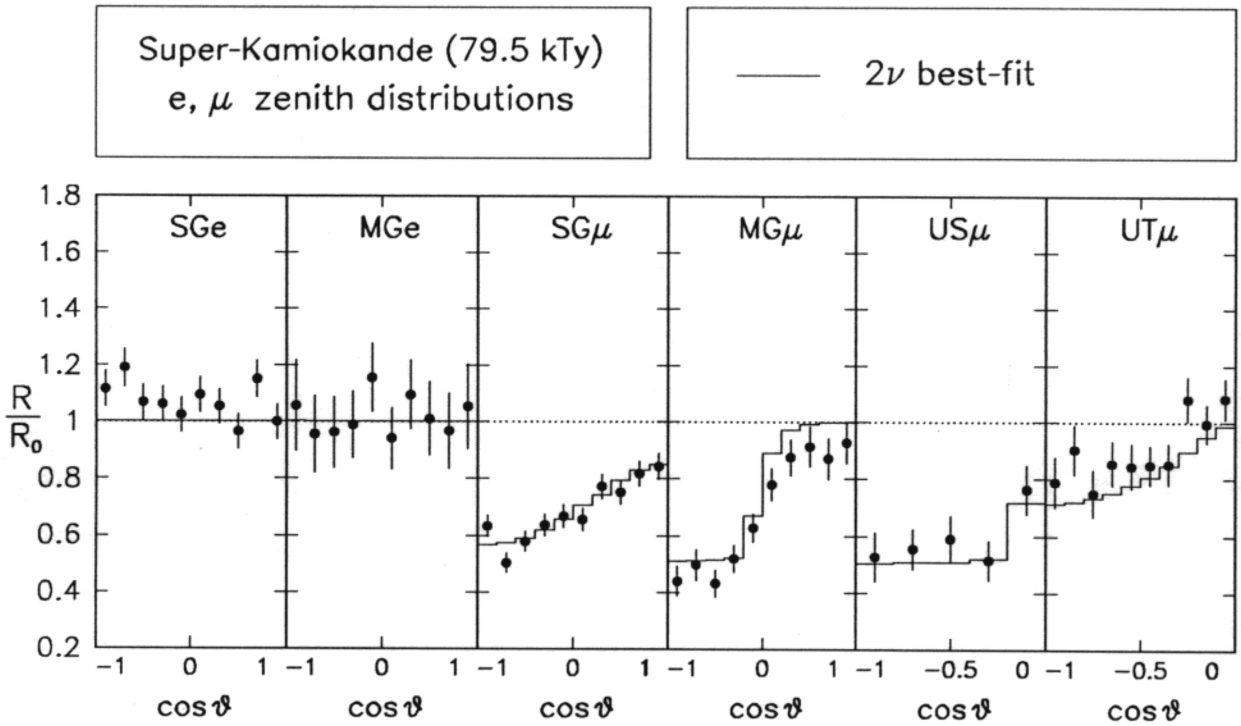


$\nu_\mu \leftrightarrow \nu_\tau$ best fit

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

$\sin^2 2\psi = 0.97$

$\chi^2_{min} = 38.5$



Deviation of best-fit $\sin^2 2\psi$ from maximal mixing <u>not</u> statistically significant ($\Delta\chi^2 < 1$)

BEYOND STANDARD 2ν ($\nu_\mu \leftrightarrow \nu_\tau$) OSC.

- **NONSTANDARD ν DYNAMICS**
  - $P_{\mu\tau} = \alpha \sin^2(\beta L E^n)$

  etc.

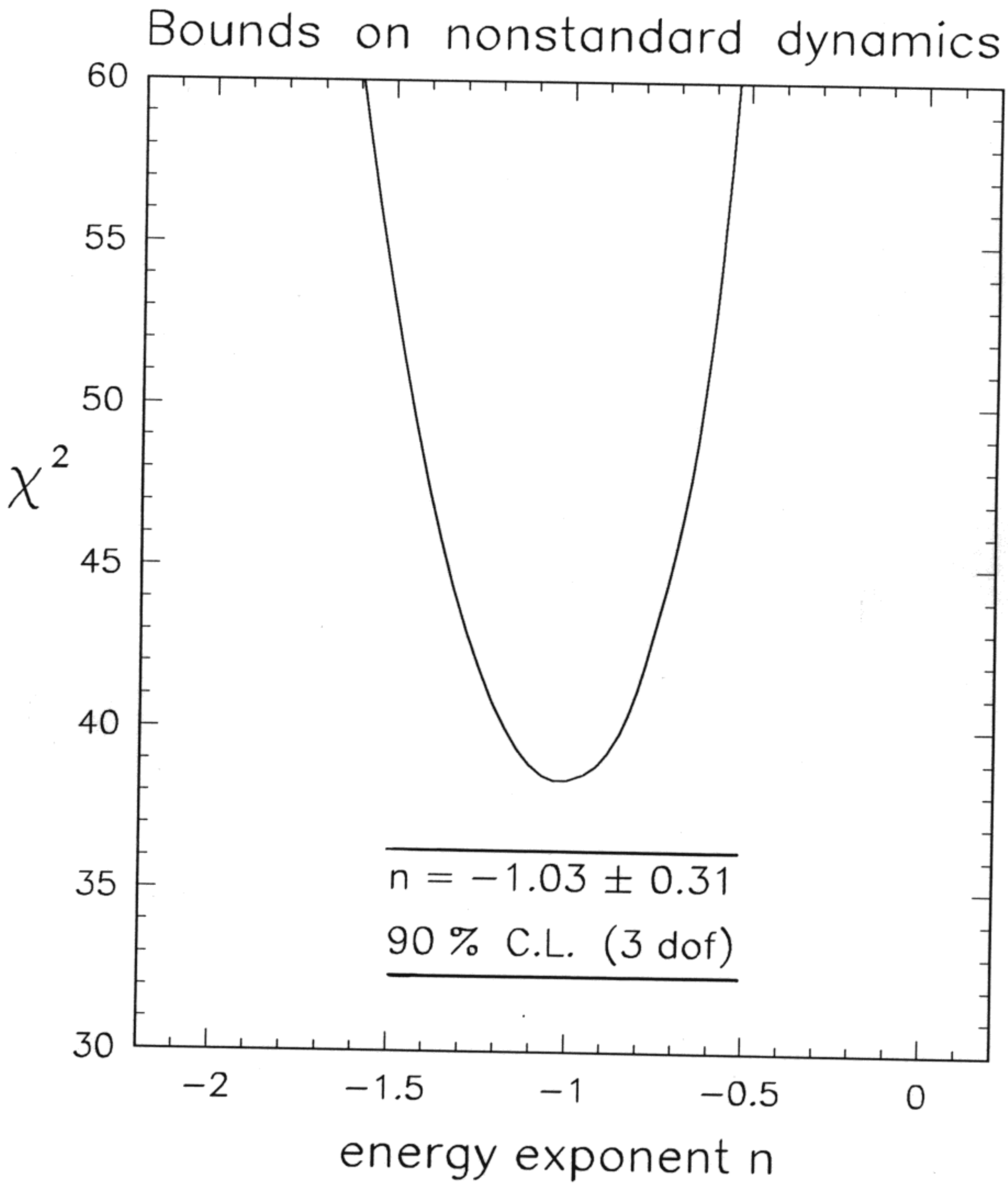
- **ADDITIONAL ν STATES**
  - **3ν** with Δm^2 hierarchy
  - **4ν** with Δm^2 hierarchy
  - **3ν** without Δm^2 hierarchy

  etc.

$H \propto E^n$

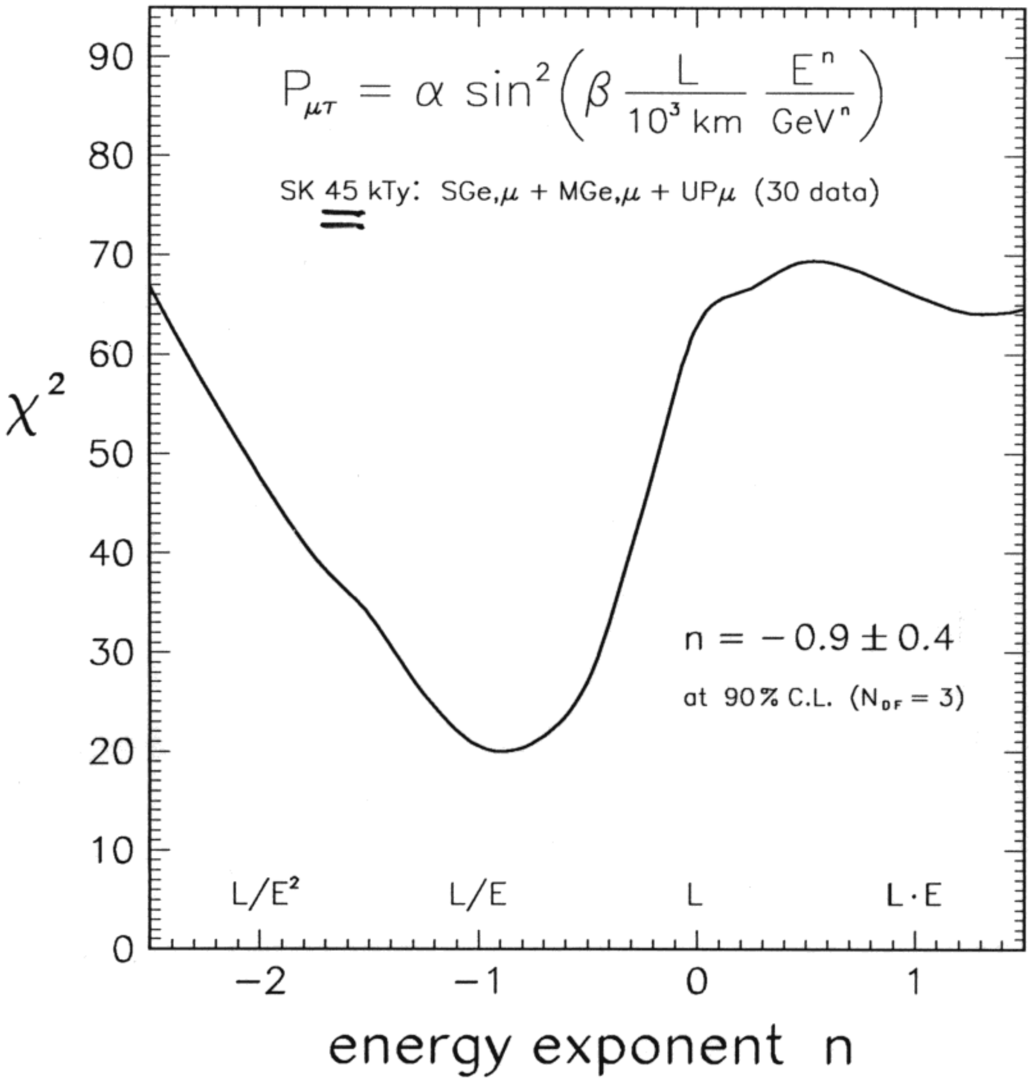
$$P_{\mu\tau} = \alpha \sin^2(\beta L E^n) \qquad n=-1 \rightarrow L/E$$

Fit with (α, β, n) free



Older analysis :

Bounds on n for unconstrained α and β



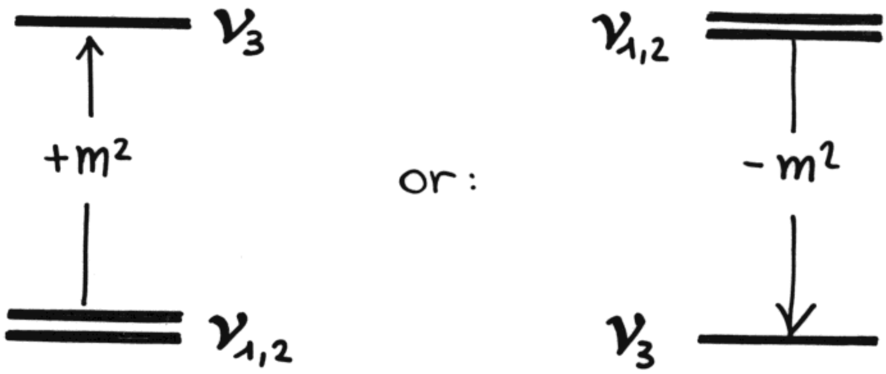
Steady improvement :

45 kTy : $n = -0.9 \pm 0.4$

79 kTy : $n = -1.03 \pm 0.31$

ADDITIONAL ν STATES:

3ν with Δm^2 hierarchy



PARAMETERS :

mass scale : $\pm m^2$

mixing:

$$|U_{e3}|^2 = \sin^2\varphi$$
$$|U_{\mu 3}|^2 = \cos^2\varphi \, \sin^2\psi$$
$$|U_{\tau 3}|^2 = \cos^2\varphi \, \cos^2\psi$$

N.B.: $\varphi = \Theta_{13}$ $\quad$ ($\varphi = 0 \rightarrow$ pure $\nu_\mu \leftrightarrow \nu_\tau$)

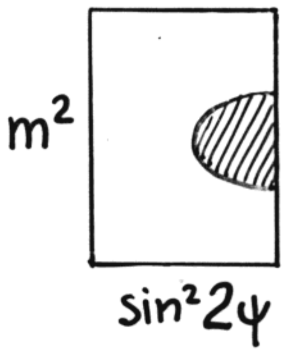
$\psi = \Theta_{23}$

$$\tan^2\psi = \frac{U^2_{\mu 3}}{U^2_{\tau 3}} = \text{relative } \nu_\mu/\nu_\tau \text{ mixing}$$

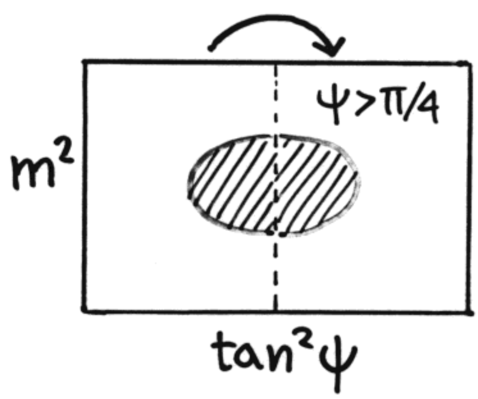
$$\tan^2\varphi = \frac{U^2_{e3}}{U^2_{\mu 3} + U^2_{\tau 3}} = \text{relative } \nu_e \text{ mixing}$$

"CONSTRUCTION" of (m^2, ψ, φ) SPACE

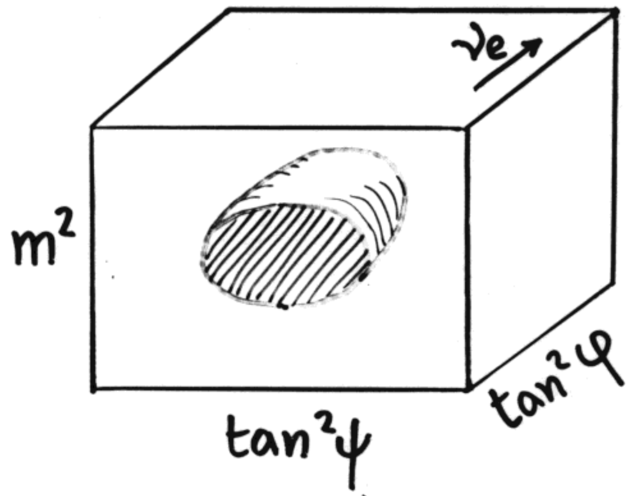
1. Take usual $\nu_\mu \leftrightarrow \nu_\tau$ plot $(m^2, \sin^2 2\psi)$ with $\psi < \pi/4$



2. Unfold second octant of ψ $(>\pi/4)$ and replace $\sin^2 2\psi$* with either
$\sin^2\psi$ (lin. scale)
or $\tan^2\psi$ (log. scale)



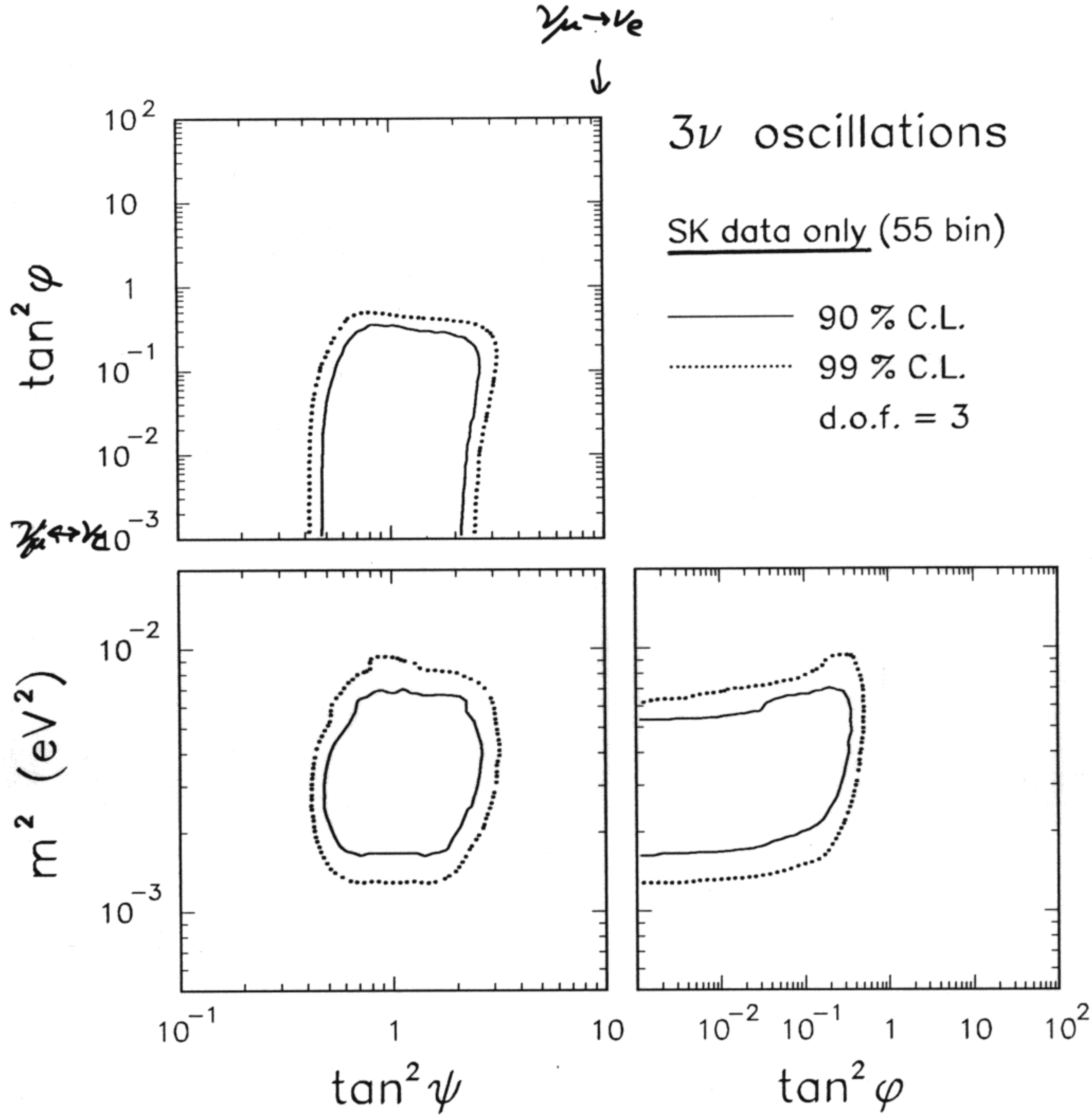
3. Allow ν_e mixing $(\varphi > 0)$



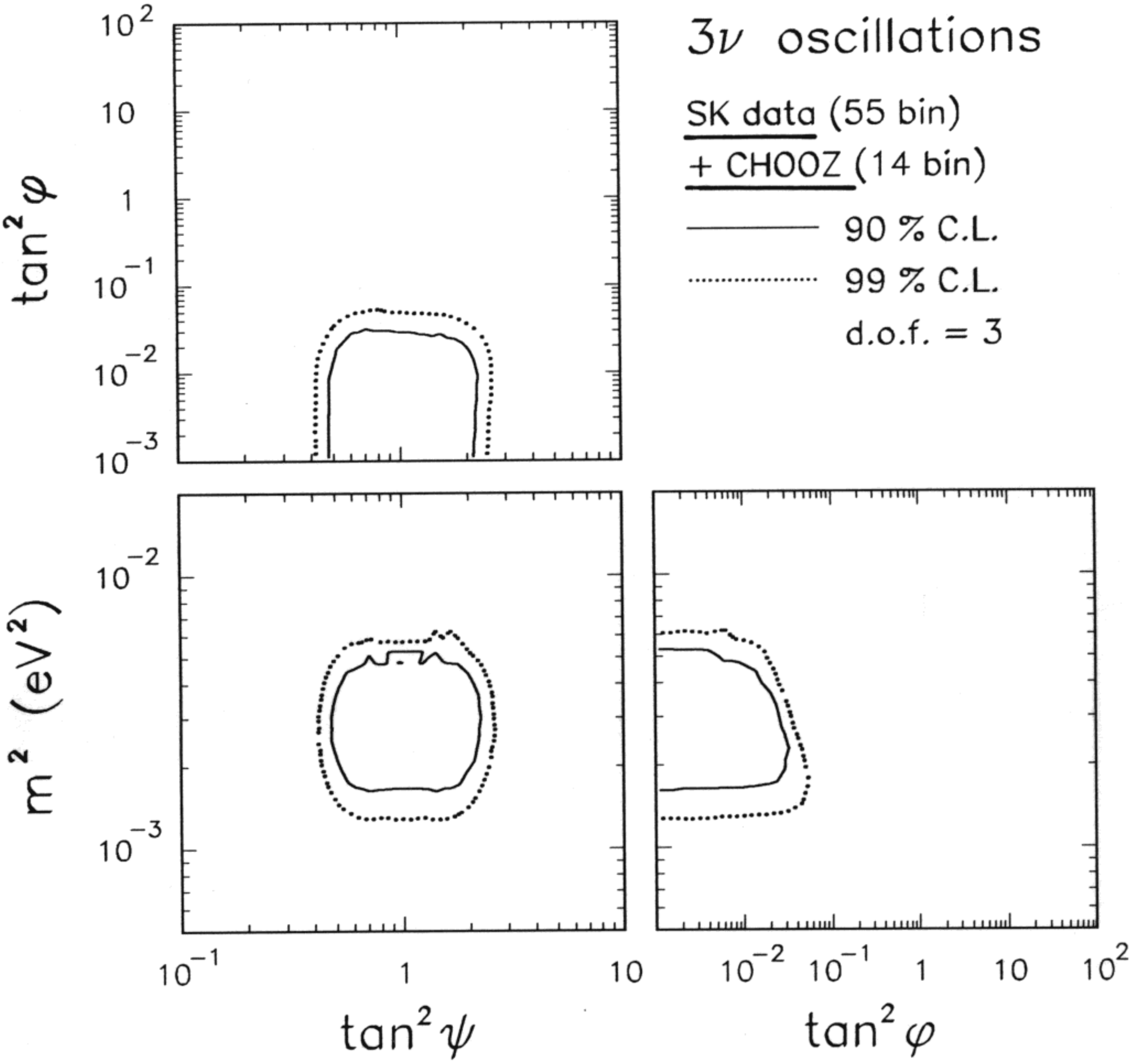
---

* $\tan^2\theta_{ij}$ (log) and $\sin^2\theta_{ij}$ (lin), slowly replacing the obsolete $\sin^2 2\theta_{ij}$ variable, were introduced in:
G.L. Fogli, E.L., Scioscia, PRD 52, 5334 (1995)
G.L. Fogli, E.L., Montanino, PRD 54, 2048 (1996)

PROJECTIONS OF ALLOWED REGIONS

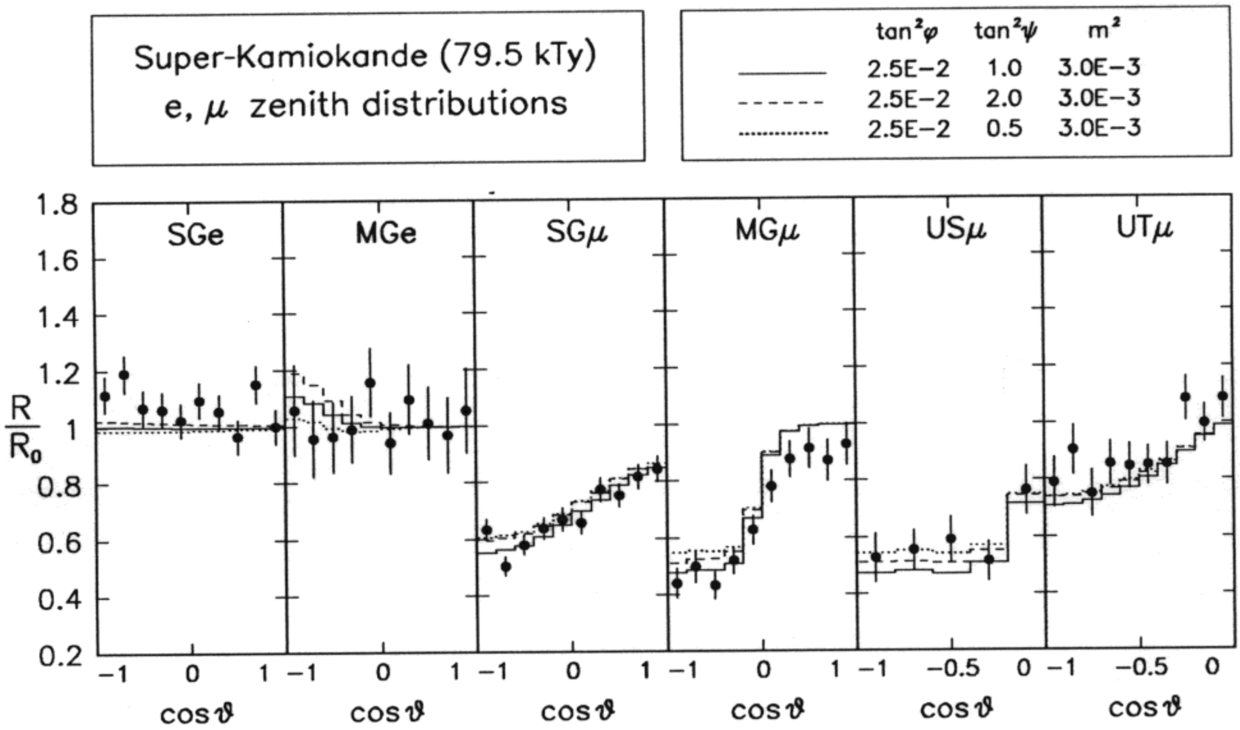


(slightly weaker bounds on $\tan^2\varphi$ for $m^2<0$)



(∼ equal bounds for $m^2 < 0$)

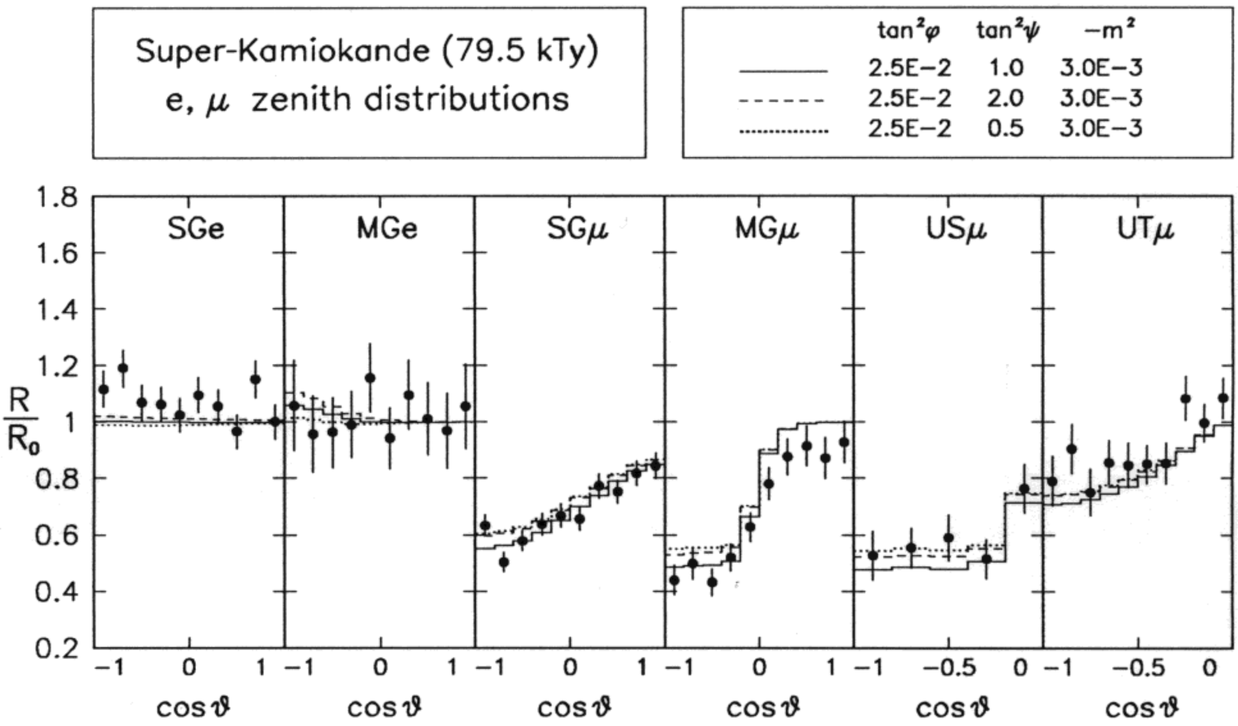
REPRESENTATIVE DISTRIBUTIONS FOR $m^2>0$



→ hard to detect $\varphi \neq 0$

(i.e., matter effects)

$m^2 < 0$

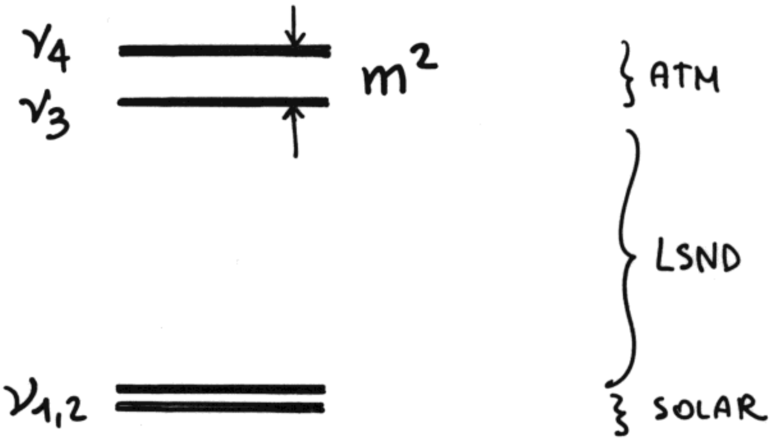


→ hard to detect sign($\pm m^2$)

i.e. ($\begin{smallmatrix}-\\ =\end{smallmatrix}$ from $\begin{smallmatrix}=\\ -\end{smallmatrix}$)

ADDITIONAL ν STATES:

4ν with Δm^2 hierarchy



(*)

PARAMETERS:

mass scale: m^2 (**)

mixing:

$$|U_{e4}|^2 \simeq 0 \quad (***)$$

$$|U_{\mu 4}|^2 = \sin^2\psi$$

$$|U_{\tau 4}|^2 = \cos^2\psi \, \cos^2\xi$$

$$|U_{s4}|^2 = \cos^2\psi \, \sin^2\xi$$

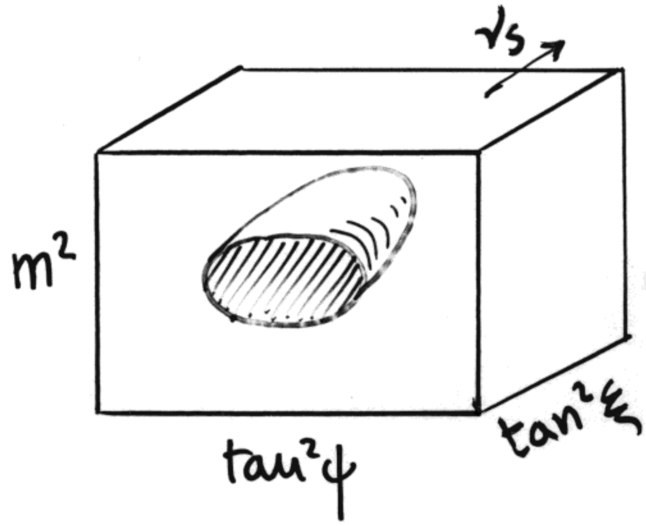
(*) atm. ν phenomenology invariant under doublet inversion (solar heavier)

(**) invariant under $m^2 \to -m^2$ AND $\psi \to \pi/2 - \psi$

(***) simplifying assumption

"CONSTRUCTION" of (m^2, ψ, ξ) SPACE

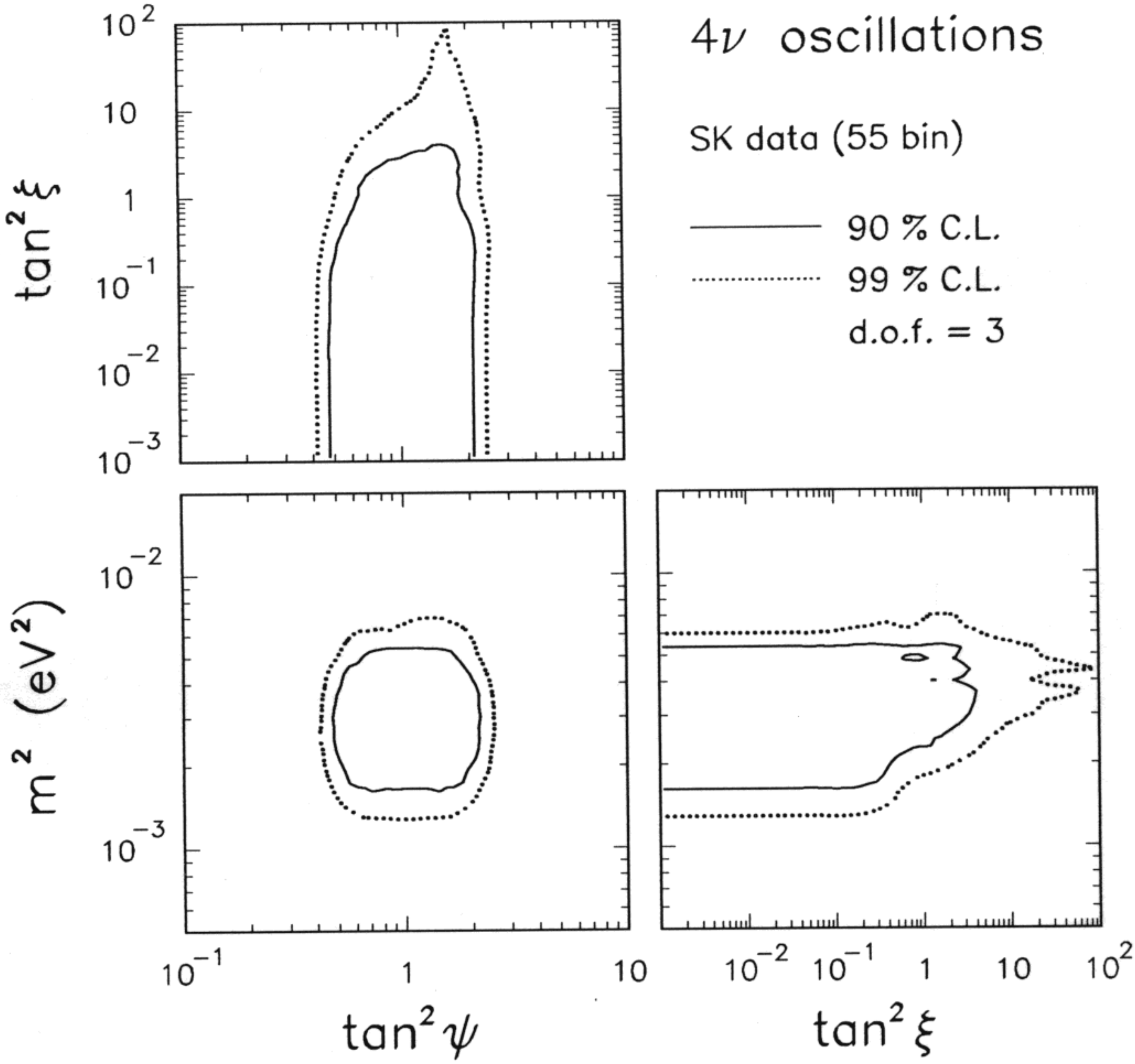
... as for the 3ν case, but now allow for ν_s (rather than ν_e) mixing:



$$\tan^2\xi = \frac{U^2_{s4}}{U^2_{\tau 4}} = \text{relative } \nu_s/\nu_\tau \text{ admixture}$$

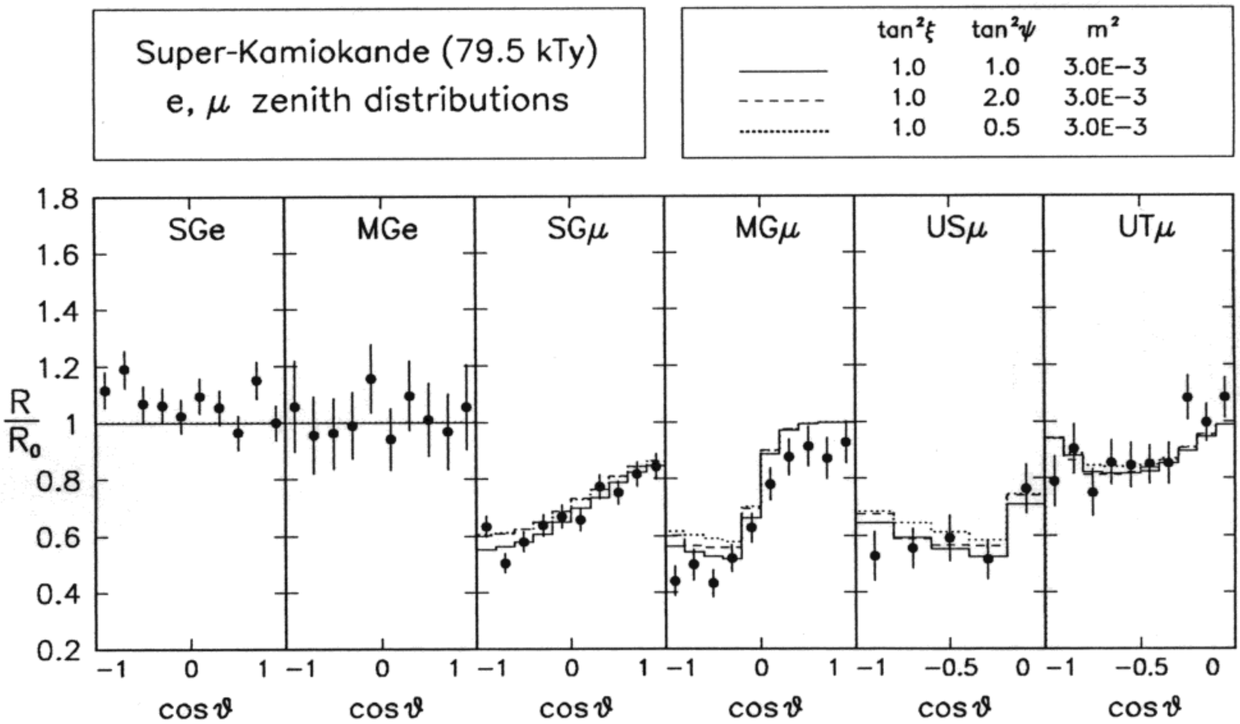
$$\tan^2\psi = \frac{U^2_{\mu 4}}{U^2_{\tau 4} + U^2_{s4}} = \text{relative } \nu_\mu \text{ admixture.}$$

PROJECTIONS OF ALLOWED REGIONS



pure $\nu_\mu \to \nu_s$ ($\tan^2\xi \to \infty$) disfavored, BUT large ν_s mix. ($\tan^2\xi \sim 1$) allowed by zenith distrib.

Representative zenith distributions at $\tan^2\xi = 1$ (50% ν_s + 50% ν_τ)



REMARK

- OTHER DATA ($\neq$ SK zenith distributions) also disfavor additional ν_s mixing
- In particular, τ-like event excess in SK favors $\nu_\mu \to \nu_\tau$ over $\nu_\mu \to \nu_s$ by $\sim 2\sigma$
- Rough estimate of effect on χ^2 fit:

$$\chi^2 \to \chi^2 + \chi^2_\tau \quad \leftarrow \text{penalty function}$$

$$\chi^2_\tau \cong 4\sin^2\xi = \begin{cases} 0 & \text{for } \nu_\mu \leftrightarrow \nu_\tau \\ 4 & \text{for } \nu_\mu \leftrightarrow \nu_s \end{cases}$$

- Previous 90% C.L. bound

$$\tan^2\xi \lesssim 4 \quad (\text{no penalty})$$

becomes

$$\tan^2\xi \lesssim 1.5 \quad (\text{with penalty})$$

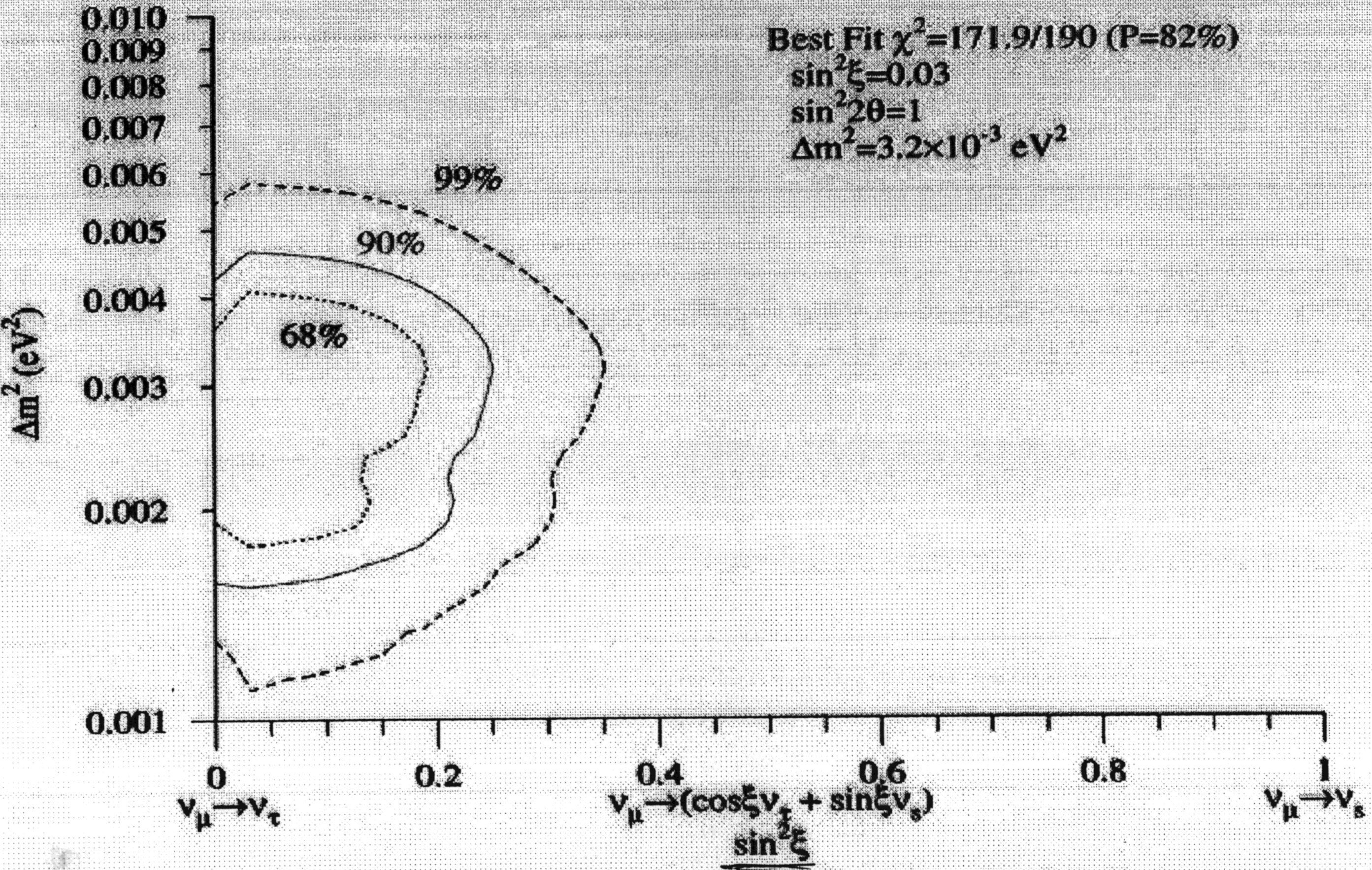
MOREOVER, SK HAS NEUTRAL-CURRENT ENRICHED EVENT SAMPLES

→

SK Global fit (C. Walter, Nufact '01)

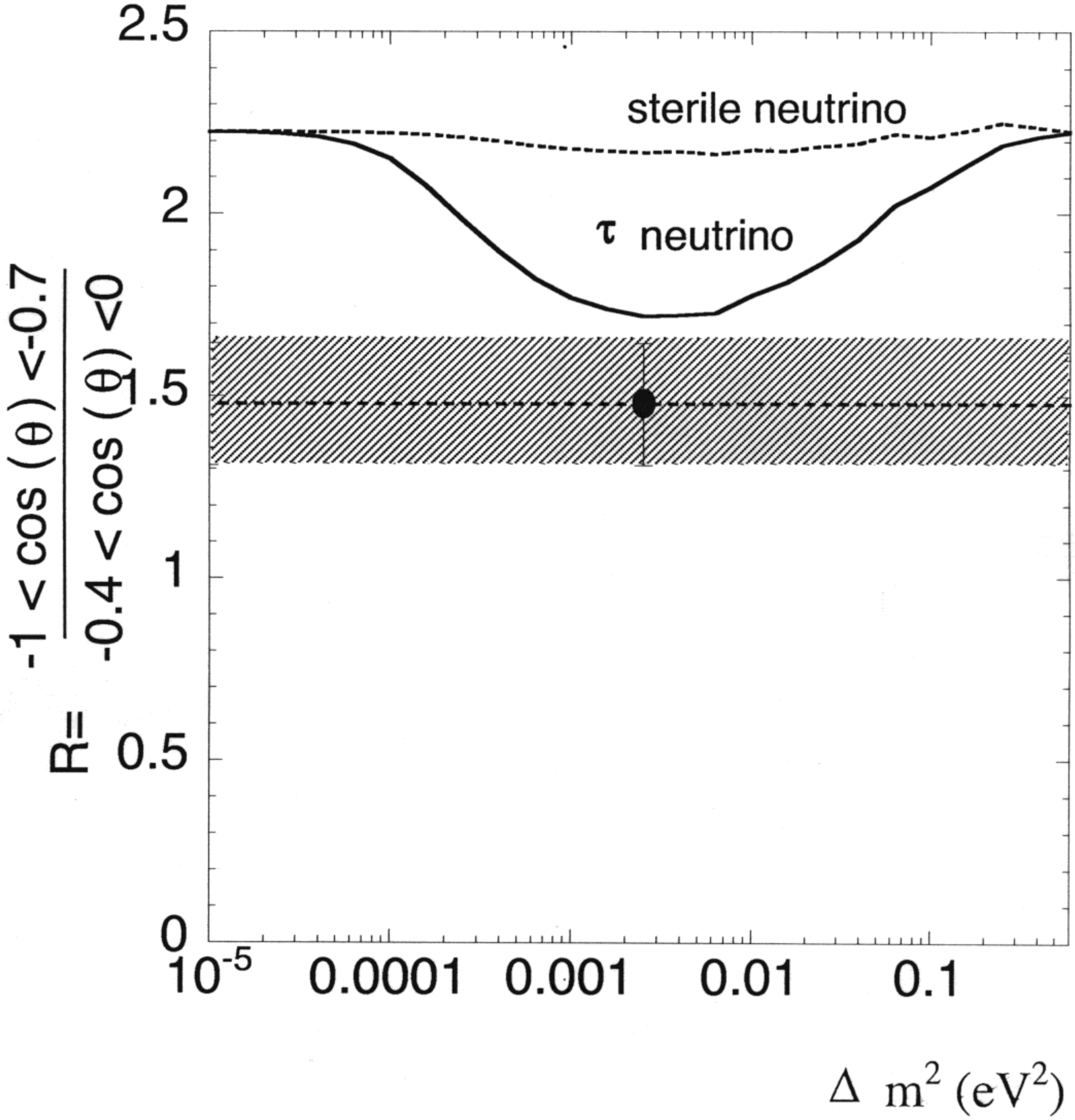
Distinguishing $\nu_\mu \Leftrightarrow \nu_\tau$ from $\nu_\mu \Leftrightarrow \nu_{sterile}$

Limits on $\nu_{sterile}$ admixture (following Fogli/Lisi/Marrone hep-ph/000299)



Admixture of $\nu_{sterile}$ is limited to <25% at 90% Confidence

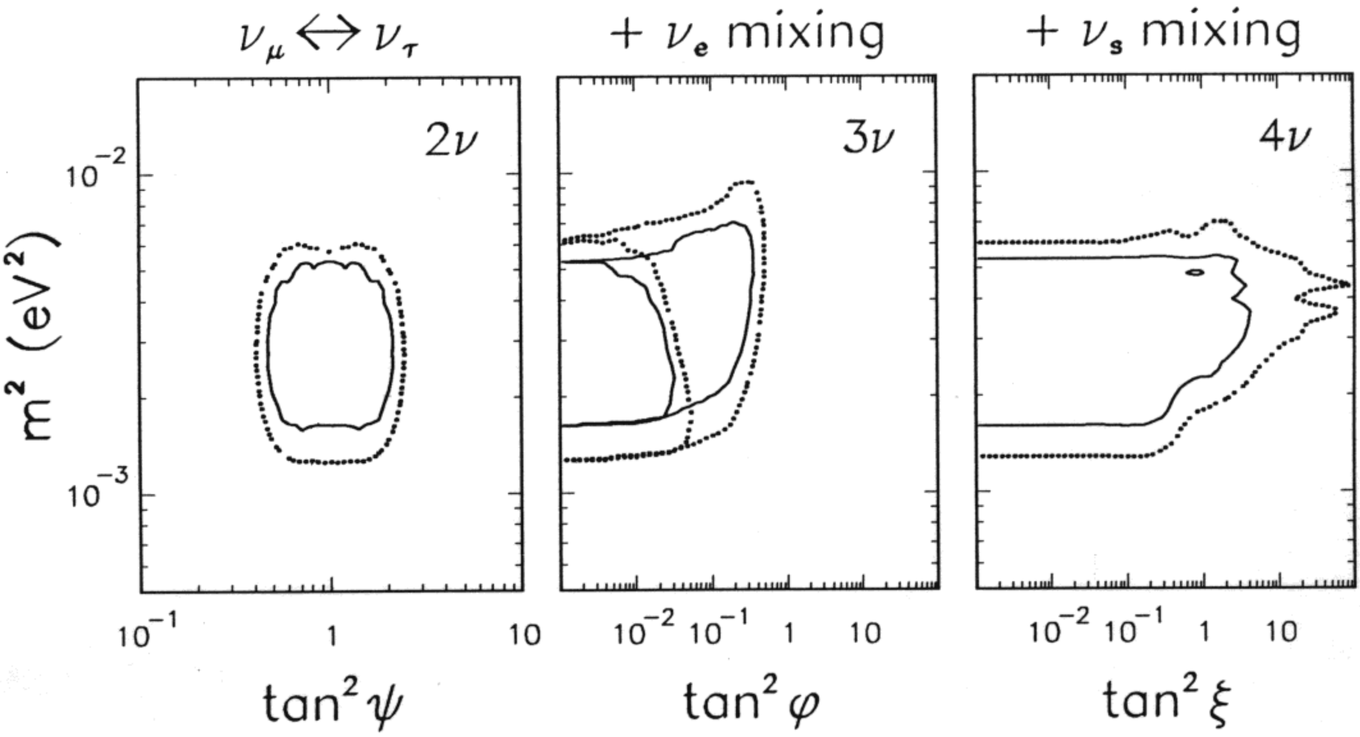
Also, recent MACRO analysis disfavors pure $\nu_\mu \to \nu_s$ at $\sim 99\%$ C.L.



→ ALL available atm. ν data likely to put a combined bound of $\sim 20 \div 30\%$ on $\sin^2\xi$ (additional ν_s admixture)

Summary of SK analysis (79.5 kTy)

assuming one dominant mass scale (m^2)



NOTES:

$\frac{U^2_{\mu 3}}{U^2_{\tau 3}} = $ 1/2 or 2 not excluded

$\tan^2\varphi \lesssim$ few % (SK + CHOOZ)

ALL DATA likely to strengthen bounds to $\tan^2\xi \lesssim 0.3$

Comment : K2K recent results

- Announced on 10 july '01 at the K2K official web site : http://neutrino.kek.jp/

- Discussed in detail by Nishikawa at the HEP Budapest Conference

- **DATA** : from April 1999 to April 2001

  Events (observed) : 44

  Events (expected) : 64 ± 10% (preliminary estimate of syst.)

- **CLAIM** : Null hypothesis (no osc.) disfavored at 97% C.L.] consistent with osc. @ $\Delta m^2 \sim 3 \times 10^{-3}$ (but no bound given)

- **DISCLAIMER** : Need more statistics to fit $(\Delta m^2, \sin^2 2\theta)_{ATM}$

expect factor ~3 improvement in # events by the year 2004

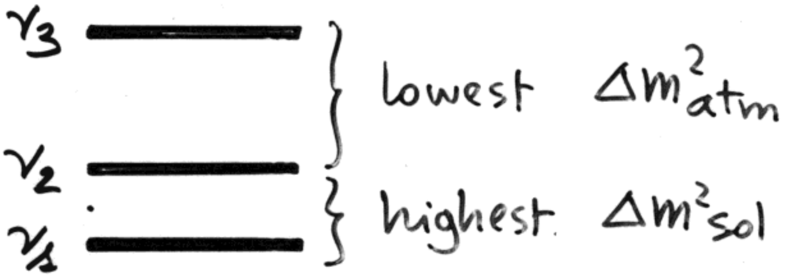
Clearly need "stabilization" of current distribution of events in energy (and time) before attempting to derive* lower bound on Δm^2_{atm} from K2K (relevant for LBL)

*(improve)

3ν beyond one mass scale

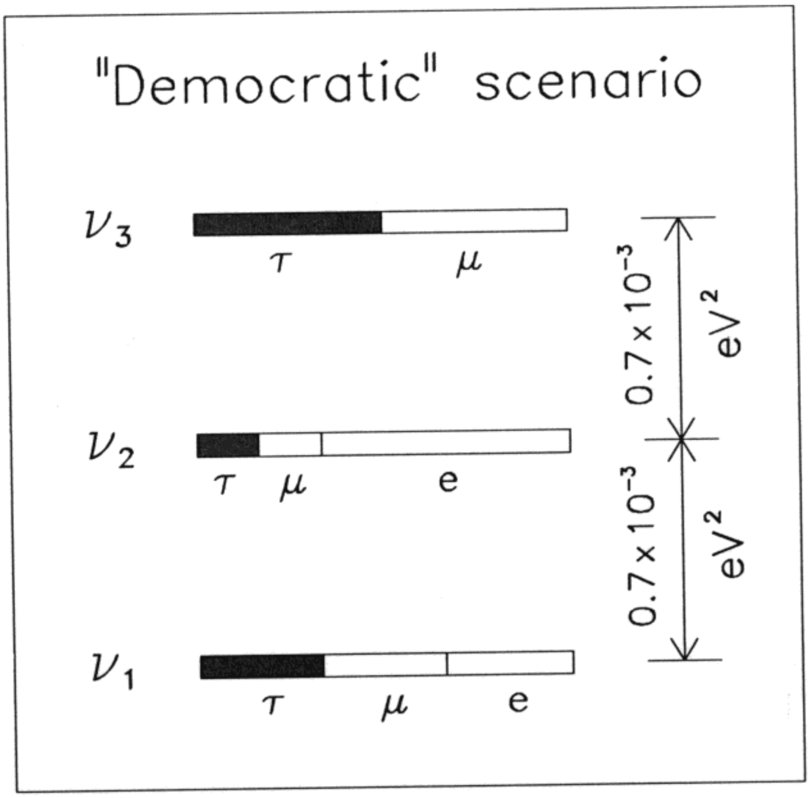
- $\Delta m^2_{atm} \gtrsim 1.5 \times 10^{-3}$ (SK + Macro + Soudan 2)
- $\Delta m^2_{sol} \lesssim 0.7 \times 10^{-3}$ (Solar + CHOOZ)
- $\rightarrow \dfrac{\Delta m^2_{sol}}{\Delta m^2_{atm}} \lesssim \dfrac{1}{2}$

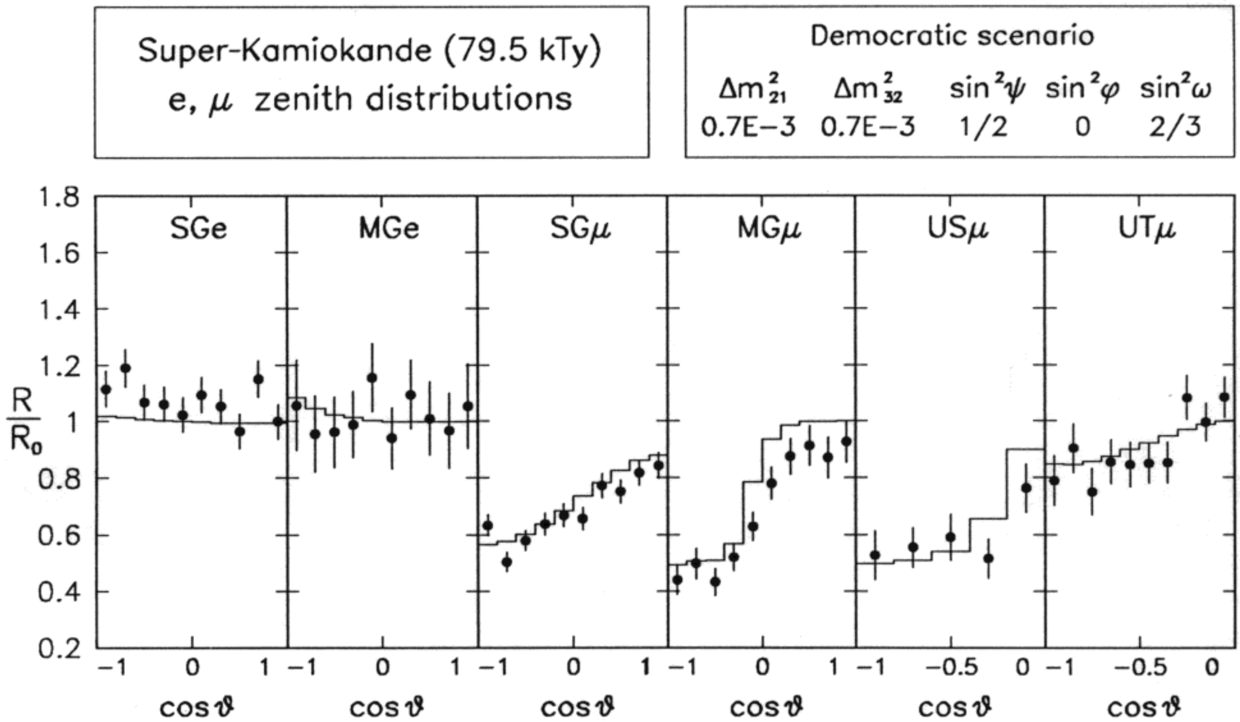
CANNOT YET EXCLUDE THAT SUCH UPPER BOUND IS ~SATURATED (non-hierarchical scenarios) :



- potentially more exciting for ν-factories

"Best" example of
non-hierarchical spectrum.

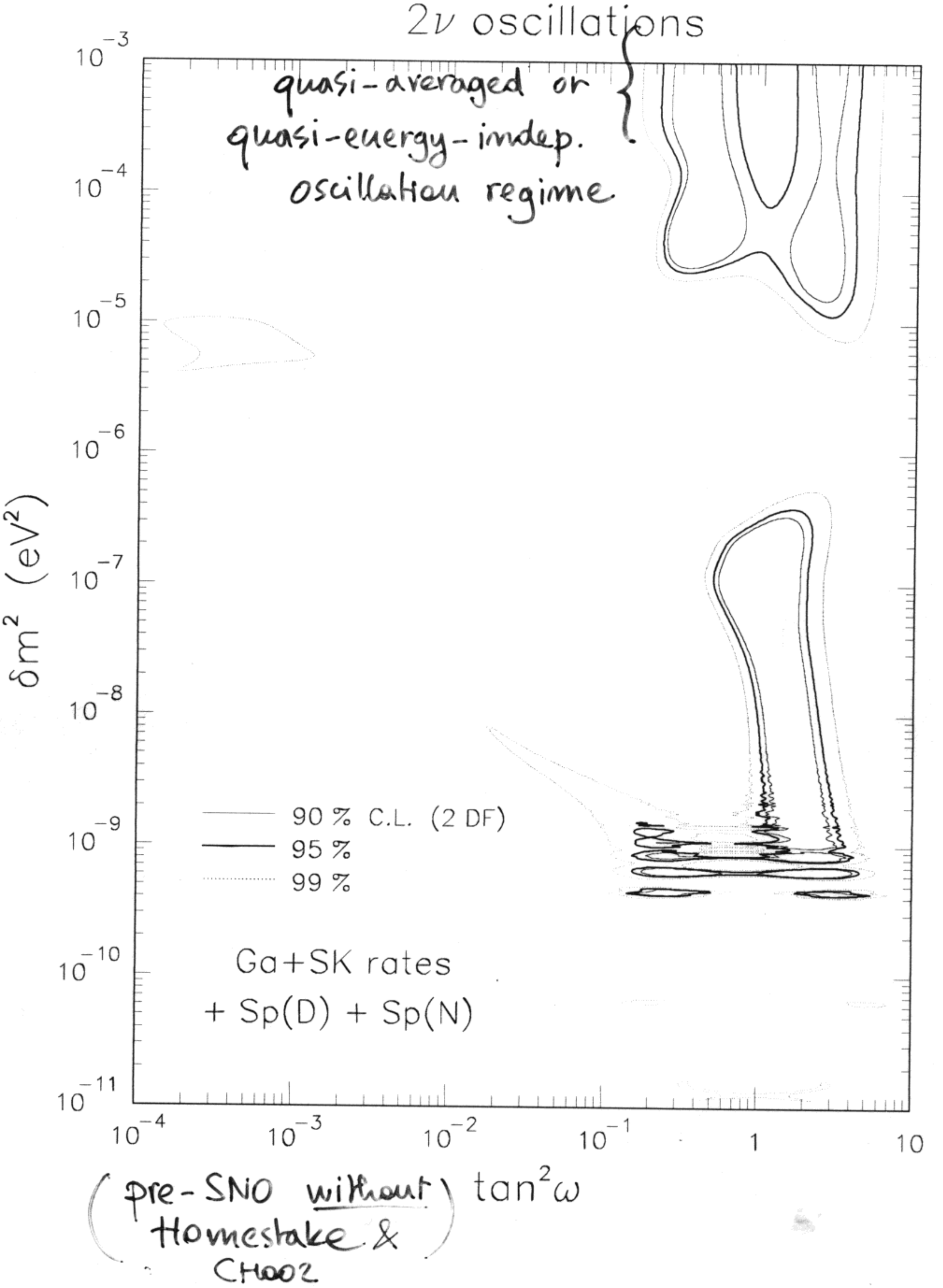


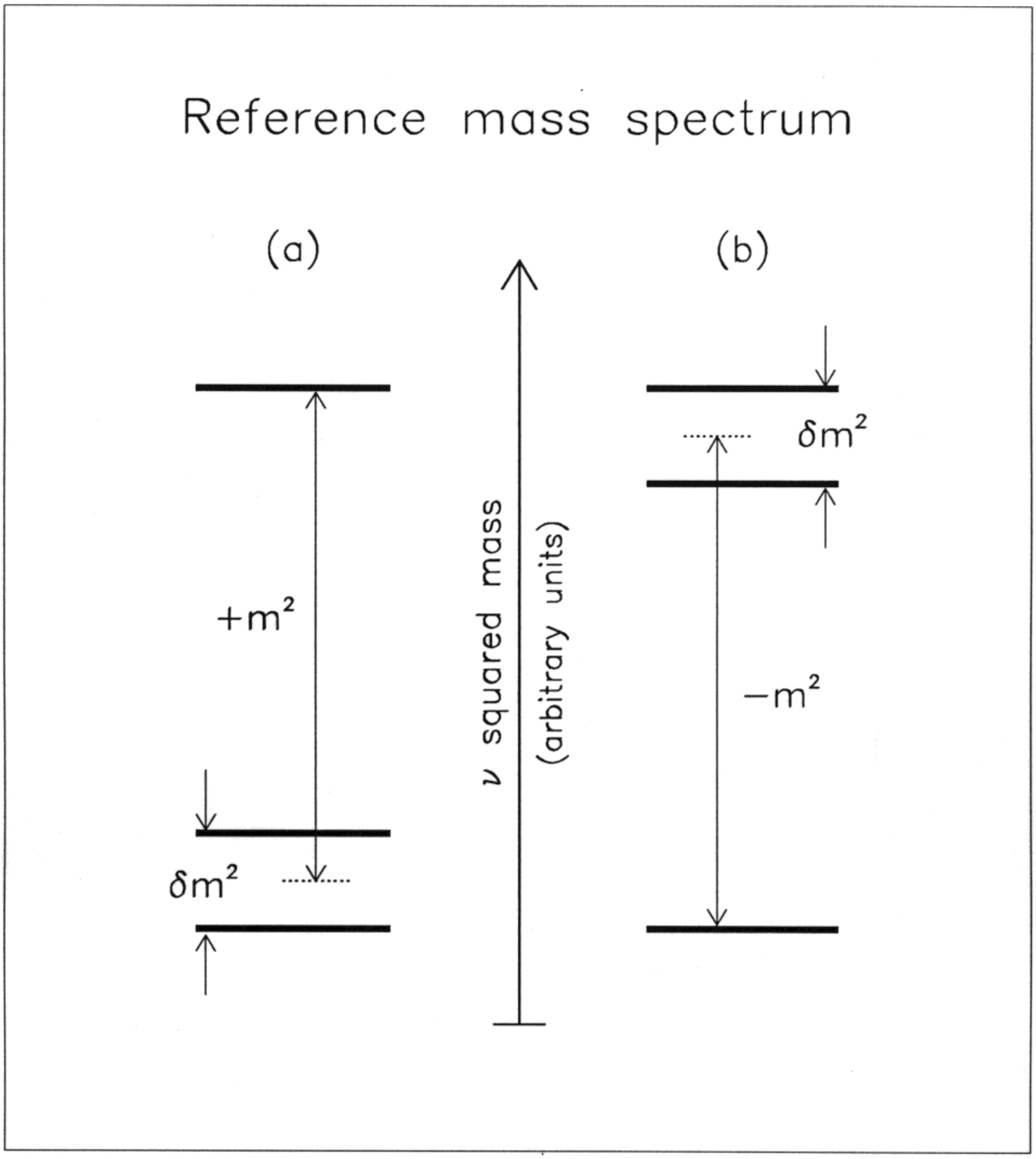


$\chi^2 \simeq 51$ (SK only) → not too bad!

$\chi^2 \simeq 61$ (SK + CHOOZ)

P_{ee} (solar) $\sim 5/9$ up to QAO corrections (Quasi Averaged Oscillations)


2ν oscillations
quasi-averaged or
quasi-energy-indep.
oscillation regime
δm² (eV²)
90 % C.L. (2 DF)
95 %
99 %
Ga+SK rates
+ Sp(D) + Sp(N)
tan²ω
(pre-SNO without Homestake & CHOOZ)

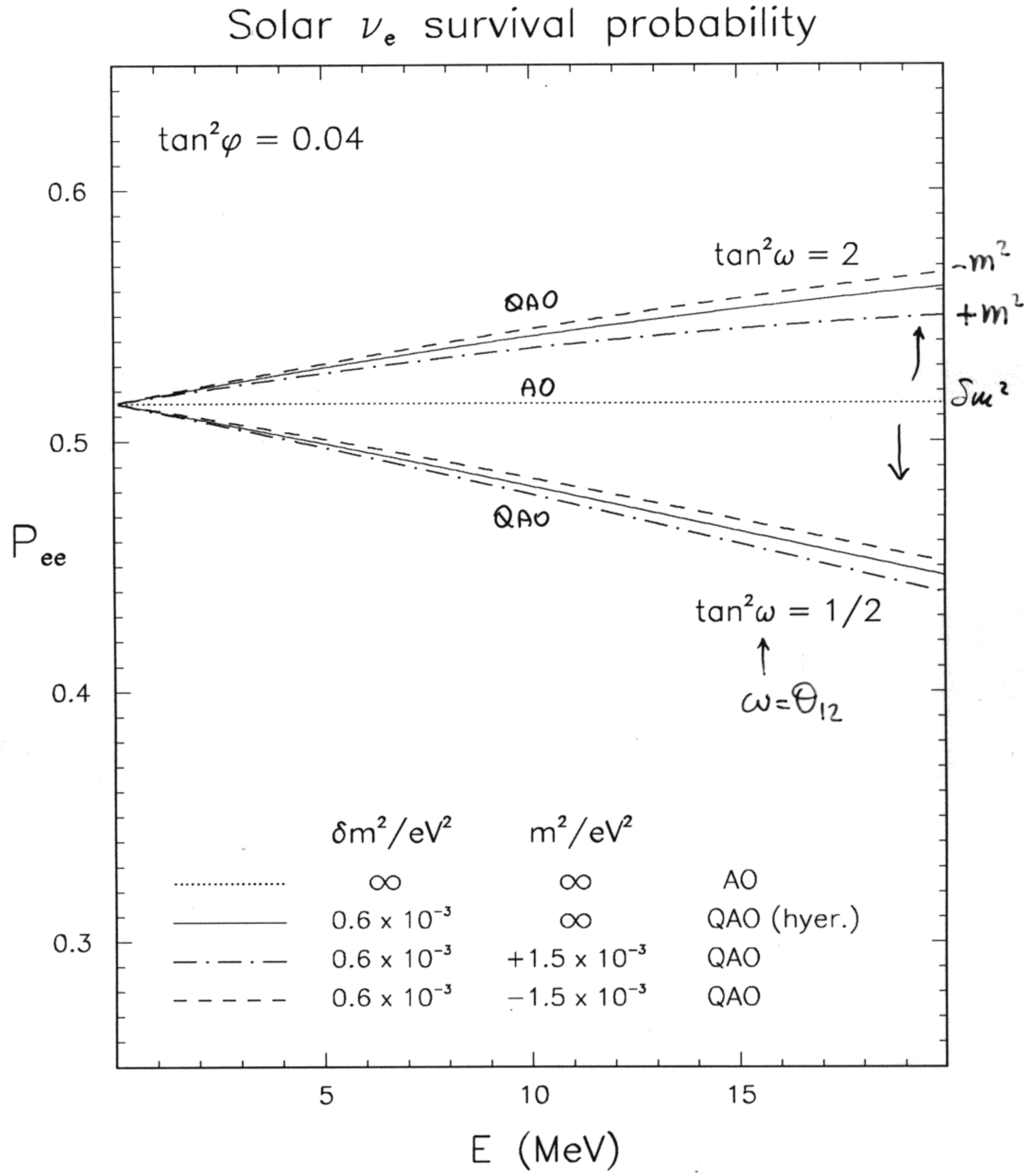


In such regime, solar ν's become slightly sensitive to : $\pm m^2 = \pm \Delta m^2_{atm}$

(unfortunately: small effect)

→ relevant only to improve accuracy of theor. calculations

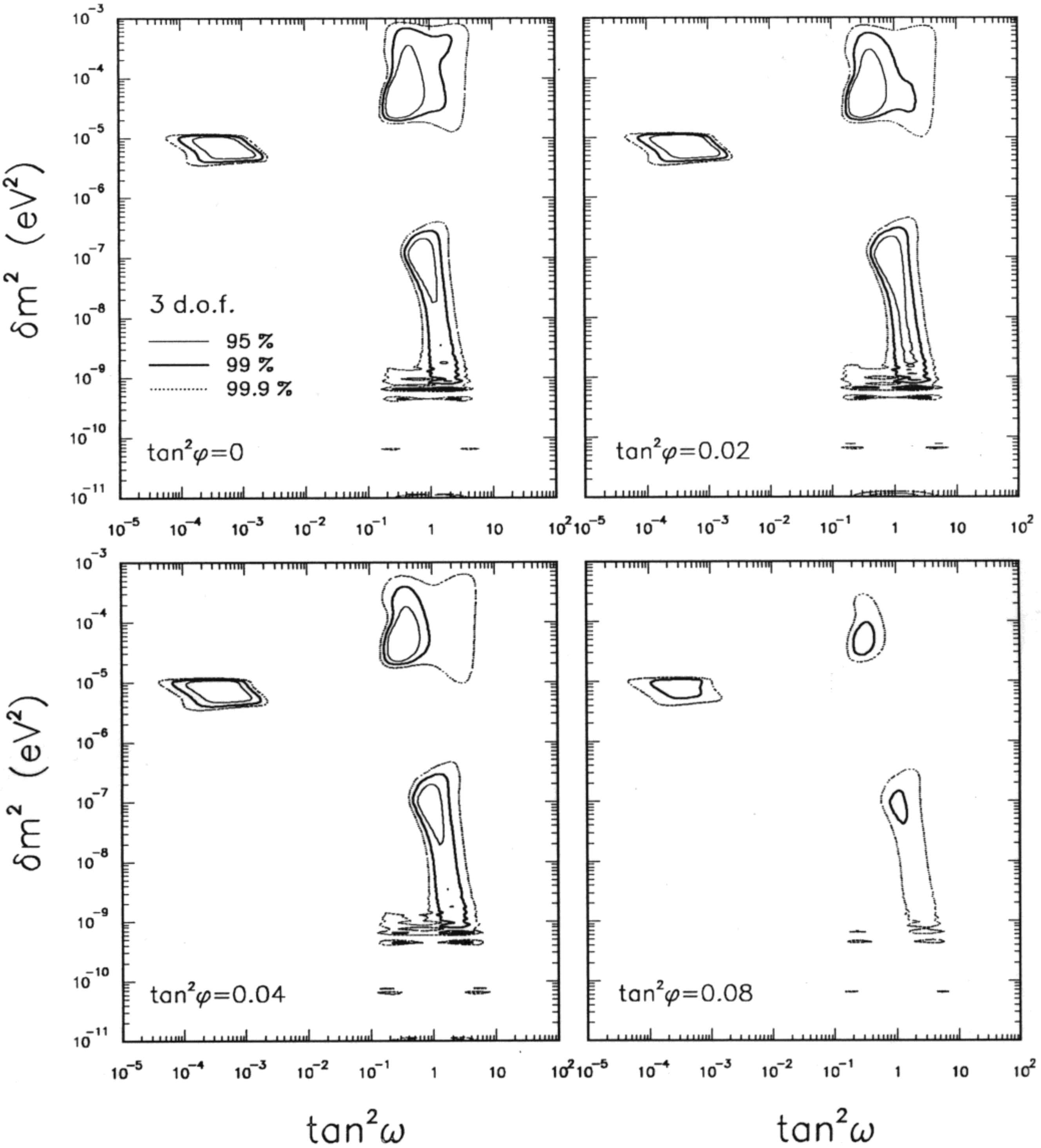
An example:



(small effect)

pre-SNO 3ν oscillations:

SOLAR + CHOOZ ($m^2 = 1.5\times10^{-3}$ eV^2)



Fit to summer 2000 data + SSM for (δm^2, m^2) finite.

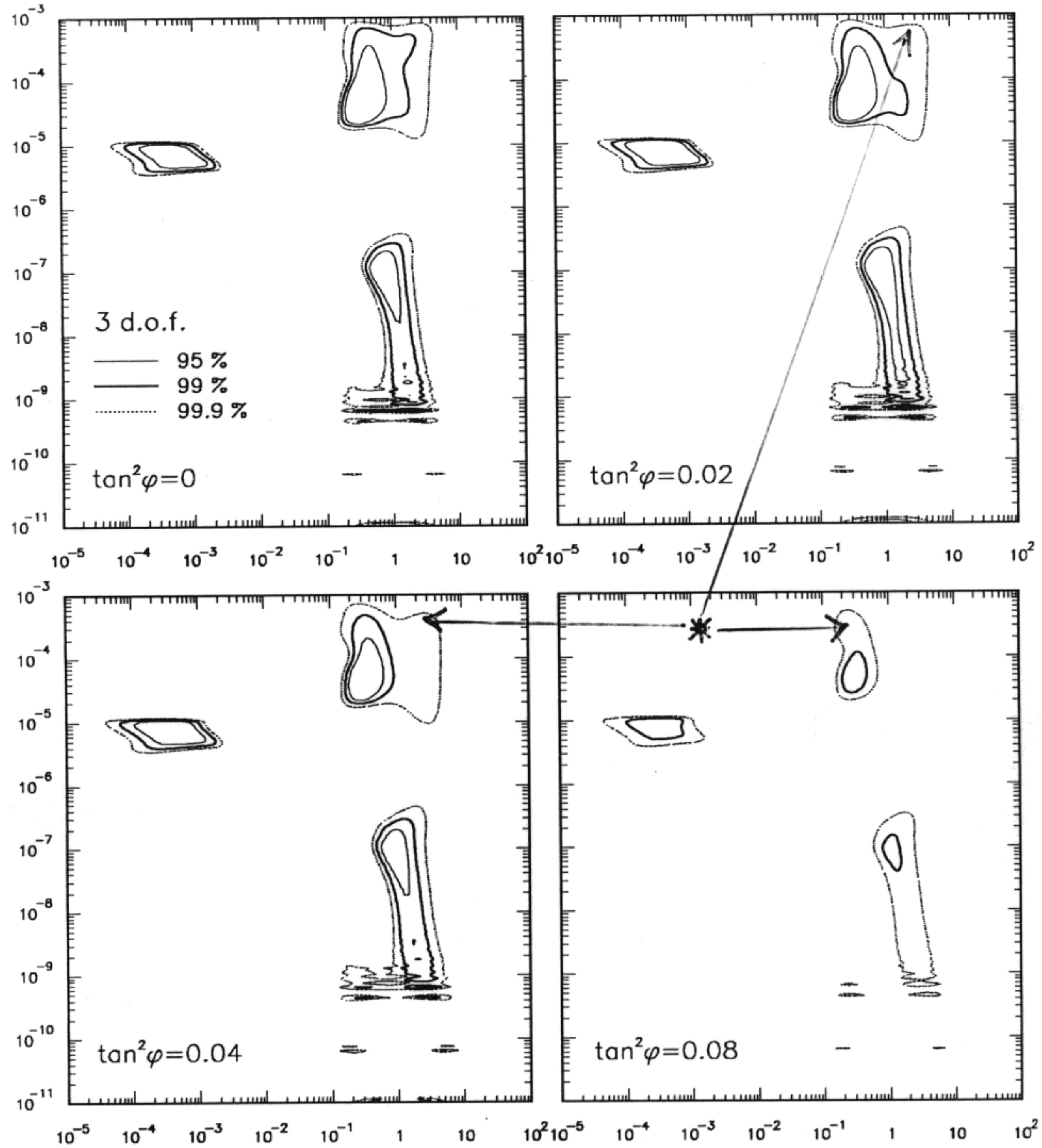
CHOOZ included.

pre-SNO

3ν oscillations:

as before, but $m^2 = -1.5\times10^{-3}$

SOLAR + CHOOZ



* very small effects of QAO regime in upper part of LMA solution, and only for $\varphi > 0$.

But: sensitivity to QAO might increase if KamLand nails down solar parameters in LMA

CONCLUSIONS

- 2ν bounds on $(m^2, \tan^2\psi)$ robust; dominant L/E dependence confirmed with high accuracy $(n = -1.03 \pm 0.31)$

- 3ν bounds on additional ν_e mixing (SK + CHOOZ) very stringent ($\tan^2\varphi \lesssim$ few%) → suppressed sensitivity of SK to sign(m^2)

- 4ν bounds on additional ν_s mixing from SK zenith distributions only are not very stringent ($\tan^2\xi \sim \mathcal{O}(1)$ allowed); however, totality of SK data + MACRO probably set limit $\tan^2\xi \lesssim 0.3$

- Non-hierarchical 3ν scenarios (e.g., "democratic" spectrum) with Δm^2_{solar} of order Δm^2_{atm} not totally excluded. Need more study since SNO favors LMA. If upper part of LMA is the "true" solution, then cross-talk between Δm^2_{sol} and Δm^2_{atm} more interesting (and difficult!)