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SMR.1317 - 23

SUMMER SCHOOL ON PARTICLE PHYSICS

18 June - 6 July 2001

NEUTRINO PHYSICS

Lecture IV

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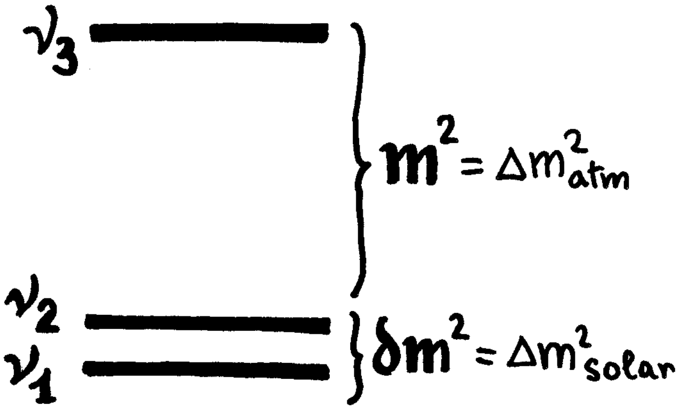
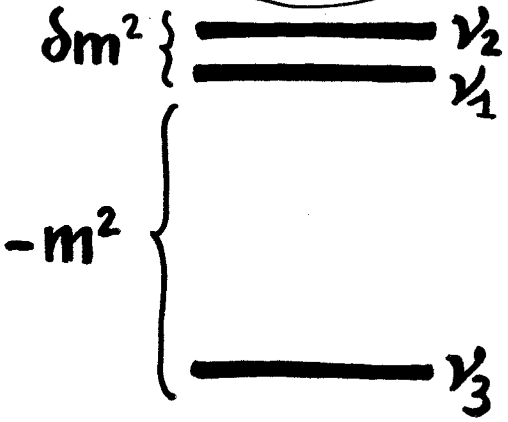
ATM. + SOLAR 3ν OSCILLATIONS

Phenomenology favors spectra with hierarchical Δm^2's :

either ...



... or



with ... $\boxed{\delta m^2 \ll m^2}$

N.B.: HIERARCHY OF Δm^2's <u>DOES NOT</u> IMPLY HIERARCHY OF $m^2(\nu_i)$

mass^2 matrix : $\mathcal{M}^2 = \begin{pmatrix} 0 & & \\ & \delta m^2 & \\ & & \pm m^2 \end{pmatrix} + \mu^2 \cdot \mathbb{1}$

$\uparrow$

absolute mass^2 scale not defined in ν-osc. experiments; must be inferred by other means.

PARAMETER SPACE (REDUCTION)

In general, the 3ν-oscillation parameter space is spanned by:

$$(\underbrace{\delta m^2, m^2}_{\text{two } \Delta m^2}, \underbrace{\omega, \varphi, \psi}_{\text{3 mixing angles}}, \underbrace{\delta}_{1\ \cancel{CP} \text{ phase}})$$

Luckily, for $\delta m^2 \ll m^2$ the parameter space can be reduced considerably at zeroth order in $\delta m^2/m^2$ (one mass scale dominance). Physical motivation:

FOR TERRESTRIAL ν EXPERIMENTS,

(accelerator, reactor, atmospheric), δm^2 is too small to be probed → can take $\delta m^2 \simeq 0$ and

$$\mathcal{M}^2_{\text{terrestrial}} \simeq \begin{pmatrix} 0 & & \\ & 0 & \\ & & \pm m^2 \end{pmatrix} + \mu^2 \cdot \mathbb{1}$$

FOR SOLAR ν EXPERIMENTS,

$m^2 = \Delta m^2_{\text{atm}}$ is so large that its oscillations can be taken as averaged (equivalent to take $\pm m^2 = \infty$),

$$\mathcal{M}^2_{\text{solar}} \simeq \begin{pmatrix} 0 & & \\ & \delta m^2 & \\ & & \infty \end{pmatrix} \quad \text{mod.}\ \mathbb{1}$$

FOR BOTH SOLAR AND TERRESTRIAL EXPTS.,

$\delta m^2/m^2 \to 0$ implies that $\cancel{CP}$ effects (if any) vanish $\Rightarrow$ can take U real

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

U real

$UU^T = 1$

In "CKM-like" (Maiani) parametrization:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c\psi & s\psi \\ 0 & -s\psi & c\psi \end{pmatrix} \begin{pmatrix} c\varphi & 0 & s\varphi \\ 0 & 1 & 0 \\ -s\varphi & 0 & c\varphi \end{pmatrix} \begin{pmatrix} c\omega & s\omega & 0 \\ -s\omega & c\omega & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\psi = \theta_{23} \qquad \varphi = \theta_{13} \qquad \omega = \theta_{12}$$

$$= U(\theta_{23}) \cdot U(\theta_{13}) \cdot U(\theta_{12})$$

Such a conventional ordering of Euler rotations turns out to be (accidentally) very useful in the context of one-mass scale dominance

→

- TERRESTRIAL EXPTS : $\mathcal{M}^2 \sim \begin{pmatrix} 0 & & \\ & 0 & \\ & & \pm m^2 \end{pmatrix} \leftarrow (\nu_1, \nu_2)$ ~degenerate

→ any rotation in (ν_1, ν_2) subspace unobservable in terrestrial experiments:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c_\psi & s_\psi \\ & -s_\psi & c_\psi \end{pmatrix} \begin{pmatrix} c_\varphi & & s_\varphi \\ & 1 & \\ -s_\varphi & & c_\varphi \end{pmatrix} \underbrace{\xcancel{\begin{pmatrix} c_\omega & s_\omega & \\ -s_\omega & c_\omega & \\ & & 1 \end{pmatrix}}}_{\substack{\text{acts on} \\ (\nu_1, \nu_2)}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

→ terrestrial experiments probe only the mixing angles $\psi = \theta_{23}$ and $\varphi = \theta_{13}$

- SOLAR EXPTS: cannot distinguish ν_μ from ν_τ in final state (energy so low that $\nu_{\mu,\tau}$ interactions identical and μ, τ production impossible)

→ any rotation in (ν_μ, ν_τ) subspace unobservable in solar ν experiments:

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} c_\omega & s_\omega & \\ -s_\omega & c_\omega & \\ & & 1 \end{pmatrix}^T \begin{pmatrix} c_\varphi & & s_\varphi \\ & 1 & \\ -s_\varphi & & c_\varphi \end{pmatrix}^T \underbrace{\xcancel{\begin{pmatrix} 1 & & \\ & c_\psi & s_\psi \\ & -s_\psi & c_\psi \end{pmatrix}}^T}_{\substack{\text{acts on} \\ (\nu_\mu, \nu_\tau)}} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

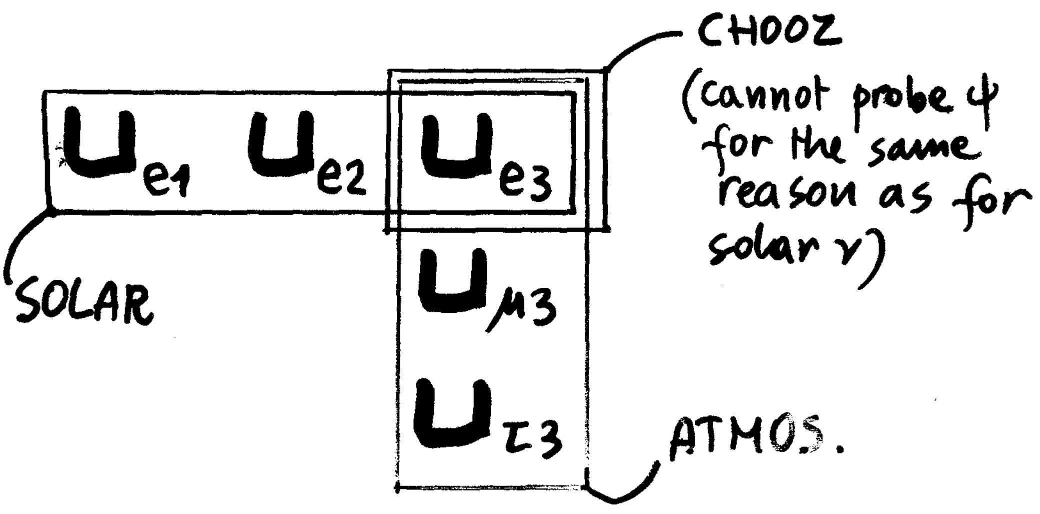
→ solar ν experiments probe only the mixing angles $\omega = \theta_{12}$ and $\varphi = \theta_{13}$

TERRESTRIAL ν PARAM. SPACE : (m^2, ψ, φ)

SOLAR ν PARAM. SPACE : $(\delta m^2, \omega, \varphi)$

$\varphi = \theta_{13}$ probed in both cases

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ \cdot & \cdot & U_{\mu 3} \\ \cdot & \cdot & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_\varphi c_\omega & c_\varphi s_\omega & s_\varphi \\ \cdot & \cdot & c_\varphi s_\psi \\ \cdot & \cdot & c_\varphi c_\psi \end{pmatrix}$$



SUMMARY OF 3ν PARAMETRIZATION AT ZEROTH ORDER IN $\delta m^2/m^2$:

TERRESTRIAL ν

PROBE m^2 (largest Δm^2),
AND THE FLAVOR COMPOSITION OF ν_3:

$$\nu_3 = U_{e3}\nu_e + U_{\mu 3}\nu_\mu + U_{\tau 3}\nu_\tau$$

$$= c_\varphi (c_\psi \nu_\tau + s_\psi \nu_\mu) + s_\varphi \nu_e$$

with $U^2_{e3} + U^2_{\mu 3} + U^2_{\tau 3} = 1$

Reduces to 2ν $(\nu_\mu \leftrightarrow \nu_\tau)$ for $U_{e3} = s_\varphi = 0$

SOLAR ν

PROBE δm^2 (smallest Δm^2)
AND THE MASS COMPOSITION OF ν_e:

$$\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$$

$$= c_\varphi (c_\omega \nu_1 + s_\omega \nu_2) + s_\varphi \nu_3$$

with $U^2_{e1} + U^2_{e2} + U^2_{e3} = 1$

Reduces to pure 2ν $(\nu_1 \leftrightarrow \nu_2)$ for $s_\varphi = 0$

no observable $\not{CP}$ effects

Relevant unitarity constraints:

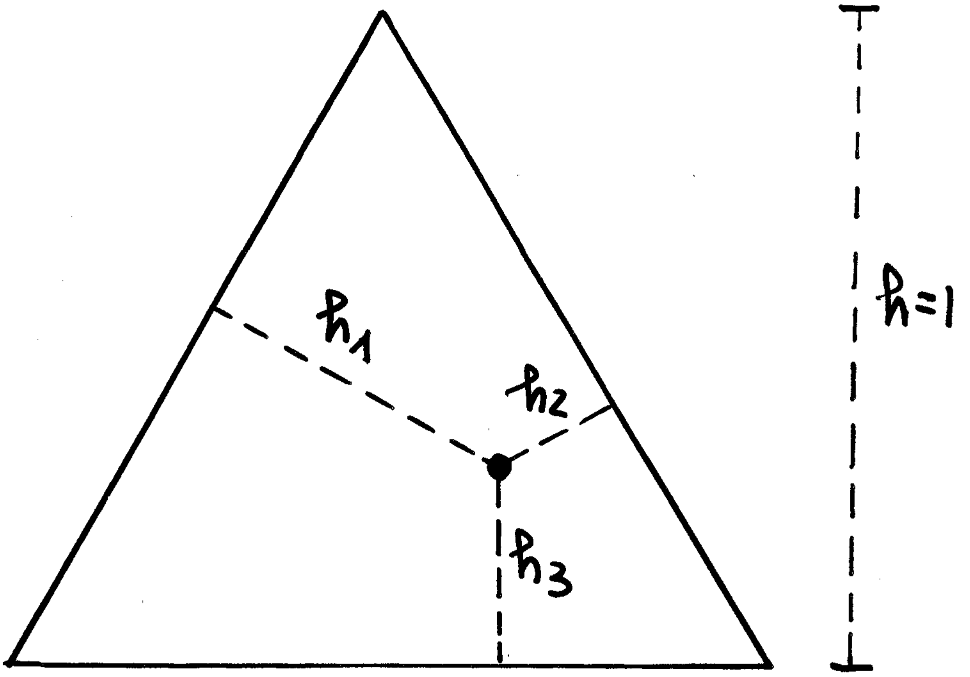
$$U_{e1}^2 + U_{e2}^2 + U_{e3}^2 = 1$$

$$U_{e3}^2 + U_{\mu 3}^2 + U_{\tau 3}^2 = 1$$

Constraints of the generic form

$$h_1 + h_2 + h_3 = 1$$

can be embedded in triangle graphs



$$h_1 + h_2 + h_3 = 1$$

FOR ANY POINT INSIDE THE △

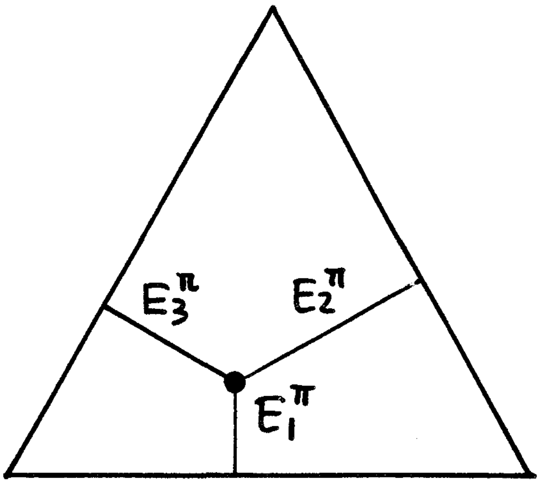
EXAMPLES :

Dalitz, 1953

K → $\pi\pi\pi$ decay

$E_1^\pi + E_2^\pi + E_3^\pi = E_{TOT}$

"Dalitz plot"

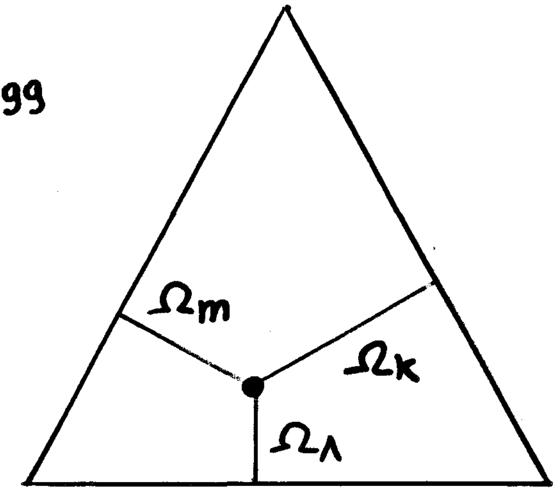


N. Bahcall, Ostriker,
Perlmutter, Steinhardt, 1999

Ω_i bounds

$\Omega_m + \Omega_K + \Omega_\Lambda = 1$

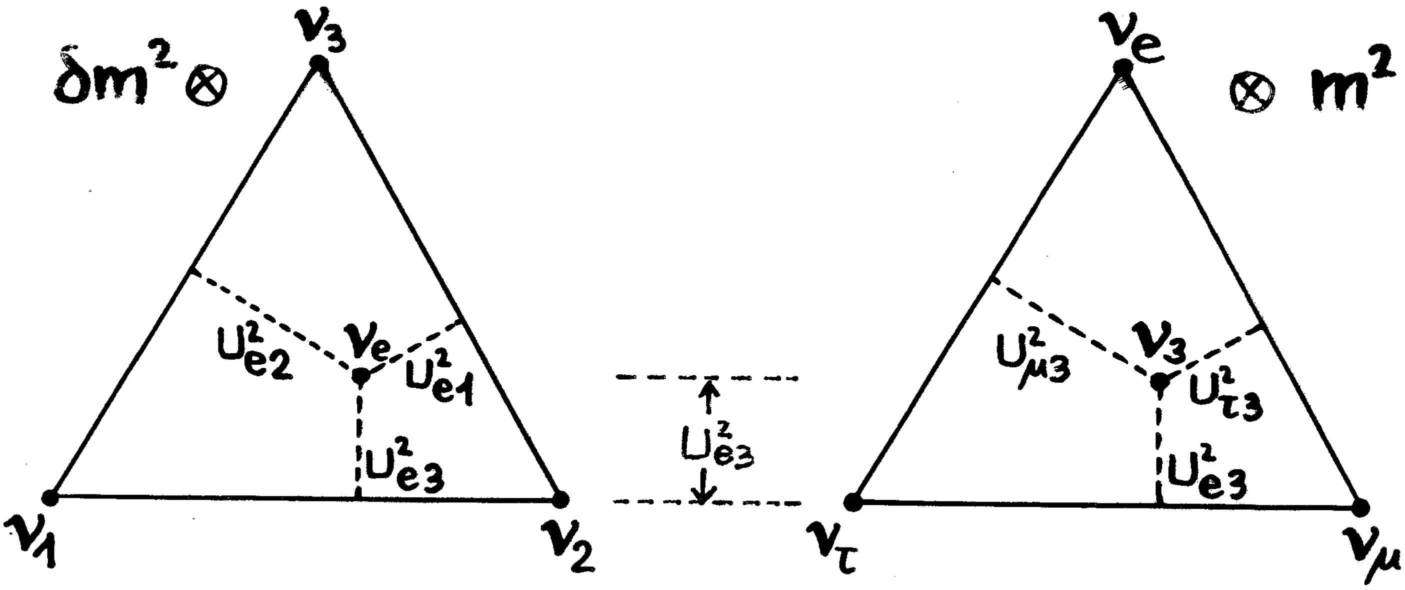
"Cosmic triangle"



→ Unitarity suggests the following representations:

SOLAR ν
parameter space:

TERRESTRIAL ν
parameter space:



$U_{e1}^2+U_{e2}^2+U_{e3}^2=1$

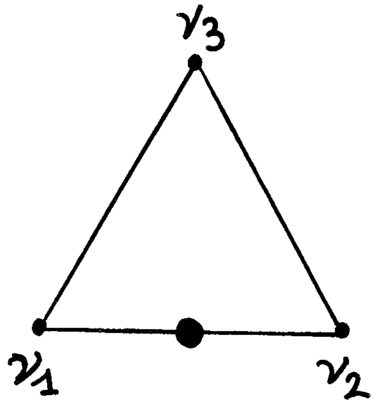
$U_{e3}^2+U_{\mu 3}^2+U_{\tau 3}^2=1$

(Lisi, Fogli, Montanino, Scioscia)

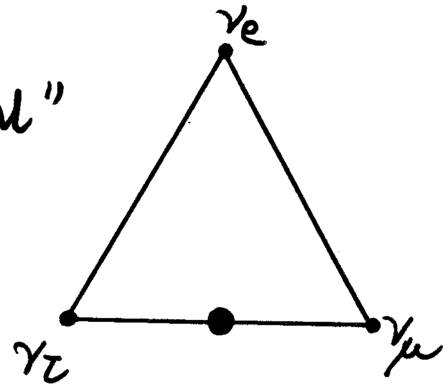
EXAMPLES

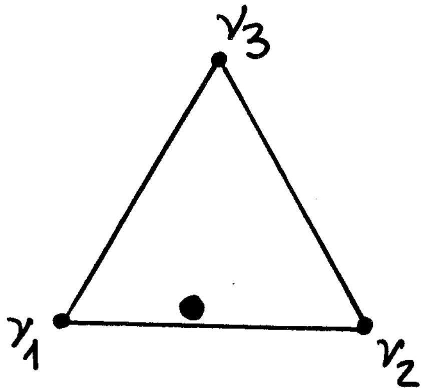
SOLAR

ATMOSPH.

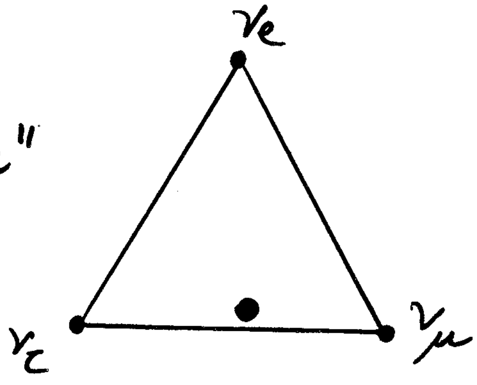


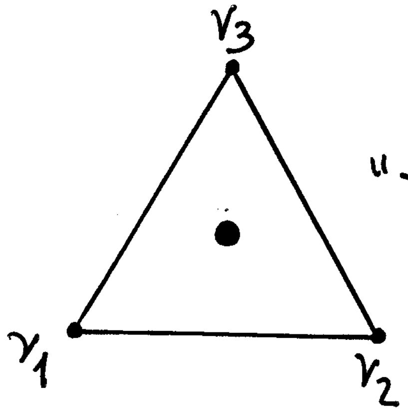
"Bi-maximal" mixing



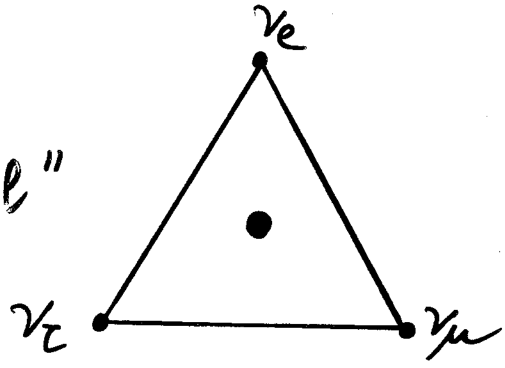


"Bi-large" mixing

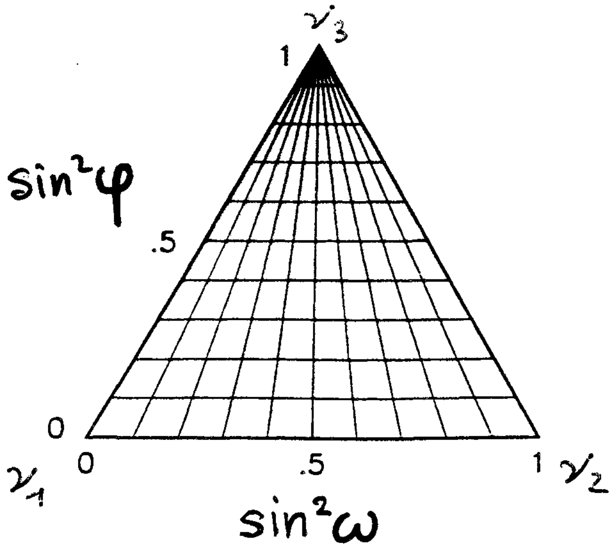




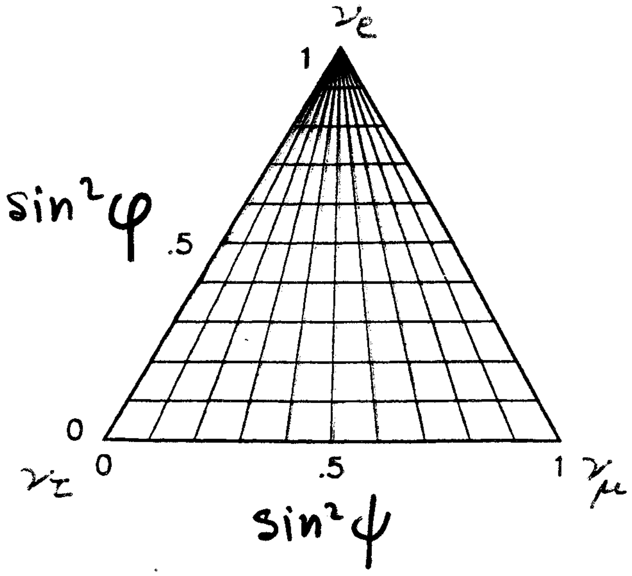
"Trimaximal" mixing



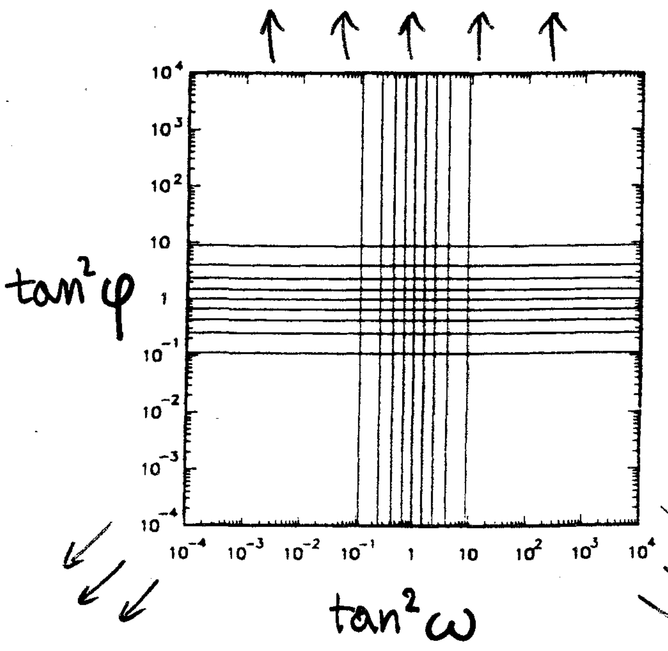
SOLAR



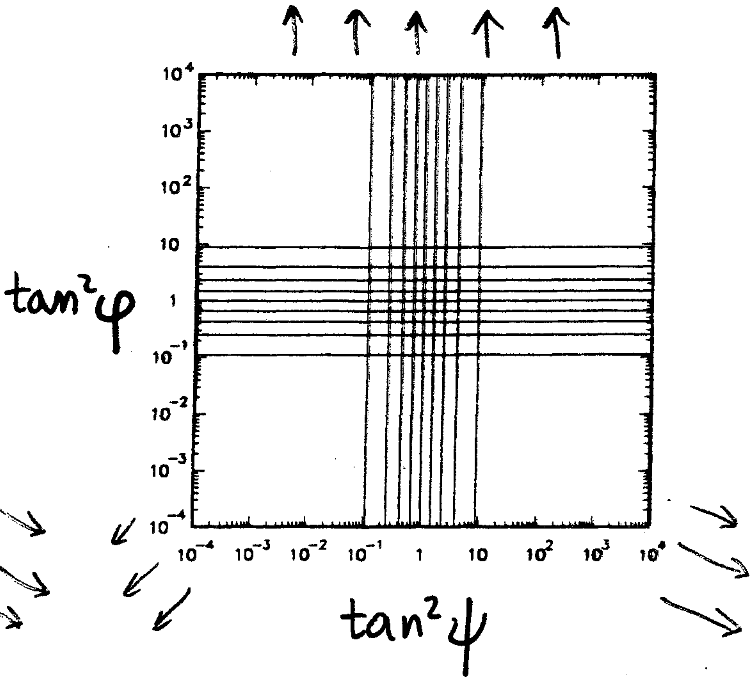
TERRESTRIAL



δm^2 fixed



m^2 fixed

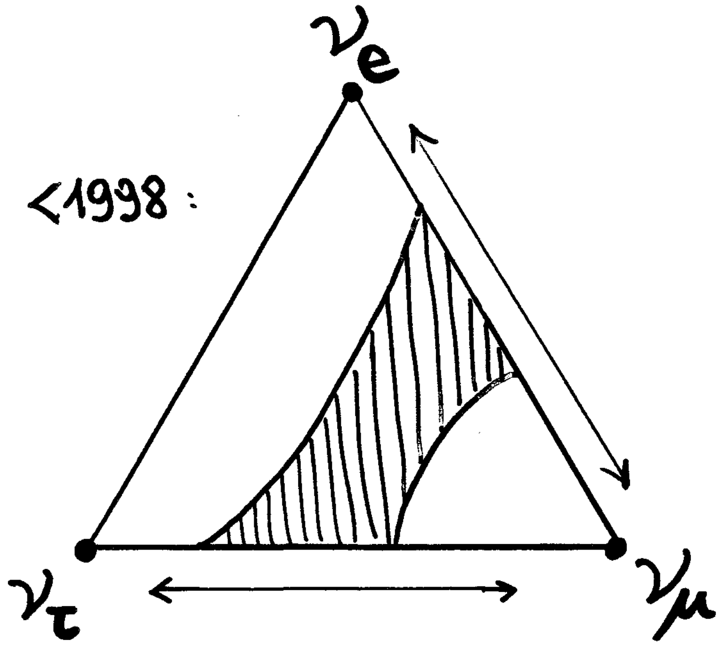


BILOGARITHMIC MIXING/MIXING REPRESENTATION

(useful to expand zones at small mixing)

ATMOSPHERIC 3ν OSCILLATIONS

<1998 :



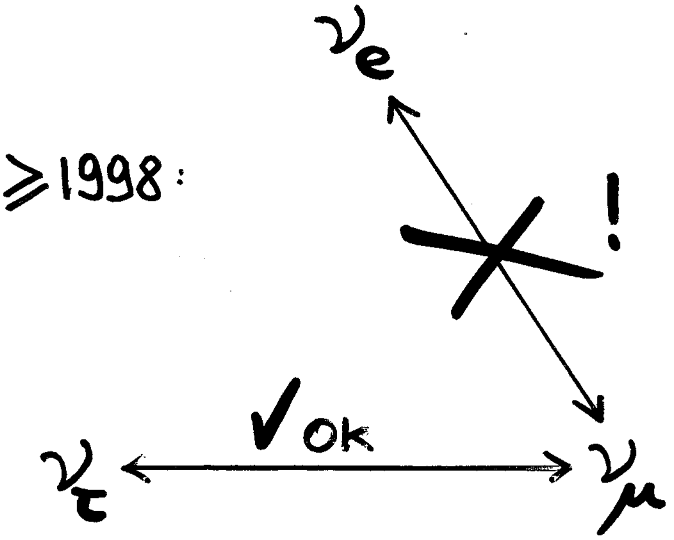
pre-SK situation:

Could not distinguish pure $\nu_\mu \leftrightarrow \nu_\tau$ and pure $\nu_\mu \leftrightarrow \nu_e$, as well as intermediate cases

▨ = ALLOWED

SK = Super-Kamiokande

≥1998 :



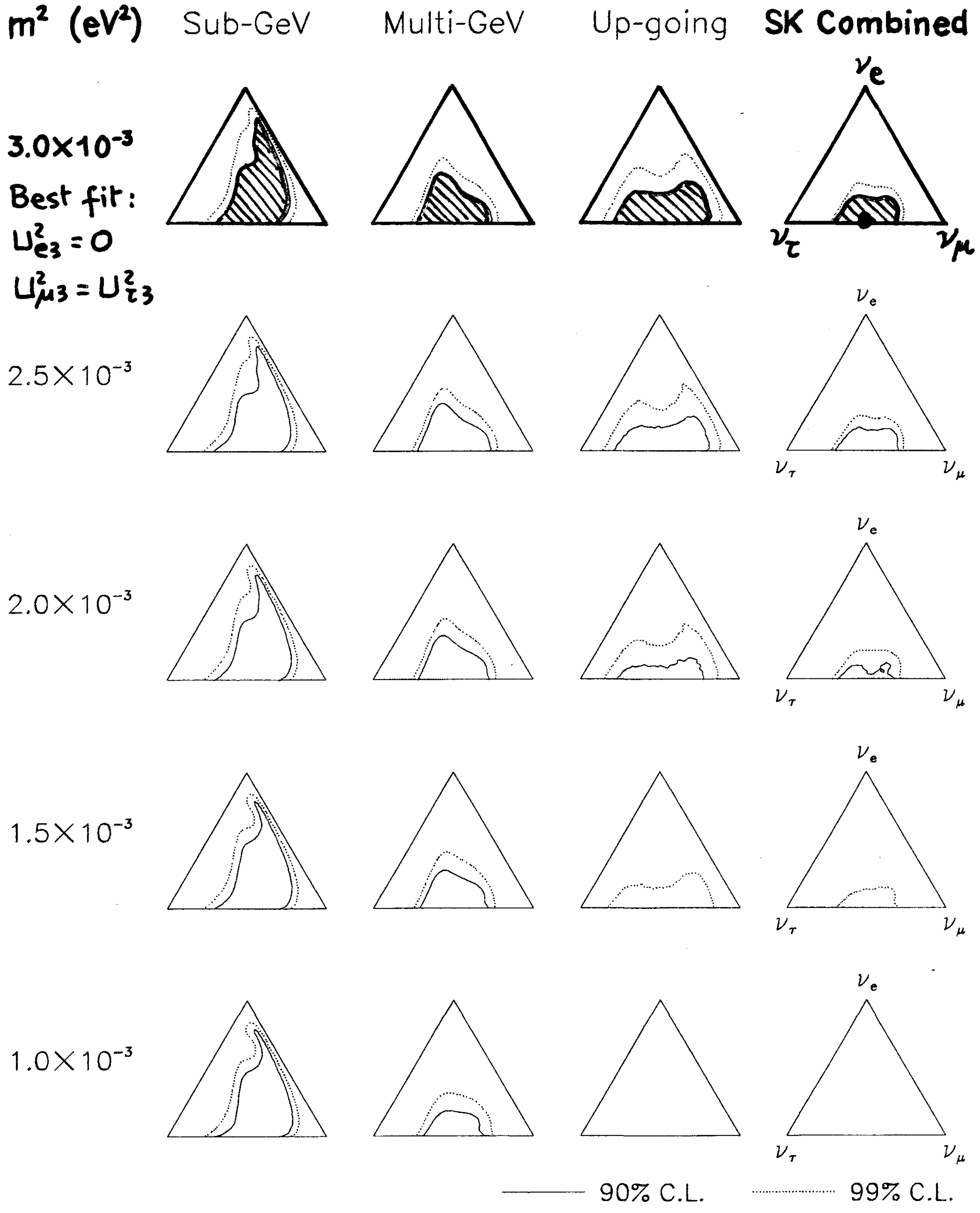
post-SK :

we expect $\nu_\mu \leftrightarrow \nu_e$ to be forbidden.

Confirmed by quantitative data analysis

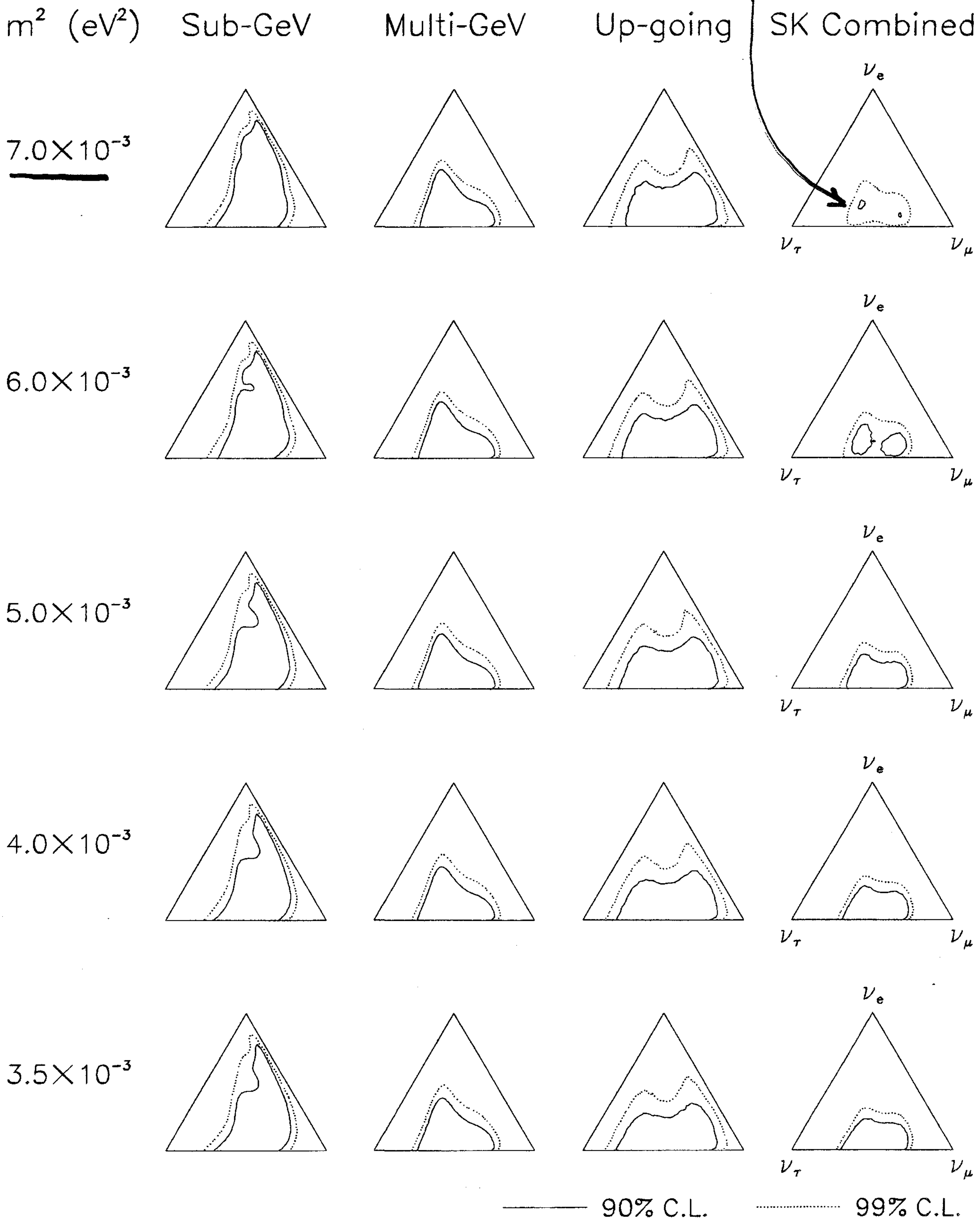
⟶

SITUATION NOW (2001)



Fogli,
E.L.,
Marrone

SLIGHT PREFERENCE FOR $U_{e3}^2 > 0$ at "HIGH" m^2 only



In general, atmospheric ν prefer small or zero values for $U_{e3}^2 = s_\varphi^2 = \sin^2\theta_{13}$

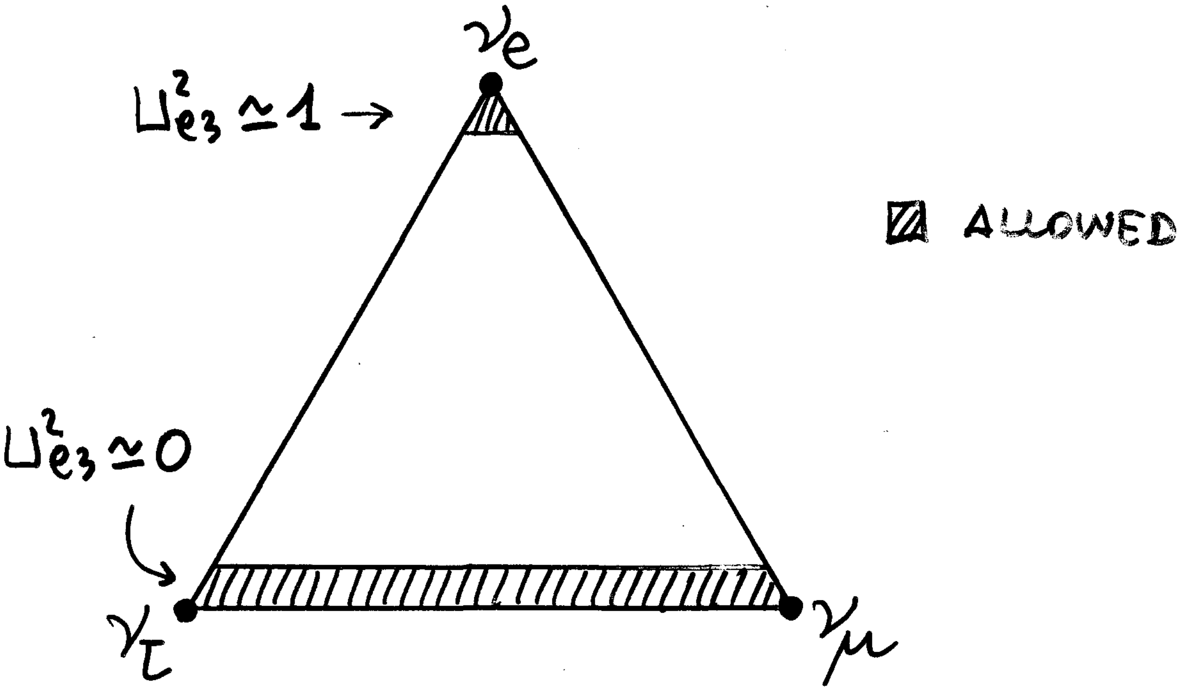
Impact of CHOOZ

$$P_{ee}^{CHOOZ} = 1 - 4U_{e3}^2(1-U_{e3}^2)\sin^2\left(\frac{m^2L}{4E}\right) \leftarrow \text{theor. } (3\nu)$$

$$\simeq 1 \quad \text{for } \Delta m^2 \gtrsim 0{,}7\times10^{-3}\ \text{eV}^2 \qquad \leftarrow \text{expt}$$

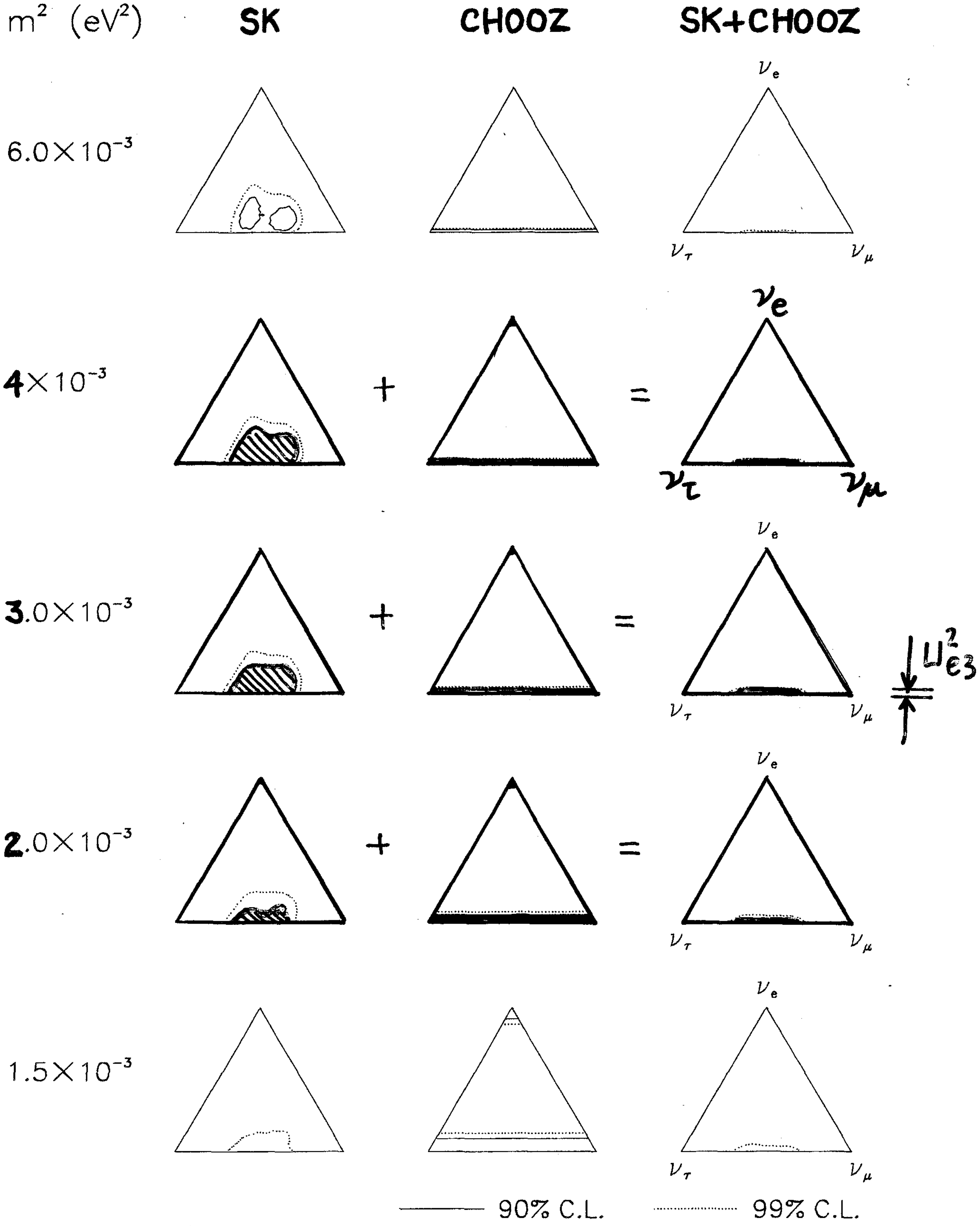
Therefore, $4U_{e3}^2(1-U_{e3}^2) \simeq 0$

$$\rightarrow \begin{cases} \text{either} & U_{e3}^2 \simeq 0 \\ \text{or} & U_{e3}^2 \simeq 1 \end{cases}$$



Quantitative analysis →

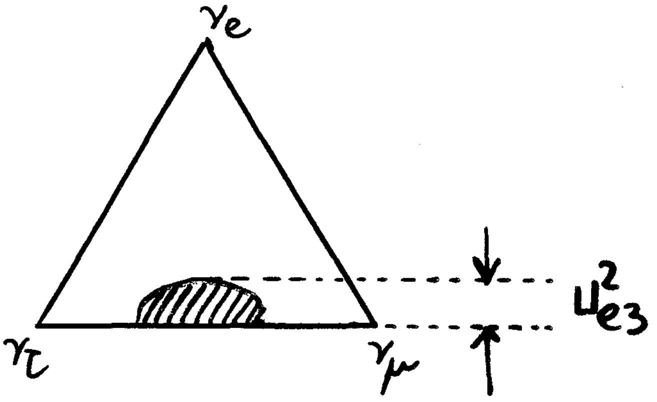
Fogli, E.L., Marrone



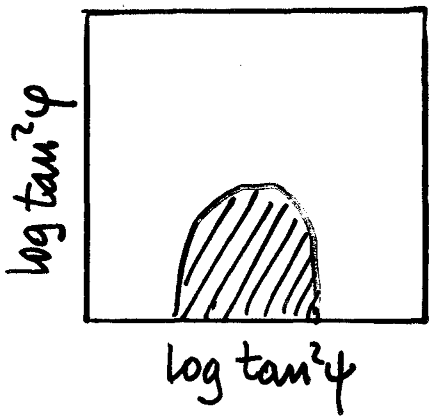
- SK + CHOOZ: $U_{e3}^2 \lesssim$ few %
- CHALLENGE FOR FUTURE EXP. TO PROVE $U_{e3}^2 \neq 0$ (no theoretical motivation for $U_{e3}^2 \equiv 0$)

Alternative representation

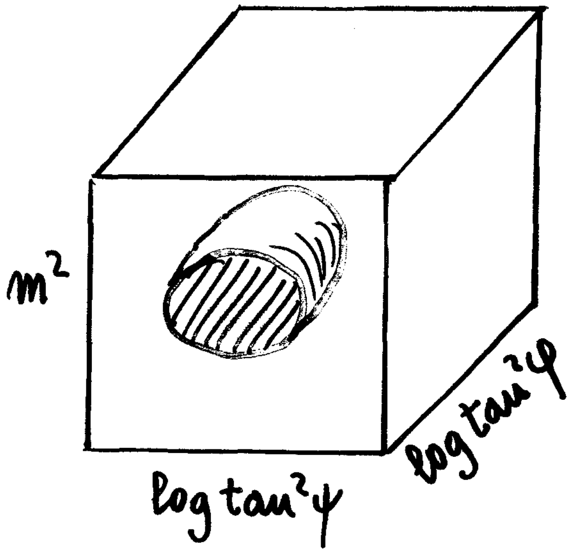
Since regions at small U_{e3}^2 are difficult to draw...



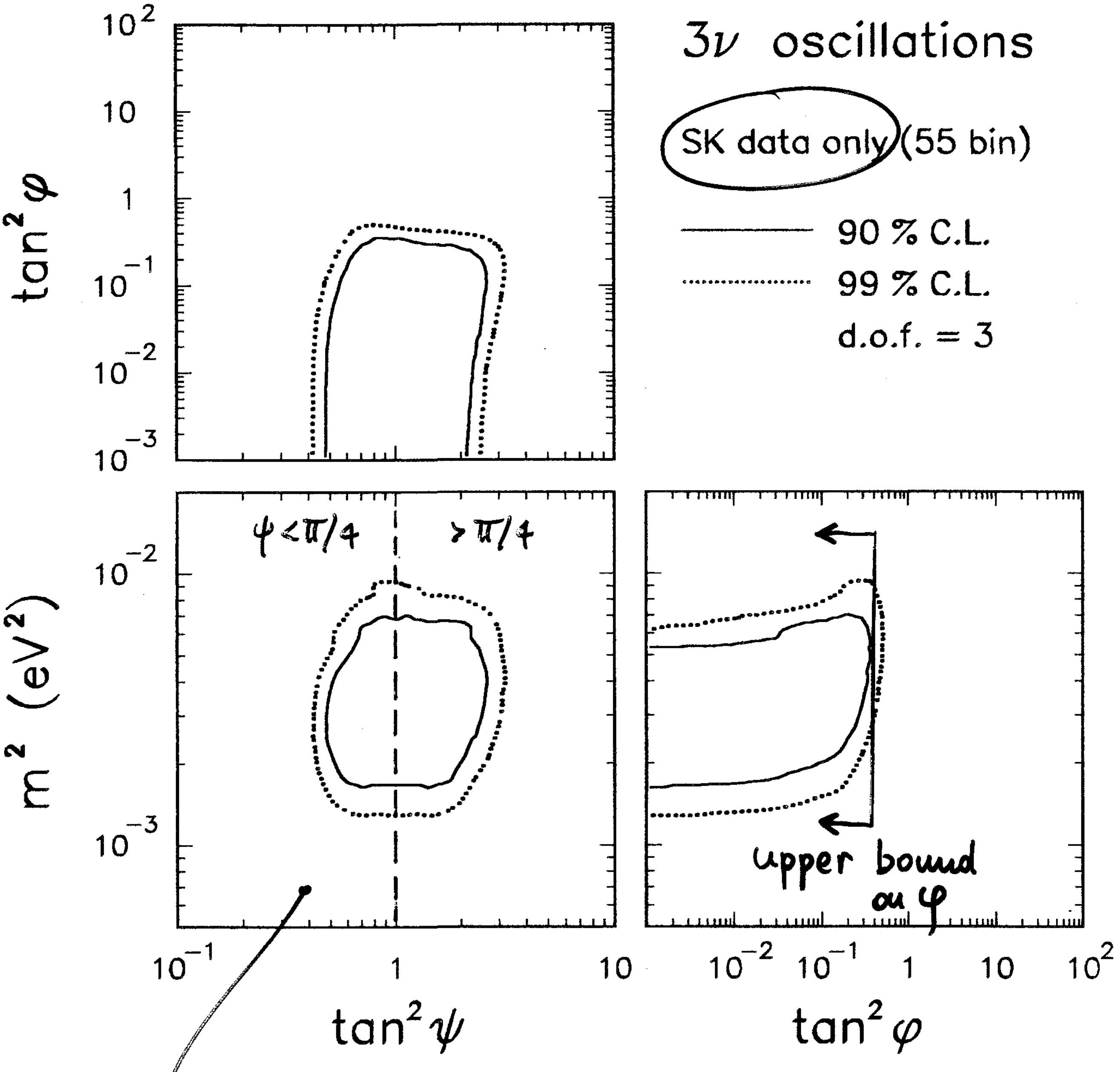
... expand in log-log plot ...



... add third dimension (m^2)



... AND PROJECT ALLOWED REGION →

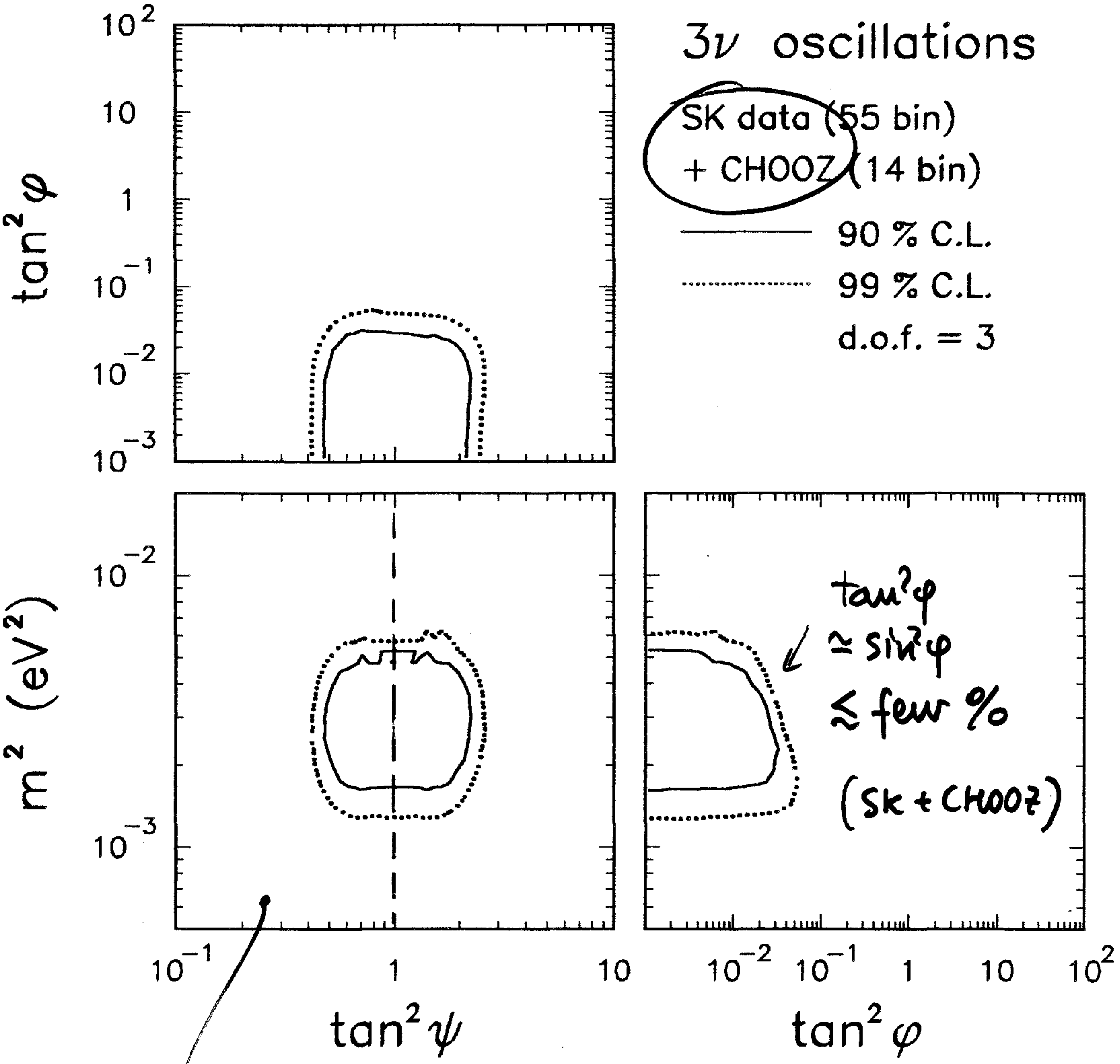


ψ < π/4

> π/4

upper bound on φ

notice octant asymmetry

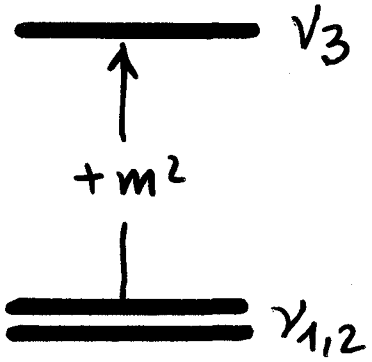


$\tan^2\varphi$
$\simeq \sin^2\varphi$
$\lesssim$ few %
(SK + CHOOZ)

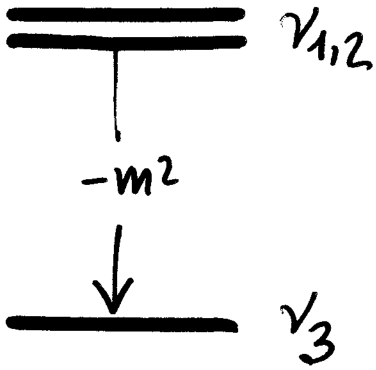
octant asymmetry
strongly reduced
(would vanish for $\varphi=0$)

Remark on mass spectrum:

previous bounds
derived for
spectrum of the kind:
("direct hierarchy")



Bounds ~ identical
for alternative
spectrum (not shown)
("inverse hierarchy")



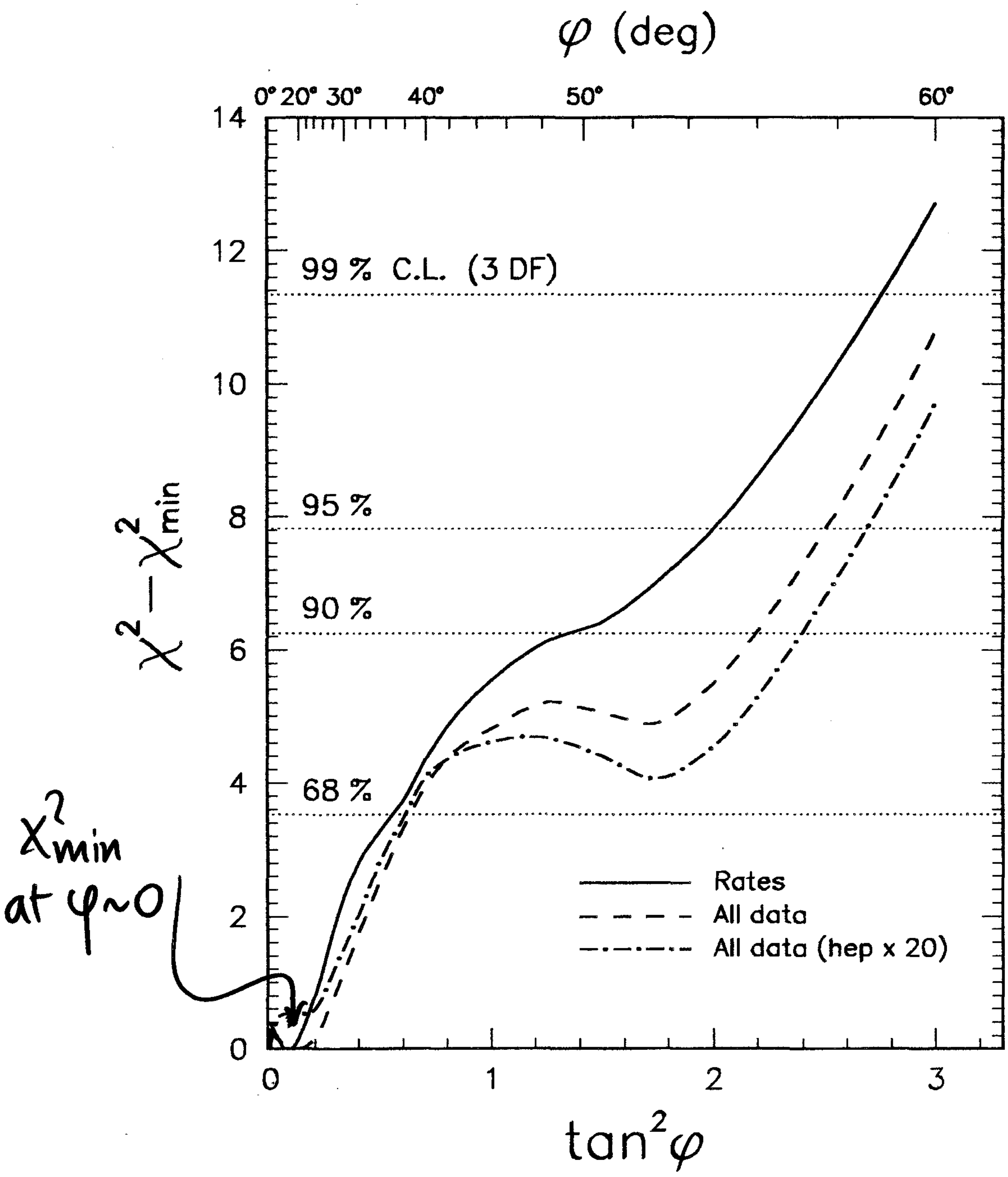
→ present phenomenology does not
discriminate the two spectra
(as far as solar+ terrestrial osc.
experiments are concerned)

SOLAR 3ν OSCILLATIONS

$$P_{ee}^{3\nu}(\text{solar}) = \cos^4\varphi \left(P_{ee}^{2\nu}\right)_{N_e \to N_e c_\varphi^2} + \sin^4\varphi$$

Generic feature : energy dependence (embedded in $P^{2\nu}$)
SUPPRESSED
at large φ

Although evidence for energy dependence is weak in solar neutrino data,
$\varphi \simeq 0$ preferred → remarkable convergence with ATM + CHOOZ data !



δm^2 and $\tan^2\omega$ unconstrained

Small φ preferred by solar ν data alone.

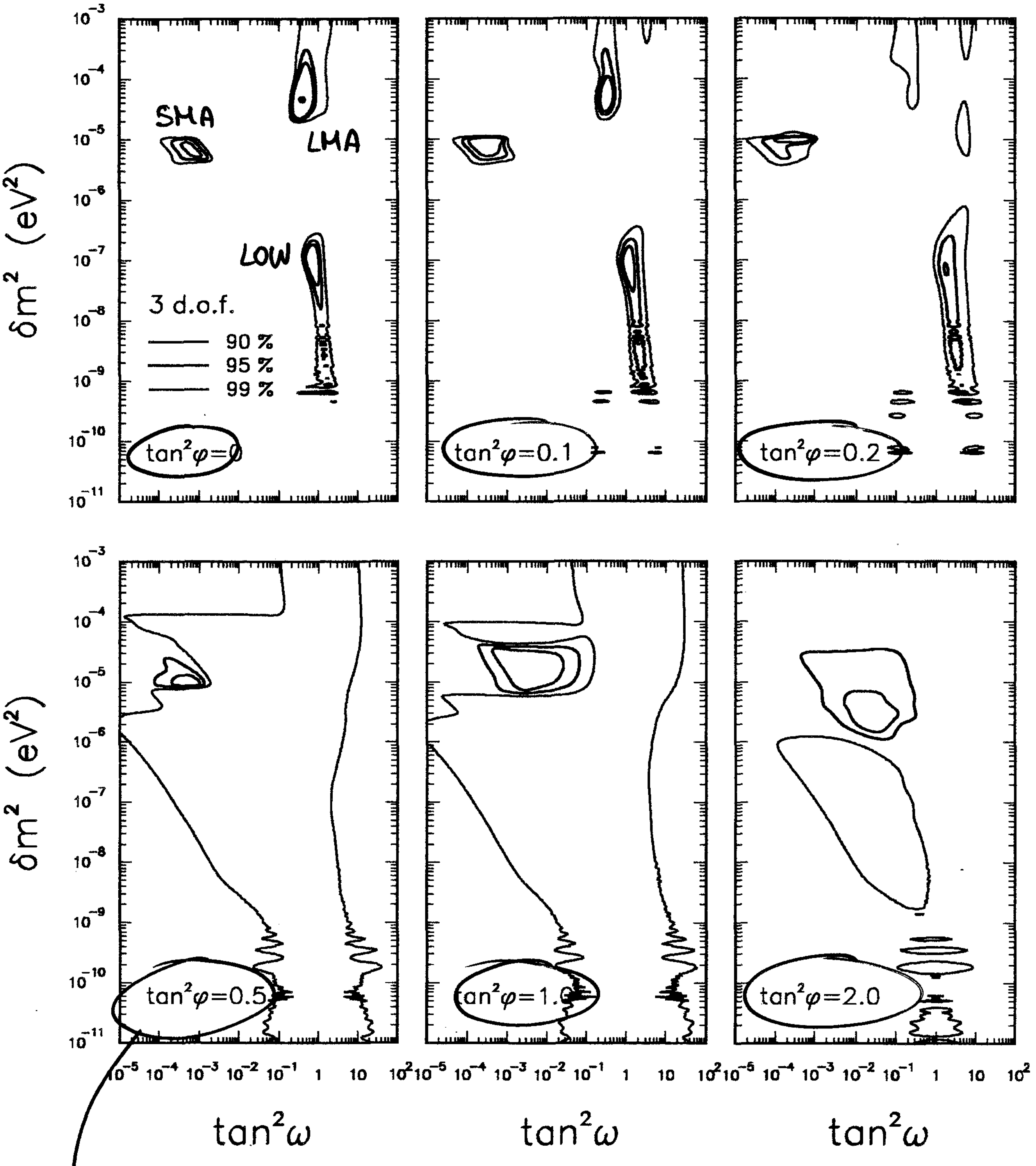
→ consistent with atm. data

→ consistent with CHOOZ.

NONTRIVIAL!

3ν oscillations:

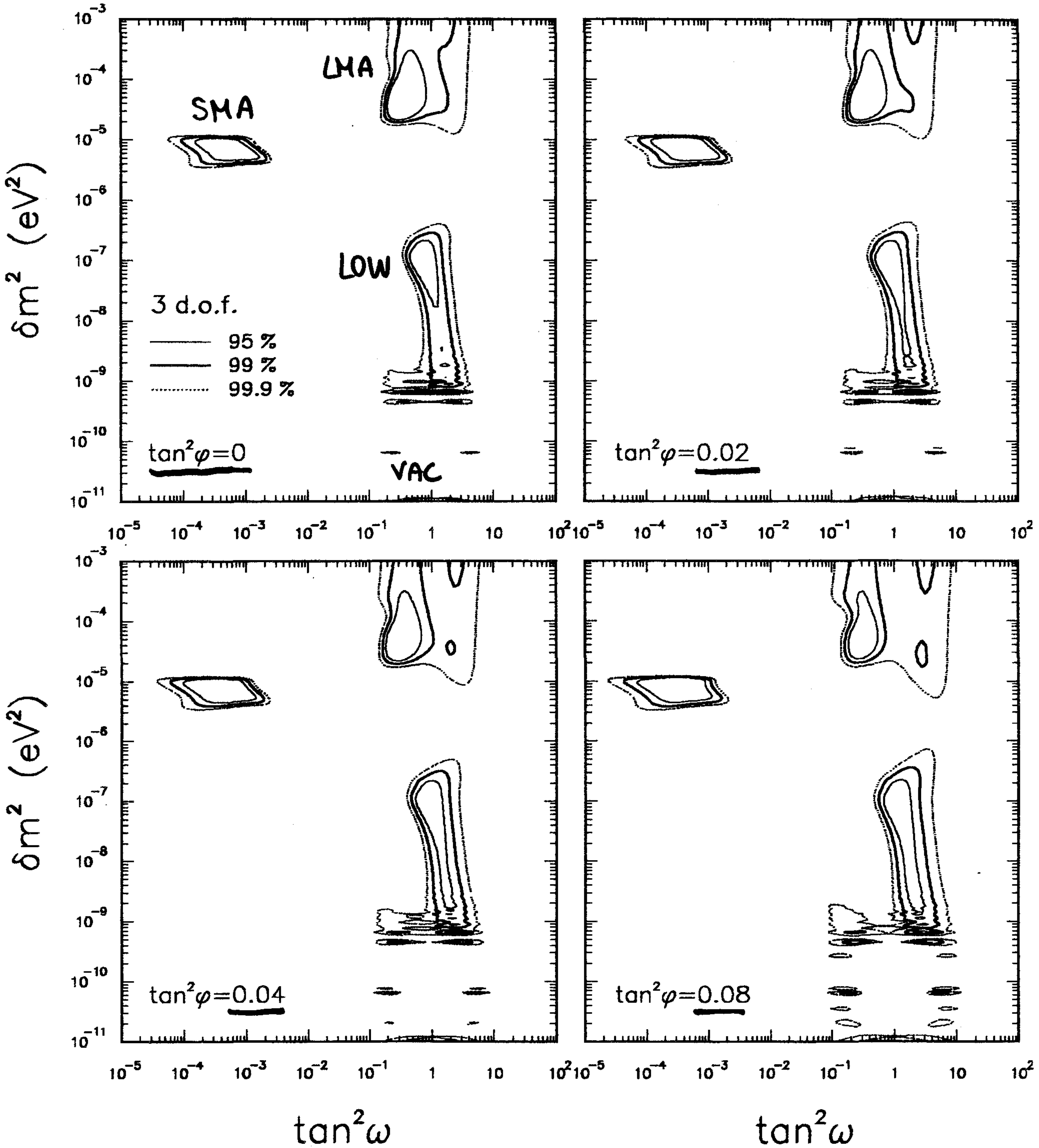
Rates(Cl+Ga+SK) + SP(D) + SP(N)



AT RELATIVELY LARGE VALUES OF φ, USUAL MSW SOLUTIONS PROFOUNDLY MODIFIED, BUT....

3ν solar oscillations

Rates(Cl+Ga+SK) + SP(D) + SP(N)



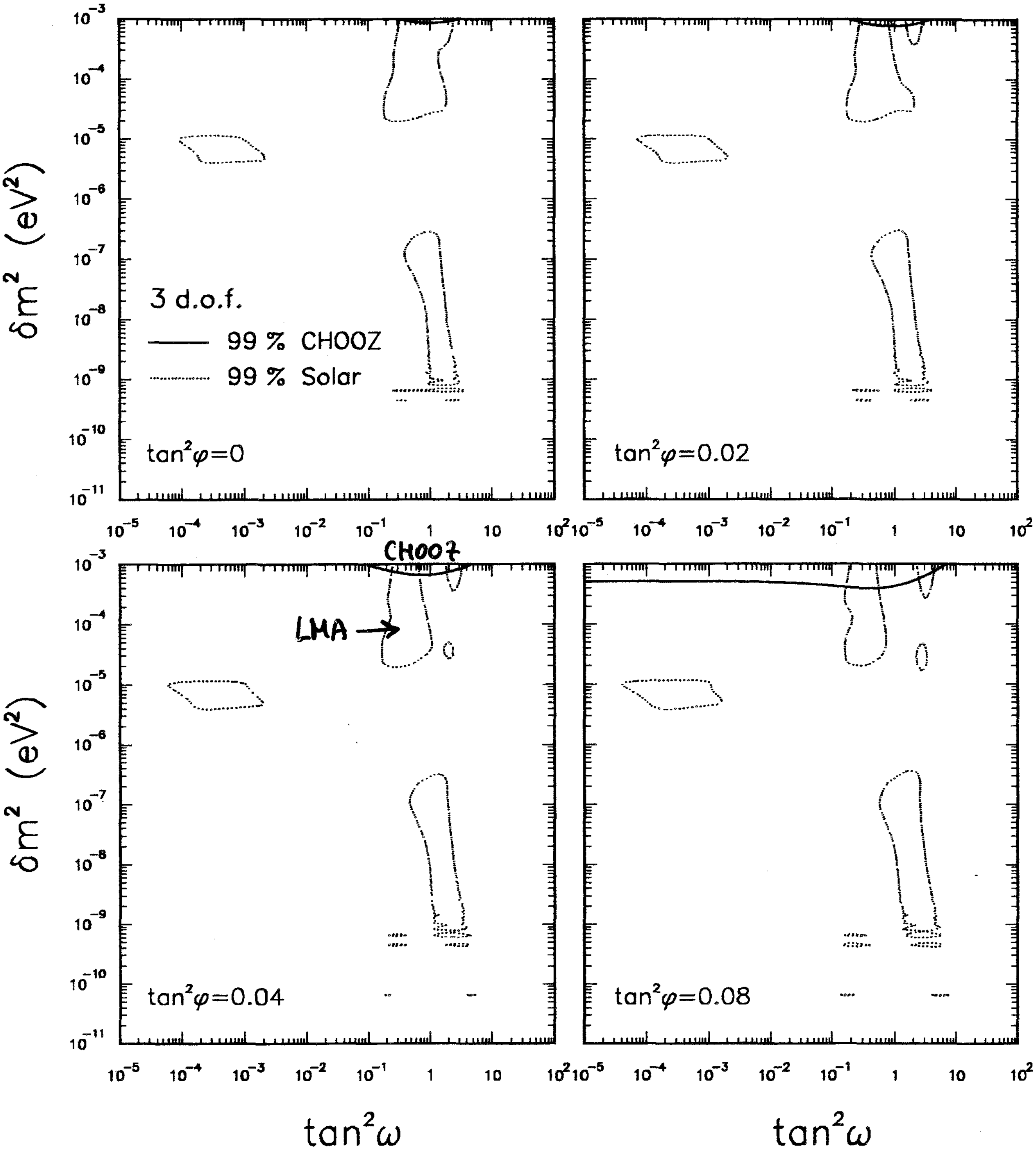
... milder modifications for $U_{e3}^2 \lesssim$ few %

(CHOOZ bound)

N.B.: CHOOZ also cuts upper part of LMA region

3ν oscillations:

CHOOZ excluded regions $(m^2 = +1.5\mathrm{x}10^{-3}\ \mathrm{eV}^2)$

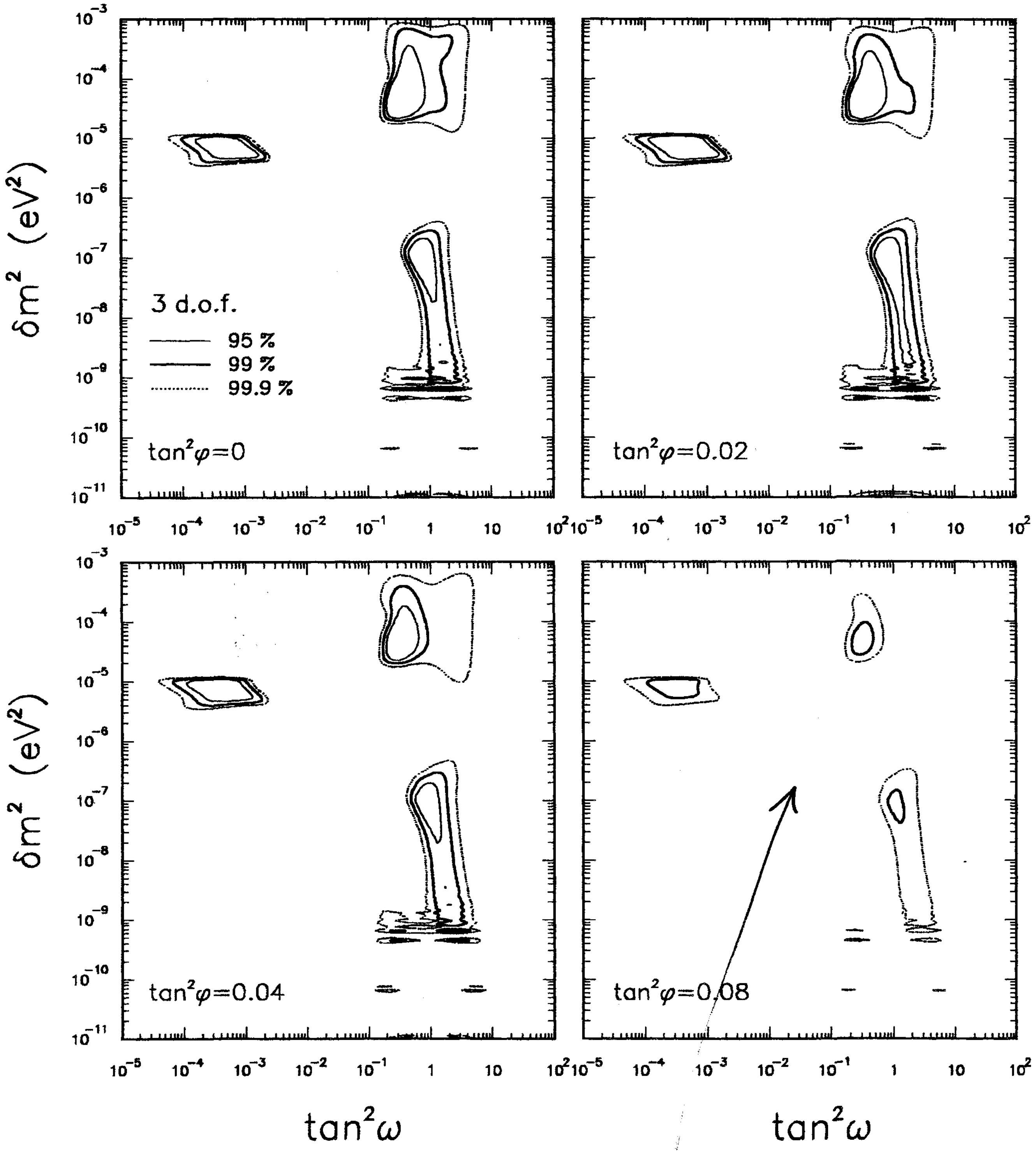


→

Final combination :

3ν oscillations:

SOLAR + CHOOZ ($m^2 = 1.5\mathrm{x}10^{-3}$ eV^2)



non-negligible effect only at the largest possible values of φ (allowed by CHOOZ)

3ν : GRAND TOTAL

$\boxed{\delta m^2 \quad U^2_{e1} \quad U^2_{e2}}$ $\boxed{U^2_{e3}}$ MUST BE $\lesssim$ few %

Depend on chosen solar ν solution:

δm^2 decr. ↓

LMA : $U^2_{e2} \lesssim U^2_{e1}$

SMA : $U^2_{e1} \sim 1$

LOW VAC : $U^2_{e1} \sim U^2_{e2}$

$\boxed{U^2_{\mu 3} \quad U^2_{\tau 3}}$ — must be $U^2_{\mu 3} \sim U^2_{\tau 3}$ within factor of two

$\boxed{m^2}$ — must be $\sim 3 \times 10^{-3}\,eV^2$ within factor of two

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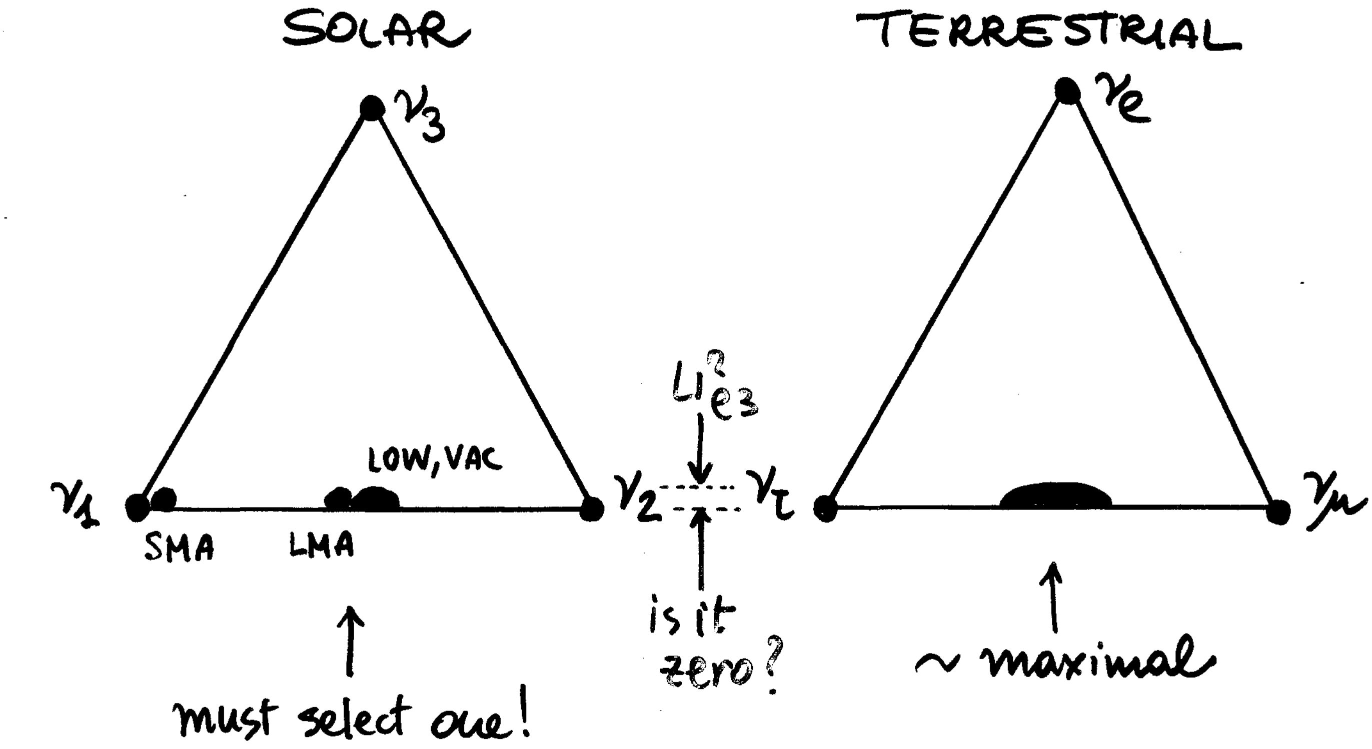
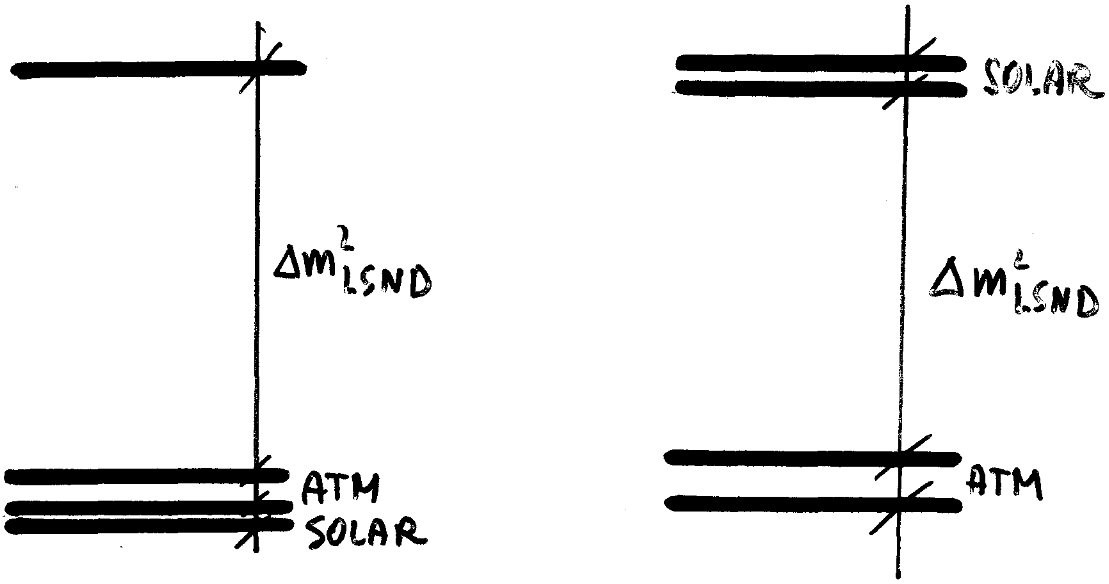


4ν oscillations

SOLAR
+ATM
+LSND

$$\underset{\substack{\uparrow \\ < 10^{-3} eV^2}}{\Delta m^2_{solar}} \ll \underset{\substack{\uparrow \\ \sim 3\times 10^{-3} eV^2}}{\Delta m^2_{atmos.}} \ll \underset{\substack{\uparrow \\ \sim \mathcal{O}(1\, eV^2)}}{\Delta m^2_{LSND}}$$

→ TWO POSSIBLE FAMILIES OF SPECTRA:

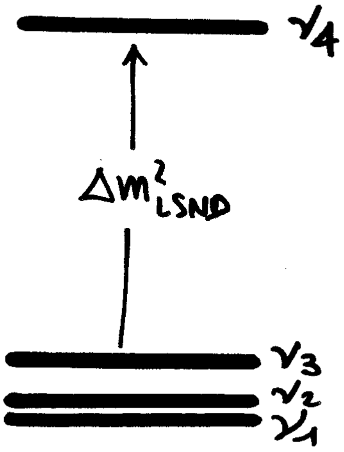


(+ spectra with $\Delta m^2_{ij} \to -\Delta m^2_{ij}$ etc.)

↑ **"<u>3+1</u>"**

↑ **"<u>2+2</u>"**

3+1 schemes



← The "lone" state ν_4 must be very close to a flavor eigenstate because:

(i) LSND oscillation $P_{\mu e}$ is small

and (ii) all other acc/reac expt. find $P_{\alpha\beta} \simeq 0$ at Δm^2_{LSND} scale

$\nu_4 \simeq \nu_e$?

NO, otherwise $P_{ee}(\text{solar}) \simeq 1$ and no explanation of solar ν deficit

$\nu_4 \simeq \nu_\mu$?

NO, otherwise $P_{\mu\mu}(\text{atm}) \simeq 1$ and no explanation of atm. ν

$\nu_4 \simeq \nu_\tau$?

NO, otherwise for atm. ν: $\nu_\mu \to \nu_e \oplus \nu_s$ with strong (unobserved) matter effects

$\nu_4 \simeq \nu_{\text{sterile}}$?

OK, since then (ν_1, ν_2, ν_3) are ~ linear combinations of $(\nu_e, \nu_\mu, \nu_\tau)$ $\simeq 3\nu$ osc.!

GOOD, BUT...

... if $\nu_4 \simeq \nu_s$ then :

- $U_{4s}^2 \simeq 1$
- U_{4e}^2 and $U_{4\mu}^2$ <u>both</u> small
  (since $U_{4e}^2 + U_{4\mu}^2 + U_{4\tau}^2 + U_{4s}^2 = 1$)

$$\rightarrow P_{\mu e}(\text{LSND}) \cong 4 \underbrace{U_{4e}^2 U_{4\mu}^2}_{\text{doubly suppressed}} \sin^2\left(\frac{\Delta m_{\text{LSND}}^2 \cdot L}{4E}\right)$$

doubly suppressed ; too small!

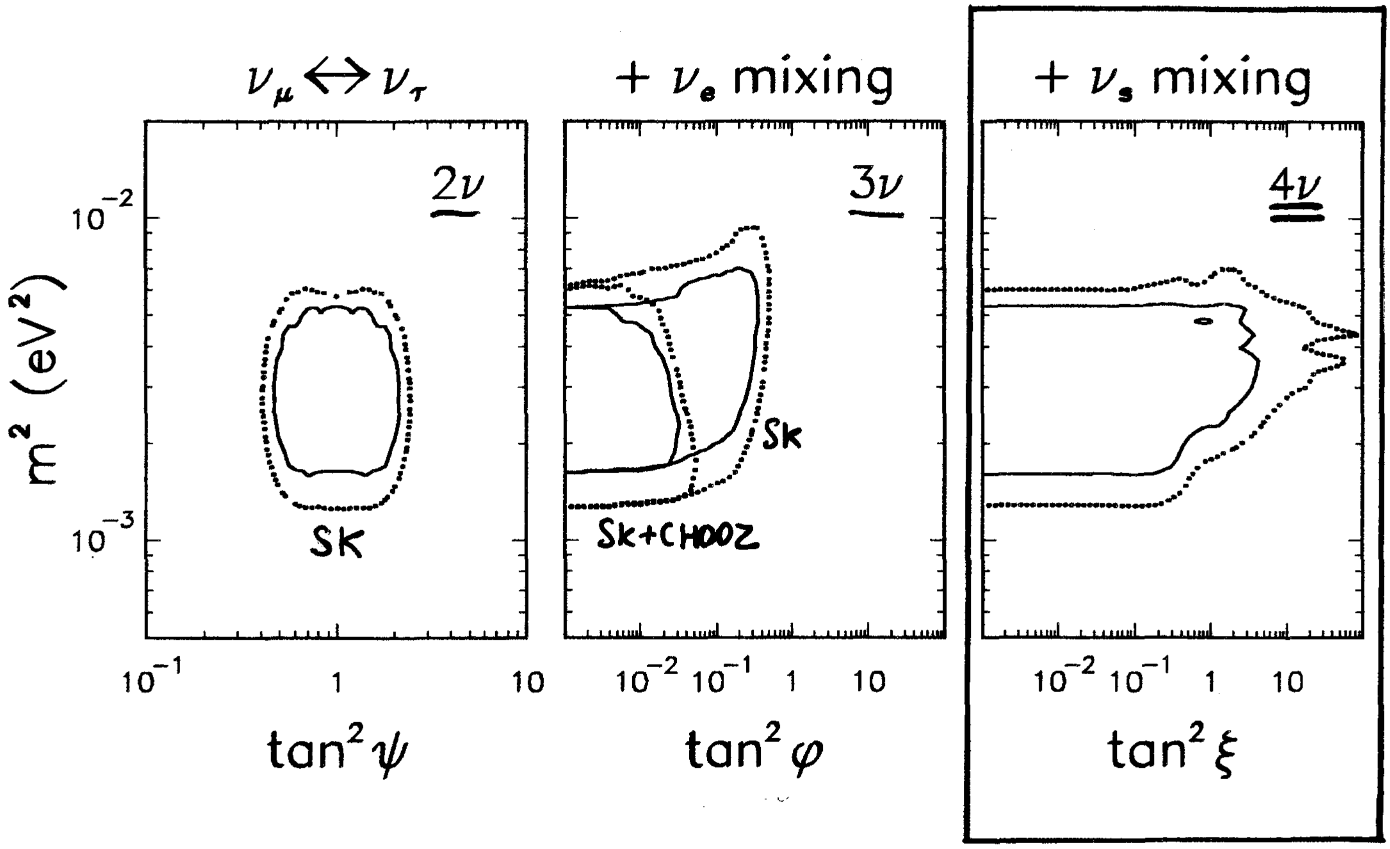
Quantitative analyses show that, including ν_e disappearance results (reactors) and ν_μ disappearance searches (accelerators) the value of $U_{4e}^2 \cdot U_{4\mu}^2$ is too small to fit the LSND data (at $\sim 3\sigma$ level)

→ "TENSION" between LSND (appearance) and reactor + accelerator (disappearance) experiments at $\sim 3\sigma$ in 3+1 SCHEMES

ATMOSPHERIC ν :

- Best fit reached for $\xi \simeq 0$ (~ pure $\nu_\mu \to \nu_\tau$)
- Using only zenith distrib. in SK, large ξ allowed

4ν analysis



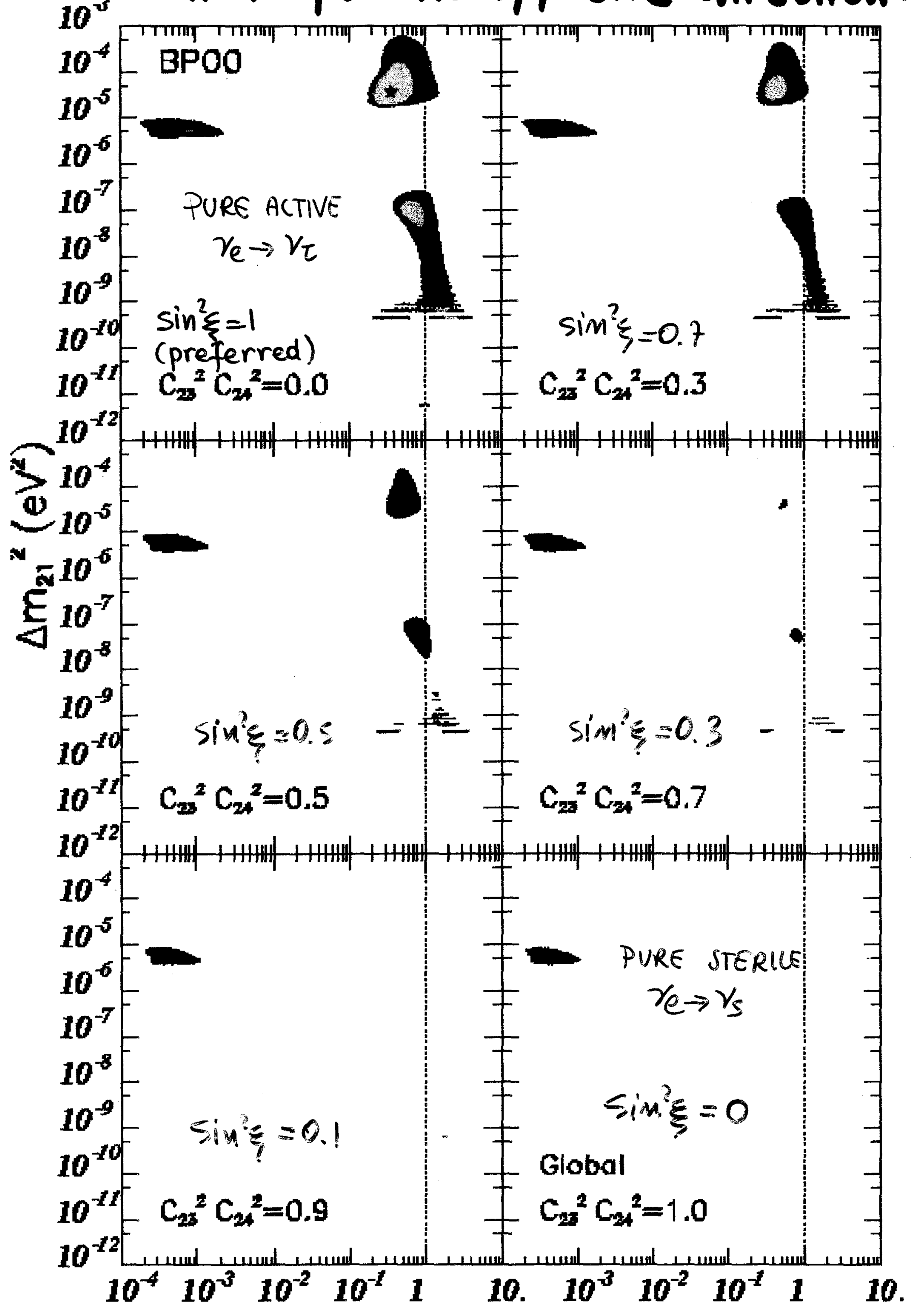
$\nu_\mu \to$ 50% ν_s + 50% ν_τ
allowed ($\tan^2\xi = 1$)

However, there are more data AGAINST additional $\nu_\mu \to \nu_s$ (on top of $\nu_\mu \to \nu_\tau$) :

- NC-enriched samples in SK
- "τ-like" event appearance
- MACRO data

→ TOTAL COMBINATION LIKELY TO GIVE $\sin^2\xi \lesssim 0.3$

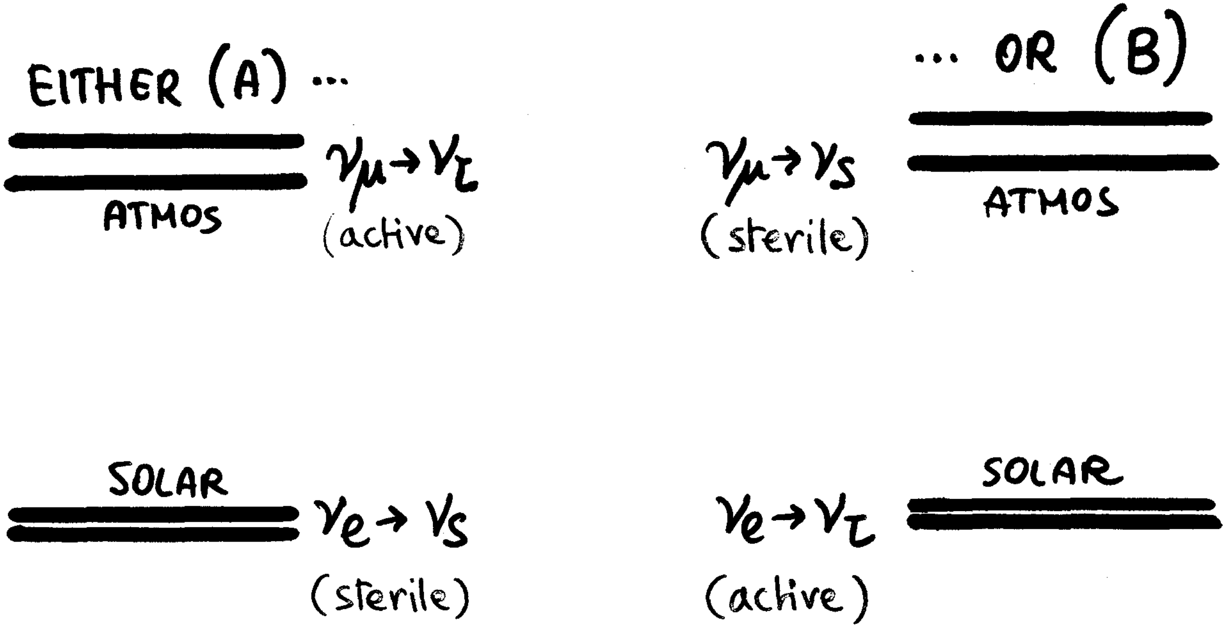
Solar ν pull in opposite direction…



(Giunti, Gonzalez-Garcia, Peña-Garay)

2+2 schemes

It was often assumed:



+ perturbations (needed to get $P_{\mu e}$ (LSND) $\neq 0$)

HOWEVER, THE ABOVE CASES ARE SUB-CASES OF A MORE GENERAL SITUATION:

ATMOS.: $\nu_\mu \to \nu_+$

SOLAR: $\nu_e \to \nu_-$

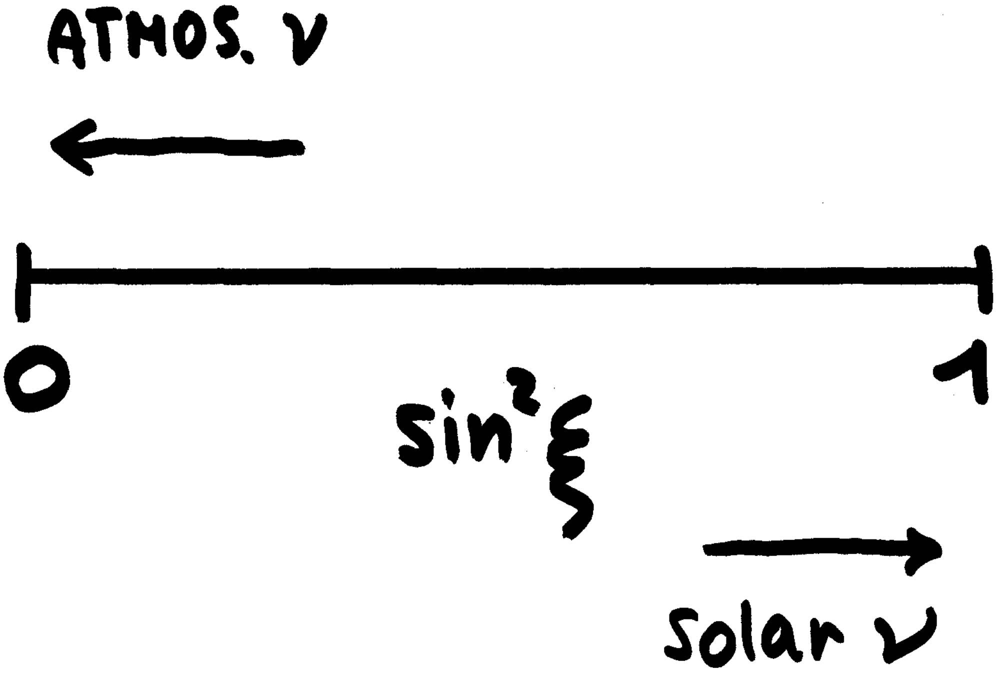
$$\begin{bmatrix} \nu_+ \\ \nu_- \end{bmatrix} = \begin{bmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{bmatrix} \begin{bmatrix} \nu_\tau \\ \nu_s \end{bmatrix}$$

→ mixed active + sterile oscillat.

get (A) for $\sin\xi = 0$

get (B) for $\sin\xi = 1$

WHAT HAPPENS FOR GENERIC ξ ?



"TENSION" BETWEEN ATMOSPHERIC AND SOLAR ν DATA IN 2+2 SCHEMES (PULL ξ IN DIFFERENT DIRECTIONS)

MAYBE TOO EARLY TO RULE OUT 2+2, BUT CERTAINLY NOT A GOOD FEATURE....

4ν summary :

- Sterile ν introduced to accommodate LSND (with solar + atm)
- Two possible mass spectra : 3+1 & 2+2
- However, in 3+1 :
  accelerator + reactor data do not converge with LSND data
- ... and in 2+2 :
  solar and atm. ν data do not converge
- Moreover, independent <u>BBN</u> data (see talk by K. Olive) prefer $N_\nu \sim 3$ rather than $N_\nu \sim 4$

Maybe too early for a definitive "no-go theorem", but life is getting hard for the sterile neutrino...

ABSOLUTE ν MASSES

Present β-decay and oscillation data already put some upper/lower bounds on the sum of ν masses $\sum_i m_{\nu_i}$:

- $\sum m_\nu$ cannot be smaller than $\sqrt{\Delta m^2_{atm}} \simeq 0.05$ eV
- Since all $\Delta m^2_{ij} \lesssim 1 \, eV^2$, and since "$m_{\nu_e}$" $\lesssim$ few eV from β-decay, also $\sum m_\nu \lesssim (N_\nu \cdot \text{few})$ eV

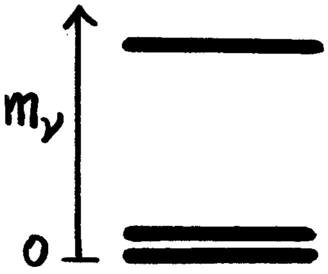
$$\downarrow$$

$$\boxed{0.05\,\text{eV} \lesssim \sum m_\nu \lesssim \mathcal{O}(10)\,\text{eV}}$$

for $N_\nu \sim 3,4$

Still, too many possible spectra allowed in this range...

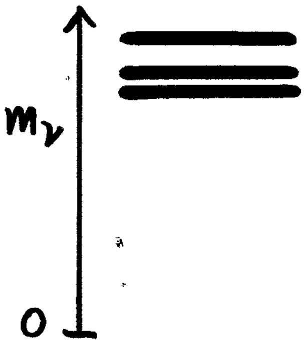
One would like to distinguish, e.g.,



$$\rightarrow \mathcal{M} \propto \begin{bmatrix} 0 & & \\ & 0 & \\ & & 1 \end{bmatrix} + \text{corrections}$$

(hierarchical)

from:



$$\rightarrow \mathcal{M} \propto \begin{bmatrix} 1 & & \\ & 1 & \\ & & 1 \end{bmatrix} + \text{corrections}$$

(degenerate)

E.g., for bimaximal mixing:

$$U(\varphi, \omega, \psi) = U\left(0, \frac{\pi}{4}, \frac{\pi}{4}\right) = \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & +\frac{1}{2} & \frac{1}{\sqrt{2}} \\ 1/2 & -1/2 & 1/\sqrt{2} \end{bmatrix}$$

$$\text{hierarchical} \longrightarrow U \mathcal{M} U^{+} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 1/2 & 1/2 \\ 0 & 1/2 & 1/2 \end{bmatrix}$$

different textures

$$\text{degenerate} \longrightarrow U \mathcal{M} U^{+} = \begin{bmatrix} 1 & & \\ & 1 & \\ & & 1 \end{bmatrix}$$

TEXTURES → UNDERLYING SYMMETRIES (G. Ross lectures)

→ need to refine info on absolute masses

CONSTRAINTS FROM $0\nu 2\beta$

- Present bounds: $\langle m_{ee} \rangle \lesssim$ few $\times 10^{-1}$ eV

- Consider, e.g., 3ν degenerate spectrum with bimaximal mixing; then:

$$\langle m_{ee} \rangle = \Big| \sum_i m_i e^{i\phi_i} U_{ei}^2 \Big|$$

$$\simeq m \Big| \sum_i e^{i\phi_i} U_{ei}^2 \Big|$$

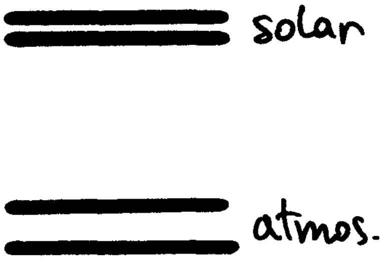
$$\overset{U_{e3}^2 \simeq 0}{\simeq} m \Big| U_{e1}^2 + U_{e2}^2 e^{i(\phi_2 - \phi_1)} \Big|$$

If m assumed to be relatively large ($\sim O(1)$ eV), the experimental bounds can be satisfied only if $e^{i(\phi_2-\phi_1)} \simeq -1$ (destructive interference of ν_1 and ν_2 contrib. in $0\nu 2\beta$ decay) → get constraints on Majorana phases

---

- However, if m large but solution is SMA (for solar ν problem) then $U_{e1}^2 \simeq 1$ and $\langle m_{ee} \rangle \simeq m$ unavoidably
  → excluded if $m \gtrsim$ few $\times 10^{-1}$ eV independ. on Majorana phases (interesting!)

Similar arguments apply to the case of 2+2 spectrum in 4ν scenarios:



If solar doublet "heavy", then solar ν solution cannot be SMA, otherwise dominant contribution to $\langle m_{ee} \rangle$ CANNOT be canceled

CLEARLY, IF $\langle m_{ee} \rangle$ UPPER LIMIT CAN BE REDUCED BY AN ORDER OF MAGNITUDE (GENIUS PROPOSAL), THEN ONE WILL PROBE CONTRIBUTIONS TO $\langle m_{ee} \rangle$ OF SIZE $\sim \sqrt{\Delta m^2_{atm}}$, AND CANCELLATIONS WILL BE MUCH MORE CONSTRAINED

→ WILL THEN LEARN A LOT ABOUT POSSIBLE MASS SPECTRA

ν mass & cosmology

- Oldest cosmological bound :

$$\sum_i m_i \lesssim 92\, h^2\, eV^2$$

to avoid overabundance of relic ν ($\Omega_\nu = 1$ if bound is saturated)

- However, well before the above bound is saturated, neutrino masses can alter the properties of
    - DARK MATTER
    - STRUCTURE FORMATION

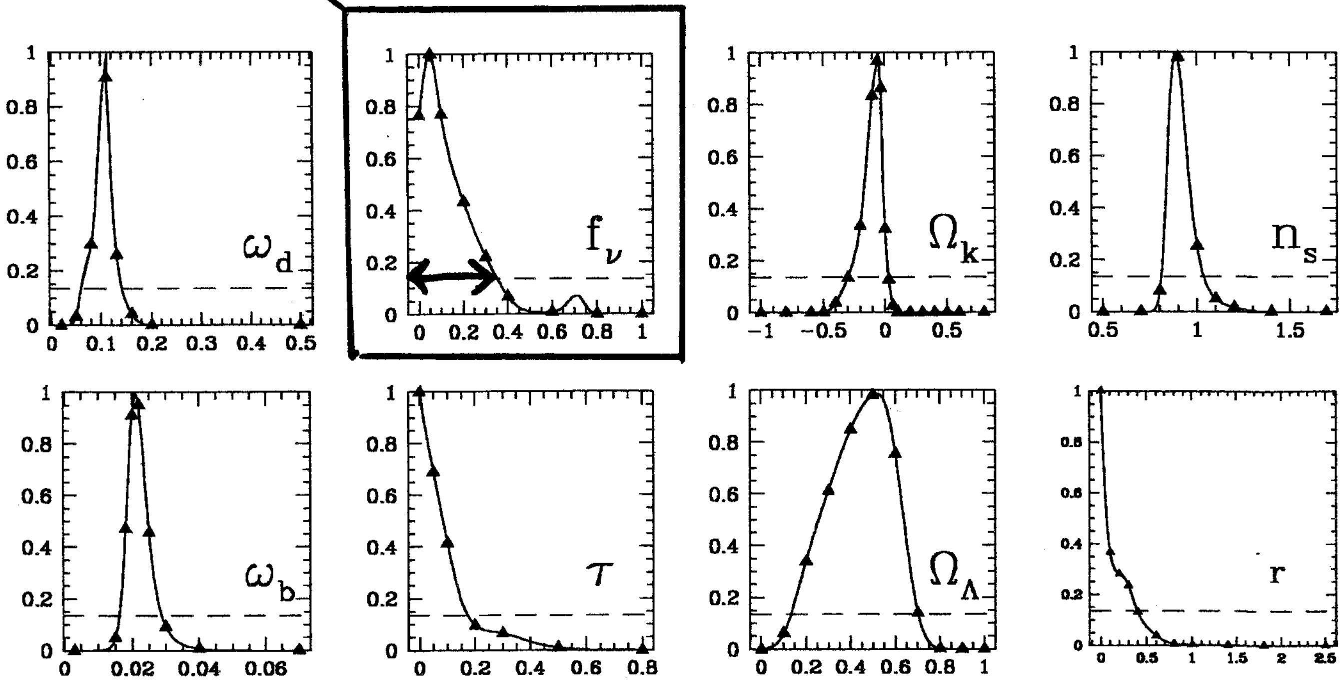
- Many effect contribute to dark matter and s.f. properties, so indications are somewhat indirect and come from multiparametric fits to cosmological/astrophysical data, now made possible by "explosion" of observational data

Wang, Tegmark, Zaldarriaga

E.g., 11-parameter fit results including

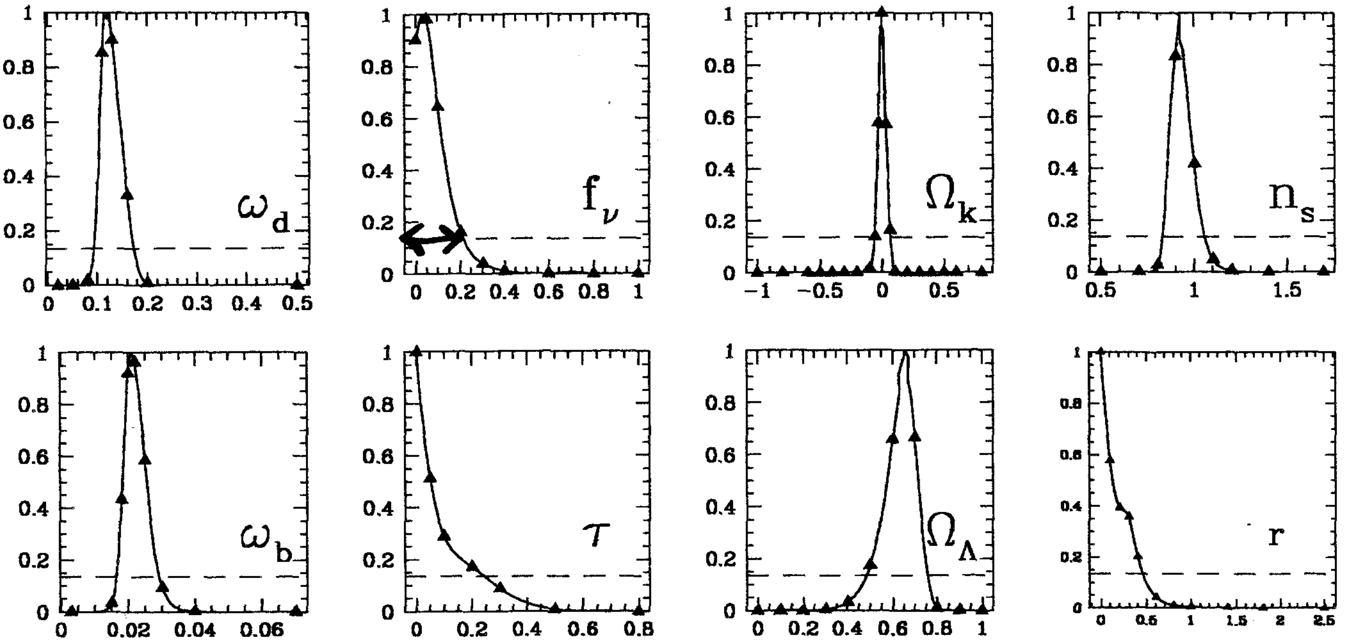
$f_\nu = \frac{\Omega_\nu}{\Omega_{DM}}$ = "fraction of hot D.M."

$\leftrightarrow$ = 95% C.L. range for f_ν



- UPPER BOUND $f_\nu \lesssim 0.35$
- No significant evidence for $f_\nu > 0$

as before, but with prior $h = 0.74 \pm 0.08$



→ in any case, f_ν preferred to be small

→ $\sum m_{\nu_i} \lesssim 4.4$ eV

↰ interestingly close
to laboratory limits

RECAP

- Solar + atm + CHOOZ data fit nicely a 3ν oscillation scheme (convergence of all data towards U_{e3}^2 small)

  Main unknowns:
  - Is $U_{e3}^2 \neq 0$?
  - Solution to solar ν problem?
  - Spectrum hierarchy?
  - .....

- 4ν scheme do not accommodate easily solar + atm + LSND data, either in 3+1 or in 2+2 schemes. Need to monitor "tension" between data with future observ.

- Present absolute ν mass indications already tell us a few interesting facts; however, decisive probes of the spectrum structure require sensitivity as low as

$$\sqrt{\Delta m^2_{atm}} \sim 5 \times 10^{-2} \text{ eV}$$

→ goal of future experiments