NO-VE Workshop

Venice, July 24th, 2001

# Impact of SNO on Solar Neutrino Oscillations

GLF

Step 1: model independent analysis (no assumption made)

Step 2: assume no $\nu_e \rightarrow \nu_s$ (only active neutrinos)

Step 3: assume $2\nu$ active (+ comments on $\nu_s$)

Step 4: assume $3\nu$ active

Conclusions

Talk prepared with the collaboration of
E. Lisi, D. Montanino and A. Palazzo

# Step 1

Tray to get maximum info from the comparison of SK and SNO with no assumption about

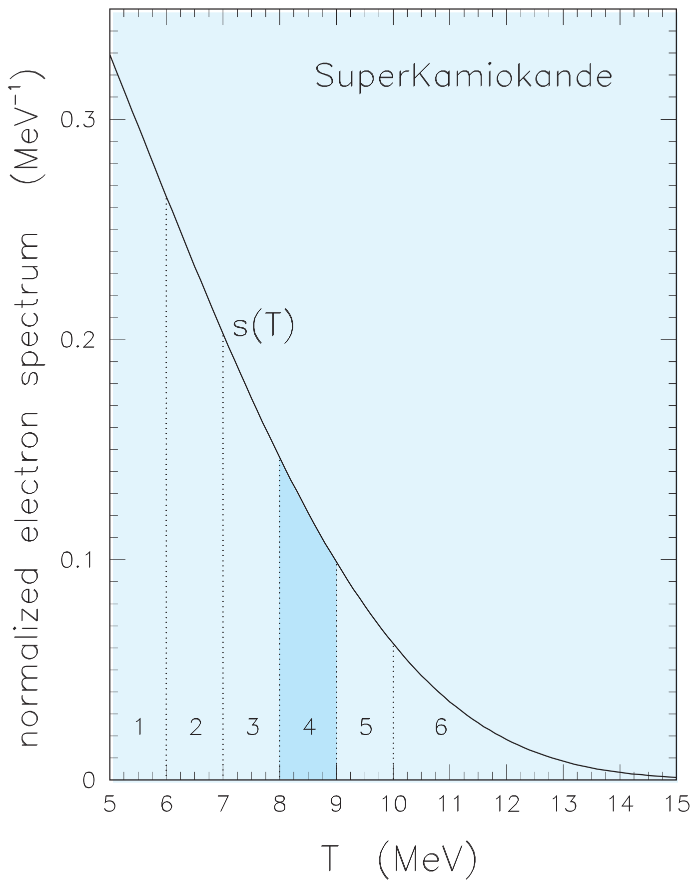
- Absolute $^{8}$B flux: we take $\Phi_B^{SSM} \rightarrow f_B \, \Phi_B^{SSM}$

  with $f_B$ free parameter

- Possible existence of $\nu_s$

- Functional shape of $P_{ee}(E_\nu)$

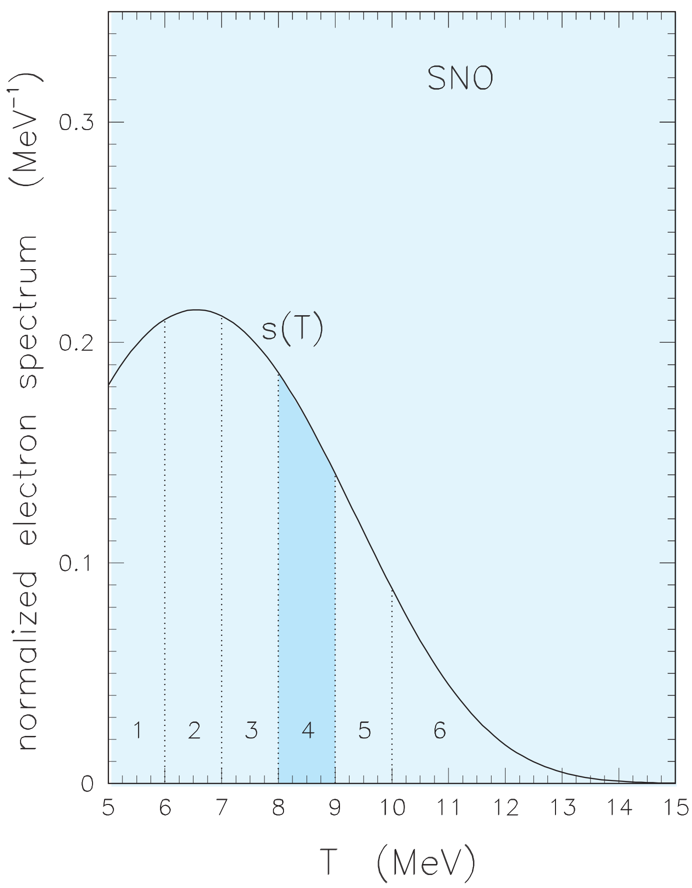
# Comparing expected SK and SNO energy spectra




SK absolute electron energy spectrum

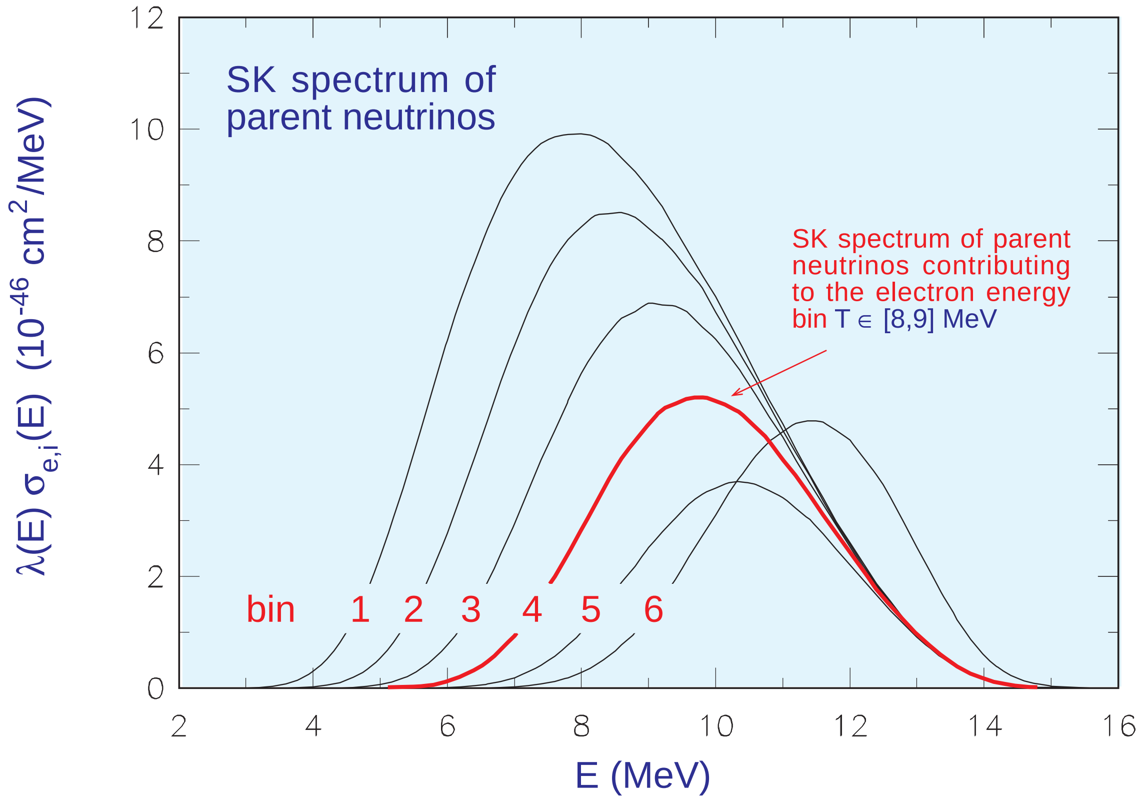
B. Faid, G.L. Fogli, E. Lisi and D. Montanino, PRD 55 (1997) 1353

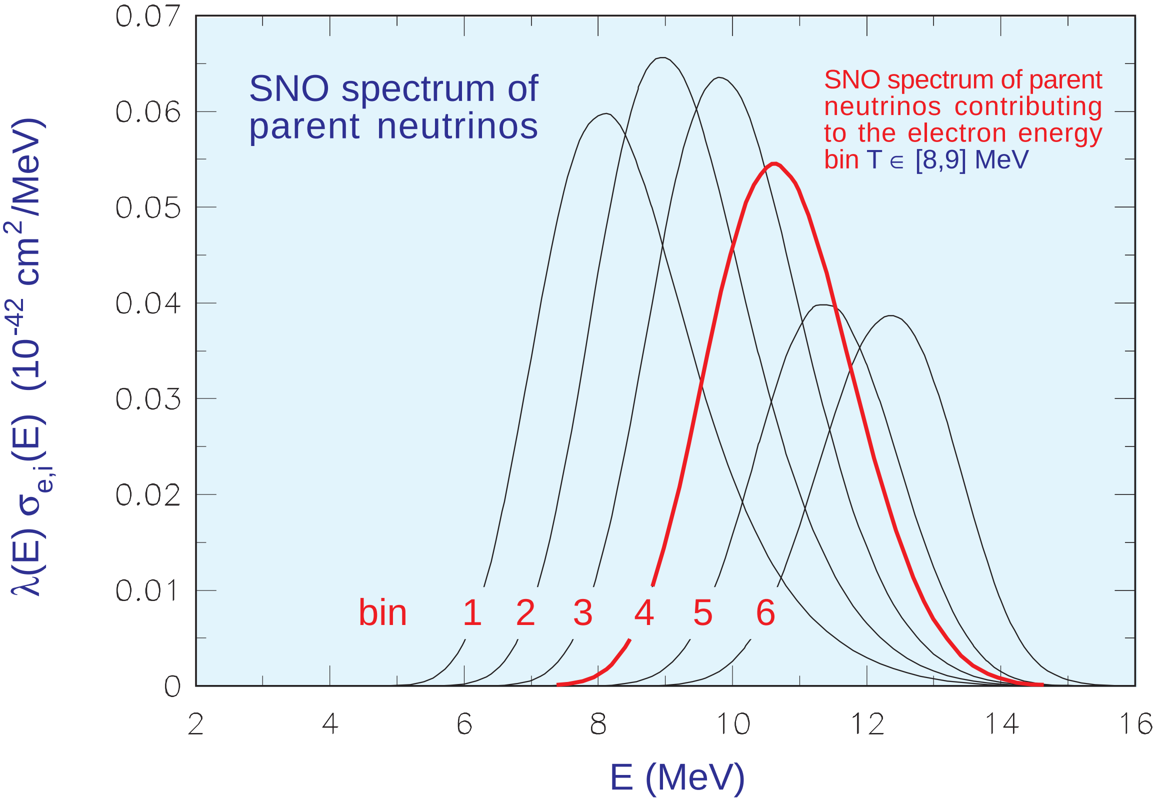
SNO absolute electron energy spectrum




not only the two absolute electron energy spectra are different ...

but also the spectra of the parent neutrinos contributing to a specific electron energy bin are different ...



this means that SK and SNO probe the $^{8}$B neutrino spectrum with different sensitivities

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different "response functions"

PROBLEM

How can we compare SK and SNO directly?

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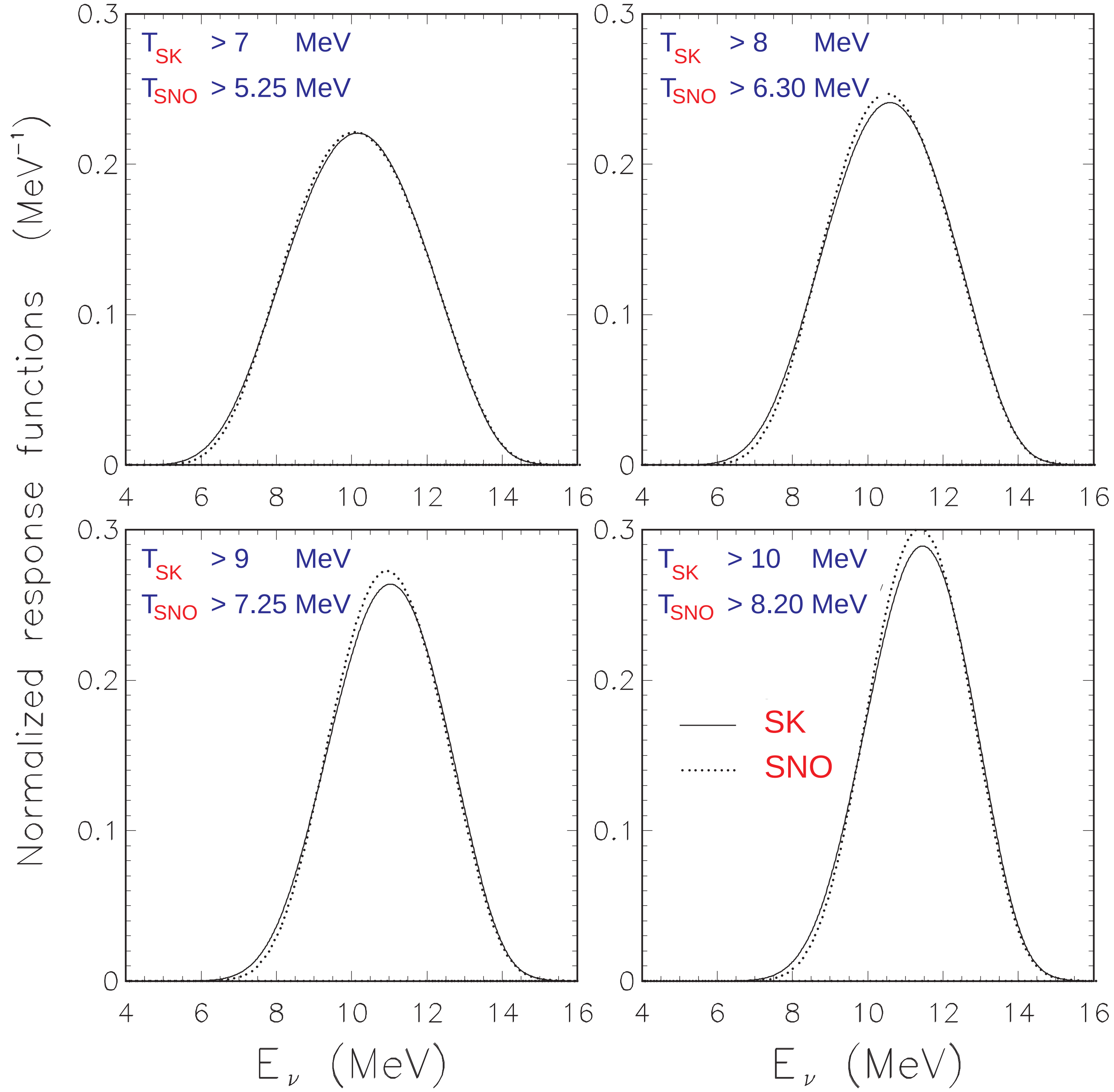
SOLUTION

It turns out that the response functions can be equalized, to a very good level of approximation, by appropriately shifting the threshold of the SK (or SNO) electron energy

# Comparing SK and SNO response functions



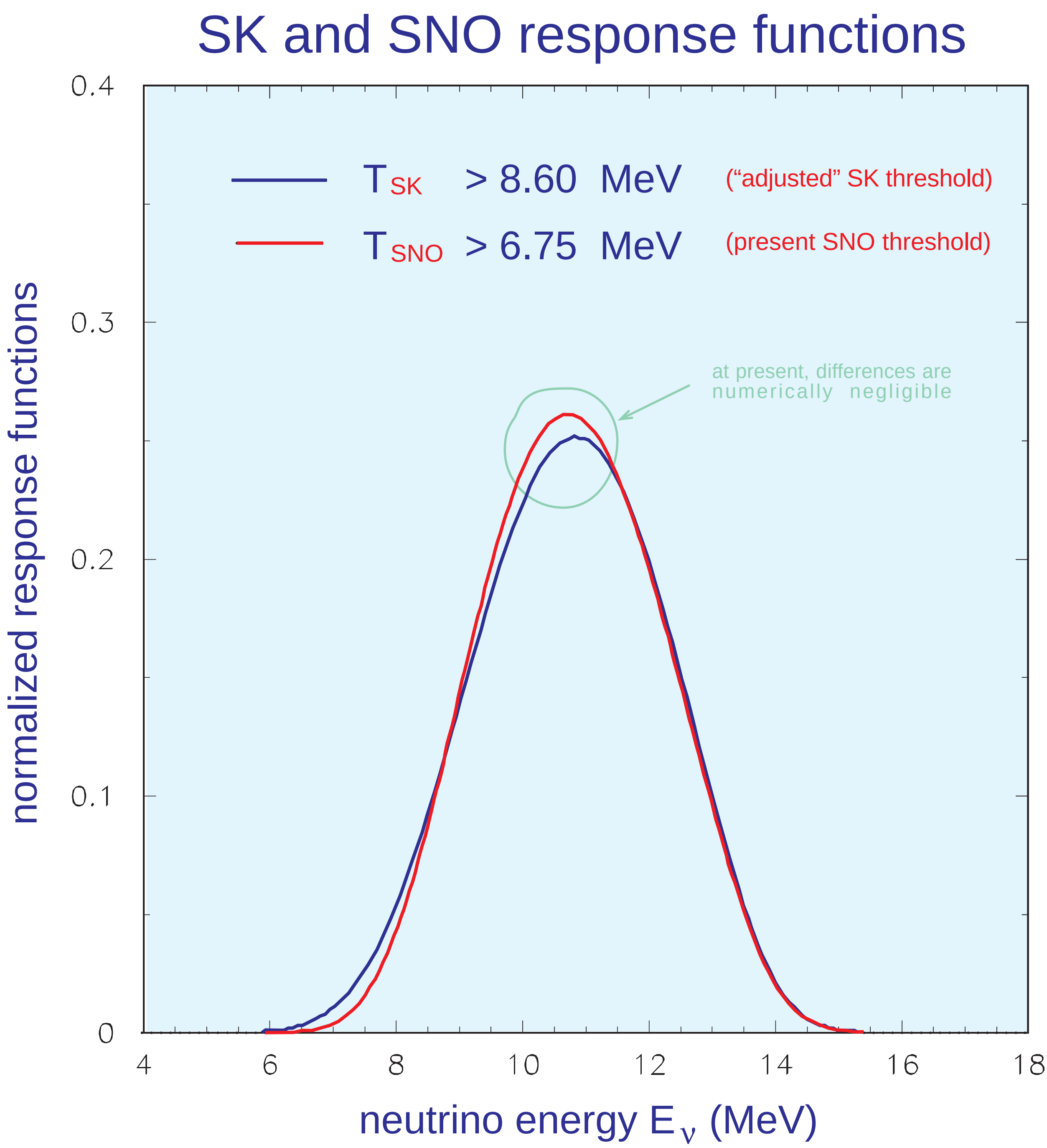

SK and SNO spectra of parent neutrinos approximately equalized for an appropriate choice of the electron energy thresholds

pre-SNO study of the SK-SNO equalization:

F. Villante, G. Fiorentini, E. Lisi, PRD 59 (1999) 013006
GLF, E. Lisi, A. Palazzo and F. Villante, PRD 63 (2001) 113016

# Present SK-SNO equalization

(using updated SK and SNO detector parameters)




CONSEQUENCE:

If the response functions are equal, it can be rigorously proven that for both SK and SNO (CC) we have the same

$\langle P_{ee} \rangle$ average of $P_{ee}(E_\nu)$ over the SK/SNO response function

Accordingly, we can write

$$\frac{SNO}{SSM} = f_B \langle P_{ee} \rangle$$

$$\frac{SK}{SSM} = \underbrace{f_B \langle P_{ee} \rangle}_{\nu_e \text{ contribution}} + \underbrace{f_B \frac{\sigma_e}{\sigma_a} \langle P_{ea} \rangle}_{\nu_a \text{ contribution}} \qquad a = \mu, \tau$$

where

$f_B$ = free factor multiplying the SSM $^8B$ flux

$\langle P_{ee} \rangle$ = average of $P_{ee}(E_\nu)$ over the response function

$\langle P_{ea} \rangle$ = average of $P_{ea}(E_\nu)$ over the response function

$\sigma_e$ , $\sigma_a$ = properly averaged $\sigma(\nu_e e)$ and $\sigma(\nu_{\mu,\tau} e)$ cross-sections

NOTE: the previous result is independent of the functional form of the various quantities and of the possible existence of the $\nu_s$

On very general ground

$$\frac{\text{SNO}}{\text{SSM}} > \frac{\text{SK}}{\text{SSM}}$$ always forbidden (would imply $\langle P_{ea} \rangle < 0$)

$$\frac{\text{SNO}}{\text{SSM}} = \frac{\text{SK}}{\text{SSM}}$$ allowed only if $\langle P_{ea} \rangle = 0$

$\Downarrow$

no active oscillations $\begin{cases} \text{either no oscillations} \\ \text{or pure } \nu_e \to \nu_s \text{ oscill.} \end{cases}$

$$\frac{\text{SNO}}{\text{SSM}} < \frac{\text{SK}}{\text{SSM}}$$ allowed only if $\langle P_{ea} \rangle > 0$: $\exists$ active oscillations

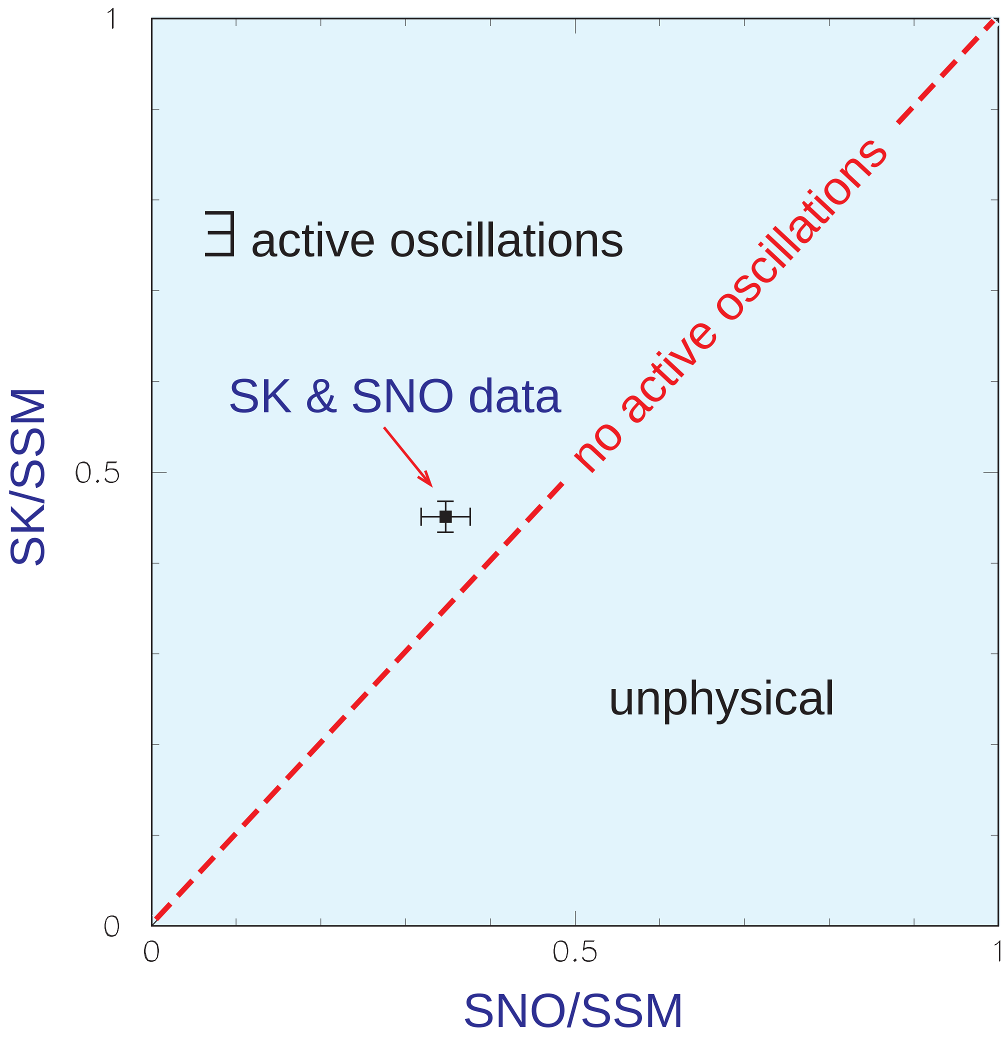
# DATA

$$\frac{\text{SNO}}{\text{SSM}} = 0.347 \pm 0.029$$

$$\frac{\text{SK}}{\text{SSM}} = 0.451 \pm 0.017$$ estimated (by SNO) by "adjusting" the SK threshold

# Pictorial view of SK vs SNO

GLF, E. Lisi, D. Montanino and A. Palazzo, hep-ph/0106247




Data are well within (> 3σ) the region where there must be active oscillations

Conclusion of the step 1:

A model-independent comparison of the solar data of SK and SNO is consistent with a strong indication in favor of active neutrino oscillations

# Step 2

Since active oscillations are demonstrated to occur, let's make a further assumption, i.e.

| there are only active oscillations: $\langle P_{es} \rangle = 0$ |
|---|

It follows

$$\langle P_{ea} \rangle = 1 - \langle P_{ee} \rangle$$

We have

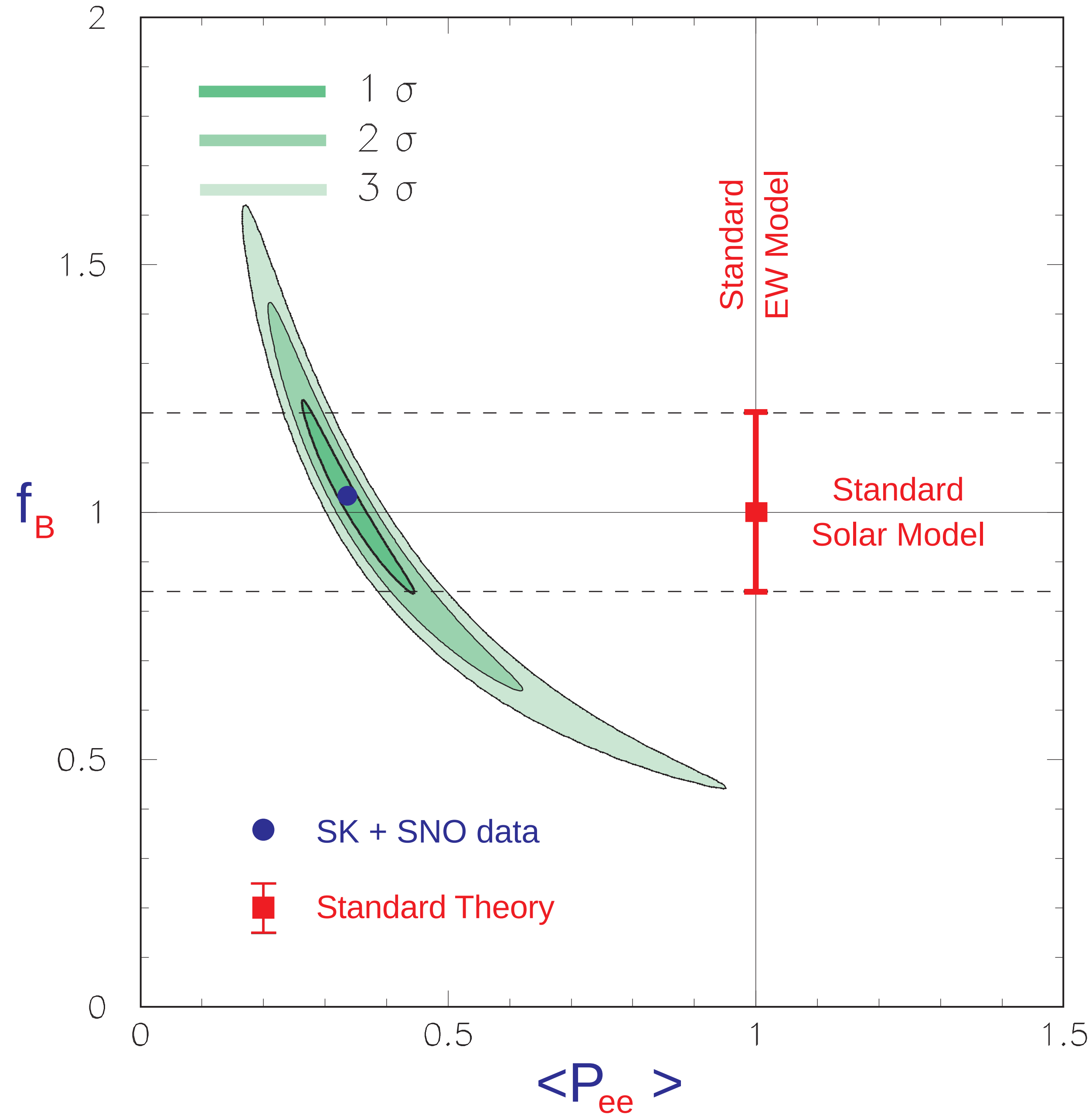
two data: $\frac{SNO}{SSM}$ , $\frac{SK}{SSM}$

two unknows: $f_B$ , $\langle P_{ee} \rangle$

FIT!

# Model-independent analysis of SK and SNO

## under the assumption of only active oscillations




- $f_B$ in agreement with the Standard Solar Model
- $<P_{ee}>$ in disagreement with the Standard EW Model

NOTE: no assumption made on the functional form of $P_{ee}(E_\nu)$

Best fit at $3\sigma$

$$f_B = 1.03^{+0.50}_{-0.58} \qquad <P_{ee}> = 0.34^{+0.61}_{-0.18}$$

In particular

$$<P_{ee}> \sim \frac{1}{3}$$

favors the LMA solution to the solar $\nu$ problem, which predicts such a value for $E_\nu \gtrsim$ few MeV

Conclusion of the step 2:

If active $\nu$ oscillations are assumed, a model-independent comparison of the solar data of SK and SNO is consistent with $\nu$ oscillations and with the SSM at more than $3\sigma$

# Step 3

We have seen that

- active $\nu$ oscillations must exist
- assuming only active oscillations the SSM prediction is reliable

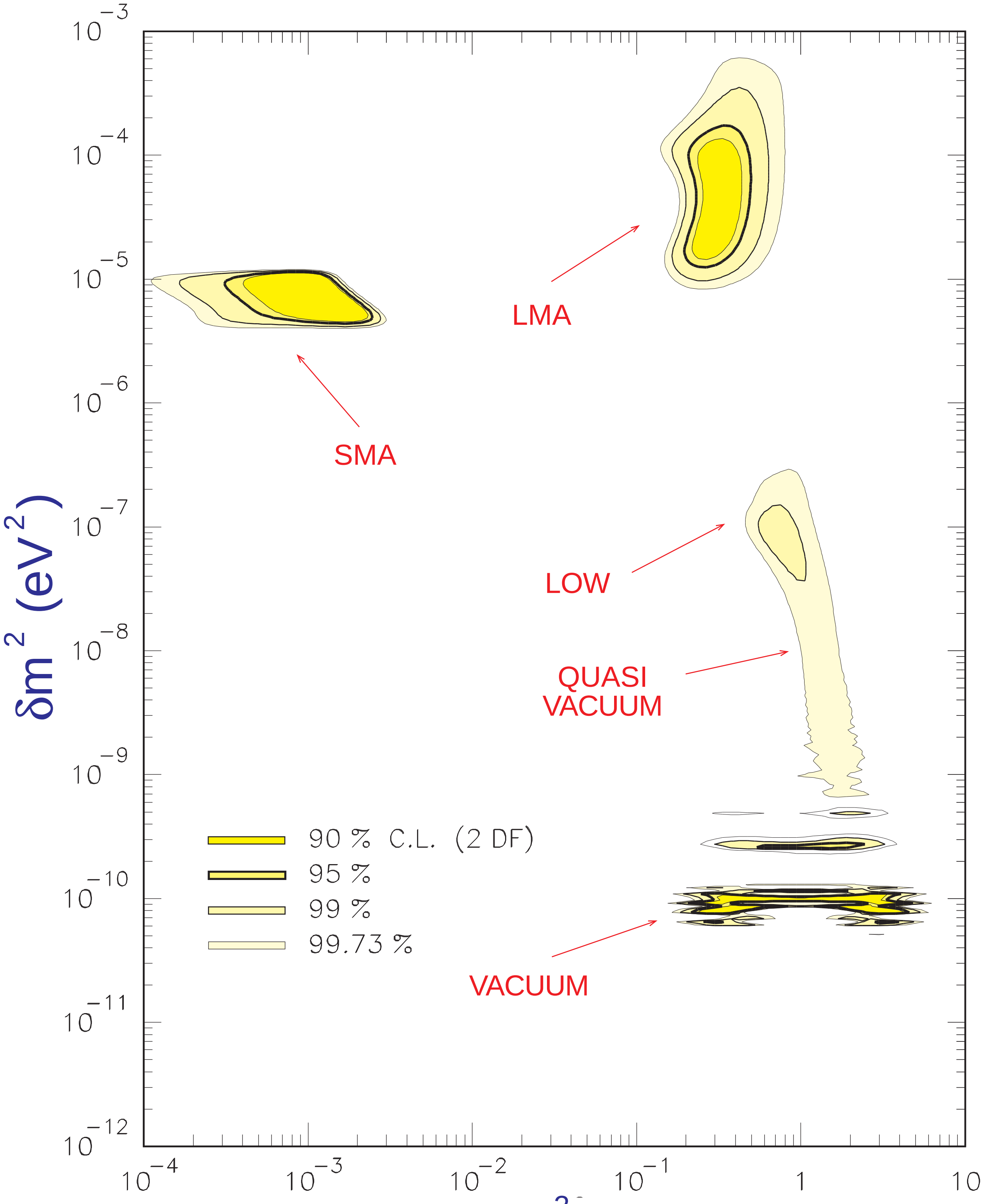
we assume then

- SSM fluxes and uncertainties (BP 00)
- a specific model of active oscillation: $2\nu$, the simplest

# 2ν oscillations (φ = 0)

Pre-SNO data: Cl+Ga+SK rates + CHOOZ

important to cut the upper part of LMA




$\chi^2_{SMA} = 7.7$

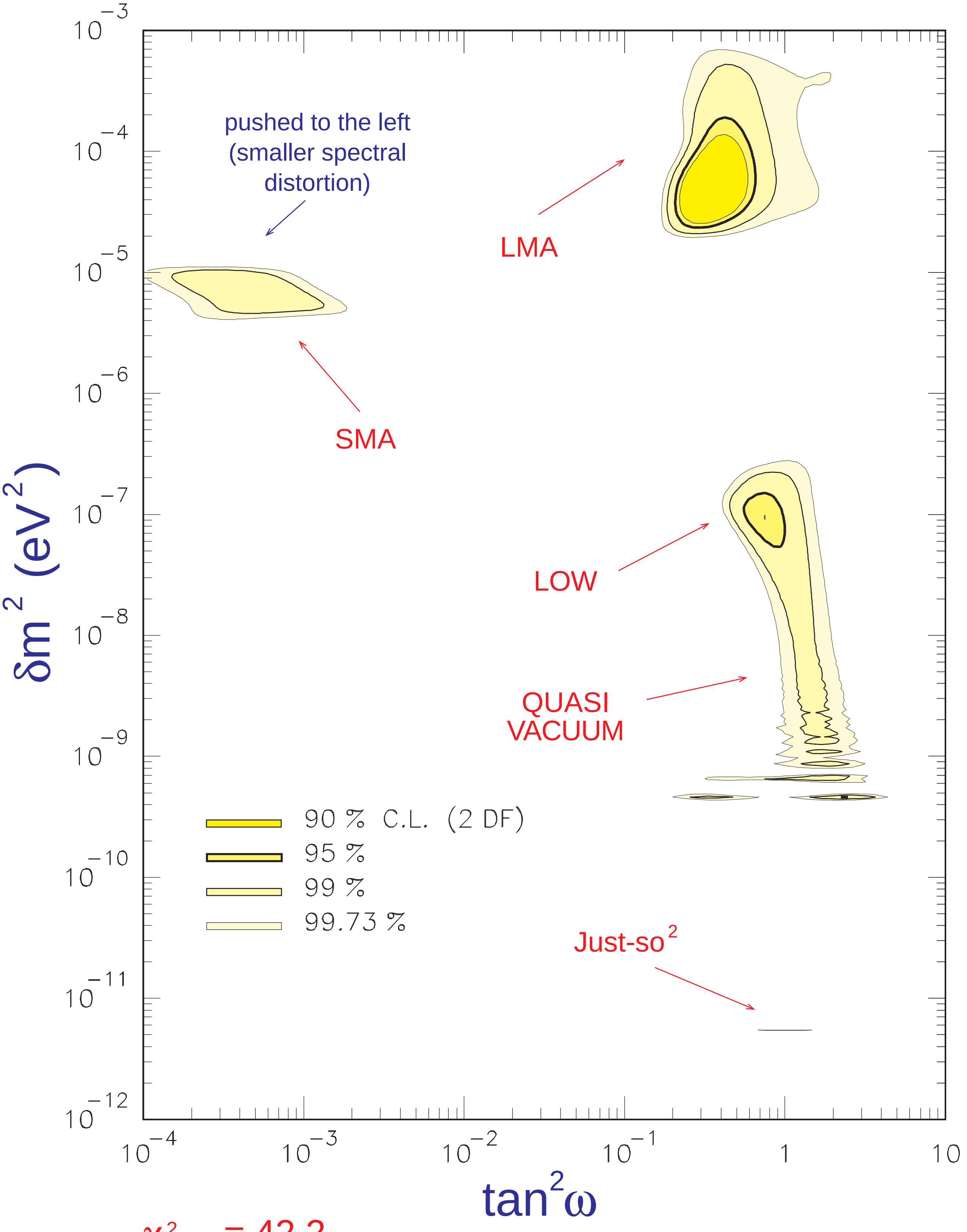
$\chi^2_{VAC} = 7.8$

$\chi^2_{LMA} = 10.6$

$\chi^2_{LOW} = 15.6$

# 2ν oscillations (φ = 0)

**Pre-SNO data:** Cl+Ga+SK rates +CHOOZ+SK D&N spectra




$\chi^2_{LMA} = 42.2$

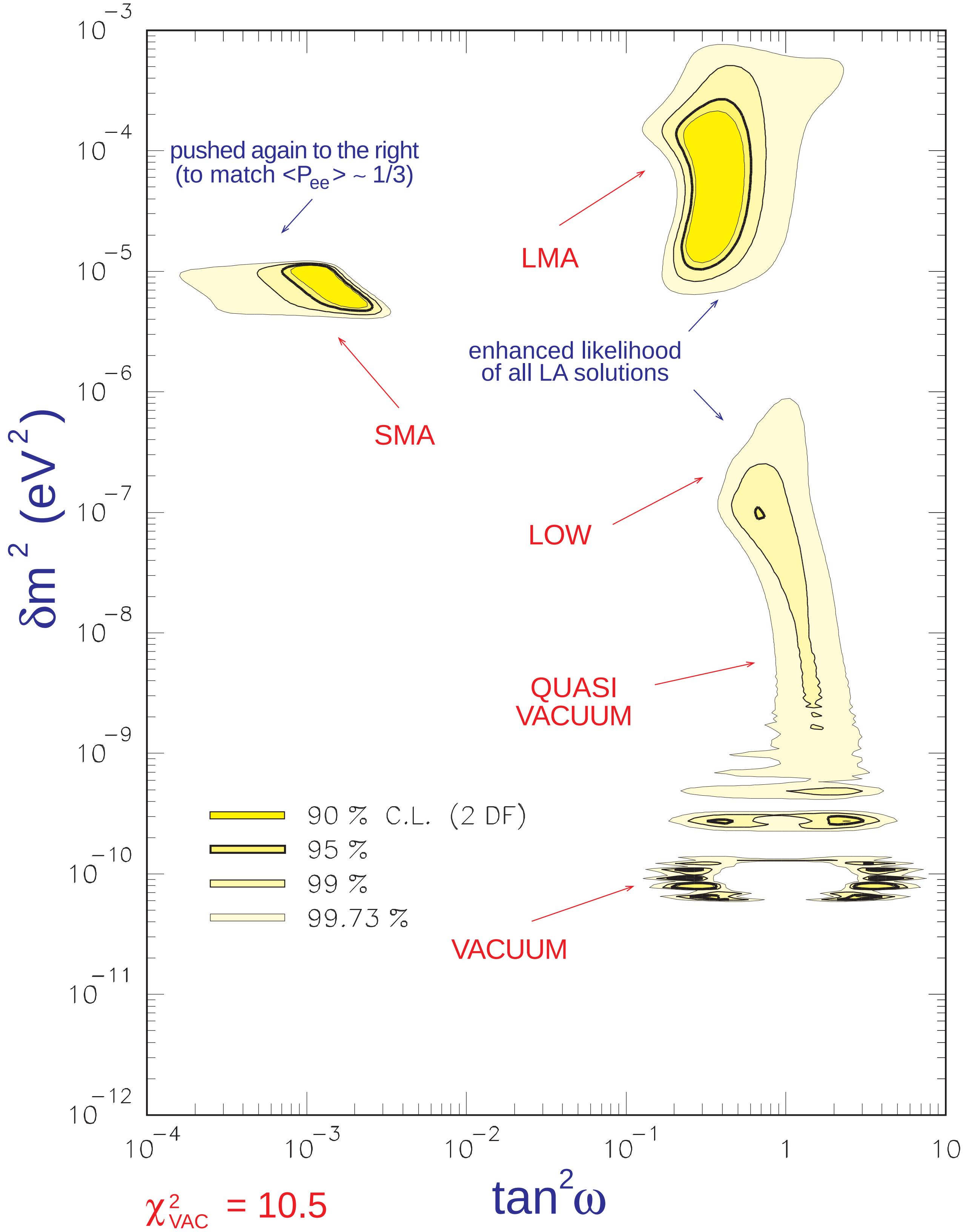
$\chi^2_{LOW} = 46.8$

$\chi^2_{QVA} = 48.1$

$\chi^2_{SMA} = 49.3$

# 2ν oscillations (φ = 0)

## Impact of SNO on rates: Cl+Ga+SK+SNO rates +CHOOZ




$\chi^2_{VAC} = 10.5$

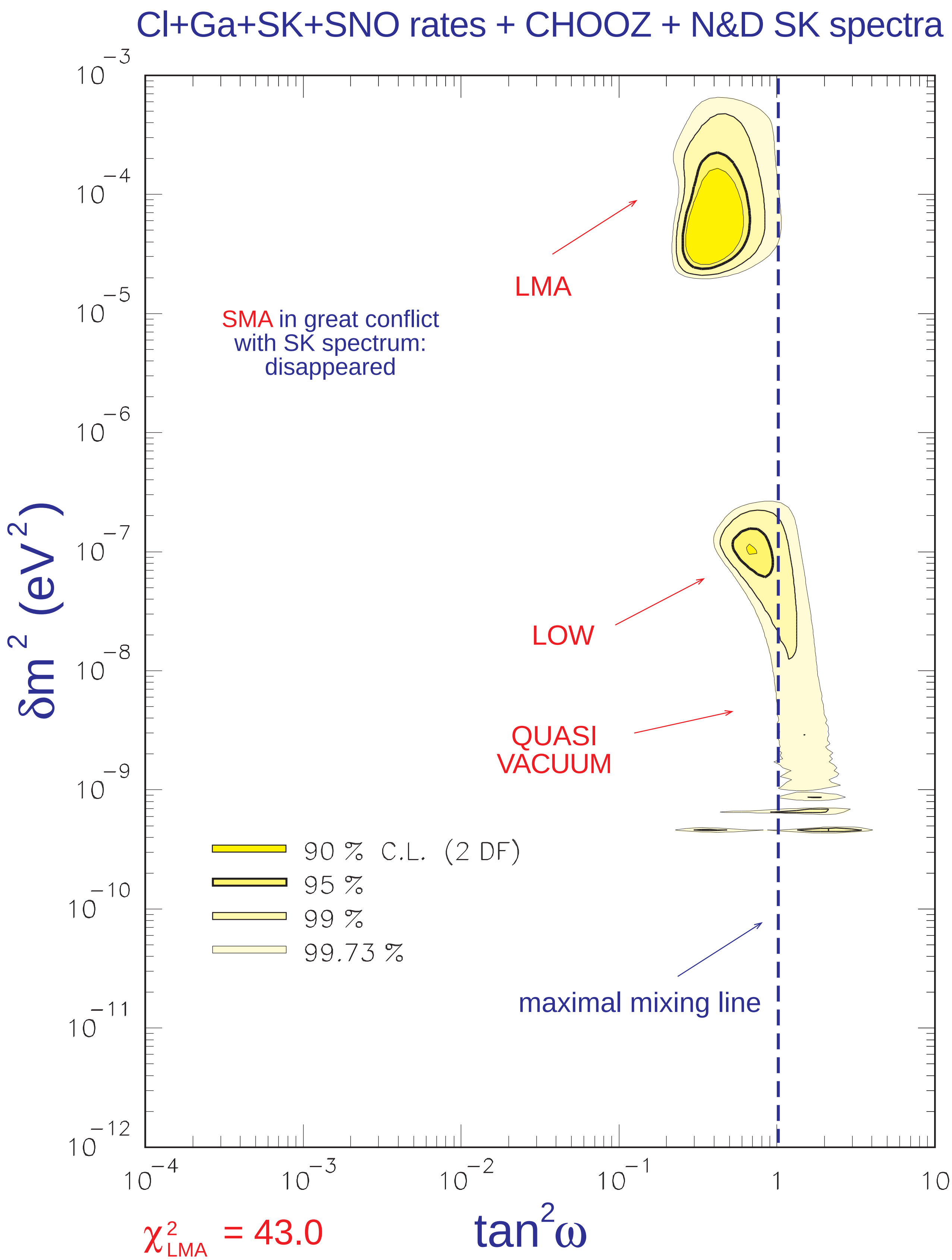
$\chi^2_{LMA} = 11.7$

$\chi^2_{SMA} = 12.0$

$\chi^2_{LOW} = 16.4$

## 2ν oscillations (φ = 0)

# Impact of SNO: all data




$\chi^2_{LMA} = 43.0$

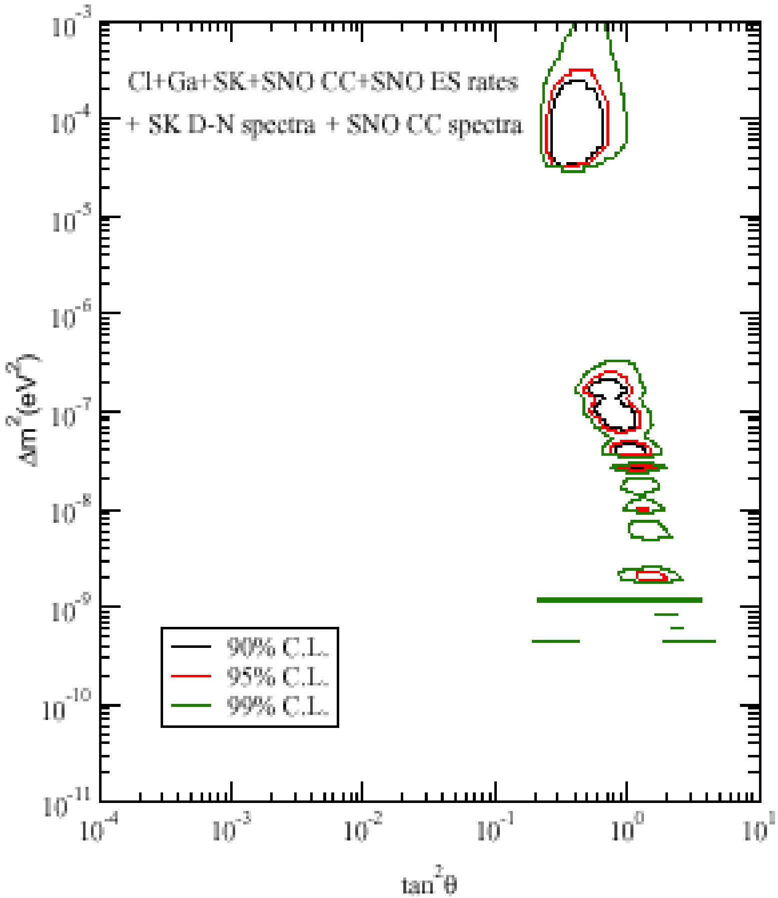
$\chi^2_{LOW} = 47.5$

$\chi^2_{QVO} = 49.0$

$\chi^2_{SMA} = 57.7$

## Similar results obtained by

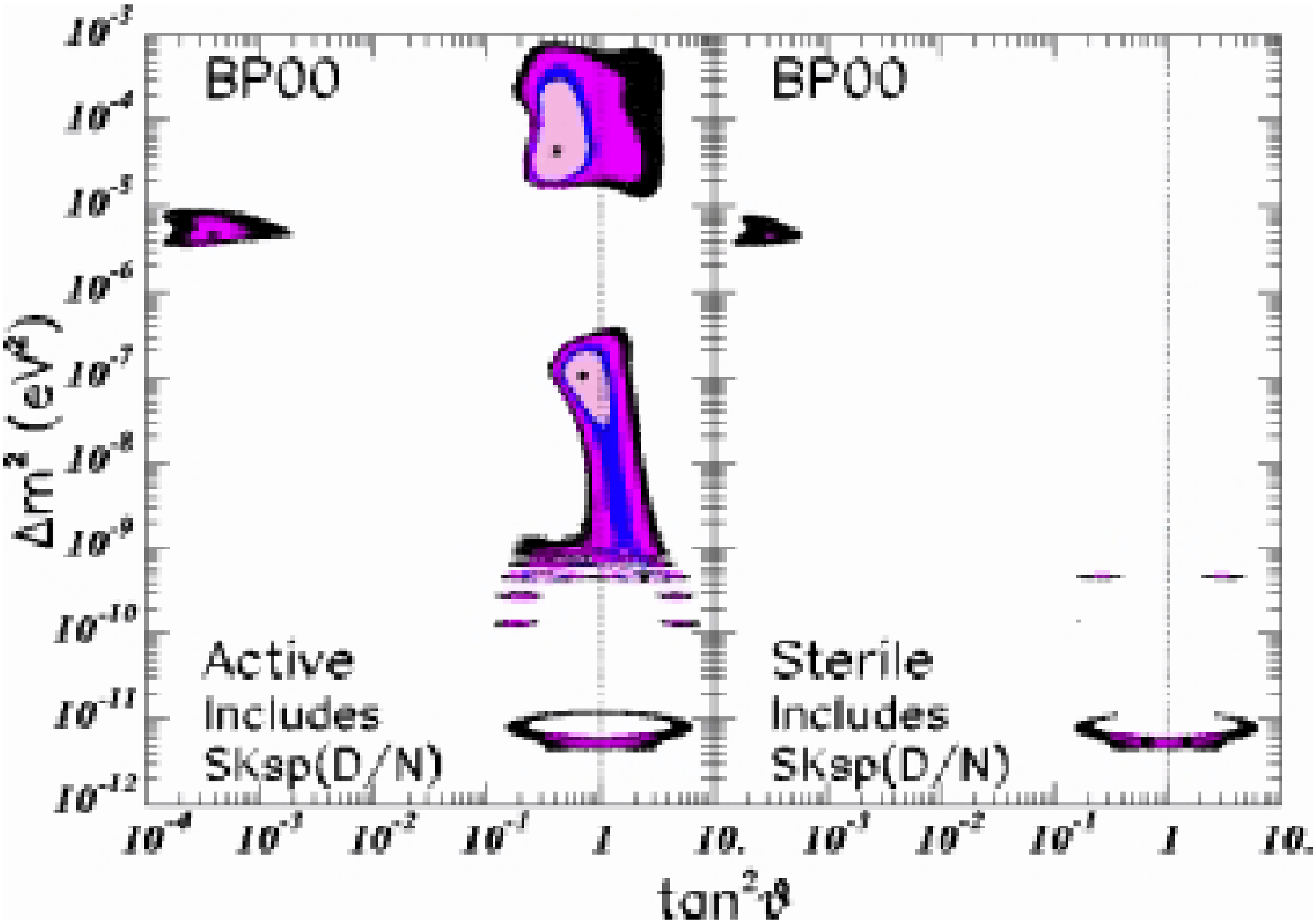
- A. Bandyopadhyay, S. Choubey, S. Goswani and K. Kar hep-ph/0106264 (shown)
- P. Creminelli, G. Signorelli and A. Strumia hep-ph/0102234 updated (not shown)



Less restrictive results obtained by

J.N. Bahcall, M.C. Gonzales-Garcia, C. Pena-Garay hep-ph/0106258 (shown)

2ν active [but $\chi^2$ (3 dof)] 2ν sterile [generally disfavored]




Two reasons:

1) Trivial: they use 3 dof, not 2 dof

2) Nontrivial: treatment of the spectrum uncertainties somewhat different

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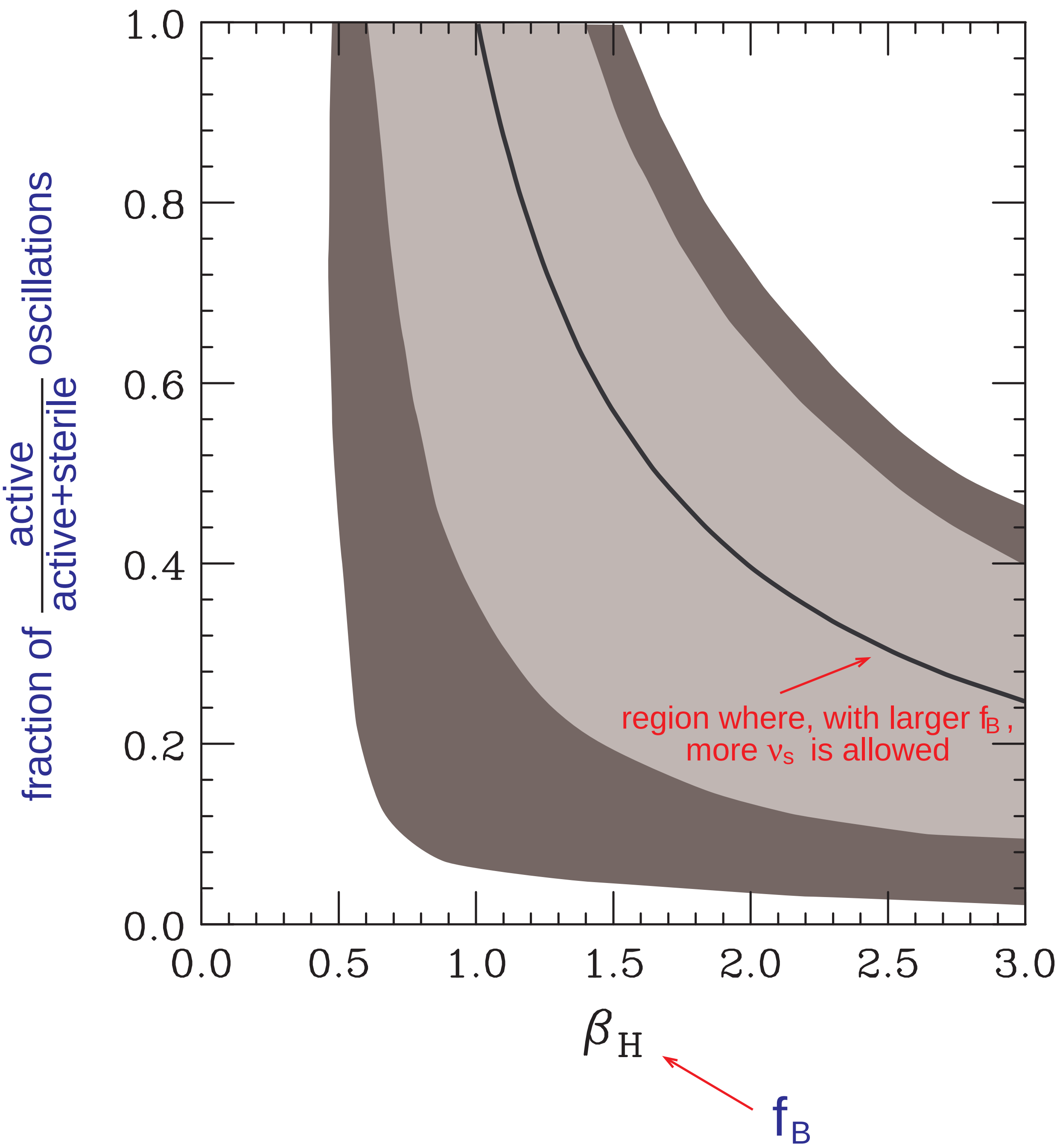
impact on "borderline" solutions as SMA, Just-so$^2$

Perhaps it's time to open a more detailed discussion on the delicate issue of spectral uncertainties and fit (work in progress)

## Sterile neutrino caveat $\nu_s$, although disfavored after SNO, can be recoverd by assuming large boron flux

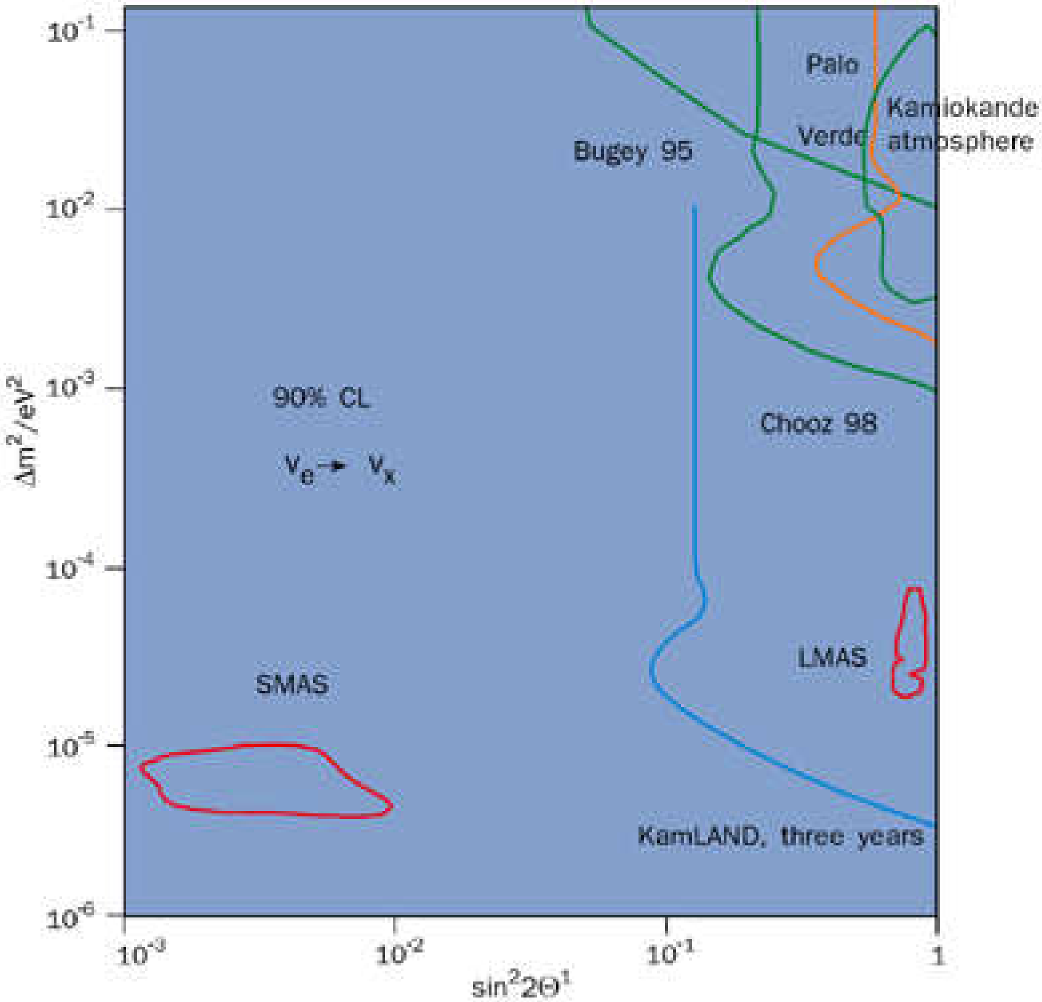
V. Barger, D. Marfatia and K. Whisnant, hep-ph/0106207




$\nu_e \to \nu_s$ "eat" the extra-flux !

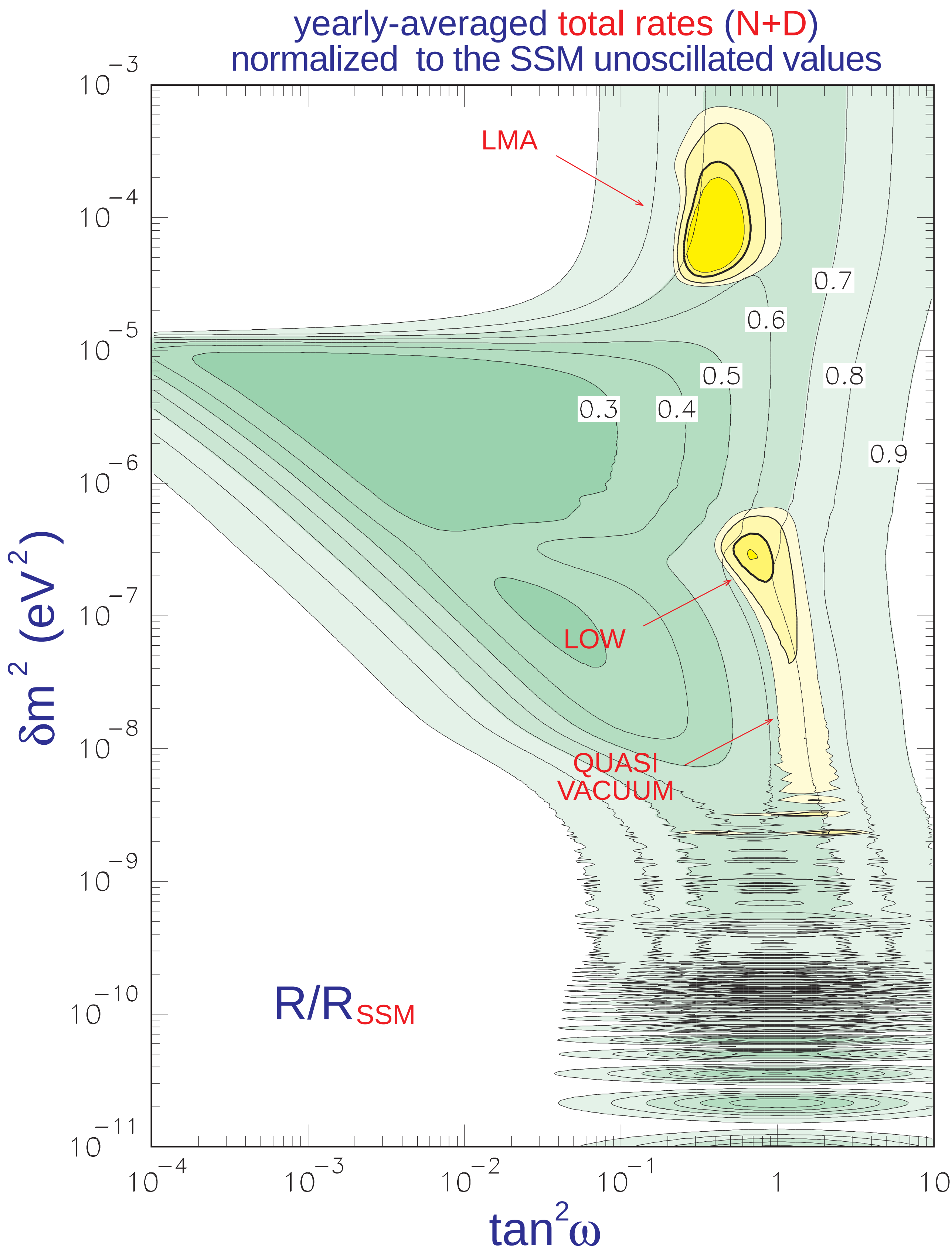
Future experiments

Potential discovery of KAMLAND



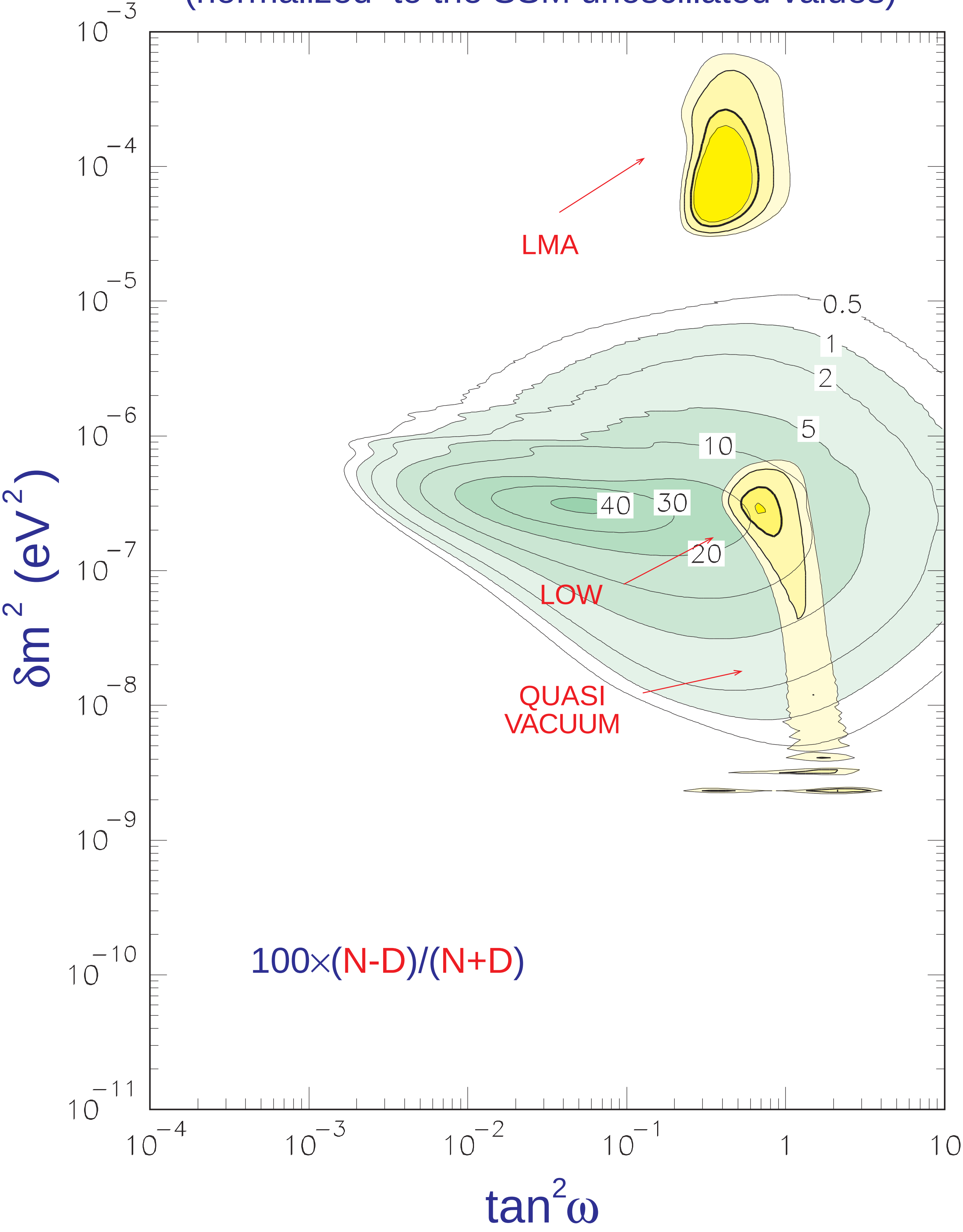
# Borexino total rates

compared with LMA and LOW solutions

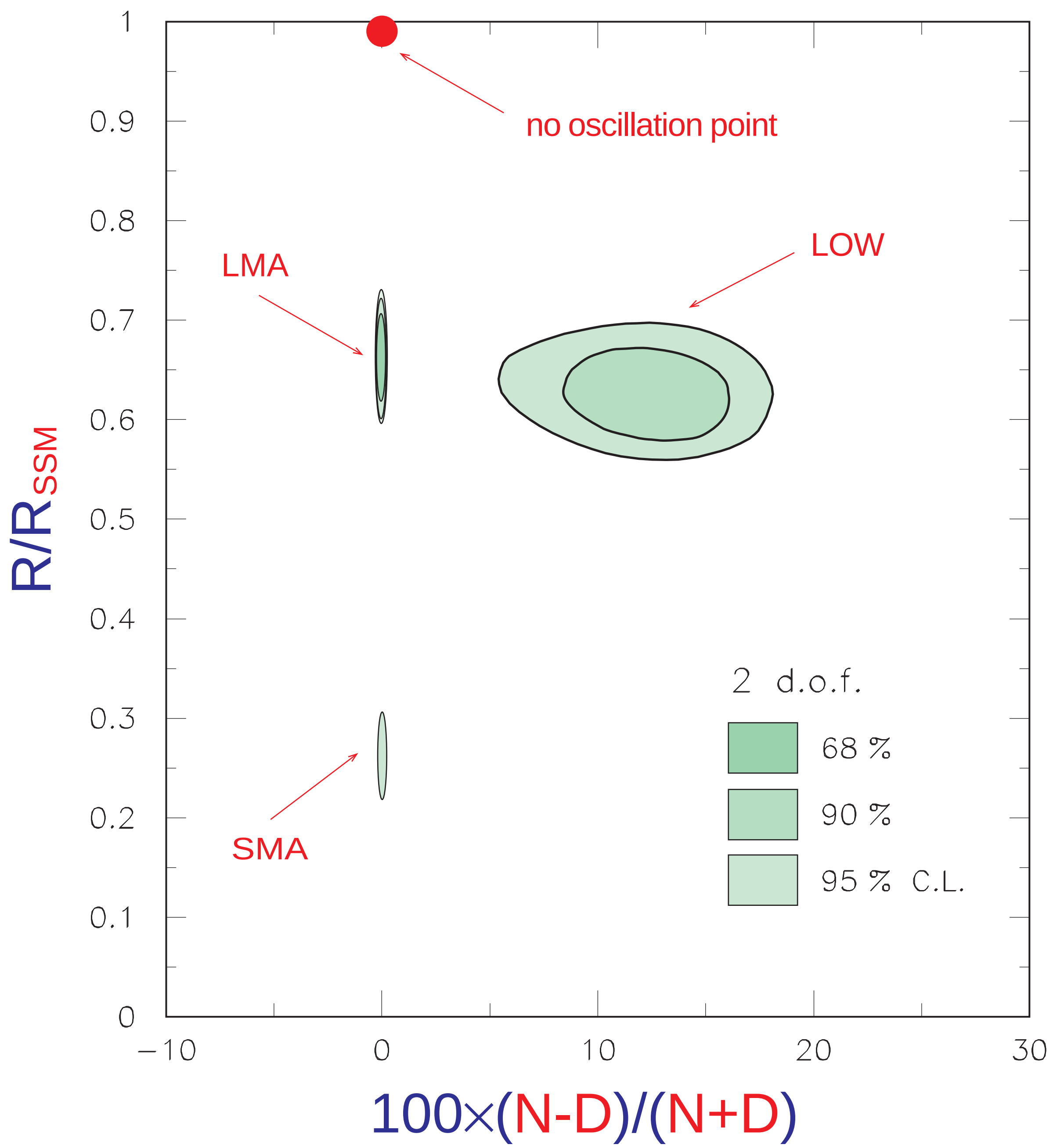


# Borexino N-D asymmetry compared with LMA and LOW solutions

yearly-averaged nighttime and daytime rates
(normalized to the SSM unoscillated values)



# Borexino discovery potential compared with SMA, LMA and LOW solutions



Conclusion of the step 3:

If 2$\nu$ active oscillations and SSM are assumed (with no $\nu_s$ ), then large mixing angle solutions (especially LMA) are favored. Concerning $\nu_s$, it is strongly disfavored and requires $f_B > 1$.

# Step 4

## Towards 3ν active oscillations

Within the "one dominant mass scale approximation":

| 2ν | | 3ν |
|---|---|---|
| $(\delta m^2, \omega)$ | $\xrightarrow{m^2 \to \infty}$ | $(\delta m^2, \omega, \varphi)$ |
| $P_{2\nu}(\nu_e \to \nu_e)$ | $\xrightarrow{m^2 \to \infty}$ | $P_{3\nu} = c_\varphi^4 P_{2\nu}\Big\vert_{N_e = c_\varphi^2 N_e} + s_\varphi^4$ |

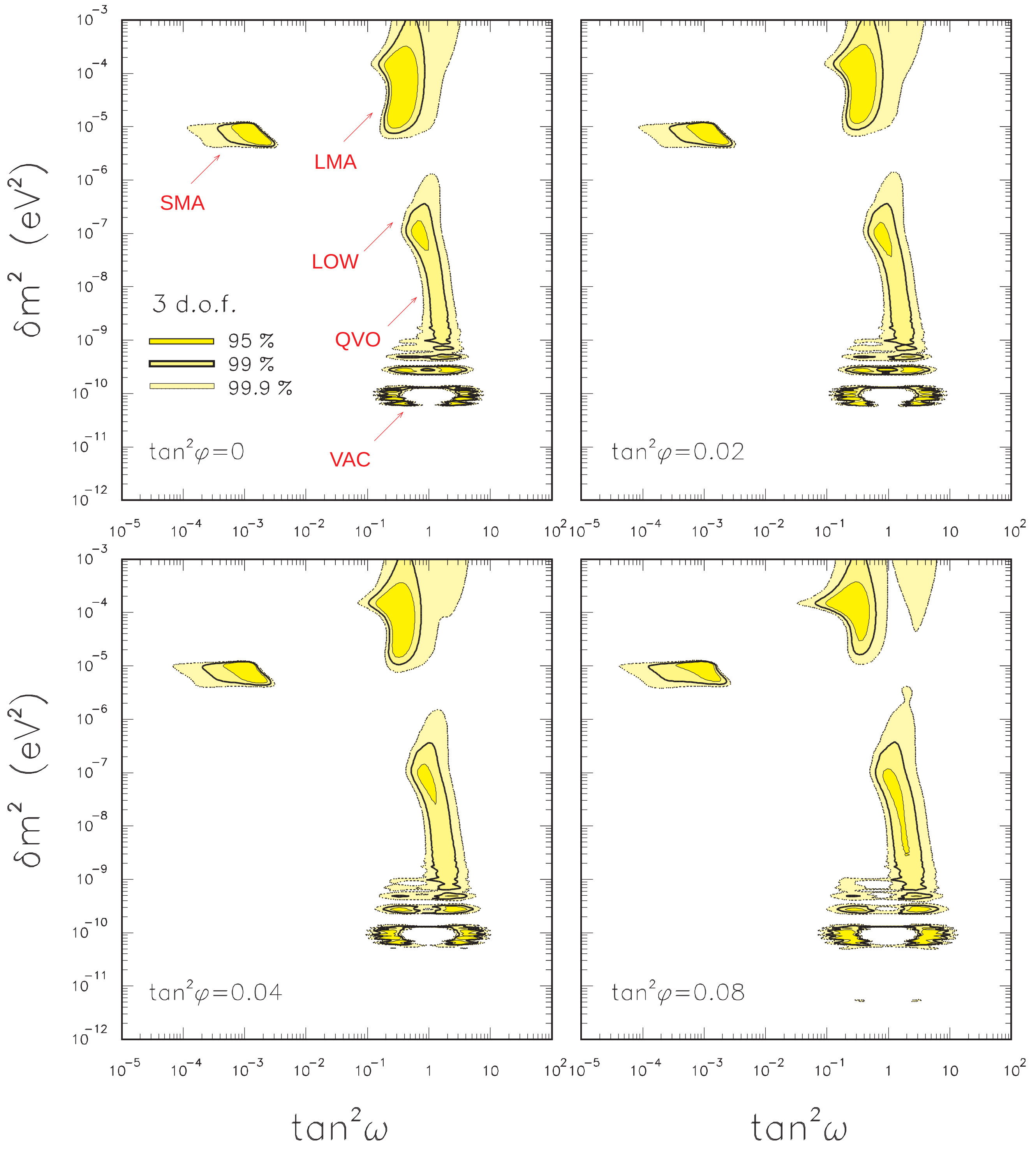
φ small (CHOOZ) implies that $P_{3\nu} \sim P_{2\nu}$, so why we study the case of unconstrained φ ?

Three reasons:

- Investigate if solar ν data alone (without CHOOZ) prefer small φ, in the same way as atmospheric data
- Study the behaviour of the usual 2ν solutions, in particular LMA and LOW, under small φ perturbations
- Going beyond the one mass scale approximation, study the effect of atmospheric parameters on solar ν data

# 3ν oscillations ($m^2 = \infty$)

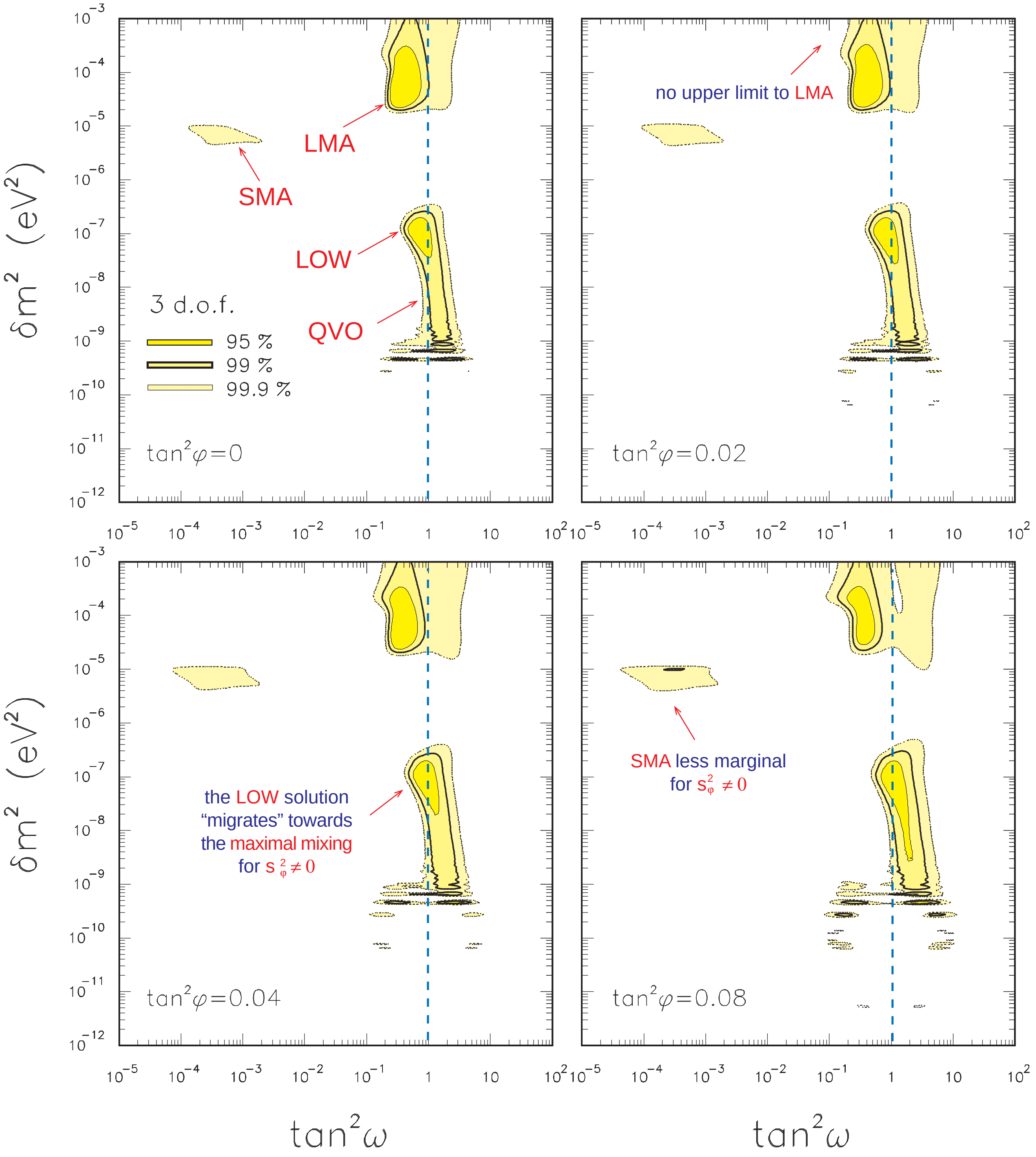
Cl+Ga+SK+SNO rates     no CHOOZ limit !




- Best fit at $s^2_\varphi = 0$
- Weak limit on $s^2_\varphi$: $s^2_\varphi < 0.7$

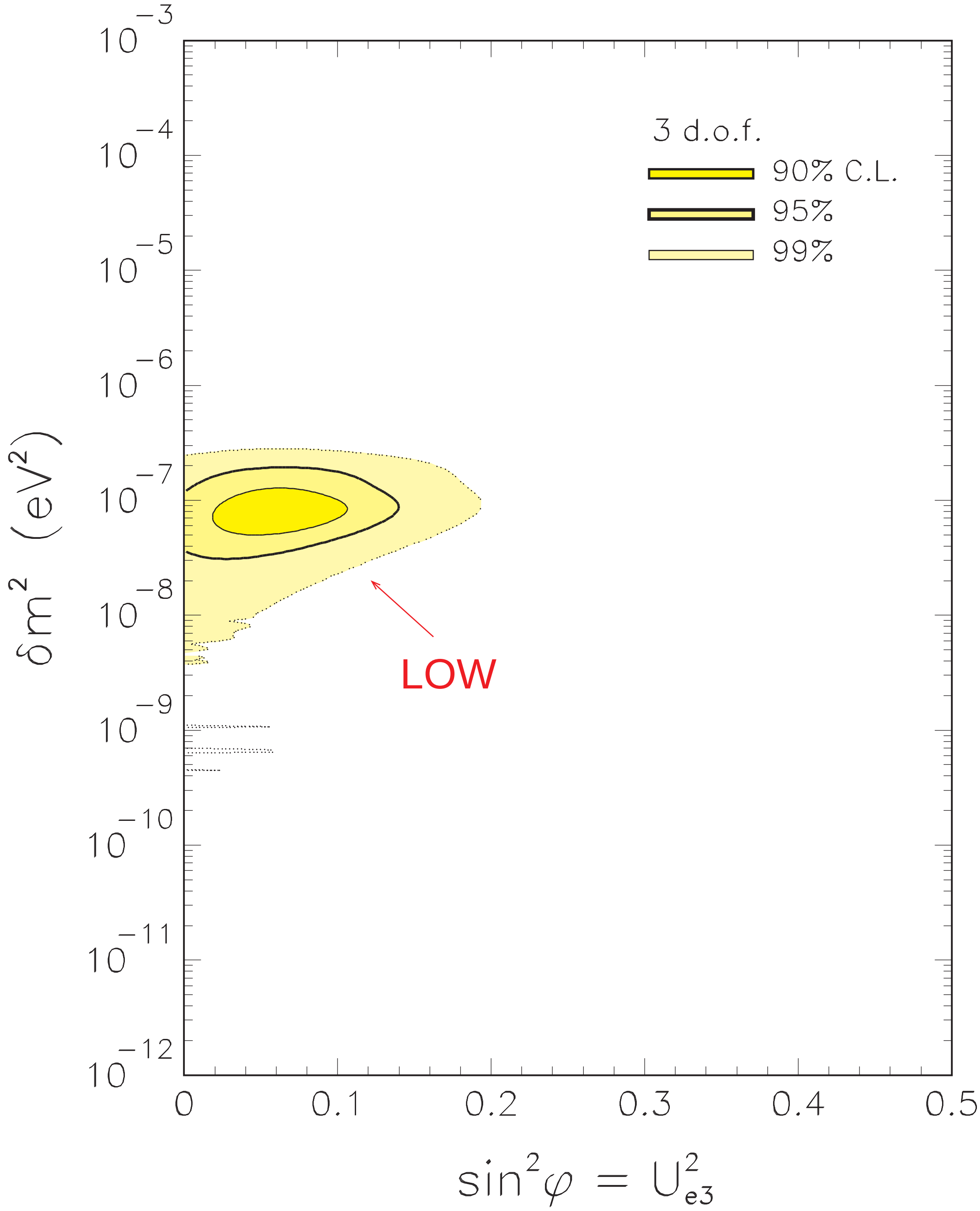
# 3ν oscillations ($m^2 = \infty$)

## Cl+Ga+SK+SNO rates + SK D&N spectra    no CHOOZ limit!



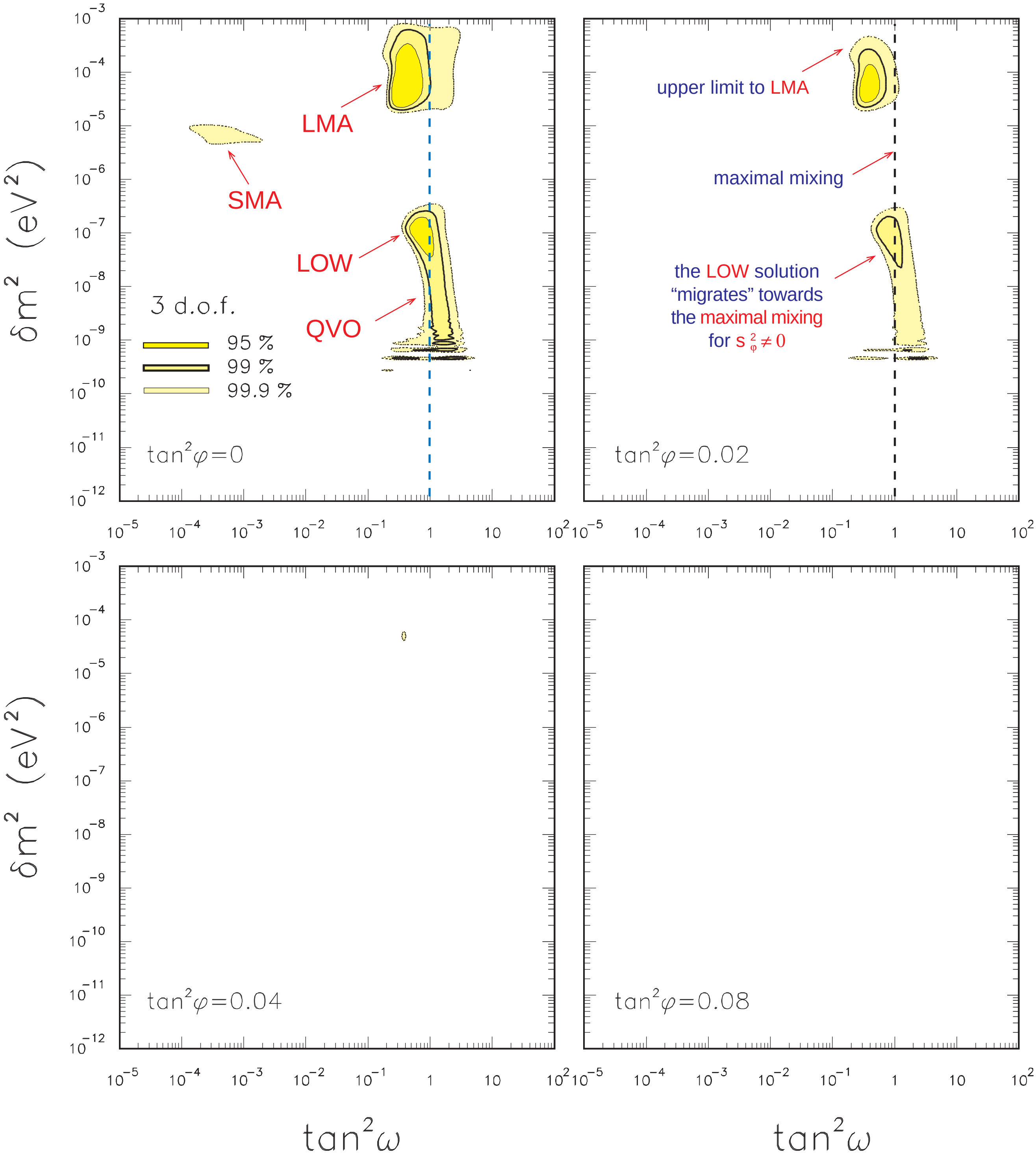
# 3ν oscillations @ maximal mixing ($U_{e1}^2 = U_{e2}^2$)

Cl+Ga+SK+SNO rates + SK D&N spectra     no CHOOZ limit!



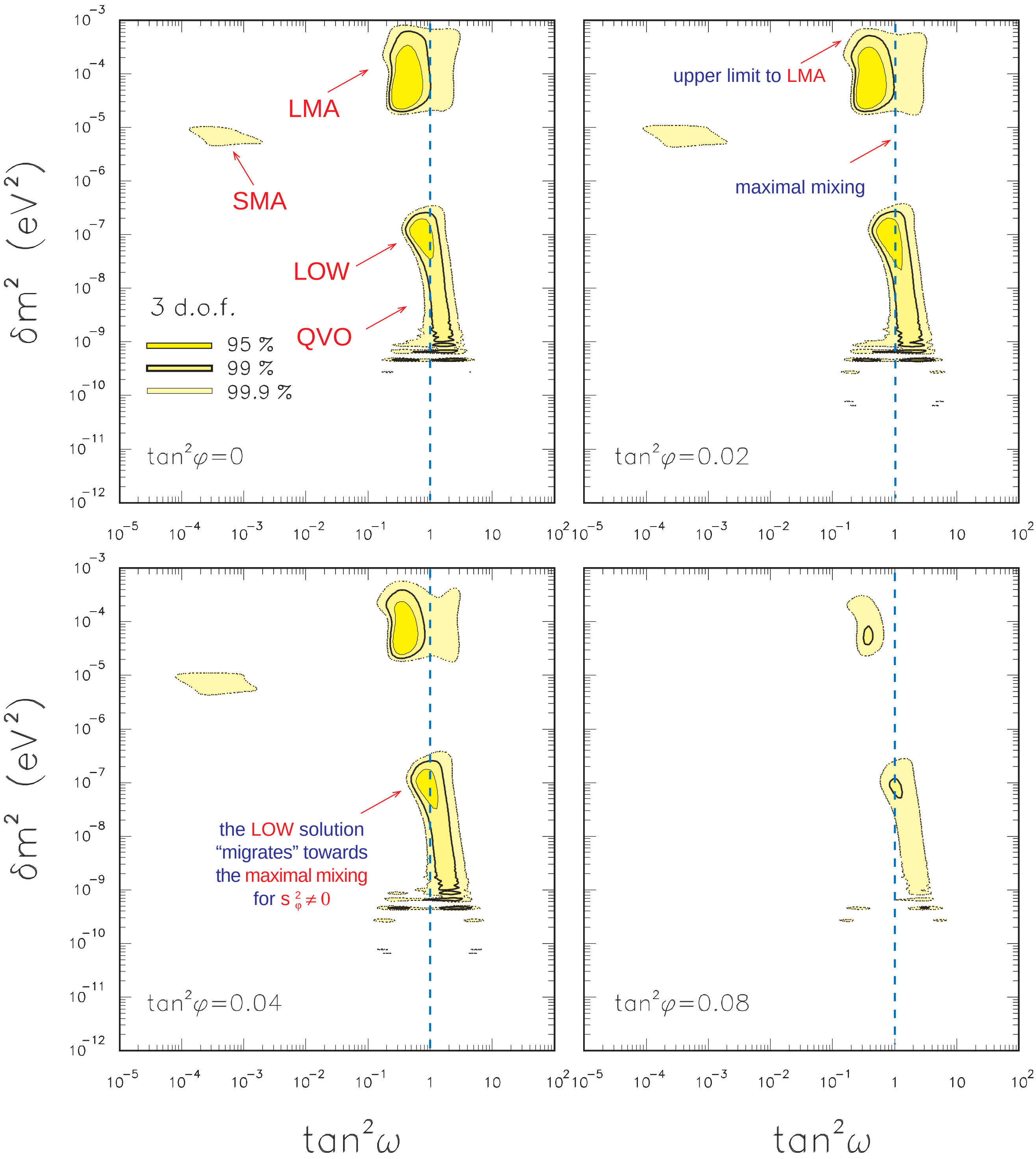
# 3ν oscillations ($m^2 = 3.0 \times 10^{-3}$ eV$^2$)

## Cl+Ga+SK+SNO rates + SK D&N spectra and CHOOZ data



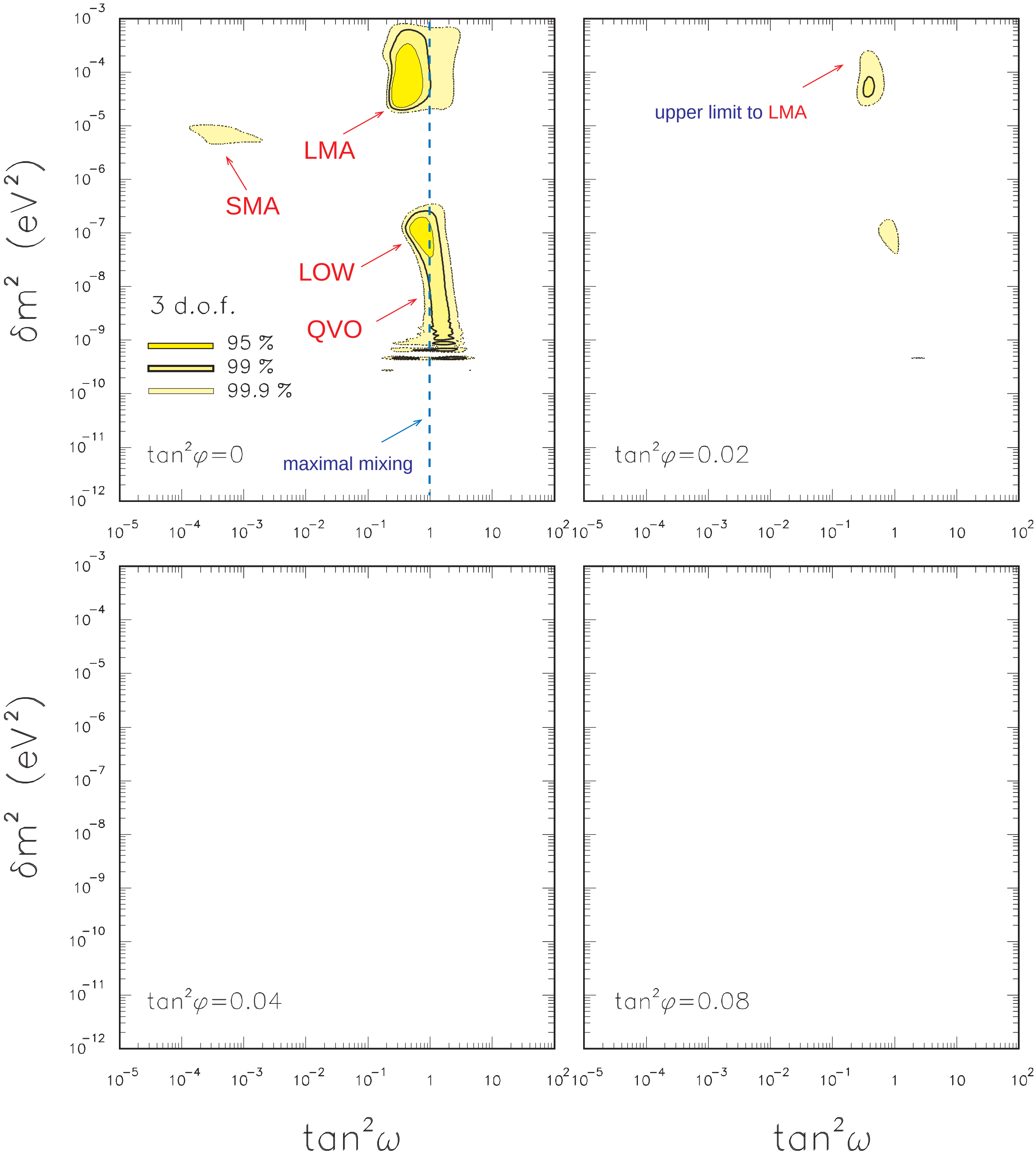
# 3ν oscillations ($m^2 = 1.5 \times 10^{-3}\ eV^2$)

## Cl+Ga+SK+SNO rates + SK D&N spectra and CHOOZ data



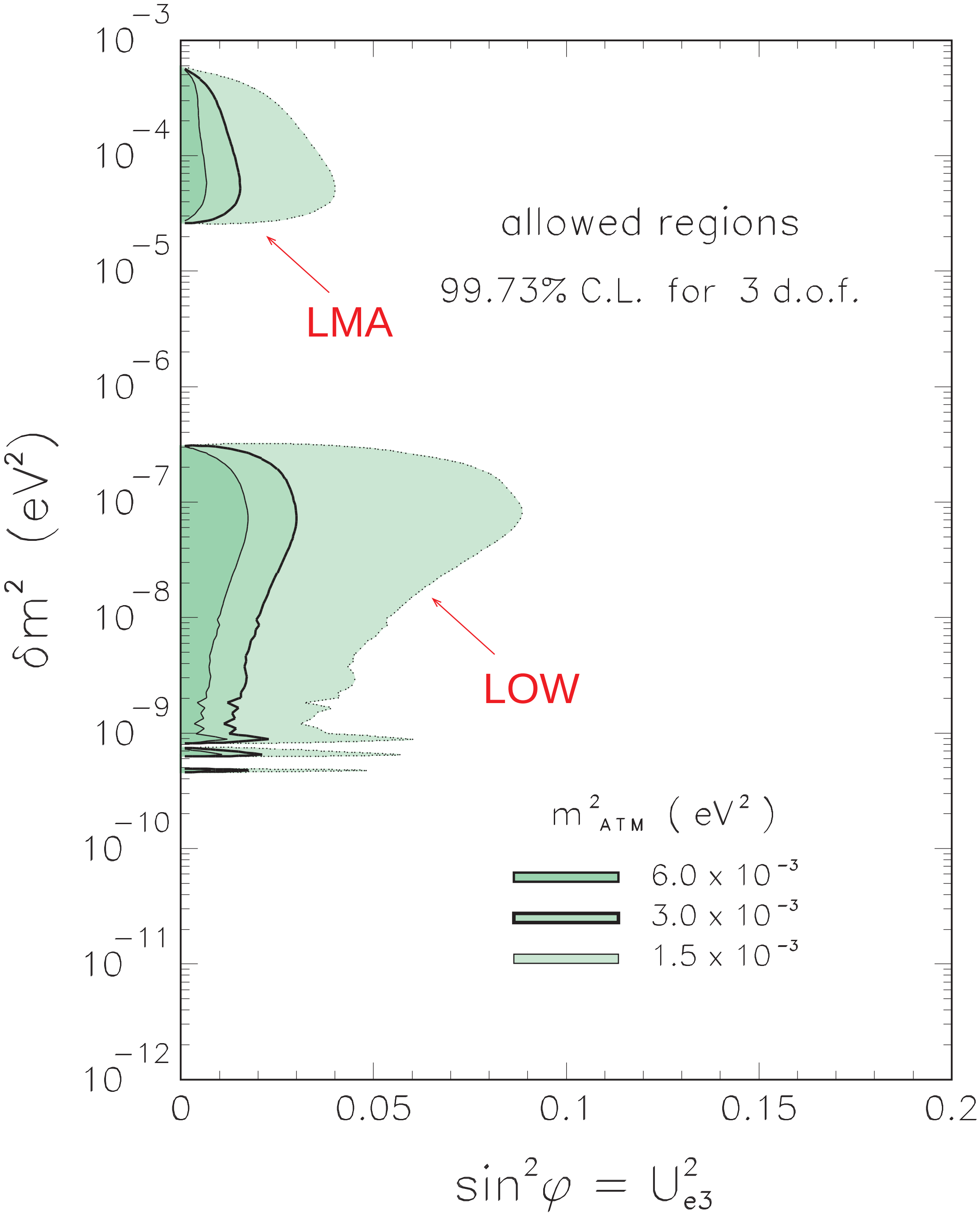
# 3ν oscillations (m² = 6.0 × 10⁻³ eV²)

## Cl+Ga+SK+SNO rates + SK D&N spectra and CHOOZ data



# $3\nu$ oscillations @ maximal mixing ($U^2_{e1} = U^2_{e2}$)

Cl+Ga+SK+SNO rates + SK D&N spectra and CHOOZ data



# Conclusions

- SNO + SK give model-independent evidence for active neutrino oscillations

- If active $\nu$ oscillations are assumed (with no $\nu_s$), then

  $f_B \sim 1$ $\langle P_{ee} \rangle \sim 1/3$

- If $2\nu$ active oscillations and SSM are assumed, then large mixing angle solutions (LMA and LOW) are strongly favored

  [Remark: additional $\nu_e \to \nu_s$ can survive if $f_B > 1$]

- If $3\nu$ active oscillations are assumed, some "perturbations" of large mixing angle solutions are possible at small $s^2_\varphi = U^2_{e3}$
  [Perturbations of interest for $\nu$ factories]

- Lots of new data in the next few years: SNO D/N, Kamland, Borexino ...

A bright future for $\nu$ physics !