XVII IFAE

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Fenomenologia della massa dei neutrini

Outline:

- Introduction
- Atmospheric Neutrinos
- Solar Neutrinos
- Absolute masses
- Summary

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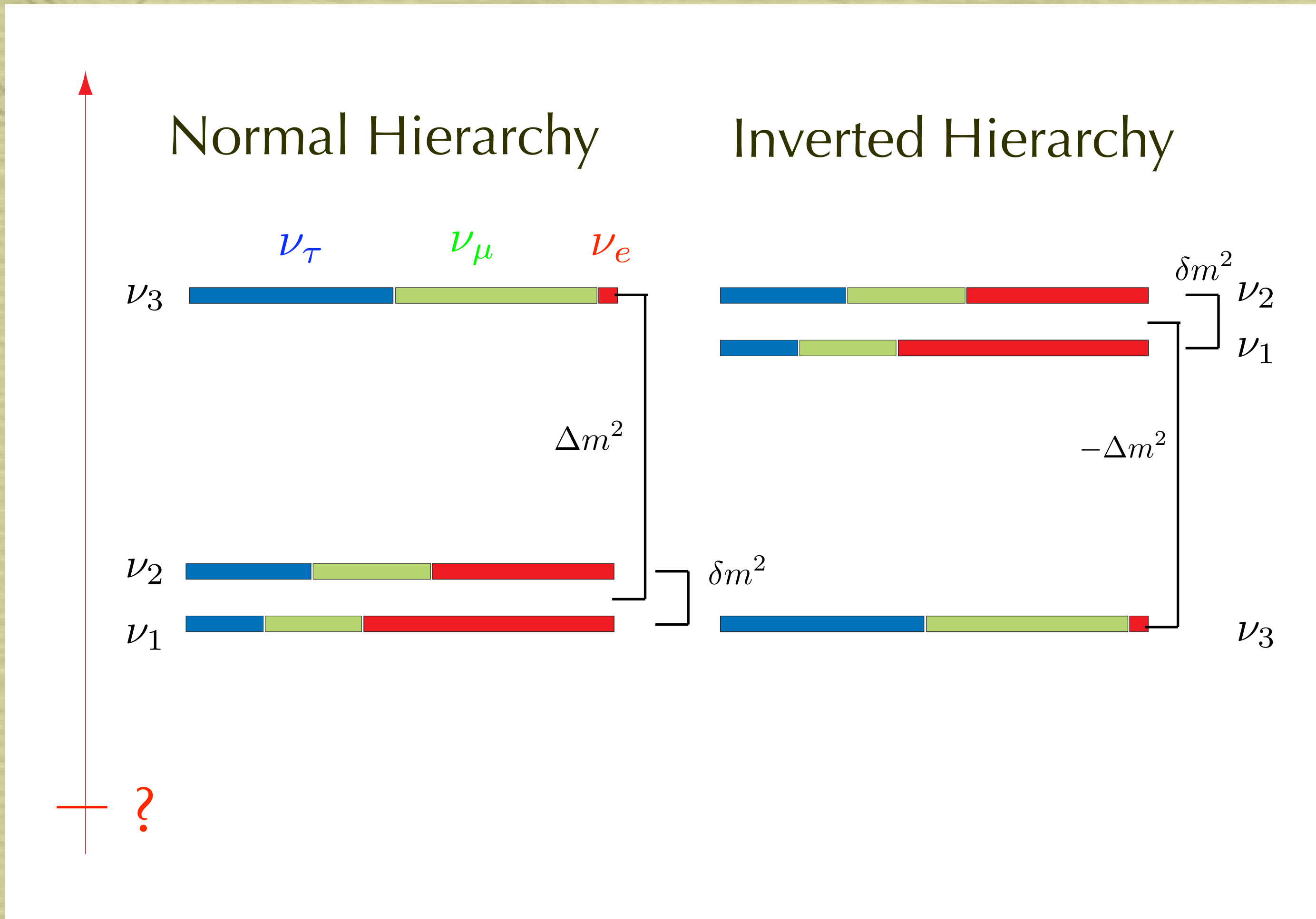
Thanks to: G.L. Fogli, E. Lisi, A.M. Rotunno, A. Melchiorri, D. Montanino and A. Palazzo

Neutrino Mass Spectrum



Only upper limits (~O(eV)) on the absolute mass scale

Two squared mass differences

$$\Delta m^2 \equiv \Delta m^2_{Atm}$$

$$\delta m^2 \equiv \delta m^2_{Sol}$$

Hierarchy

$$\pm \Delta m^2$$

Phase

$$\delta_{CP}$$

$$(\theta_{12}, \theta_{23}, \theta_{13})$$

Solar angle

Atmospheric angle

Atm. + Sol. + CHOOZ angle

The two Majorana phases and the absolute mass scale are not probed by oscillations

Neutrino Data and Experiments (... an incomplete list)

Oscillation experiments

Atmospheric neutrinos (SuperKamiokande, MACRO, Soudan2)

Accelerators and Reactors (CHOOZ, KamLAND, K2K, LSND, Bugey, Palo Verde, ...)

Solar Neutrinos Experiments (SuperKamiokande, SNO, Cl, GNO, Sage)

Absolute masses measurements

Beta decay (Mainz and Troitsk)

Neutrinoless double beta decay (Heidelberg-Moscow)

Astrophysics and Cosmology

High energy neutrinos

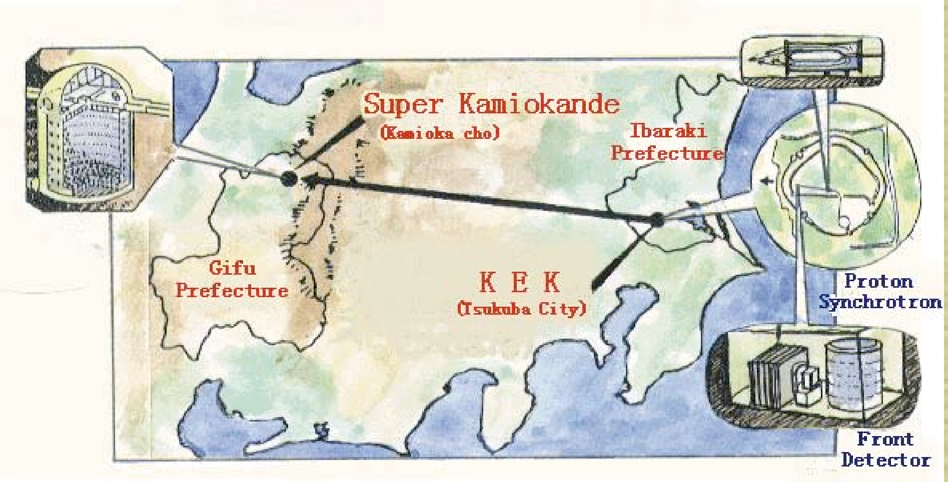
CMB anisotropies Spectrum and Large Scale Structure

Nucleosynthesis

Atmospheric Neutrino Oscillations

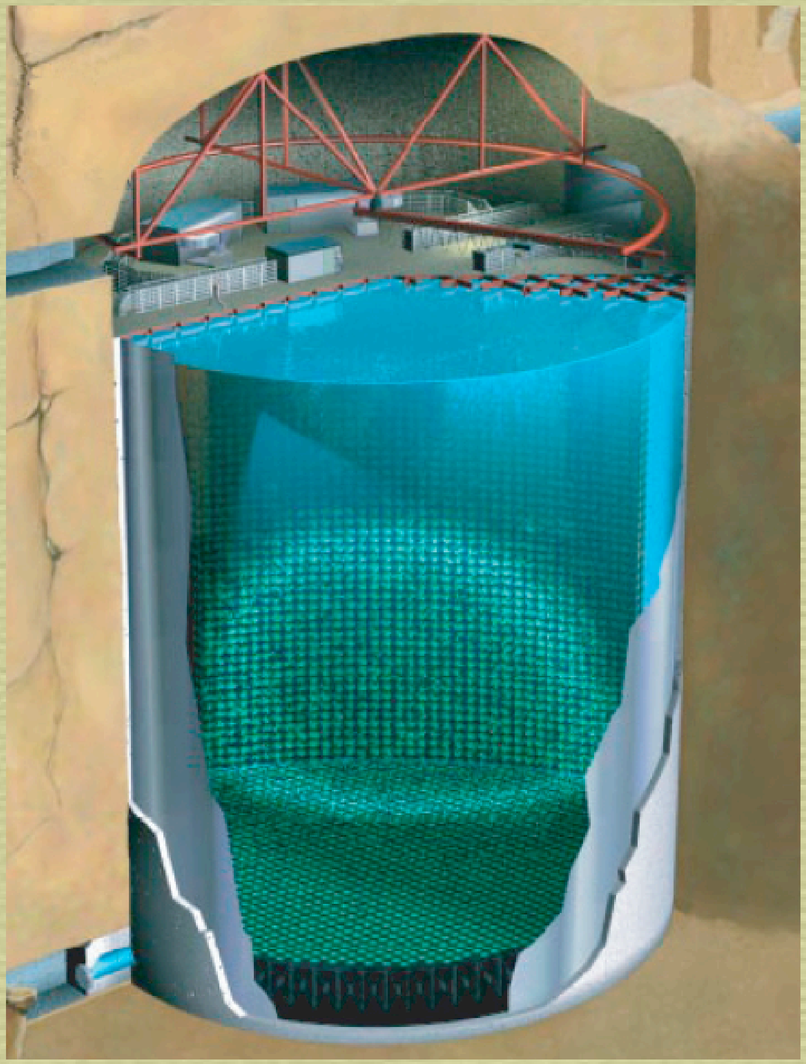
$$\begin{cases} \Delta m^2 \\ \theta_{23} \end{cases} + \quad \theta_{13}$$

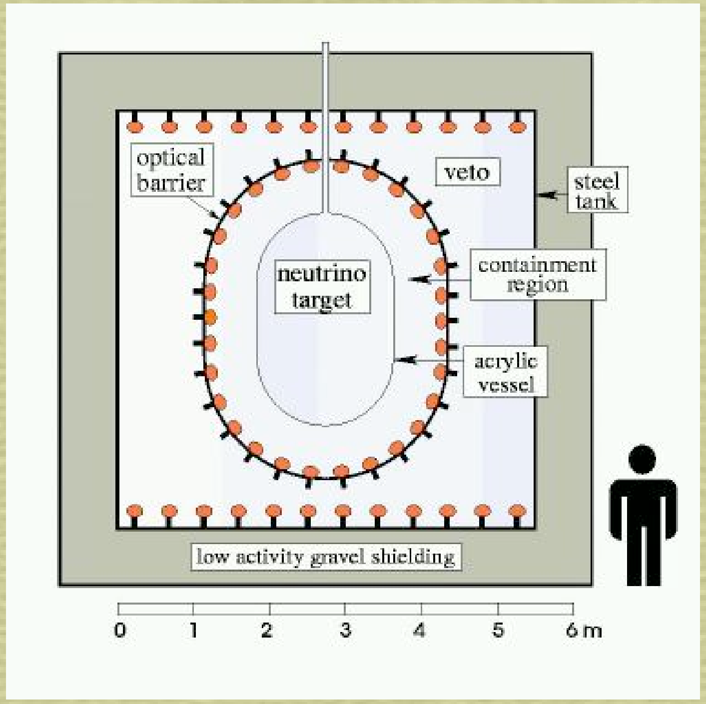
K2K spectrum (56 events)



K2K

SuperKamiokande





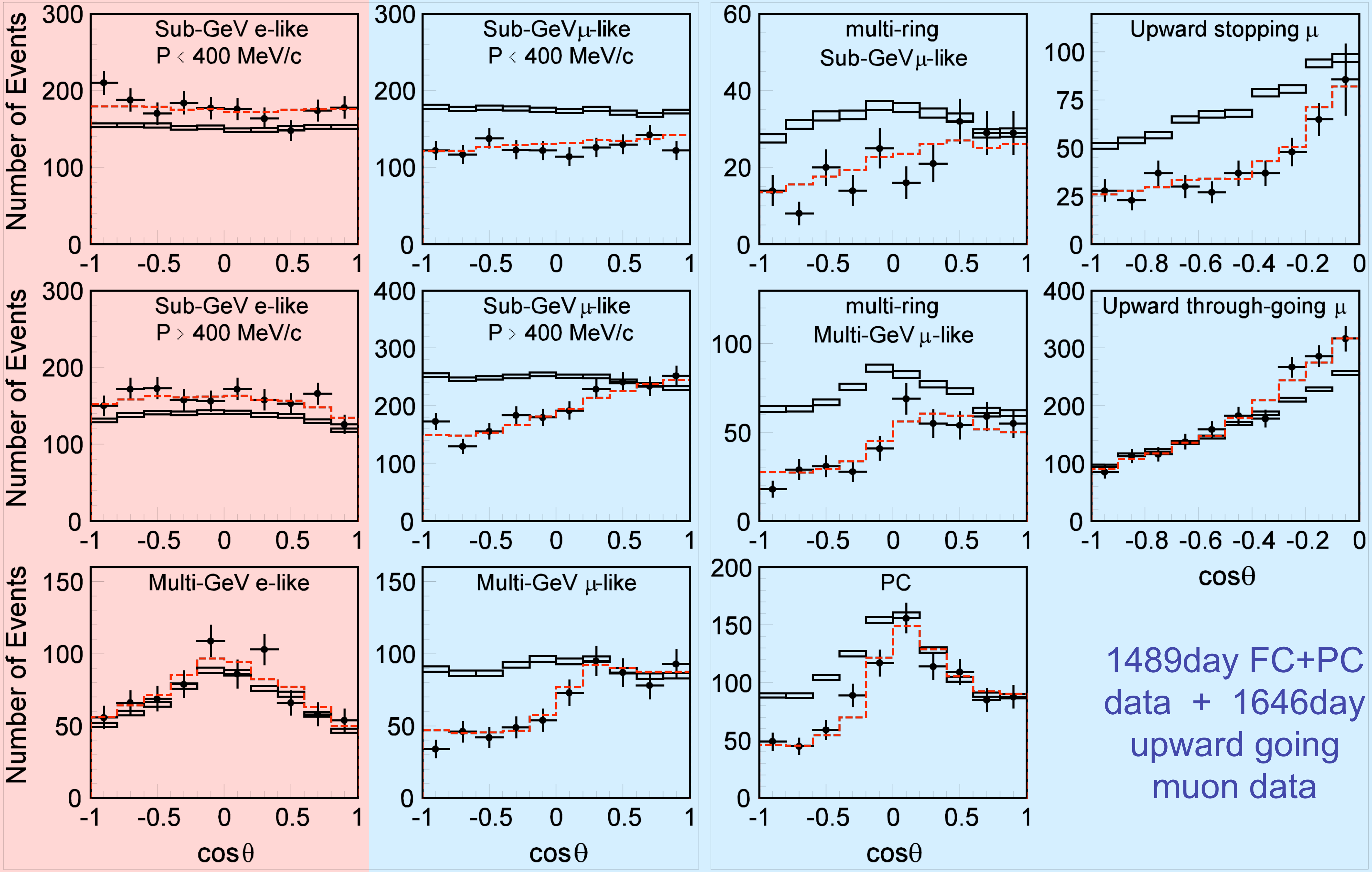
CHOOZ

$(\Delta m^2, \delta m^2, \theta_{13}, \theta_{12})$

SK number of events ~15000

Super-K atmospheric neutrino data

CC ν_e | CC ν_μ

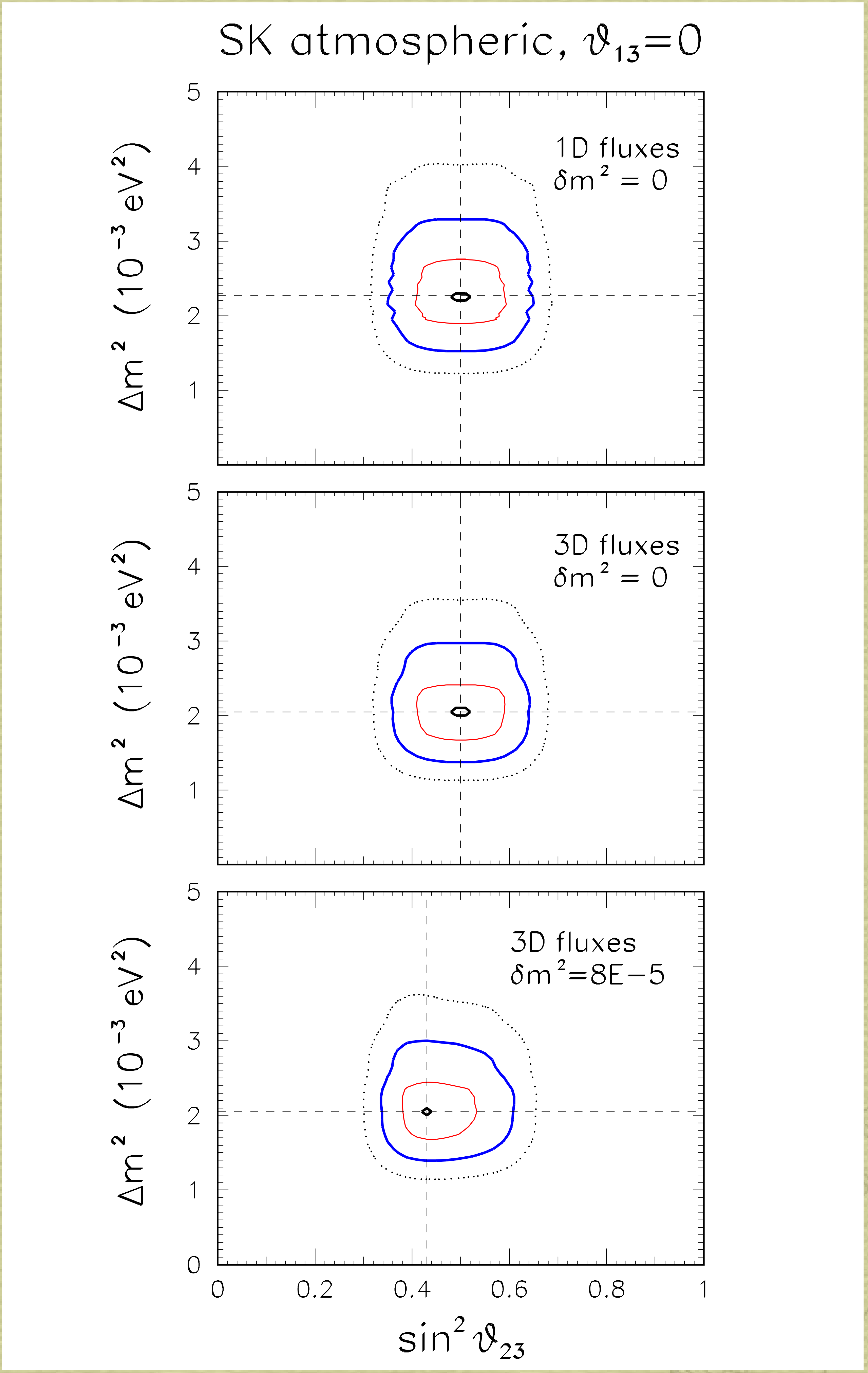


1489day FC+PC data + 1646day upward going muon data

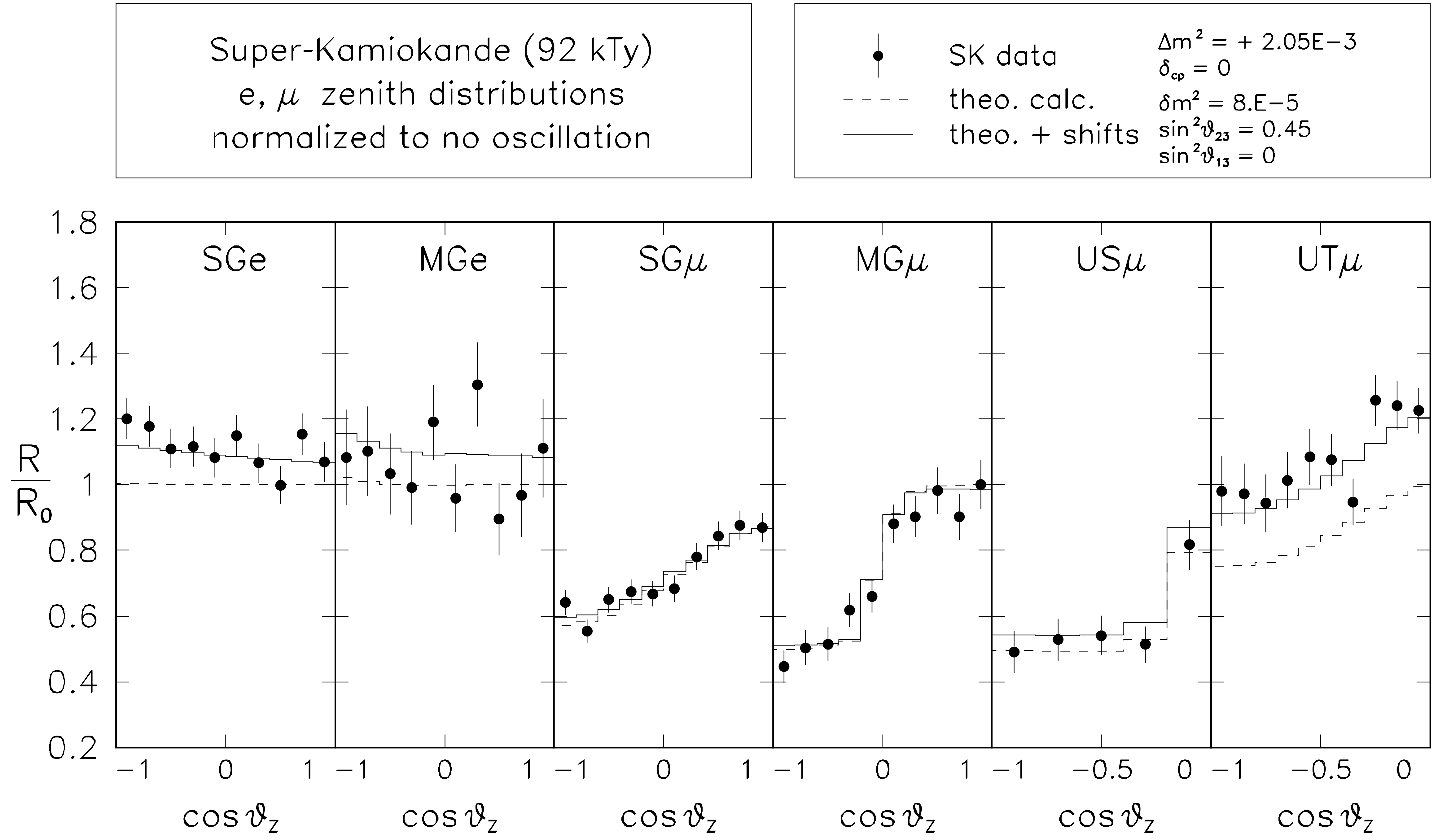
Note that here, as in the following, contours are drawn at $1, 2, 3\ \sigma$ (1 d.o.f.)

Using 3D atmospheric neutrino fluxes and improved systematics gives slighty lower values for Δm^2

Solar parameter are there and must be used in the analysis: the effect is to shift the allowed region toward to the left, to lower values of $\sin^2 \theta_{23}$



The effect of solar parameters is very small at the best fit and the shift of the SG-MG e-like distribution is dominated by the systematics



nevertheless is able to shift the allowed region toward the first octant of θ_{23}(by inducing a $\Delta\chi^2 \sim 2$)

Combination SK + K2K:

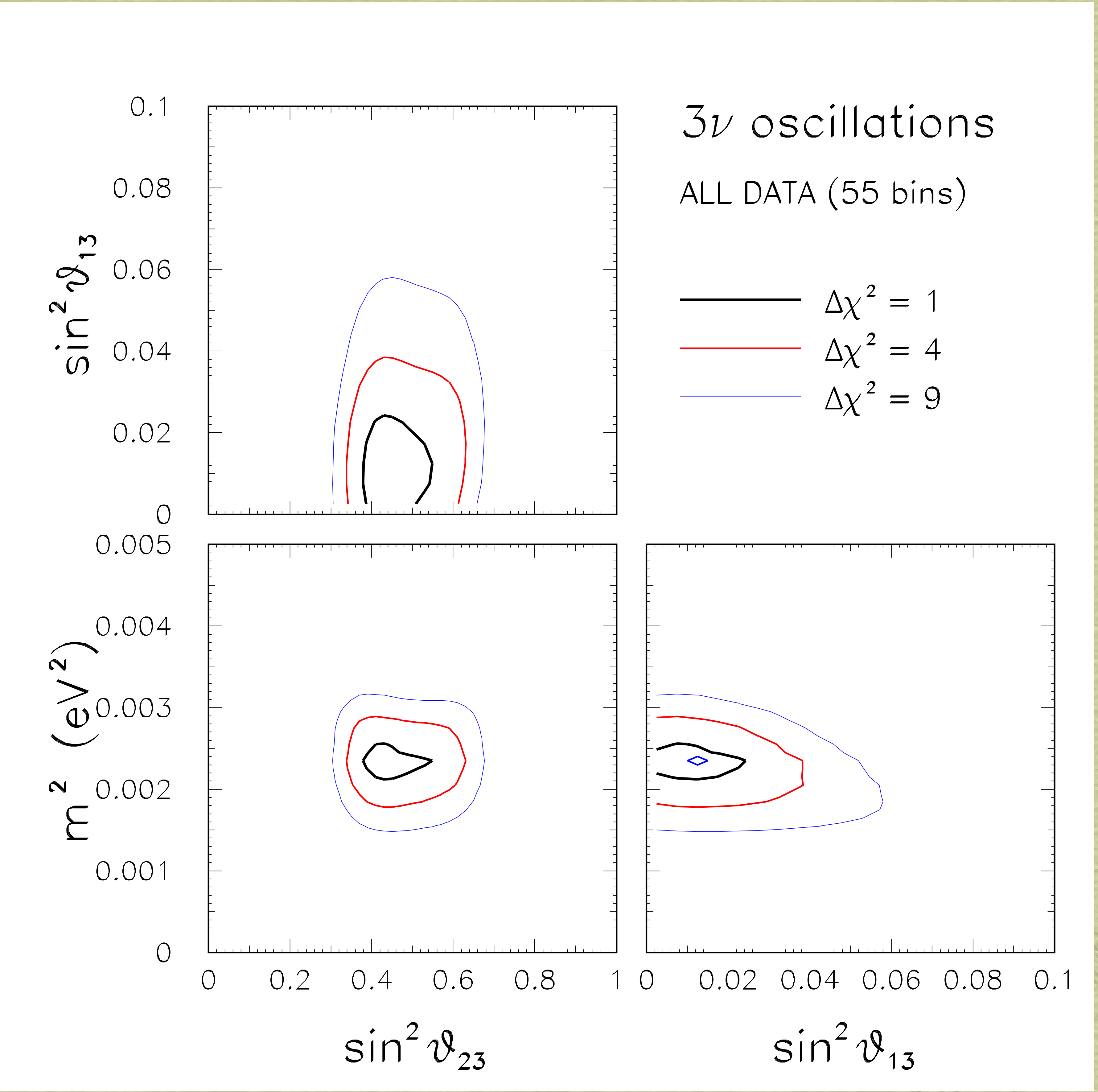
- slight increase of Δm^2 best-fit value

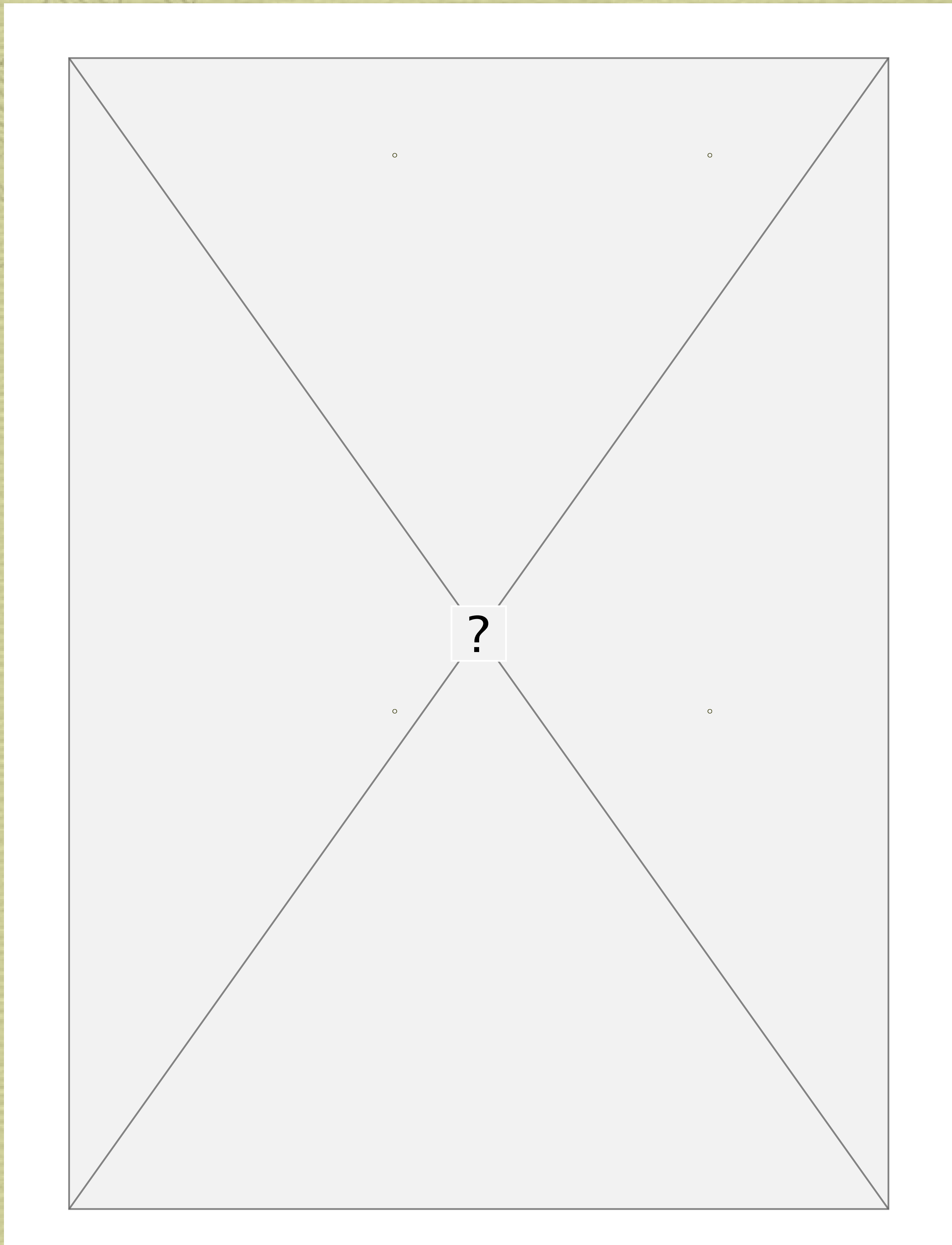
- reduced and more symmetrical errors on Δm^2

- but no effect on θ_{23}

SK alone prefers $\theta_{13} \sim 0$ but does not put a strong upper limit (contours in this figure would be open in θ_{13} without CHOOZ)

CHOOZ reactor experiment did not observe $\bar{\nu}_e$ disappearance driven by non-zero values of θ_{13}





effect of the hierachy
and/or δ_{CP} is very small

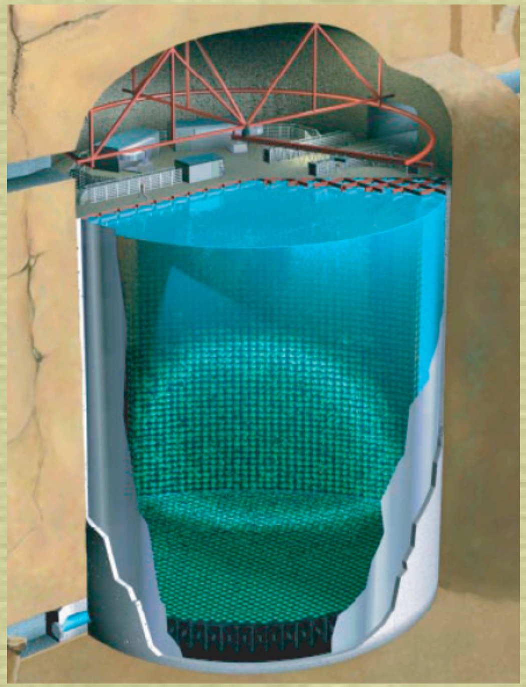
Actually, systematics in SK
overcome all these effects
(that are of few % order)

SK is not able to distinguish between
the different possibilities

Solar Neutrino Oscillations

$$\left\{\begin{array}{l}\delta m^2 \\ \theta_{12}\end{array}\right. \quad + \quad \theta_{13}$$

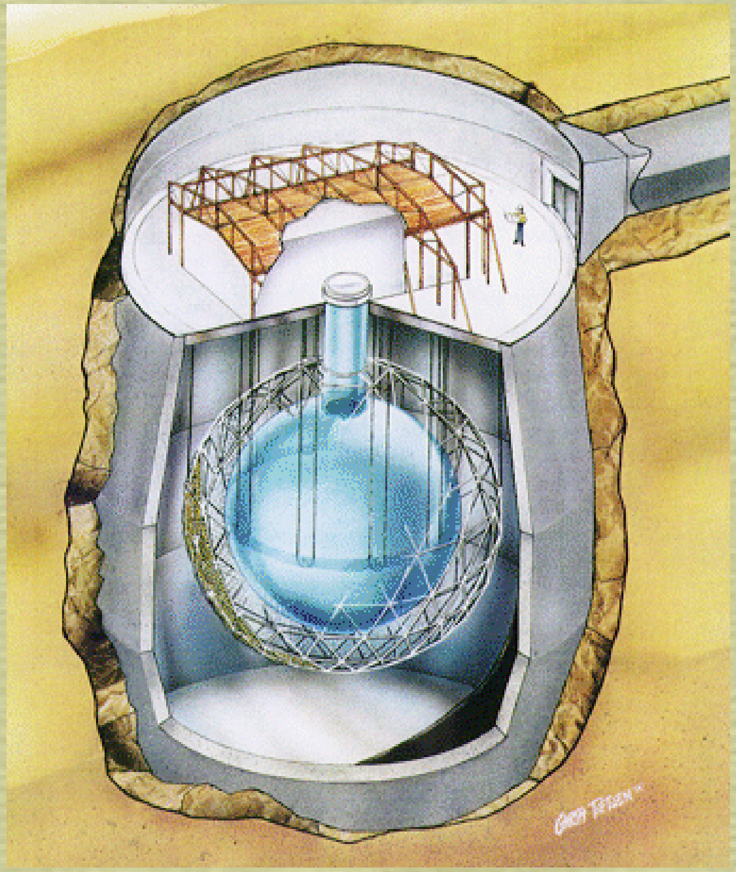
Total number of solar (SK+SNO) neutrino events ~ 30000

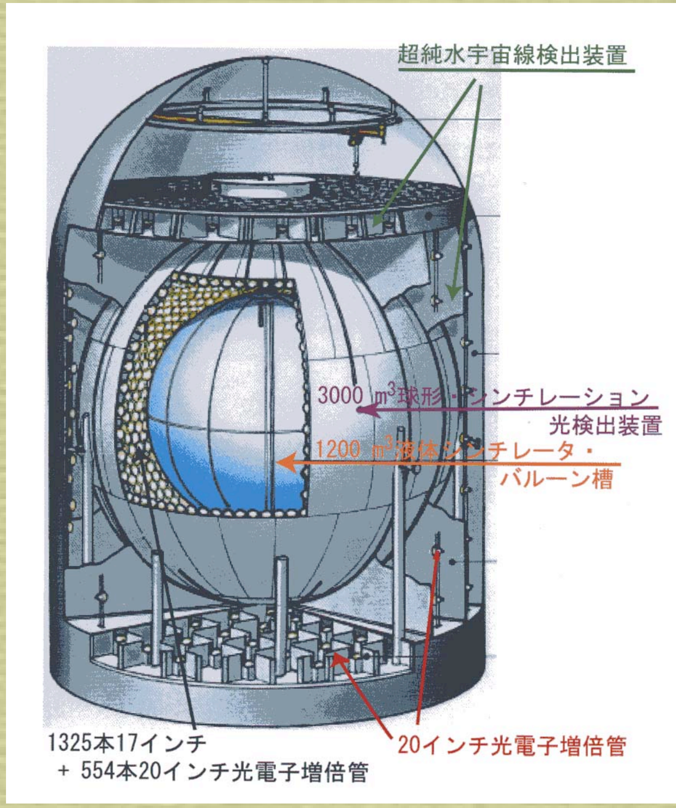


SuperKamiokande

Cl & Ga

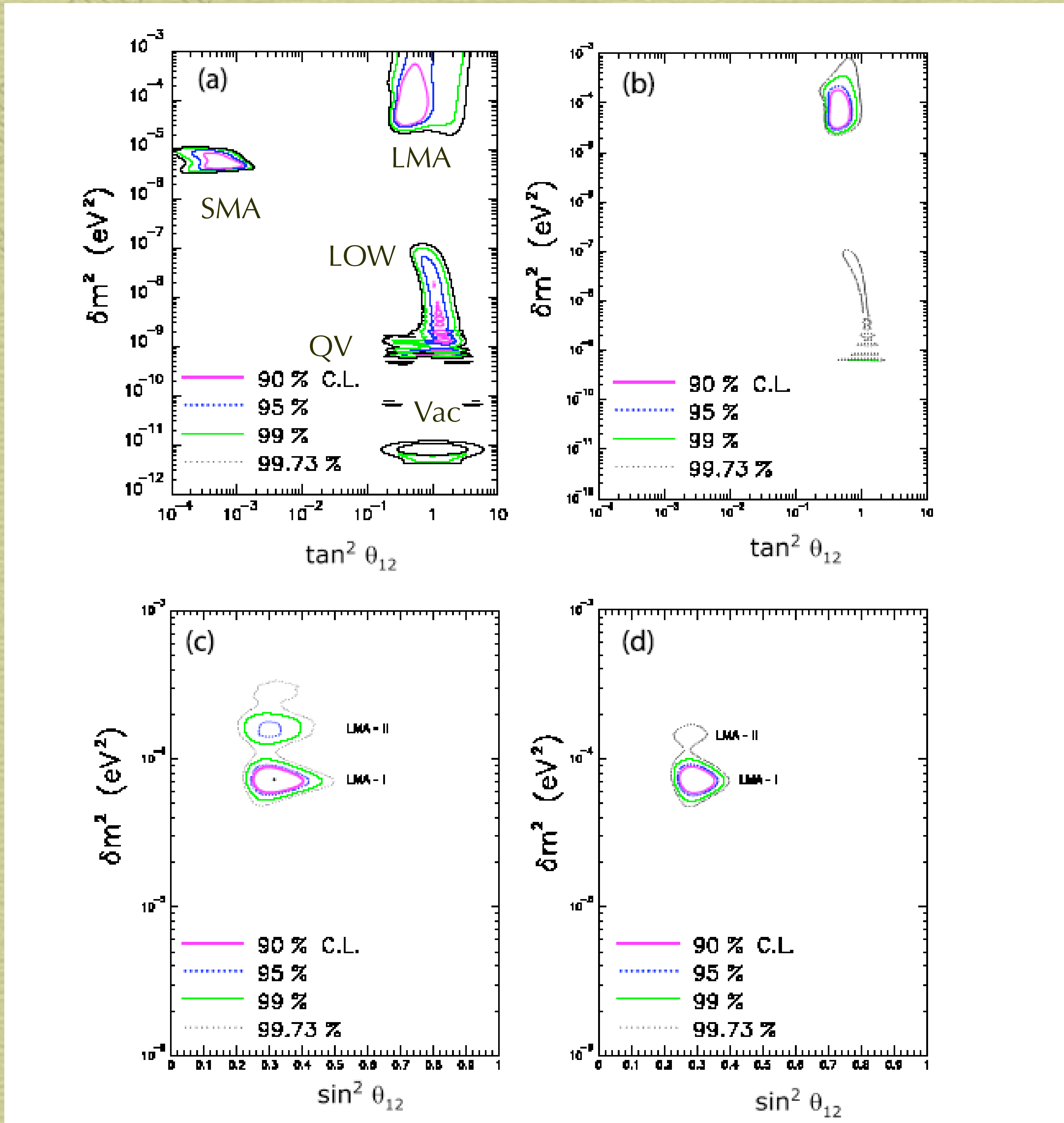
SNO





KamLAND

(258 events)



(a) Cl+Ga+SK (2001)

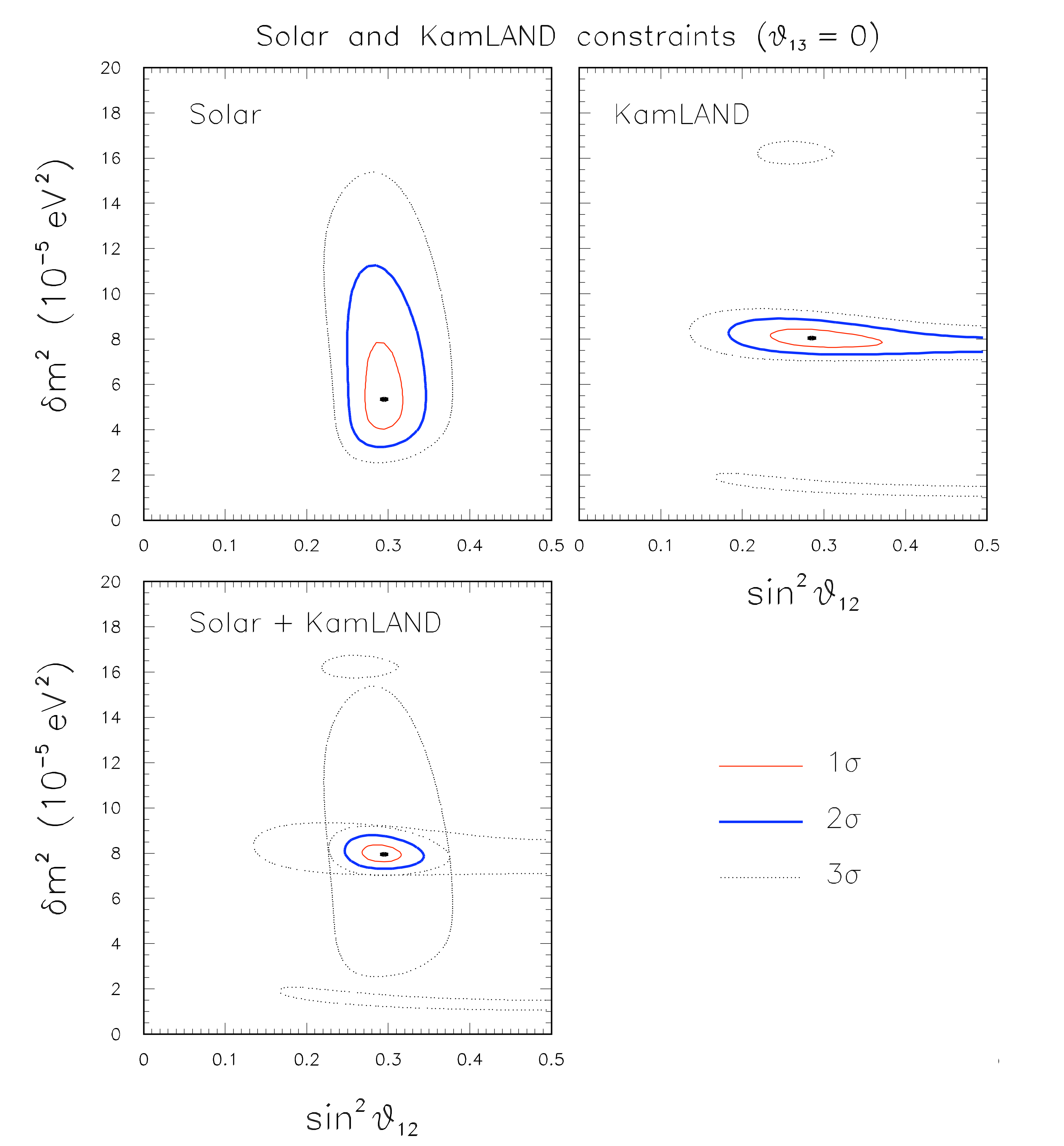
(b) + SNO I (2001-2002)

(c) + KamLAND (2002)

(d) + SNO II (2003)

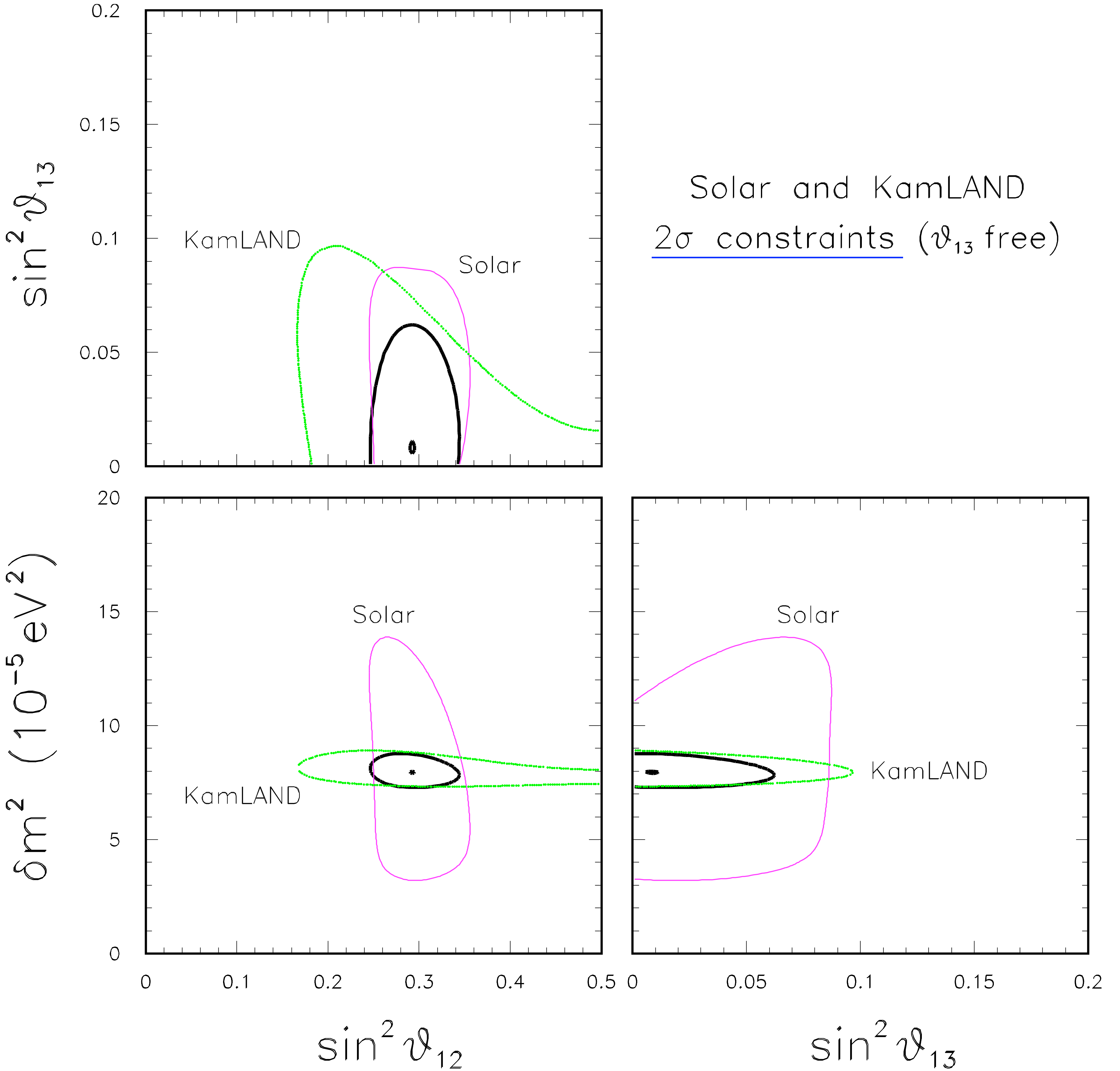
Solar DATA alone determine the LMA solution after SNO I-II

The observed KamLAND spectrum suppression strongly reduce the allowed δm^2 range and definitively rules out the old small, low, quasi-vacuum and vacuum solutions



As in the atmospheric case $\theta_{13} \sim 0$ is preferred

Even if θ_{13} is free to be non-zero the allowed range of δm^2 and of θ_{12} are not significantly enlarged



Recent final SNO II salt phase DATA

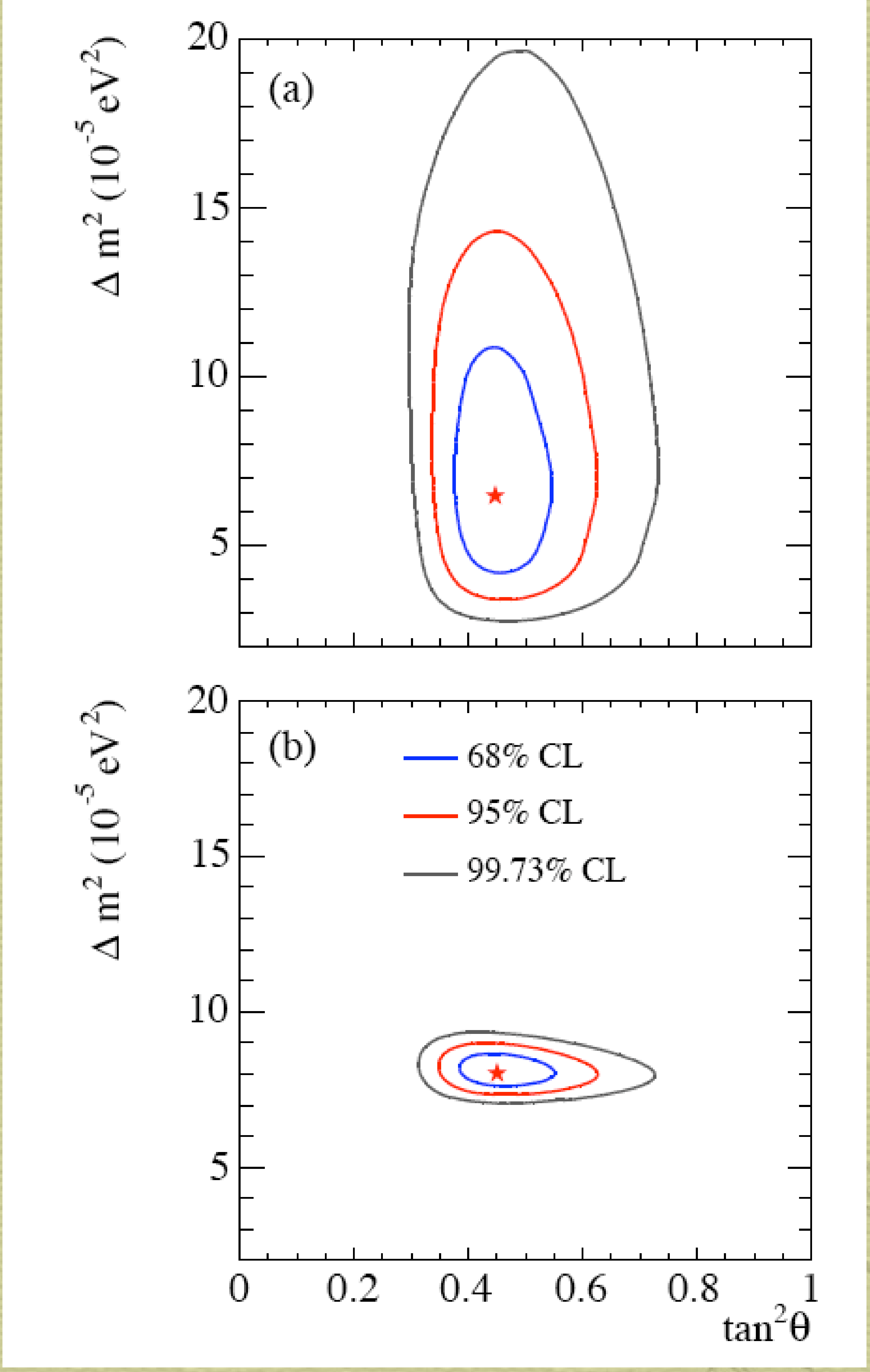
Previous results confirmed

Changes:

CC/NC ratio increased:
higher values of θ_{12} preferred

New systematics introduced,
no significant reduction of the
allowed regions

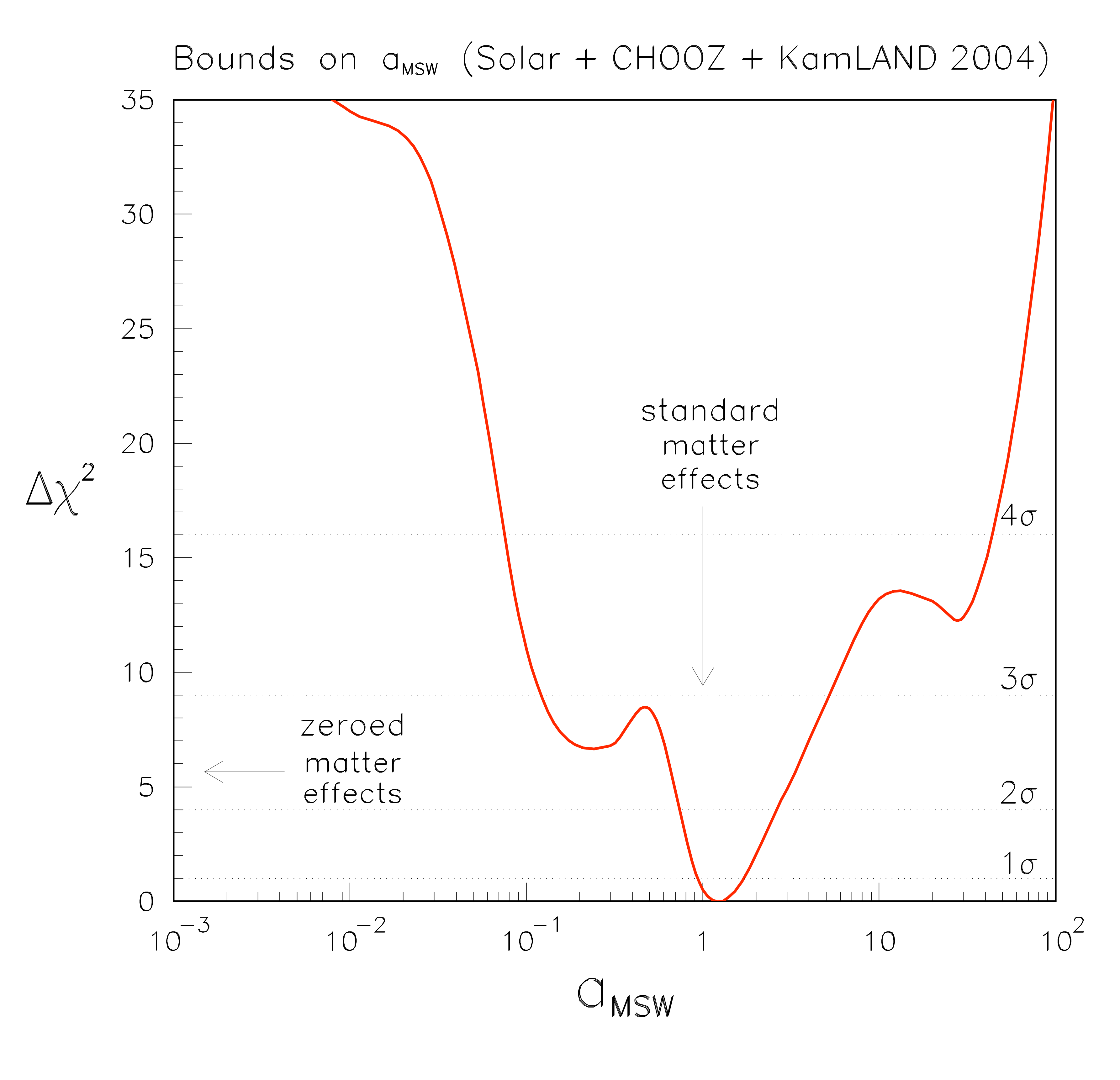
Oscillation analysis	Δm^2 (10^{-5} eV^2)	$\tan^2\theta$
SNO-only	$5.0^{+6.2}_{-1.8}$	$0.45^{+0.11}_{-0.10}$
Global solar	$6.5^{+4.4}_{-2.3}$	$0.45^{+0.09}_{-0.08}$
Solar plus KamLAND	$8.0^{+0.6}_{-0.4}$	$0.45^{+0.09}_{-0.07}$



Matter effects can be parametrized by a multiplicative constant *a*
(*a*=0 no matter, *a* = 1 standard matter)

This amounts to change the MSW potential V-> *a*V

When a is considered as a free parameter the analysis prefers *a*~1



a = 0 is completely excluded

Confirmation of MSW effect in the Sun

Absolute Masses

Three "observables"

$$m_\beta = \sqrt{c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2}$$ Mainz & Troitsk

$$m_{\beta\beta} = |c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi 3}|$$ $0\nu 2\beta$

$$\Sigma = m_1 + m_2 + m_3$$ Cosmology

8 independent parameters: three angles, three masses and two phases

$$\chi^2_{Global} = \chi^2_{osc}(\Delta m^2, \delta m^2, \theta_{12}, \theta_{13}, \theta_{23}) + \chi^2_\beta(m_\beta) + \chi^2_{\beta\beta}(m_{\beta\beta}) + \chi^2_{cos}(\Sigma)$$

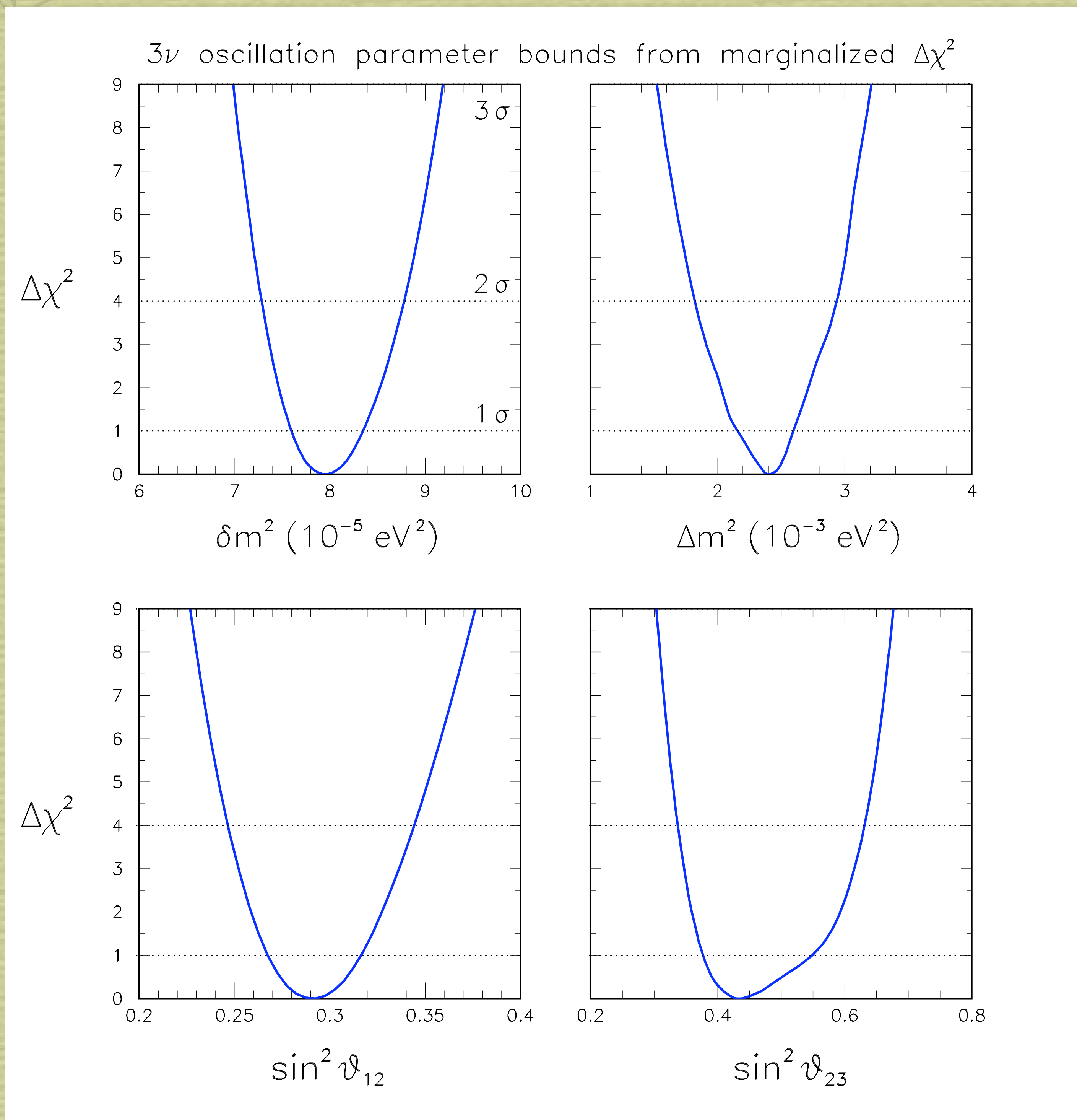
We marginalize over 5 osc. parameters $(\Delta m^2, \delta m^2, \theta_{12}, \theta_{13}, \theta_{23})$

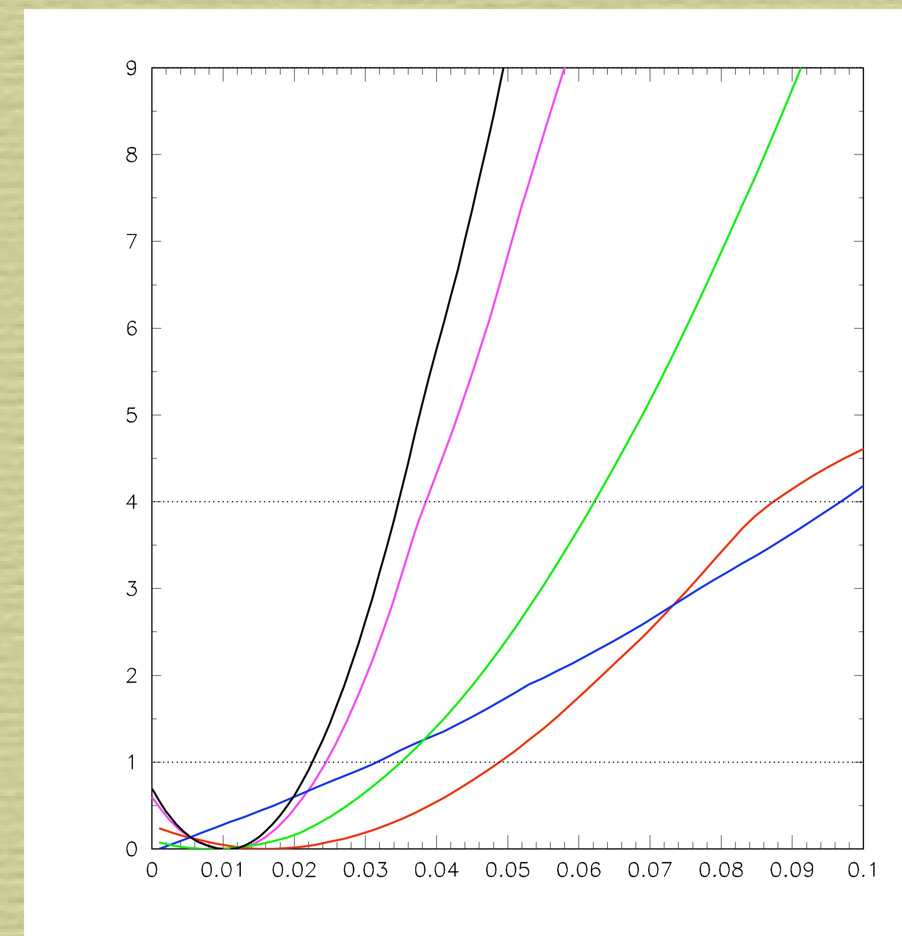
$(\Sigma, m_\beta, m_{\beta\beta})$

and use in the analysis

Global results of oscillation phenomenology as input to the absolute mass analysis

Allowed region for each oscillation parameter
after marginalization over the others





$\delta m^2 \simeq 8.0^{+0.8}_{-0.7} \times 10^{-5}\ \mathrm{eV}^2$

$\Delta m^2 \simeq 2.4^{+0.5}_{-0.6} \times 10^{-3}\ \mathrm{eV}^2$

$\sin^2\theta_{12} \simeq 0.29^{+0.05}_{-0.04}$ (SNO '05 : $0.29 \to 0.31$)

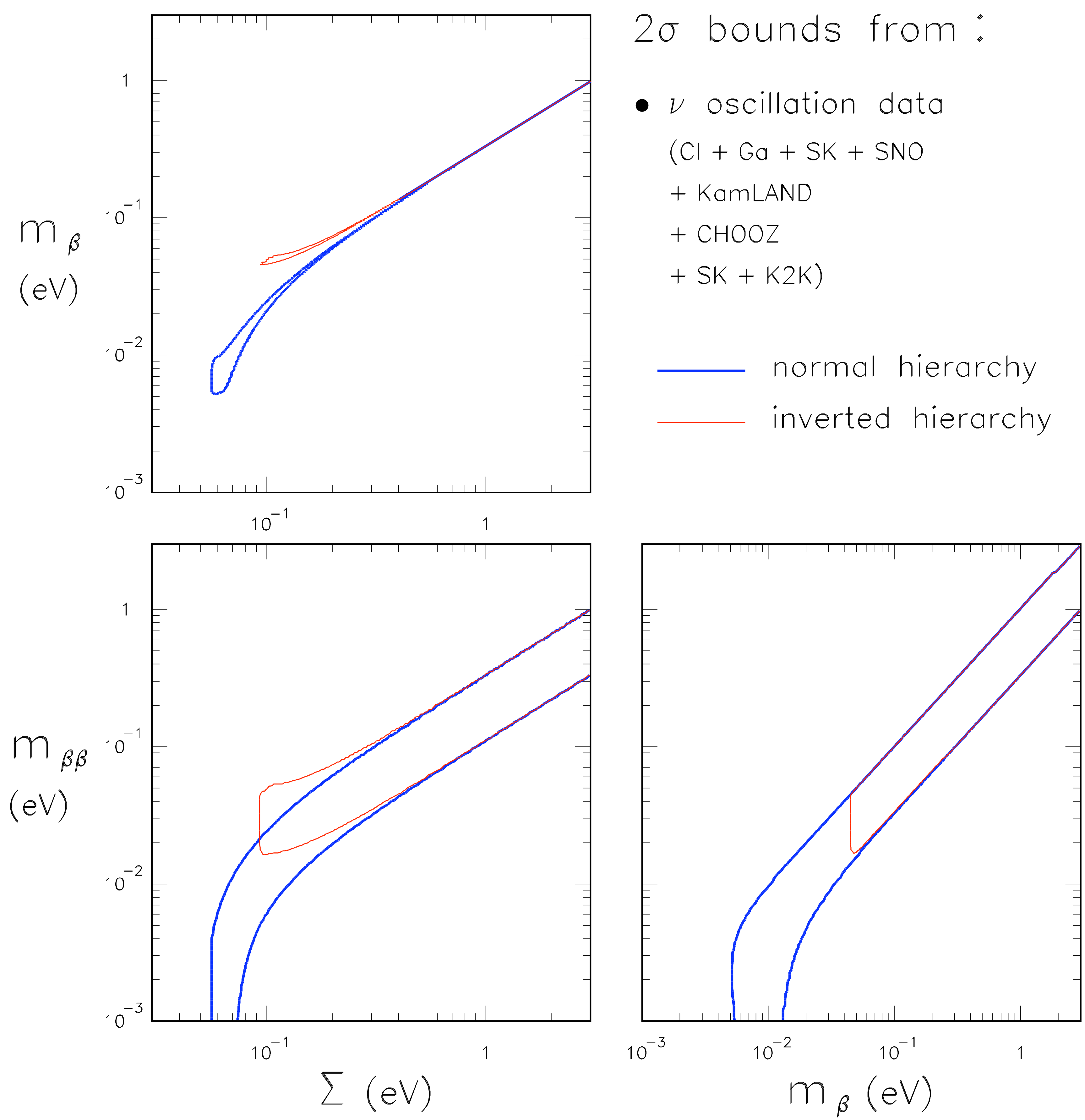
$\sin^2\theta_{23} \simeq 0.45^{+0.18}_{-0.11}$

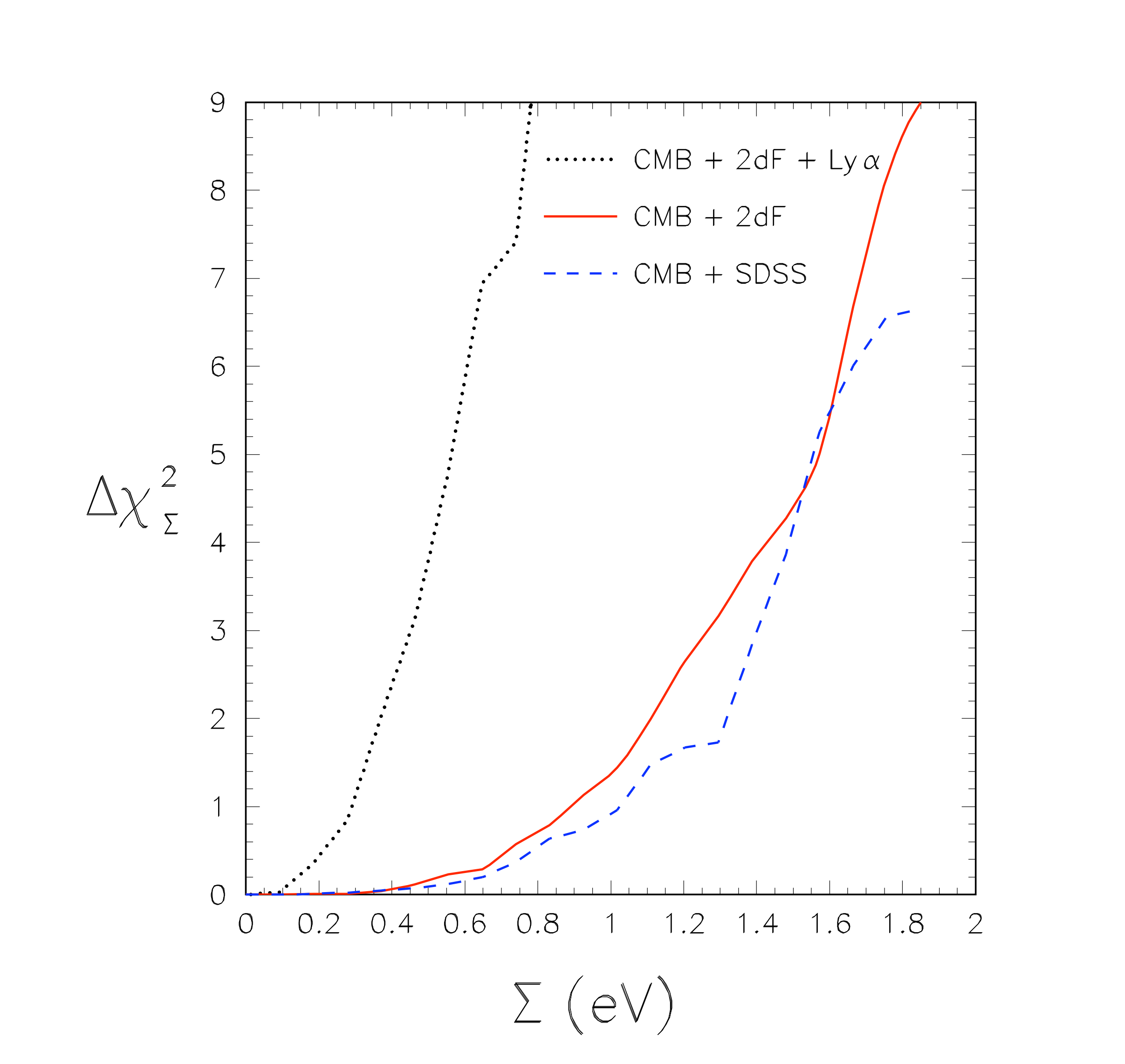
$\sin^2\theta_{13} <\sim 0.035$

Oscillation analysis constrains the $(\Sigma, m_\beta, m_{\beta\beta})$ parameter space

Above 0.5 eV Normal and Inverted hierarchy are not distinguishable

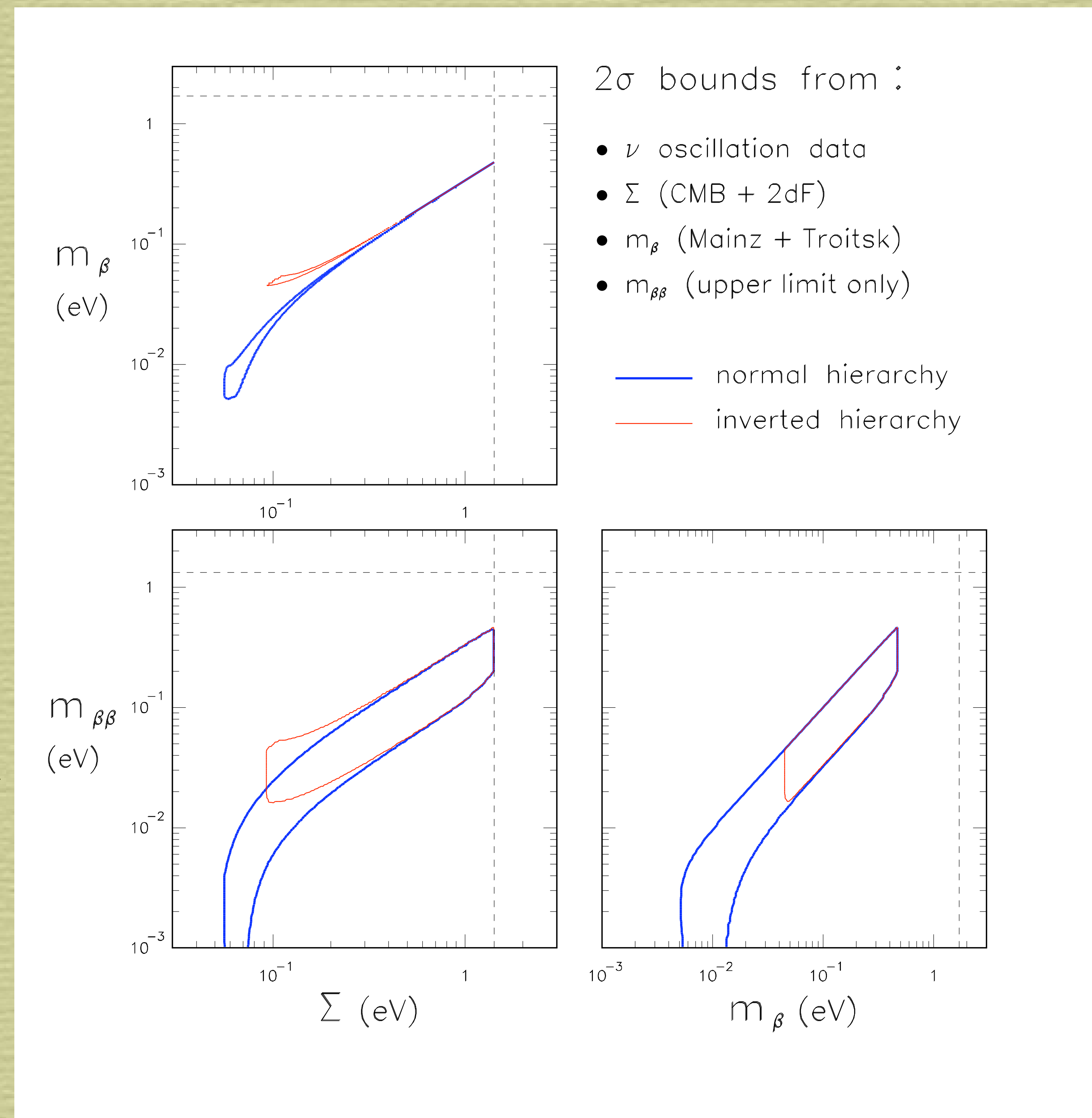
Degeneracy in $m_{\beta\beta}$ induced by the two Majorana phases





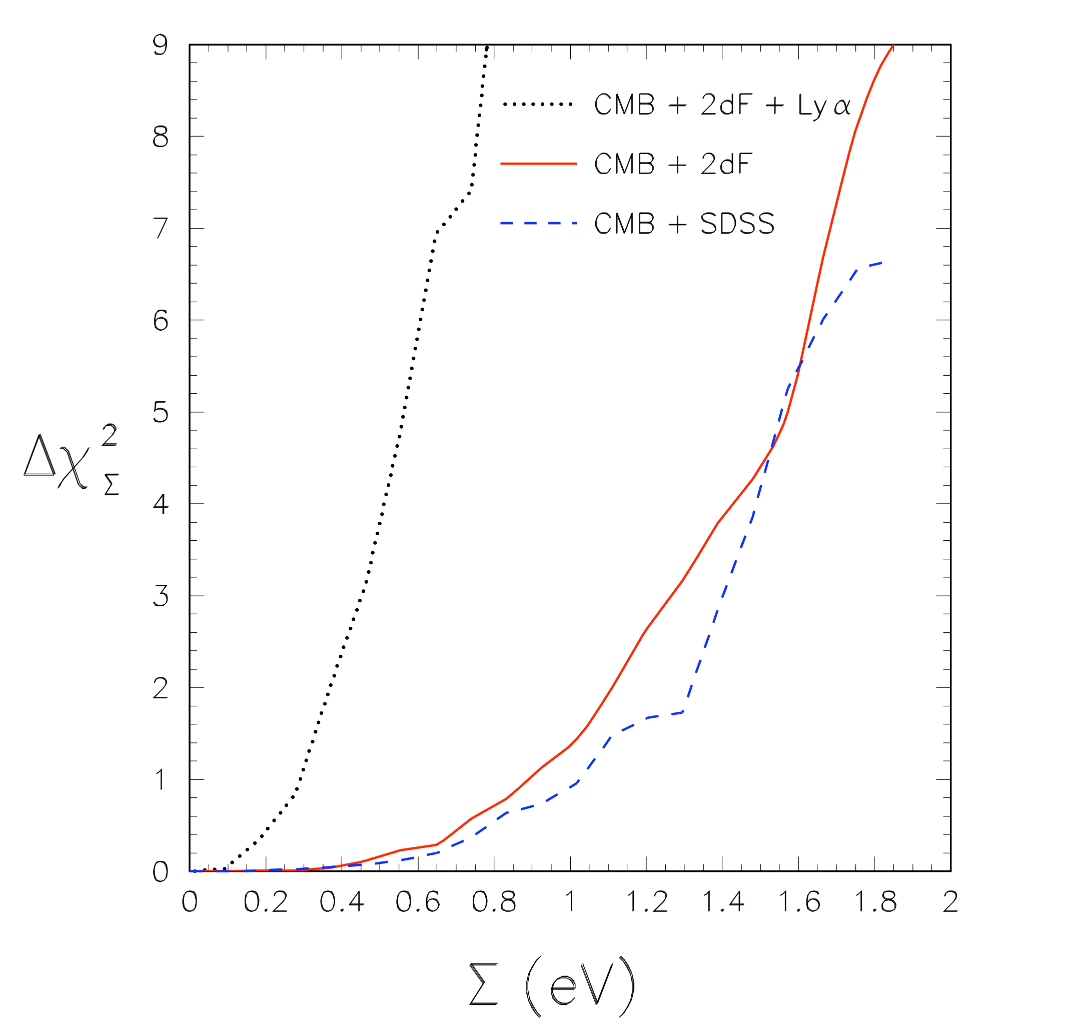
Limits from “cosmology” of order ~1 eV

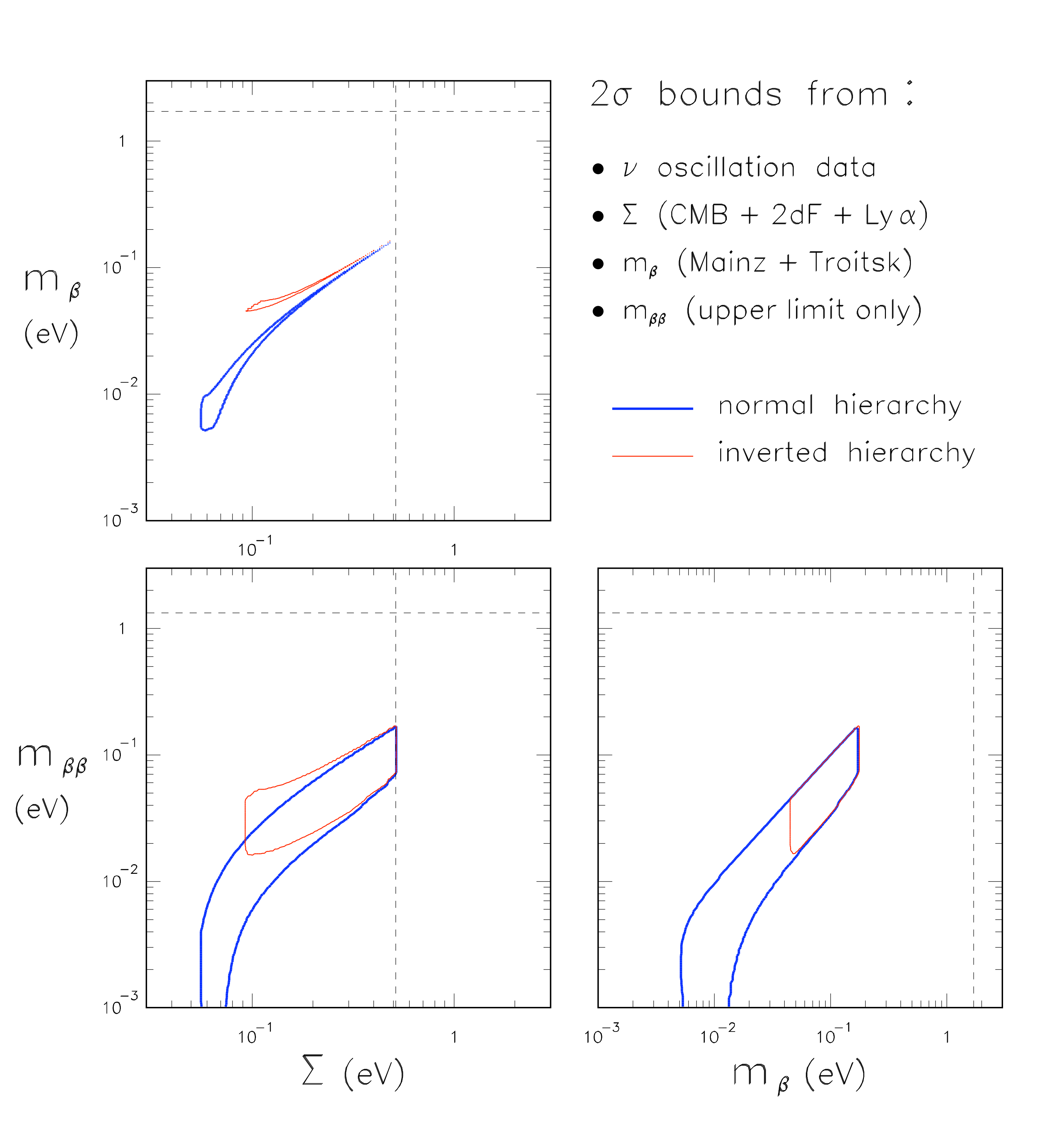
The inclusion of Ly α Forest in SDSS improves the constraints on Σ



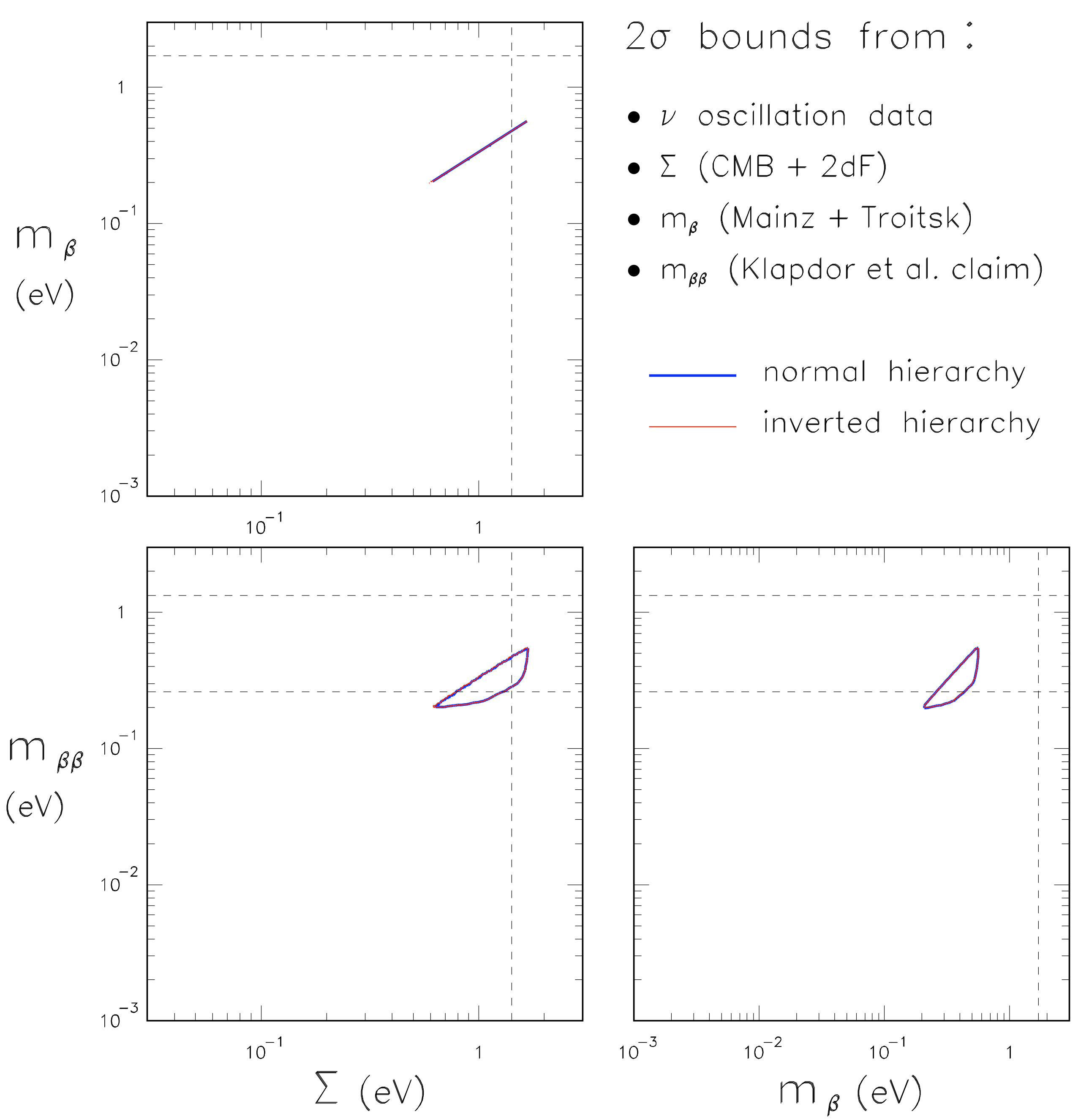
Limits from cosmology (vertical dashed line) more stringent than *negative* limits from beta decay (horizontal dashed line)

To probe the nature of the spectrum sensitivity of cosmological data should be at the level of less than 0.3 eV



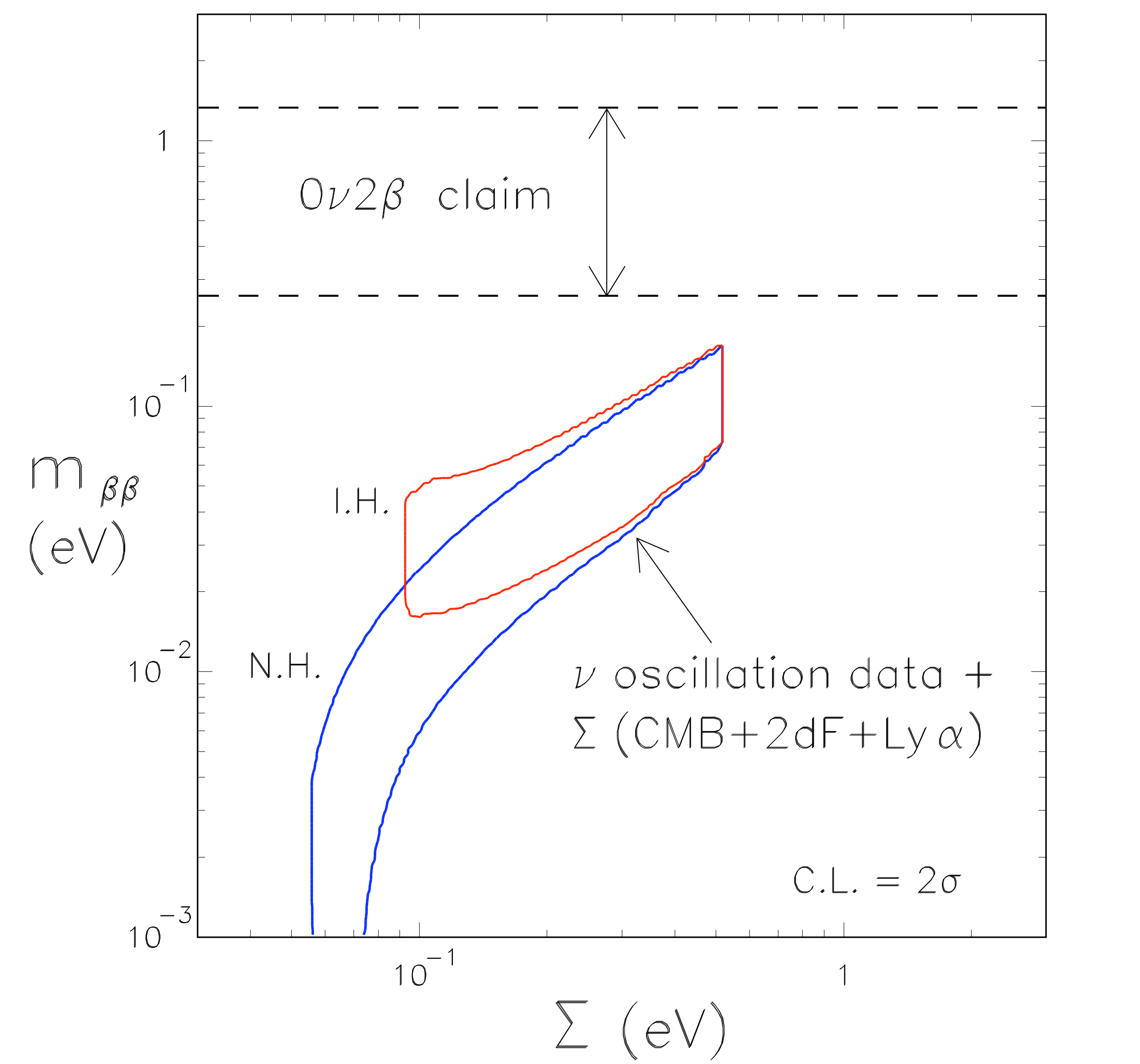


The inclusion of Ly α Forest allows to get a sub-eV limit on the sum of neutrino masses



"Small" allowed regions if the Klapdor claim of a positive signal in the Heidelberg-Moscow experiment is accepted but there is clearly a tension with the cosmological bound on Σ

The cosmological upper limit on the sum of the neutrino masses "induces" an upper limit on $m_{\beta\beta}$ that is in contrast with the Klapdor claim



SUMMARY

mass & mixings

3 flavor neutrino oscillations well established $\longrightarrow$

$(\Delta m^2, \theta_{23})$ SK + K2K $\nu_\mu \leftrightarrow \nu_\tau$

$(\delta m^2, \theta_{12})$ (LMA) Solar + KamLAND

θ_{13} only upper limit

No information on Hierarchy and δ_{CP}

SNO gives direct evidence of solar neutrino flavor transitions

MSW effect in the Sun

Absolute masses $\longrightarrow$ Limits at the level of ~1 eV

Combined analysis of oscillatory and non-oscillatory data:

Difficult to test the nature of the spectrum but upcoming experiments have great discovery potential