Rencontres de Moriond March 2005

Neutrino mass and mixing parameters - a short review -

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Outline:

- Overview of 3ν mass-mixing parameters
- Constraints from ν oscillation searches
- Constraints from non-oscillation searches
- Combining oscill. & non-oscill. ν observables
- Beyond the standard 3ν scenario (LSND)
- Conclusions

Organizers' request: "*Talk should be a short introduction aimed at PhD students in experimental (non-neutrino) particle physics*"
→ I shall skip all refs. or details for ν experts/theorists, with apologies to colleagues (for more info, see Proceedings or ask me)

3ν mixing

- Neutrinos mix (as quarks do): $$(\nu_e,\, \nu_\mu,\, \nu_\tau)^T = U\,(\nu_1,\, \nu_2,\, \nu_3)^T$$

- The standard rotation ordering of the CKM matrix for quarks happens to be useful also for neutrinos:

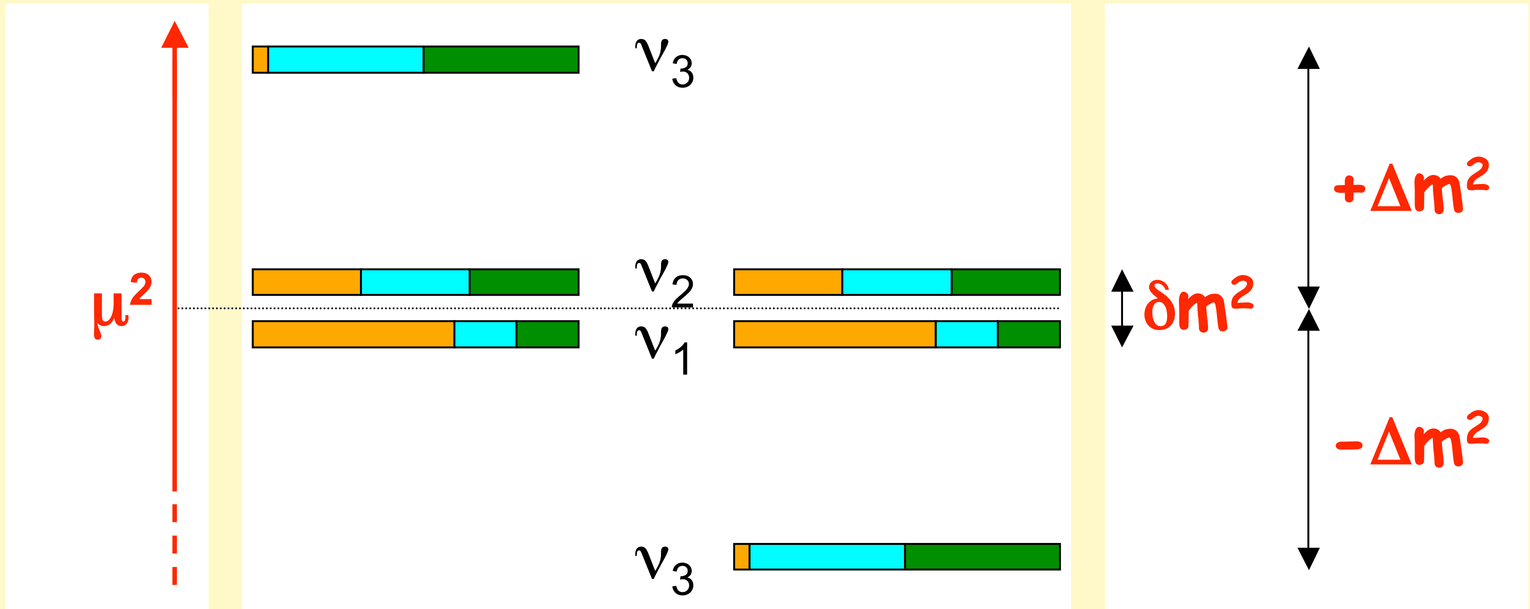
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

… but with very different angles:

$$s_{23}^2 \sim 0.5 \qquad s_{13}^2 < \text{few}\,\% \qquad s_{12}^2 \sim 0.3$$

- **Only if $s^2_{13} \neq 0$ one can hope to probe the CP-violating phase δ** (“holy grail” of future ν oscillation experiments ⇒ *see Kayser’s talk*)

3ν mass^2 spectrum and flavor content (e μ τ)



Absolute mass scale μ unknown [but < O(eV)]
Hierarchy [sign(Δm^2)] unknown
ν_e content of ν_3 unknown [but < few%]

$\delta m^2 \simeq 8.0 \times 10^{-5}\ \mathrm{eV}^2$ ("solar" splitting)
$\Delta m^2 \simeq 2.4 \times 10^{-3}\ \mathrm{eV}^2$ ("atmospheric" splitting)

3ν oscillations

$U \neq \mathbf{1} \Rightarrow$ Flavor is not conserved as neutrinos propagate

$m_i \ll E_i \Rightarrow$ $E_i = \sqrt{p^2 + m_i^2} \simeq p + \dfrac{m_i^2}{2p}$

$\Delta E \Delta t \sim 1 \Rightarrow$ Oscill. phase: $1.27 \dfrac{|m_i^2 - m_j^2|(\mathrm{eV}^2)}{E(\mathrm{GeV})} L(\mathrm{km}) \sim O(1)$

Two macroscopic oscillation lengths governed by δm^2 and Δm^2, with amplitudes governed by θ_{ij}. Leading expt. sensitivities:

$(\Delta m^2, \theta_{23}, \theta_{13})$ Atmospheric ν, K2K long baseline accelerator [(a)]

$(\delta m^2, \theta_{12}, \theta_{13})$ Solar ν, KamLAND long baseline reactor ν [(b)]

$(\Delta m^2, \theta_{13})$ CHOOZ short-baseline reactor ν [(a,b)]

(a) (ν_1, ν_2) difference weakly probed

(b) (ν_μ, ν_τ) difference not probed

Constraints on (Δm^2, θ_{23}, θ_{13}) from SK + K2K + CHOOZ

See talks by Sulak (SK) and Mariani (K2K)

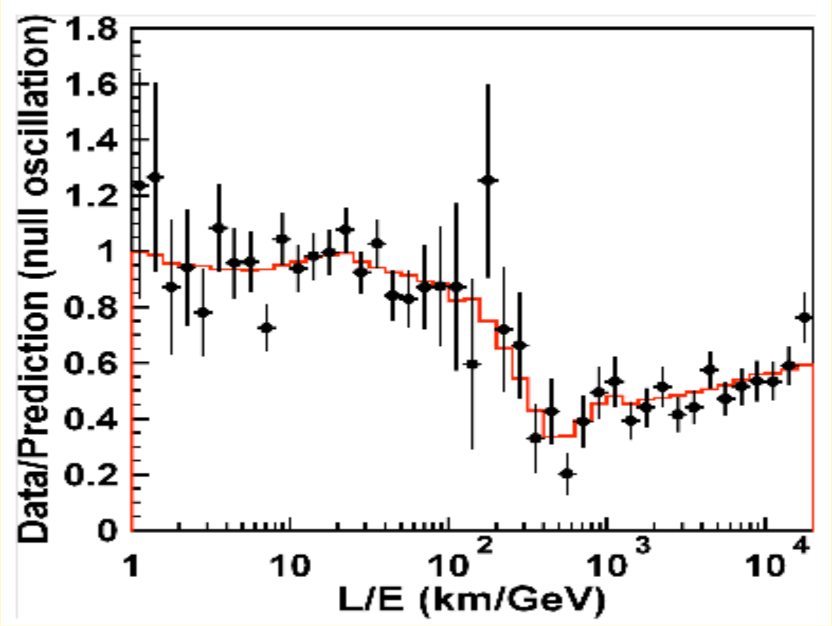
Super-Kamiokande atmospheric ν

$$E_\nu \sim 10^{-1}\text{–}10^3 \text{ GeV} \qquad L \sim 10\text{–}10^4 \text{ km} \qquad (\text{large } L/E \text{ range})$$

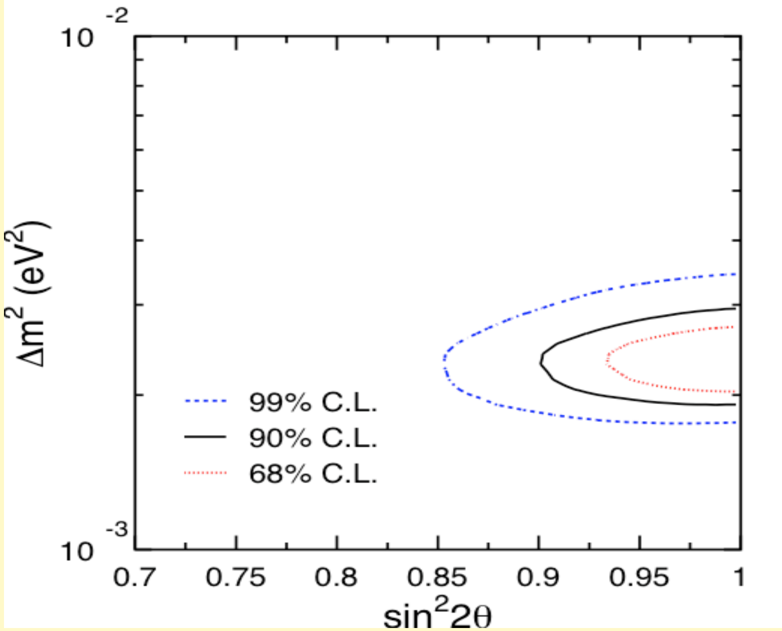
For θ_{13}~0 and δm^2~0, a very simple formula fits all SK data (+ MACRO & Soudan2)

$$P(\nu_\mu \to \nu_\tau) \simeq \sin^2 2\theta_{23} \sin^2 \left(1.27 \frac{\Delta m^2 (\text{eV})^2 \, L(\text{km})}{E(\text{GeV})}\right)$$

1st oscillation dip still visible despite large L & E smearing

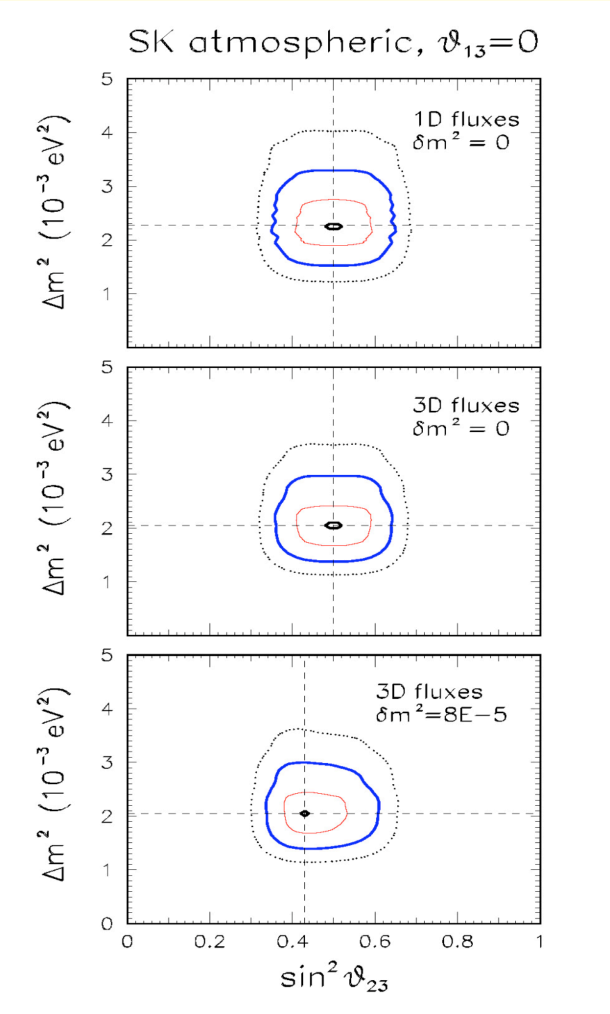


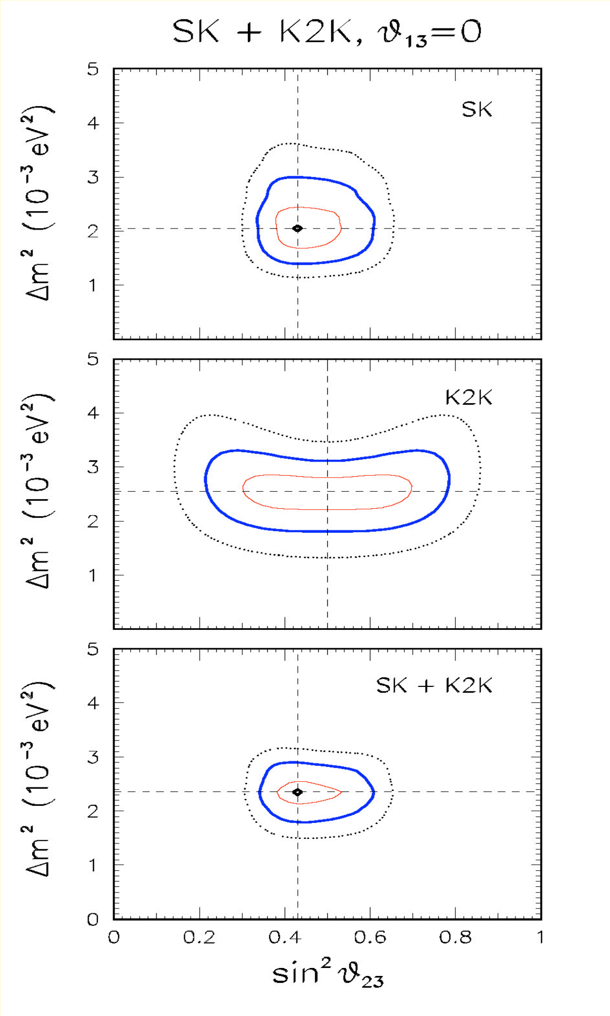
Strong constraints on the parameters (Δm^2, θ_{23})



Atmospheric ν oscillation evidence robust & confirmed with lab-ν in K2K

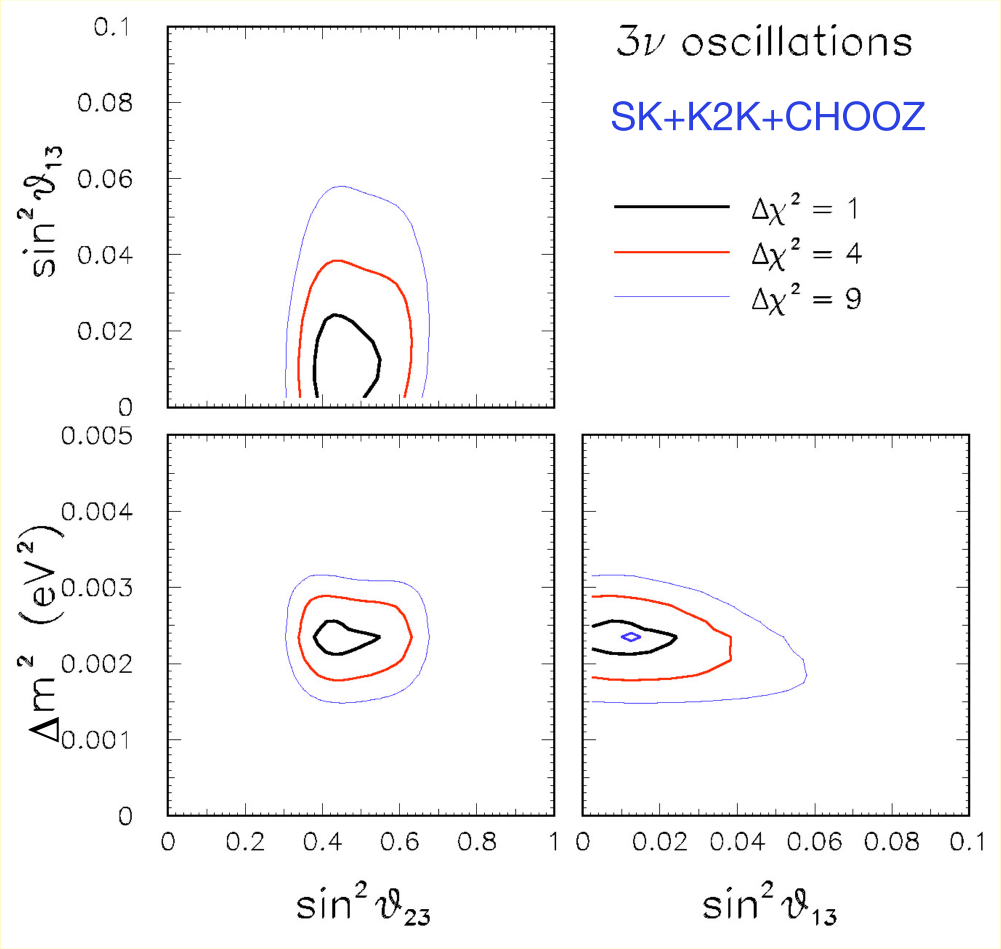
Many interesting details depend on theoretical input & subleading effects





Contours at 1, 2, 3σ (1 dof). Note linear scale for Δm^2 and $\sin^2\theta_{23}$, with 2nd octant of θ_{23} unfolded

At the Δm^2 scale of SK+K2K, nonobservation of $\nu_e \rightarrow \nu_e$ in the CHOOZ reactor experiment sets strong upper bounds on θ_{13}



Growing literature & interest in subleading effects due to θ_{13}, δm^2, sign(Δm^2), δ

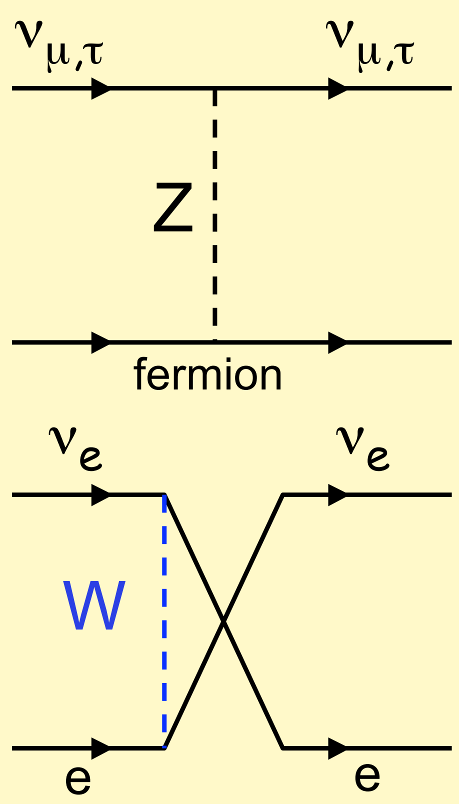
But need very significant error reduction to probe them

A challenge for future high-statistics experiments

Constraints on (δm^2, θ_{12}, θ_{13}) from solar ν + KamLAND

See talks by Sulak (SK), Berger (kamLAND), Miknaitis (new SNO data)

Solar $\nu_e \to \nu_{e,\mu,\tau}$ vs atmospheric $\nu_\mu \to \nu_\tau$: matter (MSW) effect



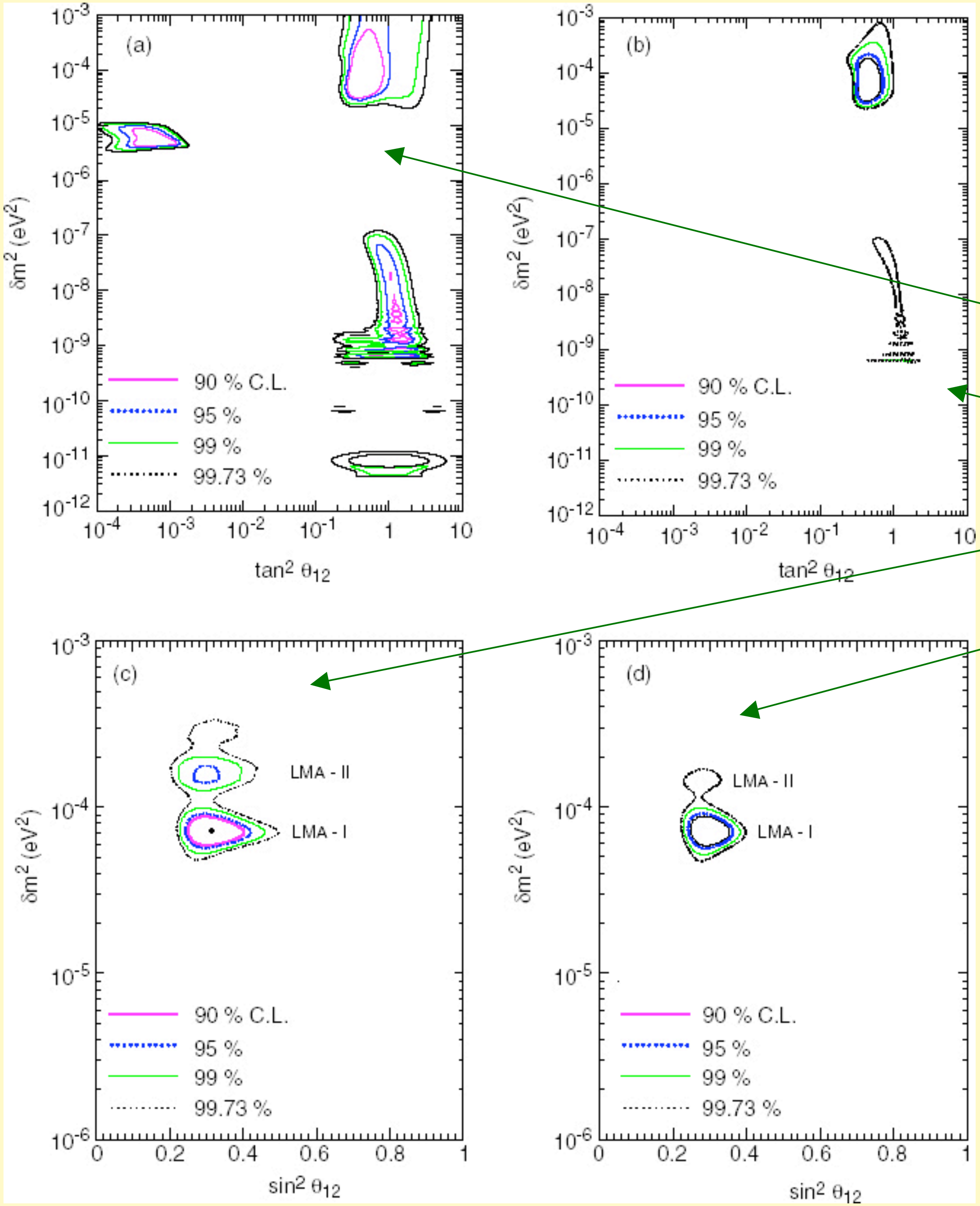
Atmospheric ν_μ and ν_τ feel background fermions in the same way (through NC); no relative phase change (~ vacuum-like)

But ν_e , in addition to NC, have CC interac. with background electrons (density N_e). Energy difference: $V = \sqrt{2}\, G_F\, N_e$

Solar ν analysis must account for MSW effects in the Sun and in the Earth

(Earth matter effects negligible for KamLAND reactor neutrinos)

Solar+KamLAND combination provide evidence for V_{sun} (not yet for V_{earth})



Dramatic reduction of the (δm^2,θ_{12}) param. space in 2001-2003

(note change of scales)

Cl+Ga+SK (2001)

+SNO-I (2001-2002)

+KamLAND-I (2002)

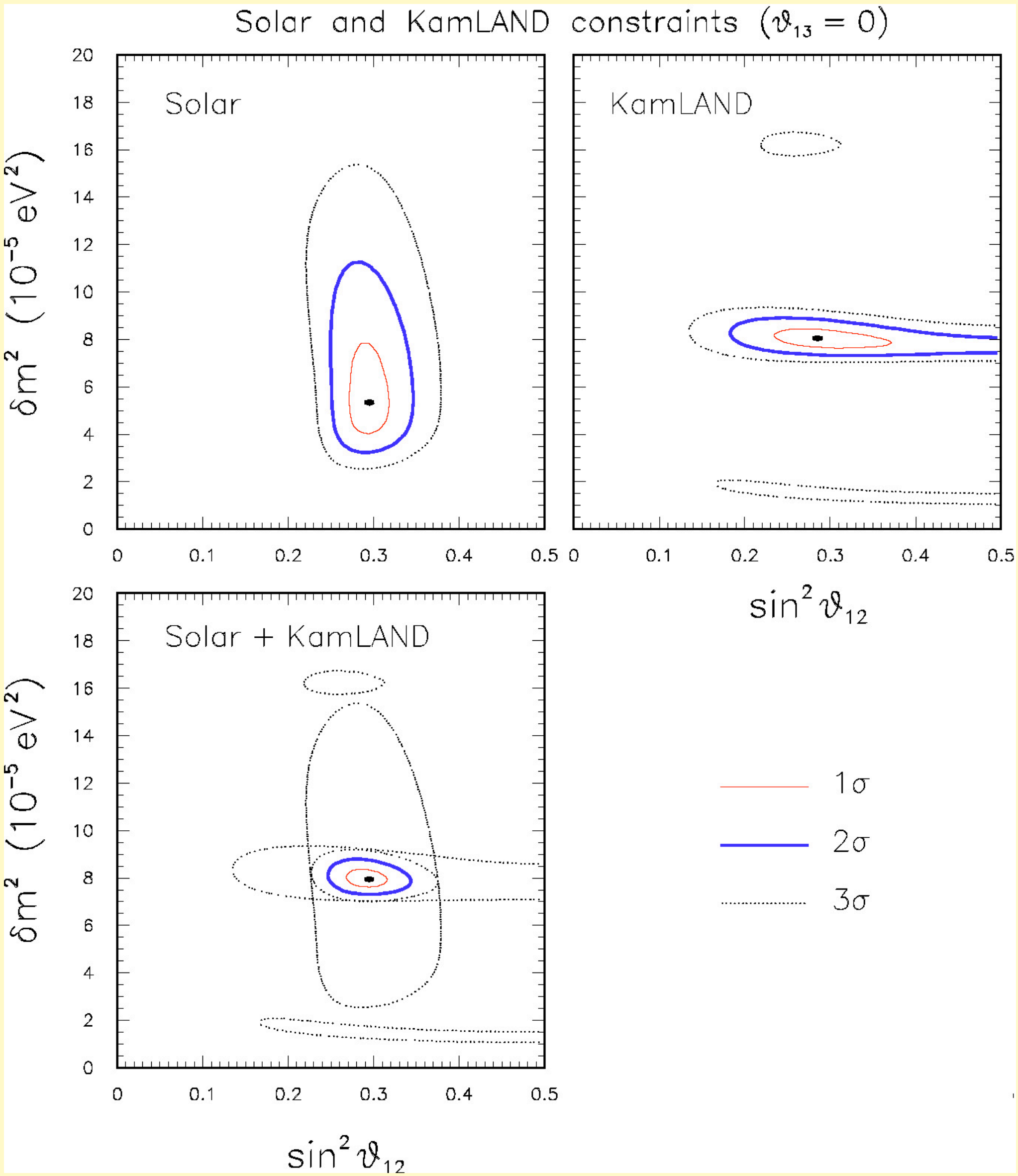
+SNO-II (2003)

(+ confirmation of solar model)

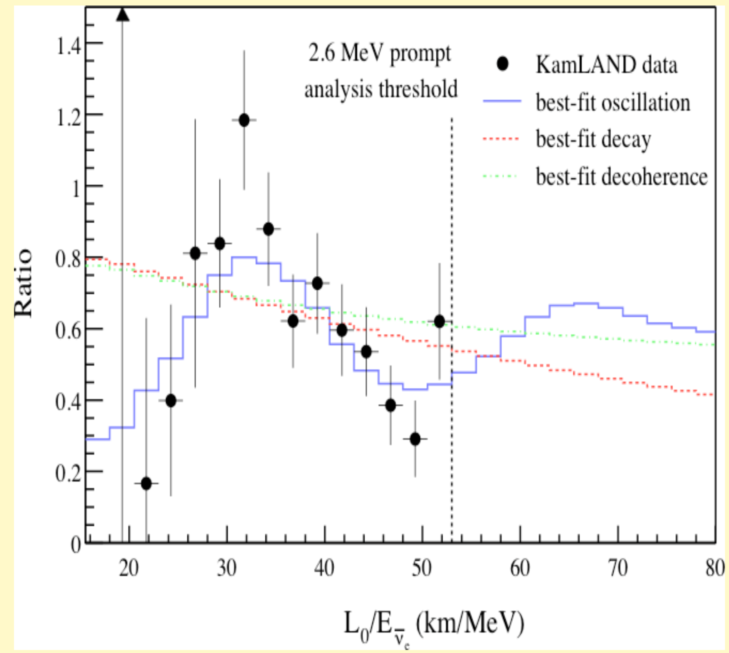
Direct proof of solar $\nu_e \to \nu_{\mu,\tau}$ in SNO through comparison of

$$\begin{aligned}
\mathrm{CC}:&\quad \nu_e + d \to p + p + e\\
\mathrm{NC}:&\quad \nu_{e,\mu,\tau} + d \to p + n + \nu_{e,\mu,\tau}\\
\mathrm{ES}:&\quad \nu_{e,\mu,\tau} + e \to e + \nu_{e,\mu,\tau}
\end{aligned}$$

… in 2004 (KamLAND-II with revised background):
unique Large Mixing Angle solution, and another change of scale…



+ evidence for oscillatory effects
in KamLAND reactor L/E spectrum

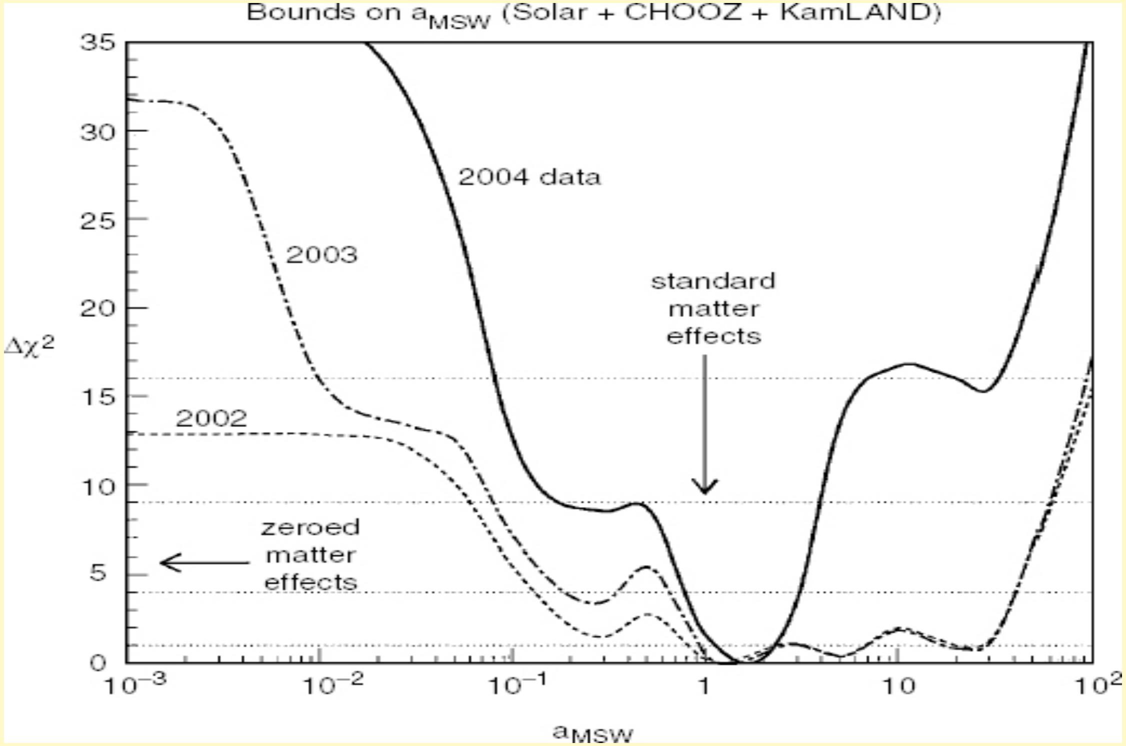


What about MSW effects?

Exercise: (1) Change MSW potential "by hand," $V \rightarrow a_{MSW} V$

(2) Reanalyze all data with $(\delta m^2, \theta_{12}, a_{MSW})$ free

(3) Project $(\delta m^2, \theta_{12})$ away and check if $a_{MSW} \sim 1$

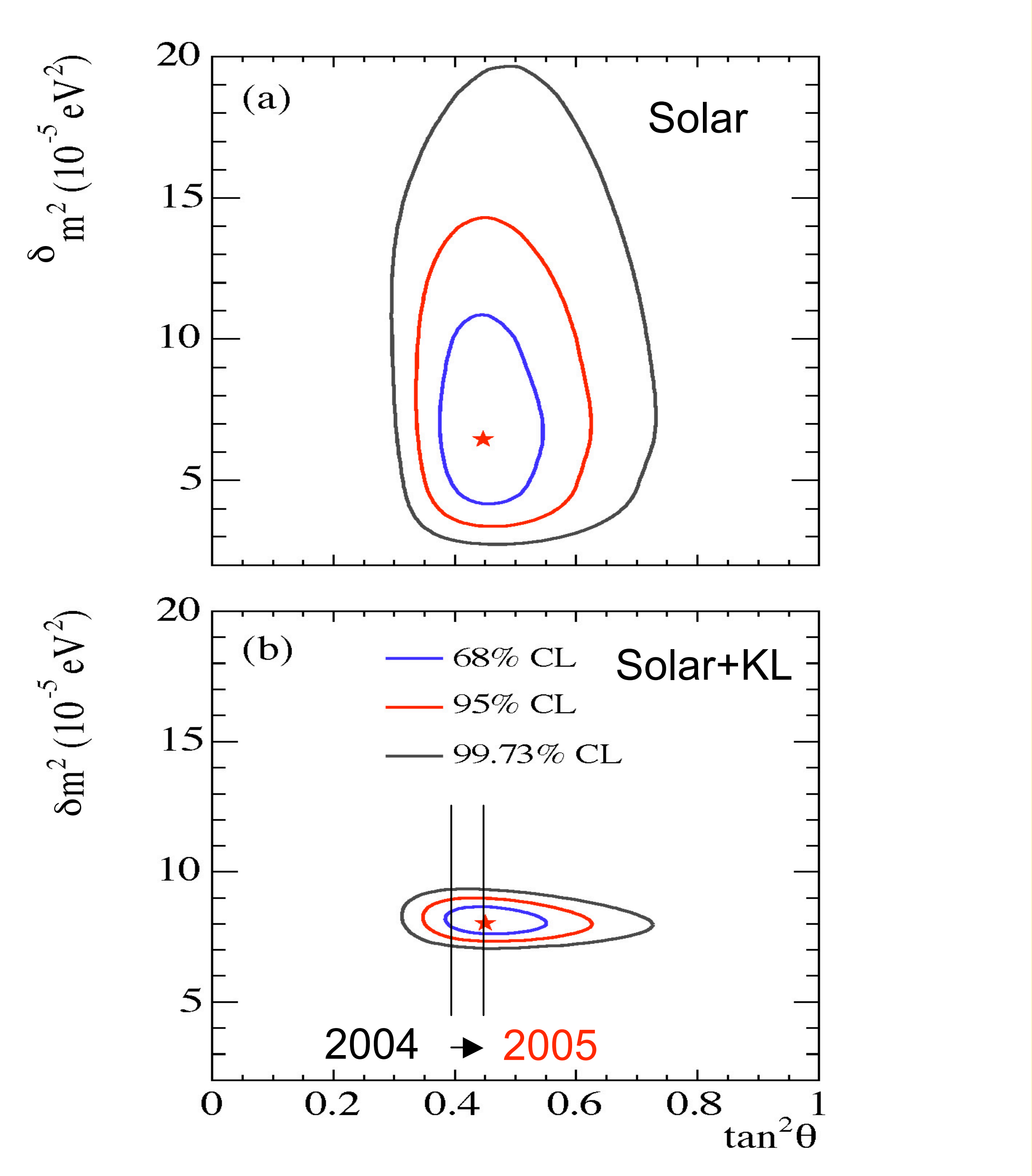


(... a way of "measuring" G_F through solar neutrino oscillations ...)

Results: with **2004** data, $a_{MSW} \sim 1$ confirmed within factor of ~2 and $a_{MSW} \sim 0$ excluded → **Evidence for MSW effects in the Sun**

But: expected subleading effect in the Earth (day-night difference) still below experimental uncertainties.

2005 (last week): new data + detailed analysis from SNO

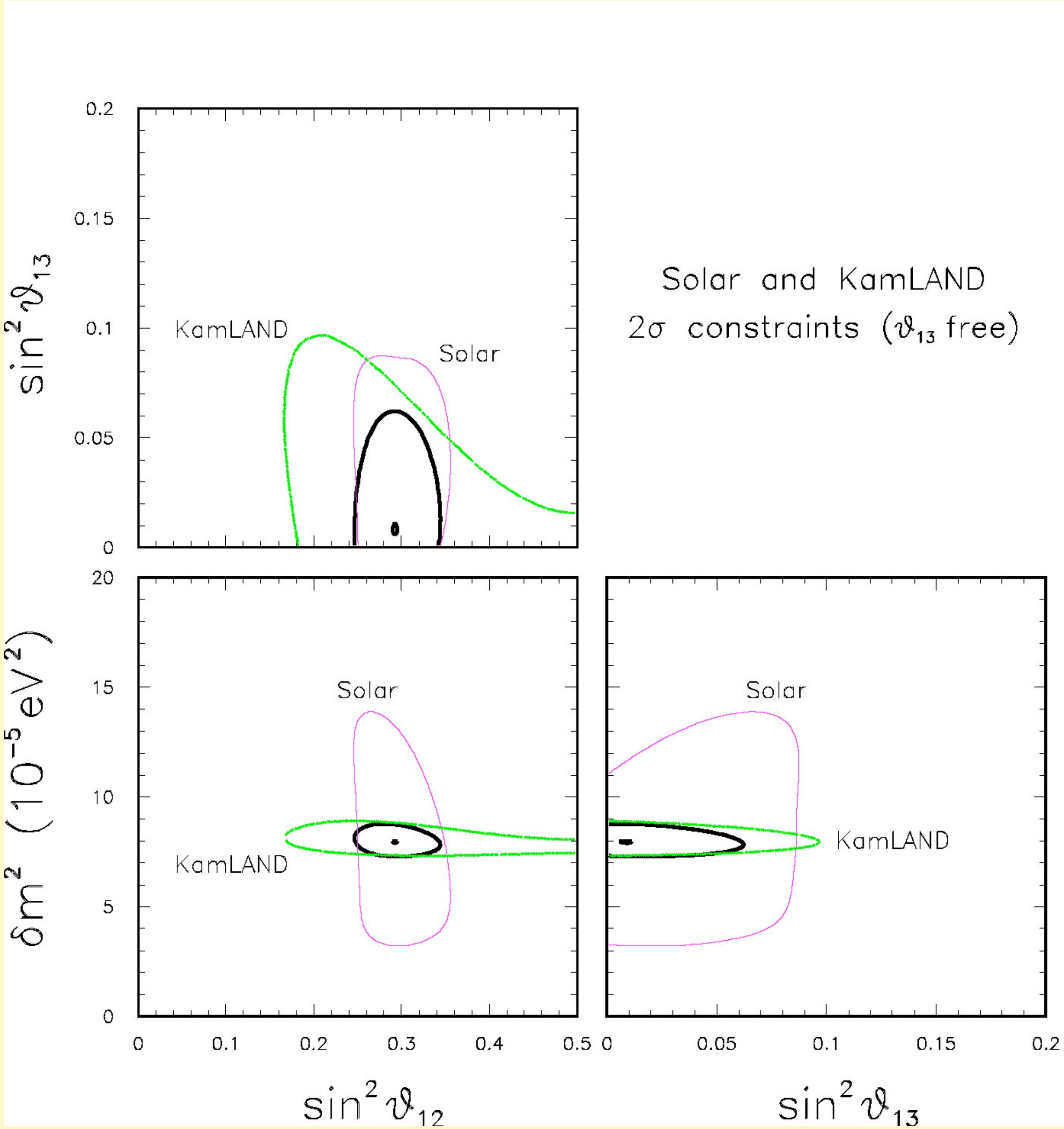


Previous results basically confirmed

Slightly higher ratio CC/NC ~ $P(\nu_e \rightarrow \nu_e)$

Slight shift (<1σ upwards) of allowed range for θ_{12}

3ν analysis of 2004 solar+KamLAND data (θ_{13} free)

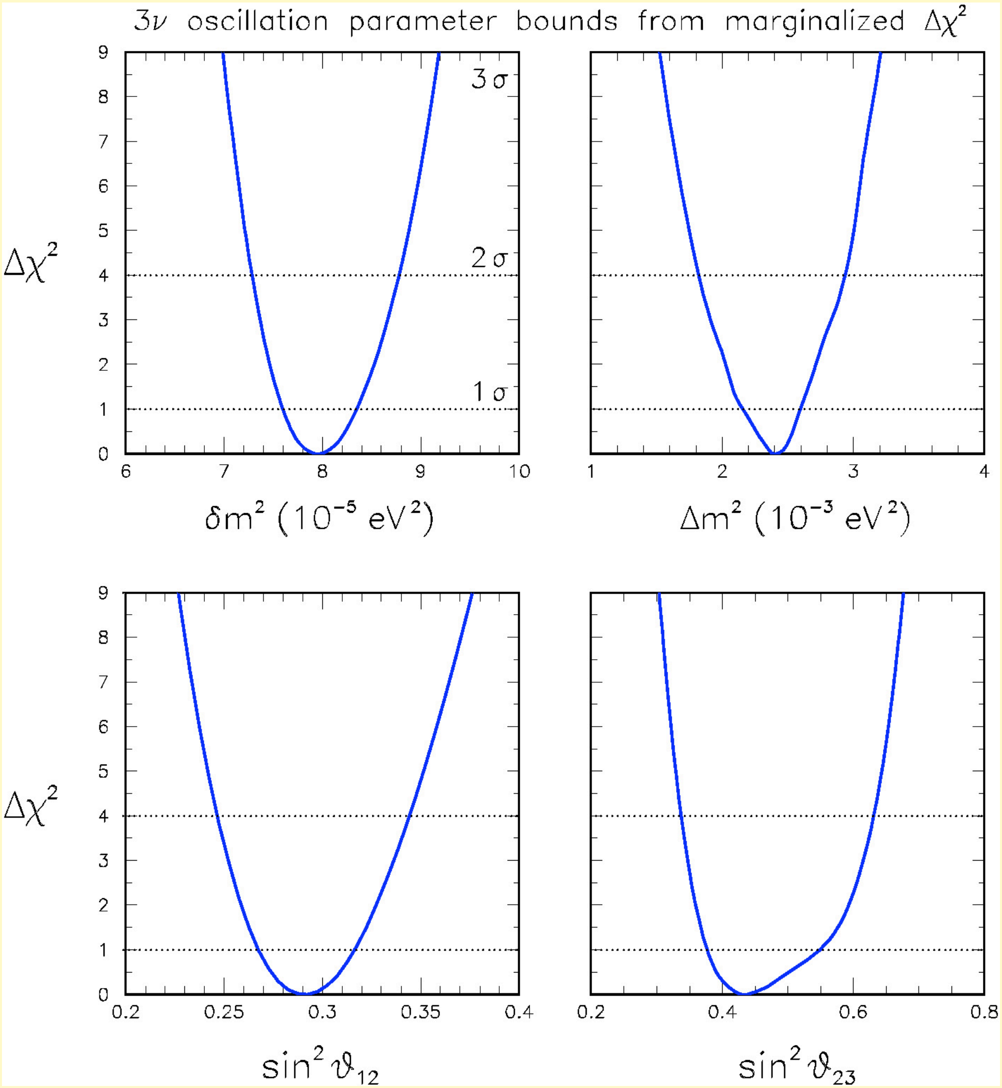


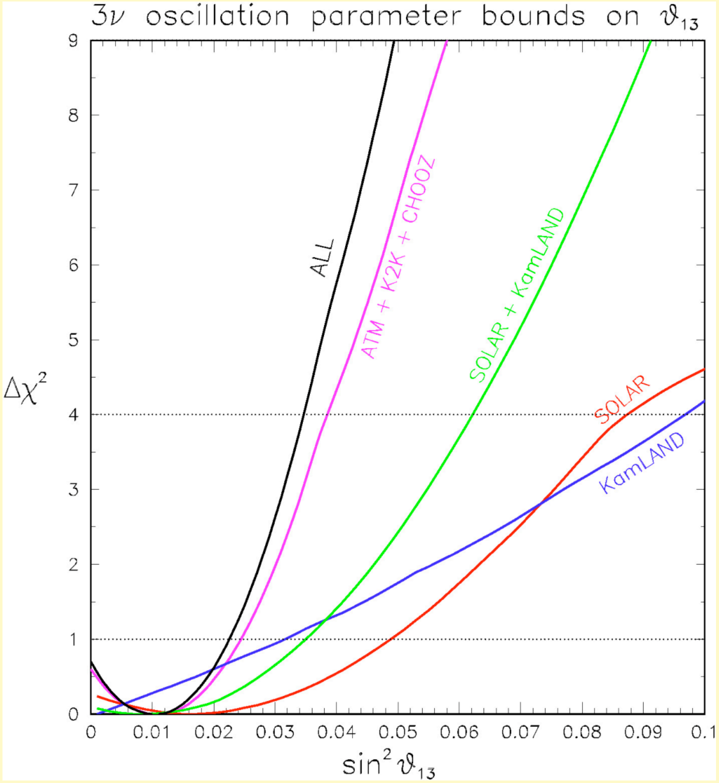
Solar and KamLAND data also prefer θ_{13}~0 (nontrivial consistency with SK+CHOOZ)

Bounds on (δm^2,θ_{12}) not significantly altered for unconstrained θ_{13}

"Grand Total" from global analysis of oscillation data

Marginalized $\Delta\chi^2$ curves for each parameter (2004)





Numerical ±2σ ranges (95% CL for 1dof), 2004 data:

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

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

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

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

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

$$\mathrm{sign}(\pm\Delta m^2):\ \ \mathrm{unknown}$$

$$\mathrm{CP\ phase}\ \delta:\ \ \mathrm{unknown}$$

Note: Precise values for θ_{12} and θ_{23} relevant for model building (see talk by Tanimoto)

Probing absolute ν masses through non-oscillation searches

Three main tools (m_β, $m_{\beta\beta}$, Σ):

1) β **decay**: $m^2_i \neq 0$ can affect spectrum endpoint. Sensitive to the "effective electron neutrino mass": *(most direct method)*

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

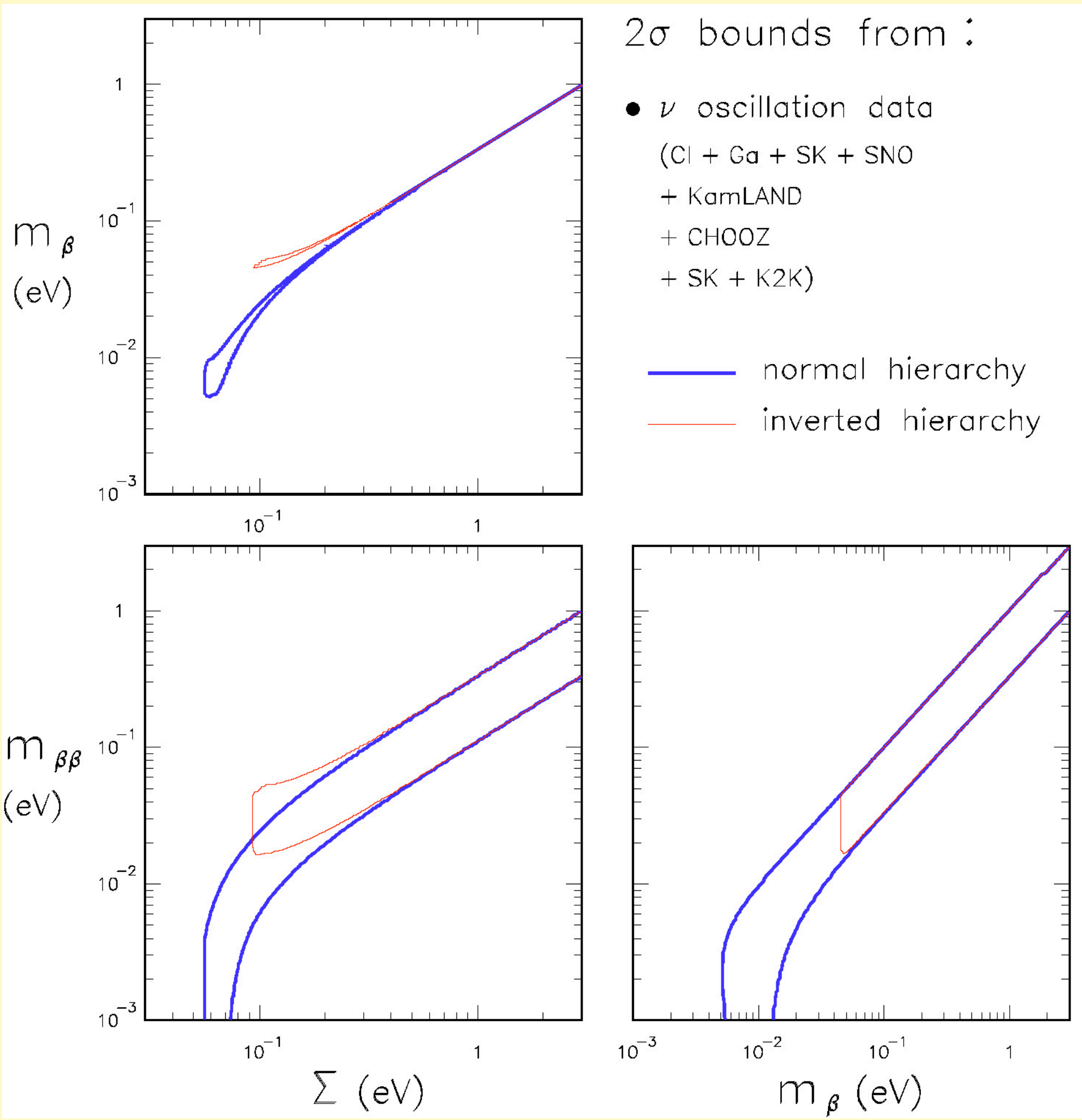
2) **0ν2β decay**: Can occur if $m^2_i \neq 0$ and $\nu = \bar{\nu}$. Sensitive to the "effective Majorana mass" (and phases): *(several talks this afternoon)*

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

3) **Cosmology**: $m^2_i \neq 0$ can affect large scale structures in (standard) cosmology constrained by CMB+other data. Probes: *(see talk by Pastor)*

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

Even without non-oscillation data, the (m_β, $m_{\beta\beta}$, Σ) parameter space is constrained by previous oscillation results:



Significant covariances

Partial overlap between the two hierarchies

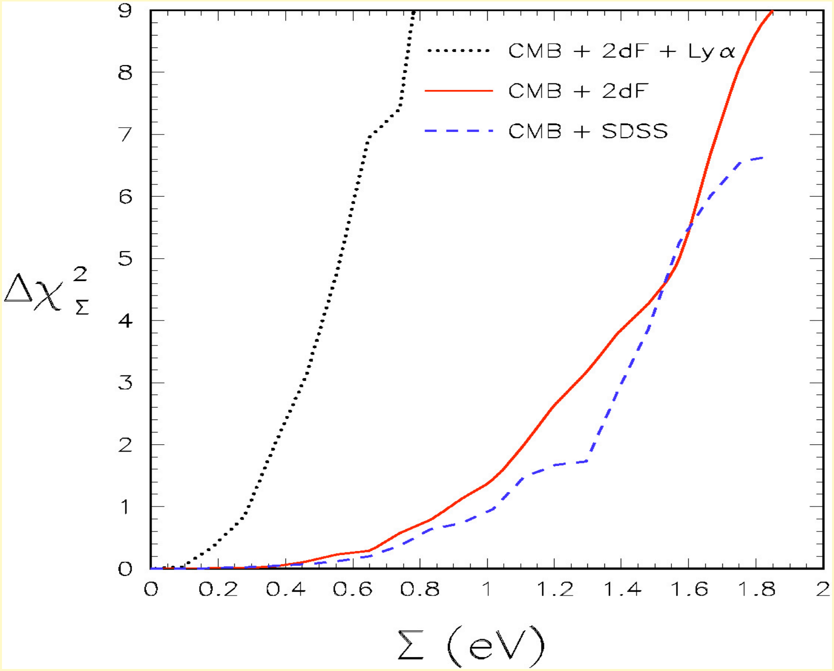
Large $m_{\beta\beta}$ spread due to unknown Majorana phases

But we do have information from non-oscillation experiments:

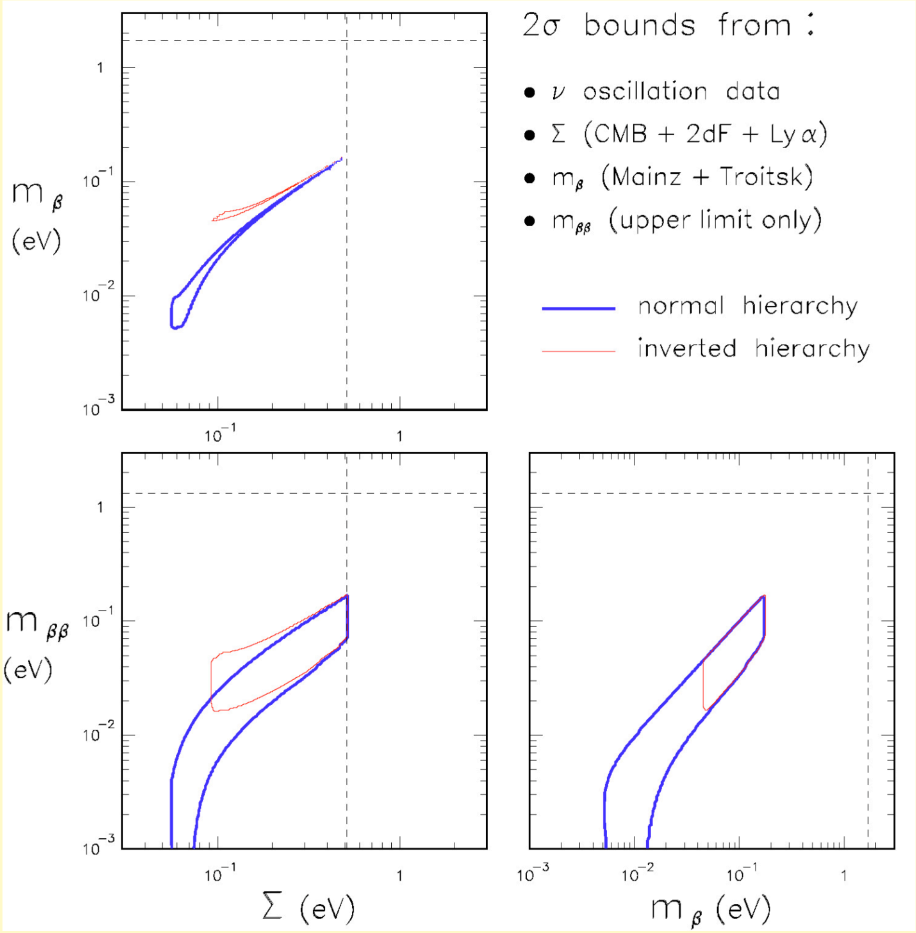
1) β **decay**: no signal so far. Mainz & Troitsk expts: m_β < O(eV)

2) **$0\nu2\beta$ decay**, no signal in all experiment, except in the most sensitive one *(Heidelberg-Moscow)*. Rather debated claim.
Claim accepted: **$m_{\beta\beta}$ in sub-eV range** (with large uncertainties)
Claim rejected: **$m_{\beta\beta}$ < O(eV).**

3) **Cosmology**. Upper bounds:
Σ < eV/sub-eV range,
depending on several inputs and priors. E.g.,

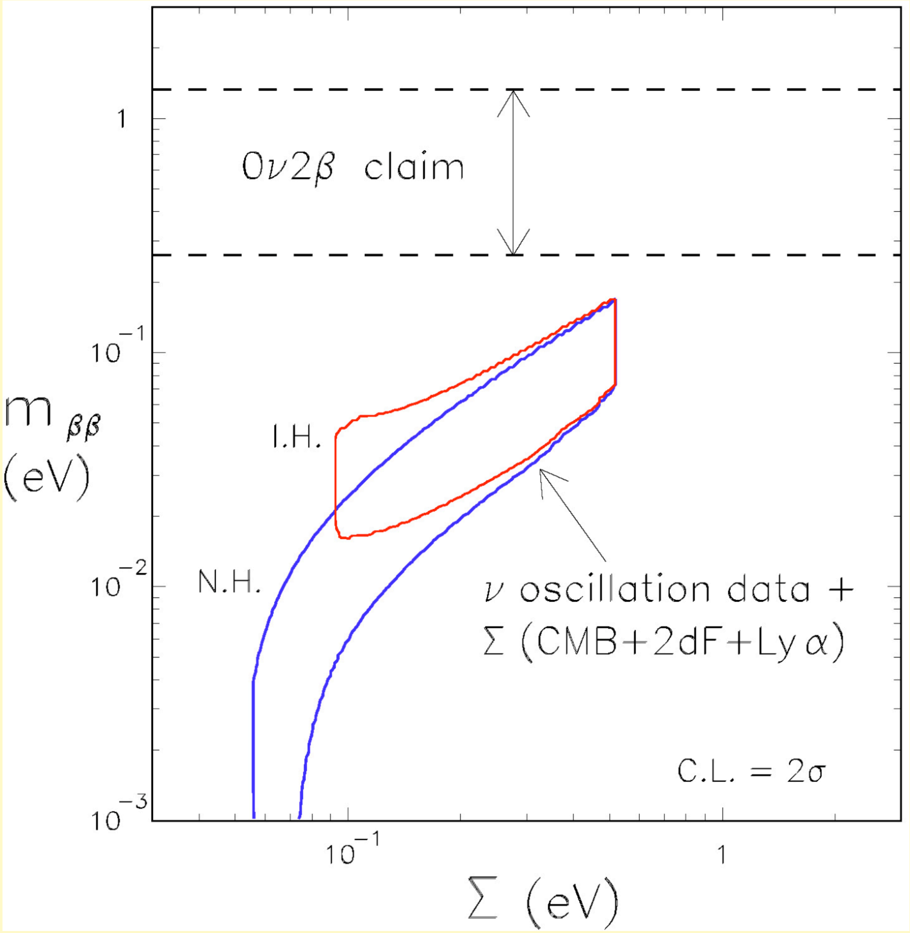


0ν2β claim rejected



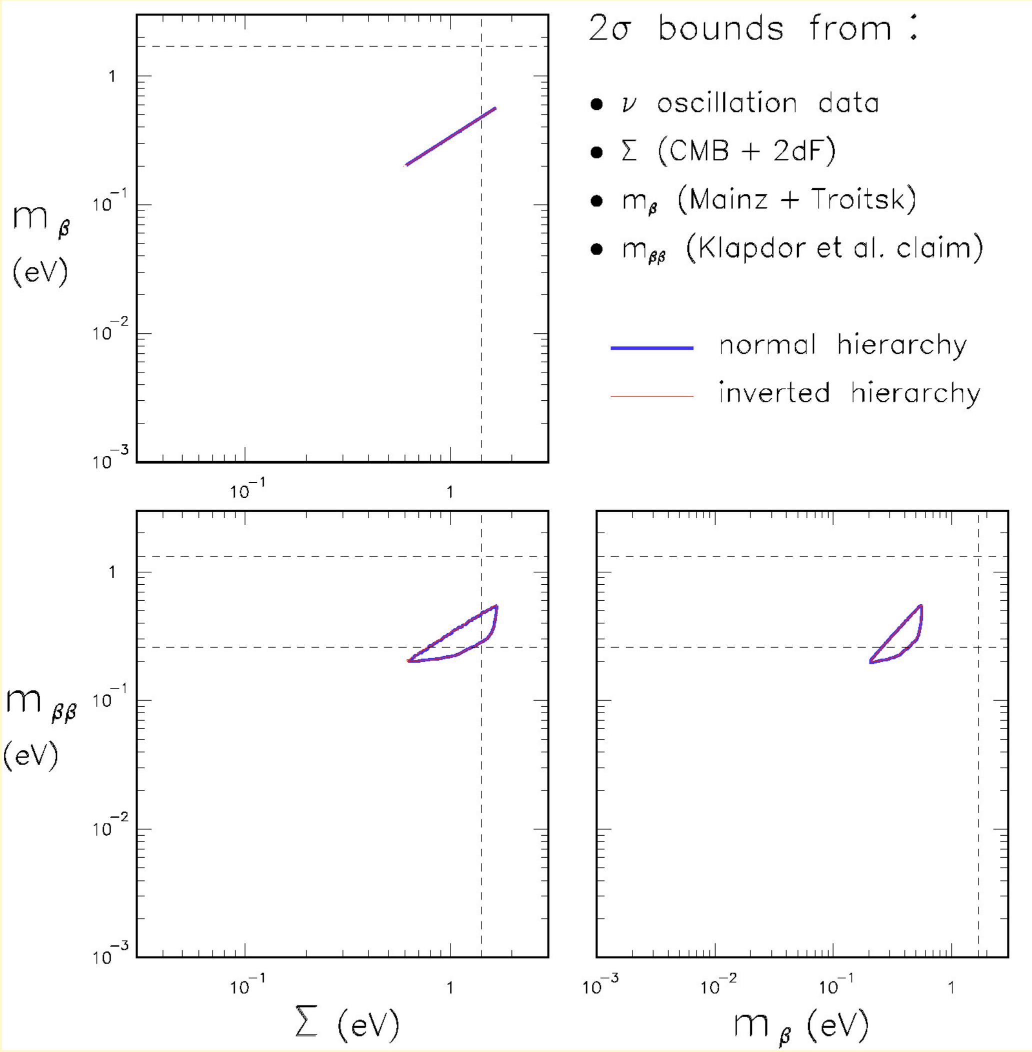
Cosmological bound dominates, but does not probe hierarchy yet

0ν2β claim accepted



Tension with cosmological bound
(no combination possible at face value)
But: too early to draw definite conclusions

E.g., if 0ν2β claim accepted & cosmological bounds relaxed:



Combination of all data (osc+nonosc.) possible

Complete overlap of the two hierarchies (degenerate spectrum with "large" masses)

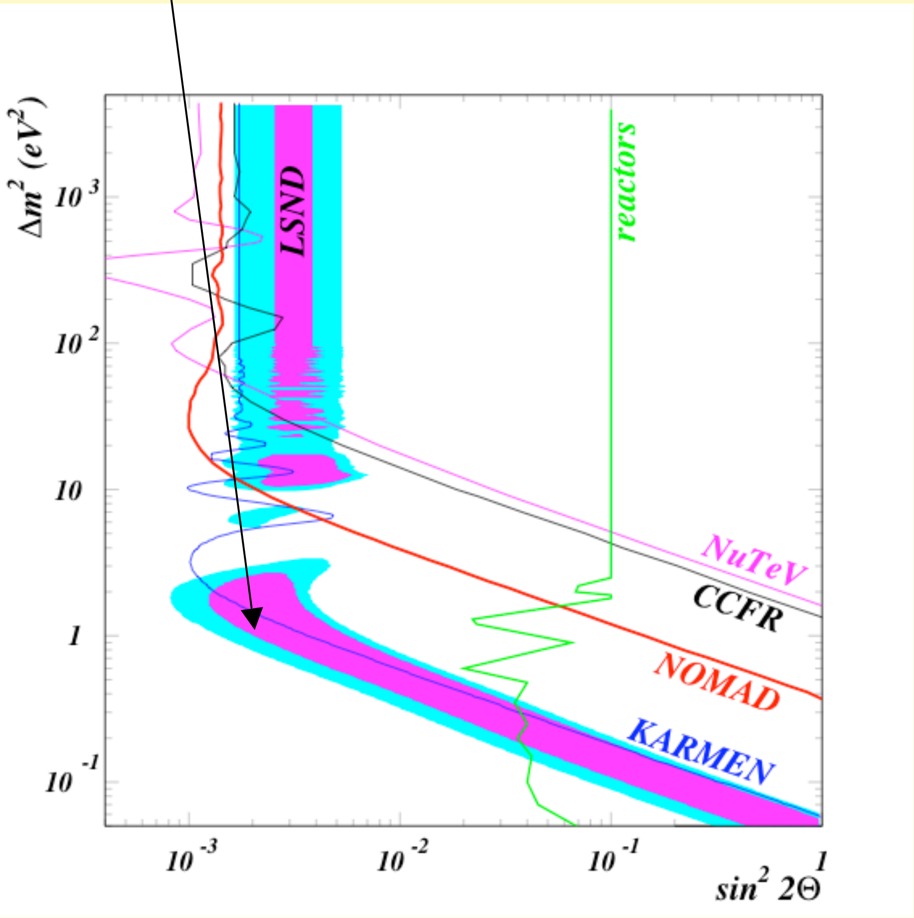
High discovery potential in future (m_β, $m_{\beta\beta}$, Σ) searches

Beyond three-neutrino mixing: LSND

Many theoretical reasons to go beyond the standard 3ν scenario

A purely experimental reason: the puzzling LSND oscillation claim

$\Delta M^2 \sim O(eV^2)$ with very small mixing?



Solutions invented so far (new sterile states, new interactions or properties) seem rather "ad hoc" and/or in poor agreement with world neutrino data

If MiniBoone (talk by McGregor) confirms LSND this year, many ideas will be revised, and the neutrino session of Moriond 2006 will be fun!

Conclusions

Great progress in recent years …

Neutrino mass & mixing: established fact
Determination of ($\delta m^2, \theta_{12}$) and ($\Delta m^2, \theta_{23}$)
Upper bounds on θ_{13}
Oscillation-induced spectral distortions
Direct evidence for solar ν flavor change
Evidence for matter effects in the Sun
Upper bounds on ν masses in (sub)eV range
…………

Determination of θ_{13}
Leptonic CP violation
Absolute m_ν from β-decay and cosmology
Test of $0\nu2\beta$ claim and of Dirac/Majorana ν
Matter effects in the Earth
Normal vs inverted hierarchy
Beyond the standard 3ν scenario
Deeper theoretical understanding
…………

… and great challenges for the future!