NuFact Summer Institute Capri 2005

Physics of massive ν_s

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LECTURE III

An *almost* up-to-date phenomenological overview of the three-neutrino mass-mixing parameters

(complete 2005 update + details in next lecture)

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

3ν mixing - brief recap

- Neutrinos fields mix:

$$(\nu_e,\, \nu_\mu,\, \nu_\tau)^T = U\,(\nu_1,\, \nu_2,\, \nu_3)^T$$

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

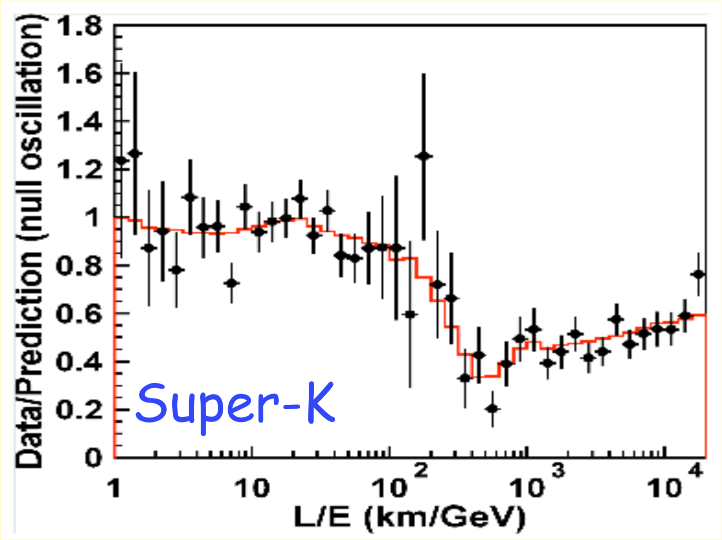
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

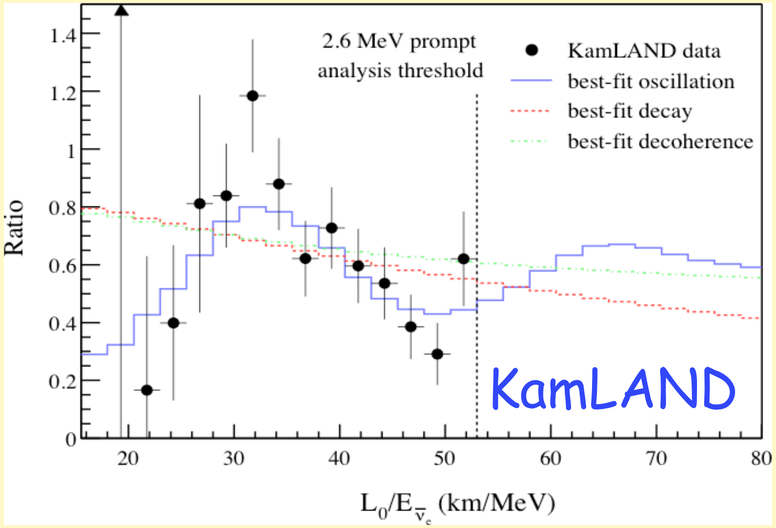
… but with very different angles - we shall see that:

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

- **Only if $s^2_{13} \neq 0$ one can hope to probe the CP-violating phase δ** ("holy grail" of future ν oscillation experiments like nu-factories)

Neutrino fields mix … and oscillate, with at least two frequencies. "Textbook" plots:





Δm^2-driven oscillations

δm^2-driven oscillations

(about half-period seen in both cases)

3ν oscillations (remind also Lec. II, one-dominant-mass-scale approximation)

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

Status of 3-neutrino framework:

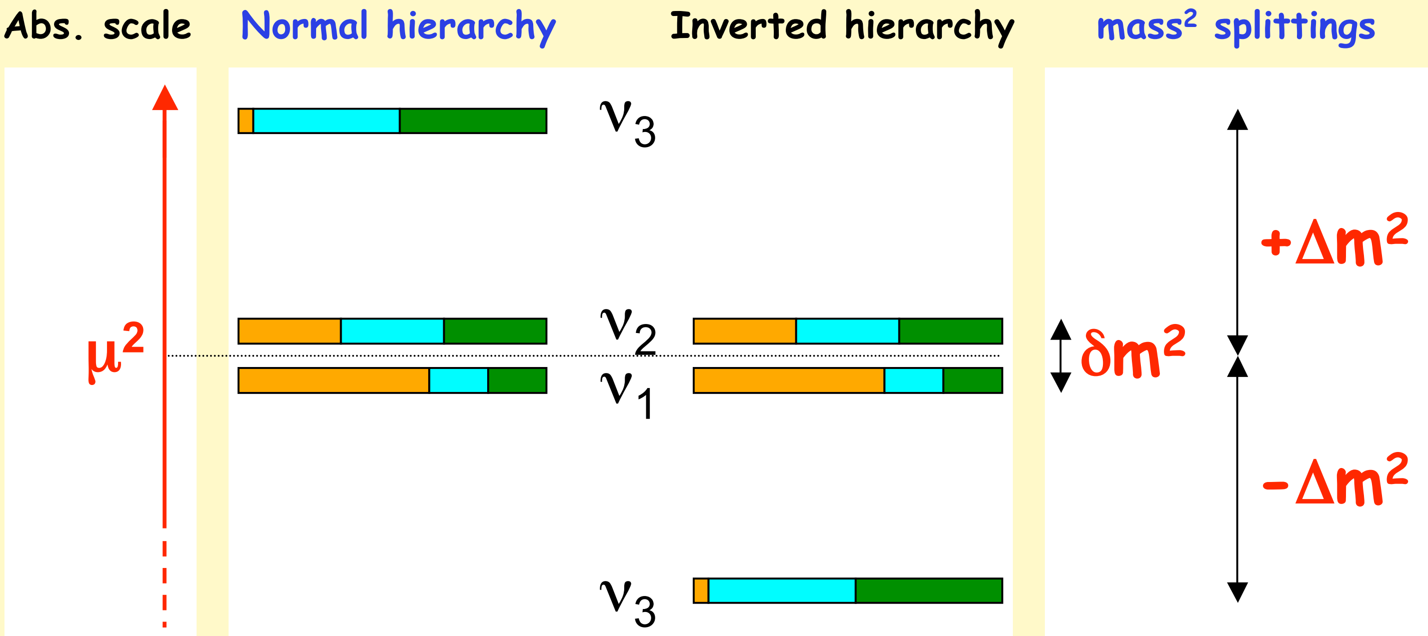
$(\Delta m^2, \theta_{23})$	robust upper + lower bound from atmospheric & accelerator data
$(\delta m^2, \theta_{12})$	robust upper + lower bound from solar & reactor data
$V_{MSW} = 0$	L/E vacuum osc. pattern recently seen in atm. & react. data
$V_{MSW} \neq 0$	matter effects recently established in solar neutrinos
θ_{13}	upper bound from CHOOZ reactor data + above data
μ	upper bound from laboratory (+ 1st lower bound?) & cosmology
Sign(Δm^2)	unknown (is the hierarchy normal or inverted ?)
δ	unknown (is there leptonic CP violation ?)
φ_2, φ_3	unknown (are there Majorana phases?)

Questions beyond the standard 3-neutrino framework:

$\dim(H)=3+N_S$?	*Light sterile neutrinos?*
$V=V_{MSW}+\Delta V$?	*New (subleading) interactions in medium?*
$H \neq H^+$?	*Neutrino decay ?*
$i d\nu/dx \neq H\nu$?	*Non-hamiltonian evolution (decoherence)?*

...

3ν mass² spectrum and flavor content (e μ τ)



Absolute mass scale μ unknown [but < O(eV)]

Hierarchy [sign(Δm^2)] unknown

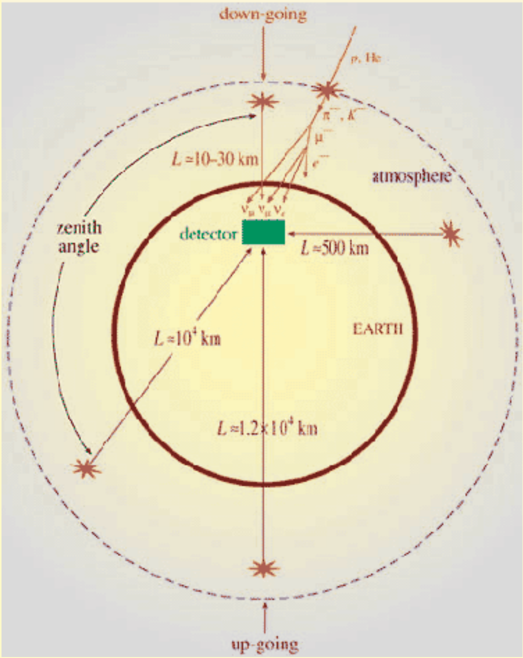
ν_e content of ν_3 unknown [but < few%]

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

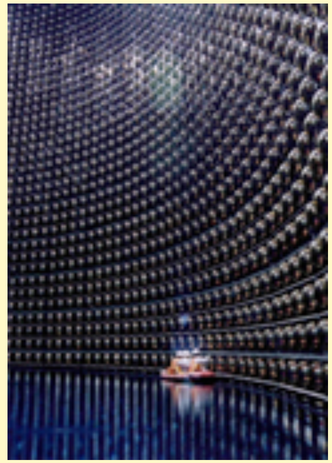
$\Delta m^2 \simeq 2.4 \times 10^{-3}$ eV^2 ("atmospheric" splitting)

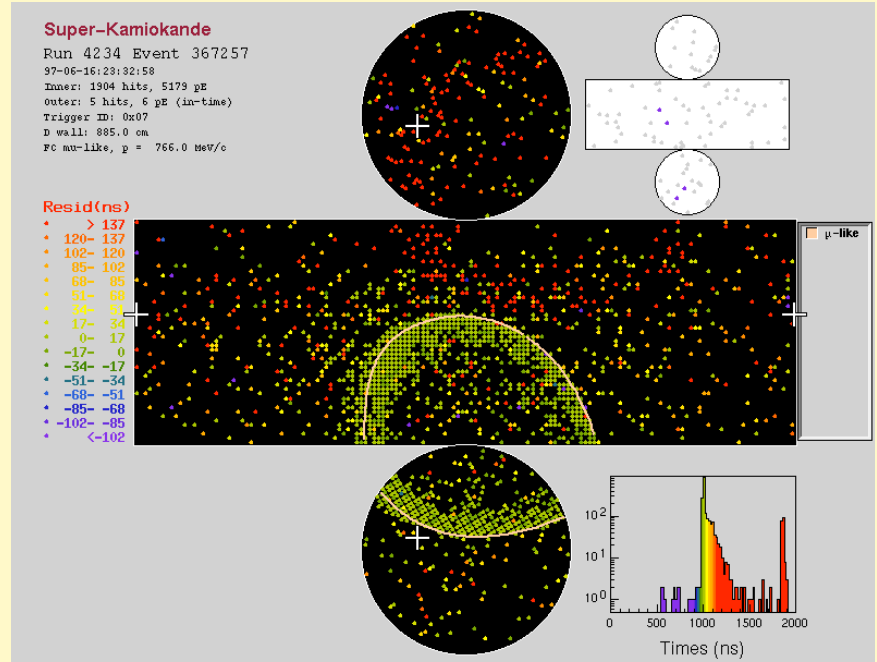
Constraints on $(\Delta m^2, \theta_{23}, \theta_{13})$ from SK + K2K + CHOOZ

Figure 4



Super-Kamiokande





ν_e induced events: ~ as expected

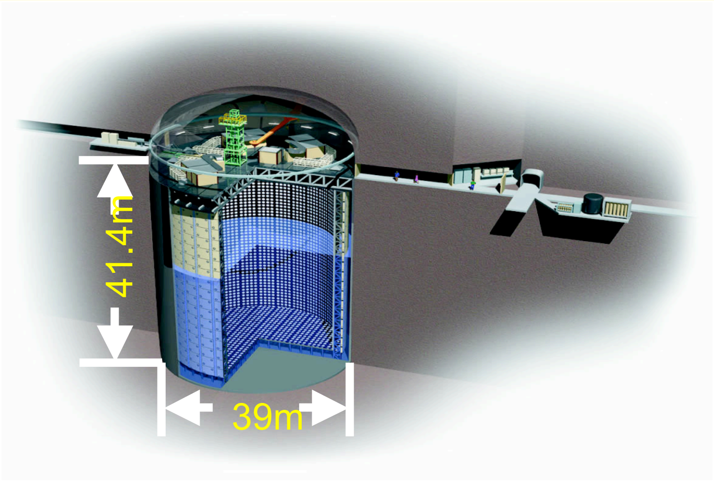
ν_μ induced events: deficit from below

Channel $\nu_\mu \rightarrow \nu_e$? **No** (or subdominant)

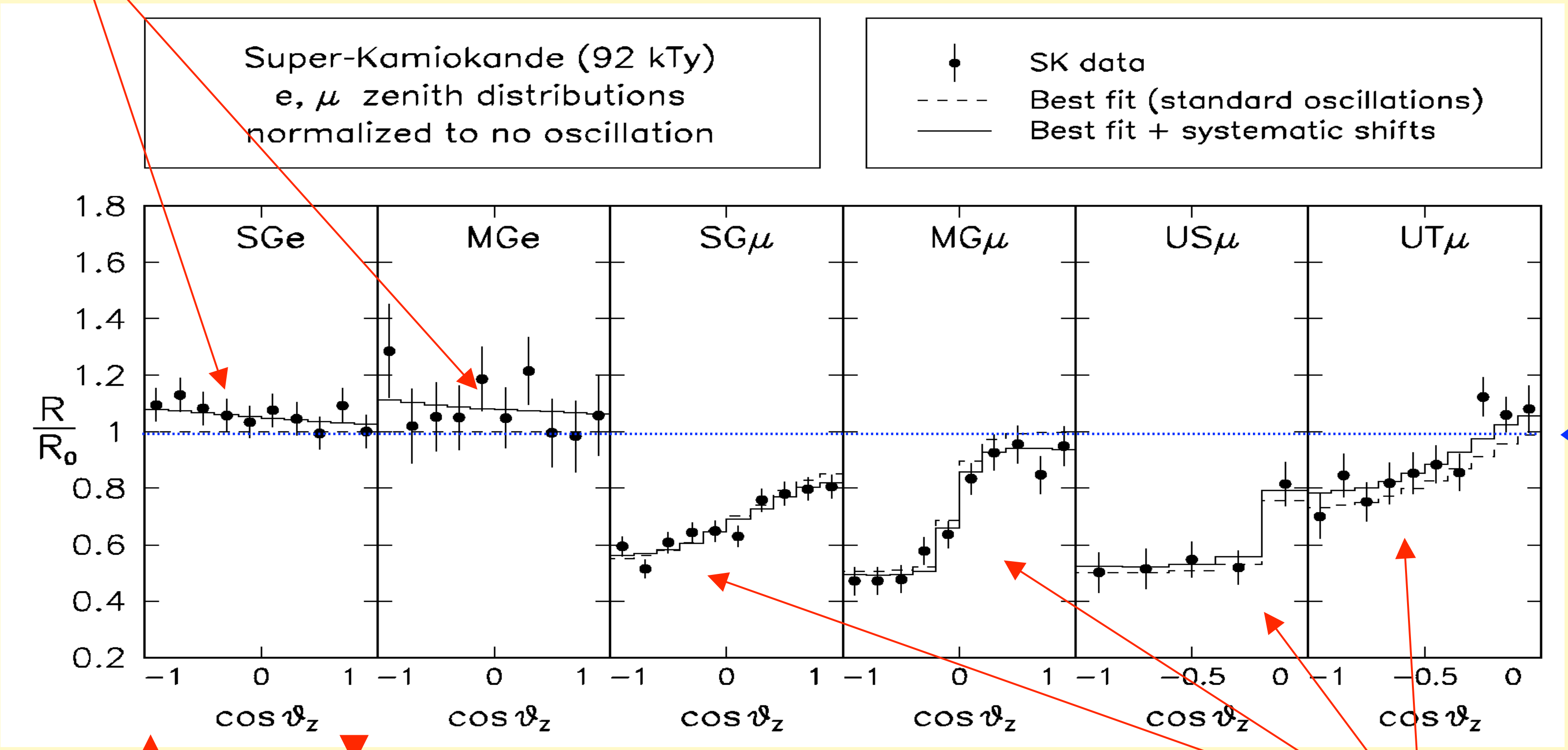
Channel $\nu_\mu \rightarrow \nu_\tau$? **Yes** (dominant)

Atmospheric neutrinos: Super-Kamiokande

SGe	Sub-GeV electrons
MGe	Multi-GeV electrons
SGμ	Sub-GeV muons
MGμ	Multi-GeV muons
USμ	Upward Stopping muons
UTμ	Upward Through-going muons



electrons ~OK



no osc.

up

down

muon deficit from below

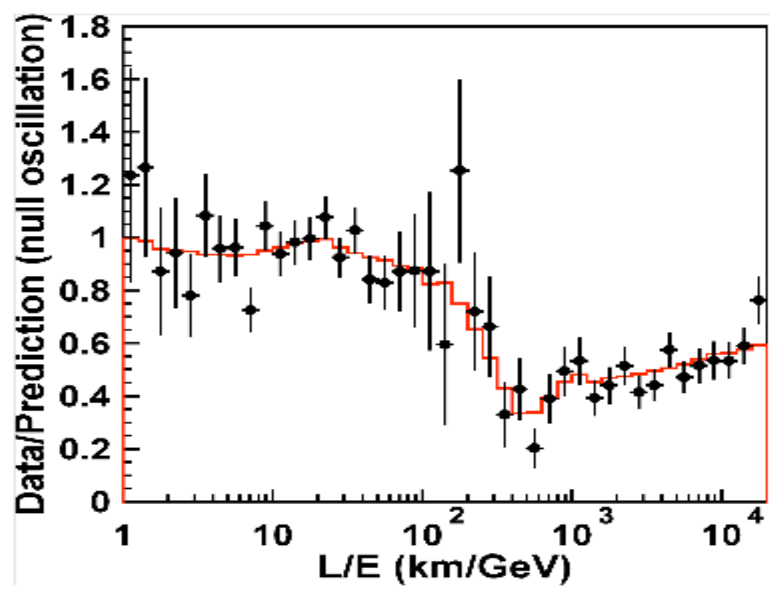
Super-Kamiokande atmospheric ν

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

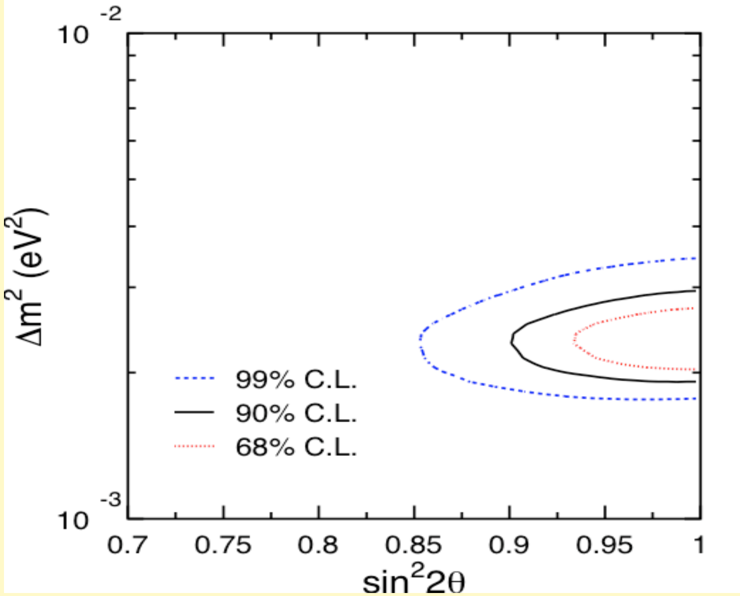
For θ_{13}~0 and δm^2~0, a very simple formula fits all SK data (+ MACRO & Soudan2)

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

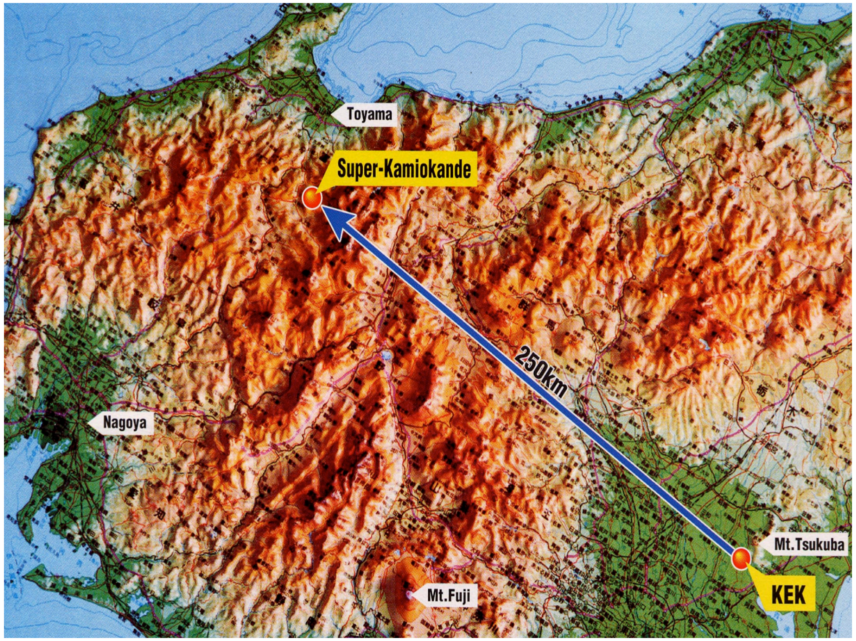
1st oscillation dip still visible despite large L & E smearing

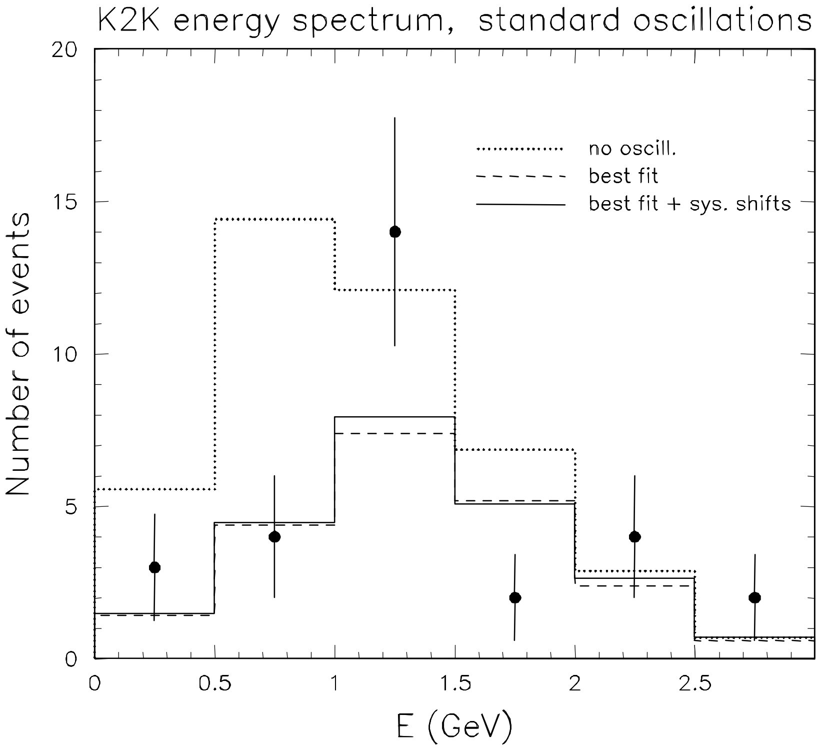


Strong constraints on the parameters (Δm^2, θ_{23})



First-generation LBL accelerator experiment: KEK-to-Kamioka (K2K)





Aimed at testing disappearance of accelerator ν_μ in the same range probed by atmospheric ν:

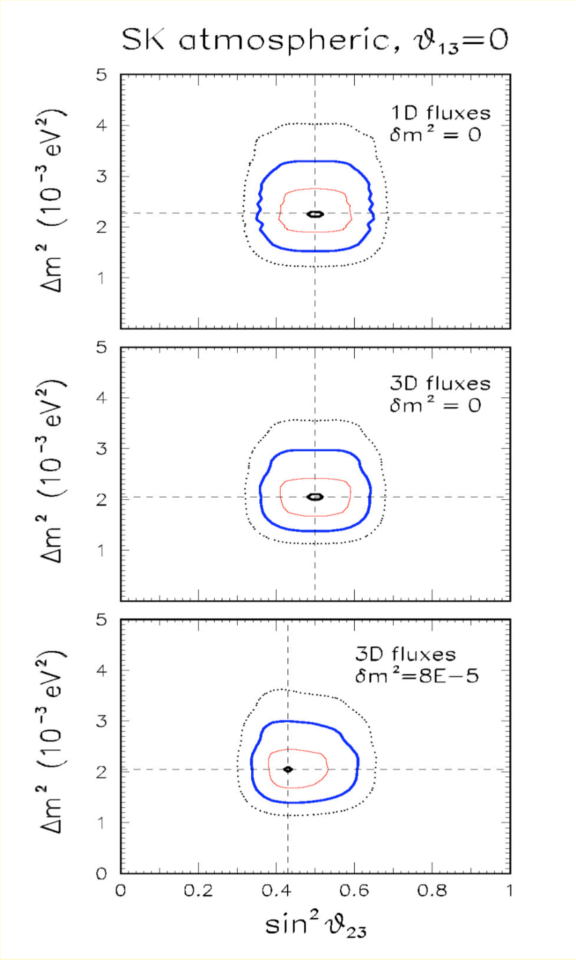
$(L/E)_{K2K}$~(250 km/1.3 GeV)~$(L/E)_{ATM}$

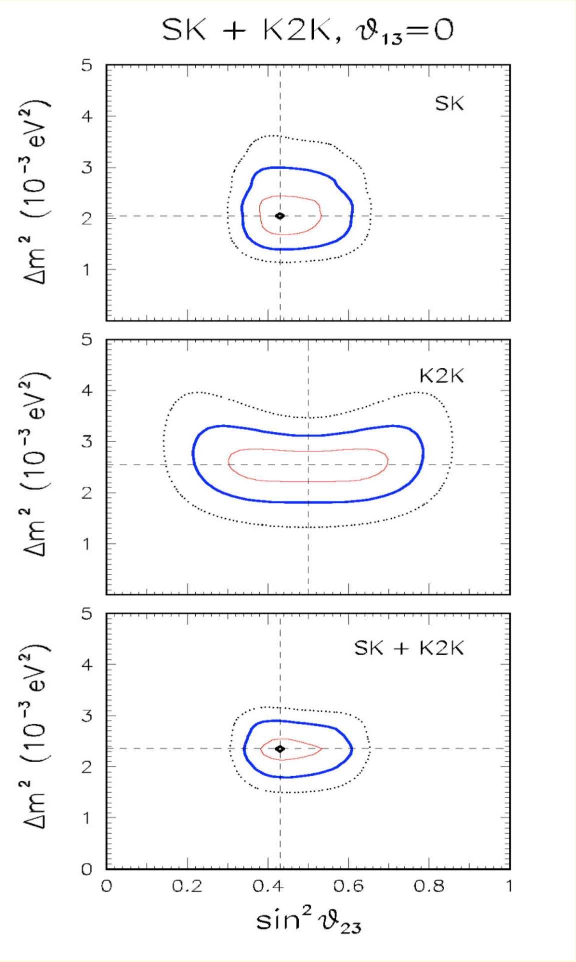
2002: muon disappearance observed at >99% C.L.

No electron appearance.

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

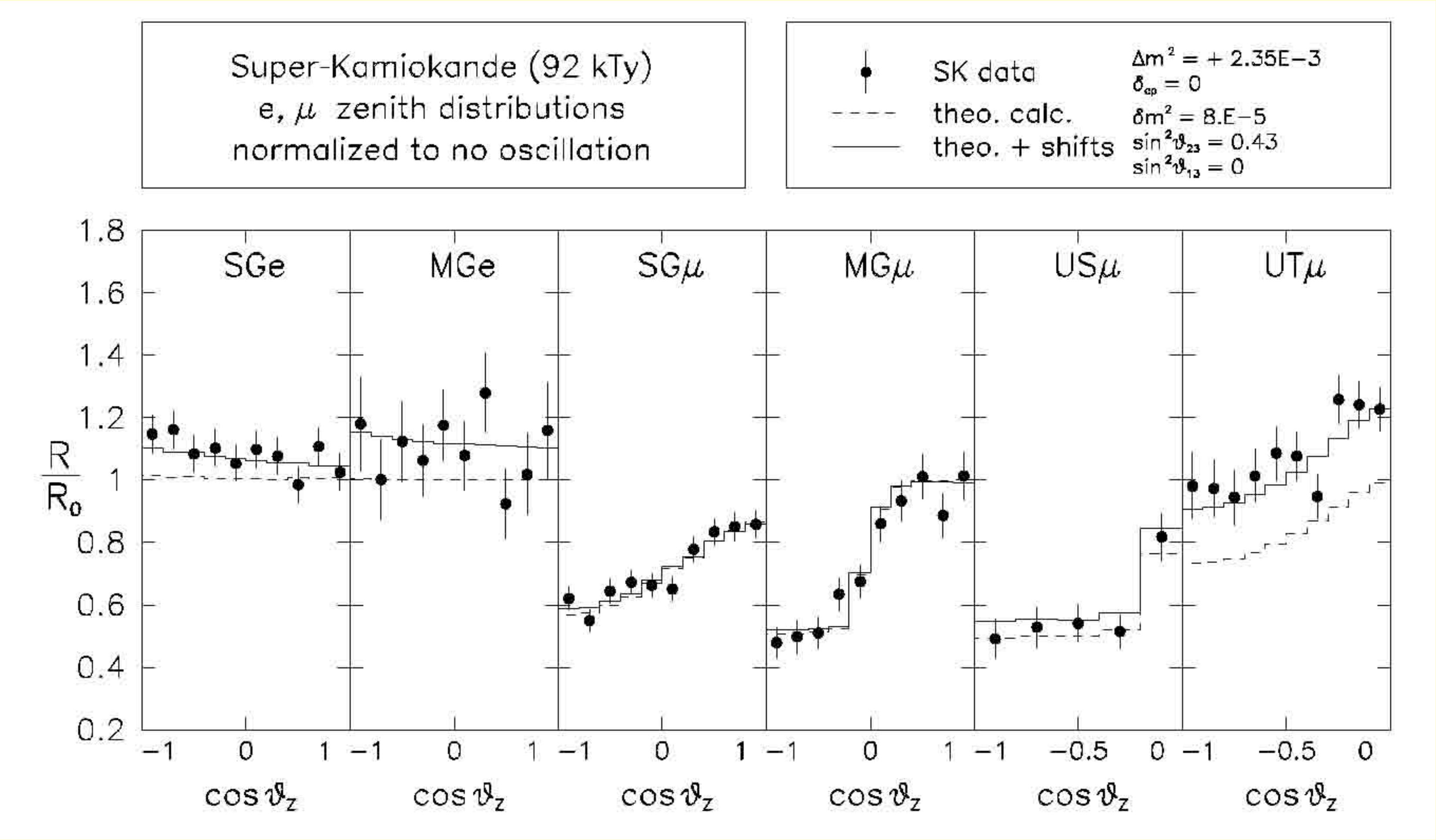
Many interesting details depend on theoretical input & subleading effects





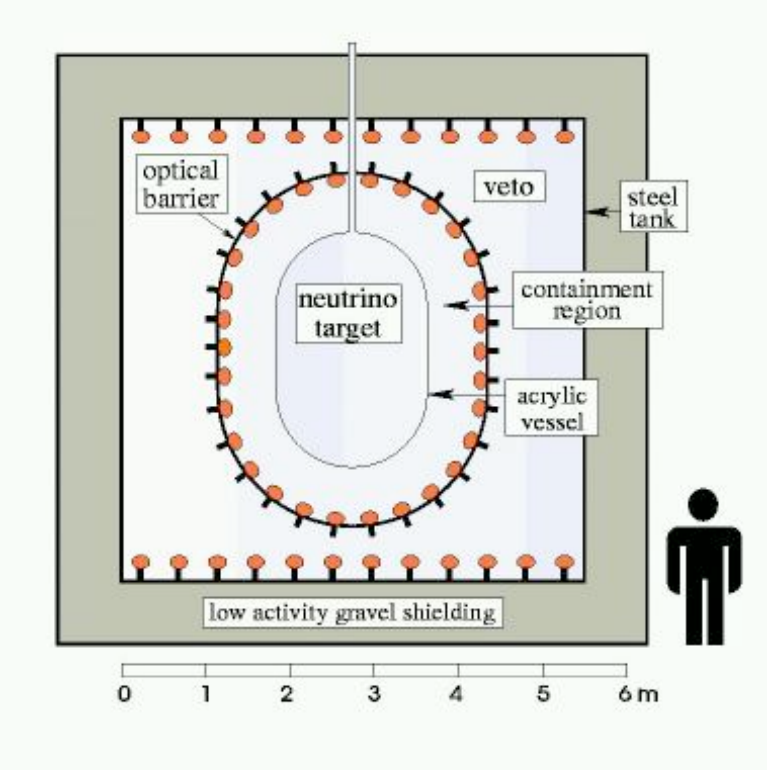
Contours at 1, 2, 3σ (1 dof). Note linear scale for Δm^2 and $\sin^2\theta_{23}$, with 2nd octant of θ_{23} unfolded

… more about subleading effects (induced by "solar parameters")
vs systematic errors
in the Super-Kamiokande zenith distributions



The CHOOZ reactor experiment and θ_{13}

- Searched for disappearance of reactor ν_e (E~few MeV) at distance L=1 km
- L/E range comparable to atmospheric ν → probe the same Δm^2
- No disappearance signal was found (1998) → Exclusion plot in $(\Delta m^2, \theta_{13})$ plane
- Results also confirmed by later reactor experiment (Palo Verde)

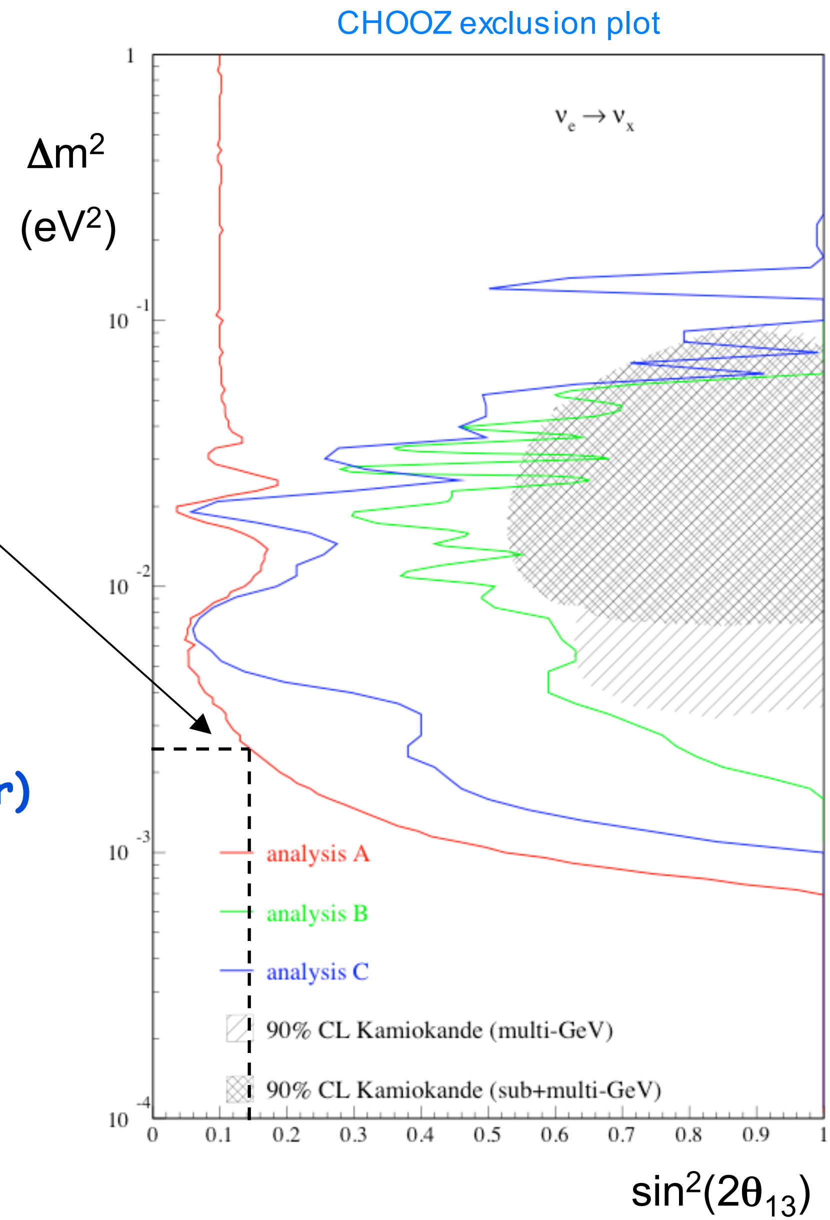


A crucial and beautiful "small-scale" experiment

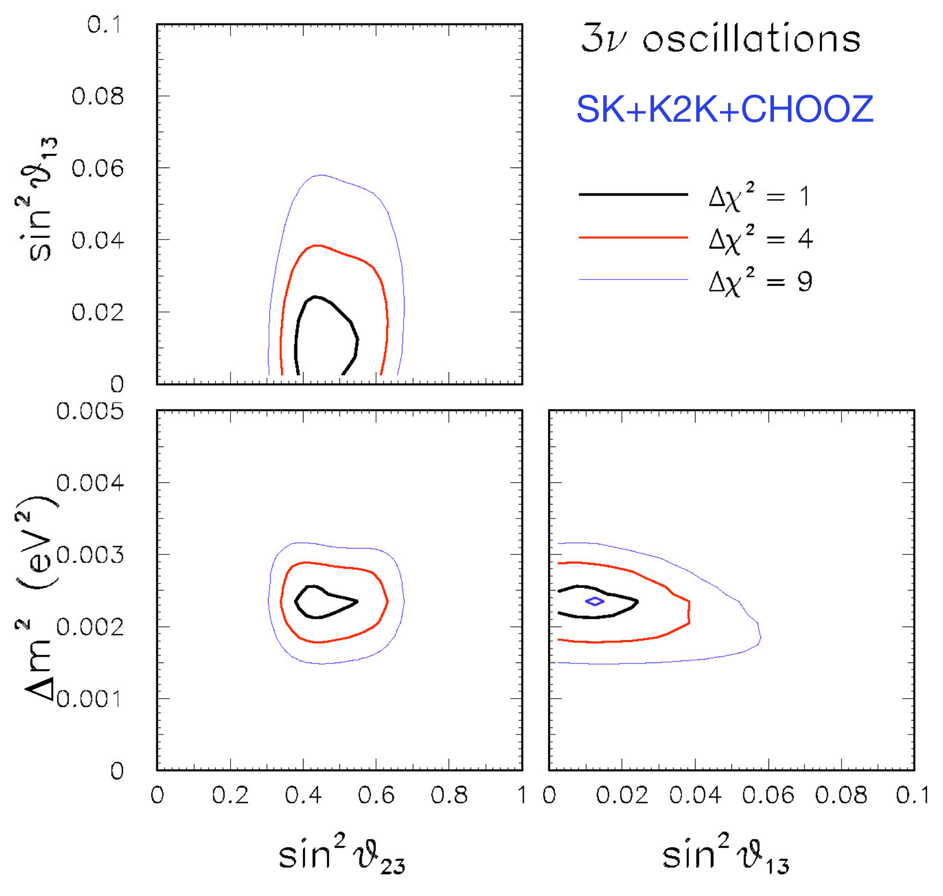
The CHOOZ reactor experiment and θ_{13}

- For any value of $\Delta m2$ in the SK+K2K range, get stringent upper bound on θ_{13}

Feverish world-wide activity to make one –or more- new reactor experiment with higher θ_{13} sensitivity (=smaller error)



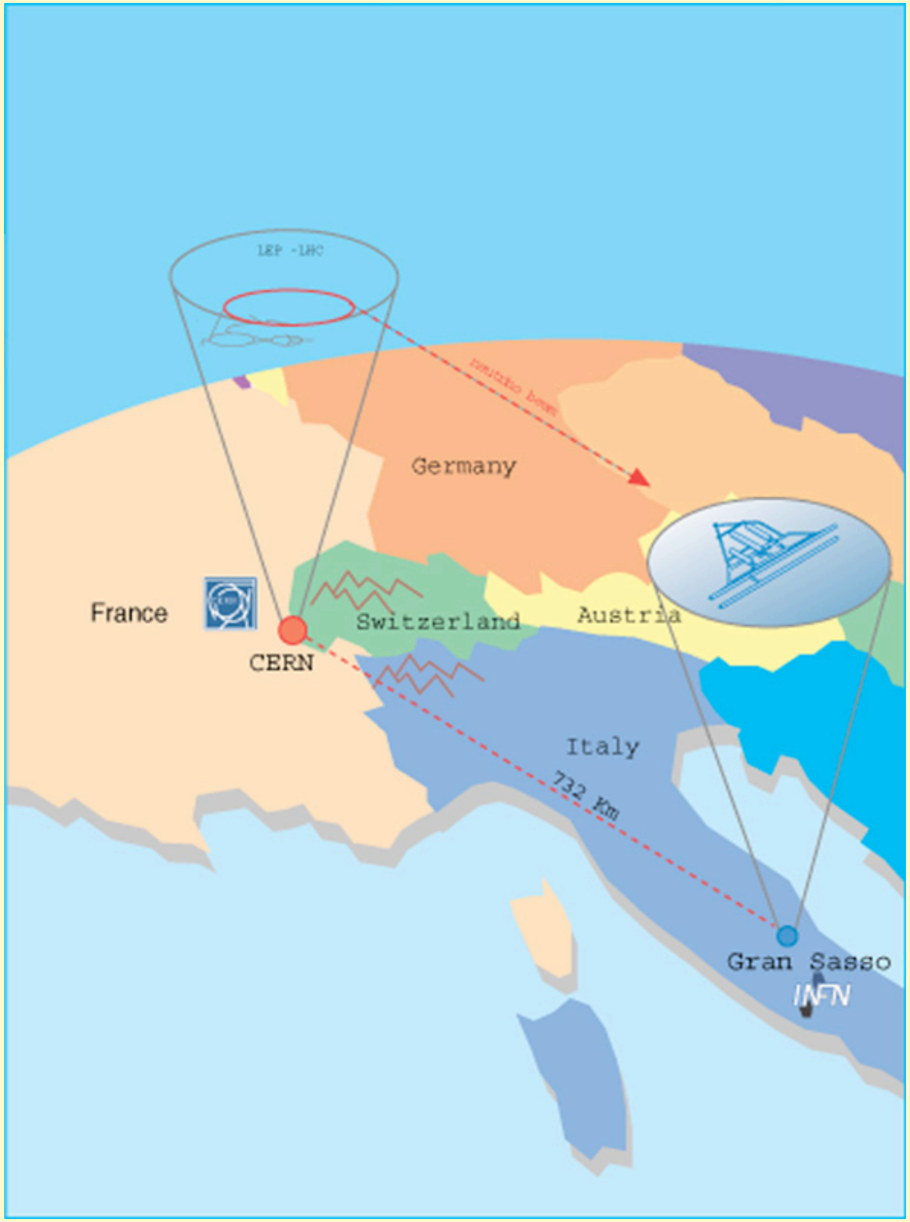
At the Δm^2 scale of SK+K2K, nonobservation of $\nu_e \to \nu_e$ in the CHOOZ reactor experiment sets upper bounds $\sin^2\theta_{13}$ < few %



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



Missing piece in puzzle:

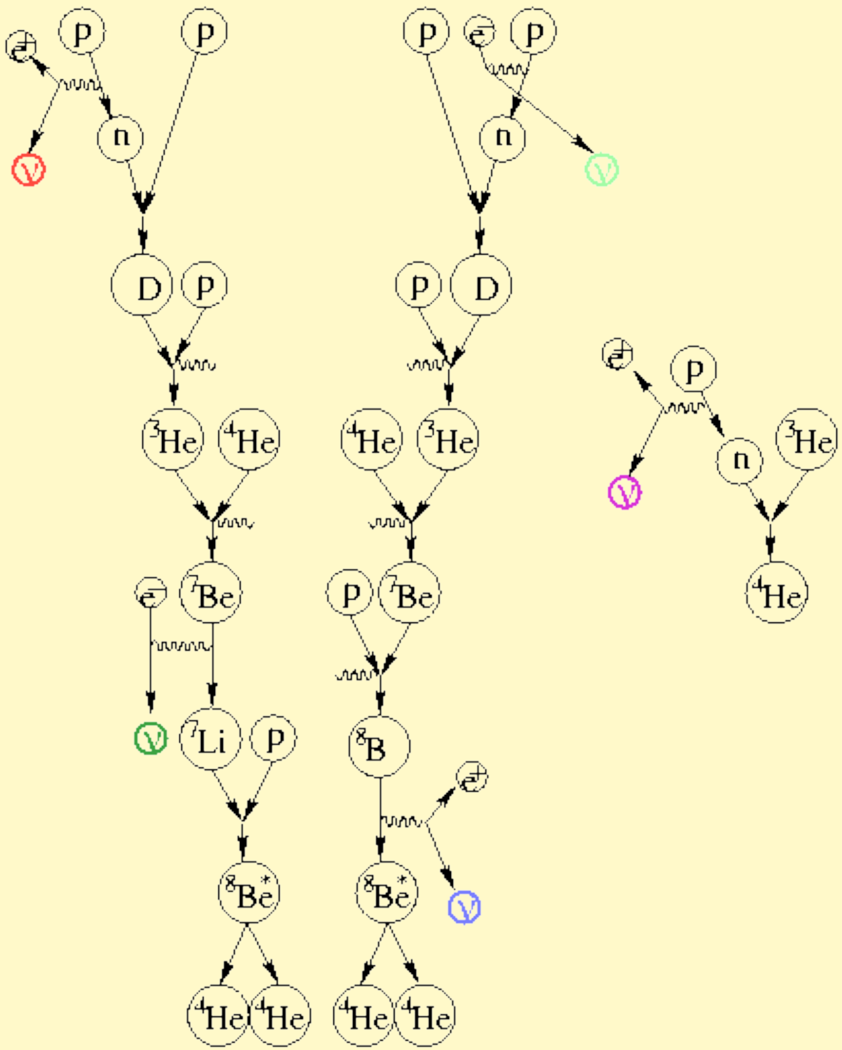
ν_τ appearance

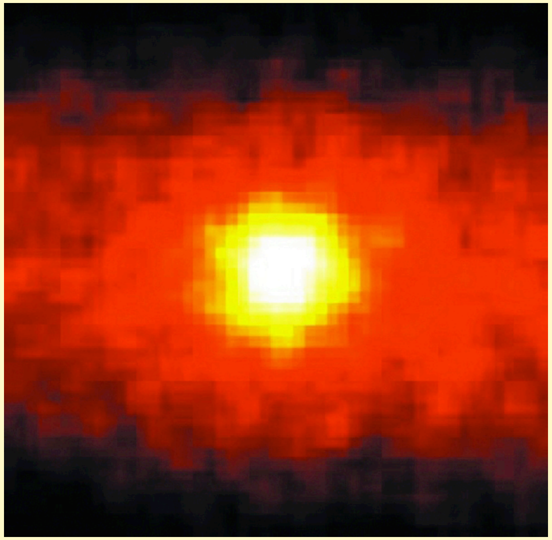
(only 2-sigma hint in Super-K)

Will be studied at
Laboratori Nazionali
del Gran Sasso
(OPERA, ICARUS)
with
CERN neutrino beam

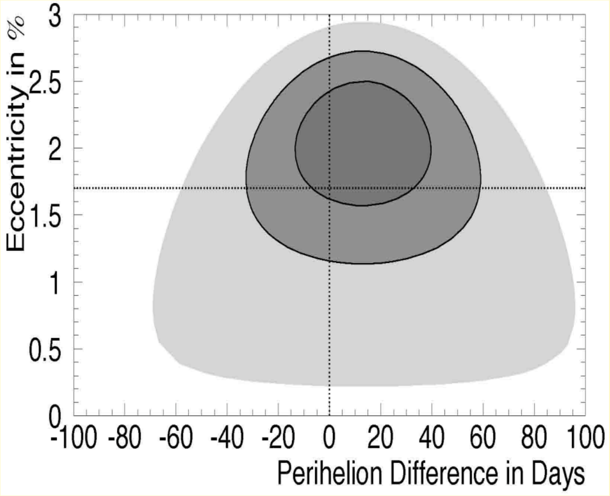
Constraints on (δm^2, θ_{12}, θ_{13}) from solar ν + KamLAND

Solar neutrinos (ν_e)



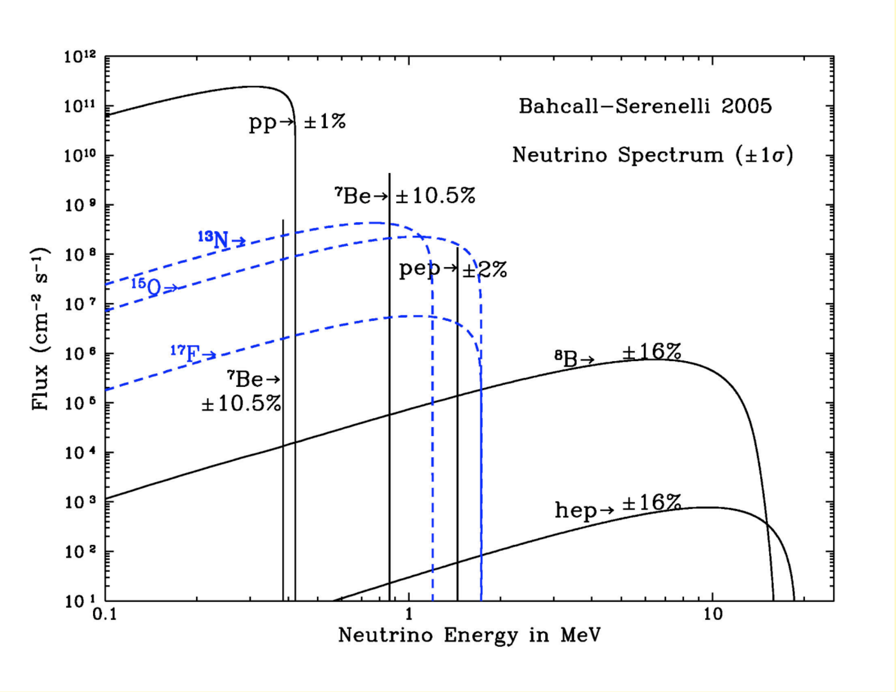


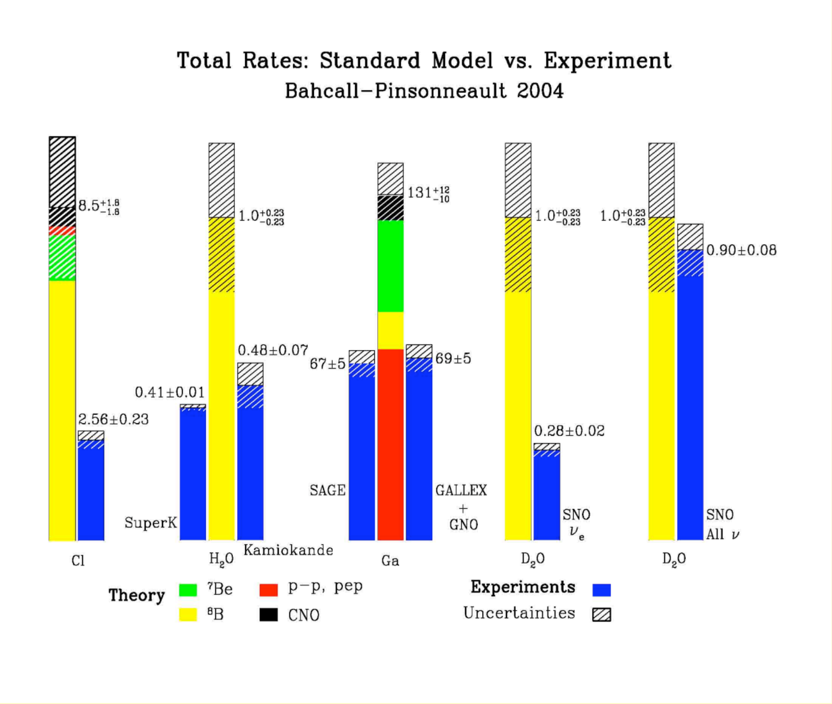
The Sun seen with neutrinos (SK)



Earth orbit from solar ν (SK)

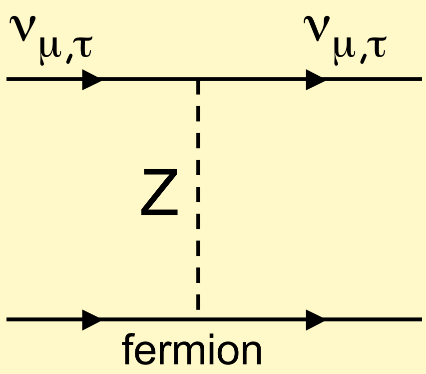
Standard Solar Model: neutrino energy spectrum…



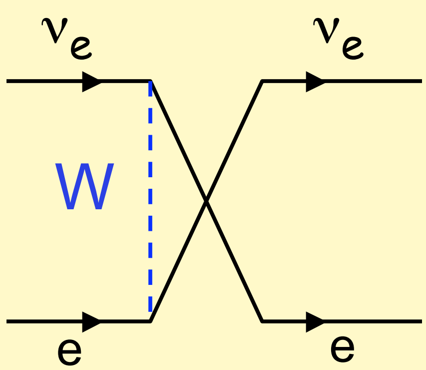


… and experimental deficit

Reminder - 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: $V = \sqrt{2}\, G_F\, N_e$

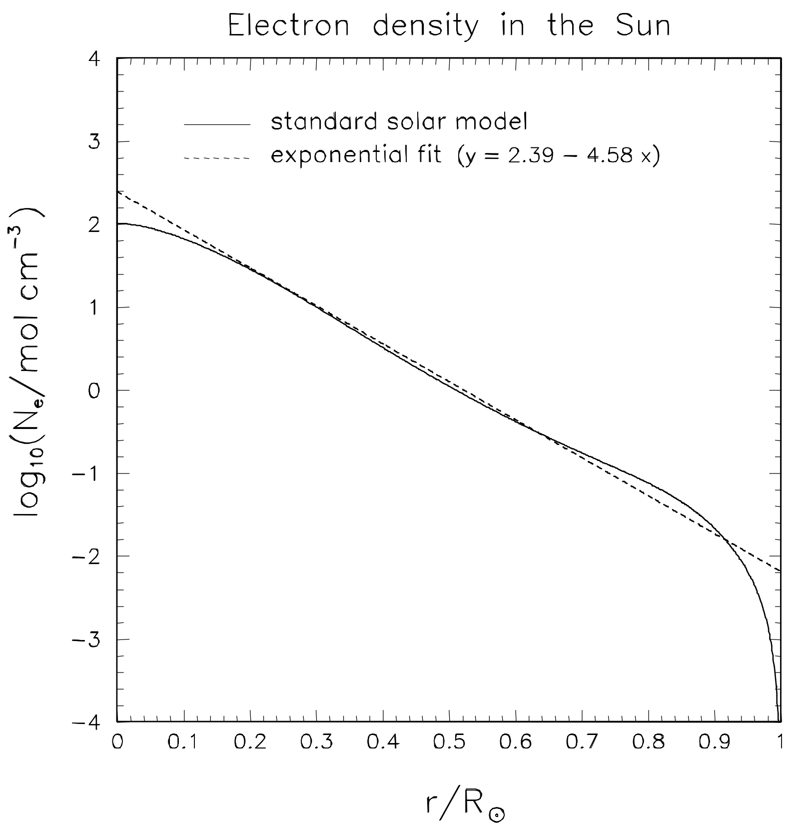
Solar ν analysis must account for MSW effects in the Sun and in the Earth
(Earth matter effects negligible for KamLAND reactor neutrinos)
Solar+KamLAND combination provide evidence for V_{sun} (not yet for V_{earth})

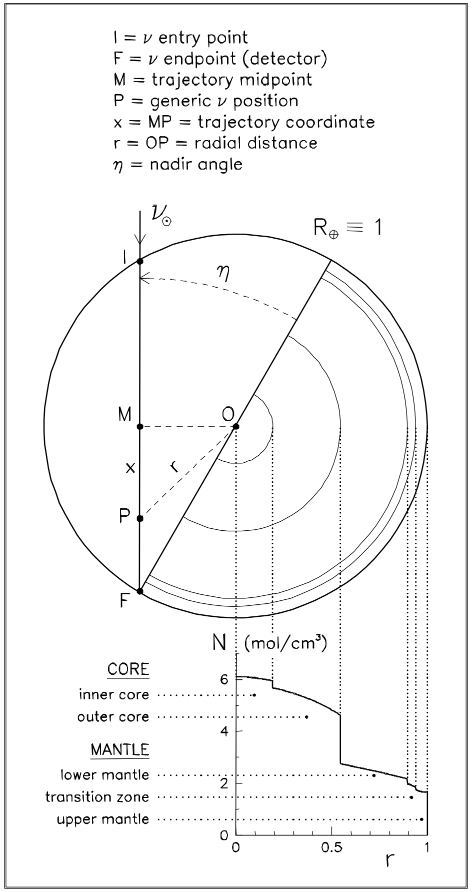
Reminder - Solar neutrinos: Oscillation analysis

- **Leading parameters: (δm^2, θ_{12})**
- **MSW effects must be carefully taken into account**

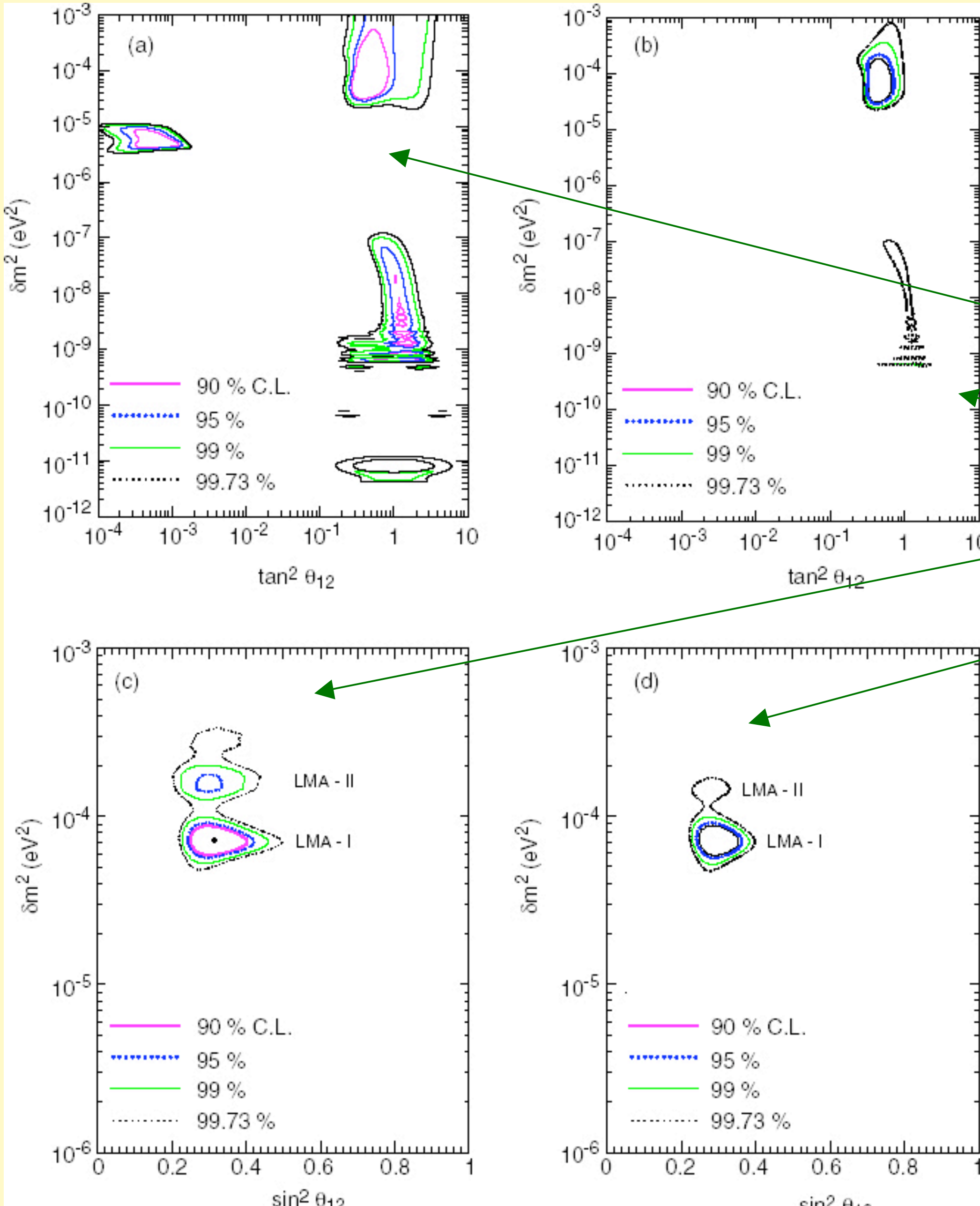
→ need electron density profile in the Sun (always) …

… and in the Earth (for night-time trajectories)





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 $\nu_e \rightarrow \nu_{\mu,\tau}$ in SNO through comparison of

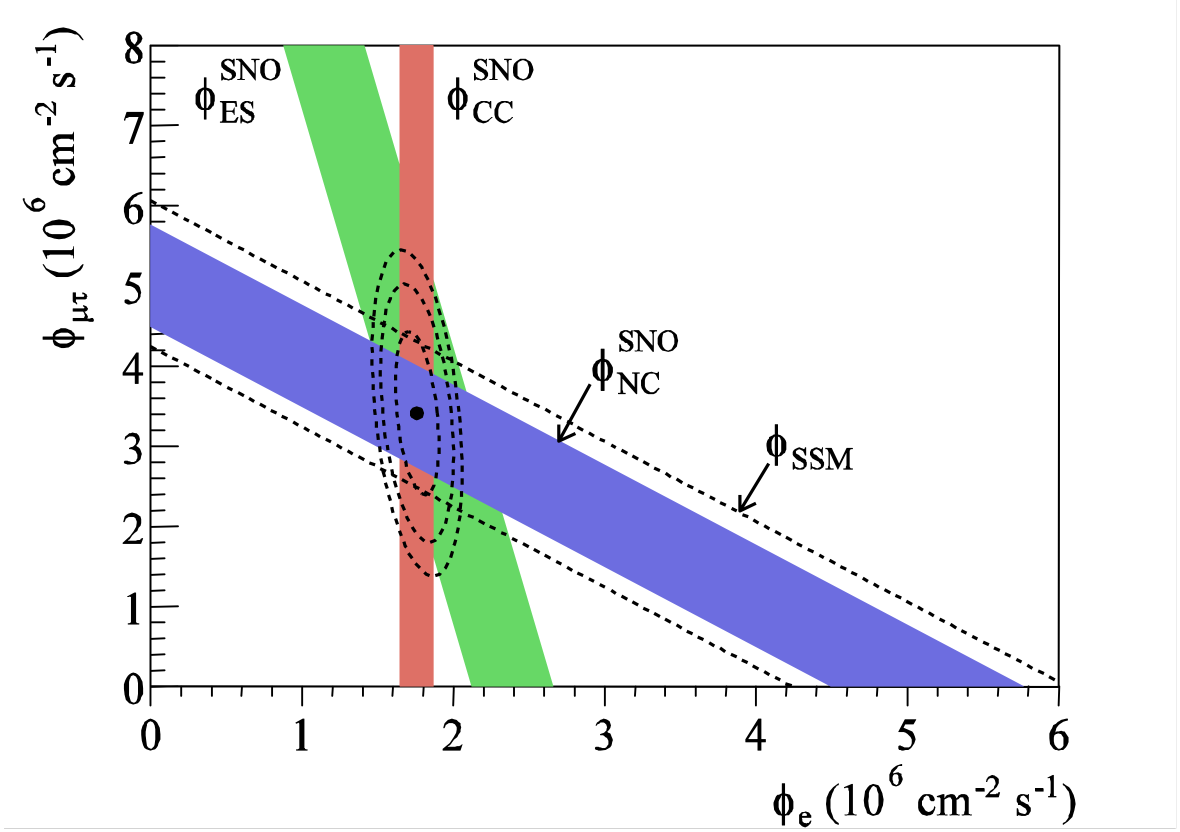
$$\begin{aligned} CC &: \quad \nu_e + d \rightarrow p + p + e \\ NC &: \nu_{e,\mu,\tau} + d \rightarrow p + n + \nu_{e,\mu,\tau} \\ ES &: \nu_{e,\mu,\tau} + e \rightarrow e + \nu_{e,\mu,\tau} \end{aligned}$$

Solar neutrinos: The 1st SNO breakthrough (2002)

- **Solar neutrino deficit in Cl, Ga, Č expt.: model-independent proof desirable**
- **Proof provided beyond any doubt by CC/NC event ratio in SNO:**

$$R = \frac{R_{CC}}{R_{NC}} = \frac{\Phi(\nu_e)}{\Phi(\nu_e) + \Phi(\nu_\mu) + \Phi(\nu_\tau)} = P(\nu_e \to \nu_e) \text{ independently of SSM}$$

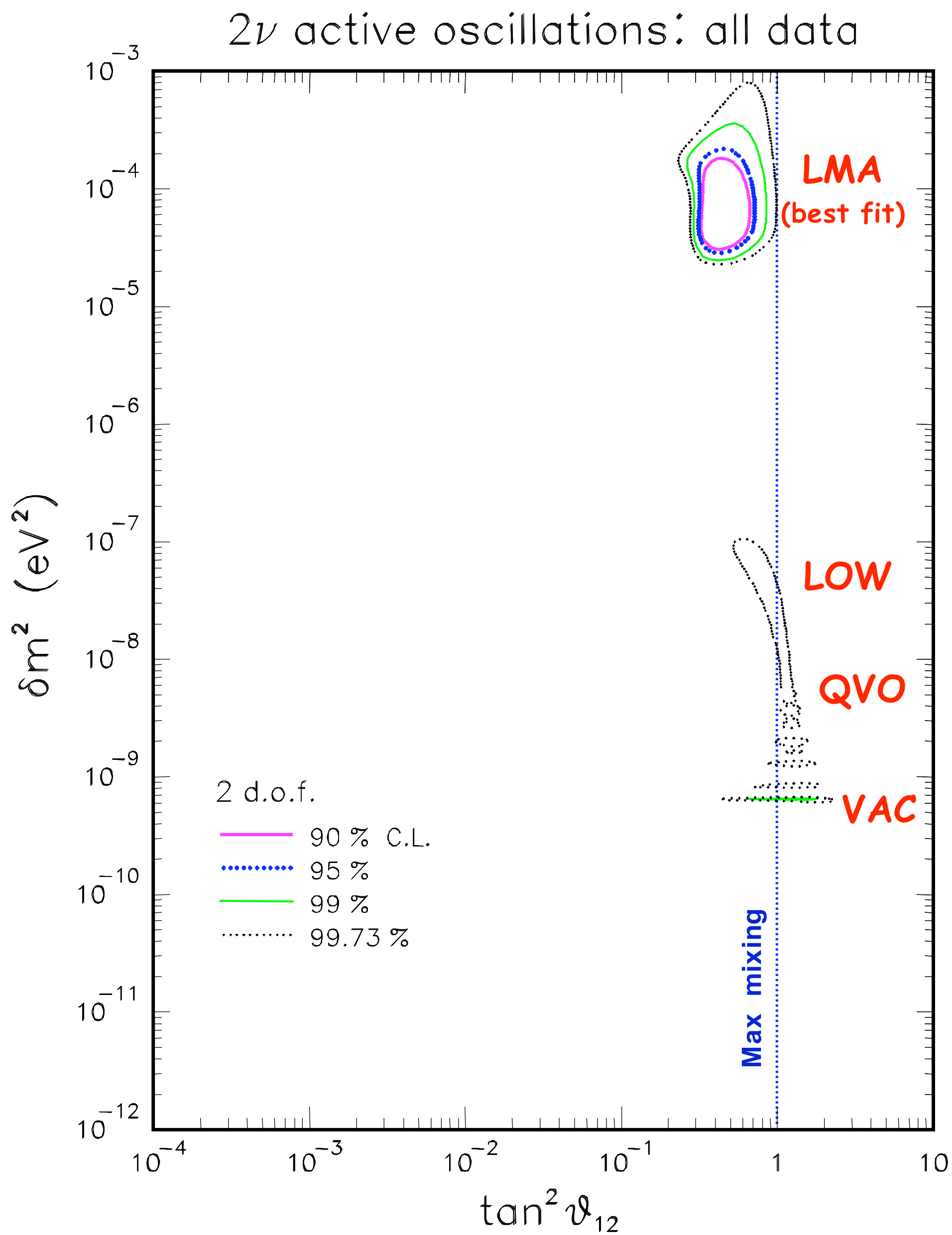
- **R~1/3 was found → solar ν_e must oscillate into $\nu_{\mu\tau}$**



Solar neutrinos: Oscillation analysis (as of summer 2002)

All experiments combined (summer '02)

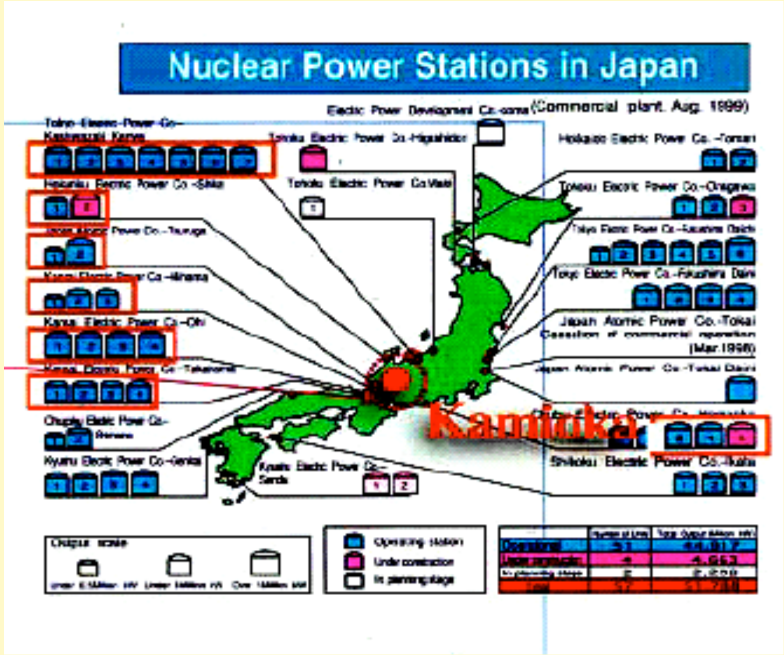
(90, 95, 99, 99.73% C.L.)

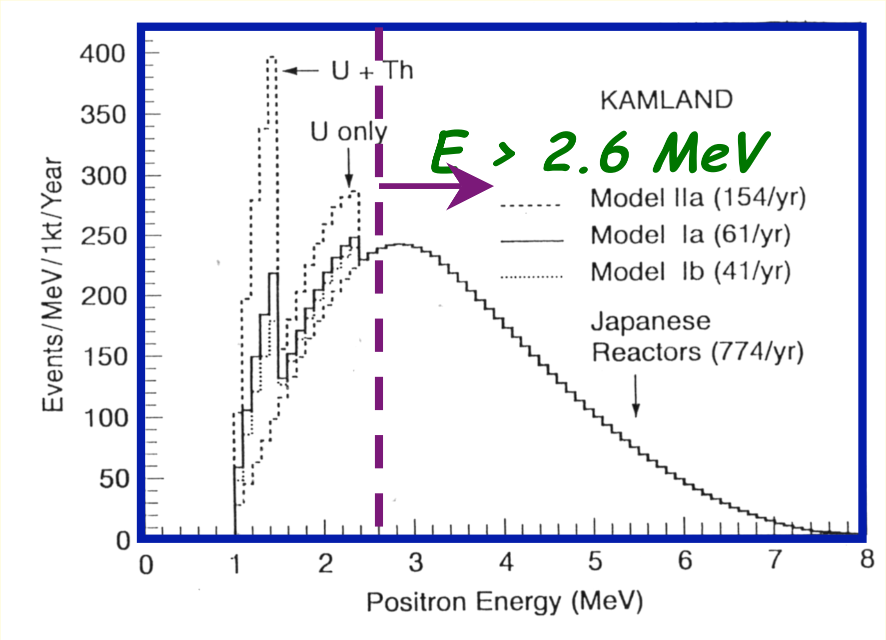


Jargon:

- **LMA** Large Mixing Angle
- **LOW** Low δm^2
- **QVO** Quasi-vacuum oscillations
- **VAC** Vacuum oscillations
- (**SMA** Small mixing angle, †2001)

Man-made reactor neutrinos: KamLAND

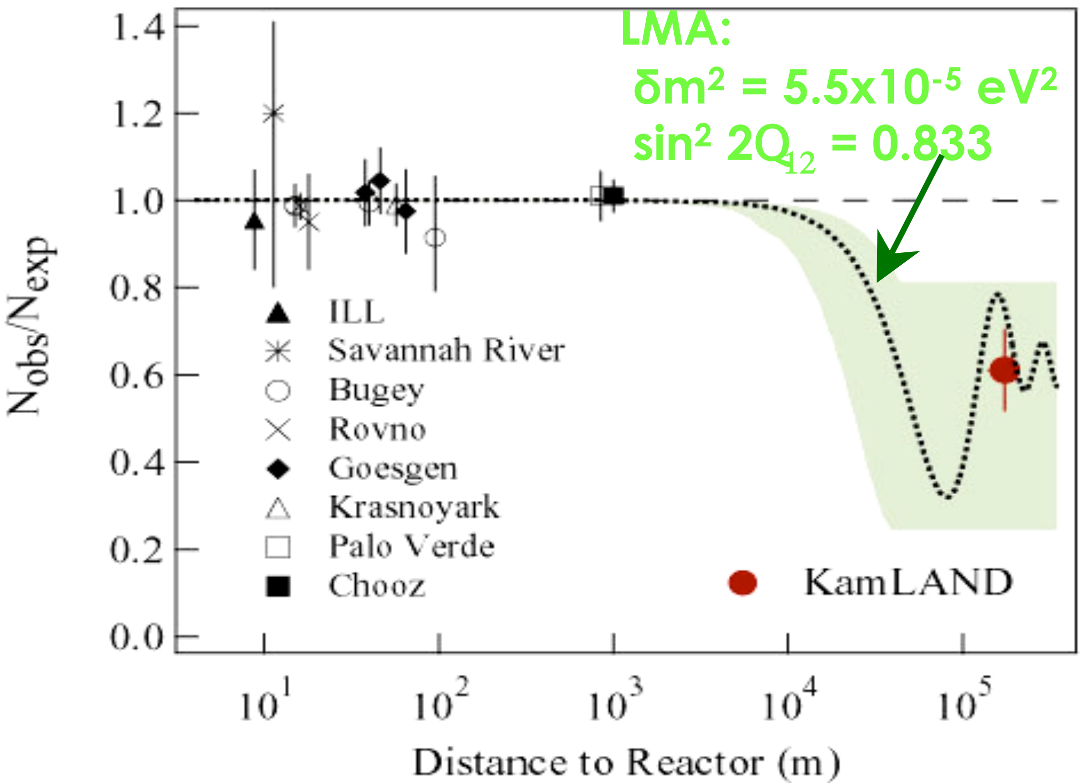




- **Average distance: ~180 km (two orders of magnitude greater than CHOOZ)**
- **CHOOZ was mainly sensitive to Δm^2 ~ few x 10^{-3} eV^2**
- **KamLAND is mainly sensitive to δm^2 ~ few x 10^{-5} eV^2 (LMA range!)**
- **KamLAND also opens fundamental new field of geoneutrino physics**

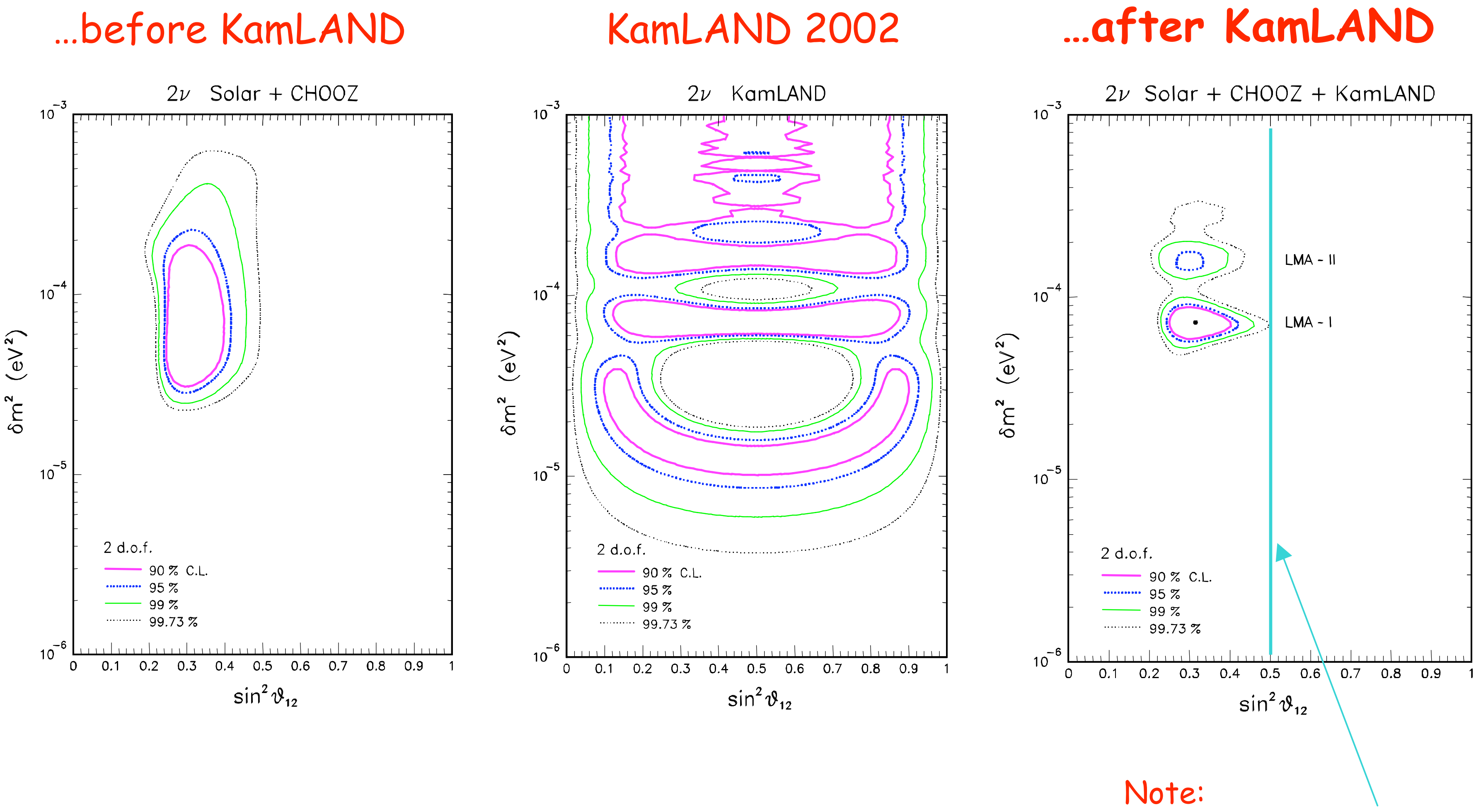
KamLAND breakthrough (December 2002)

Disappearance of reactor ν_e **measured**



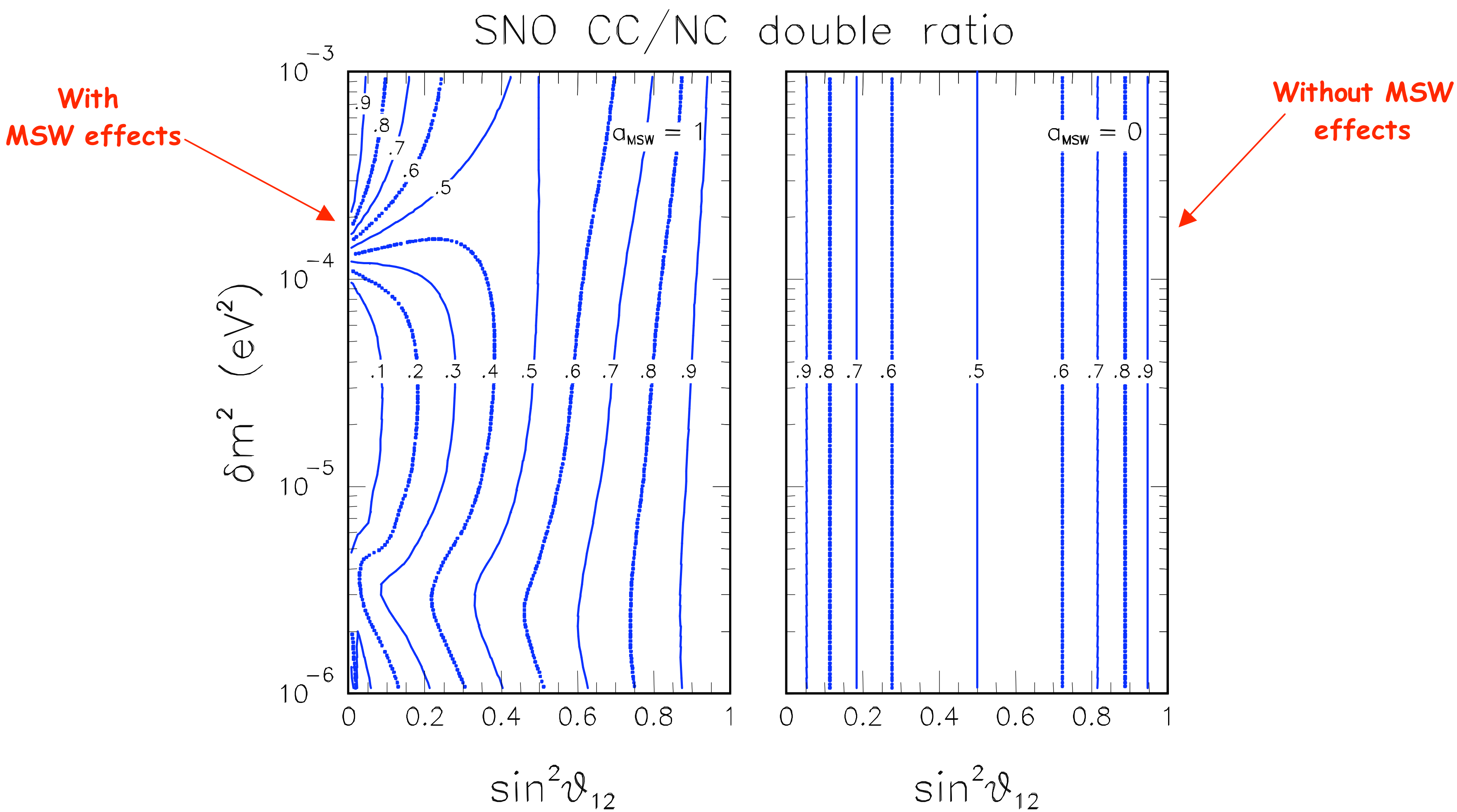
LMA solution confirmed; all others ruled out

KamLAND impact on $(\delta m^2, \theta_{12})$ parameter space



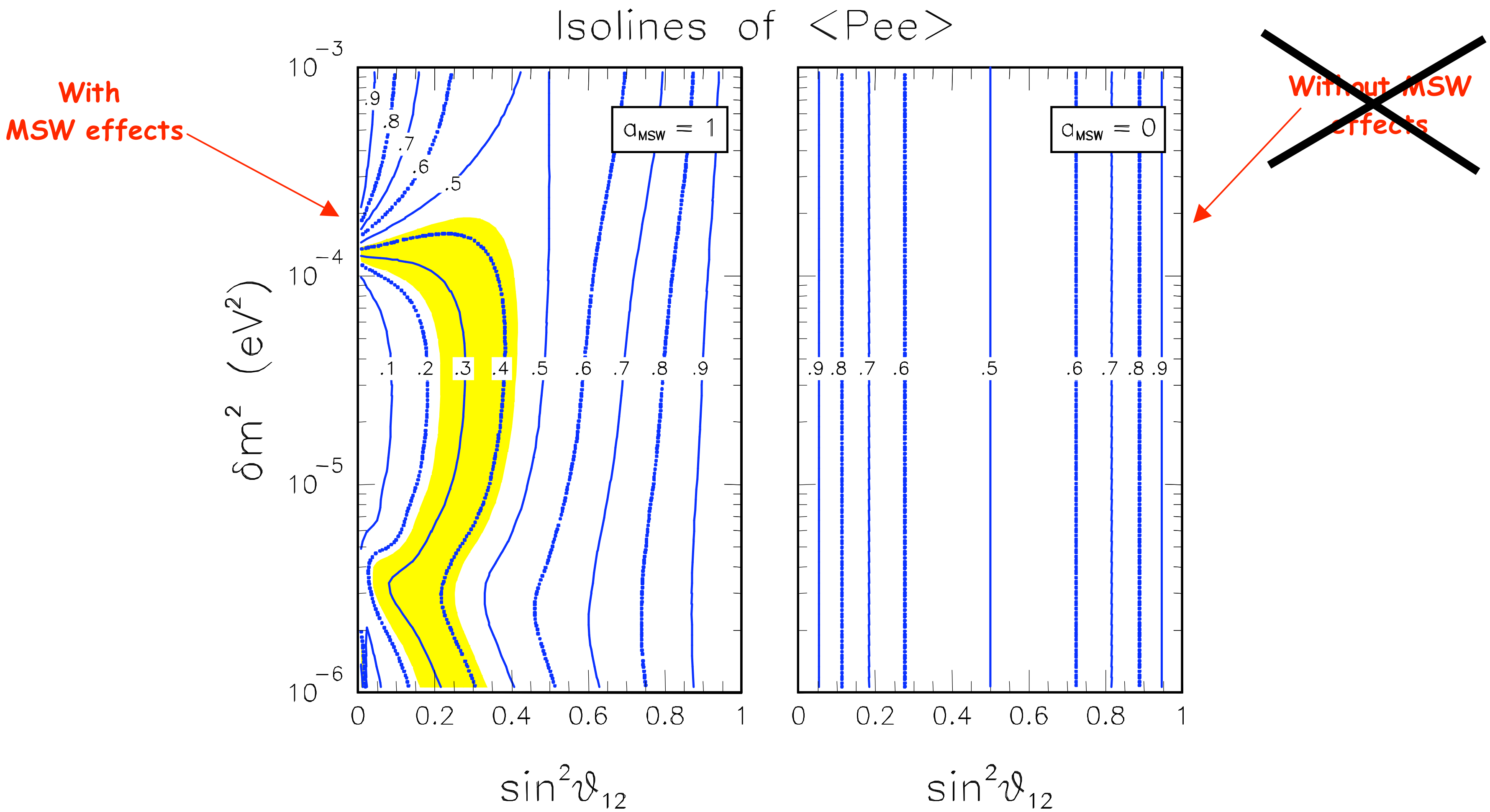
Note:
Maximal θ_{12} mixing
not ruled out in 2002

Why should we care about (non)maximal θ_{12}



In LMA, SNO CC/NC can be <0.5 only WITH matter effects AND mixing <π/4

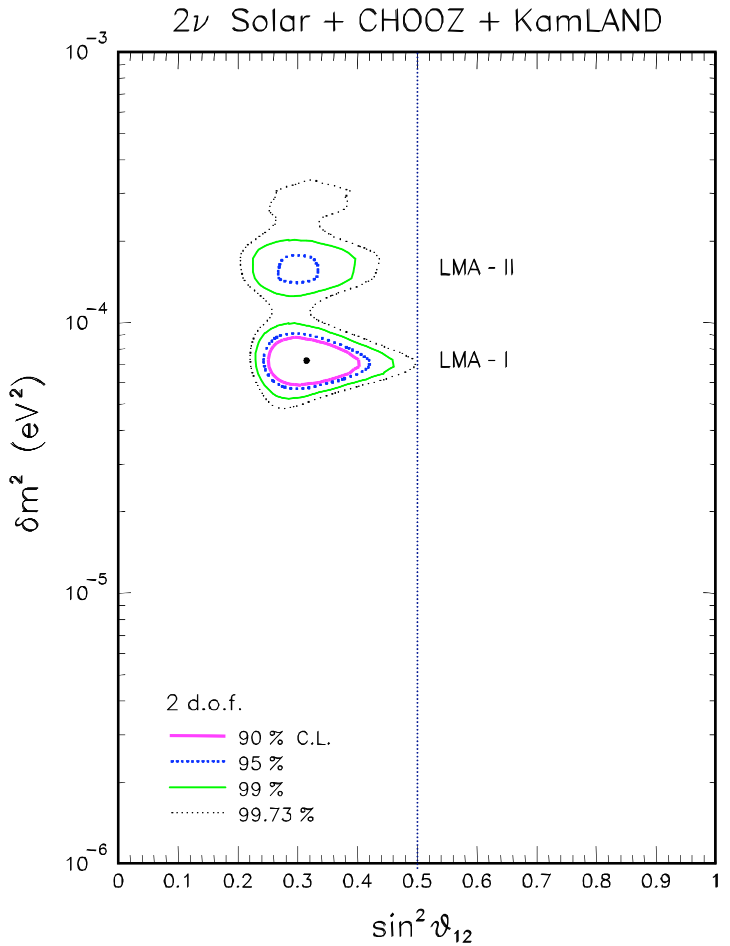
The 2nd SNO breakthrough (September 2003): maximal mixing ruled out



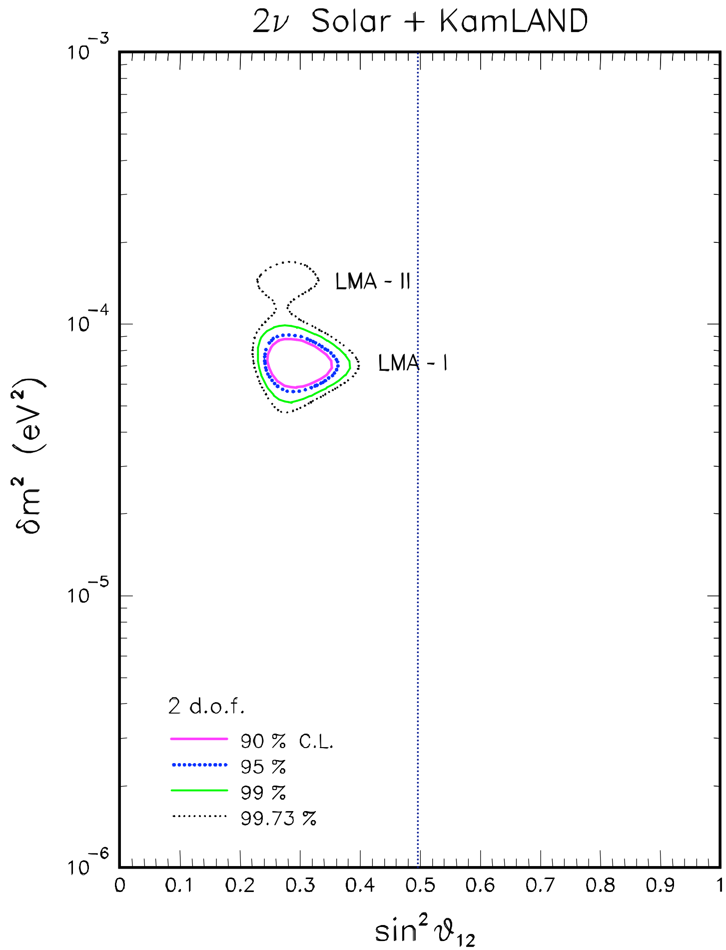
Compelling evidence for matter effects in the Sun

LMA analysis (as of september 2003)

Still: LMA-I vs LMA-II ambiguity

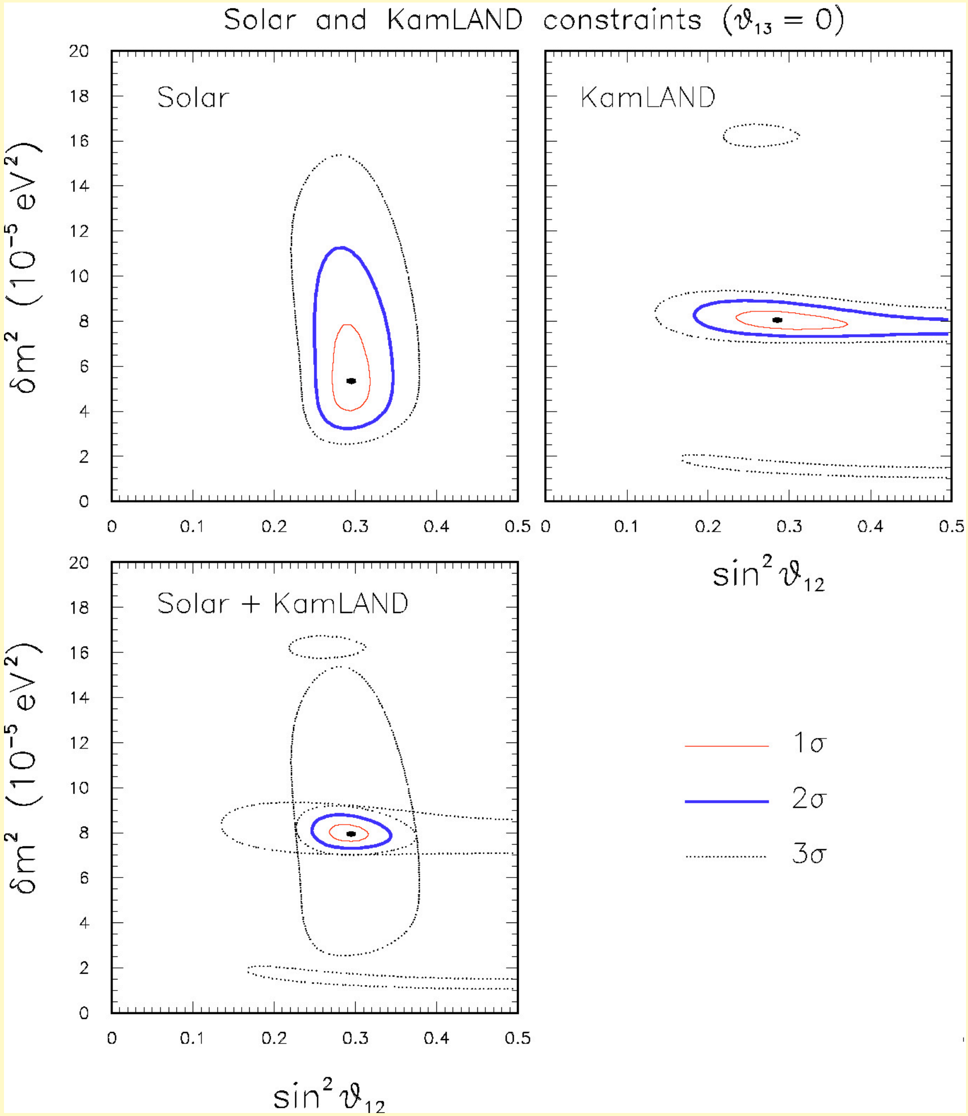


Before SNO 2003

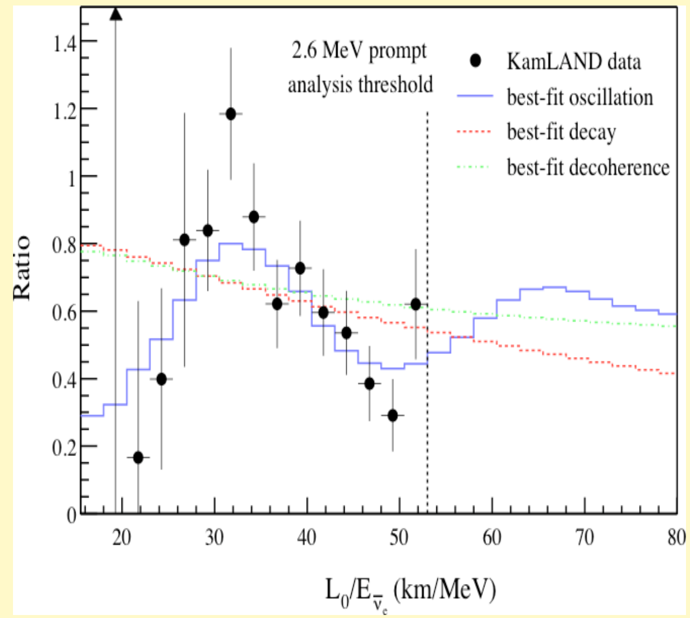


After SNO 2003

… in **2004** (KamLAND-II with revised background):
unique Large Mixing Angle solution, and change to linear scales…



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

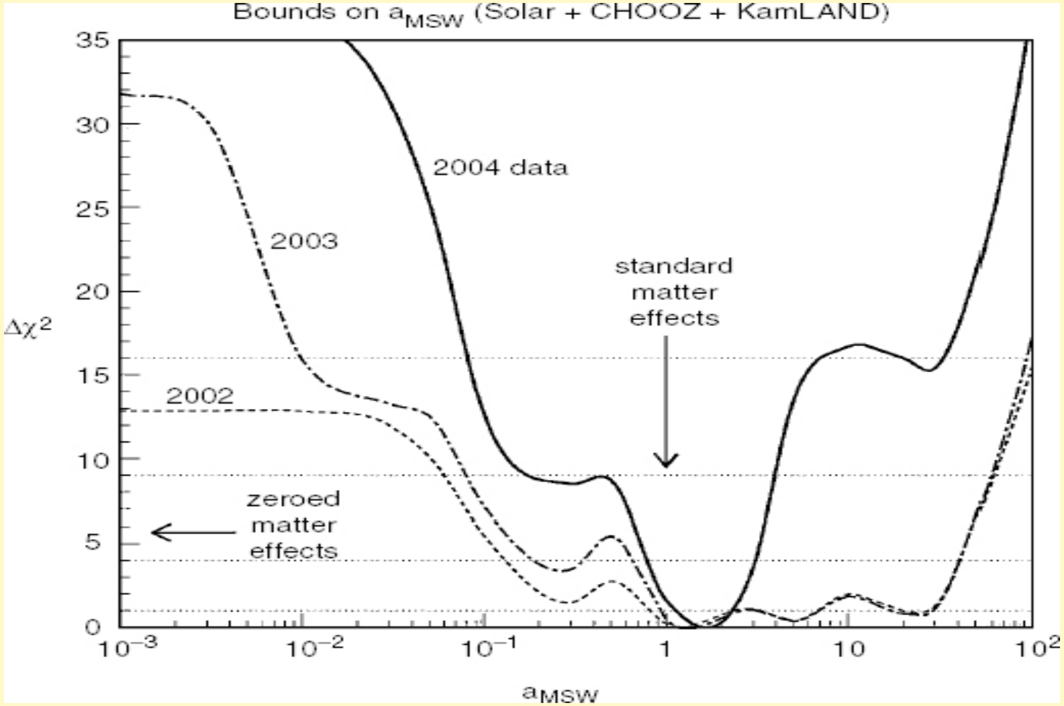


What about MSW effects?

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 **$a_{MSW} \sim 1$**

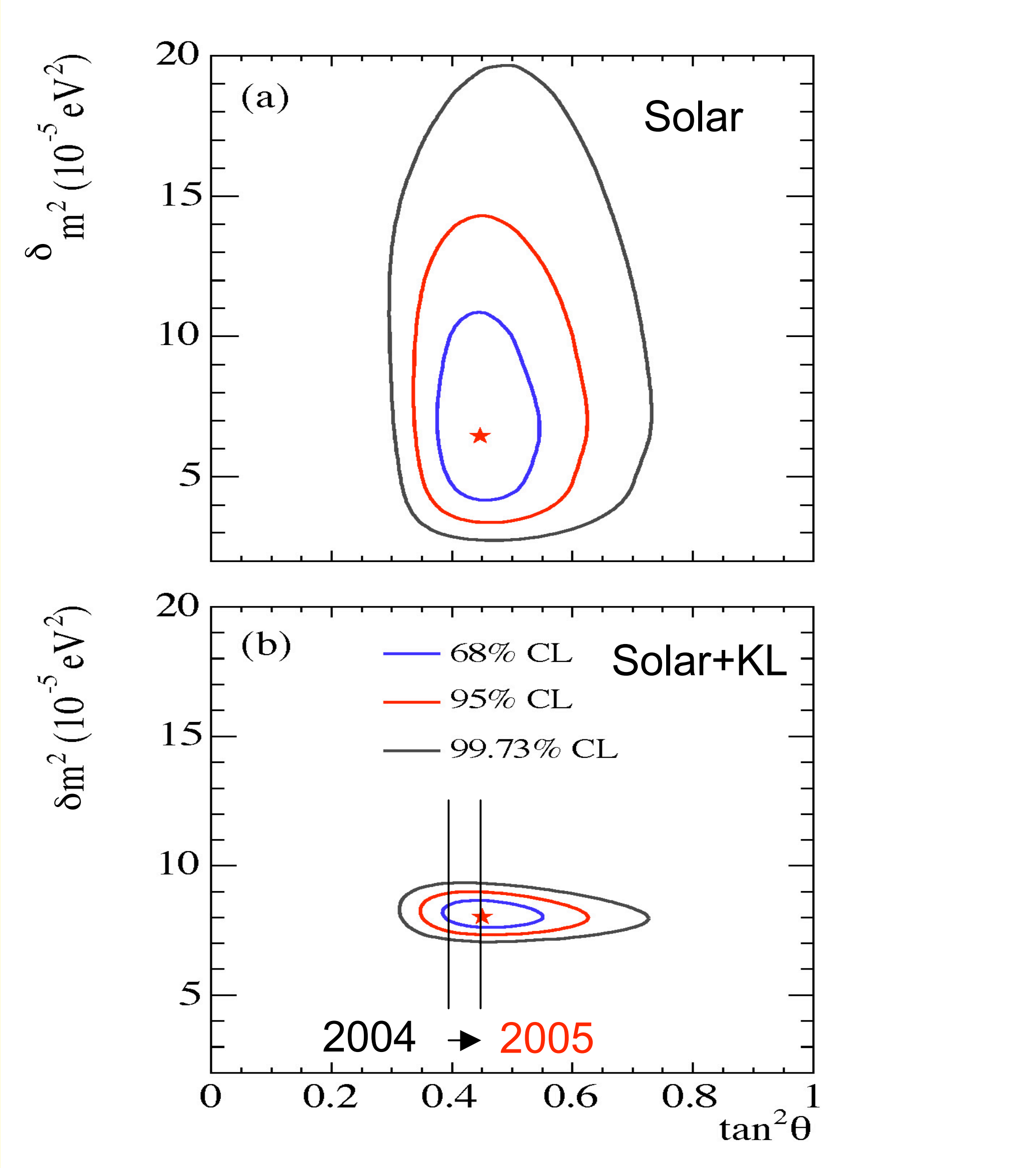


(… a way of "measuring" G_F through solar neutrino oscillations …)

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

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

2005 (March): new data + detailed analysis from SNO

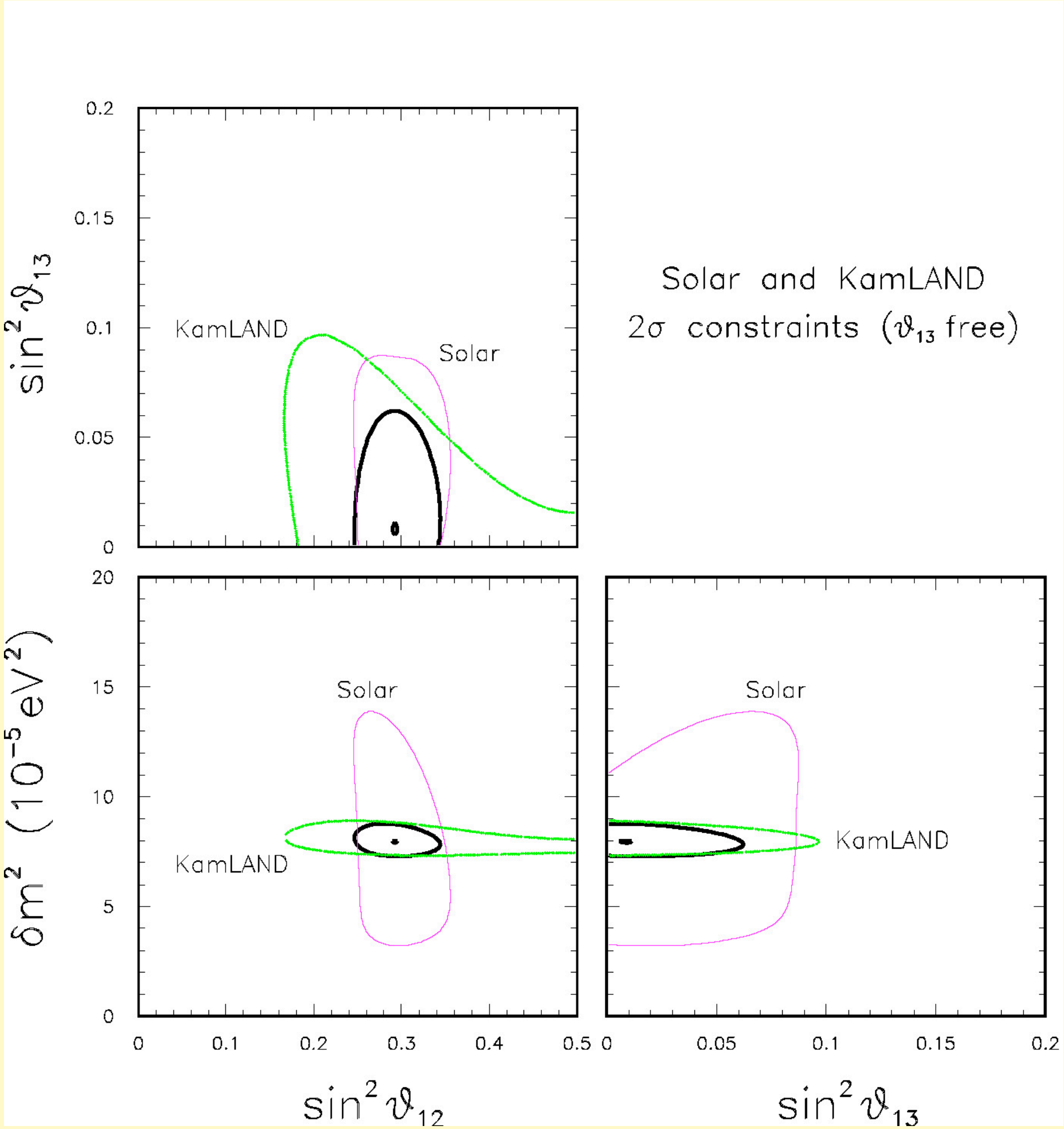


Previous results basically confirmed

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)

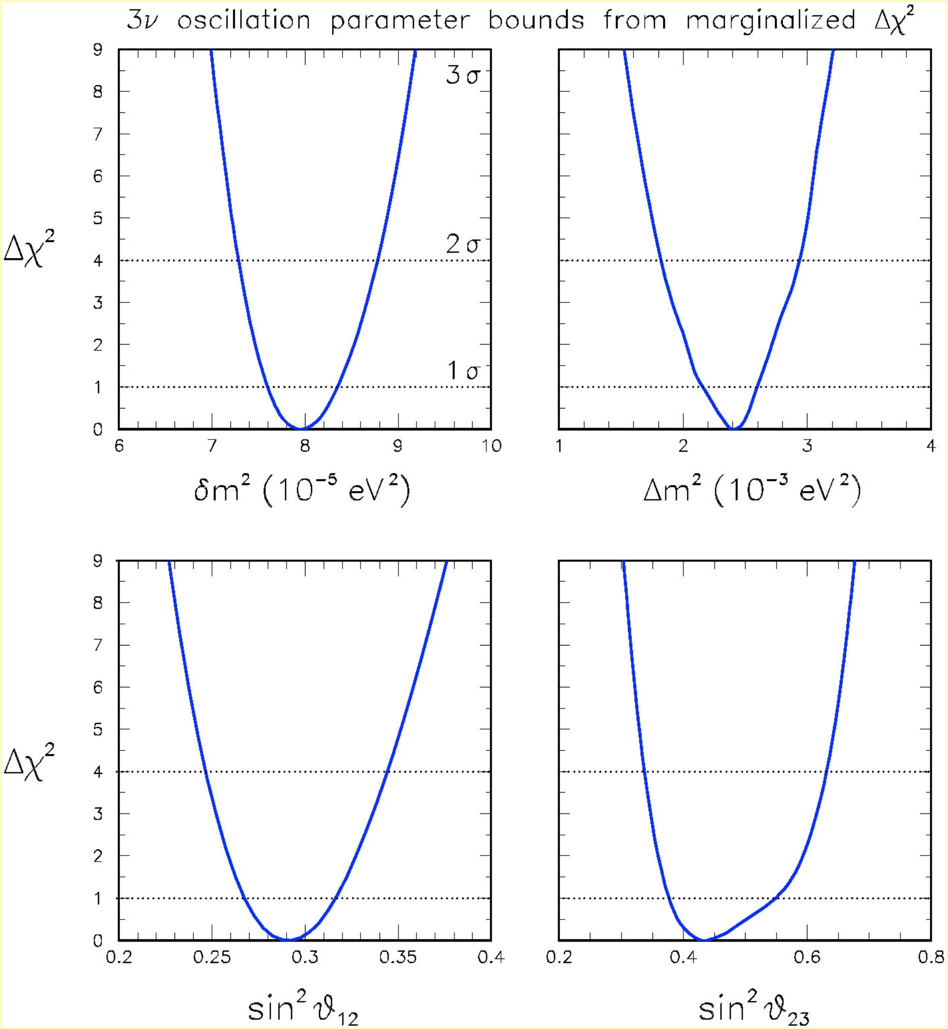


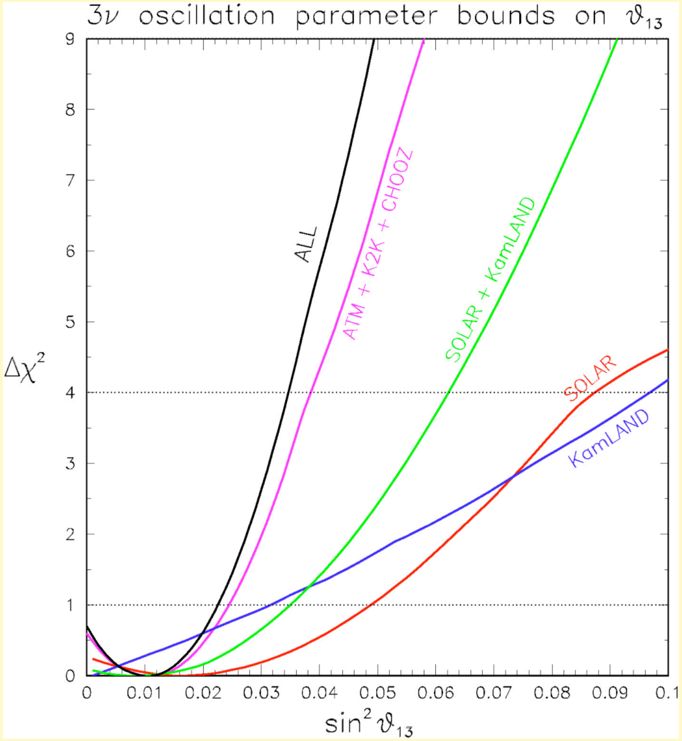
Solar and KamLAND data also prefer θ_{13}~0 (nontrivial consistency with SK+CHOOZ)

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:

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

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

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

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

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

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

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

Note: Precise values for θ_{12} and θ_{23} relevant for model building

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":

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

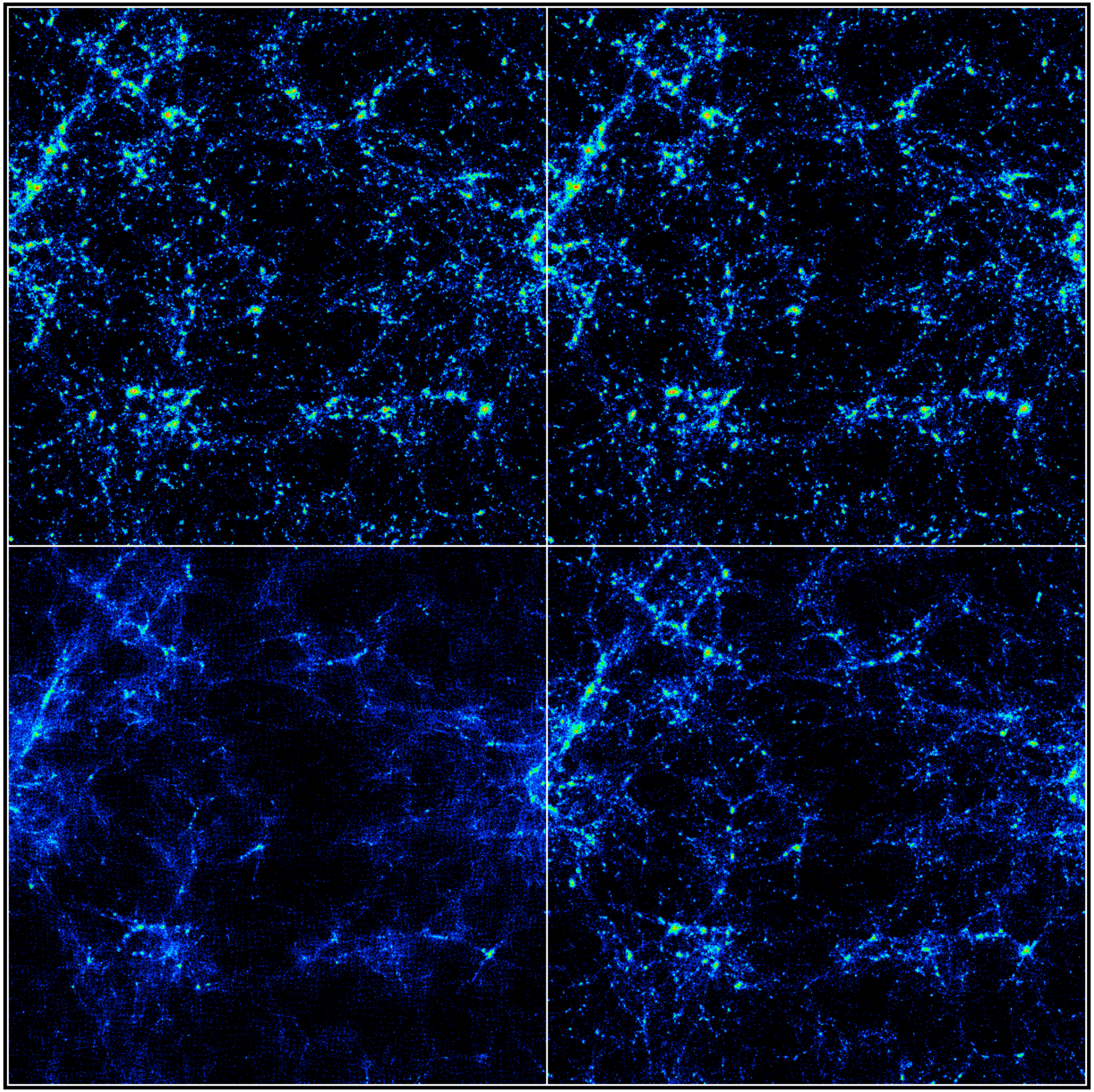
2) **0ν2β decay**: Can occur if $m^2_i \neq 0$ and $\nu=\bar{\nu}$. Sensitive to the "effective Majorana mass" (and phases):

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

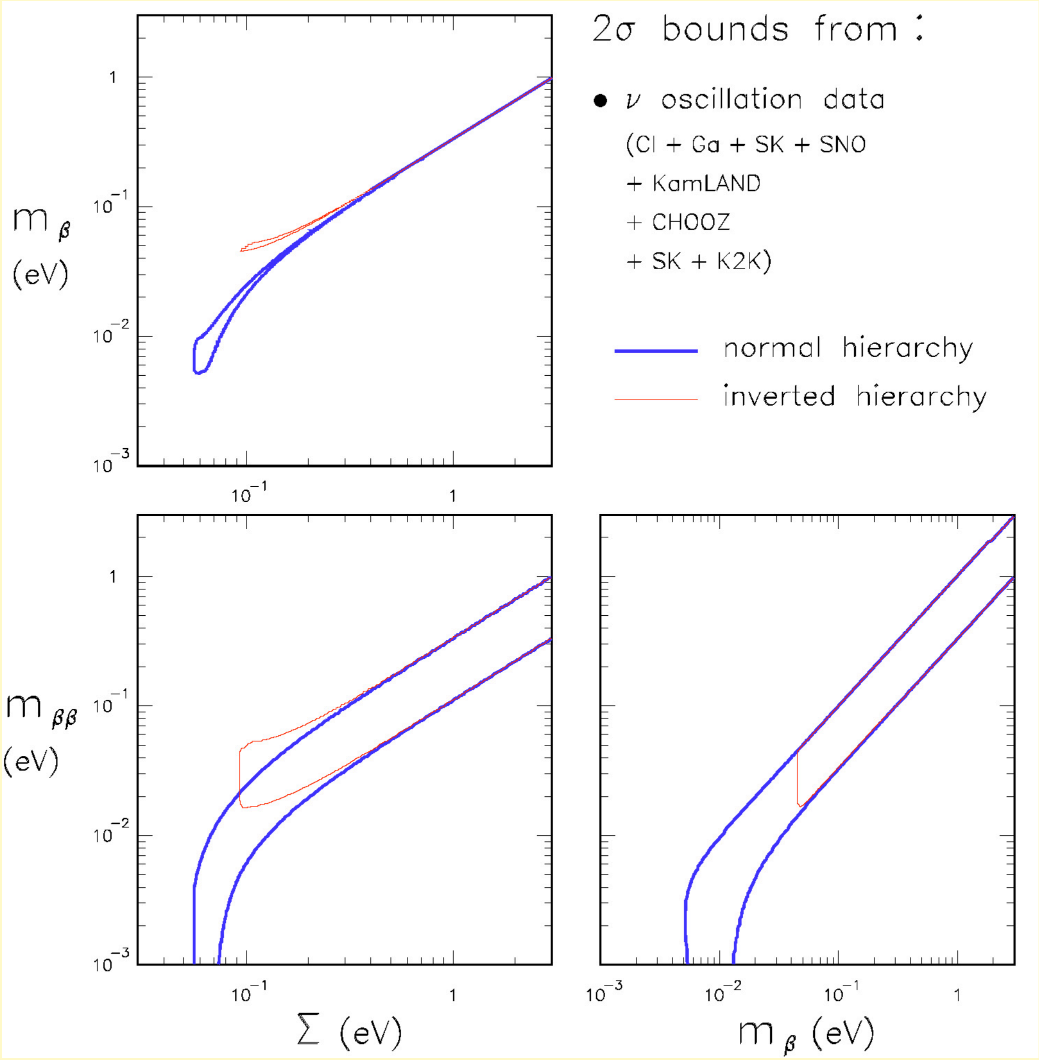
3) **Cosmology**: $m^2_i \neq 0$ can affect large scale structures in (standard) cosmology constrained by CMB+other data. Probes:

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

$m_\nu =$ 0 1
7 4
eV



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

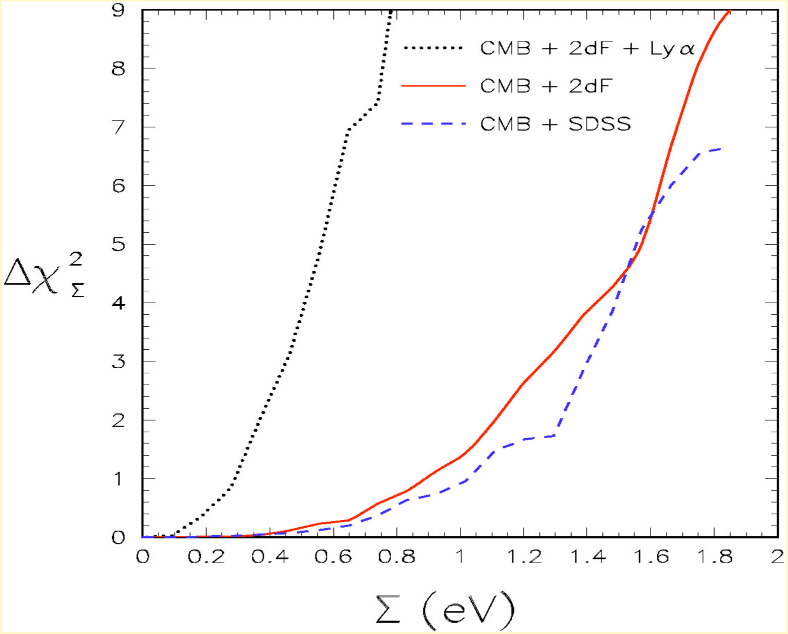
Large $m_{\beta\beta}$ spread due to unknown Majorana phases

But we do have information from non-oscillation experiments:

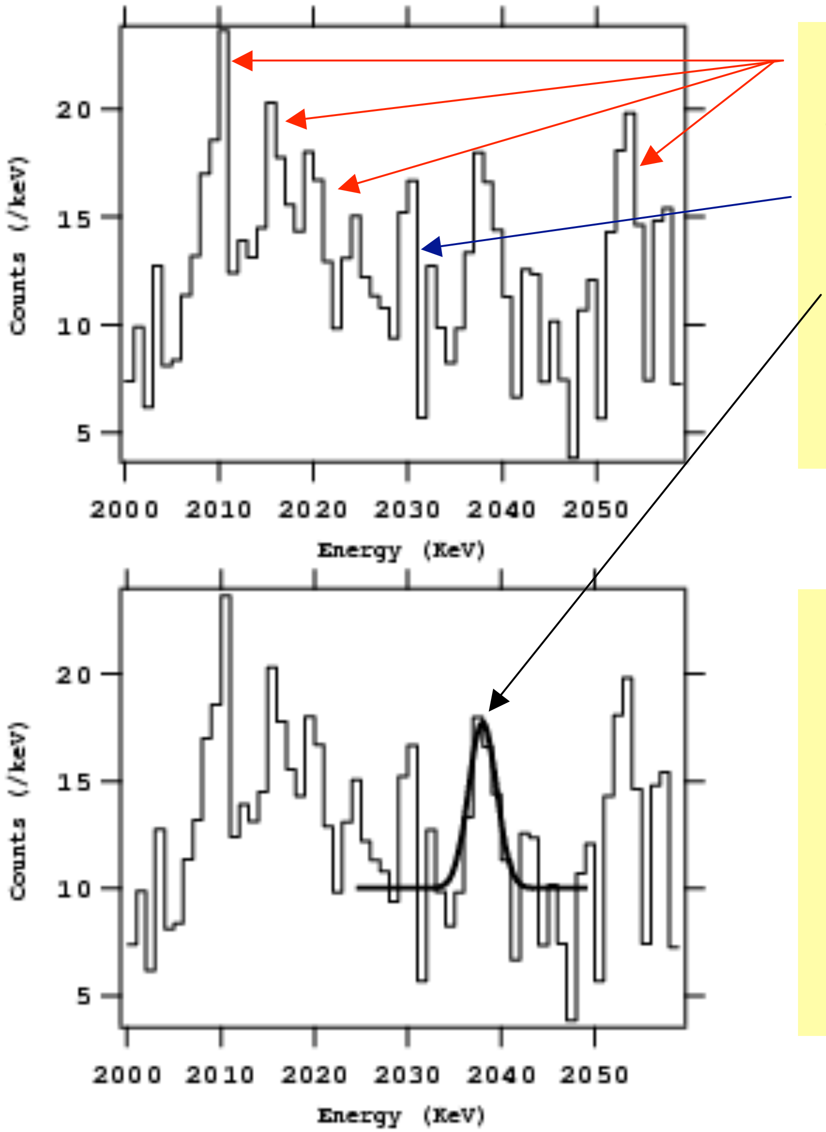
1) β **decay**: no signal so far. Mainz & Troitsk expts: m_β < O(eV)

2) **0ν2β 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 decay: Heidelberg-Moscow experiment final analysis (March 2004)



Four lines at 2010, 2017, 2022, 2053 keV are identified as due to ^{214}Bi decay

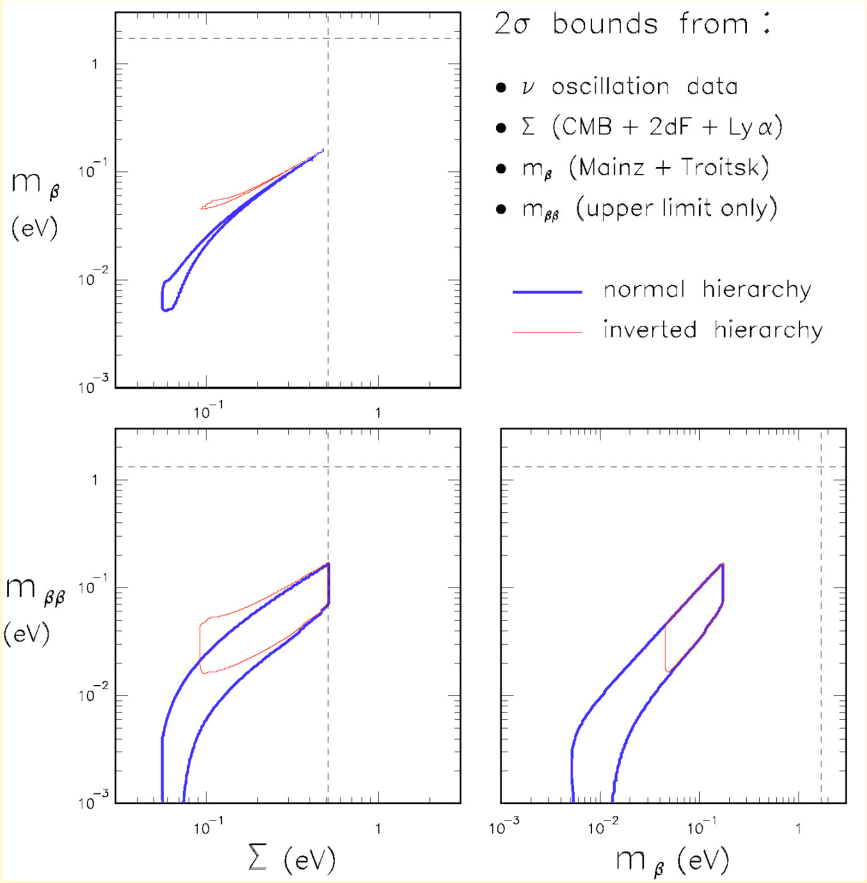
One possible line at 2030 keV is not identified

Claimed 0nbb line at ~2039 keV is now more clearly seen "by eye". Statistically, it emerges at about 4σ C.L. (~23 events)

We might have reached an "LSND-like" situation:

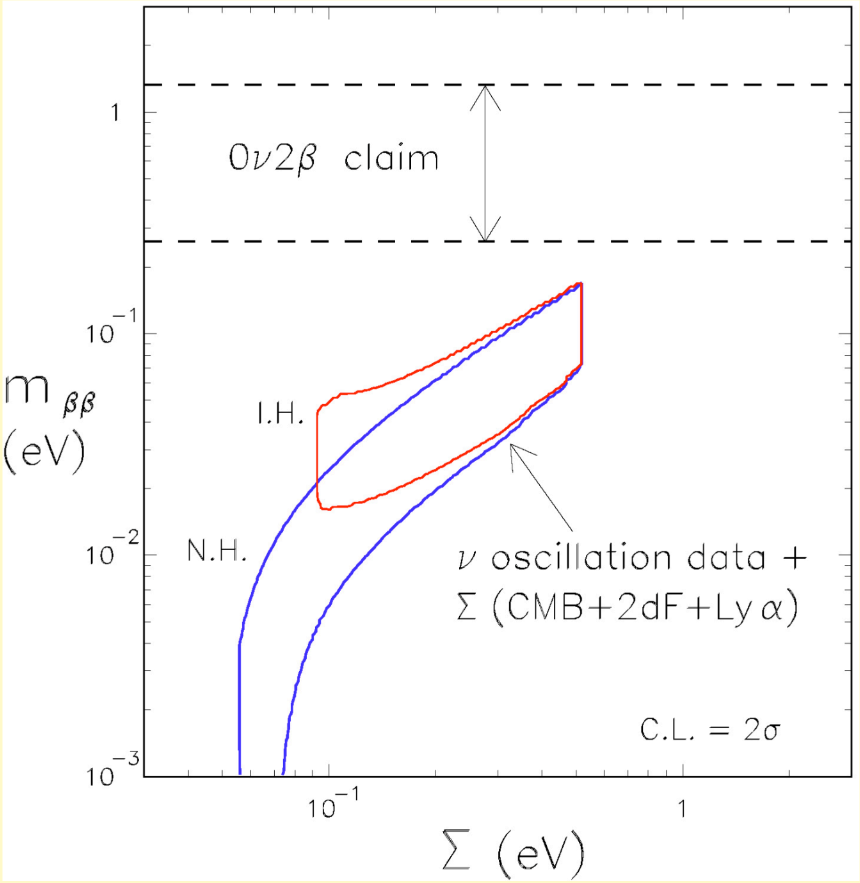
- Initial claim is rather controversial
- Then, further data/analysis strengthen it
- No current experiment can disprove it
- It will stay with us for a long time and will demand more sensitive expt. checks

0ν2β claim rejected



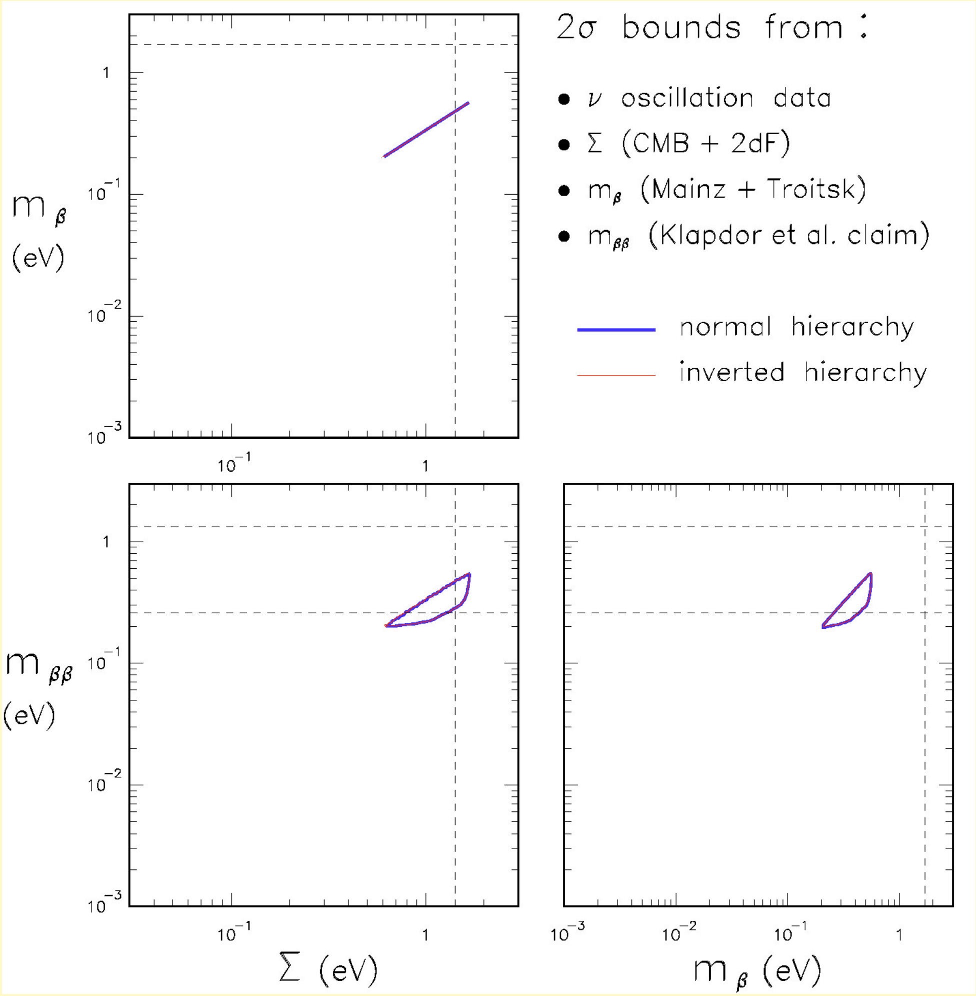
Cosmological bound dominates, but does not probe hierarchy yet

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)

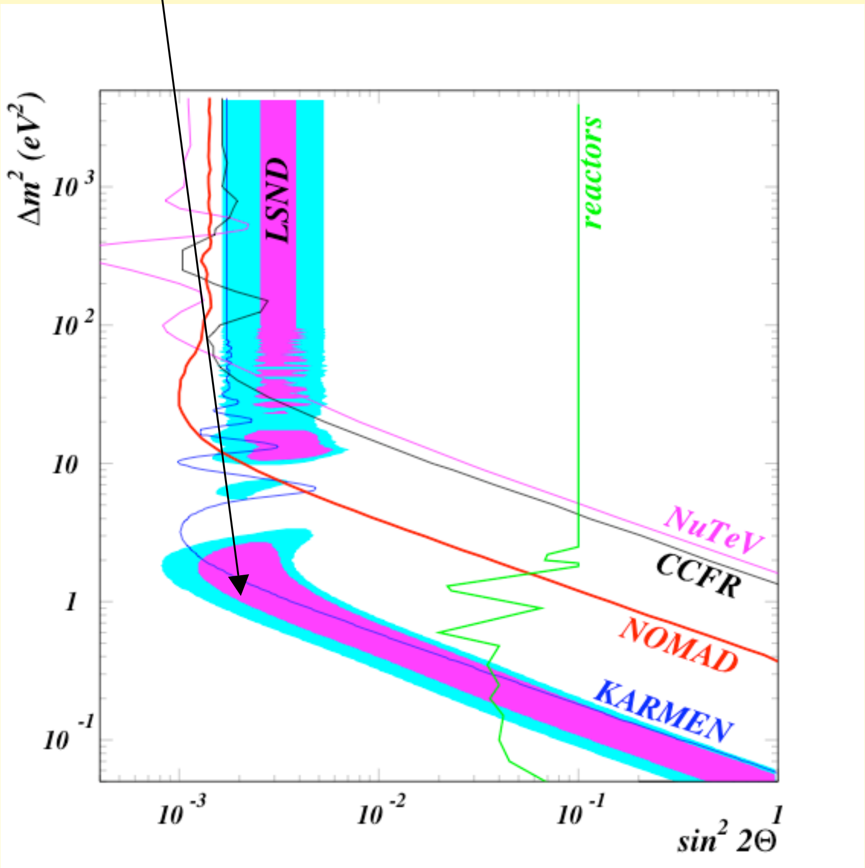
High discovery potential in future (m_β, $m_{\beta\beta}$, Σ) searches

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 confirms LSND this year (2005), many ideas will be revised, and neutrino schools > 2006 will really 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!