Convegno di Fisica Teorica

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Fisica dei neutrini: situazione attuale

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Thanks to: G.L. Fogli, D. Montanino, A. Marrone, A. Palazzo, A. Mirizzi, A.M. Rotunno

Outline

- Introduction
- Status of 3ν oscillations
- Absolute neutrino masses
- Conclusions

Disclaimer: given the large number of papers in the field of neutrinos physics (about 10^3/year in the last decade), references are omitted altogether in this talk

INTRODUCTION

- We have now compelling evidence that the Hamiltonian H of neutrino flavor evolution,

$$i\frac{d\nu_\alpha}{dx} = H_\alpha^\beta \cdot \nu_\beta$$

is **nontrivial** (=not prop.to unity):

$$H_\beta^\alpha \neq E_\nu \cdot \delta_\beta^\alpha$$

→ flavor non conservation

- Barring one controversial experiment (LSND), all differences ΔH from triviality (= massless ν) are consistent with a three-neutrino mass-mixing framework:

$$\Delta H = (\Delta H_{kin} + \Delta H_{dyn}) = \left(\frac{U_D U_M \cdot M^2 \cdot U_M^+ U_D^+}{2E_\nu} + V_{MSW}(x) \right)$$

kinematical mass-mixing term

dynamical MSW term in matter

$U_D =$ (Dirac) mixing matrix

$M^2 =$ Squared mass matrix

$U_M =$ Majorana phase matrix (unobservable in oscillations)

- **Relevant three-neutrino parameters:**

$$U_D = U(\theta_{23})\, U(\theta_{13}, \delta)\, U(\theta_{12})$$

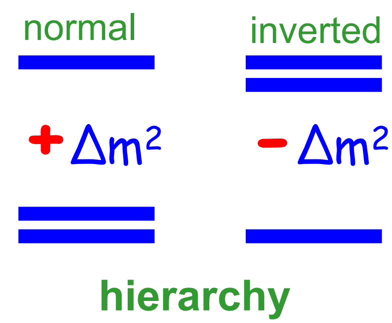
3 mixing angles → θ_{23}, θ_{13}, θ_{12}

CP phase → δ

$$M^2 = \mu^2 + \mathrm{diag}(0, \delta m^2, \pm\Delta m^2)$$

absolute mass scale → μ^2

"solar" $\Delta(\mathrm{mass})^2$ → δm^2 << "atmospheric" $\Delta(\mathrm{mass})^2$ → $\pm\Delta m^2$



$$U_M = \mathrm{diag}(1, \exp(i\varphi_2), \exp(i\varphi_3))$$

Possible Majorana phases → φ_2, φ_3

- **Relevant dynamical parameter in matter:**

$$V_{MSW} = \mathrm{diag}(\sqrt{2}\, G_F N_e(x), 0, 0)$$

electron density → $N_e(x)$

(can modify the vacuum oscillation phase $\Delta m^2 \cdot L/E$)

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 oscillation pattern recently seen in atmospheric 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
$\mathrm{Sign}(\Delta m^2)$	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 (to explain LSND)?*
$V=V_{MSW}+\Delta V$?	*New (subleading) interactions in medium?*
$H \neq H^+$?	*Neutrino decay ?*
$i d\nu/dx \neq H\nu$?	*Non-hamiltonian evolution (decoherence)?*

...

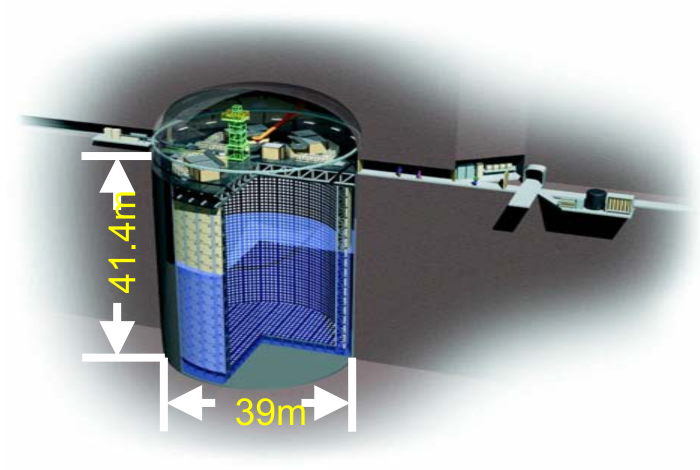
Three-neutrino oscillation phenomenology:

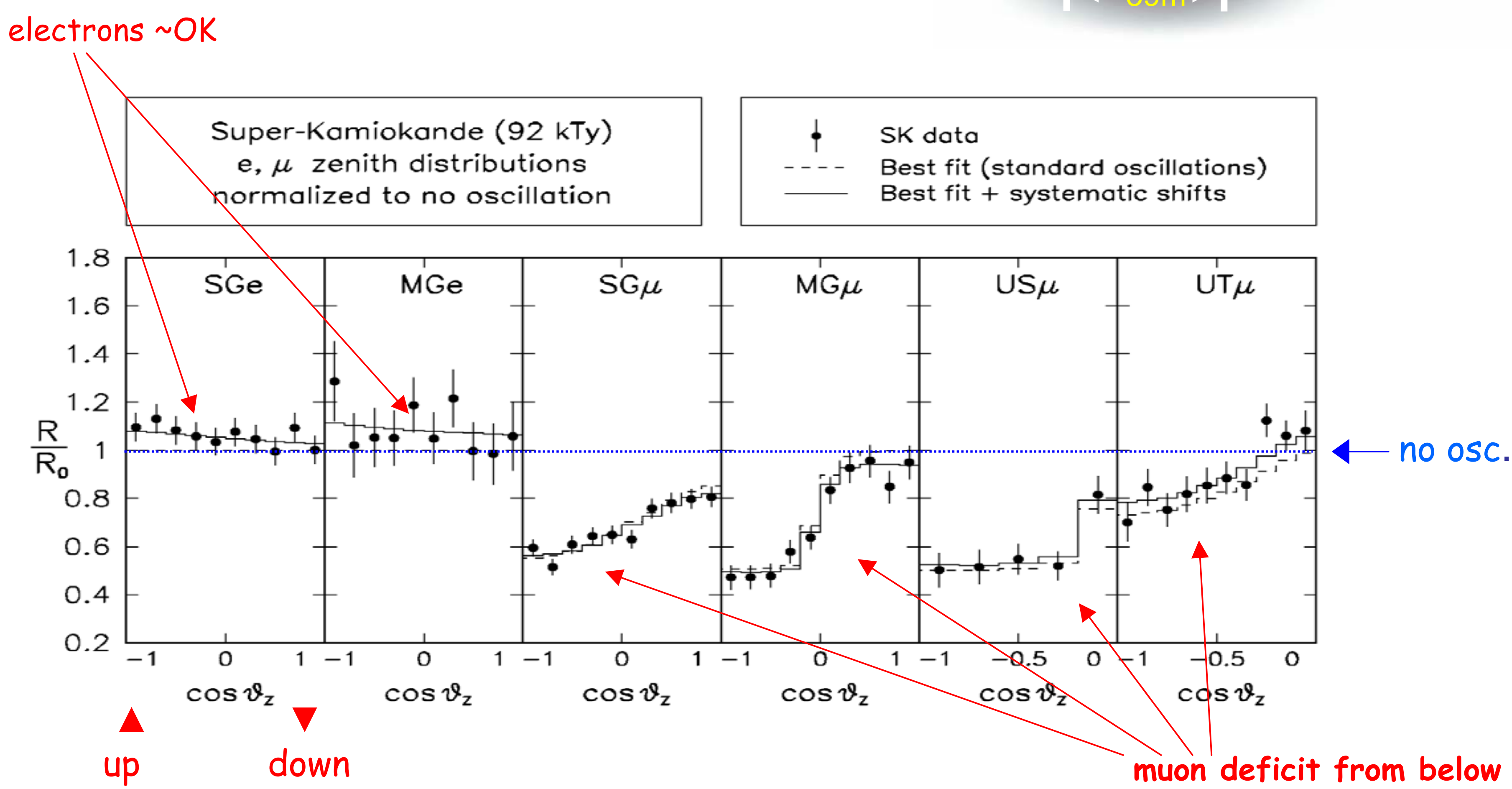
Status of $(\Delta m^2, \theta_{23})$ and L/E pattern

from atmospheric neutrinos
and K2K long-baseline accelerator neutrinos

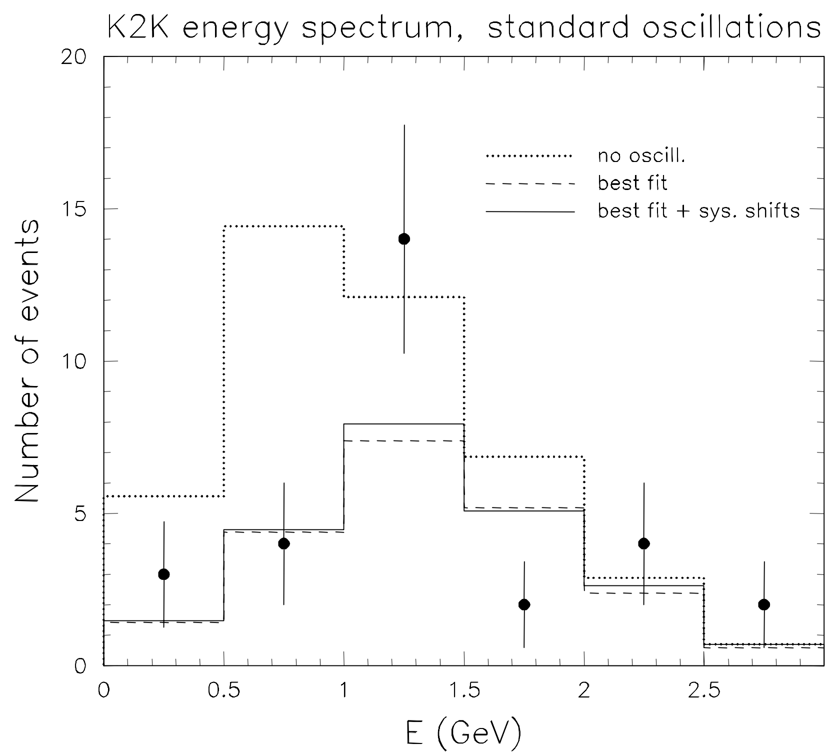
Atmospheric neutrinos: Super-Kamiokande

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





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



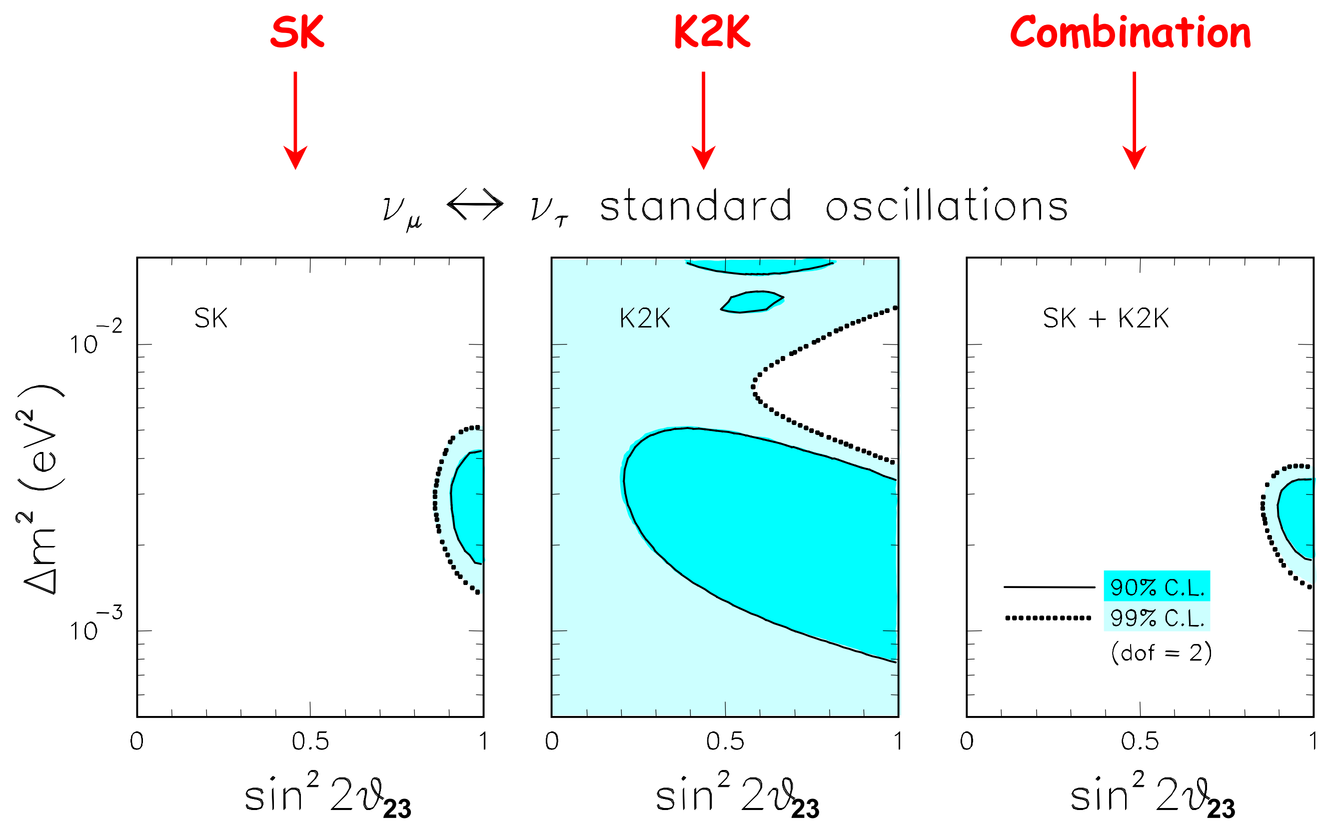
Aimed at testing disappearance of accelerator ν_μ in the same range probed by atmospheric ν:

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

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

No electron appearance.

Our combined oscillation analysis of SK+K2K observables (2003)



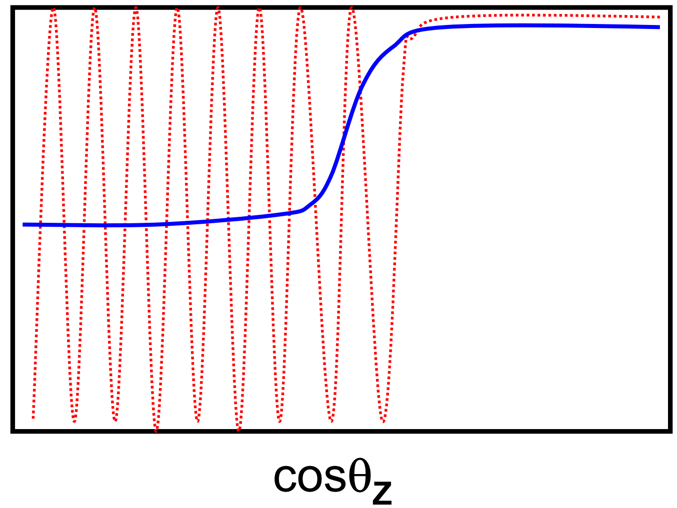
Joint bounds on the leading parameters (Δm^2, θ_{23}) prefer

$\Delta m^2 \sim (2\text{-}4) \cdot 10^{-3}$ eV^2 (best-fit at ~2.6) and maximal mixing, $\theta_{23} \sim \pi/4$

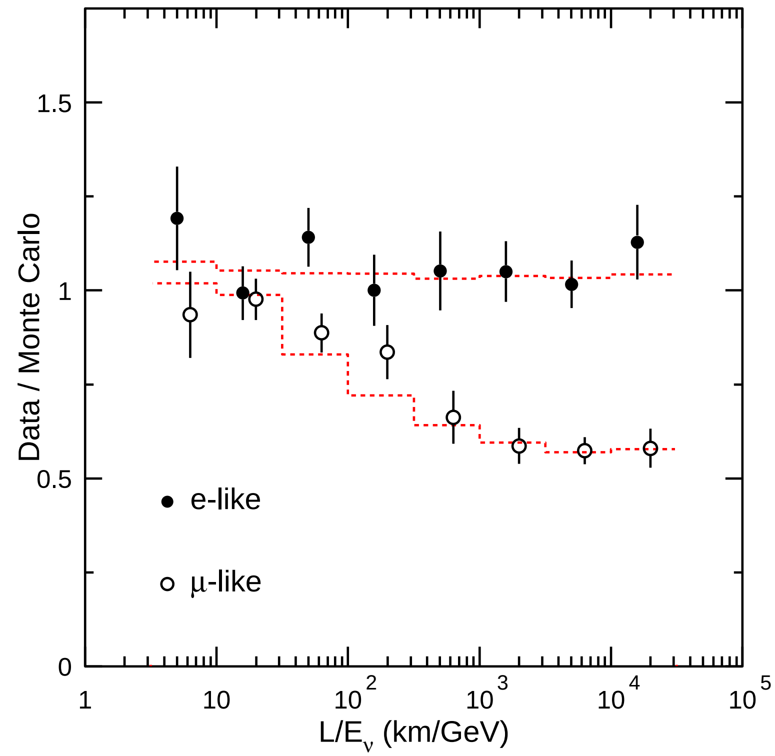
(Consistent with MACRO & Soudan-2 experiments)

L/E and Δm² : February 2004 SK update

- Until recently, it was thought that the oscillatory pattern - if any – had to be hidden in the SK zenith distributions
- Reason: Large uncertainty in L (direction) and E (energy) smear out oscillations

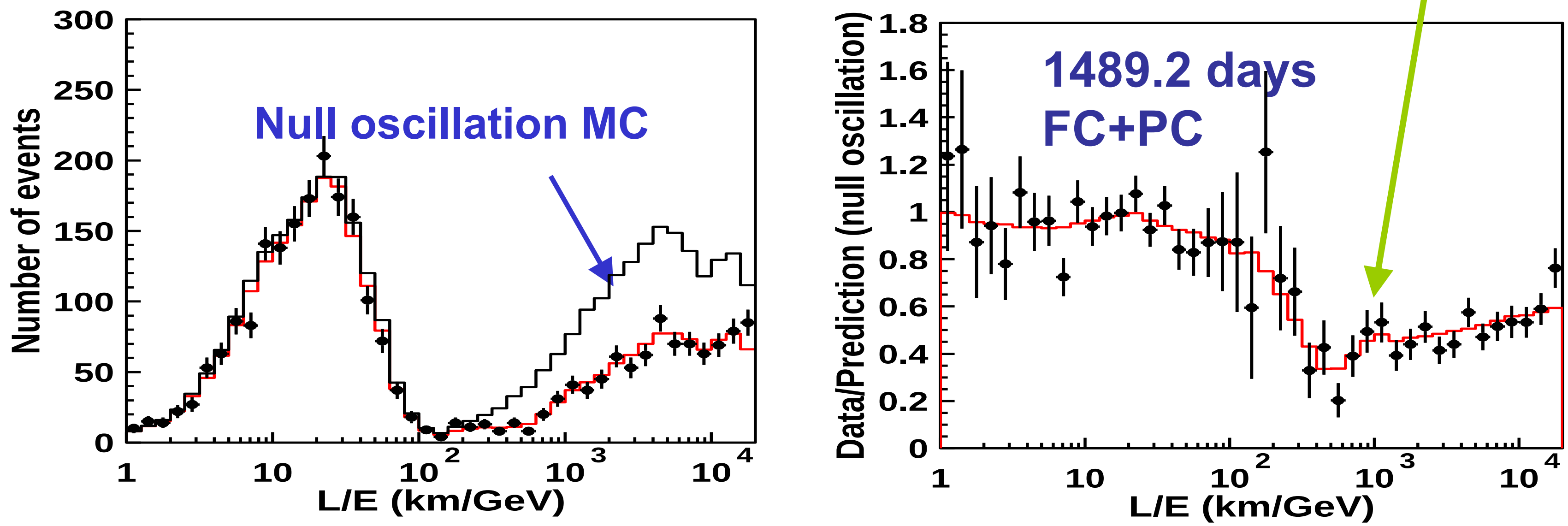


- ***Earlier*** SK data analyses replacing $\cos(\theta_Z)$ with the "most probable" L/E parameter also led to similar (pessimistic) conclusions. Ditto for other experiments (MACRO, Soudan 2)
- Observation of at least one oscillation cycle (disppearance + reapparance) was considered a task for future LBL or atmospheric experiments with higher "L/E resolution" and thus higher sensitivity to Δm²



L/E and Δm^2 : February 2004 SK update *(continued)*

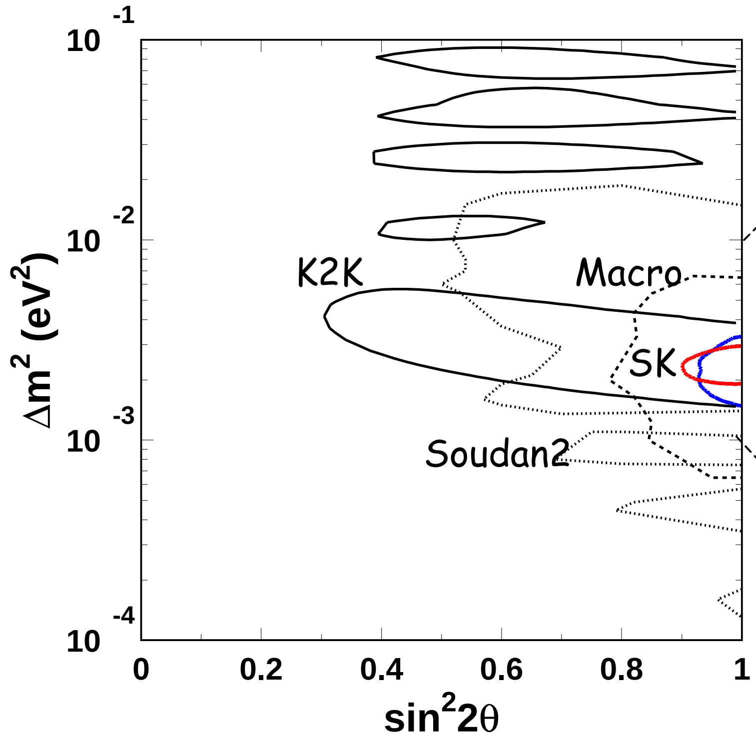
But, using a subset of events with best "L/E" resolution, the SK Collaboration claims observation of first oscillation dip.
Surprising and Very Interesting!

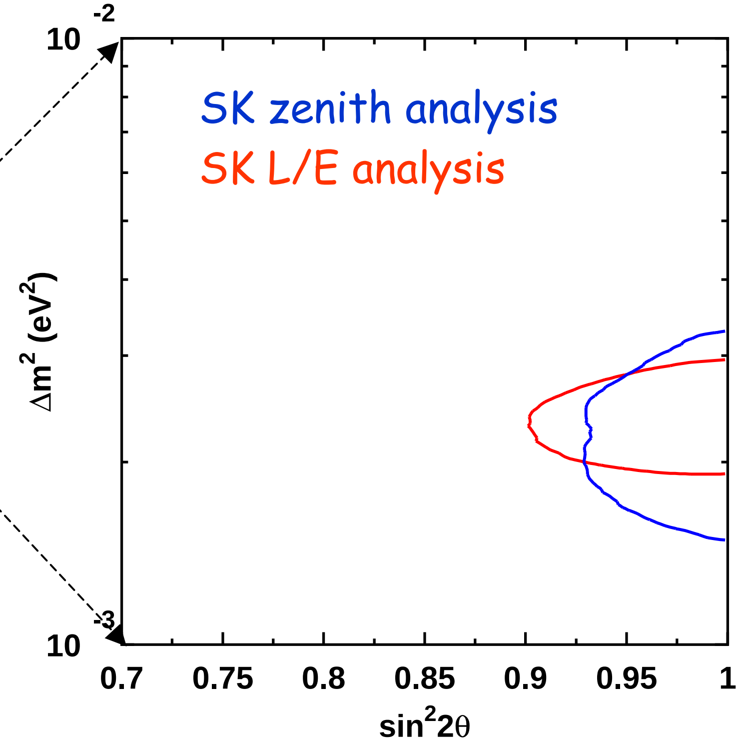


Let me add, however, some personal cautionary remarks:

- Dip falls in the region of lowest statistics (~10 events/bin)
- MonteCarlo is used twice: both for "MC" (of course!) and to assign "L/E" to data
- Systematics not small: responsible for deviations from 1 and $\frac{1}{2}$ aymptotic plateau
- Analysis is valid if and only if $\theta_{13}=0$ (pure $\nu_\mu \rightarrow \nu_\tau$ oscillations)
- Analysis not reproducible outside the Collaboration

L/E and Δm^2 : February 2004 SK update *(end)*





If confirmed, the SK L/E analysis would:

- Significantly improve the determination of Δm^2 , with best fit at 2.4×10^{-3} eV^2
- Establish vacuum oscillations as dominant explanation of atmospheric nu data
- Rule out surviving nonoscillatory explanations (decay and decoherence)
- Taken together, the SK L/E analysis and the ~2σ claim for τ neutrino appearance might somehow diminish the "psychological impact" (although not the physics relevance) of 1st generation LBL experiments (OPERA, ICARUS, MINOS)

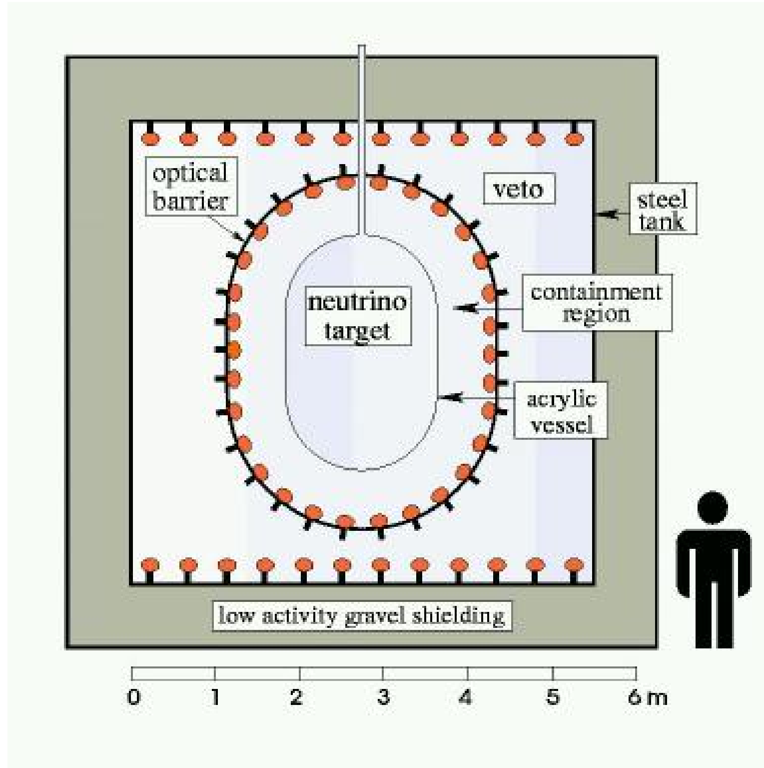
Three-neutrino oscillation phenomenology:

Status of $(\Delta m^2, \theta_{13})$

from CHOOZ reactor data

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 $\rightarrow$ probe the same Δm^2
- No disappearance signal was found (1998) $\rightarrow$ 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}
- Our analysis of SK+K2K+CHOOZ
  +other data
  +subleading corr.:

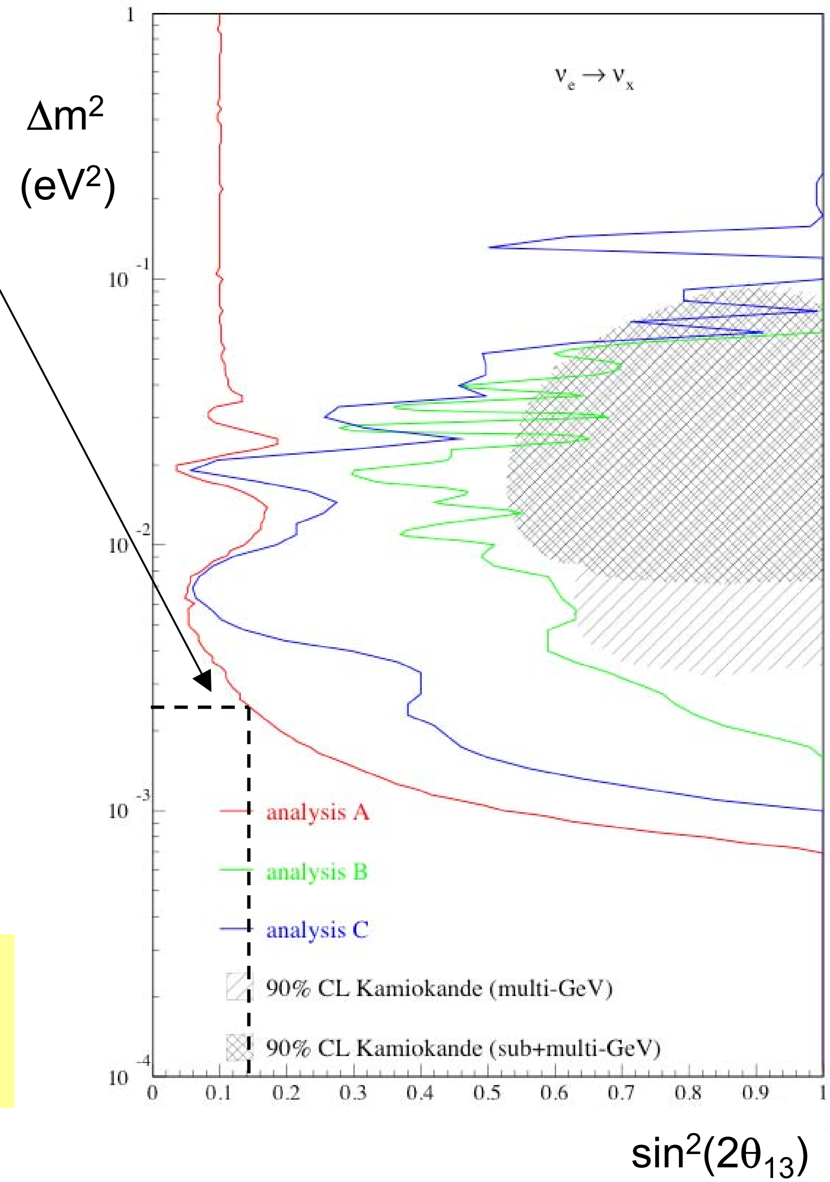
$\sin^2\theta_{13} < 0.06 \quad (3\sigma)$

(up to about ±0.01 bound shifts due to variations in SK atmospheric data and analysis in the last two years)

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

MARCH 2004: "Double CHOOZ" approved !
Double CHOOZ = CHOOZ + near detector
(announcement given at Niigata reactor workshop)

CHOOZ exclusion plot



Three-neutrino oscillation phenomenology:

Status of $(\delta m^2, \theta_{12})$ and Matter effects

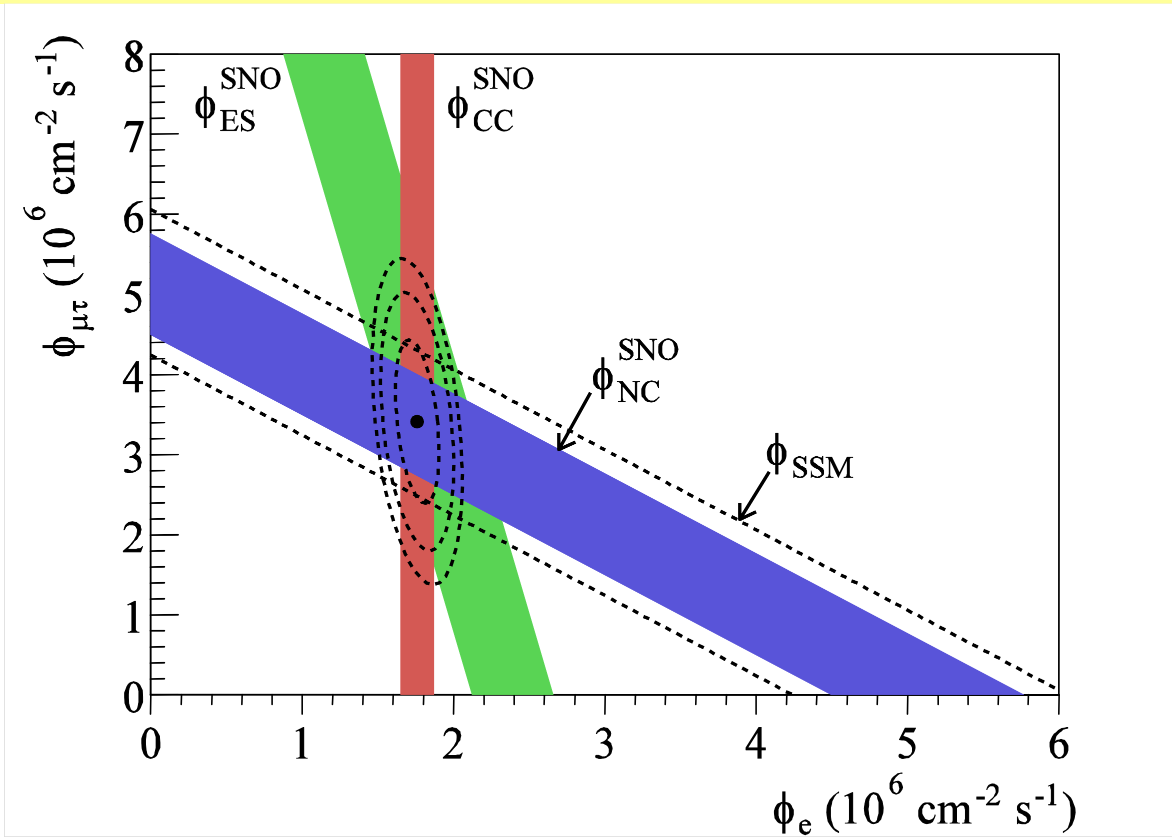
from solar neutrinos
and KamLAND reactor neutrinos

Solar neutrino problem: The 1st SNO breakthrough (2002)

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

$$R = \frac{\varphi_{CC}}{\varphi_{NC}} = \frac{\varphi(\nu_e)}{\varphi(\nu_e)+\varphi(\nu_\mu)+\varphi(\nu_\tau)} = P(\nu_e \leftrightarrow \nu_e) \quad \text{independently of SSM}$$

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

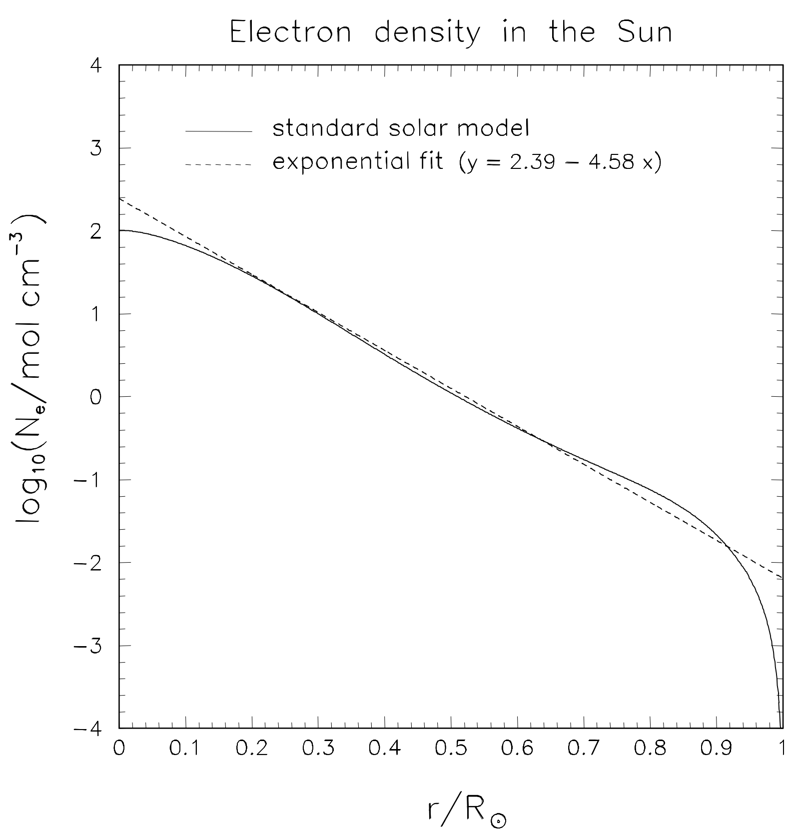


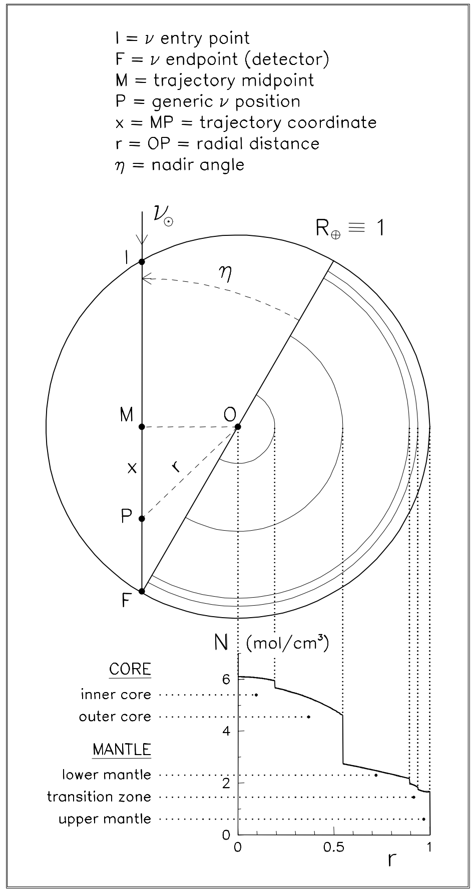
Solar neutrinos: Oscillation analysis

- **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)

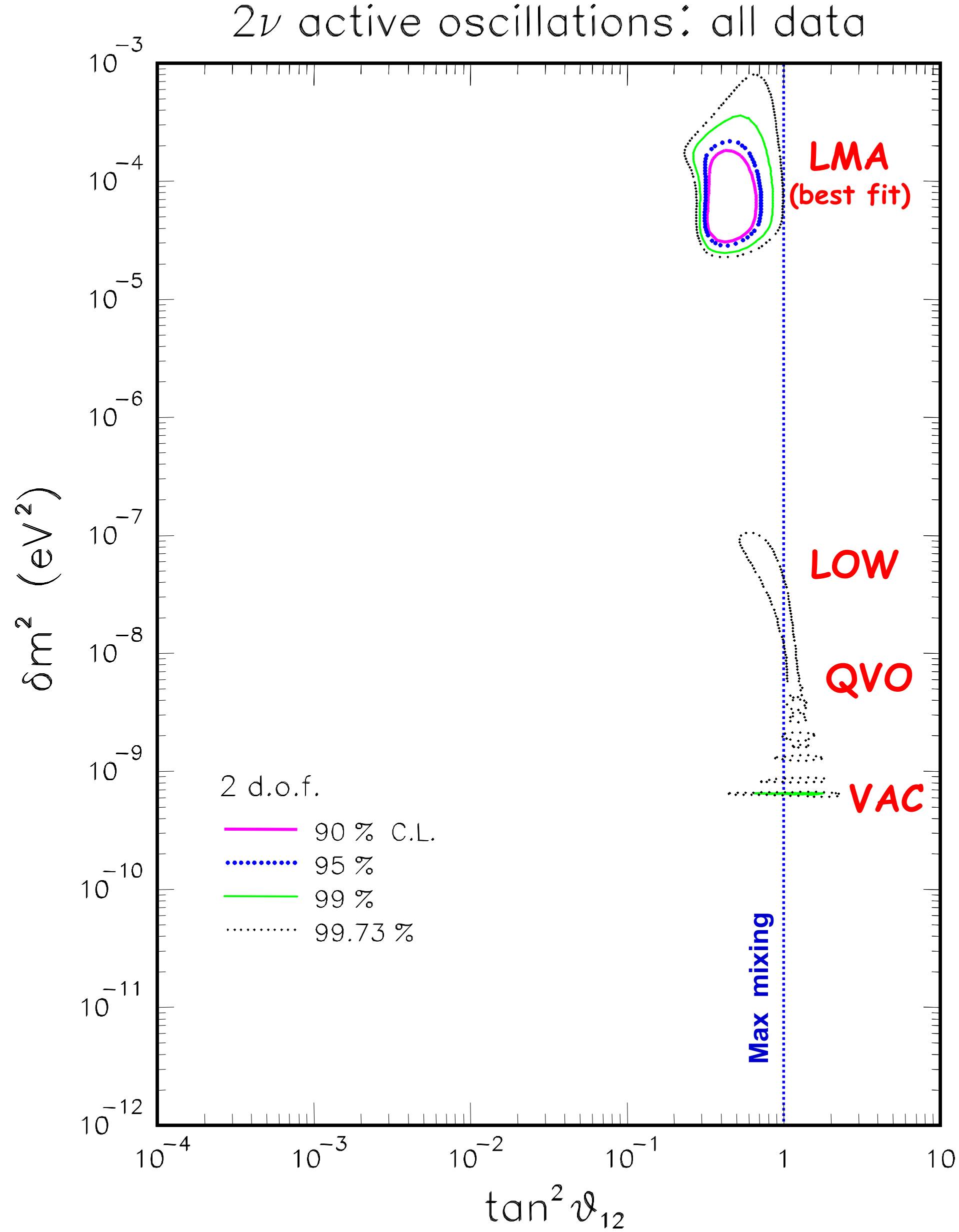




Solar neutrinos: Oscillation analysis (as of summer 2002)

Cl+Ga+SK+SNO experiments combined, summer 2002

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



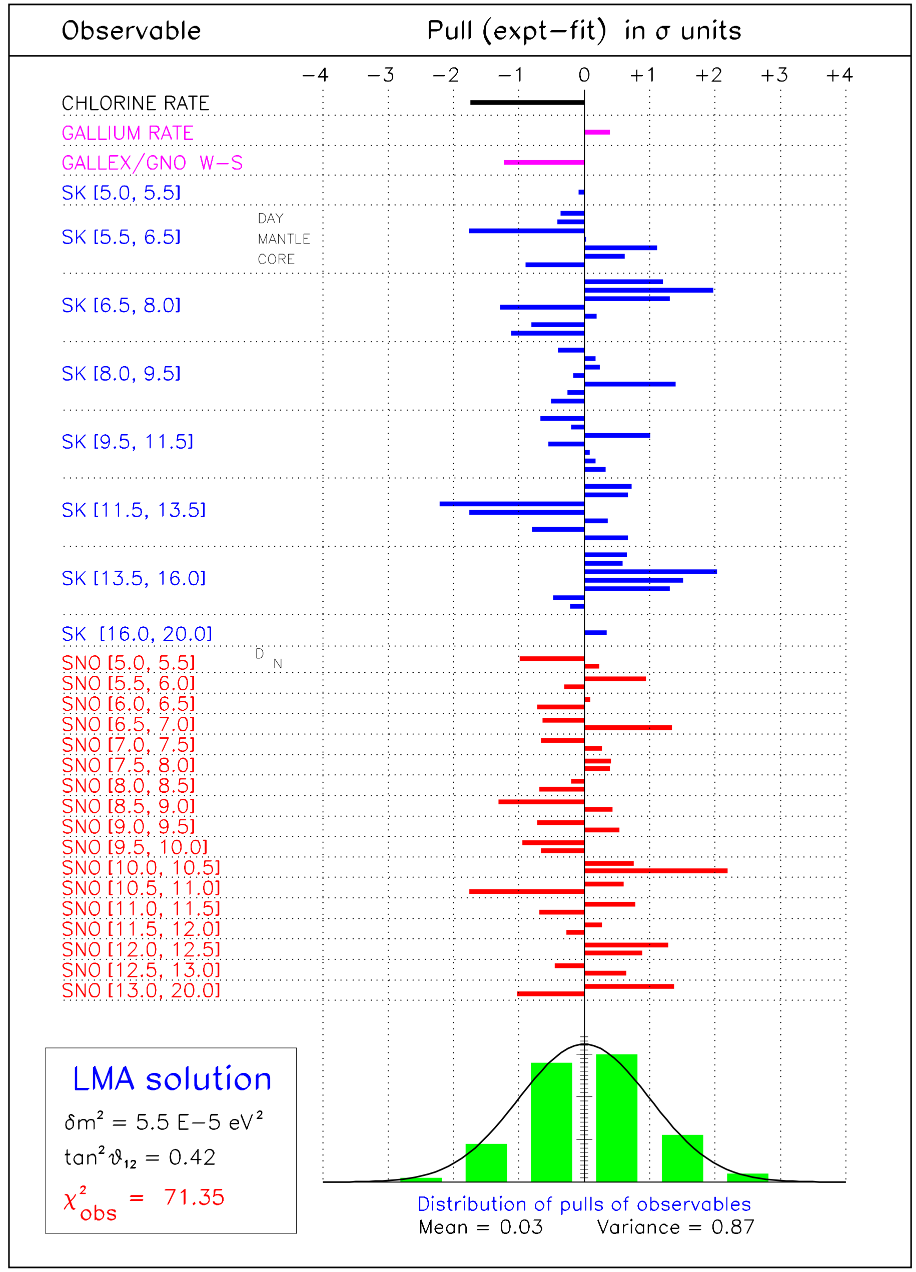
Jargon:

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

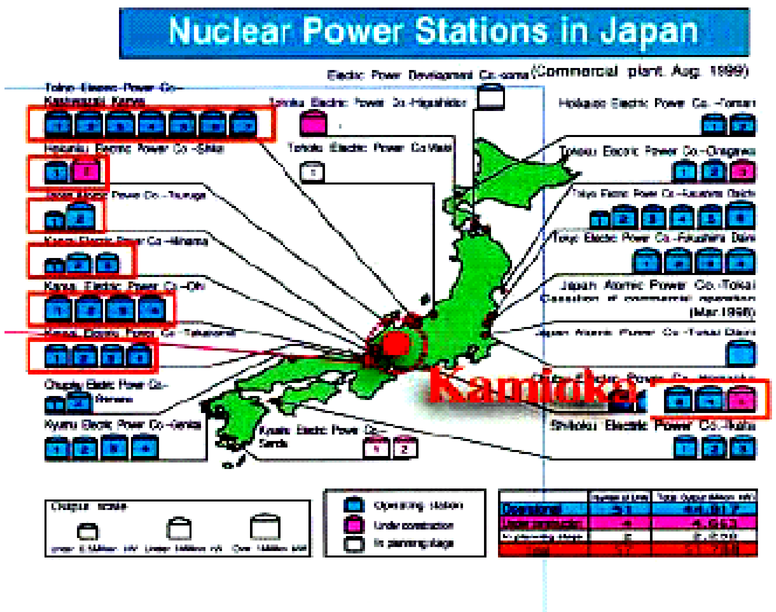
Solar neutrinos: LMA pull analysis
(as of summer 2002)

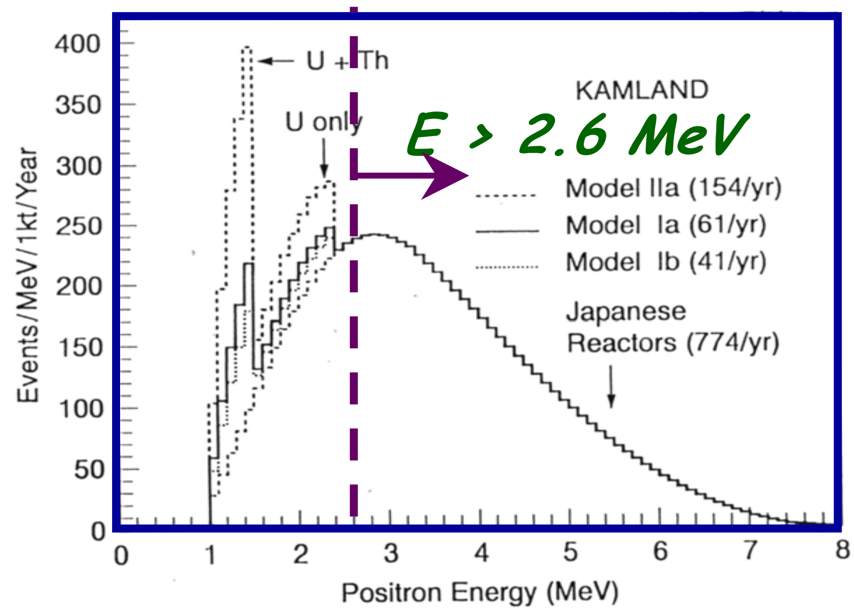
(Analogous to LEPEWWG global fit to the Standard Electroweak Model)

Excellent statistical behavior.
Is LMA the true solution?



Man-made reactor neutrinos: KamLAND

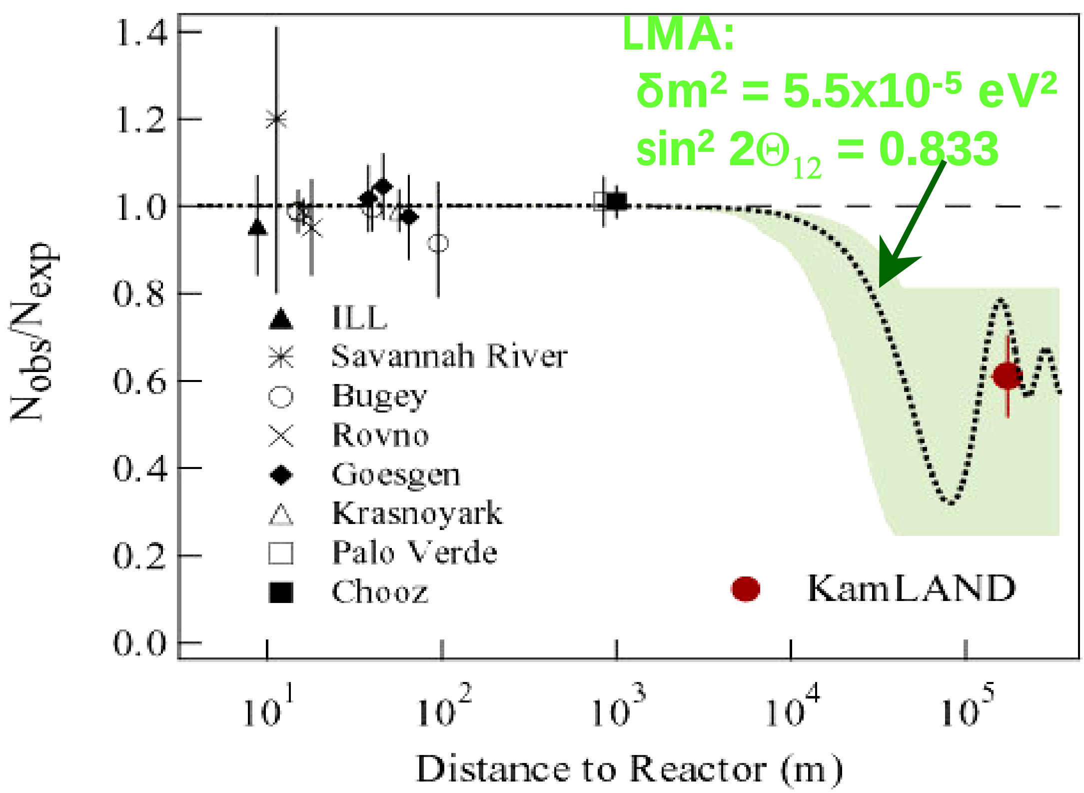




- **Average distance: ~180 km (two orders of magnitude greater than CHOOZ)**
- **CHOOZ was mainly sensitive to Δm^2 ~ few x 10^{-3} eV^2**
- **KamLAND is mainly sensitive to δm^2 ~ few x 10^{-5} eV^2 (LMA range!)**
- KamLAND will also open fundamental new field of geoneutrino physics

KamLAND breakthrough (December 2002)

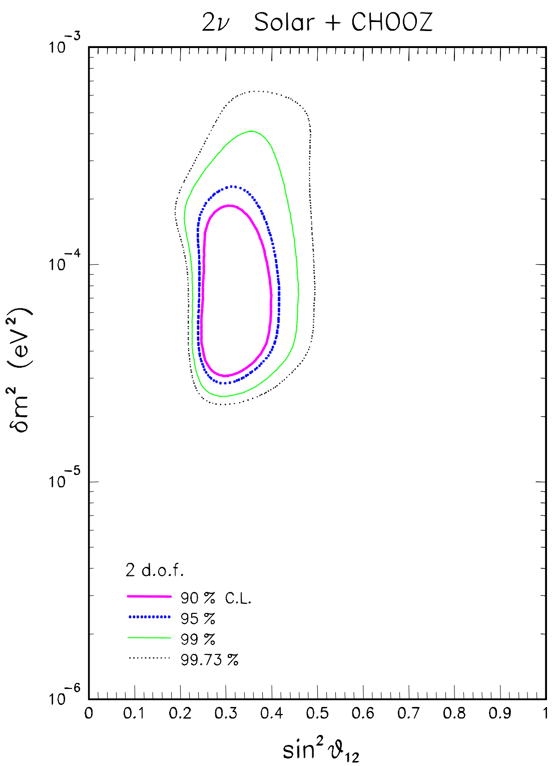
Disappearance of reactor ν_e **measured**



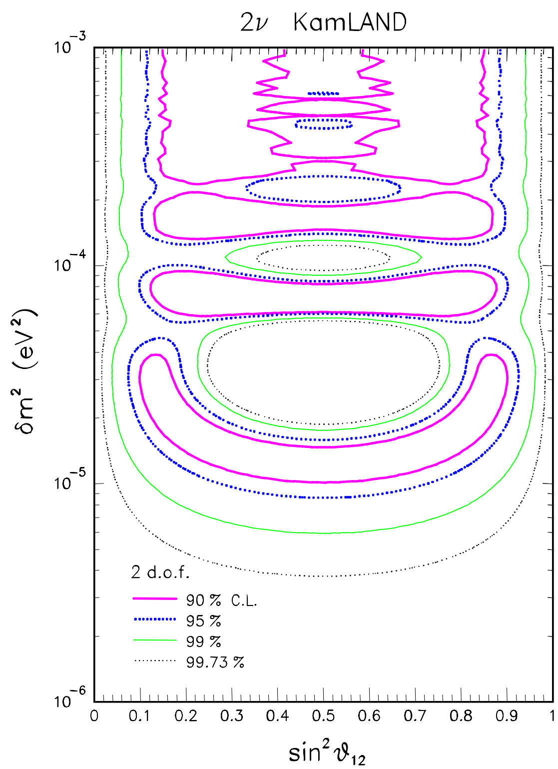
LMA solution confirmed; all others ruled out

KamLAND impact on (δm^2, θ_{12}) parameter space

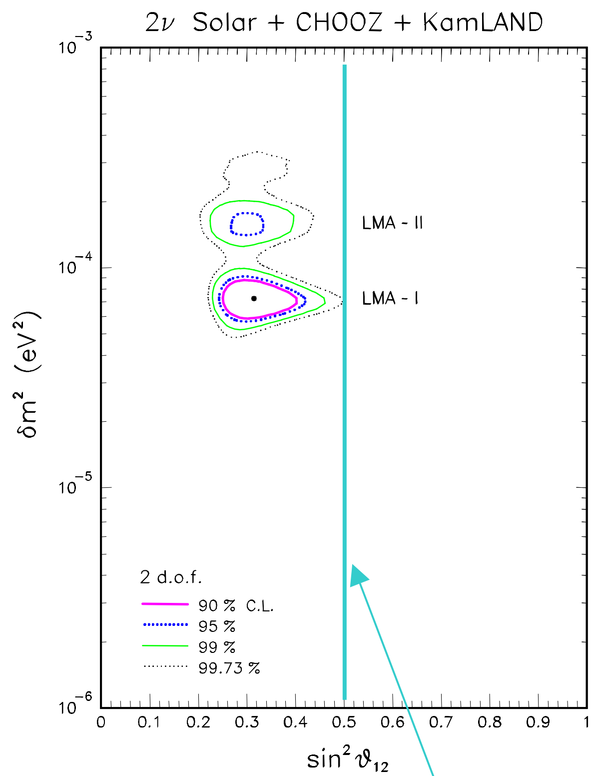
...before KamLAND



KamLAND

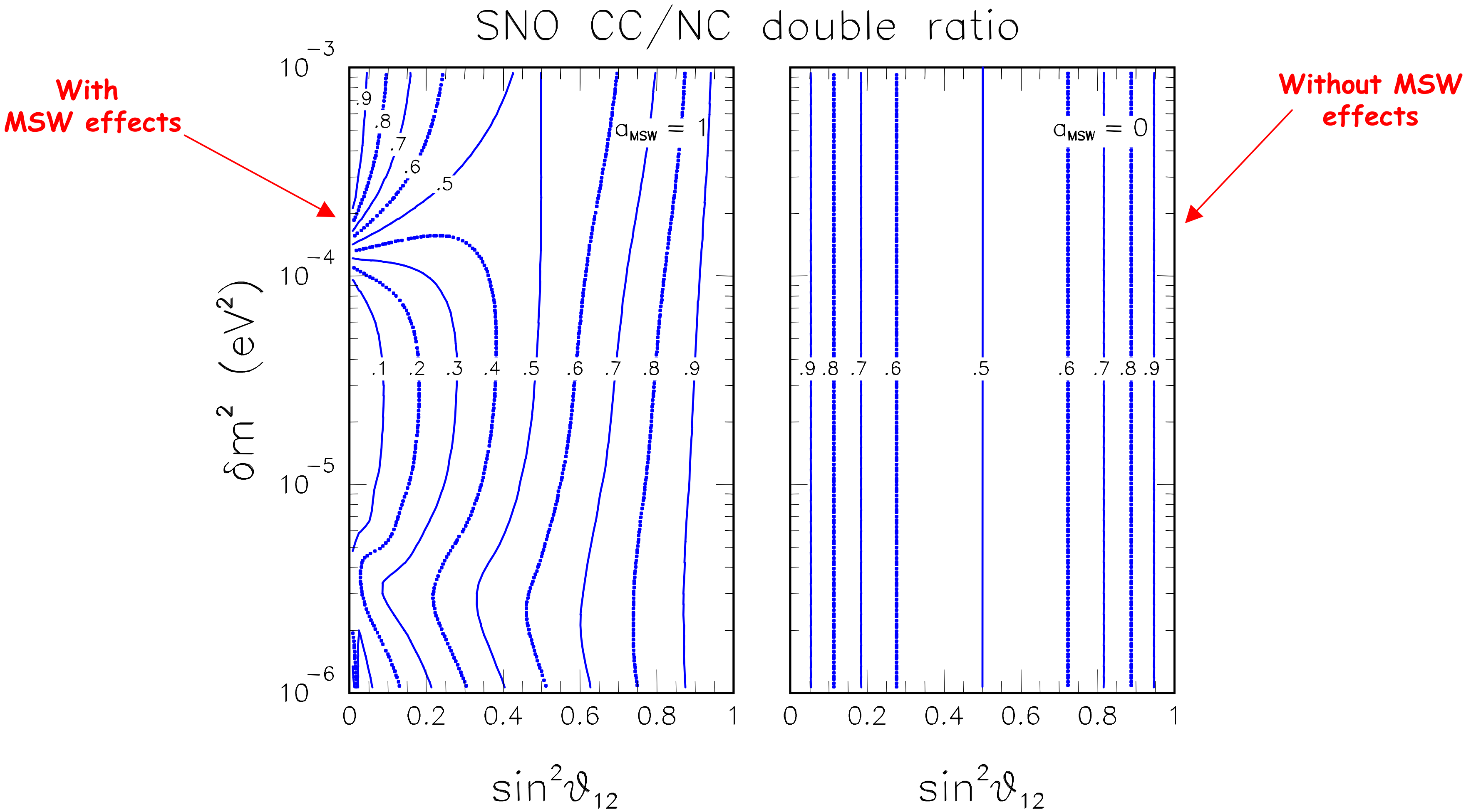


...after KamLAND



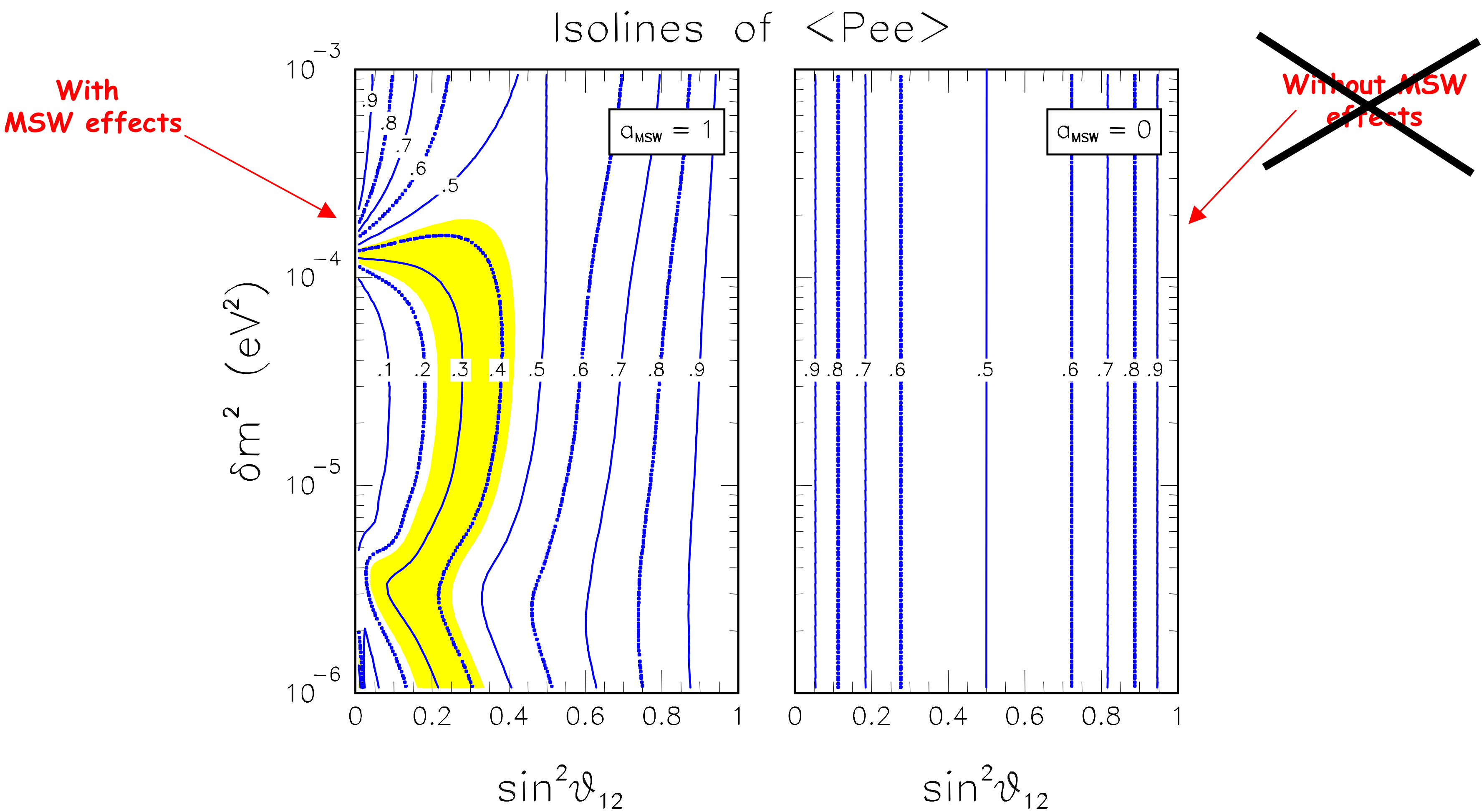
Note:
Maximal θ_{12} mixing
was not ruled out

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

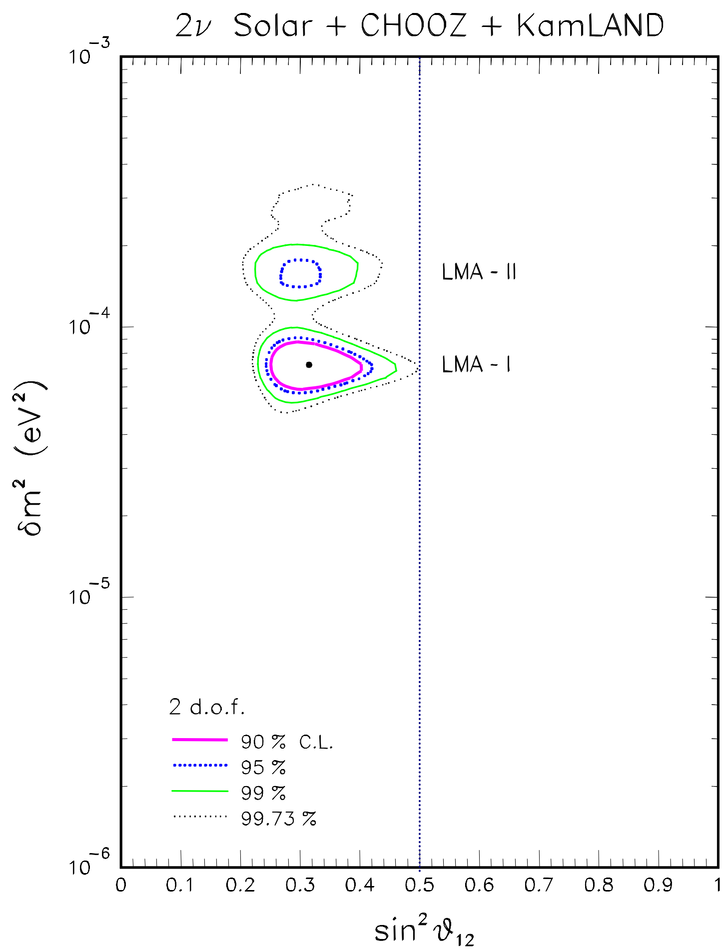
The 2nd SNO breakthrough (September 2003): maximal mixing ruled out



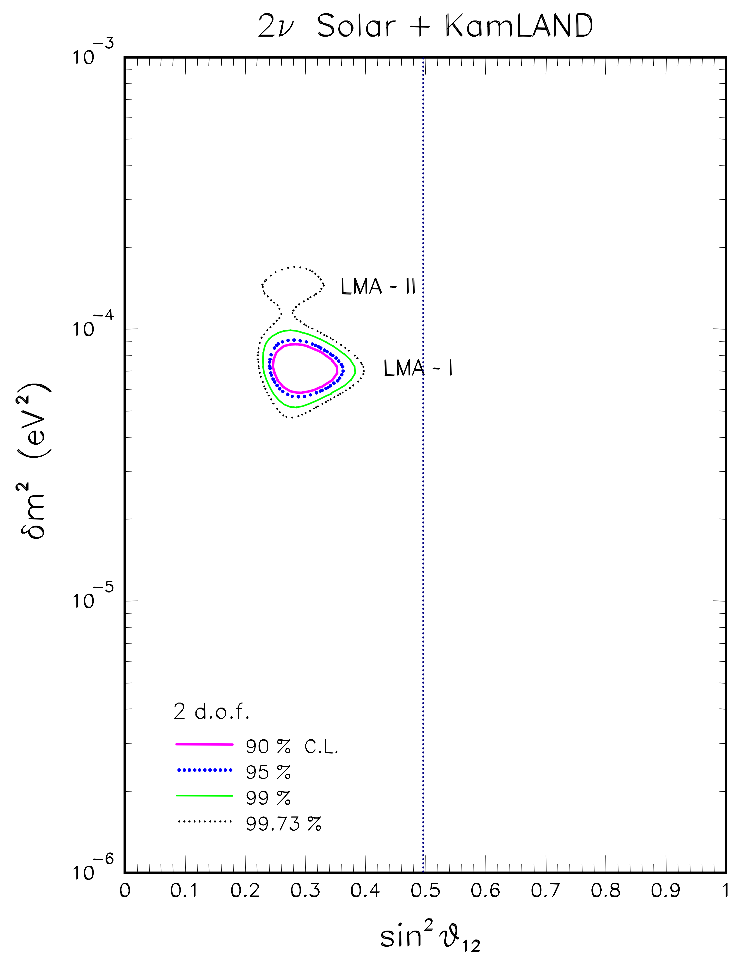
Compelling evidence for matter effects in the Sun

Updated LMA analysis (as of september 2003)

Note: LMA uniquely selected by solar data only!



Before SNO 2003



After SNO 2003

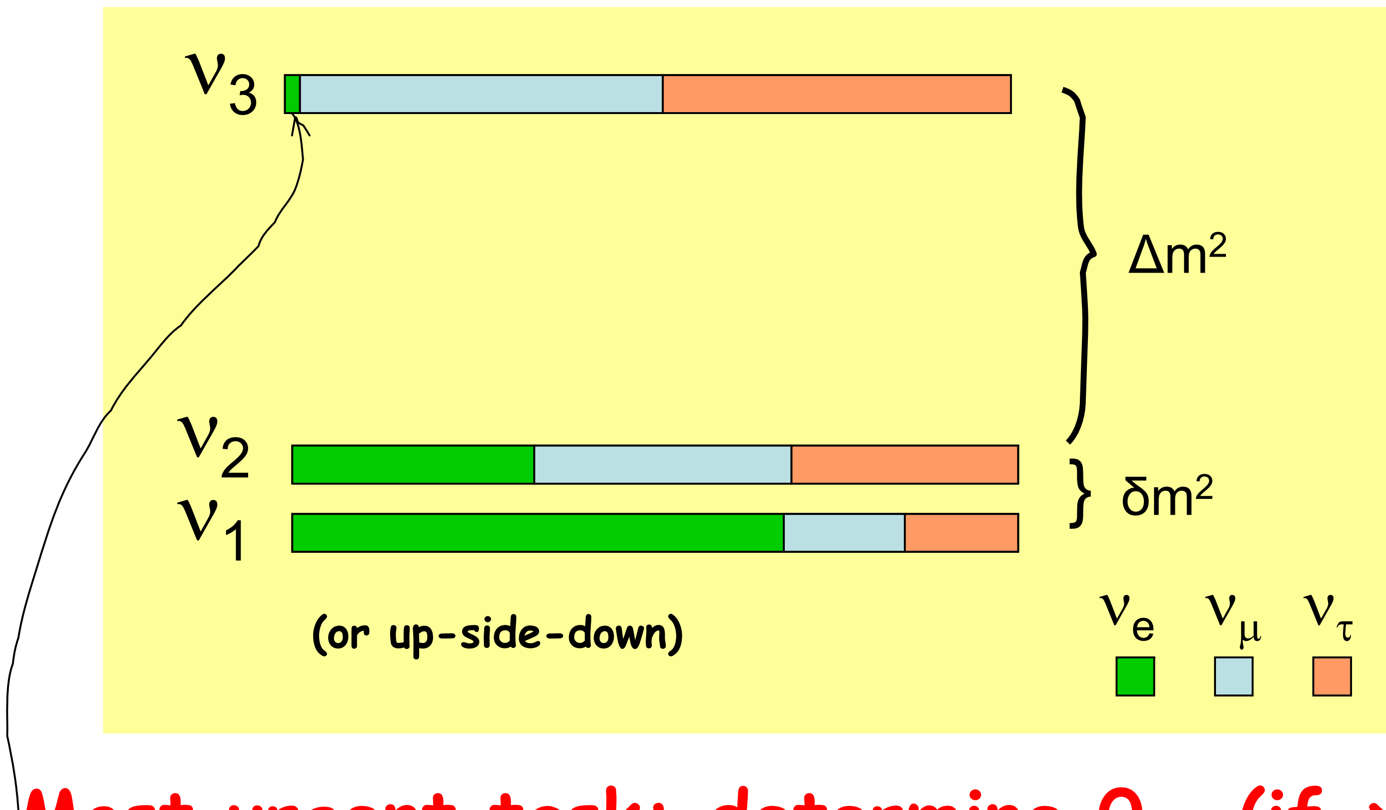
A numerical summary (with approx. 1σ errors):

- Neutrino mass and mixing established
- Vacuum oscillation pattern tested
- Matter effects (in the Sun) established

• $\delta m^2/eV^2$	~ 7.0×10^{-5}	± 12%
• $\Delta m^2/eV^2$	~ 2.4×10^{-3}	± 20%
• $\sin^2\theta_{12}$	~ 0.3	± 9%
• $\sin^2\theta_{23}$	~ 0.5	±15%
• $\sin^2\theta_{13}$	< 0.02	(1σ)

→ Gross kinematical and dynamical structure of three-neutrino Hamiltonian understood.
Start of "precision era"

A pictorial summary of three-flavor mixing:



Most urgent task: determine θ_{13} (if >0) !

Without it, no access to CP phase and hierarchy …

CP-violation and hierarchy: accessible to future accelerator experiments with baseline so long to probe both mass differences:

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = \; & \underbrace{4\,c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}}_{\text{Leading term}} \\
& + 8\,c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} \cos\delta - s_{12} s_{13} s_{23}) \cos\Delta_{32} \underbrace{\sin\Delta_{31}}_{\text{Hierarchy}} \sin\Delta_{21} \\
& - 8\,c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \underbrace{\sin\delta}_{\text{CP odd}} \sin\Delta_{32} \sin\Delta_{31} \sin\Delta_{21} \\
& + 4\,s_{12}^2 c_{13}^2 (c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2\,c_{12} c_{23} s_{12} s_{23} s_{13} \underbrace{\cos\delta}_{\text{CP even}}) \sin^2\Delta_{21} \\
& - 8\,c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2\,s_{13}^2) \underbrace{\frac{aL}{4E}}_{\text{MSW term}} \cos\Delta_{32} \sin\Delta_{31}
\end{aligned}
$$

Explosion of interest in last few years (Nu factories, superbeams, beta-beams)

Experiments look promising but also challenging (and costly);
so far, one approved (**T2K, Tokai-to-Kamioka**) at least for the 1st phase

Prospects depend, of course, on (unknown) size of prefactor $\sin^2\theta_{13}$

With oscillations we cannot access

Absolute masses

We need different tools:

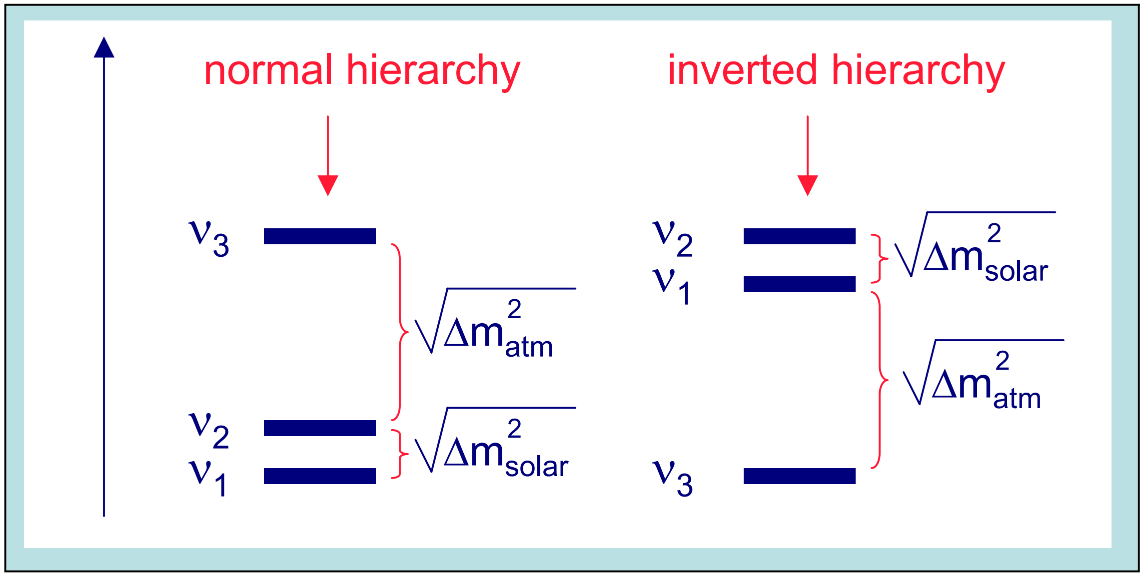
Beta decay

Neutrinoless beta decay

Cosmology

Absolute neutrino masses

From oscillations we find indication about two mass differences, related to “solar” and “atmospheric” ν oscillations, with two possible hierarchies



From the experiment:

$$\begin{cases} \sqrt{\Delta m^2_{solar}} \sim 7 \times 10^{-3}\ \text{eV} \quad \text{(LMA-I)} \\ \sqrt{\Delta m^2_{atm}} \sim .045 \quad \text{eV} \end{cases}$$

It follows

Normal hierarchy:

$$\begin{cases} m_1 = \text{free } (\geq 0) \\ m_2 = \sqrt{m_1^2 + \Delta m^2_{solar}} \\ m_2 = \sqrt{m_3^2 + \Delta m^2_{atm} + \Delta m^2_{solar}} \end{cases}$$

Inverted hierarchy:

$$\begin{cases} m_3 = \text{free } (\geq 0) \\ m_1 = \sqrt{m_3^2 + \Delta m^2_{atm}} \\ m_2 = \sqrt{m_3^2 + \Delta m^2_{atm} + \Delta m^2_{solar}} \end{cases}$$

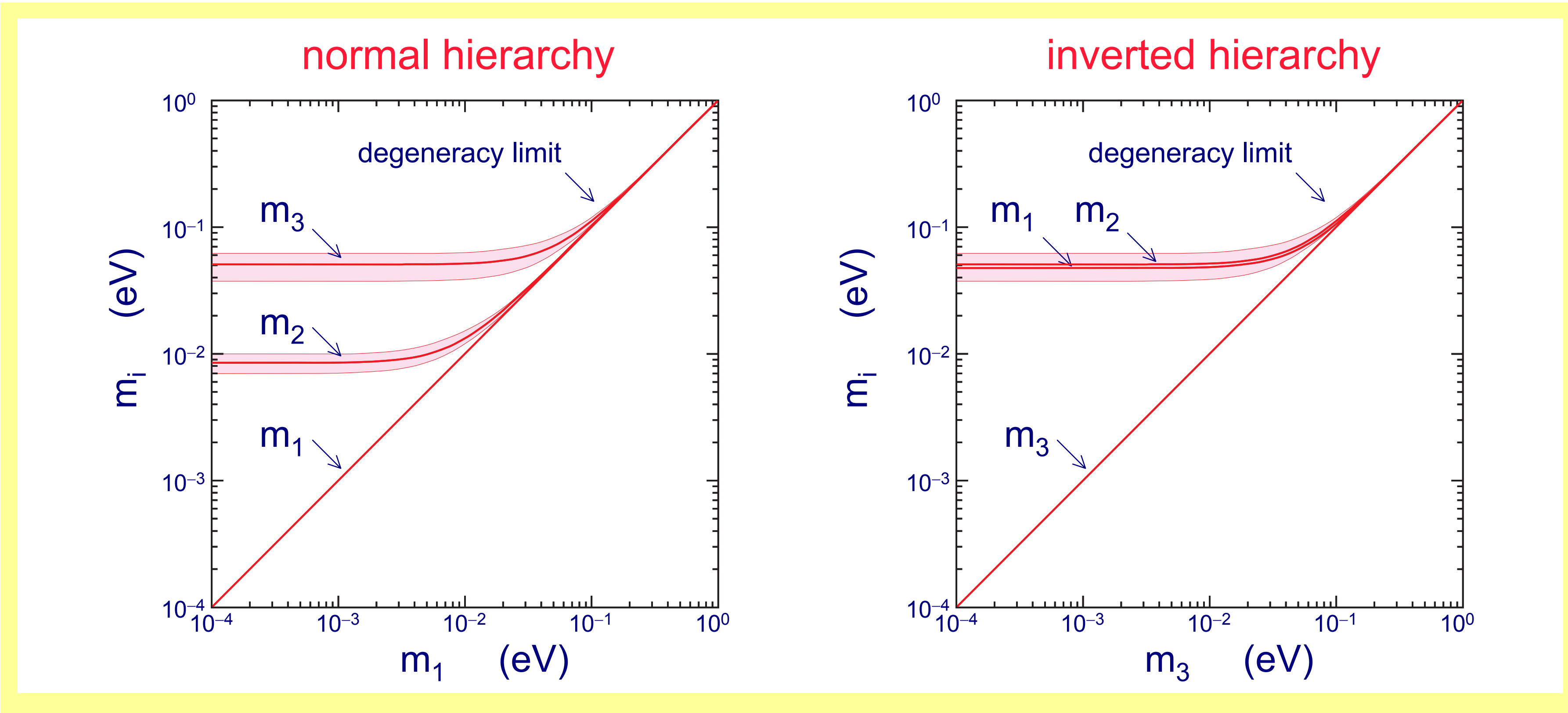
The two hierarchies tend to merge phenomenologically only for large masses

$(m_i^2 >> \Delta m^2_{atm})$

↓

quasidegenerate spectrum

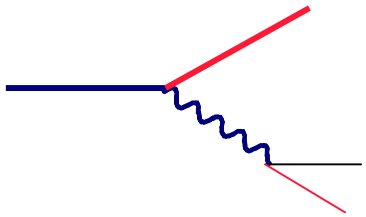
two alternative absolute spectra …



… with their present 3σ uncertainties.

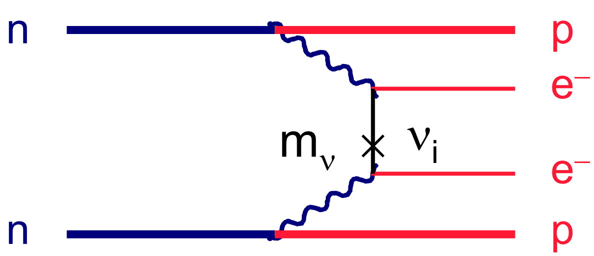
- Ambiguity in the interpretation of the experimental searches of the absolute n masses
- **Experimental sensitivity down to** O($\sqrt{\Delta m^2_{atm}} \sim 0.05$ eV) **needed to discriminate hierarchies!**

Different combinations of masses probed



β decay probes

$$m_\beta^2 = \sum |U_{ei}|^2 m_i^2$$



(Only for Majorana neutrinos)

0ν2β decay probes

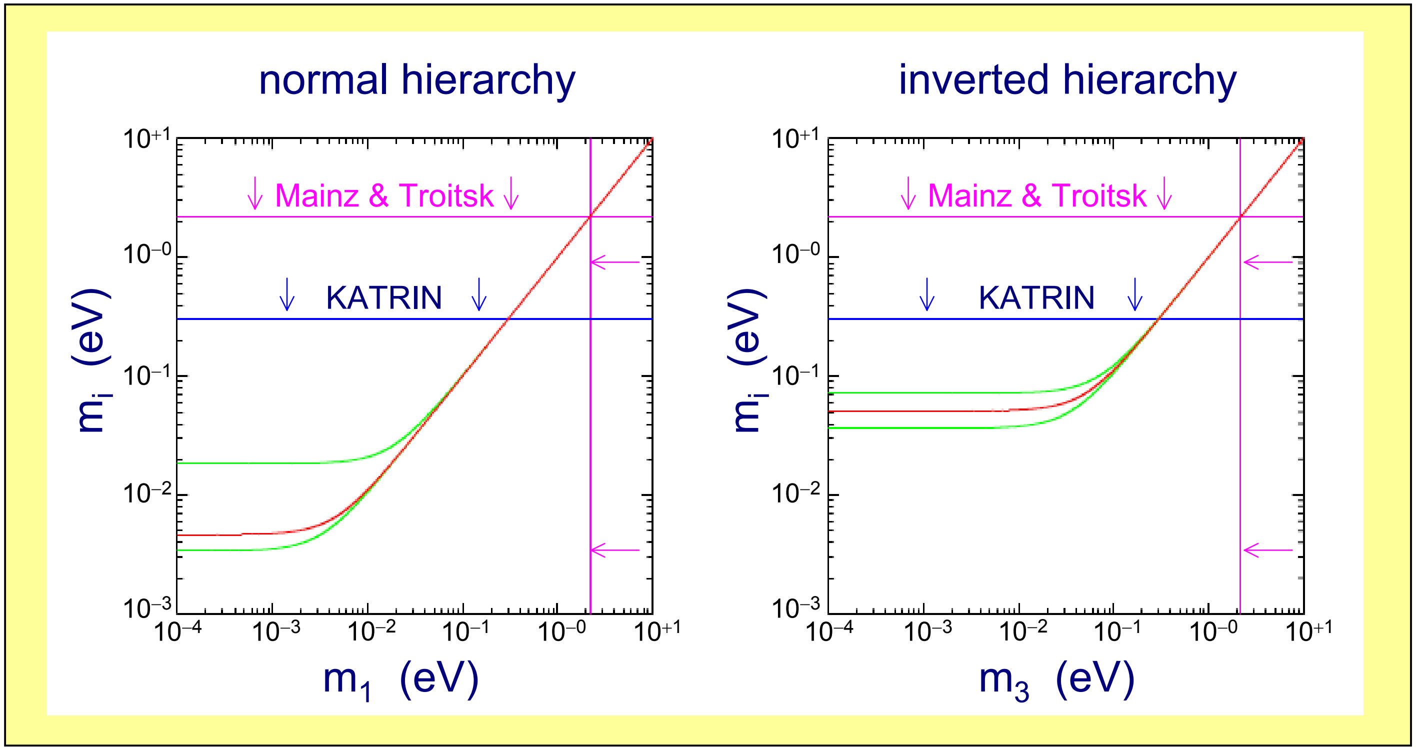
$$m_{ee} = |\sum U_{ei}^2 m_i|$$

$$\Omega_\nu h^2 = \sum_{\nu_i} \frac{m_{\nu_i}}{92.5 \text{ eV}}$$

cosmology probes

$$\sum m_i$$

- **β decay** current limits: $m_\beta \leq 2.2$ eV (95%C.L.) (Mainz, Troitsk, hep-ex/0210050)
- future limits: $m_\beta \leq$ few $\times 10^{-1}$ eV (KATRIN experiment, 2010?)
- these limits can be compared with the two absolute spectra:

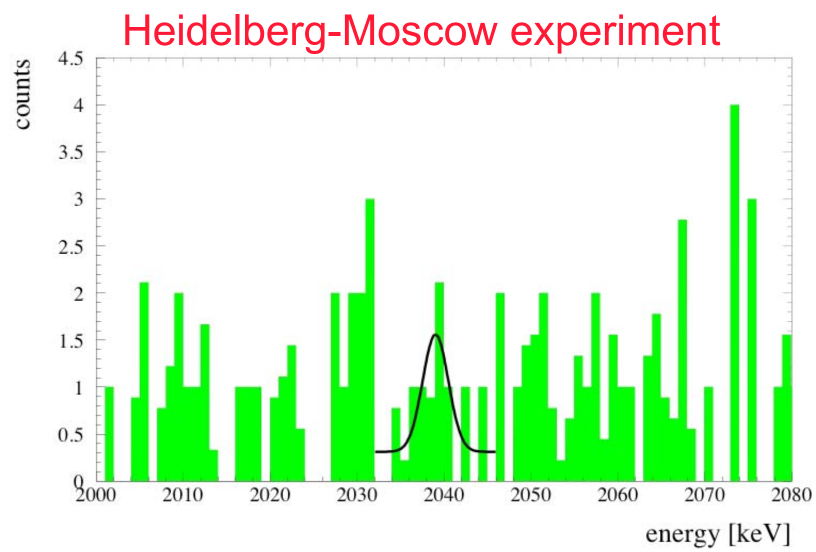


→ useful to probe the “degenerate spectrum”

→ not enough to discriminate hierarchies

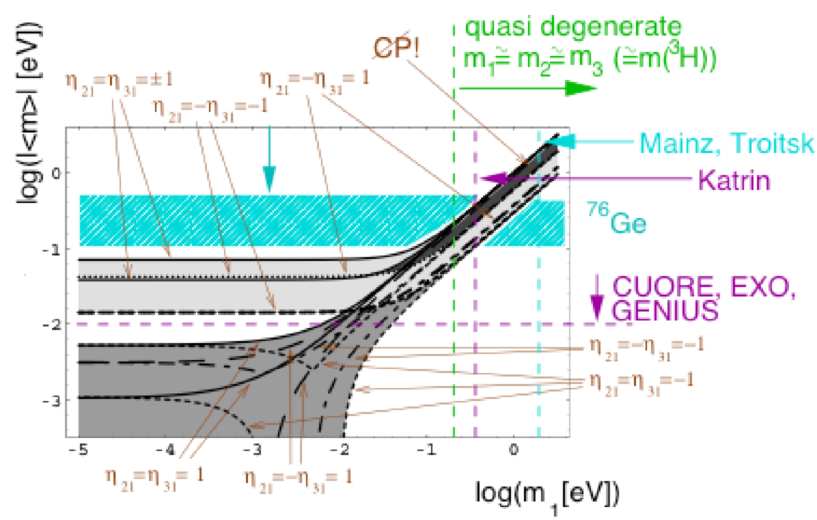
0ν2β decay (in 2003)

- Situation last year: all experiments compatible with m_{ee} ~ 0, except for the Heidelberg-Moscow expt, claiming m_{ee} ~ 0.1-0.6 eV (controversial result & lively debate).

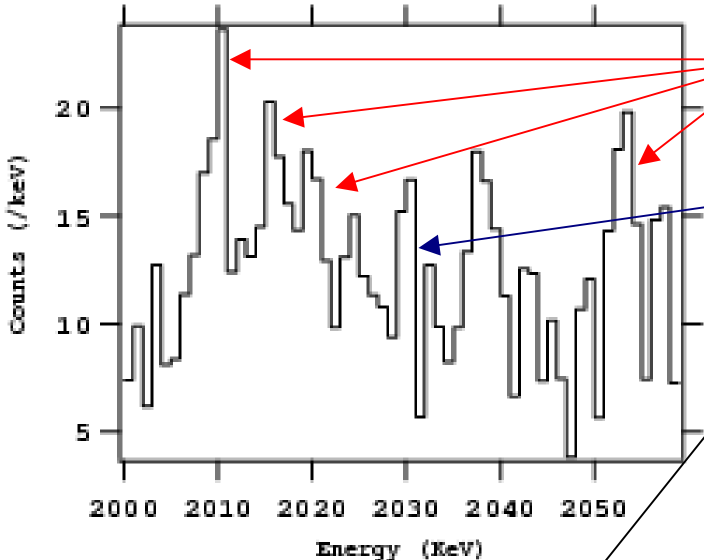


- Future prospects: sensitivity to m_{ee} can be pushed down by an order of magnitude in CUORE, GENIUS, EXO. Together with KATRIN, these experiments will completely probe the "degenerate" case, and will start to probe the region where normal and inverted spectra branch out.

Compiled by Vuilleumier (2003)



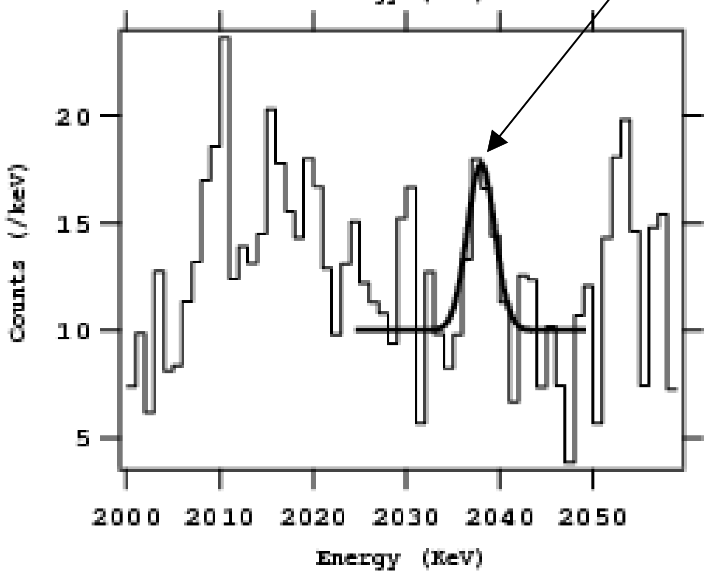
0ν2β decay: Heidelberg-Moscow experiment final analysis (March 2004)



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



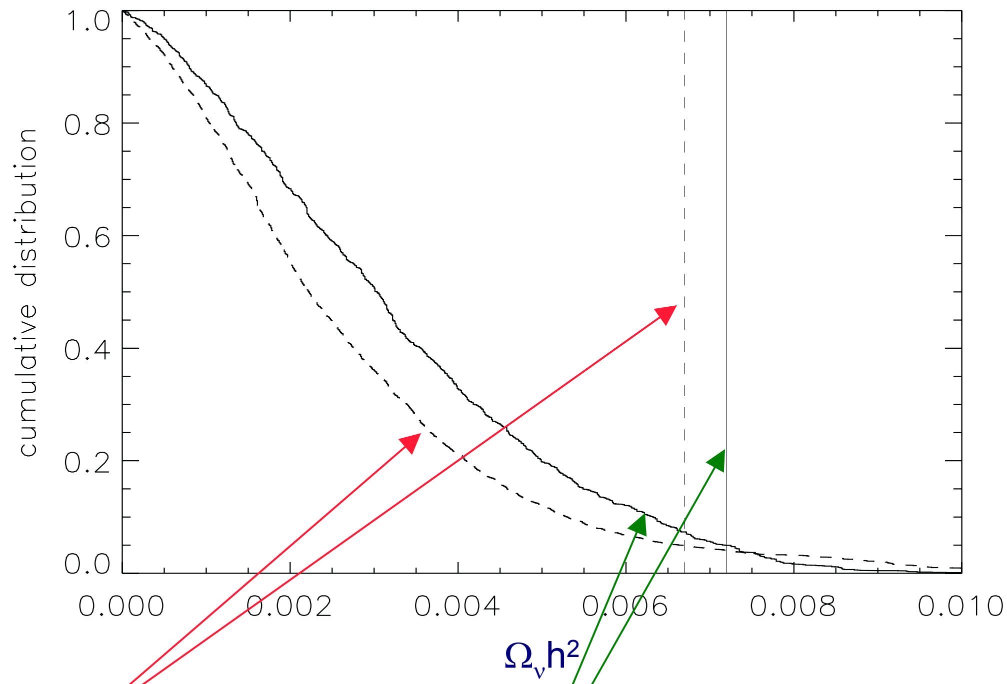
We might have reached an "LSND-like" situation:

- 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

There is one important difference with LSND, however: the possible neutrinoless double-beta decay signal (m_{ee} ~ 0.1-0.9 eV) is not in conflict with other ν data.

Cosmology

After WMAP (2003), typical upper bounds are in the range of a few x 10^{-1} eV^2, depending on data set, priors, and correlations with other cosmological parameters



E.g., from the fit to $\Omega_\nu h^2$ one derives at 95% C.L.:

- $\Omega_\nu h^2 < 0.0067$ from WMAPext + 2dFGRS
- $\Omega_\nu h^2 < 0.0076$ with WMAPext + 2dFGRS + Lyman α forest

i.e.

- $\sum m_i < 0.62$ eV
- $\sum m_i < 0.70$ eV

⇒

- $m_\nu < 0.21$ eV
- $m_\nu < 0.23$ eV

for quasi degenerate neutrinos

But: conservative approach on priors can weaken bound by factor 2~3;
Future surveys needed to make bounds more robust or to find a signal.

Conclusions

- **"Pioneeristic era"** of neutrino oscillation searches concluded
- Neutrino flavor oscillations and matter effects have been established
- Leading 3ν mass-mixing parameters are measured with 10-20% accuracy
- Absolute neutrino masses are being probed in the (sub)eV range
- But: θ_{13}, δ, hierarchy… are still "Terra Incognita"
- Surprises (4ν ? Nonstandard inter.?) not excluded at subleading level
- A lot of work to be done in the (just started) **"Precision era"** of ν physics