QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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TIFF (Uncompressed) decompressor
are needed to see this picture.

Neutrino Oscillations

[The most exciting "Adventure in Physics" of the last ten years]

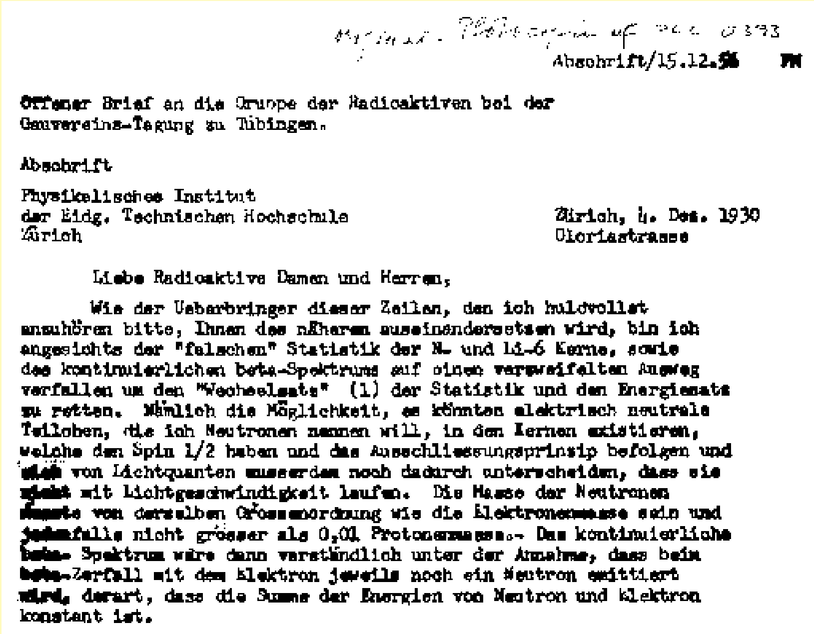
Gianluigi Fogli
Università di Bari

"Laurea ad Honorem" to Prof. Masatoshi Koshiba

Outline

- A few historical notes
- Neutrino oscillations
- Open problems
- Conclusions

75 years ago (1930), Wolfgang Pauli suggests the existence of a new small particle as "desperate remedy" to interpret the continuous spectrum of β-decay



Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

First kinematical properties: spin 1/2, small mass, no charge

A few years after (1933-34), the new particle is "baptized" neutrino (ν) by Enrico Fermi, with a first attempt of describing its dynamical properties (weak interactions)


ANNO IV · VOL. II · N. 12 QUINDICINALE 31 DICEMBRE 1933 · XII

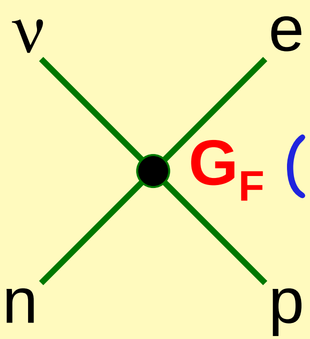
LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del prof. ENRICO FERMI

Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

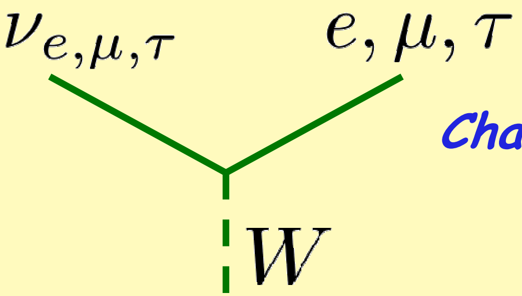


G_F (Fermi constant)

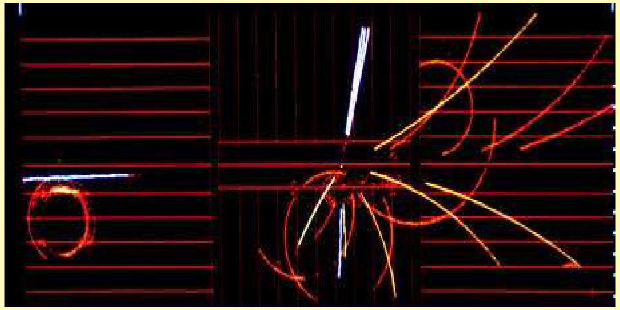
Today, after more than 70 years, several further properties have been discovered. In particular, neutrinos appear in three different "flavors", together with the corresponding leptons (e, μ, τ)

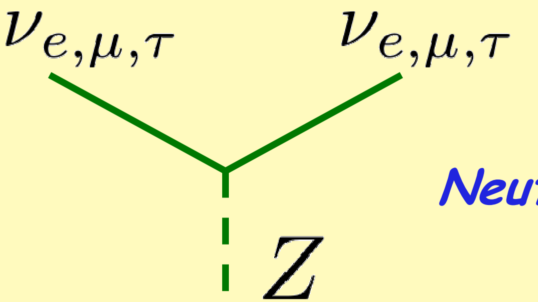
$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \quad \begin{matrix} \leftarrow & q = 0 \\ \leftarrow & q = -1 \end{matrix} \quad (\Delta q = 1)$$

Moreover, we know that Fermi interaction proceeds through the exchange of charged vector bosons W, or a neutral vector boson Z

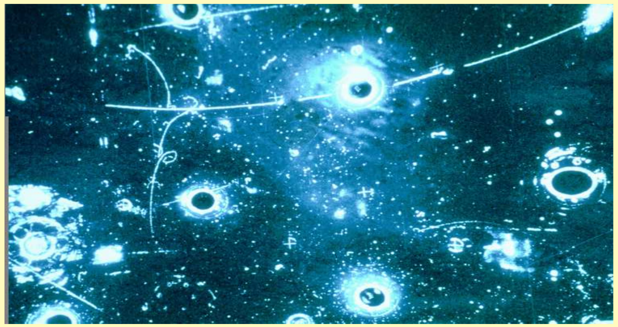


Charged current (Δq=1)





Neutral current (Δq=0)



However, in spite of many considerable progresses, only recently it has been possible to attempt of answering some of the fundamental questions asked in the past century:

How small is the neutrino mass ?
(Pauli, Fermi, in the thirties)

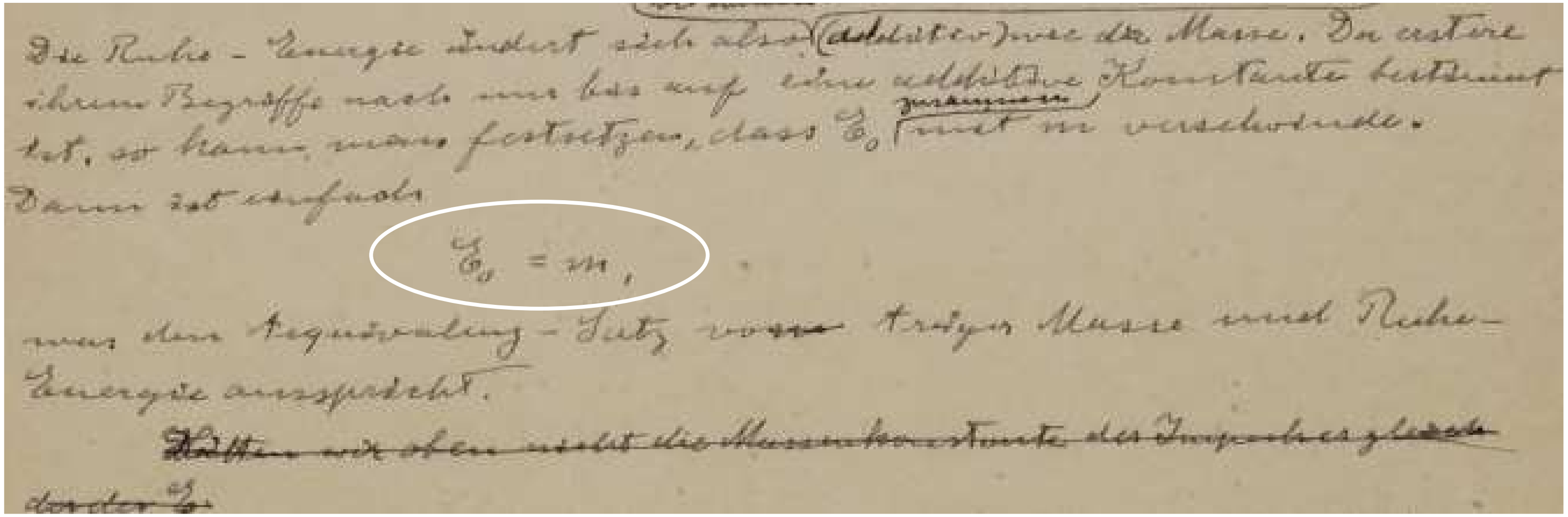
Can a neutrino transform into its antiparticle ?
(Majorana, in the thirties)

Can a neutrino of a given flavor transform into a neutrino of a different flavor ("oscillate") ?
(Pontecorvo, Maki-Nakagawa-Sakata, in the sixties)

In particular, as we will see, it is possible to answer positively and with well-constructed arguments to the third question.

Flavor oscillations of neutrinos

In the centenary of the "***annus mirabilis***", we cannot avoid to start from the well-known equation …


Die Ruhe-Energie ändert sich also (additiv) wie die Masse. Da erstere ihrem Begriffe nach nur bis auf eine additive Konstante bestimmt ist, so kann man festsetzen, dass E_0 zusammen mit m verschwinde. Dann ist einfach

$E_0 = m$,

was den Äquivalenz-Satz von träger Masse und Ruhe-Energie ausspricht.

~~Hätten wir oben nicht die Massenkonstante des Impulses gleich~~
~~durch E_0~~

… i.e., if p≠0:

$$E = \sqrt{m^2 + p^2}$$

In general, for massive particles, we adopt the limit $p \ll m$

$$E \simeq m + \frac{p^2}{2m}$$

… conversely, for neutrinos, the appropriate limit is $p \gg m$

$$E \simeq p + \frac{m^2}{2p}$$

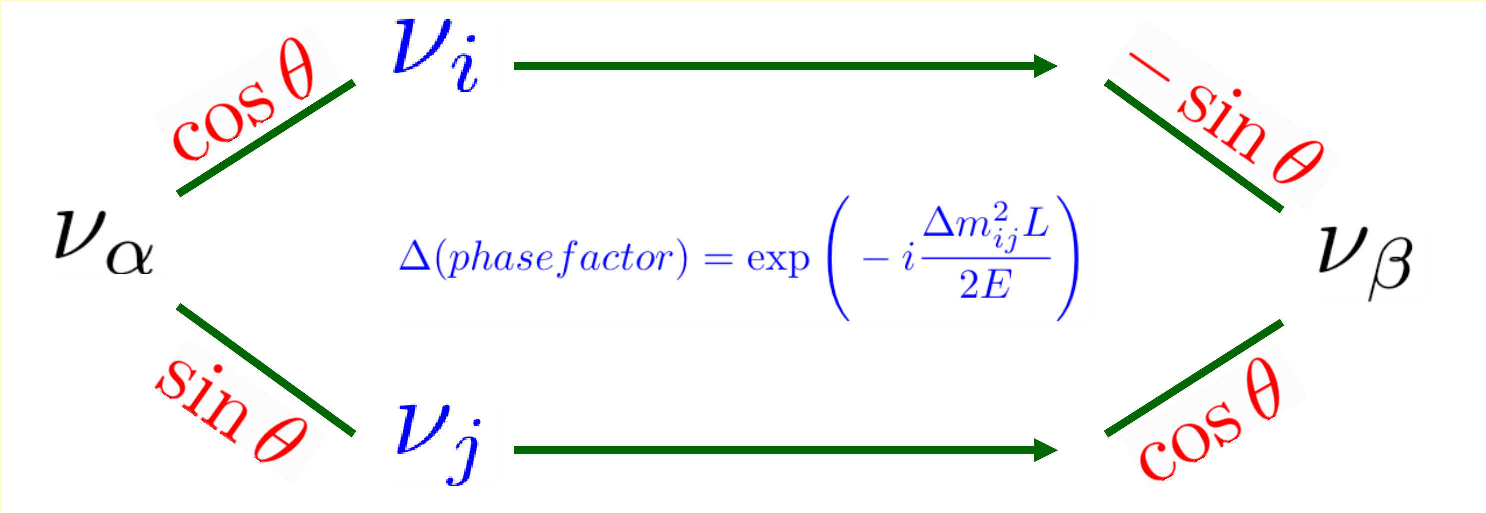
This means that the difference in energy of two neutrinos ν_i and ν_j of masses m_i and m_j in the same beam is given by $(p_i = p_j \simeq E)$

$$\Delta E \simeq \frac{\Delta m_{ij}^2}{2E}$$

Pontecorvo: neutrinos of different mass (ν_i, ν_j) can mix to form neutrinos of given flavor (ν_α , ν_β)

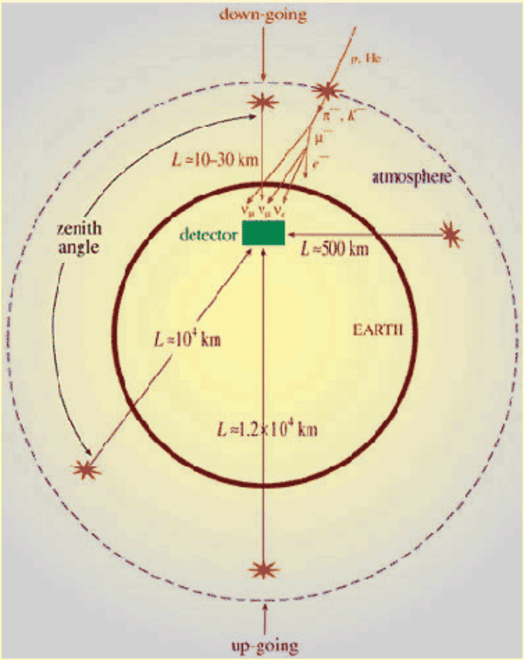
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

What happens is a typical quantum-mechanical effect:

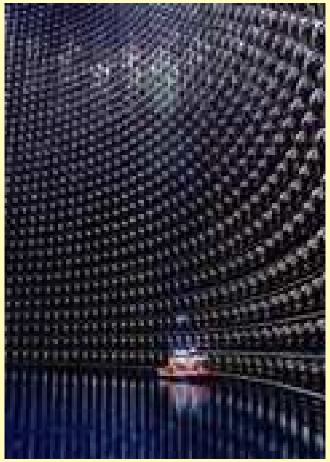


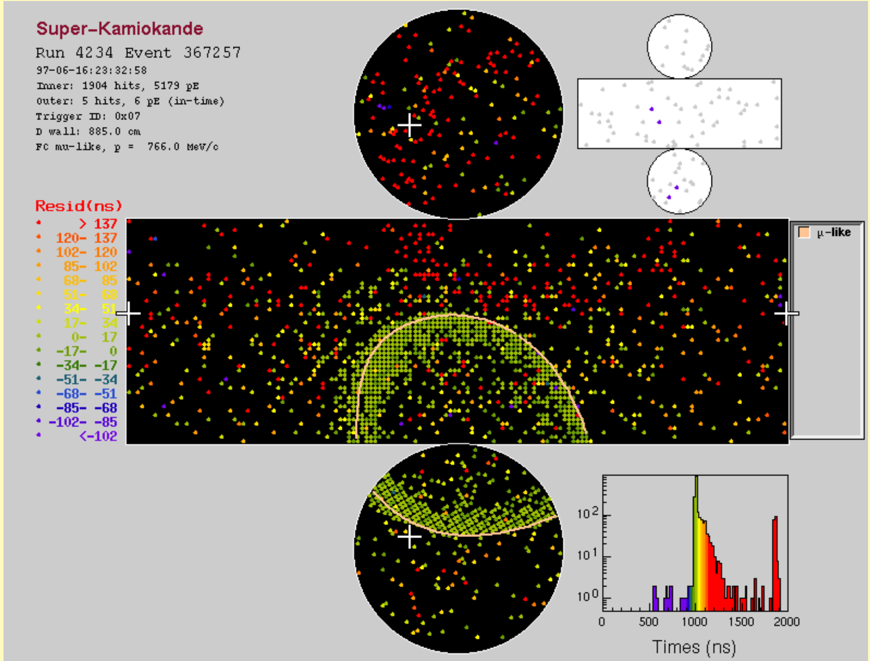
$$P(\nu_\alpha \to \nu_\beta) = 4\sin^2\theta\cos^2\theta\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$ (flavor oscillation)

This is the simplest case, with only two neutrinos involved and negligible interaction effects. It is really surprising that this is just the case that takes place - at a good level of approximation - in the phenomenology of atmospheric neutrinos, where the previous simple formula for P justifies data on ~ 7 orders of magnitude in L/E in the Super-Kamiokande experiment (as well as in MACRO and Soudan2).



Super-Kamiokande





Events induced by ν_e: ~ as expected

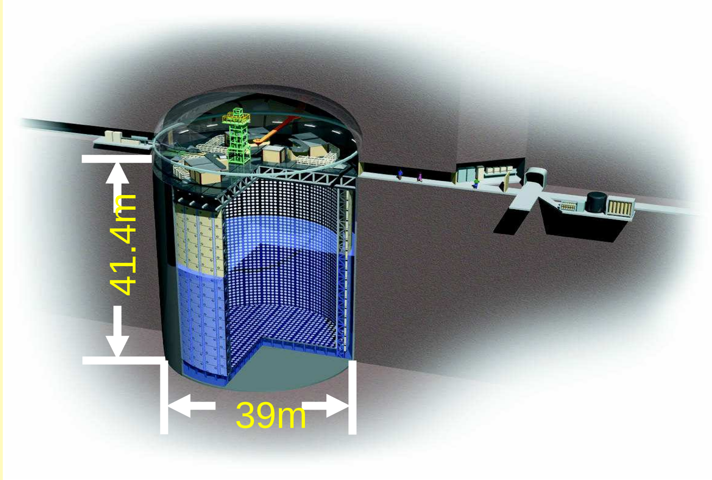
Events induced by ν_μ: deficit from below

$\nu_\mu \to \nu_e$ **oscillations? No** (or subdominant)

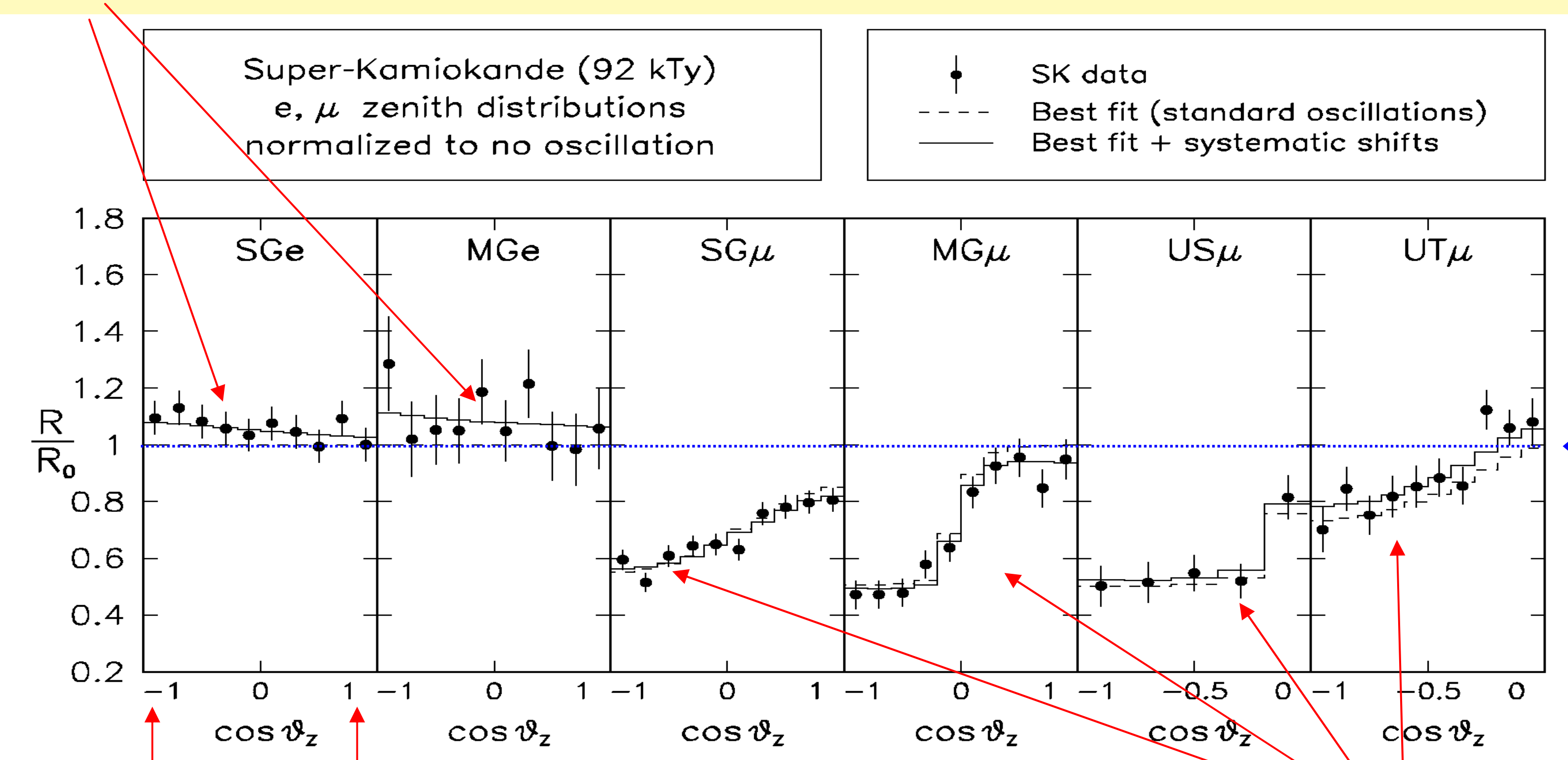
$\nu_\mu \to \nu_\tau$ **oscillations? Yes** (dominant)

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



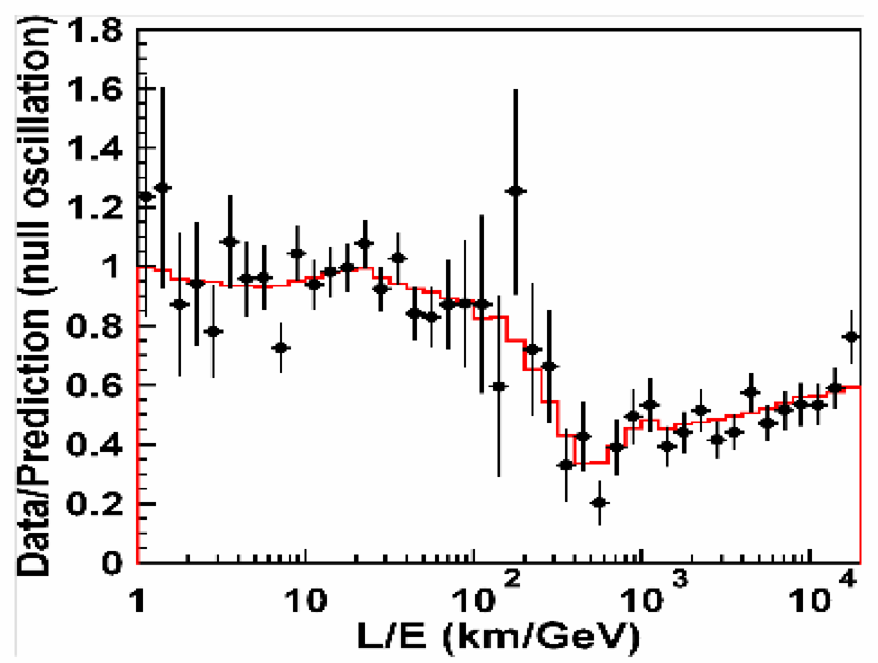
electrons ~ OK



no oscillation

up down

muon deficit from below

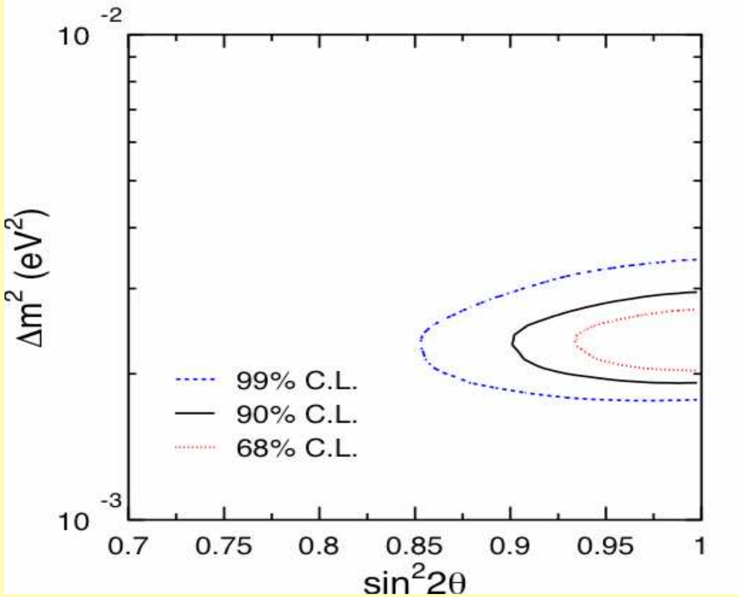


The first half-cycle and the first dip begin to appear with high statistics. The poor resolution for large L/E does not allow to see a complete oscillation (averaged oscillations).

Strong limits on the mass-mixing parameters (Δm^2, θ) are derived.

Limits symmetrical in the two θ octants in the case of pure $\nu_\mu \rightarrow \nu_\tau$ oscillations.

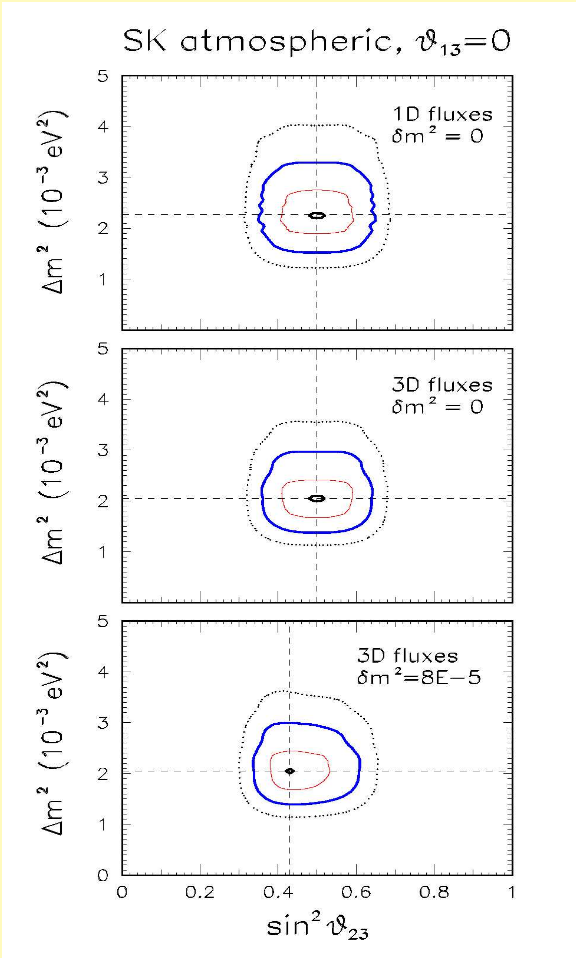
Preferred value $\theta \sim \pi/4$: very large when compared with the quark mixing.

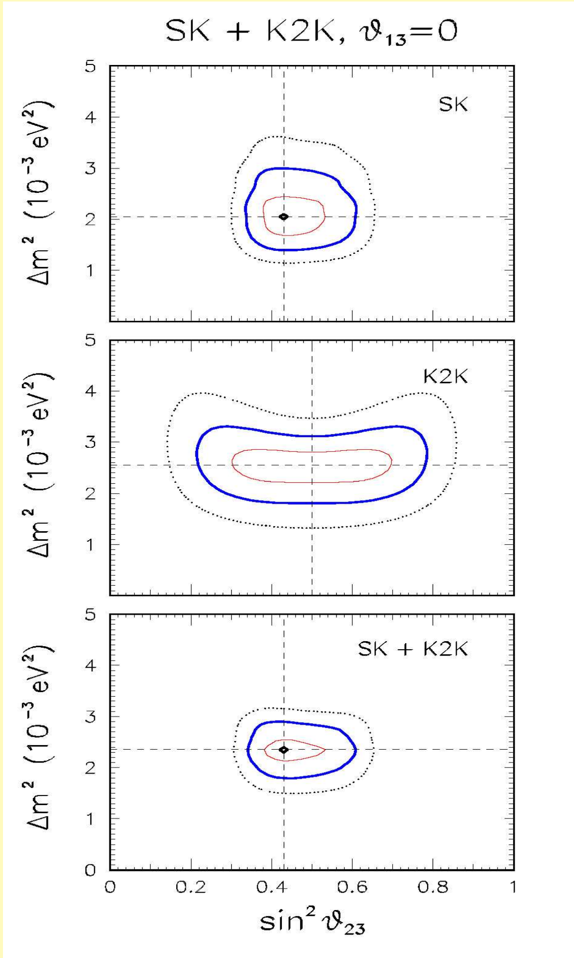


More on atmospheric ν oscillations:

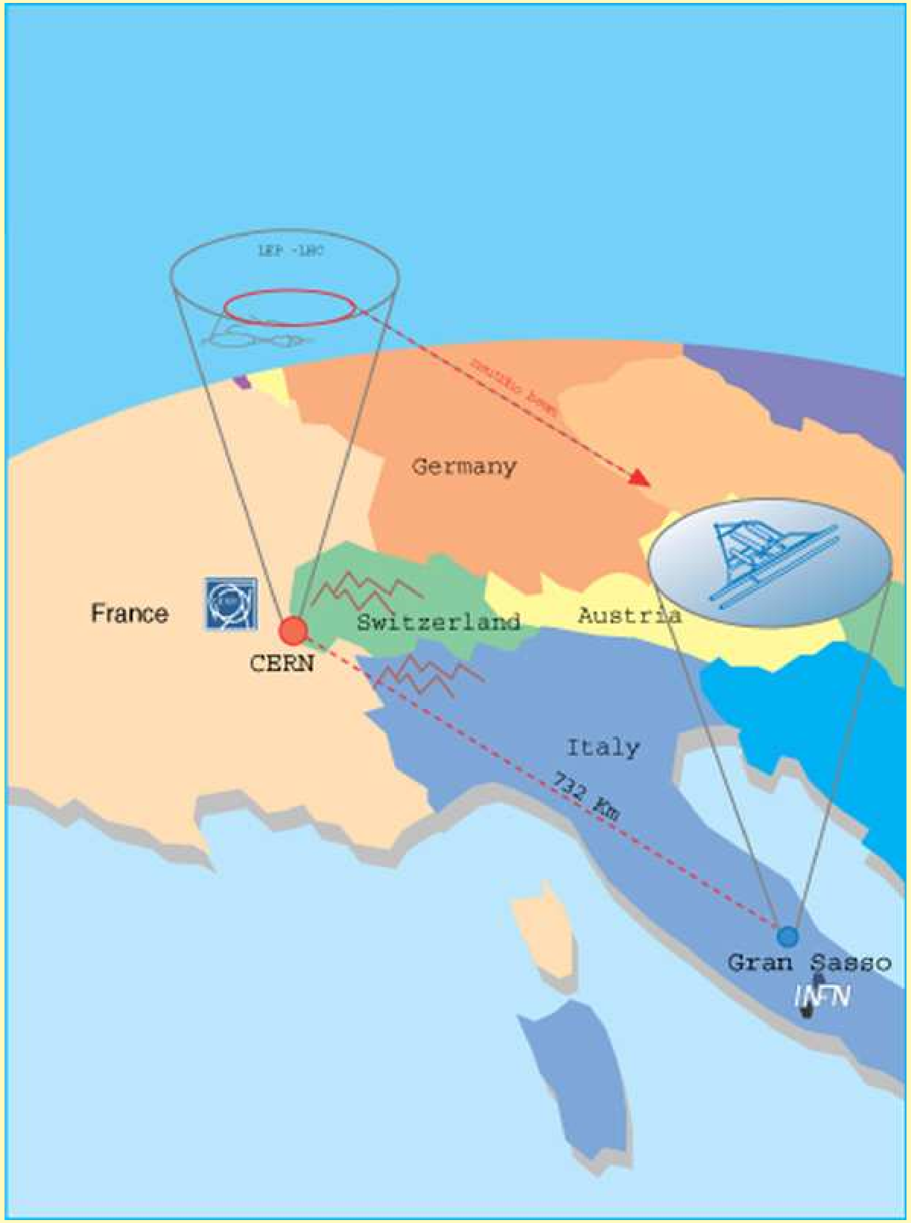
We begin to be sensitive to subdominant effects

parameters confirmed by accelerator ν (K2K)





Note: 1) linear scale in Δm^2 and $\sin^2\theta_{23}$; 2) asymmetry in the θ_{23} octants.

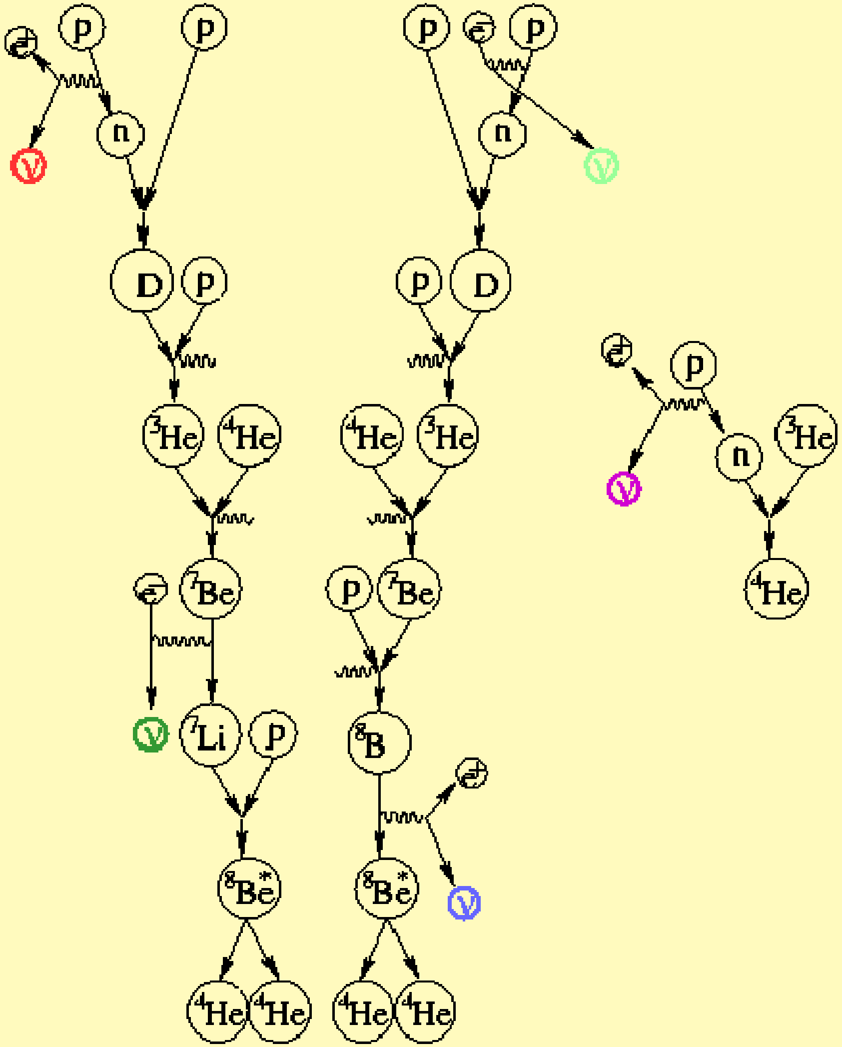


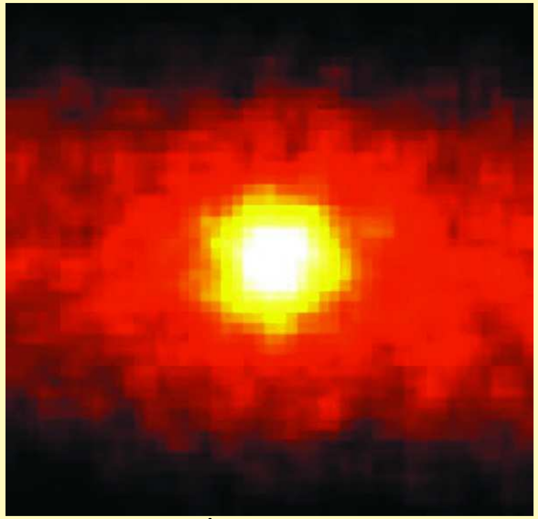
A missing element:
ν_τ appearance

It will be studied
in two experiments
OPERA, ICARUS
in construction at the
Laboratori Nazionali
del Gran Sasso
with a neutrino beam
coming from CERN

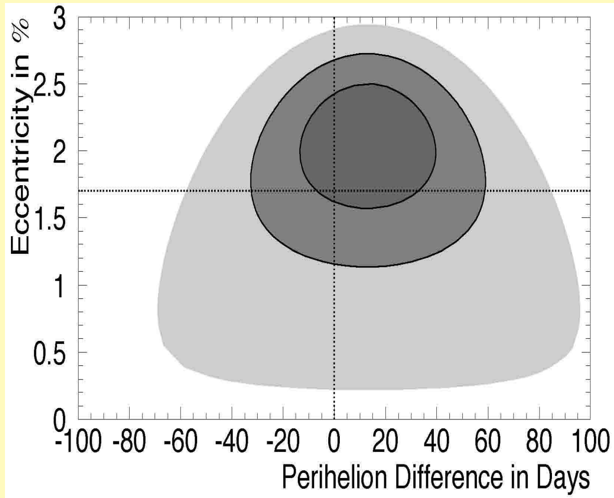
Solar Neutrinos (ν_e)

[Looking at the sky from underground]





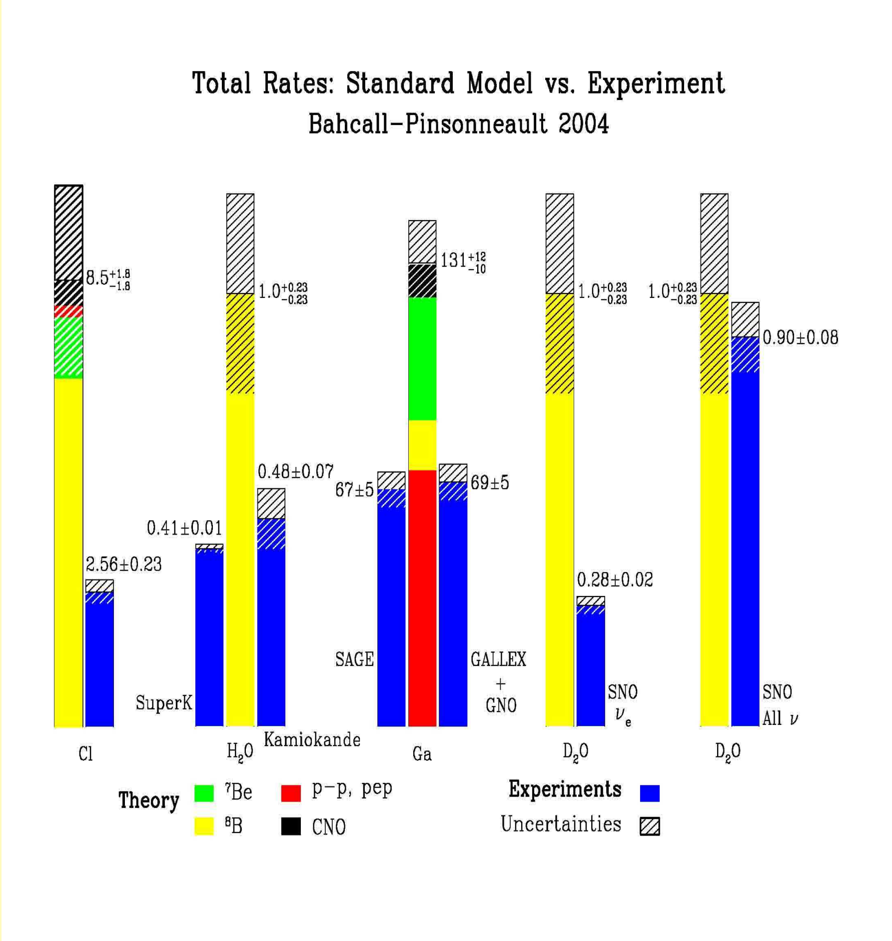
The Sun
as seen with neutrinos (SK)



Earth's orbit
as seen with neutrinos (SK)

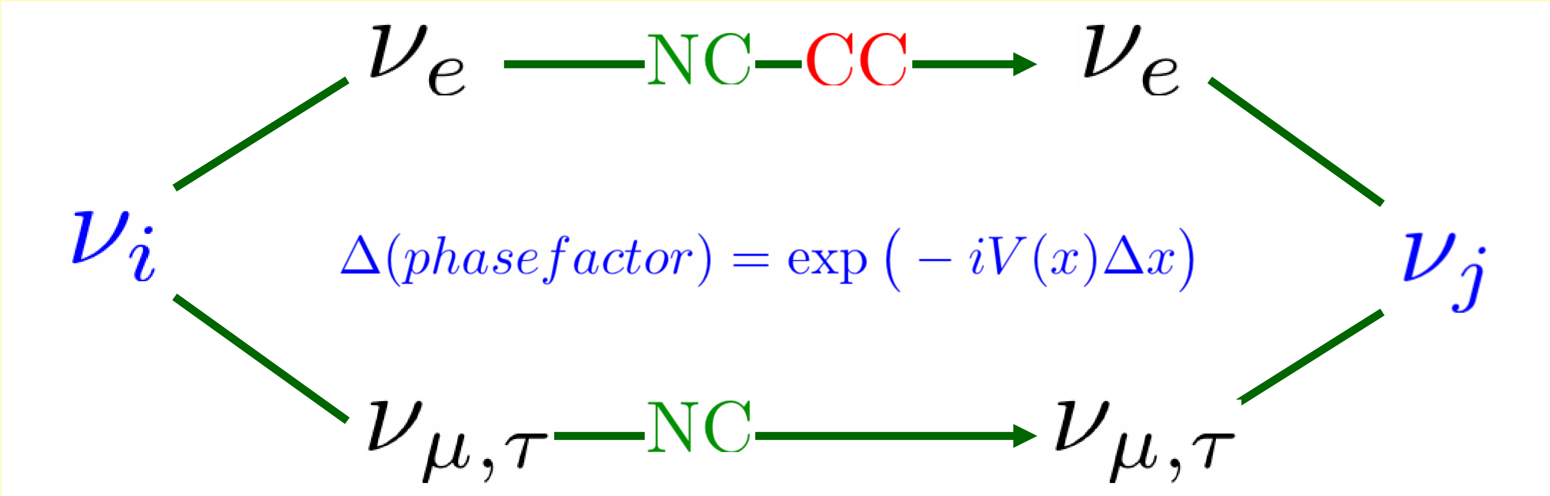
The solar neutrino deficit: 50 years of research

Davis & Bahcall



Gallex/GNO

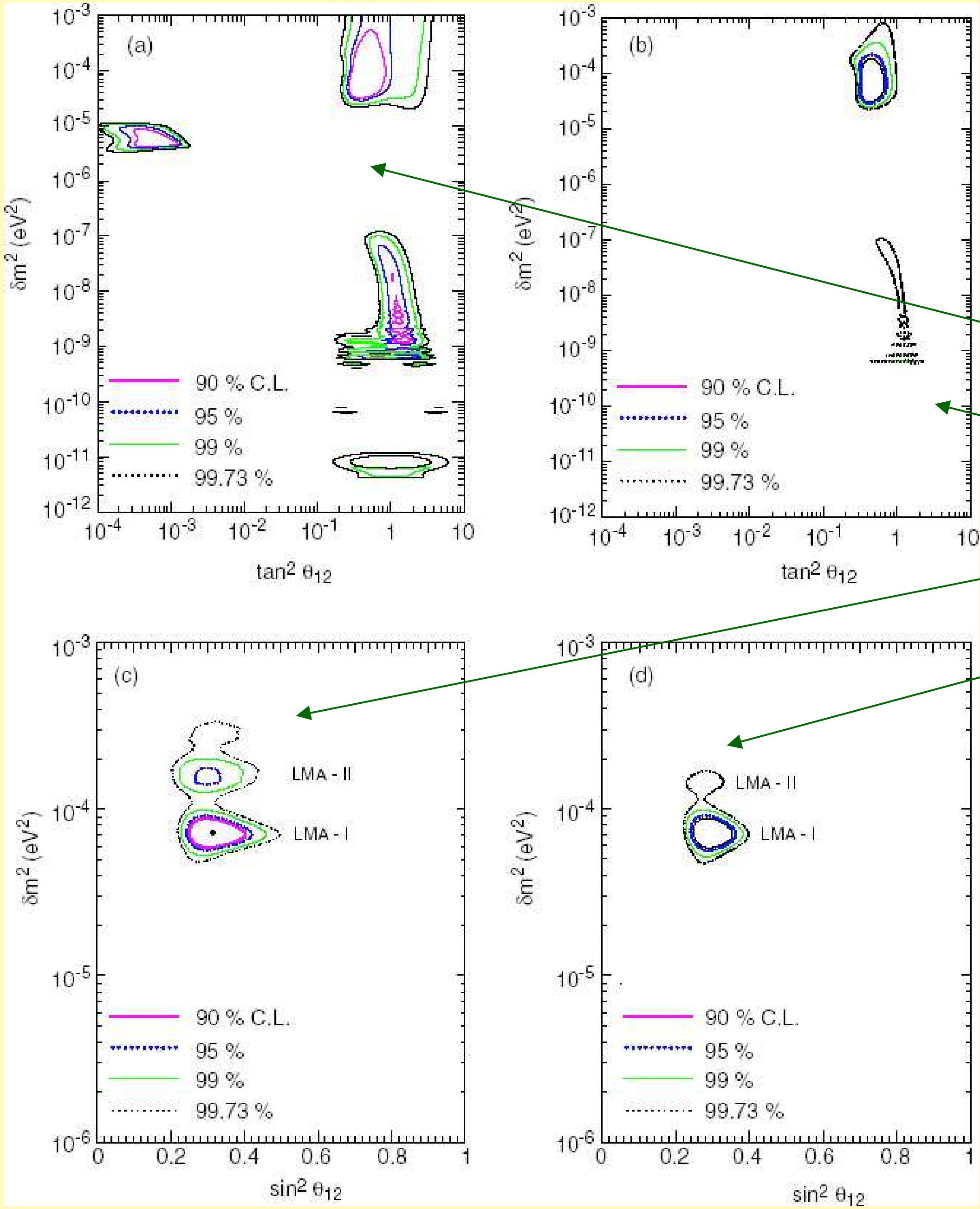
Fundamental difference between atmospheric (~ $\nu_\mu \to \nu_\tau$) and solar ($\nu_e \to \nu_{\mu,\tau}$) neutrino oscillations: ν_e in the Sun interacts with the e^- of the solar matter (CC interaction)



Difference of interaction energies:

$$V(x) = V_e - V_{\mu,\tau} = \sqrt{2}\,G_F\,N_e(x) \quad [N_e = \text{electron density}]$$

[Mikheyev-Smirnov-Wolfenstein (MSW), '70-'80]



Impressive reduction of the parameter space (δm^2,θ_{12}) in the years **2001-2003** (note the different scales !)

Cl+Ga+SK (2001)

+SNO-I (2001-2002)

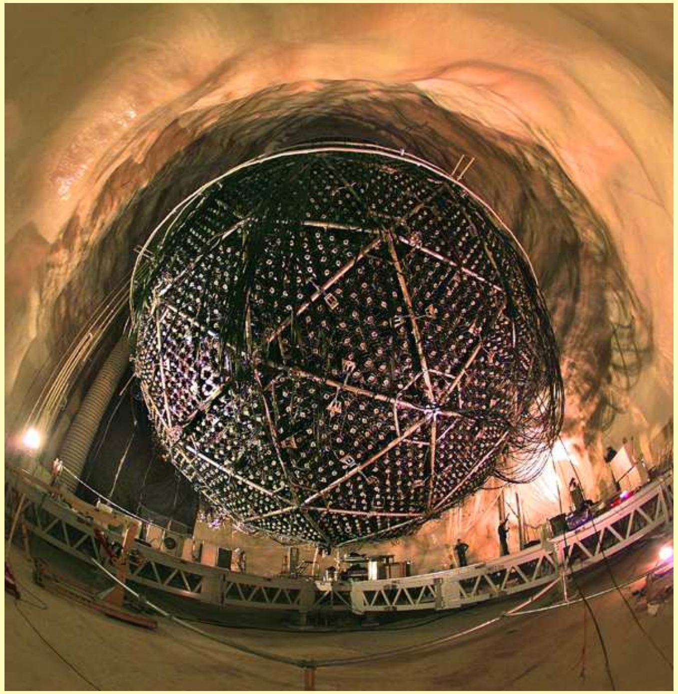
+KamLAND-I (2002)

+SNO-II (2003)

Standard Solar Model confirmed

Direct proof of $\nu_e \rightarrow \nu_{\mu,\tau}$ in SNO from the comparison of

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



Sudbury Neutrino Observatory

1000 tons of deuterium
(available only in Canada)

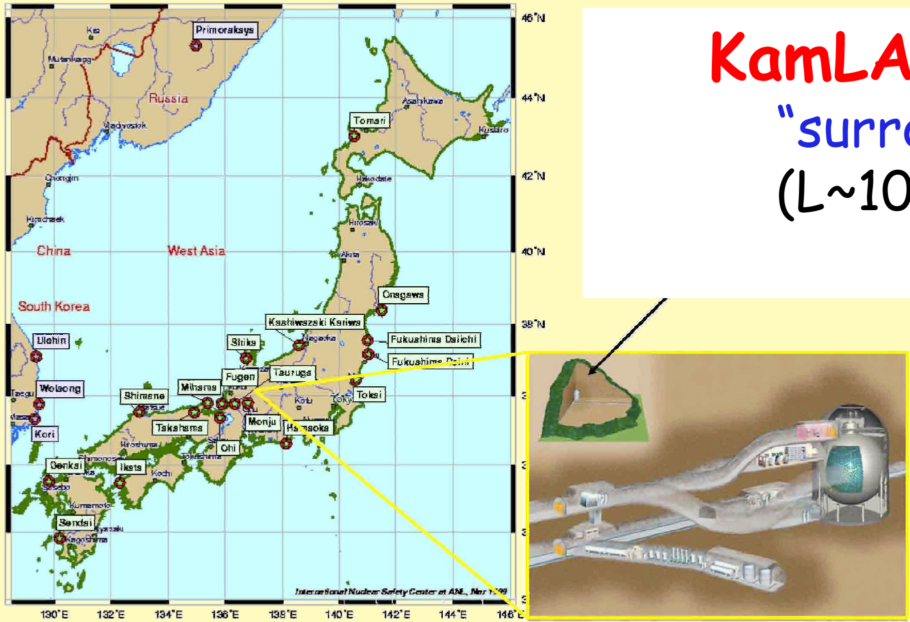
$$\begin{aligned} \mathrm{CC}: &\quad \nu_e + d \to p + p + e \\ \mathrm{NC}: &\quad \nu_{e,\mu,\tau} + d \to p + n + \nu_{e,\mu,\tau} \\ \mathrm{ES}: &\quad \nu_{e,\mu,\tau} + e \to e + \nu_{e,\mu,\tau} \end{aligned}$$

$$\frac{\mathrm{CC}}{\mathrm{NC}} \sim \frac{\phi(\nu_e)}{\phi(\nu_e) + \phi(\nu_{\mu,\tau})}$$

then:

$$\frac{\mathrm{CC}}{\mathrm{NC}} < 1 \;\Rightarrow\; \phi(\nu_{\mu,\tau}) > 0 \;\Rightarrow\; \nu_e \to \nu_{\mu,\tau}$$

SNO, 2002: ***CC/NC ~ 1/3***
Model-independent evidence of "flavor changing" effect !

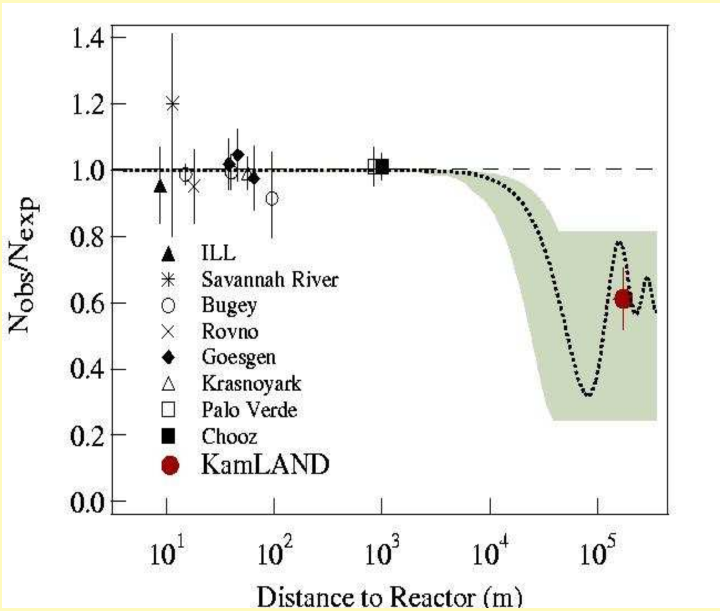


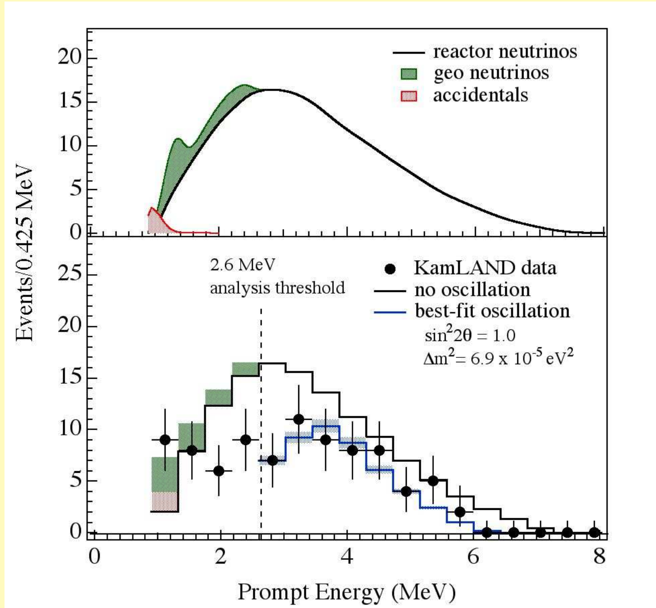
KamLAND: 1000 tons of mineral oil,
"surrounded" by nuclear reactors
(L~100-200 km, E_ν ~ a few MeV)

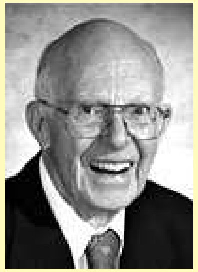
$$\text{oscillation phase}: \quad \frac{\delta m^2 L}{4E} \sim O(1)$$

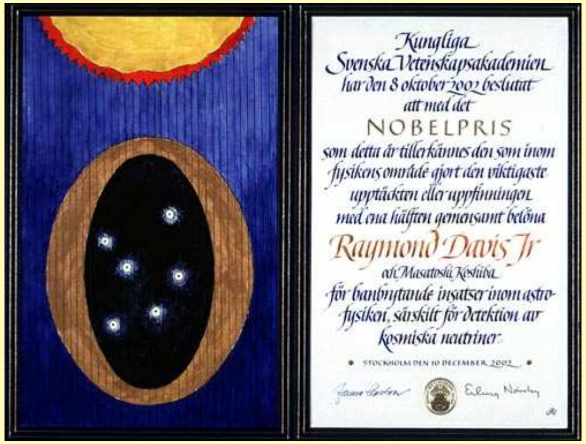
$$\text{if} \quad \delta m^2 \simeq 10^{-4} - 10^{-5}\ \text{eV}^2$$

2002:









Nobel 2002

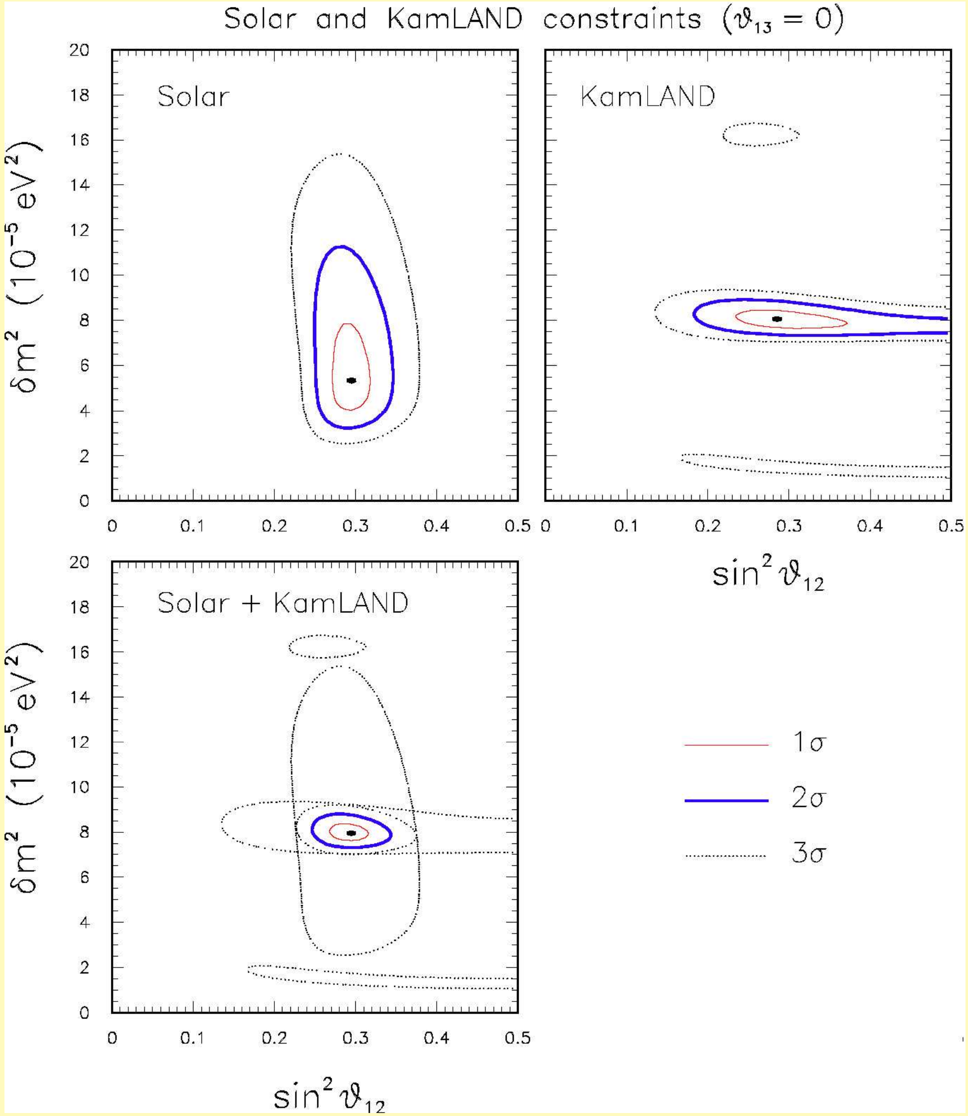
1905: annus mirabilis for physics (in general)

2002: annus mirabilis for solar neutrino physics

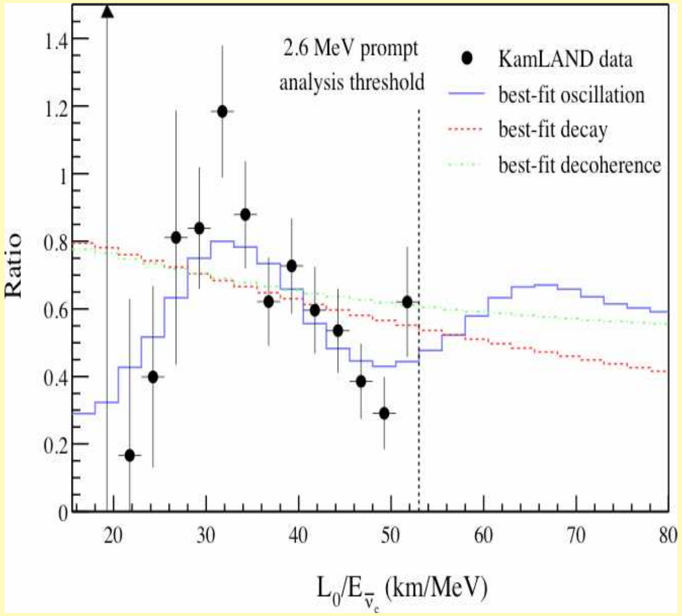
The year 2002 is likely to be remembered as the *annus mirabilis* of solar neutrino physics. On April 20, direct and highly significant evidence for ν_e flavor change into active states was announced by the Sudbury Neutrino Observatory (SNO) experiment [1], crowning a four-decade long [2] series of beautiful observations [3, 4, 5, 6, 7, 8, 9, 10, 11] of the solar ν_e flux deficit [12, 13]. On October 8, the role of solar neutrino physics in shaping modern science was recognized through the Nobel Prize jointly awarded to Raymond Davis, Jr., and Masatoshi Koshiba, for their pioneering contributions to the detection of cosmic neutrinos [14]. Finally, on December 6, clear "terrestrial" evidence for the oscillation solution to the solar neutrino deficit was reported by the Kamioka Liquid scintillator AntiNeutrino Detector (KamLAND), through the observation of long-baseline reactor $\overline{\nu}_e$ disappearance [15]. The seminal idea of studying lepton physics by detecting solar [16, 17] and reactor [16, 17, 18] neutrinos keeps thus bearing fruits after more than 50 years.

(from: G.L.F., E.Lisi, A. Marrone, D. Montanino, A.Palazzo, A.M. Rotunno, hep-ph/0212127)

… **2004**: a unique solution well identified (Large Mixing Angle)



+ evidence for a half-cycle of oscillation in KamLAND

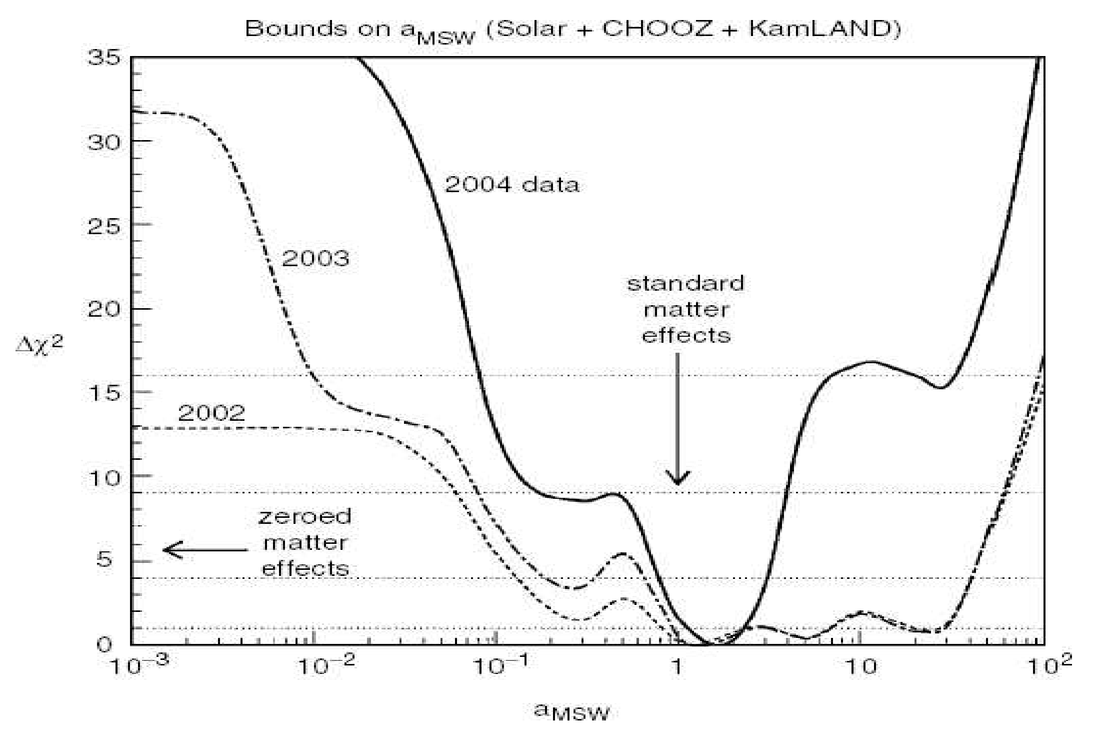


What can we say about the MSW effect ?

An exercise: 1. Let the MSW potential be parameterized as $\mathbf{V(x)} \rightarrow \mathbf{a_{MSW}V(x)}$

2. Consider all the data with (δm^2, θ_{12}, a_{MSW}) free

3. Marginalize (δm^2, θ_{12}) and check if $\mathbf{a_{MSW} \sim 1}$



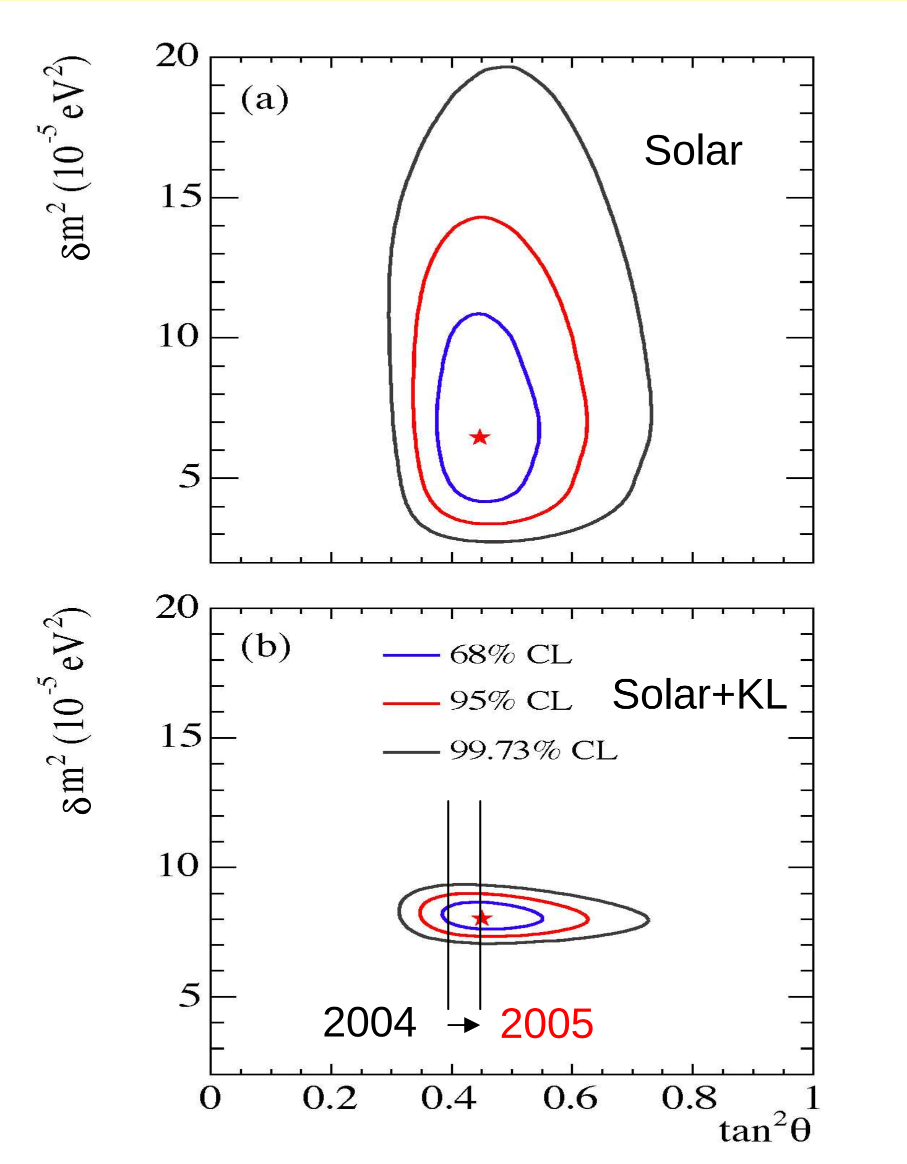
(… how to "measure" G_F through solar neutrino oscillations…)

Results: with the **2004** data { $a_{MSW} \sim 1$ within a factor ~ 2; $a_{MSW} \sim 0$ excluded

Clear evidence for the MSW effect in the solar matter

[However, subdominant MSW effects expected from the Earth crossing (day-night effect) are still too small with respect to the experimental uncertainties.]

2005 (three months ago): new important results from SNO



Previous results confirmed

Ratio CC/NC ~ $P(\nu_e \to \nu_e)$ slightly higher

Small change of θ_{12} (<1σ) towards higher values

State-of-the-art (2004 data, ±2σ errors)

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

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

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

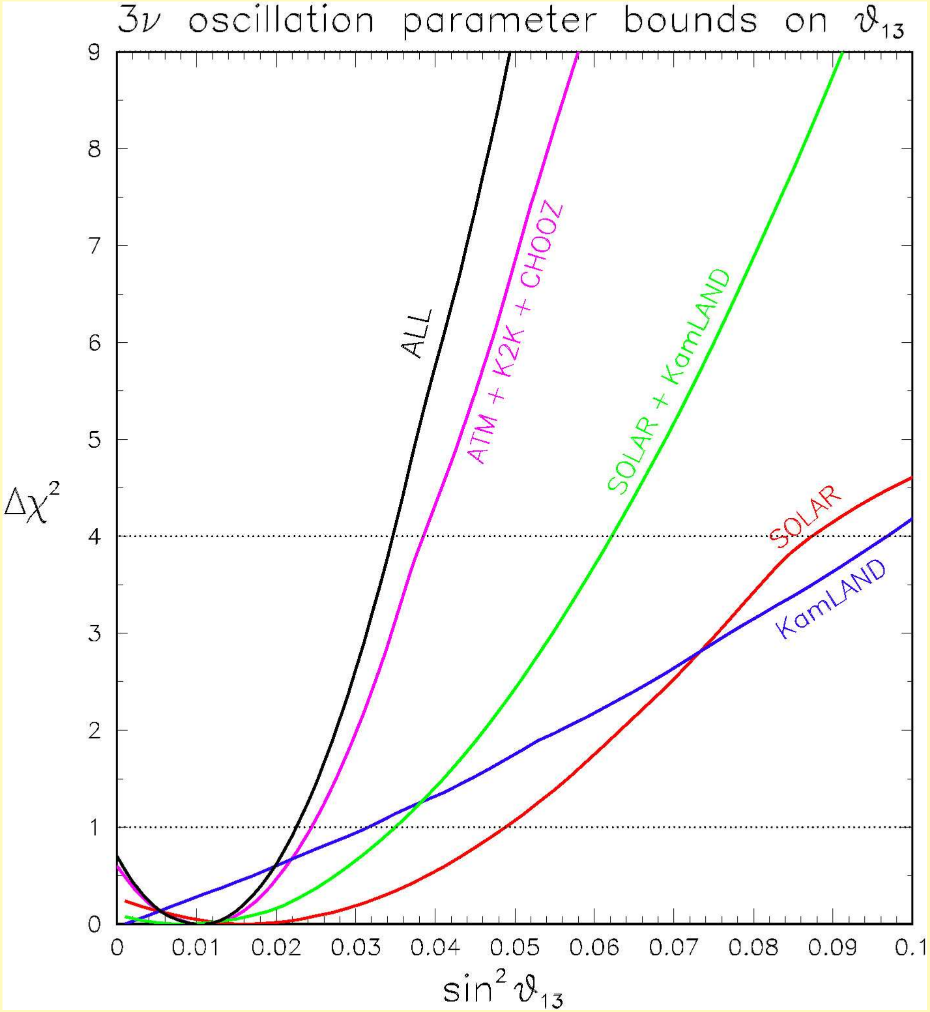
$$\sin^2\theta_{23} \simeq 0.45^{+0.18}_{-0.11}$$

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

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

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

All the experiments indicate θ_{13} small or zero
(in particular CHOOZ with reactor neutrinos)
→ A non trivial consistency, which makes difficult future research….



Conclusions

Impressive progresses in the recent years …

Non-zero neutrino masses and mixings
Determination of ($\delta m^2, \theta_{12}$) and ($\Delta m^2, \theta_{23}$)
Upper limits on θ_{13}
Spectral distortions induced by oscillations
Direct evidence for solar ν oscillations
Evidence of MSW effect in the Sun
Upper limits on m_ν of order (sub)eV
…………

Determination of θ_{13}
CP violation in the leptonic sector
Absolute masses from β-decay and cosmology
Test of controversial signals ($0\nu2\beta$, LSND)
MSW effect from Earth matter
Normal vs. inverted hierarchies
Physics beyond the standard 3ν scenario
A deeper theoretical understanding
…………

… and great challenges in the future

A lot of work is still to be done in neutrino physics …

Planisphaerium Neutrinorum
Terra Cognita I
$(\vartheta_{12}, \Delta m^2_{12})$
Terra Incognita I
$(\vartheta_{13}, \delta_{CP}, \nu_S, \dots)$
Terra Incognita II
$(m_\nu, \nu \equiv \bar{\nu}, \dots)$
Terra Cognita II
$(\vartheta_{23}, \Delta m^2_{23})$
Atlas
Coelestis
ν_e ν_1 ν_μ ν_2 ν_τ ν_3
ν_α ν_β $\bar{\nu}_\beta$ $\bar{\nu}_\alpha$
NOVA
$\bar{\nu}_e, \nu_x$
MCMLXXXVII
NOW
MMIV
ν_e
ELIGIO LISI