1998: Neutrino Oscillation Discovery

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Neutrino Oscillations, Twenty Years After

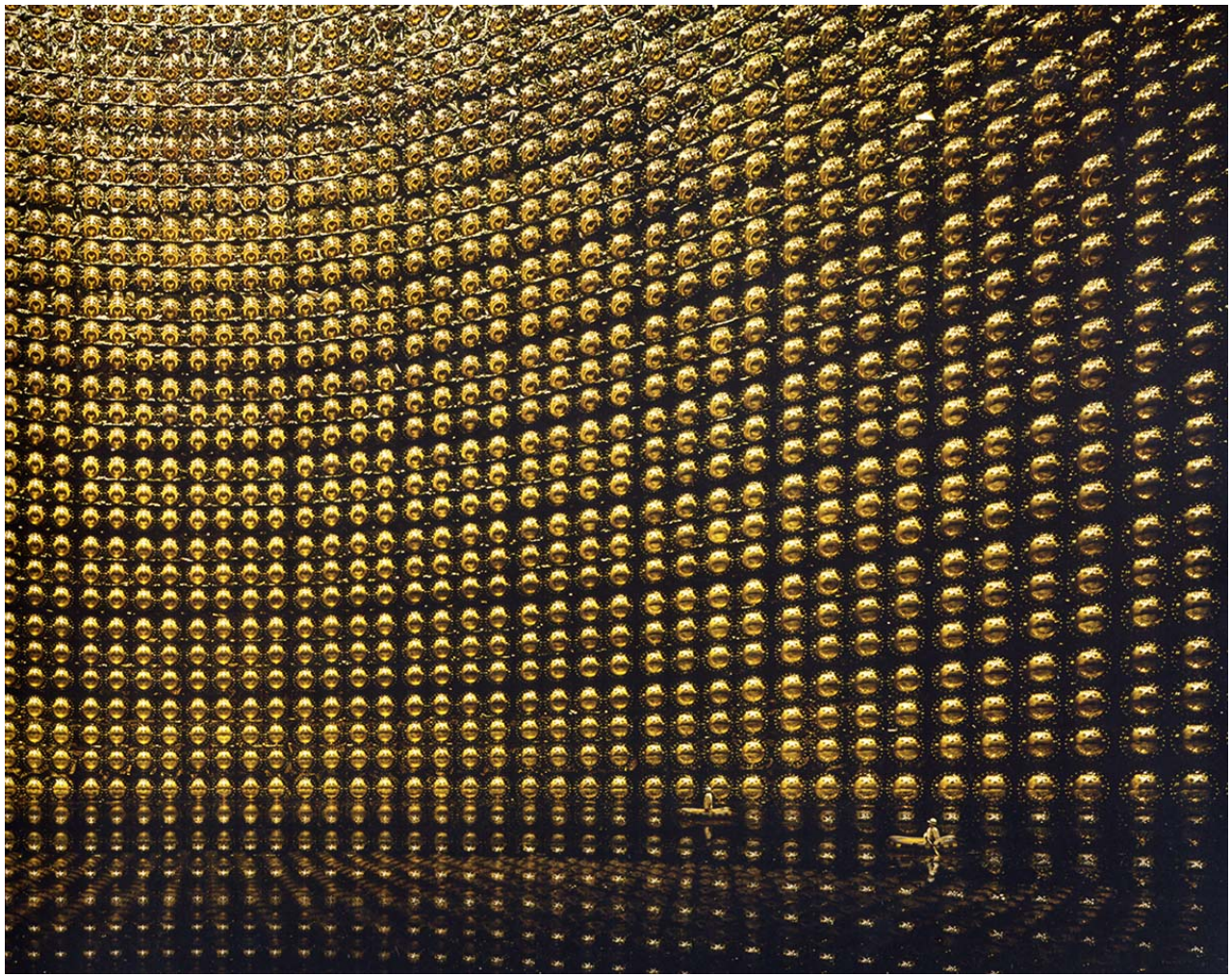


Photo by Andreas Gursky, detail.

Pontecorvo 1959: The Birth of Neutrino Oscillations

*INVERSE β-PROCESSES AND NON-CONSERVATION OF LEPTON CHARGE**

B.Pontecorvo

Joint Institute for Nuclear Research, Dubna

In conclusion it is interesting to underline that, independently of the plausibility of the concrete effects which were discussed above, non-conservation of neutrino charge under the condition that neutrino and antineutrino are distinguishable entities (or, which is the same, the existence of two Majorana neutrinos with different combined particles) inevitably leads to effects of the Gell-Mann-Pais-Piccioni type [2]. Under the above assumptions, effects of transformation of neutrino into antineutrino and vice versa may be unobservable in the laboratory because of large values of R, but will certainly occur, at least, on an astronomic scale.

*JINR Preprint P-95, Dubna, 1957.

Pontecorvo 1946: Solar Neutrinos

*INVERSE β PROCESS**

B.M.Pontecorvo

There are several elements which can be used for neutrino radiation in the suggested investigation. Chlorine and Bromine, for example, fulfil reasonably well the desired conditions. The reactions of interest would be:

$\nu + {}^{37}\mathrm{Cl} \rightarrow \beta^- + {}^{37}\mathrm{Ar}$ $\quad$ $\nu + {}^{79,81}\mathrm{Br} \rightarrow \beta^- + {}^{79,81}\mathrm{Kr}$

${}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl}$ $\quad$ ${}^{79,81}\mathrm{Kr} \rightarrow {}^{79,81}\mathrm{Br}$

(34 days; *K* capture) $\quad$ (34 h; emission of positrons of 0.4 MeV).

The experiment with Chlorine, for example, would consist in irradiating with neutrinos a large volume of Chlorine or Carbon Tetra-Chloride, for a time of the order of one month, and extracting the radioactive ${}^{37}\mathrm{Ar}$ from such volume by boiling.

SOURCES

The neutrino flux from the sun is of the order of 10^{16} neutrinos/cm^2· sec. The neutrinos emitted by the sun, however, are not very energetic. The use of high intensity piles permits two possible strong neutrino sources:

*National Reserach Council of Canada, Division of Atomic Energy. Chalk River, 1946, Report PD-205. This version was kindly provided by Prof. W.F.Davidson.

Pontecorvo's paper on neutrino detection.
Chalk River, 1946, Report PD-205 **CLASSIFIED**

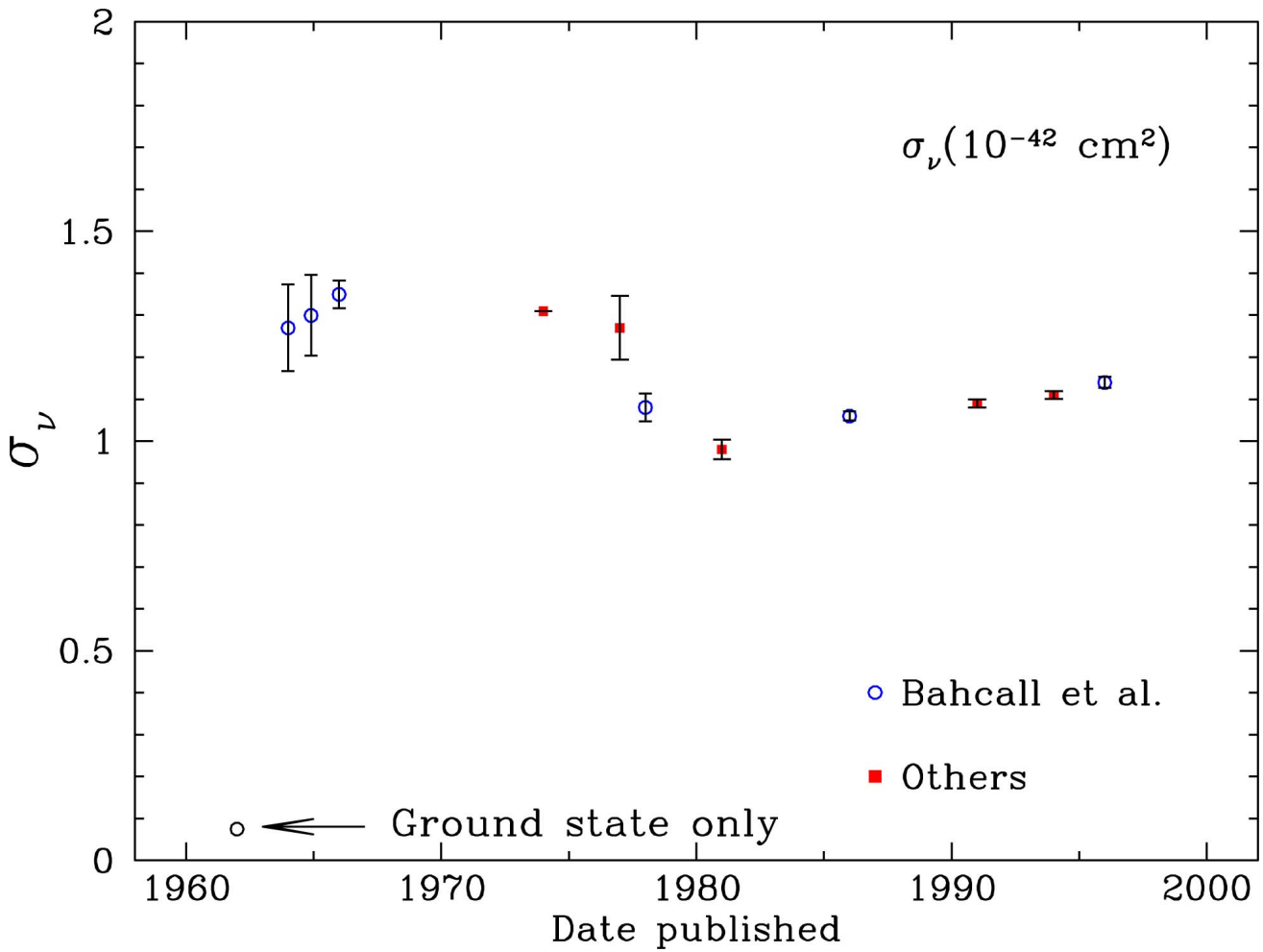
Homestake Neutrino Experiment

Ray Davis, jr. and John Bahcall, Homestake Mine, 1964.

Observed flux $\approx 1/3$ of the expected one (Davis 1994).

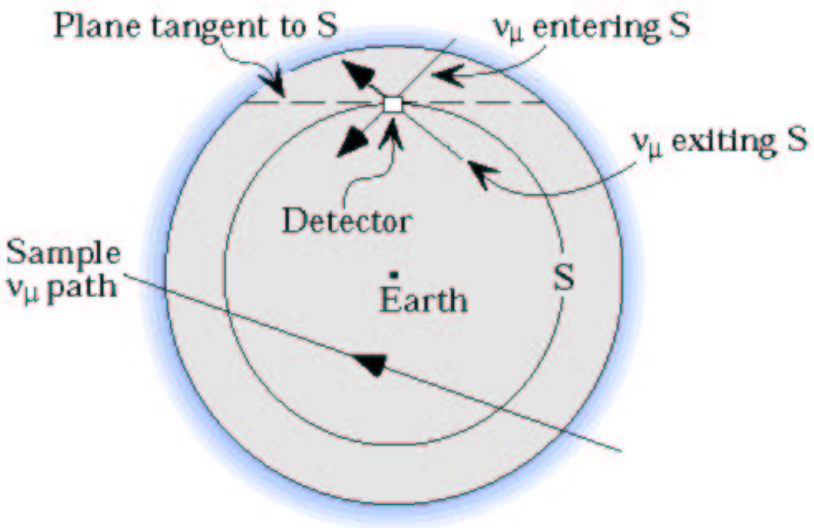
Neutrino Oscillation? Neutrino decay? Solar Model wrong?

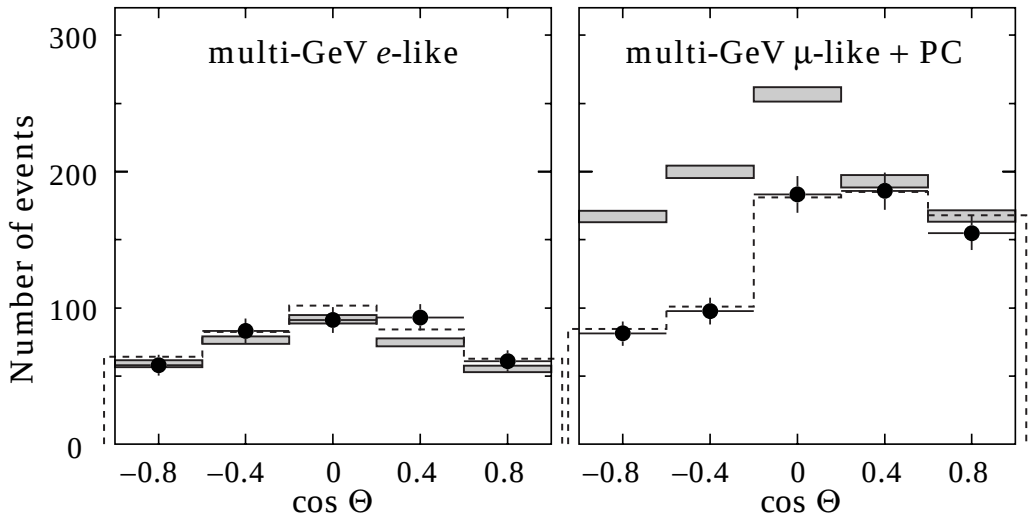
John Bahcall



John Bahcall's determinations of the ν_e-CL^{37} cross section

Superkamiokande 1988: Muon Neutrinos Oscillate . . .

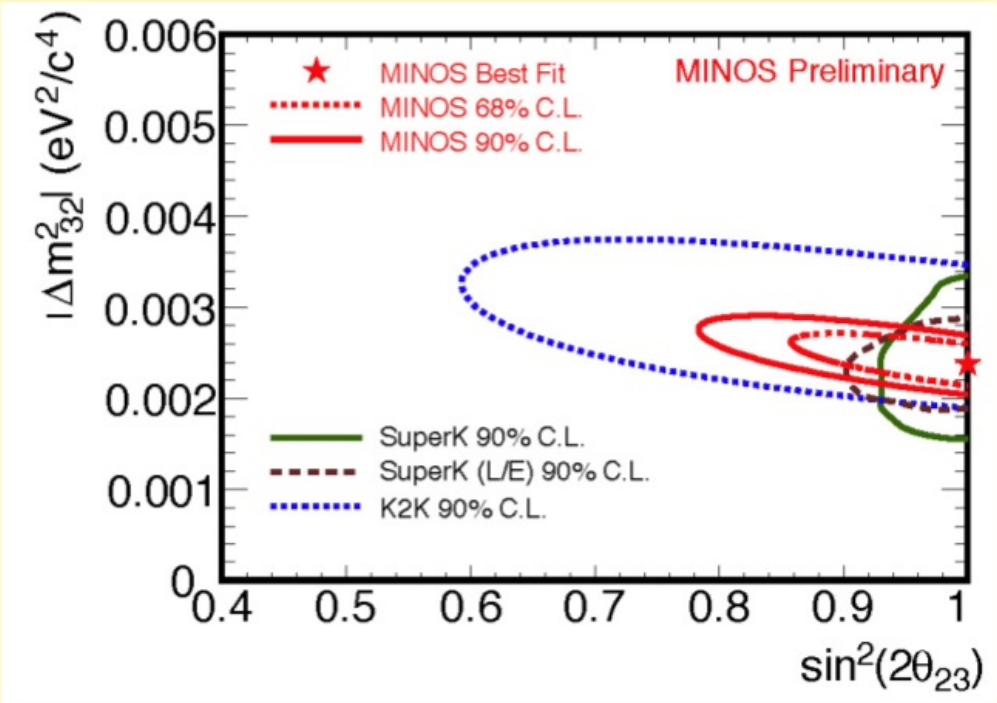




. . . and electron neutrinos do not.

New ν_μ Oscillation data from Accelerator Experiments

(Δm^2, θ_{23}) - complementarity of atmospheric/accelerator ν

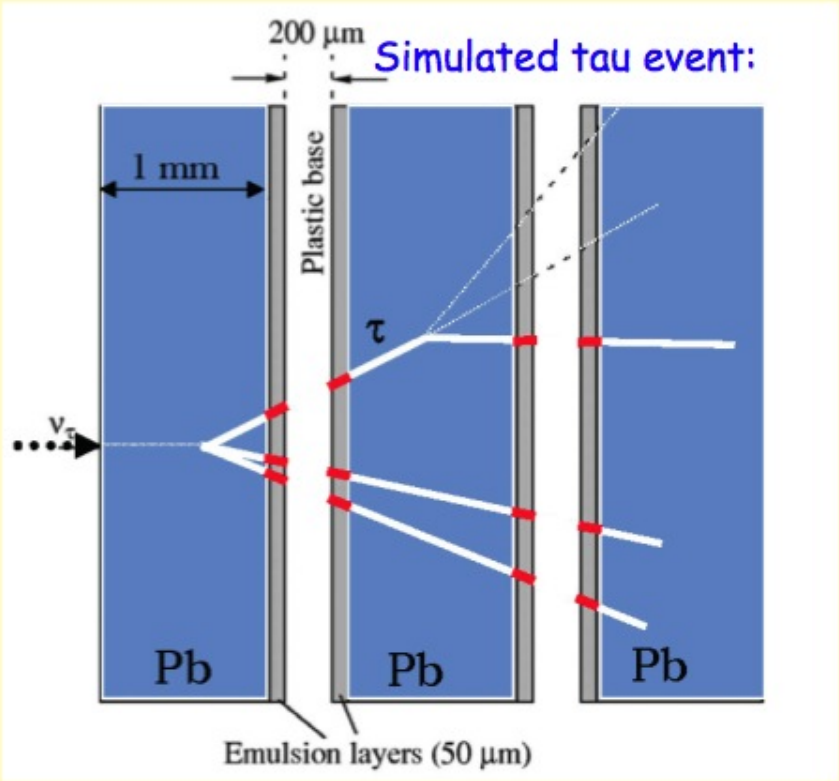


All results consistent with muon flavor disappearance and no electron appearance - hence, **with $\nu_\mu \to \nu_\tau$ oscillations**. Missing piece: direct observation of ν_τ appearance

Yellow pictures from Eligio Lisi's talk at the INFN Program Committee, 2008

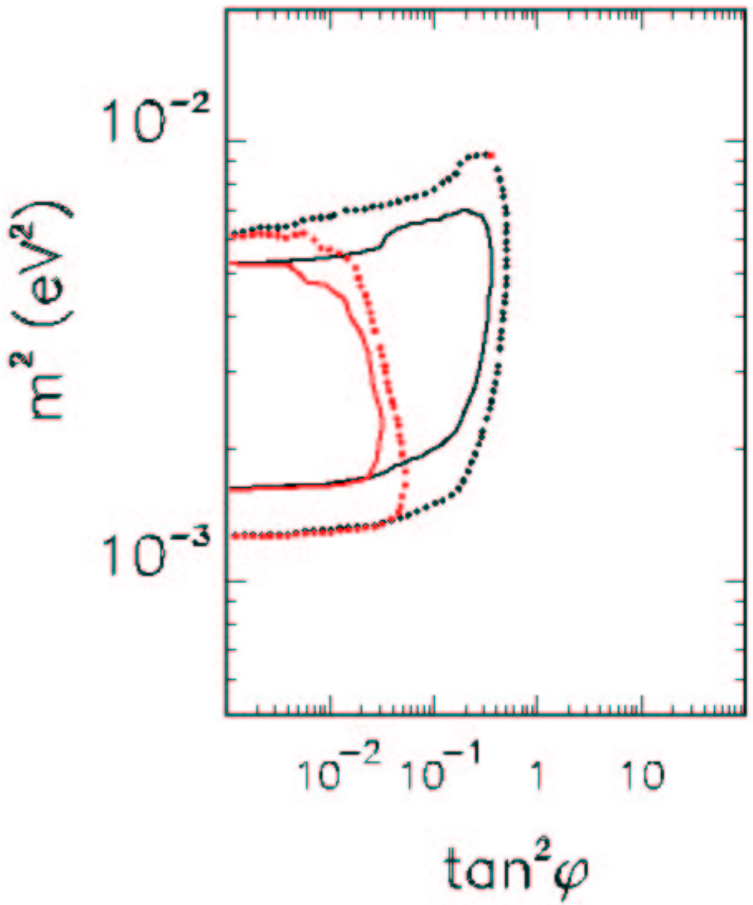
OPERA $\nu_\mu \rightarrow \nu_\tau$ Oscillations

Unmistakable evidence from precise tau-event reconstruction: OPERA



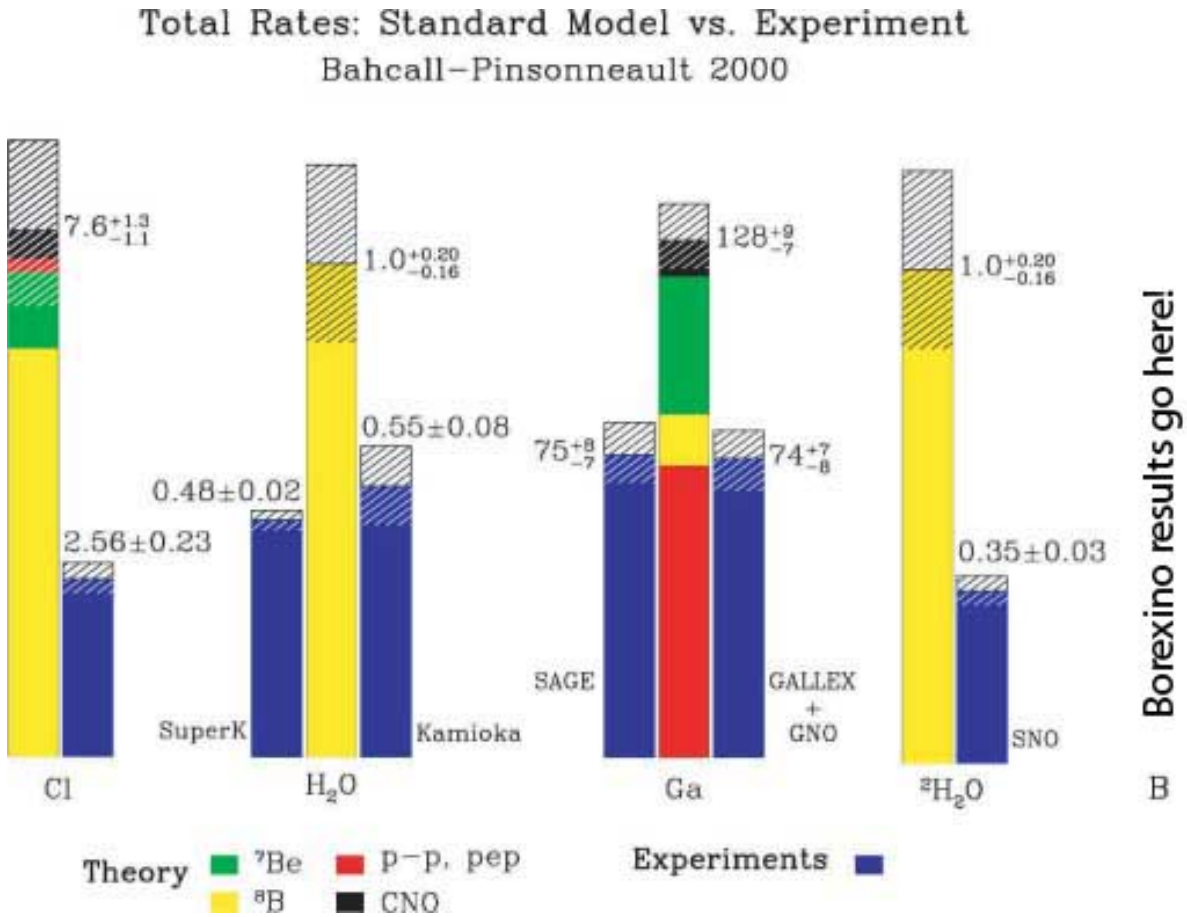
Beam tuned to relatively high E; suppresses oscillations (small L/E) but enhances **tau production**. Rate $\propto(\Delta m^2)^2$.

Reactor Experiments



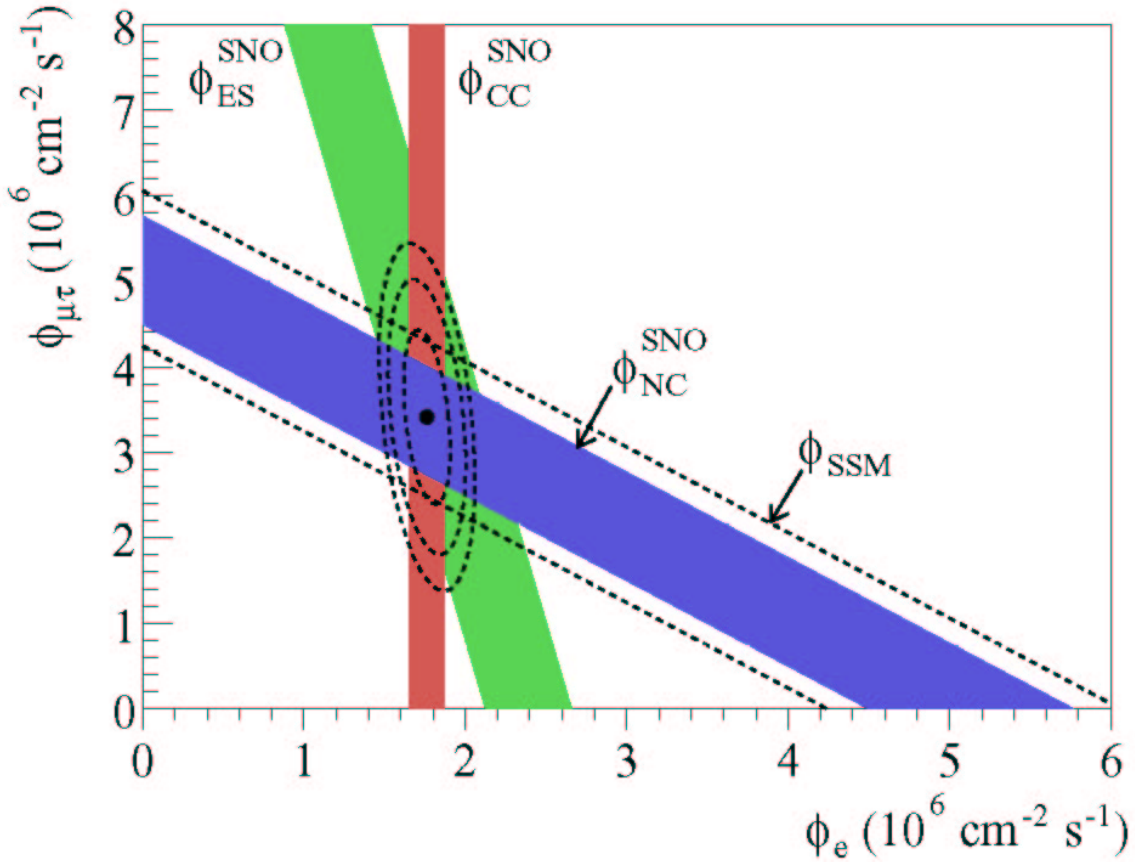
The Chooz limit on θ_{13}, the mixing of ν_e at the atmospheric frequency.
New experiments: Chooz-II, Dayan Bay.

The Solar Neutrino Deficit



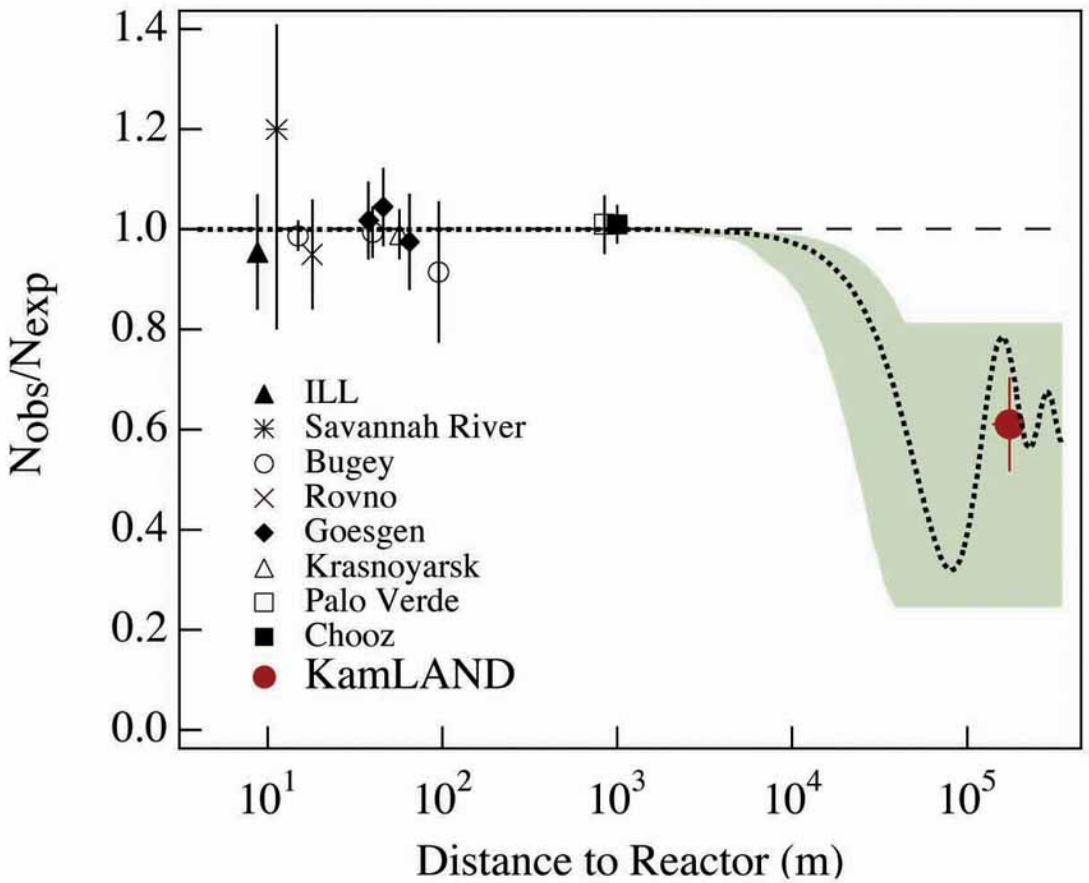
It fits with the oscillation hypothesis,
SNO and KamLAND gave two complementary tests.

SNO



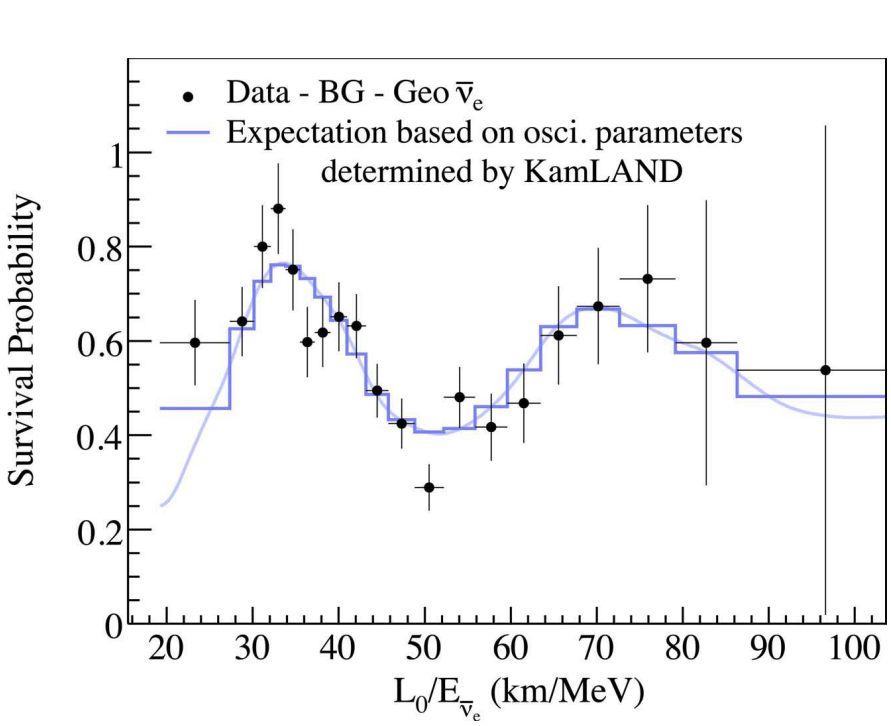
It is oscillations! Missing electron neutrinos are still seen as ν_τ, ν_μ in neutral current reactions

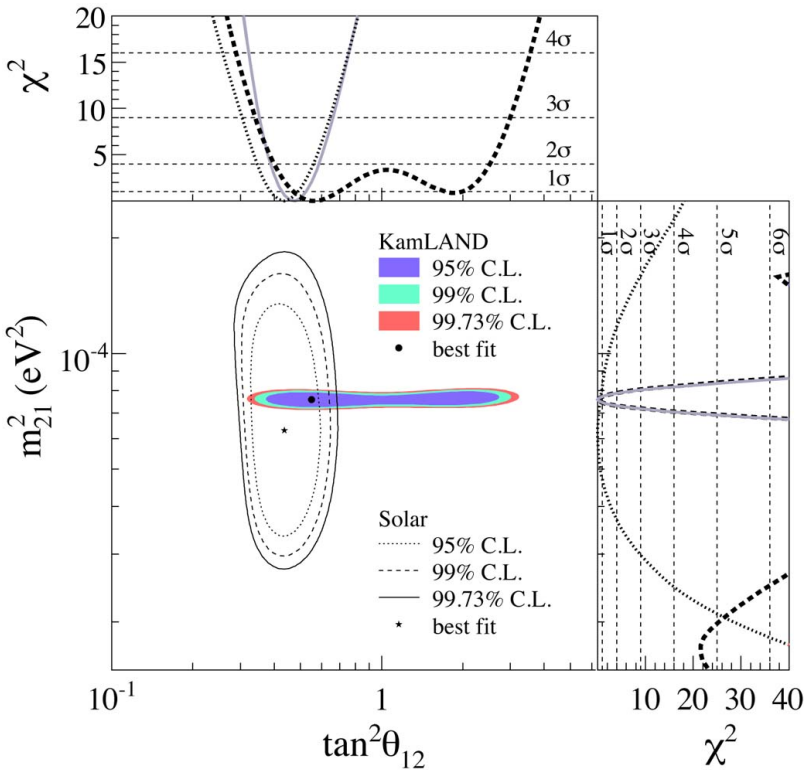
KamLAND 2001



The 2001 KamLAND results demonstrated ν_e oscillations at the solar frequency.

KamLAND 2008



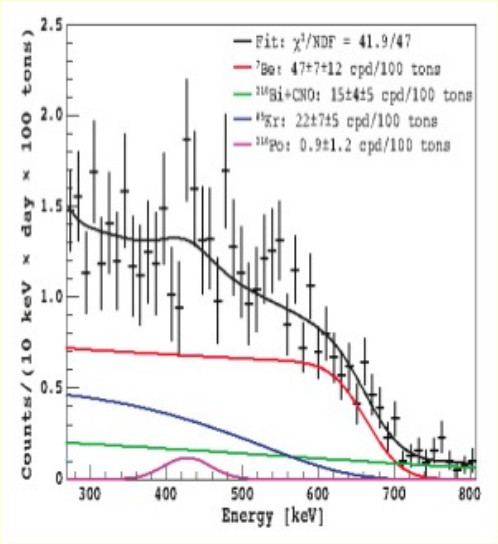


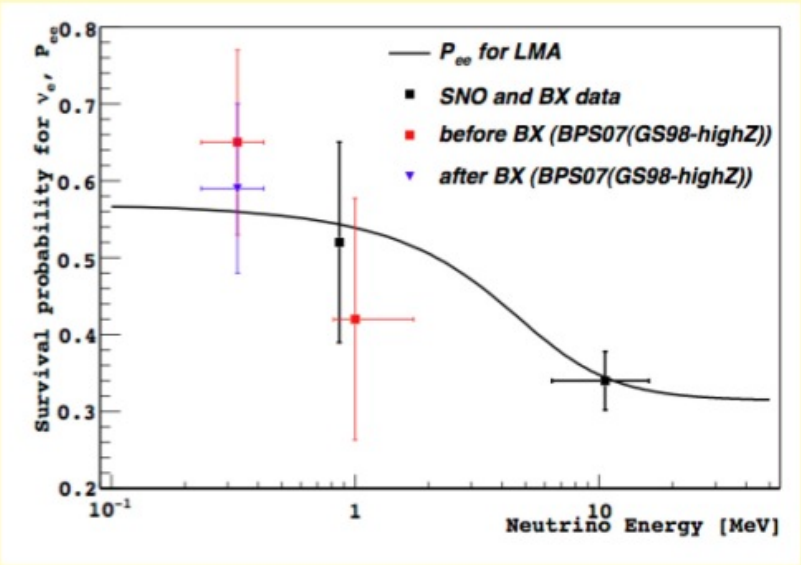
Best determination of m^2_{12}.
An impressive textbook example of neutrino oscillations!

KamLAND Collaboration, arXiv:0801.4589.

Borexino 2007

BOREXINO first results





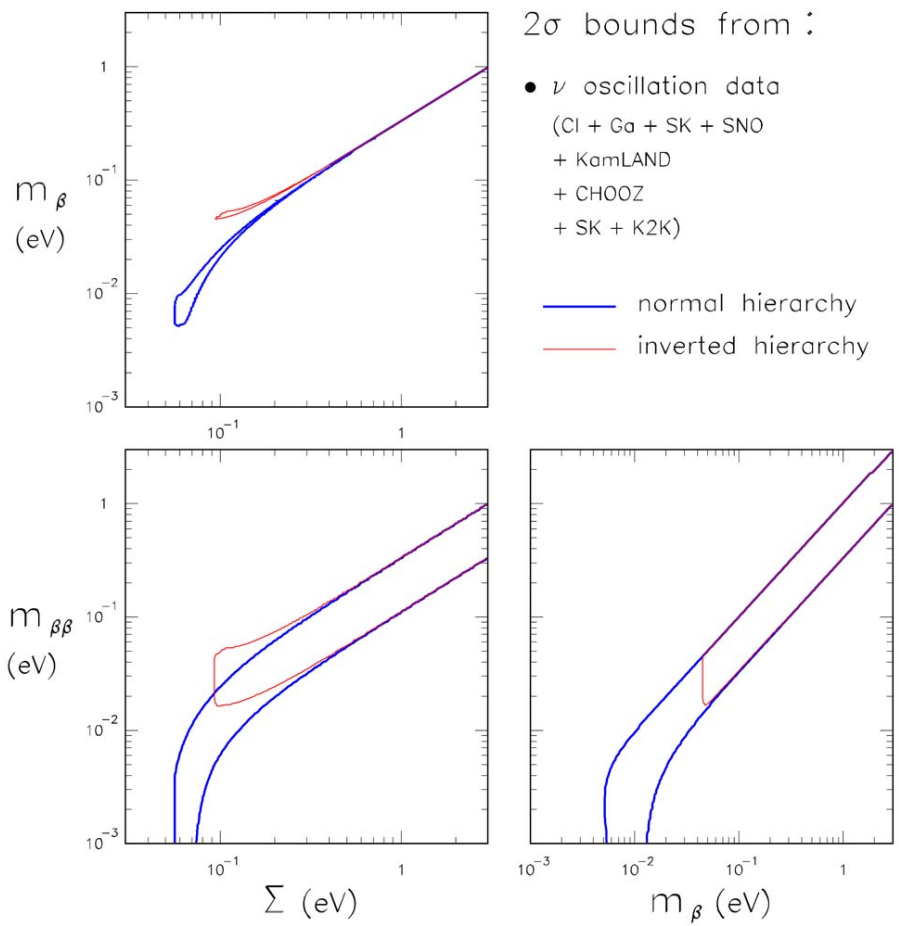
Rate consistent with
MSW expectations
within latest SSM
(from A. Ianni, TAUP 2007)

^{7}Be rate = $47 \pm 7_{stat} \pm 12_{sys}$(max)

LMA yearly averaged: 49±4
No osc. : 75±4 (2.6σ excluded)

A return to John Bahcall's program: the study of the Sun.
But also real time study of the neutrino flux:
The exploration of neutrino-matter interaction.

Neutrino Mass



Experiments are under preparation for measuring m_β — KATRIN, MARE — and $m_{\beta\beta}$ — CUORICINO.

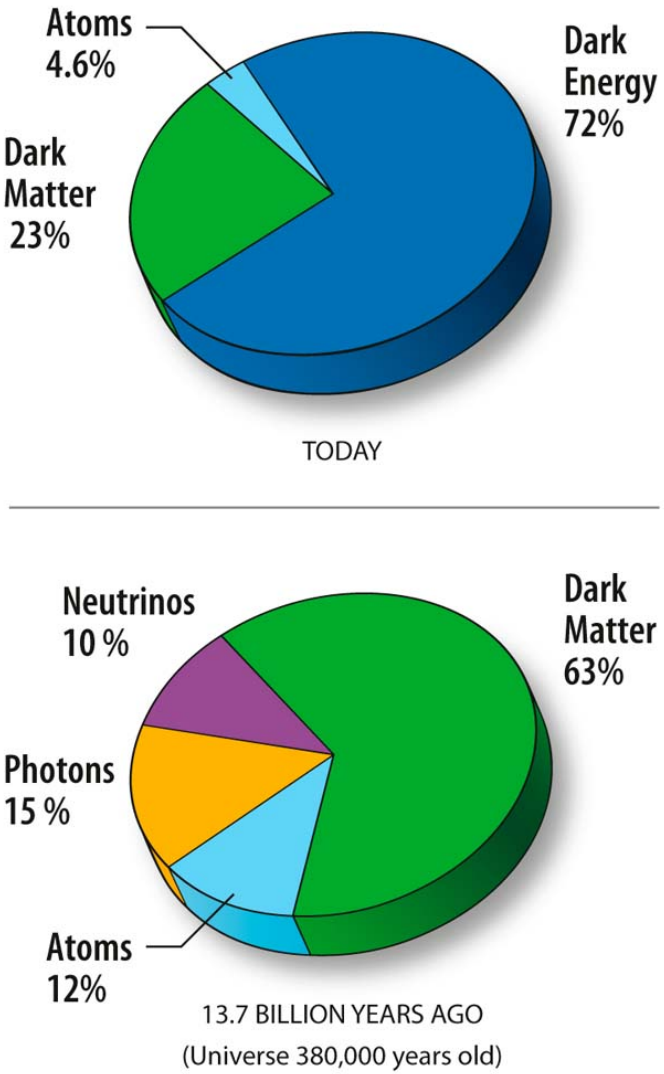
From Fogli et al. arXiv:hep-ph/0408045v2

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

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

$$m_{\beta\beta} = [c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 e^{i\phi_2} m_2^2 + s_{13}^2 m_3^2 e^{i\phi_3}]^{1/2}$$

The role of cosmology



The best limit on the sum of neutrino masses, $\sum m_\nu < 0.66$ eV comes from cosmological data.

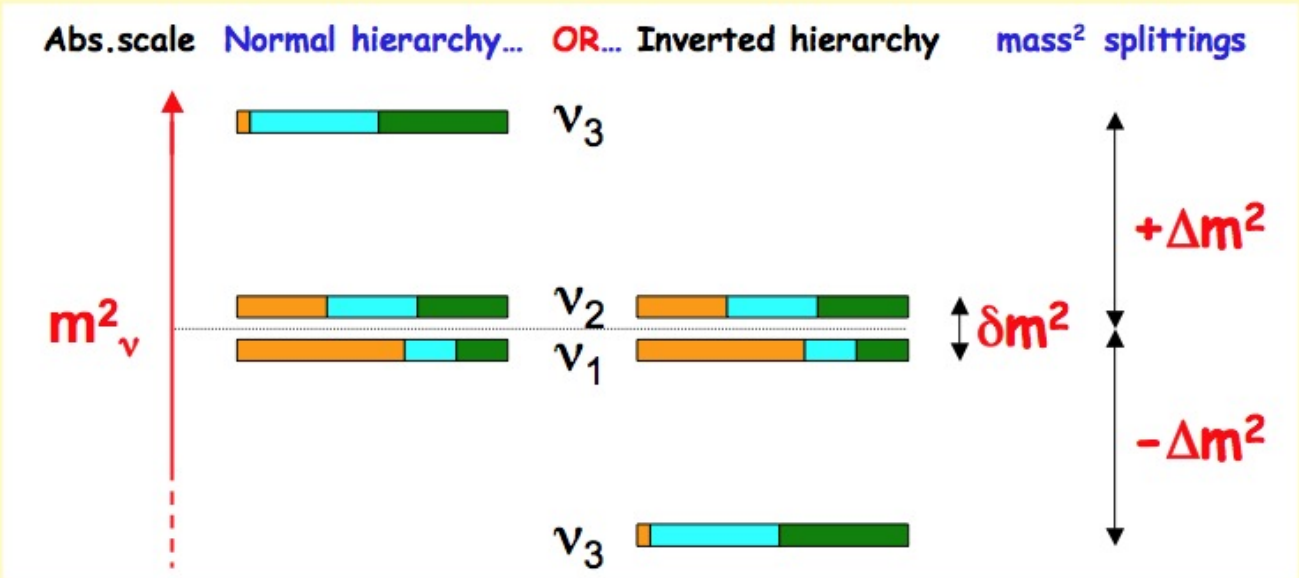
The CMB fluctuation spectrum is sensitive to the presence of non-relativistic neutrinos in the decoupling era ($T_\gamma \approx 0.7$eV). On this basis WMAP obtains a limit $\sum m_\nu < 1.3$ eV, and a stronger limit, $\sum m_\nu < 0.66$ eV using other "safe" data.

More stringent limits could be obtained, but are not at this time firmly established.

Where we Stand.

3ν: One-slide, one-significant-digit summary

may be enough for many purposes! (flavors = e μ τ):



$\delta m^2 \sim 8 \times 10^{-5}$ eV^2 $\quad \sin^2\theta_{12} \sim 0.3$

$\Delta m^2 \sim 3 \times 10^{-3}$ eV^2 $\quad \sin^2\theta_{23} \sim 0.5$

$m_\nu < O(1)$ eV $\quad \sin^2\theta_{13} <$ few%

sign$(\pm\Delta m^2)$ unknown $\quad \delta$ (CP) unknown

We Have a Long Road Ahead.

3ν: One-slide, one-significant-digit summary

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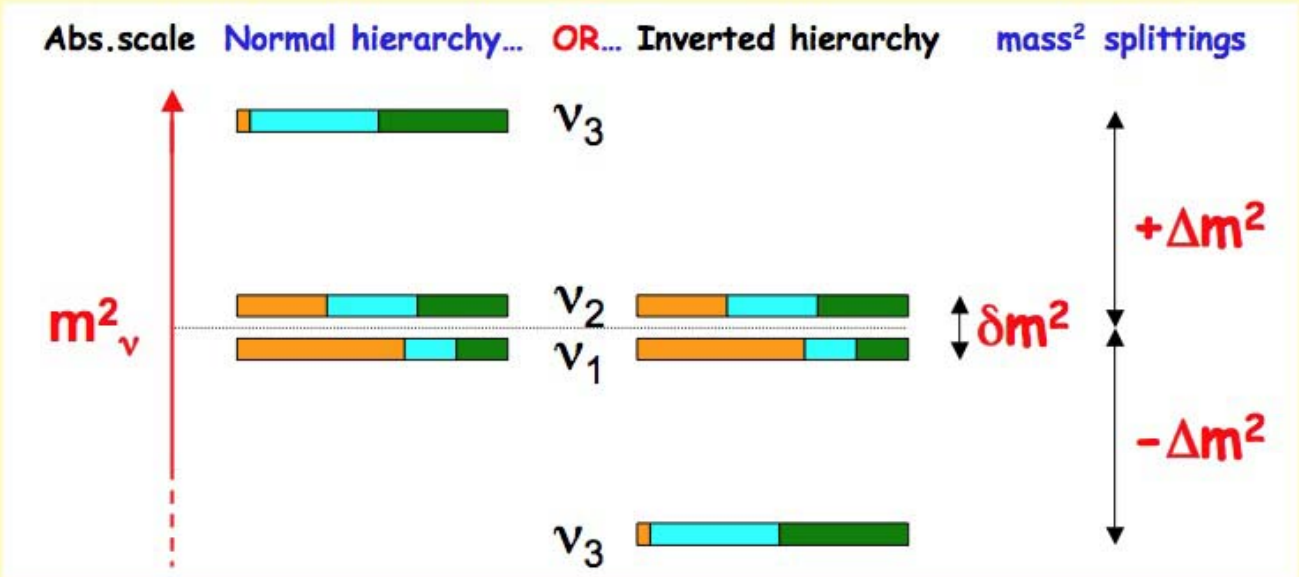

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And to Conclude

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Thank you for your attention.

Also Borrowing this Slide!