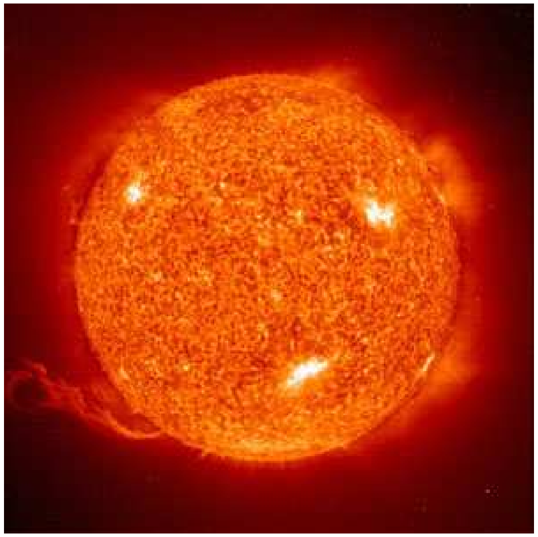
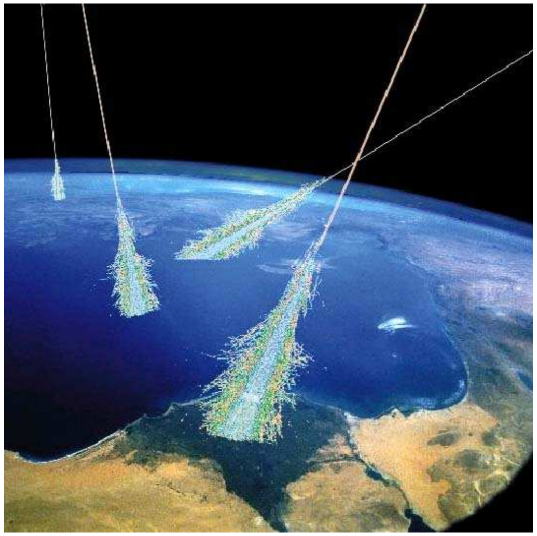
Revealing Pauli's "dark" matter was only a question of time and ingenuity...





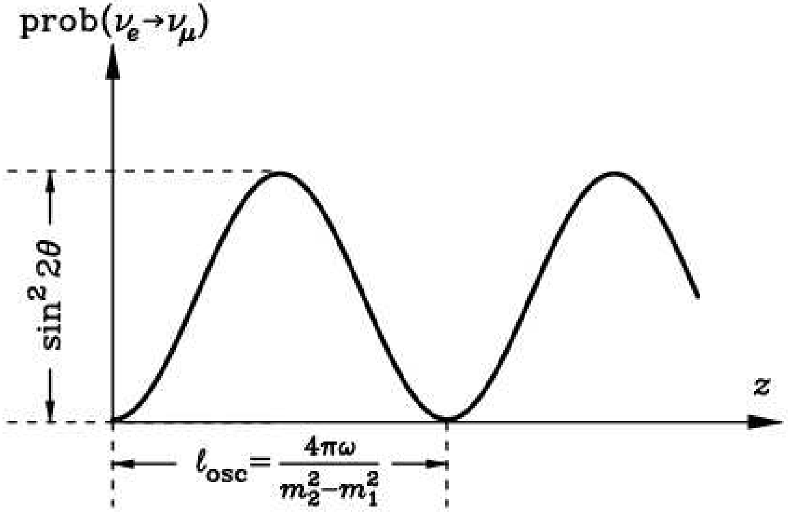
Reminder neutrino oscillation formulae

In vacuum:

$$P_{\alpha\beta} = \sin^2 2\theta \ \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right) \rightarrow \text{appearance}$$

$$P_{\alpha\alpha} = 1 - P_{\alpha\beta} < 1 \rightarrow \text{disappearance}$$

$$\boxed{L_{\text{osc}}(km) = 2\pi \frac{E_\nu(GeV)}{1.27\Delta m^2(eV^2)}}$$



In constant matter density (eg. neutrino beam crossing the mantle of the Earth)

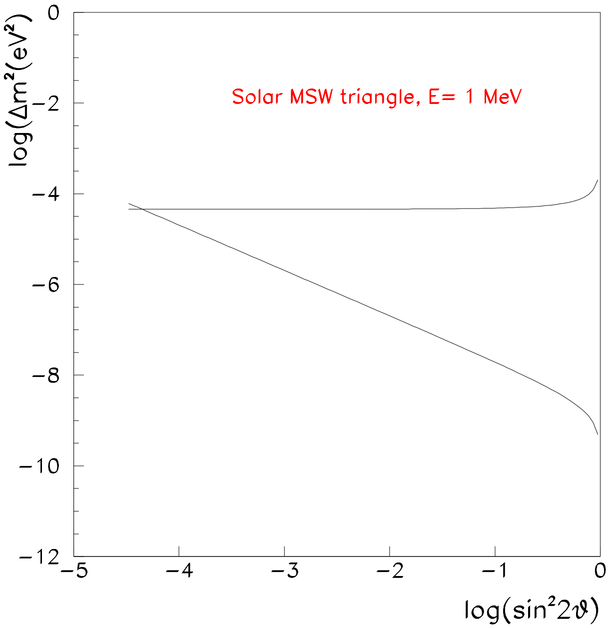
$$\sin^2 2\tilde{\theta} = \frac{\left(\Delta m^2 \sin 2\theta\right)^2}{\left(\Delta m^2 \cos 2\theta \pm 2\sqrt{2}\, G_F E\, N_e\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

$$\Delta \tilde{m}^2 = \sqrt{\left(\Delta m^2 \cos 2\theta \pm 2\sqrt{2} E\, G_F\, N_e\right)^2 + \left(\Delta m^2 \sin 2\theta\right)^2}$$

$$\boxed{N_e^{res} = \frac{|\Delta m^2 \cos 2\theta|}{2\sqrt{2} E G_F} \leftrightarrow \sin^2 2\tilde{\theta} = 1}$$

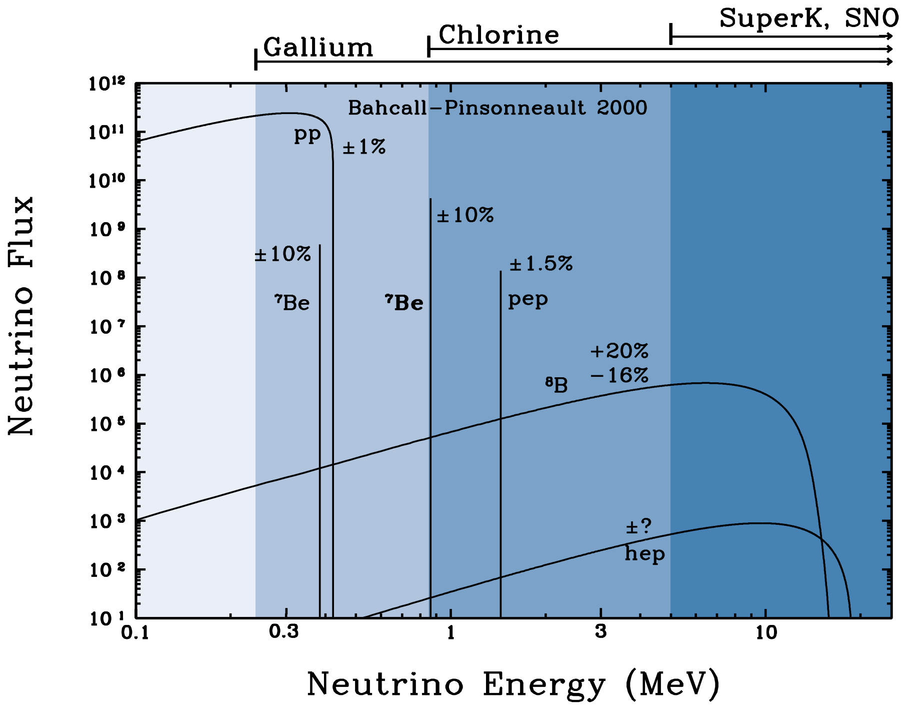
In the variable density (eg. solar or supernova neutrinos):

Inside the MSW triangles, there is maximal flavour transitions for small vacuum mixing angle



Evidence for neutrino oscillations

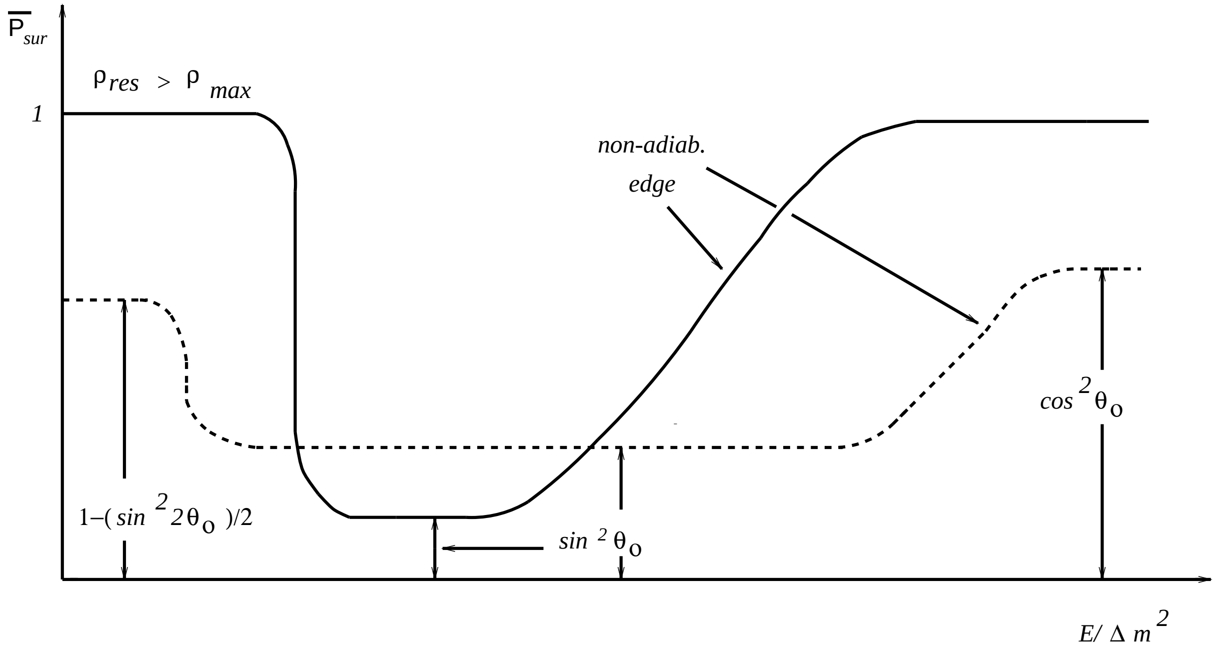
The solar puzzle ν_e deficit



Long history...and a Nobel Prize in 2002 ...for the detection of cosmic neutrinos !

Exp.	Tech.	E_ν^{th}	data/SSM
Homestake ('68)	^{37}Cl(ν, e^-) ^{37}Ar	> 0.81 MeV	0.30(5)
Gallex⊕Sage ('90)	^{71}Ga(ν, e^-) ^{71}Ge	> 0.23 MeV	0.58(6)
K⟶SK ('95)	Cerenkov	> 6.5 MeV	0.39(6)
SNO ('99)	Cerenkov	> 6.75 MeV	0.29(5)

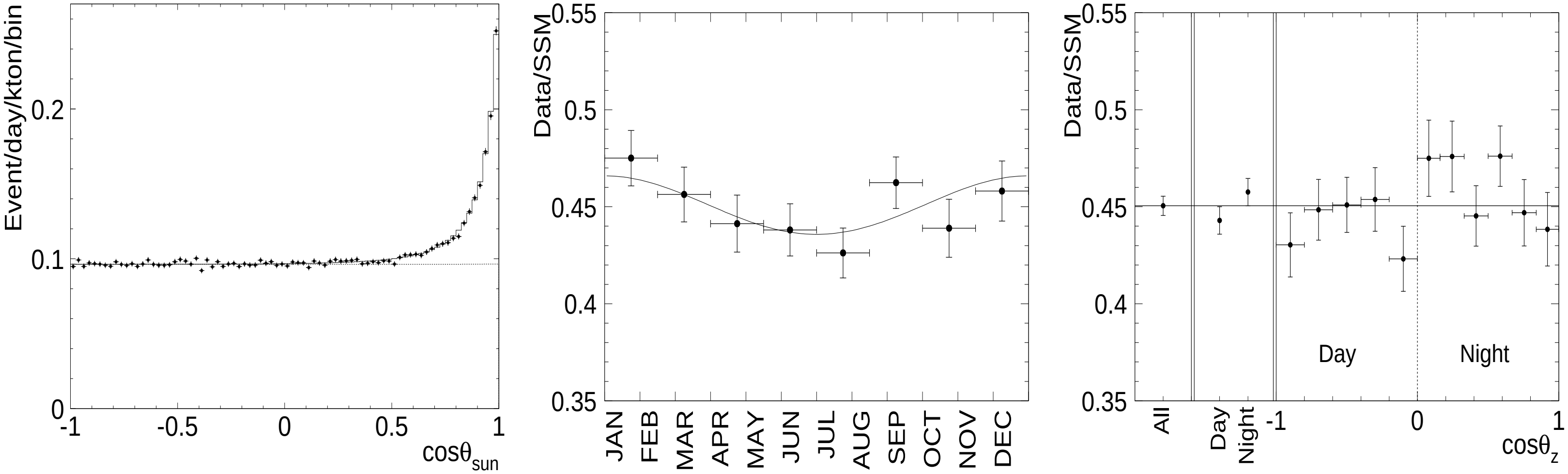
Energy dependence of $P(\nu_e \to \nu_e)$ for the sun flux:

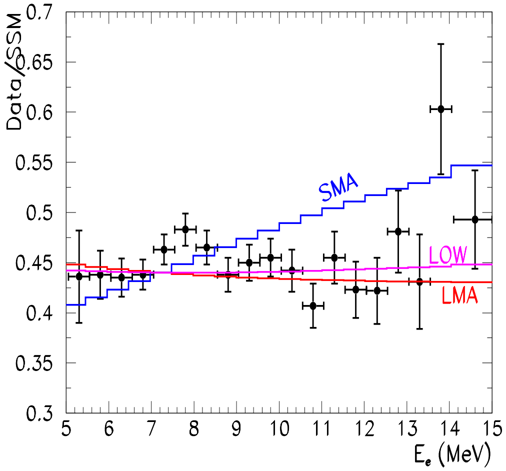


The three recent milestones

SuperKamiokande (since 1998): $\nu_e + e^- \to \nu_e + e^-$

First real time experiment: information on direction and energy of the ν's

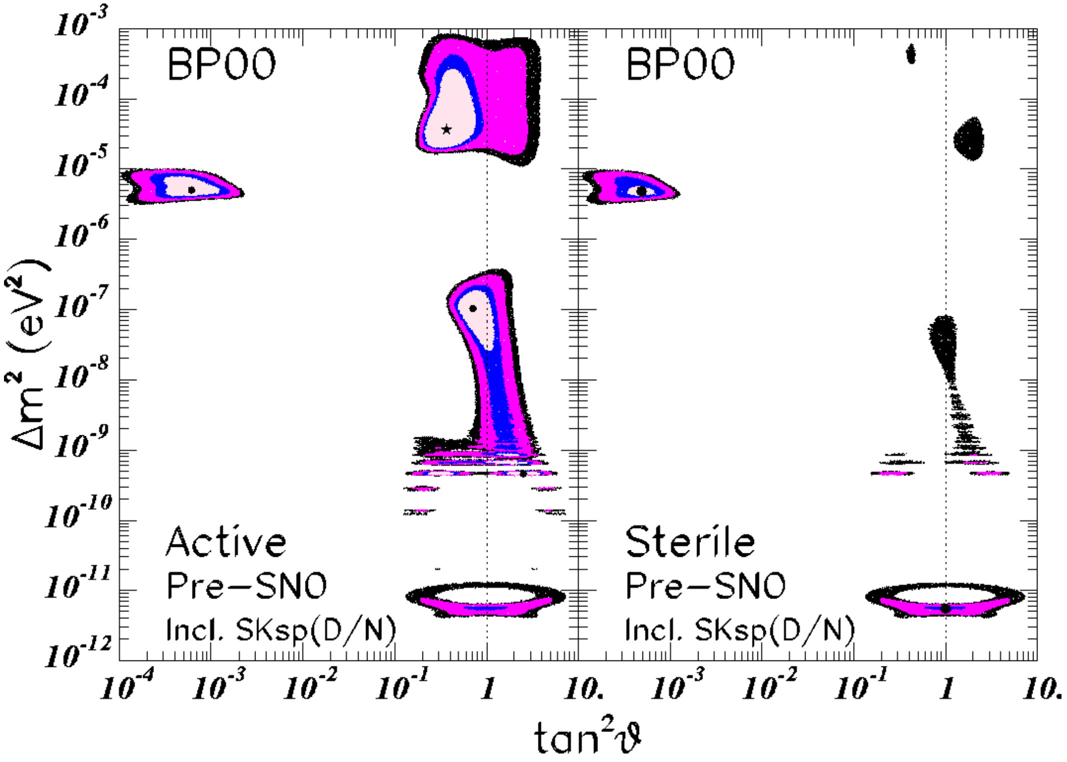


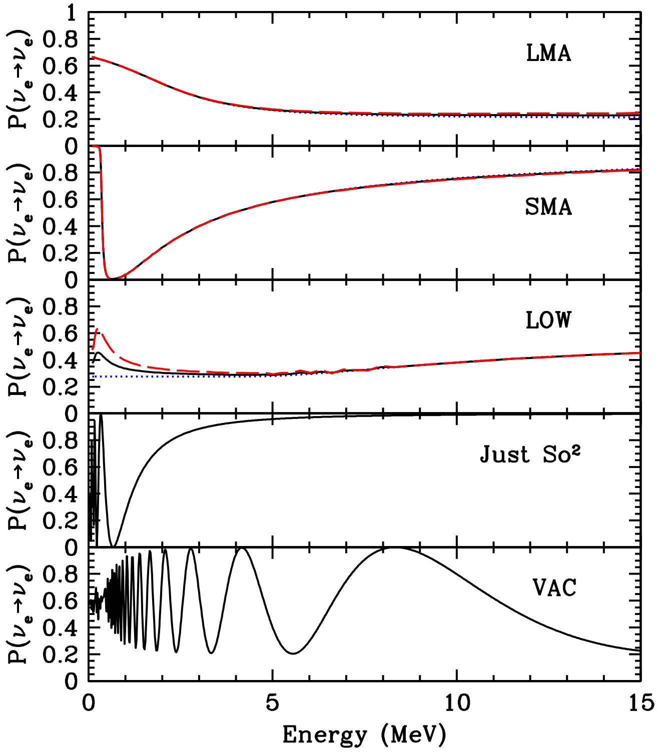


The neutrinos definitely come from the Sun, expected seasonal variation, no spectral distorsion and no significant day-night asymmetry

Global Fits 2000

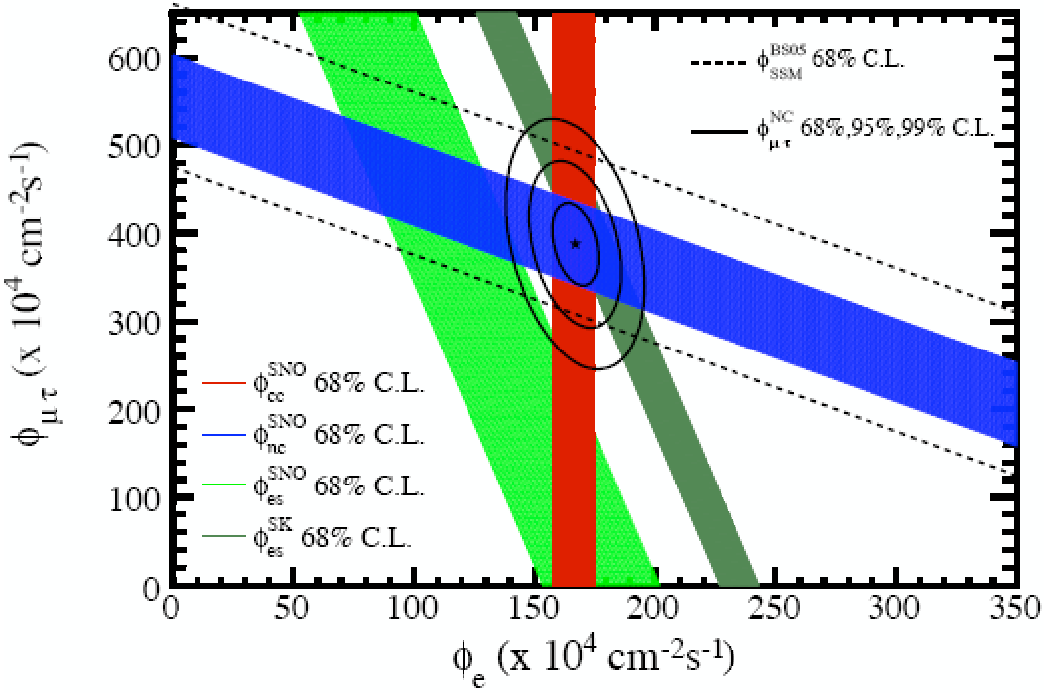
At the beginning the signal was very clear but the situation was rather confusing....





SNO (since 2001):

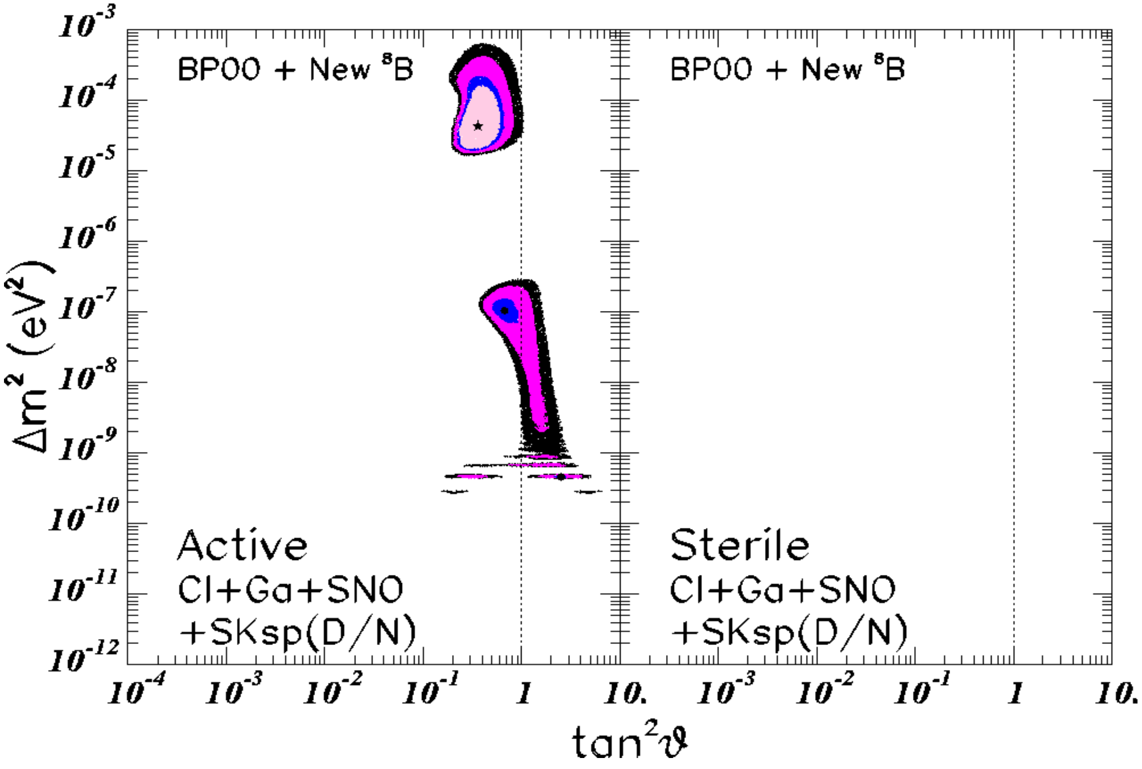
$$\begin{array}{lcr} (CC) & \nu_e + d \rightarrow p + p + e^- & E_{thres} > 5 MeV \\ (NC) & \nu_x + d \rightarrow p + n + \nu_x \quad x = e, \mu, \tau & E_{thres} > 2.2 MeV \end{array}$$



The Sun shines other active species (ν_μ, ν_τ) about two times more than it shines ν_e: the first direct demonstration of flavour transitions in the solar flux (independent on the solar model) !

$\phi^{CC} = 1.67(9) \times 10^6 cm^{-2} s^{-1} \quad \phi^{NC} = 5.54(48) \times 10^6 cm^{-2} s^{-1} \quad \phi^{ES} = 1.77(26) \times 10^6 cm^{-2} s^{-1}$

Global Fits 2002



KamLAND (since 2002):

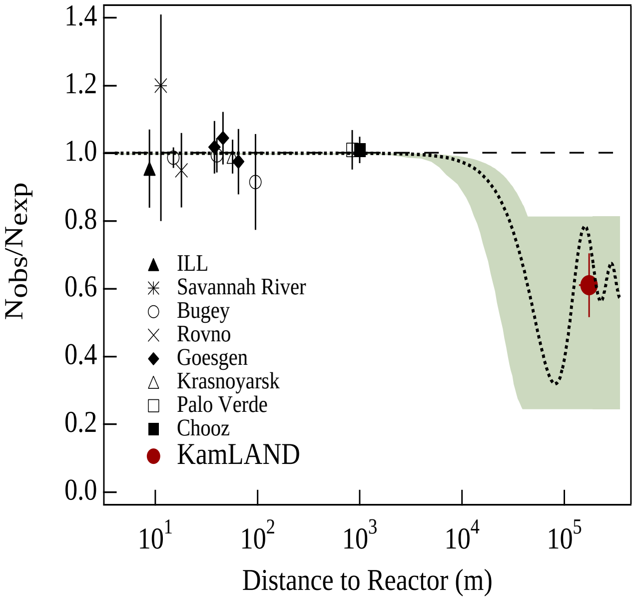
1Kton of liquid scintillator, which measures the flux of reactor neutrinos:

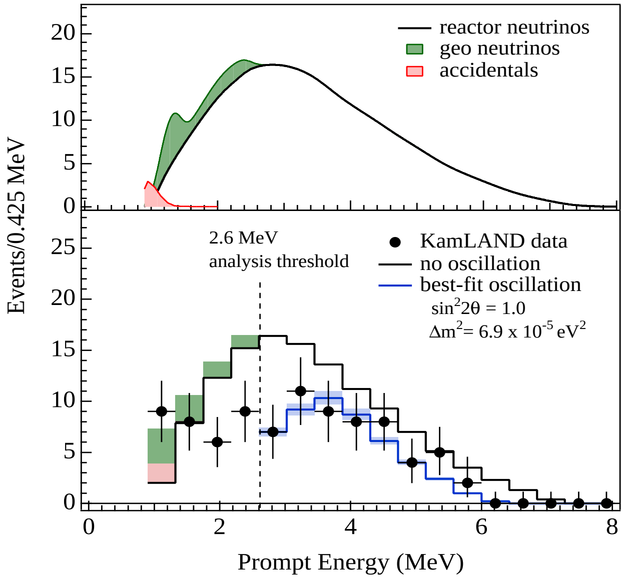
$$\bar{\nu}_e + p \to e^+ + n \qquad E_{th} > 2.6 MeV$$

from a cluster of nuclear plants around Kamioka $\langle L \rangle = O(175)$km

$$\langle E_\nu(\text{MeV})\rangle / L(100km) \sim 10^{-5}\text{eV}^2$$

Very good sensitivity to the LMA-MSW region!

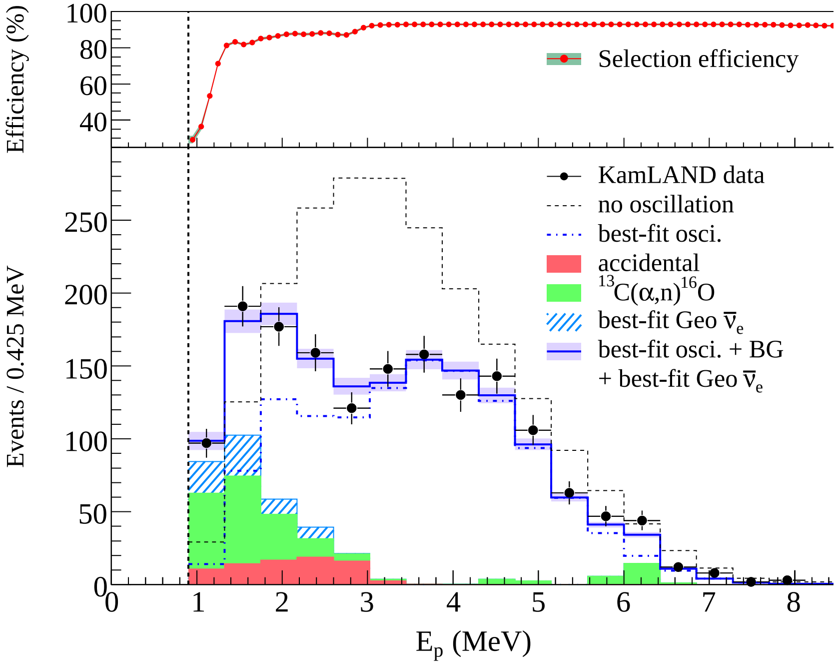


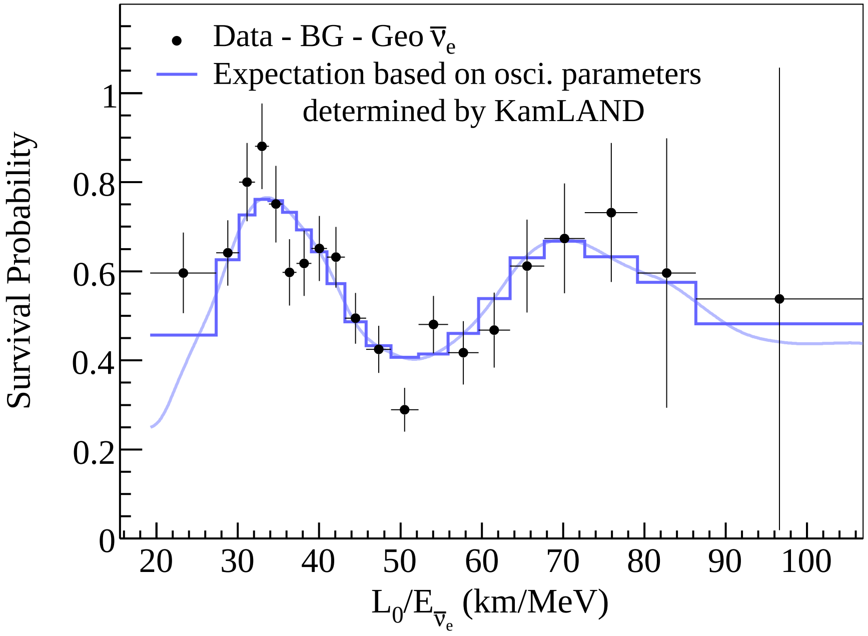


$$\frac{N_{obs}}{N_{exp}} = 0.611 \pm 0.094$$

Reactor fluxes contain less $\bar{\nu}_e$ than expected and show the expected E/L dependence !

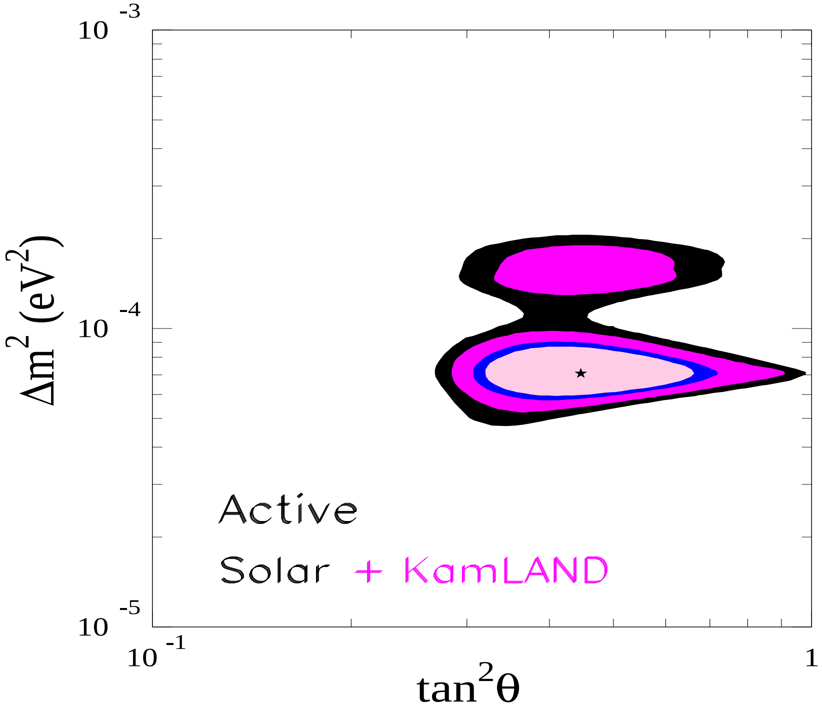
Now with lower threshold they can even measure geo-neutrinos!

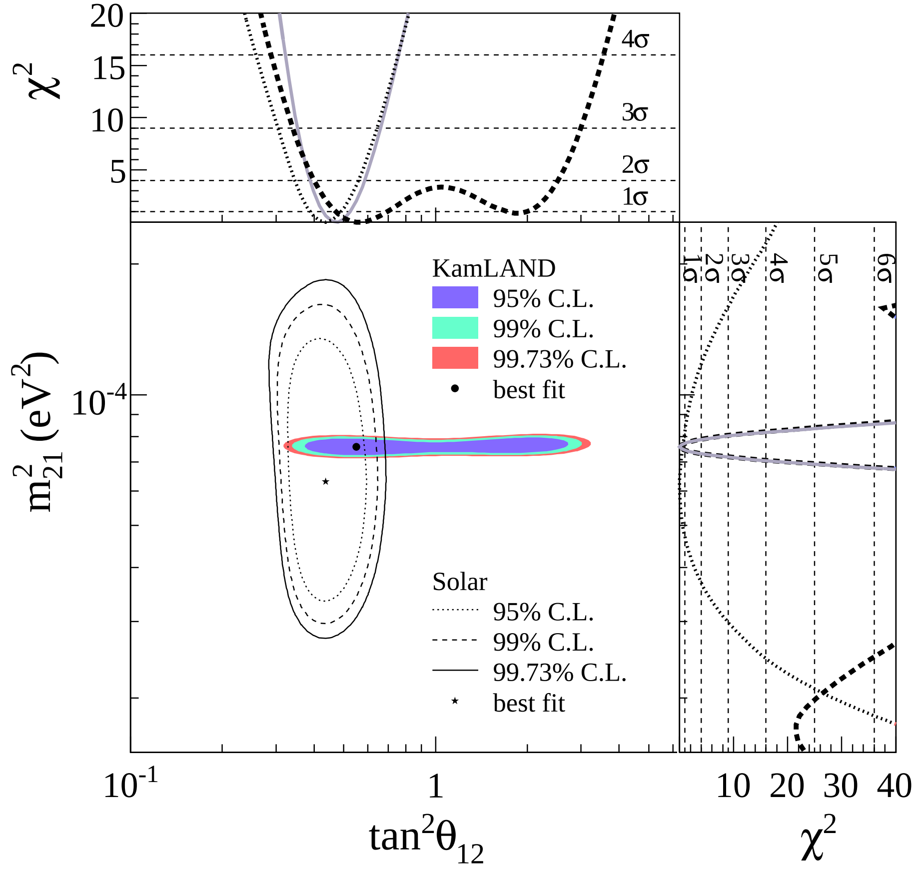




KamLAND Coll.

Global Fits: from 2003 to 2007





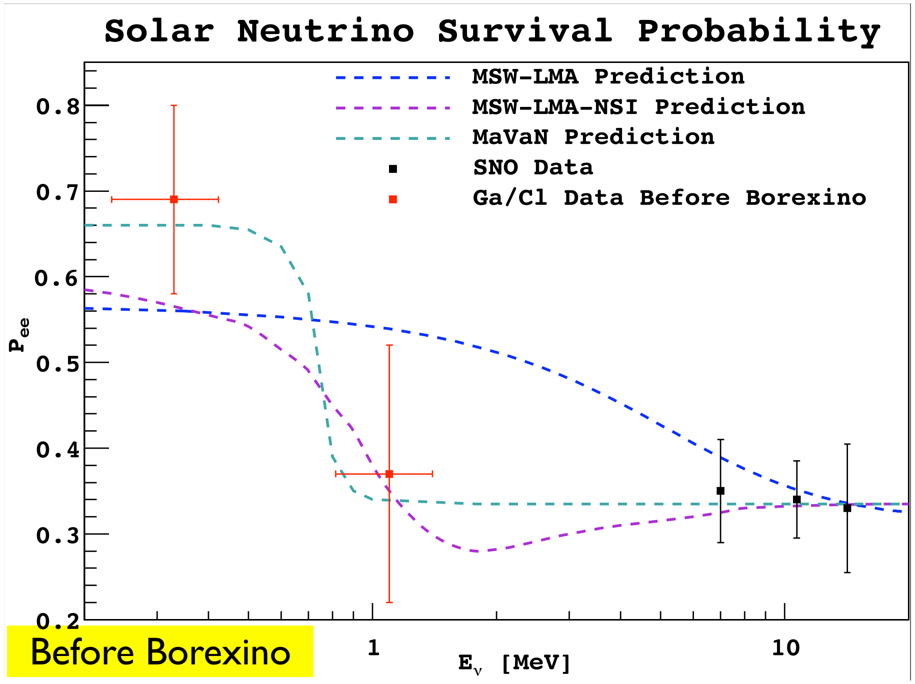
We will see that this solution that makes new discoveries in this field very likely!

Borexino

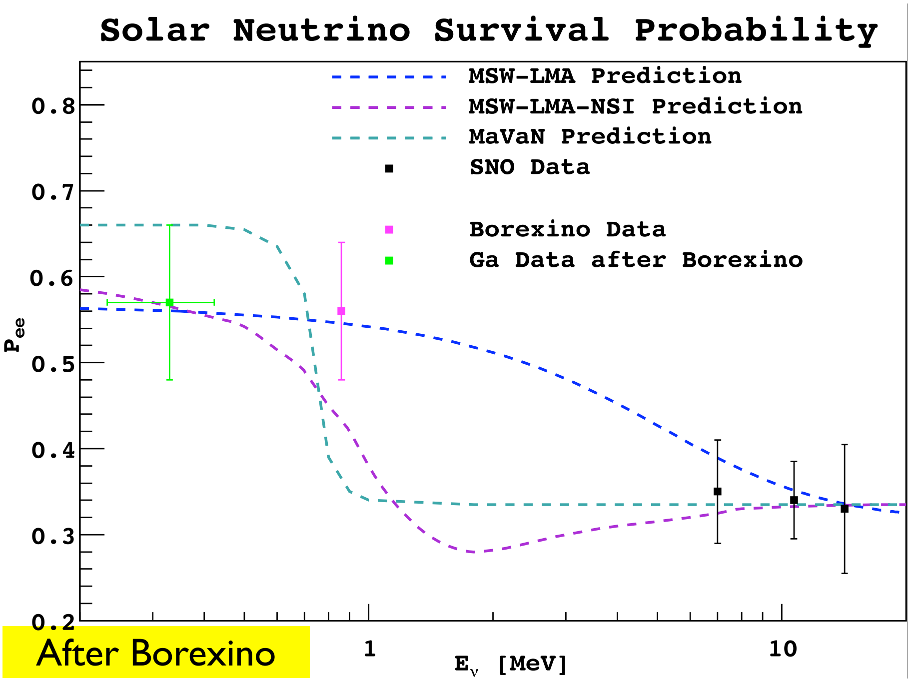
Borexino experiment is the lowest-threshold-real-time solar neutrino experiment that presented first results last year

They gave the first measurement of the ^7Be flux:

$$\Phi(^7Be) = 5.08(25) \times 10^9 cm^{-2} s^{-1}$$



Before Borexino



After Borexino

Solar neutrino experiments have done fundamental discoveries and are now becoming usefull for other applications

- Precise understanding of the Sun from solar neutrino fluxes

- Earth science from geoneutrinos

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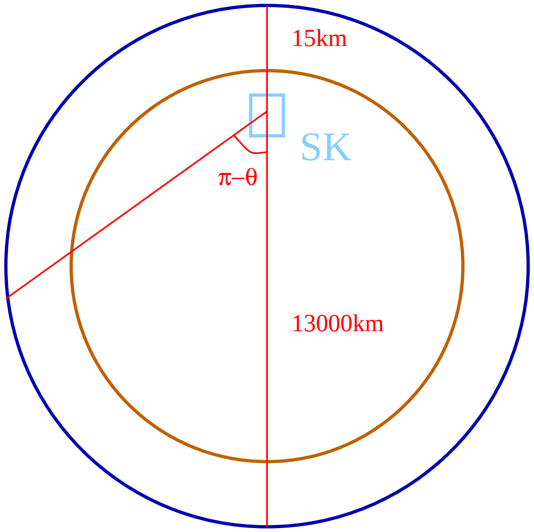
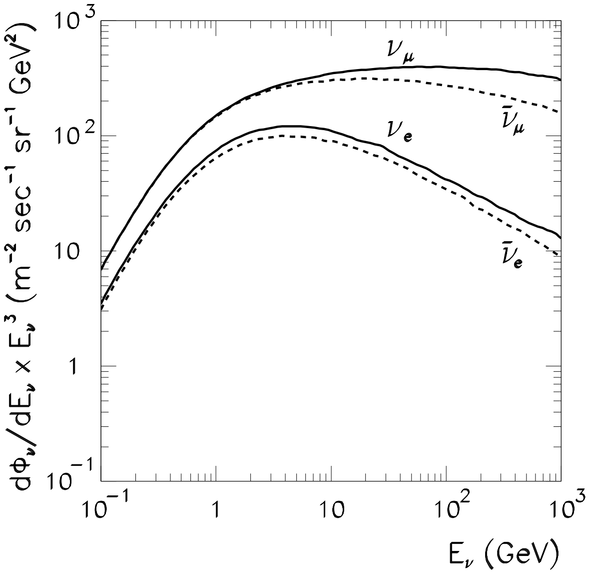
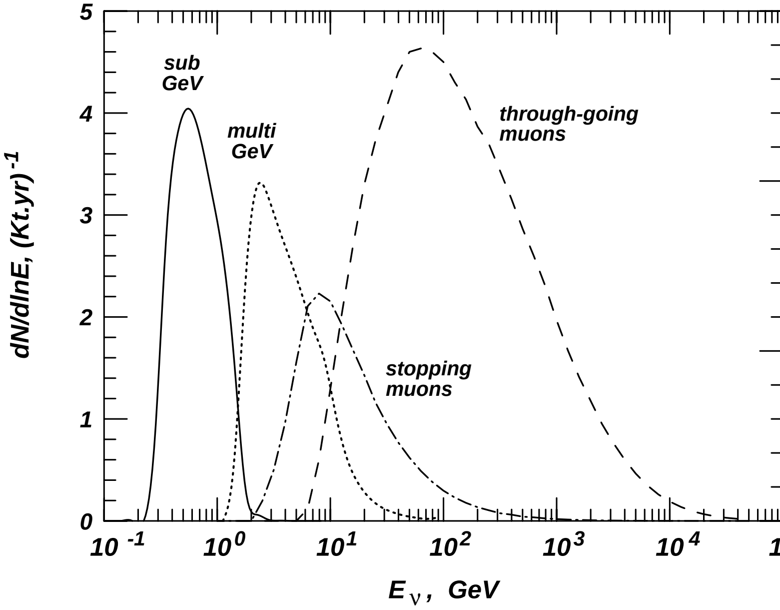
Geoneutrinos reveal Earth's inner secrets

Atmospheric ν anomaly

ν are produced in the atmosphere when primary cosmic rays impinge on it producing K, π which subsequently decay:



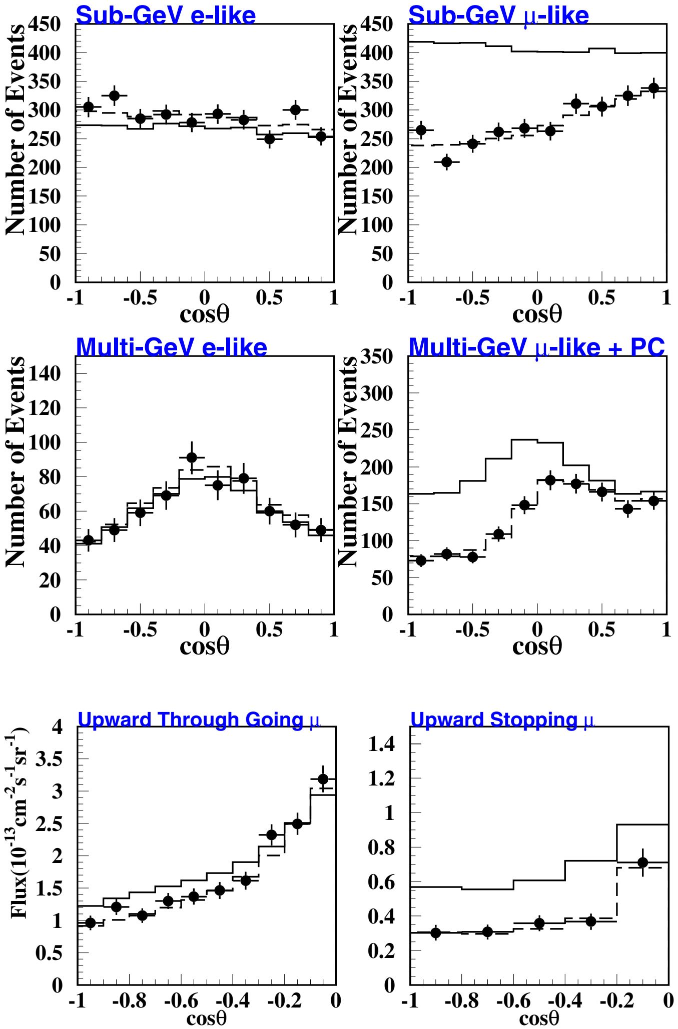




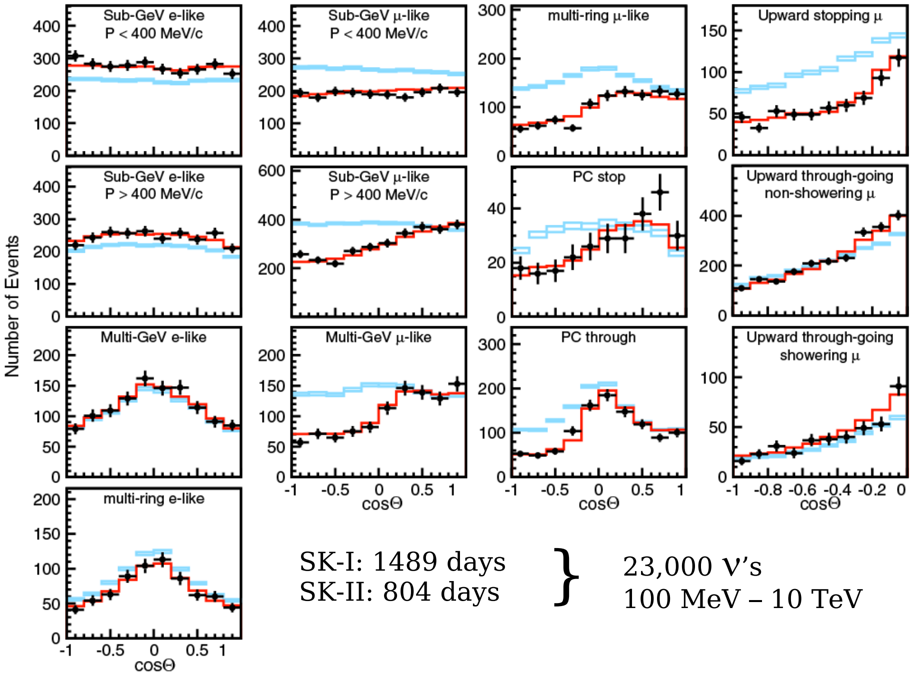
At low energies one expects $N_\mu/N_e \simeq 2$

A deficit was observed in the ratio N_μ/N_e events: Soudan2, IMB, Kamiokande...

SuperKamiokande (since 1998)

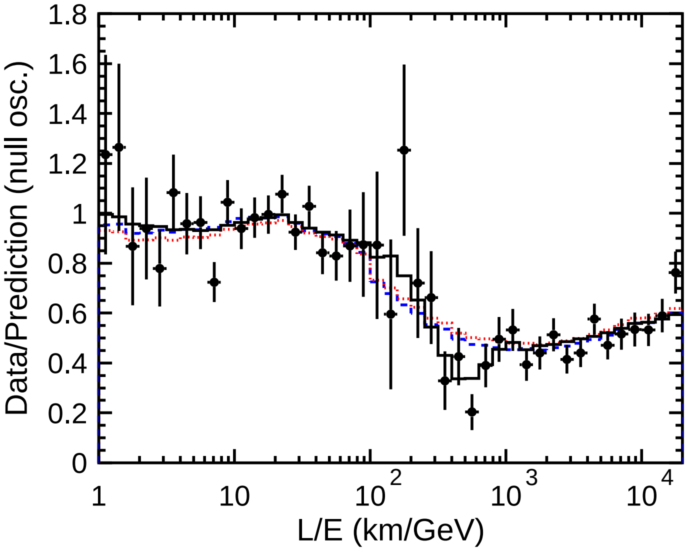


Less $\nu_\mu/\bar{\nu}_\mu$ than expected from below



SK-I: 1489 days
SK-II: 804 days } 23,000 ν's
100 MeV – 10 TeV

Evidence for the expected E/L dependence



Long-baseline Accelerator Neutrino Beams

Confirmation of the oscillation hypothesis in "man-made" ν sources

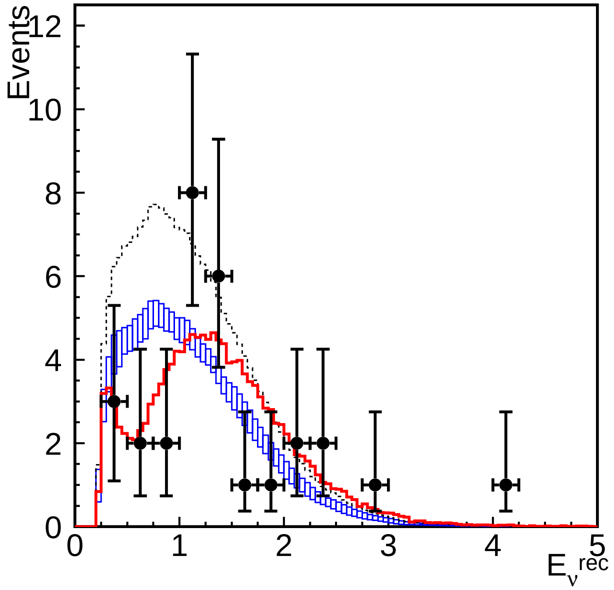
$$|\Delta m^2_{\text{atmos}}| \sim \frac{E_\nu(1-10GeV)}{L(10^2-10^3km)}$$

ν beams in this energy range can easily be produced at accelerators

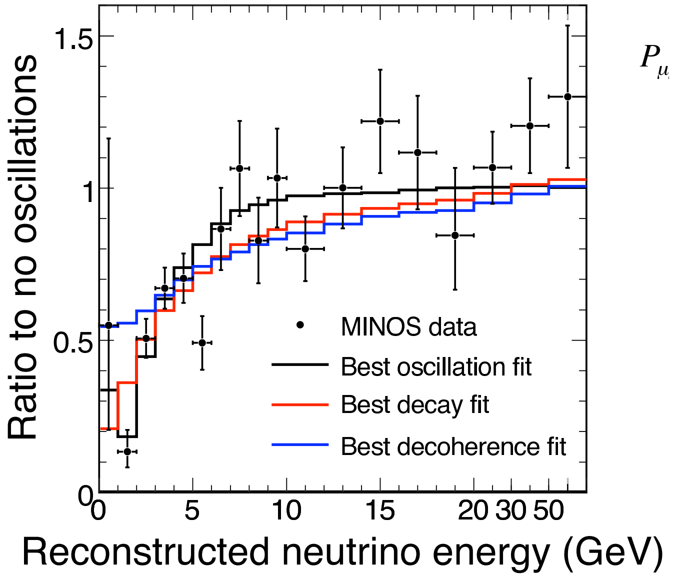
$$\begin{array}{lll} p \quad \longrightarrow \quad \text{Target} \rightarrow \pi^+, K^+ \rightarrow & \nu_\mu \; (\% \; \nu_e, \, \bar{\nu}_\mu, \, \bar{\nu}_e) \\ & \nu_\mu \rightarrow \nu_x \end{array}$$

Three such conventional beams

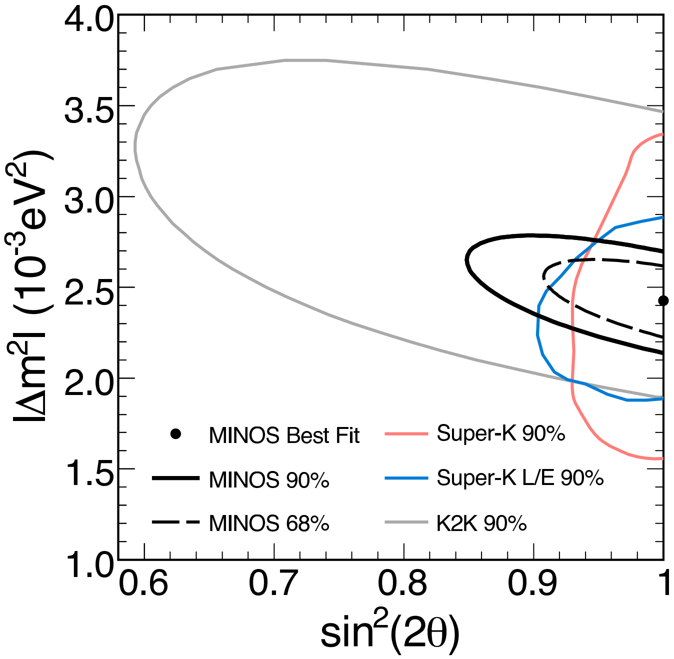
KEK-Kamioka (235km):	K2K	$\nu_\mu \rightarrow \nu_\mu$
Fermilab-Soudan (730km)	MINOS	$\nu_\mu \rightarrow \nu_\mu$
CERN-Gran Sasso (730km)	OPERA	$\nu_\mu \rightarrow \nu_\tau$



K2K $\nu_\mu \rightarrow \nu_\mu$

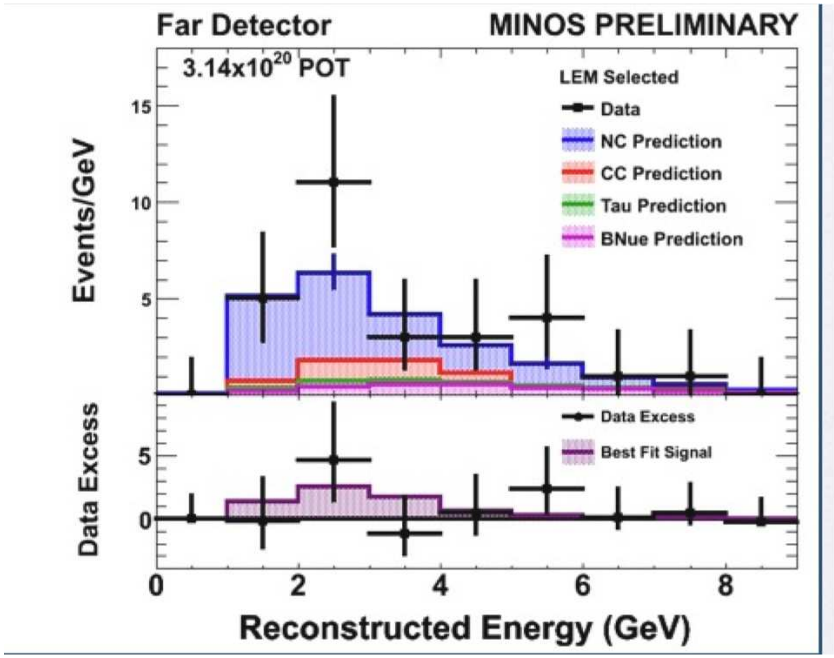


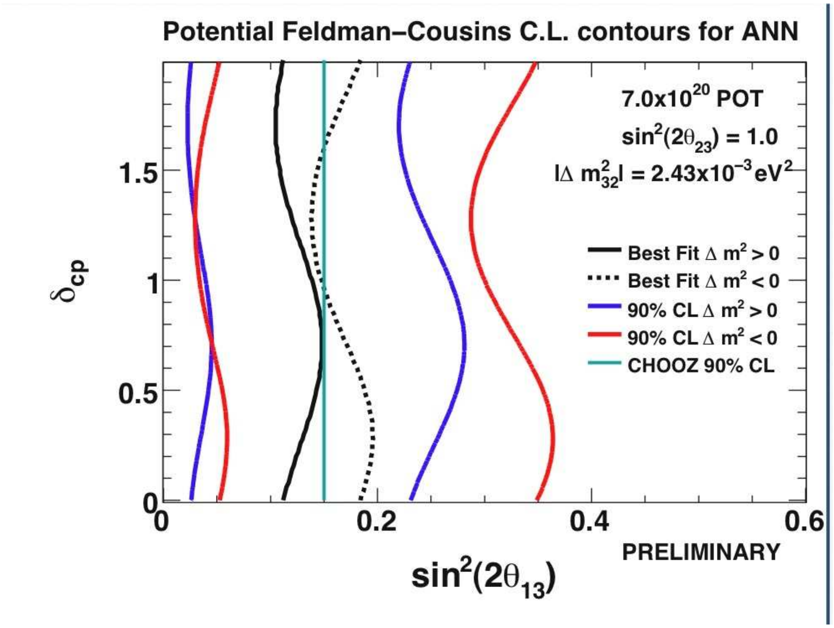
P_μ



MINOS $\nu_\mu \rightarrow \nu_\mu$

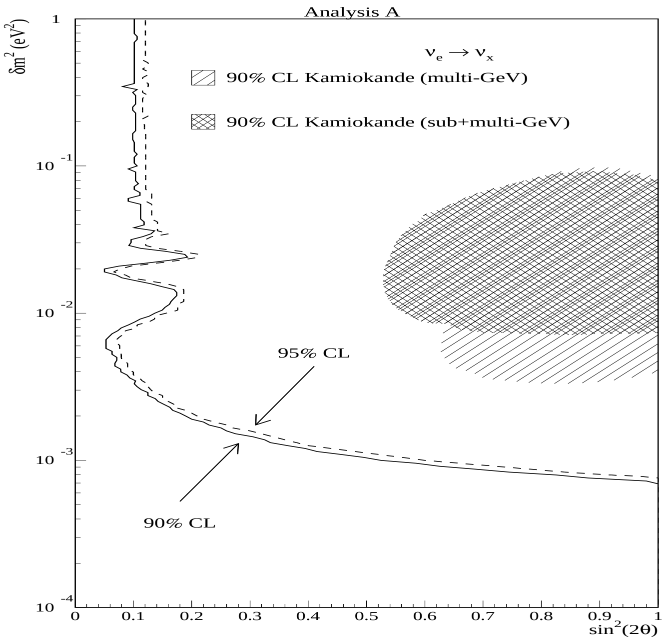
MINOS: $\nu_\mu \to \nu_e$ last month!





CHOOZ: $\bar{\nu}_e \rightarrow \bar{\nu}_e$

Reactor ν experiment at $L \sim 1km$: disappearance $P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1$ in the atmospheric range



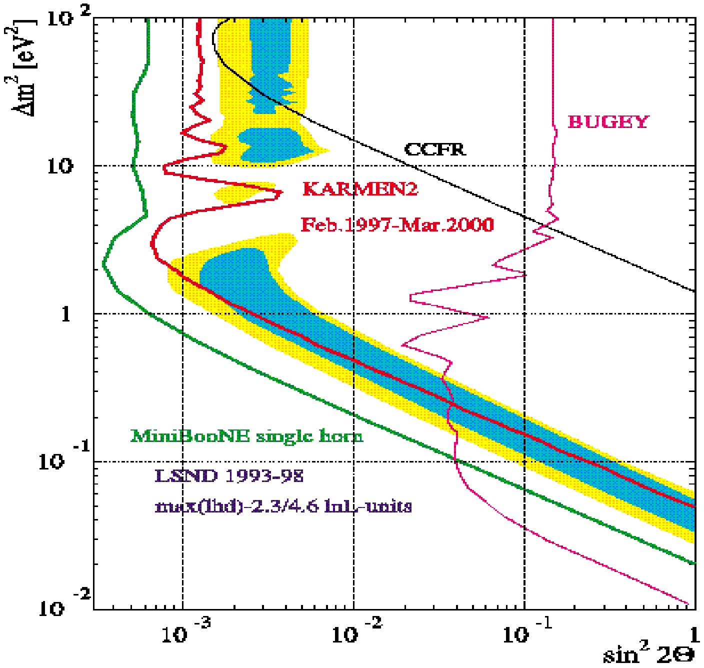
As we will see this negative signal has been essential in figuring out the puzzle: the atmospheric oscillation does not involve ν_e

LSND First positive signal of oscillations in a laboratory ν beam:

$$\begin{array}{llll} \pi^+ \longrightarrow & \mu^+ & \nu_\mu & \\ & & \nu_\mu \longrightarrow \nu_e & \mathrm{DIF}(28 \pm 6/10 \pm 2) \\ & \mu^+ & \longrightarrow e^+\nu_e\bar{\nu}_\mu & \\ & & \qquad \bar{\nu}_\mu \longrightarrow \bar{\nu}_e & \mathrm{DAR}(64 \pm 18/12 \pm 3) \end{array}$$

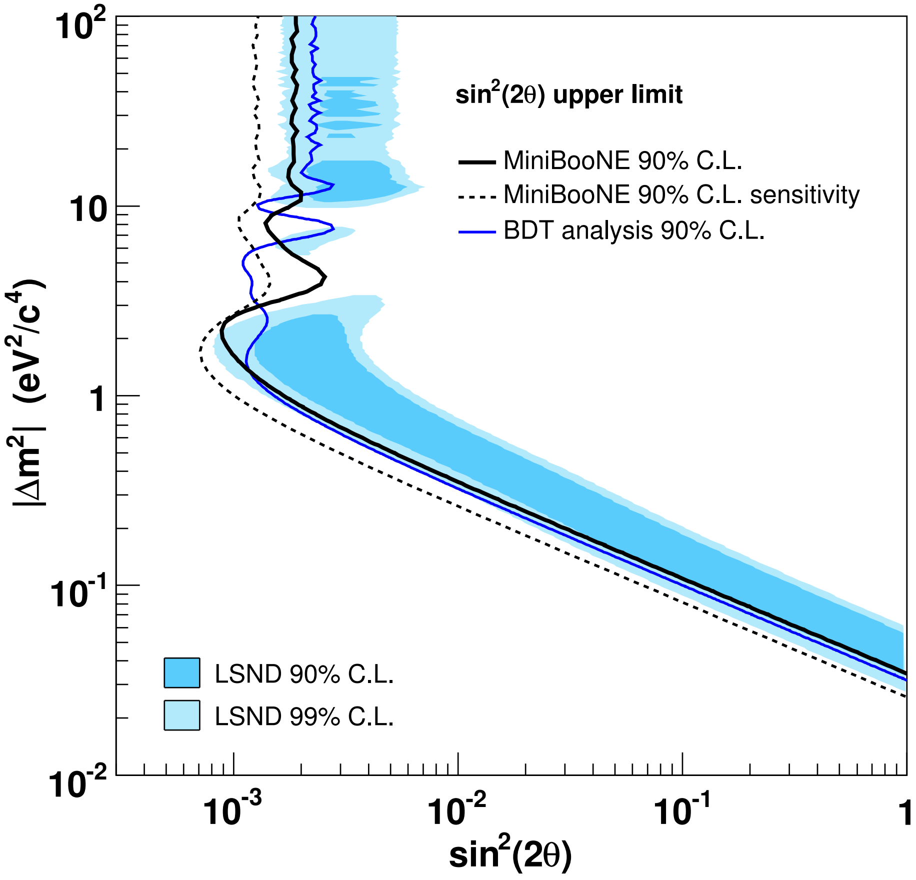
Best fit: $\Delta m^2 = 1.2$ eV^2, $\sin^2 2\theta = 0.003$

But KARMEN ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) did not confirm this signal



MiniBOONE

Last year first (negative) results of an experiment designed to test the LSND anomaly: $\nu_\mu \to \nu_e$



Does all this fit in the SM with massive ν ?

$$\underbrace{|\Delta m^2_{solar}|}_{5\cdot 10^{-5}\mathrm{eV}^2 - 2\cdot 10^{-4}\mathrm{eV}^2} \ll \underbrace{|\Delta m^2_{atmos}|}_{10^{-3}\mathrm{eV}^2 - 6\cdot 10^{-3}\mathrm{eV}^2} \ll \underbrace{|\Delta m^2_{LSND}|}_{0.1 - 1\mathrm{eV}^2}$$

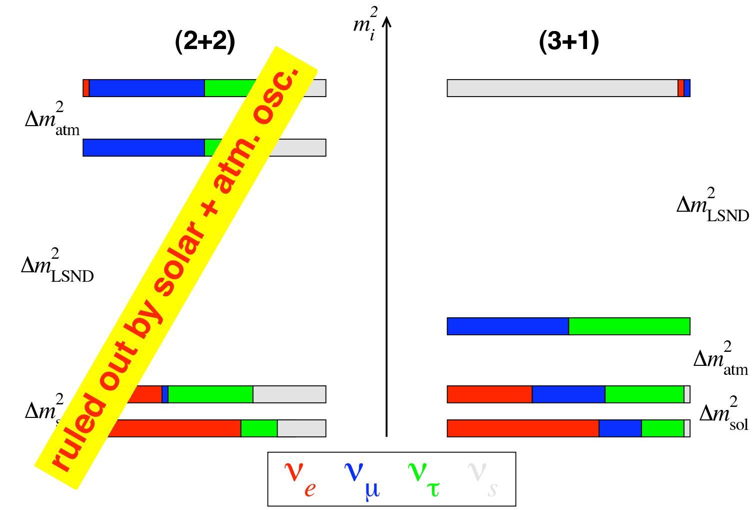
- The mixing of the three standard neutrinos ν_e, ν_μ, ν_τ can only explain two of the anomalies

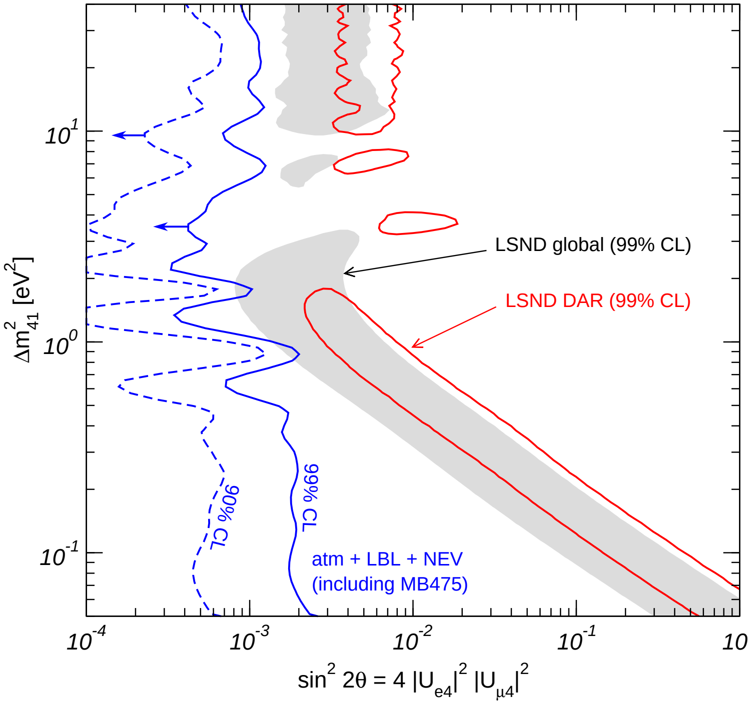
- The explanation of the three set of data requires the existence of a sterile ν species: $N_\nu = 2.984 \pm 0.008$

Fate of light sterile neutrinos and LSND

Before MiniBOONE, there were already problems with models with an extra sterile neutrino

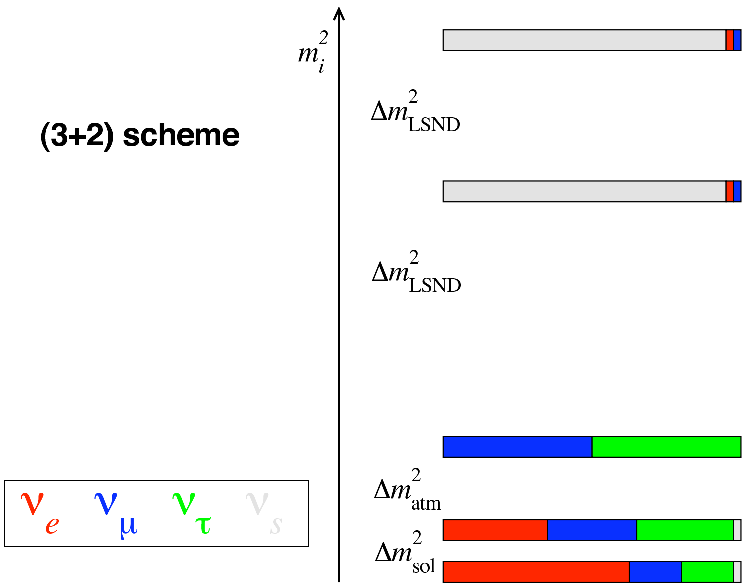
Global analysis of solar $\oplus$ atmospheric $\oplus$ LSND with 4-ν fit the data poorly

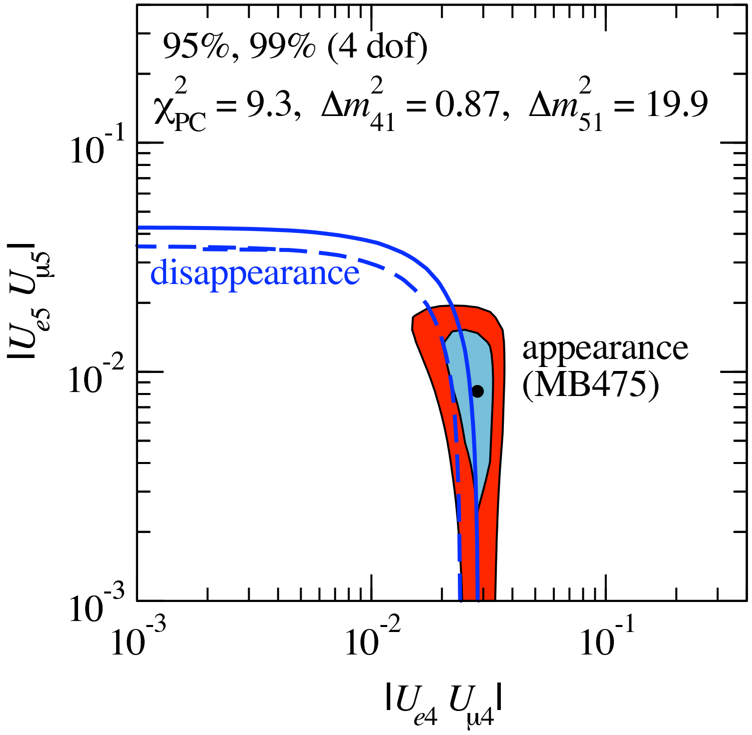




Strong constraints from cosmology: WMAP results: $N_\nu < 4$, $\sum_i m_i < \mathcal{O}(1)eV$

But then people came about with a $3+2$ schemes where CP violation could reconcile LSND with MiniBOONE!





Standard scenario: drop the LSND result

Standard scenario: solar $\oplus$ atmos. with 3-ν

Let us assign:

$$\Delta m^2_{23} = m^2_3 - m^2_2 = \Delta m^2_{atmos}, \qquad \Delta m^2_{12} = m^2_2 - m^2_1 = \Delta m^2_{solar}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{MNS}(\theta_{12}, \theta_{13}, \theta_{23}, \delta) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Solar and atmospheric anomalies approximately decouple as independent 2-by-2 mixing phenomena because

- Hierarchy between the two mass splittings: $|\Delta m^2_{atmos}| \gg |\Delta m^2_{solar}|$
- Small θ_{13}: $\sin\theta_{13} = V_{e3}$

I. $E_\nu/L \sim \Delta m^2_{23}$:

$$\begin{aligned}
P(\nu_e \to \nu_\mu) &= s^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right) \\
P(\nu_e \to \nu_\tau) &= c^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right) \\
P(\nu_\mu \to \nu_\tau) &= c^4_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right) \\
P(\bar\nu_e \to \bar\nu_e) &= 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right)
\end{aligned}$$

Chooz implies θ_{13} unobservably small: in the atmospheric range the leading oscillation is $\nu_\mu \to \nu_\tau$

Experiments in the atmospheric are described approximately by 2-ν mixing with

$$(\Delta m^2_{23}, \theta_{23}) = (\Delta m^2_{atmos}, \theta_{\rm atmos}),$$

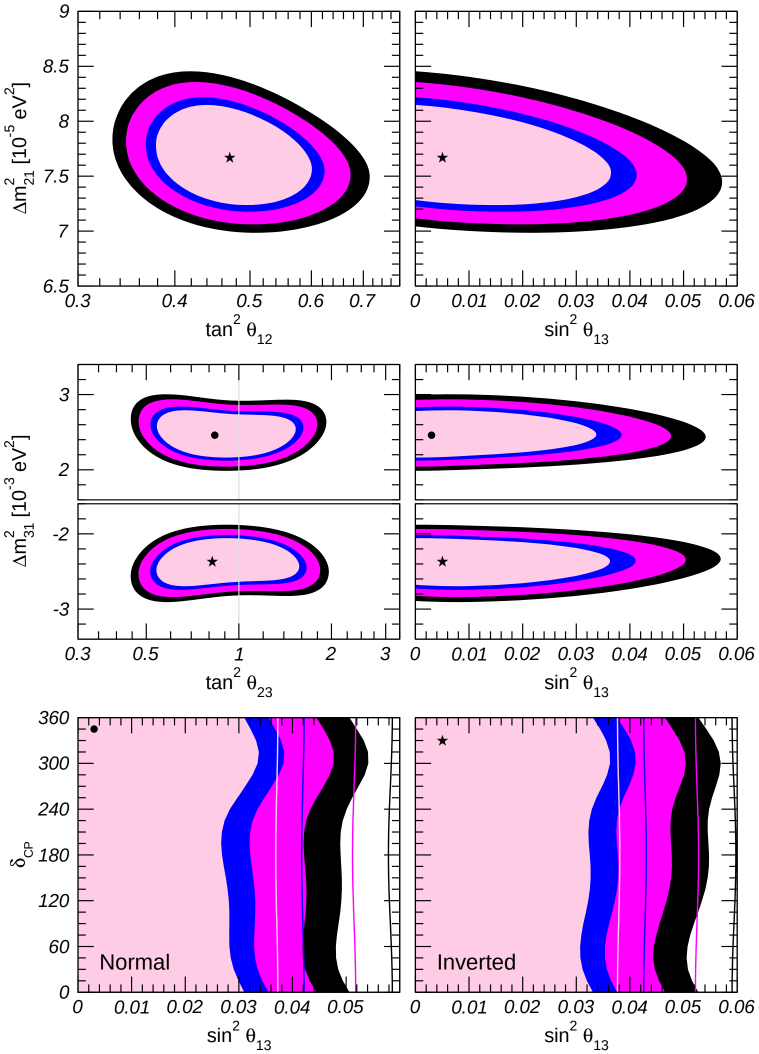
II. $E_\nu/L \sim \Delta m^2_{12}$:

$$P(\nu_e \to \nu_e) \simeq c^4_{13}\left(1 - \sin^2 2\theta_{12}\,\sin^2\left(\frac{\Delta m^2_{12}}{4E}\,L\right)\right) + s^4_{13}$$

Experiments in solar range are described approximately by 2-ν mixing with:

$$(\Delta m^2_{12}, \theta_{12}) = (\Delta m^2_{\mathrm{solar}}, \theta_{\mathrm{solar}})$$

When solar and atmospheric fits are done in the context of three families nothing changes too much



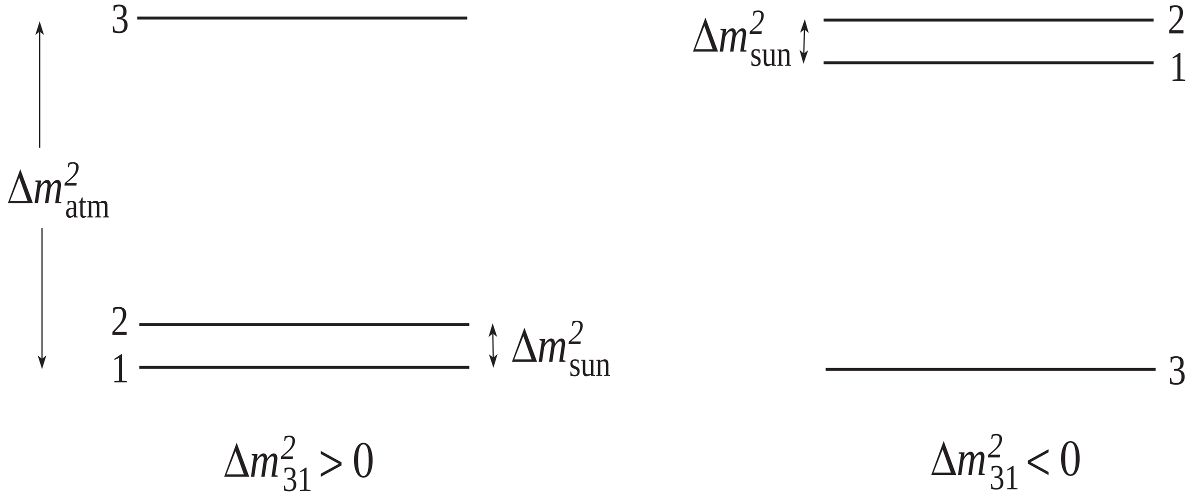
At 2σ:

$$\theta_{23} = 36.9^\circ - 51.3^\circ$$
$$\theta_{12} = 32.3^\circ - 37.8^\circ$$
$$\theta_{13} < 10.3^\circ$$
$$\Delta m^2_{12} = 7.66(35) \times 10^{-5} eV^2$$
$$\Delta m^2_{23} = 2.38(27) \times 10^{-3} eV^2$$

Gonzalez-Garcia, Maltoni

What we know about m_ν and V_{MNS}

ν spectrum:



ν mixing matrix:

$$|V_{MNS}| \simeq \begin{pmatrix} 0.77-0.86 & 0.5-0.63 & 0-0.22 \\ 0.22-0.56 & 0.44-0.73 & 0.57-0.80 \\ 0.21-0.55 & 0.40-0.71 & 0.59-0.82 \end{pmatrix}$$

$\theta_{13} \leq 10°$ δ unconstrained

Very different to the quark mixing matrix:

$$V_{CKM} \simeq \begin{pmatrix} 1 & O(\lambda) & O(\lambda^3) \\ O(\lambda) & 1 & O(\lambda^2) \\ O(\lambda^3) & O(\lambda^2) & 1 \end{pmatrix} \quad \lambda \sim 0.2$$

Two striking features:

- Large mixing angles, in particular one is close to maximal
- Near tri-bimaximal mixing pattern

$$V_{tri-bi} \simeq \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

The level of precision is much worse than for the quark sector → some homework to do...