Unbound Neutrino Roadmaps

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Experimental Data : 2006

Experiment	Observable (# Data)	Measured/SM
Chlorine	Average Rate (1)	[CC]=0.30 ± 0.03
SAGE+GALLEX/GNO	Average Rate (1)	[CC]=0.52 ± 0.03
Super-Kamiokande	Zenith Spectrum (44)	[ES]=0.406 ± 0.013
SNO (pure D_2O phase)	Day-night Spectrum (34)	[CC]=0.30 ± 0.02
		[ES]=0.41 ± 0.05
		[NC]=0.88 ± 0.11
SNO (salt phase)	Average Rates (3)	[CC]=0.29 ± 0.02
		[ES]=0.41 ± 0.05
		[NC]=0.85 ± 0.08
KamLAND	Spectrum (13)	[CC]= 0.66 ± 0.06
CHOOZ	Spectrum (14)	[CC]= 1.01 ± 0.04
K2K	Spectrum (15)	[CC](ν_μ) = $0.70^{+0.11}_{-0.10}$
MINOS	Spectrum (15)	[CC](ν_μ) = $0.64^{+0.08}_{-0.08}$
Atmospheric	Zenith Angle (55)	[0.5-1.0]

adapted from hep-ph/0406294

2 ν Oscillation Interpretation

“The data of the atmospheric SK and K2K/MINOS experiments are perfectly described if we assume that ν_μ ($\bar{\nu}_\mu$) survival probability has the standard two-neutrino form

$$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = 1 - \frac{1}{2}\sin^2 2\,\theta_{23}\,(1 - \cos\frac{\Delta m^2_{32}\,L}{2E}), \qquad (1)$$

where E is the neutrino energy, L is the distance between neutrino source and neutrino detector and $\Delta m^2_{ik} = m^2_i - m^2_k$ (m_i, m_k are neutrino masses, $m_1 < m_2 < m_3$).

The data of the reactor KamLAND experiment are well described if we assume that oscillations of the reactor $\bar{\nu}_e$'s are driven by Δm^2_{21} and $\bar{\nu}_e$ survival probability has the two-neutrino form

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \frac{1}{2}\sin^2 2\,\theta_{12}\,(1 - \cos\frac{\Delta m^2_{21}\,L}{2E}). \qquad (2)$$

Let us notice that there are the following two reasons, why existing neutrino oscillations data are described by the two-neutrino expressions (1) and (2) :

1.

$$\Delta m^2_{21} \ll \Delta m^2_{32}. \qquad (3)$$

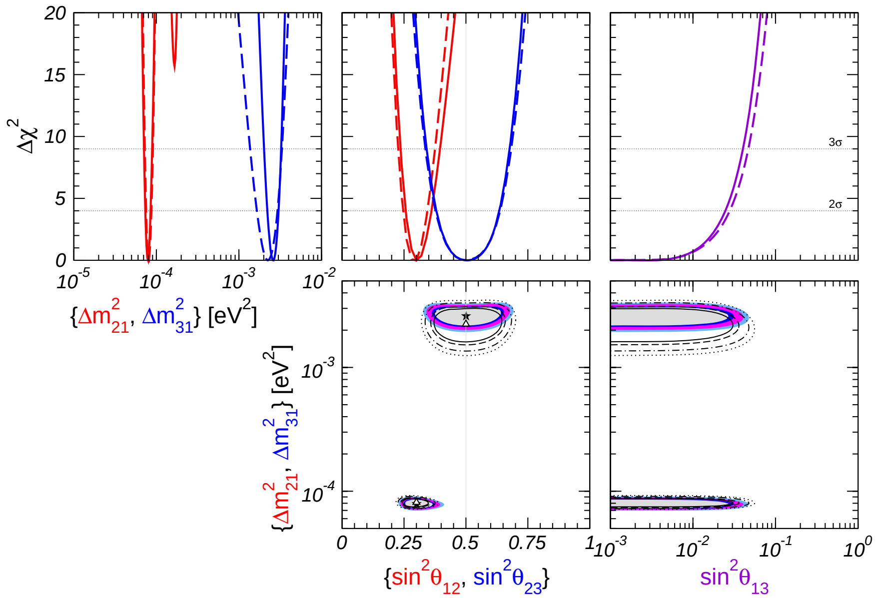
2.

$$|U_{e3}| \ll 1 \qquad (4)$$

This last inequality follows from the negative result of the reactor CHOOZ experiment .”

hep-ph/0411117

Status of global $3\,\nu$ fits: Bilarge



parameter	best fit	2σ	3σ
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	7.9	7.3–8.5	7.1–8.9
$\Delta m^2_{31}\ [10^{-3}\mathrm{eV}^2]$	2.6	2.2–3.0	2.0–3.2
$\sin^2\theta_{12}$	0.30	0.26–0.36	0.24–0.40
$\sin^2\theta_{23}$	0.50	0.38–0.63	0.34–0.68
$\sin^2\theta_{13}$	0.000	$\leq$ 0.025	$\leq$ 0.040

hep-ph/0405172 v5 - 30 june 2006

Some warnings on proposed LBL ν roadmaps

experiment	status	name	start	cost in Meuro
Reactor LBL	approved	Daya Bay	2010	40
Reactor LBL	proposal	Double-CHOOZ	2009	10
Long baseline	approved	T2K	2009	130
Long baseline	proposal	Noνa	2011?	160
Long baseline	proposals	super-beam	2010?	500?
WČ (1000 kton)	proposals	HyperK, UNO?	2015?	500?
Long baseline	discussions	ν factory	2020?	2000?

Table 1: *adapted from hep-ph/0606054*

- time scale are long (order of 10 yr) and costs are high : difficult approval !
- ”precision measurements” in a ν theoretical framework which is not well understood : Why mixing angles are large ? Why lepton mixing is differet from quark mixing ?

add more data : SBL experiments

Experiment	Oscillation Channels
Bugey	$\bar{\nu}_e \longrightarrow \bar{\nu}_e$
CDHS	$\overset{(-)}{\nu}_\mu \longrightarrow \overset{(-)}{\nu}_\mu$
CCFR	$\overset{(-)}{\nu}_\mu \longrightarrow \overset{(-)}{\nu}_\mu, \overset{(-)}{\nu}_\mu \longrightarrow \overset{(-)}{\nu}_e, \overset{(-)}{\nu}_e \longrightarrow \overset{(-)}{\nu}_\tau, \overset{(-)}{\nu}_e \longrightarrow \overset{(-)}{\nu}_e$
LSND	$\bar{\nu}_\mu \longrightarrow \bar{\nu}_e, \nu_\mu \longrightarrow \nu_e$
KARMEN	$\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$
NOMAD	$\nu_\mu \longrightarrow \nu_e, \nu_\mu \longrightarrow \nu_\tau, \nu_e \longrightarrow \nu_\tau$
CHORUS	$\nu_\mu \longrightarrow \nu_\tau, \nu_e \longrightarrow \nu_\tau$
NuTeV	$\overset{(-)}{\nu}_\mu \longrightarrow \overset{(-)}{\nu}_e$

One possible global explanation of the three anomalies (solar - atmospheric - LSND) is that an extra light sterile neutrino generates one of them.

3+1 ν Interpretation

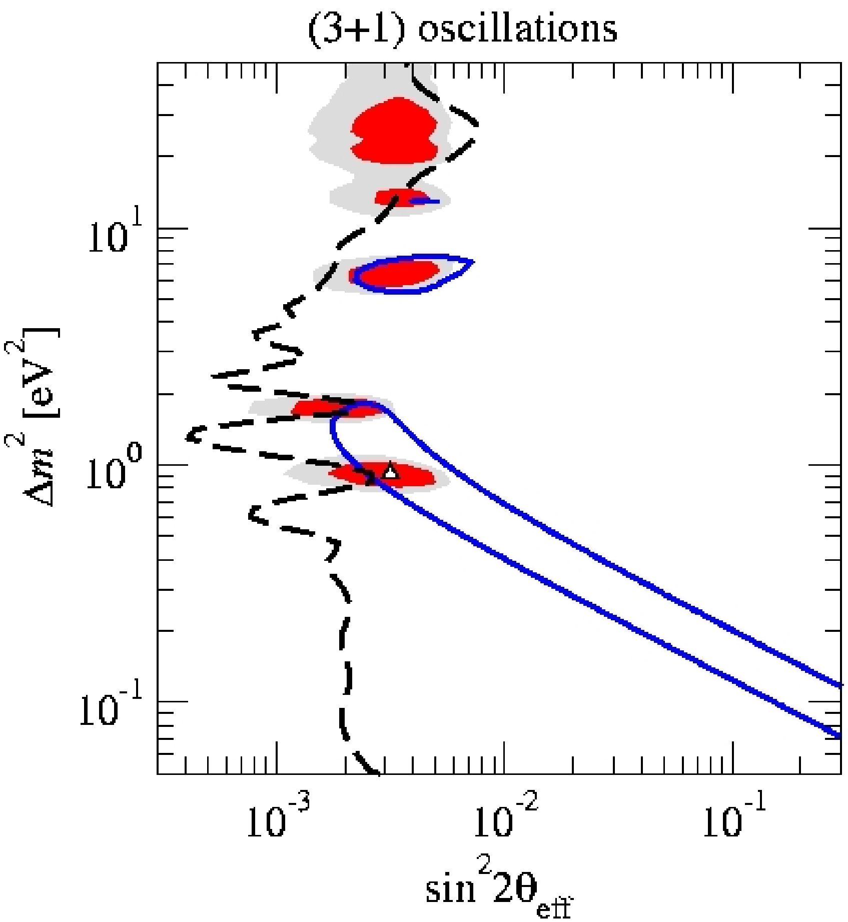
model and number of free parameters		$\Delta\chi^2$	mainly incompatible with	main future test
ideal fit		0		$?$
$3+1: \ \Delta m^2_{\rm sterile} = \Delta m^2_{\rm LSND}$	9	$6+9?$	BUGEY + cosmology?	MINIBOONE
$3+2: \ \Delta m^2_{\rm sterile} = \Delta m^2_{\rm LSND}$	14	$4+9+?$	BUGEY + cosmology?	MINIBOONE
$\Delta L = 2$ decay $\bar{\mu} \to \bar{e}\bar{\nu}_\mu\bar{\nu}_e$	6	$12+6$	KARMEN + TWIST	
3 ν and ~~CPT~~ (no $\Delta\bar{m}^2_{\rm atm}$)	10	20	SK atmospheric	$\bar{\nu}_\mu$ LBL?
3 ν and ~~CPT~~ (no $\Delta\bar{m}^2_{\rm sun}$)	10	25	KamLAND	KamLAND
normal 3 neutrinos	5	25	LSND	MINIBOONE
$2+2: \ \Delta m^2_{\rm sterile} = \Delta m^2_{\rm sun}$	9	40	SNO	SNO
$2+2: \ \Delta m^2_{\rm sterile} = \Delta m^2_{\rm atm}$	9	50	SK atmospheric	ν_μ LBL

Table 2: *Interpretations of solar, atmospheric and LSND data, ordered according to the quality of their global fit. A $\Delta\chi^2 = n^2$ roughly signals an incompatibility at n standard deviations.*

The relatively better global fit is obtained with a 3+1 spectrum (sterile LSND oscillations).

hep-ph/0606054

3+1 ν fit



Allowed regions for LSND+KARMEN (solid) and SBL disappearance+atmospheric neutrino experiments (dashed) at 99% CL, and the combination of these data (shaded regions) at 90% and 99% CL. (hep-ph/0505216)

Bugey : 2 detector limits

B. Achkar et al. / Nuclear Physics B 434 (1995) 503–532 527

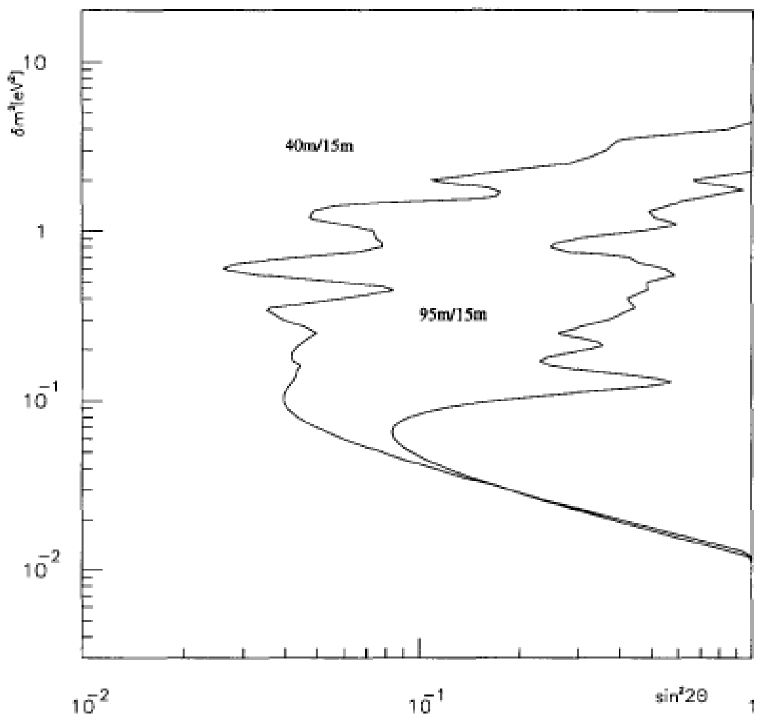


Fig. 16. 90% C.L. exclusion contours obtained from the ratios of the positron energy spectra measured at 40/15 and 95/15 meters.

2 detectors Bugey 90 % C.L. (raster scan) limits do not exclude active-sterile mixing with $\delta m^2 > 5\,\mathrm{eV}^2$

Bugey : high δm^2 limit

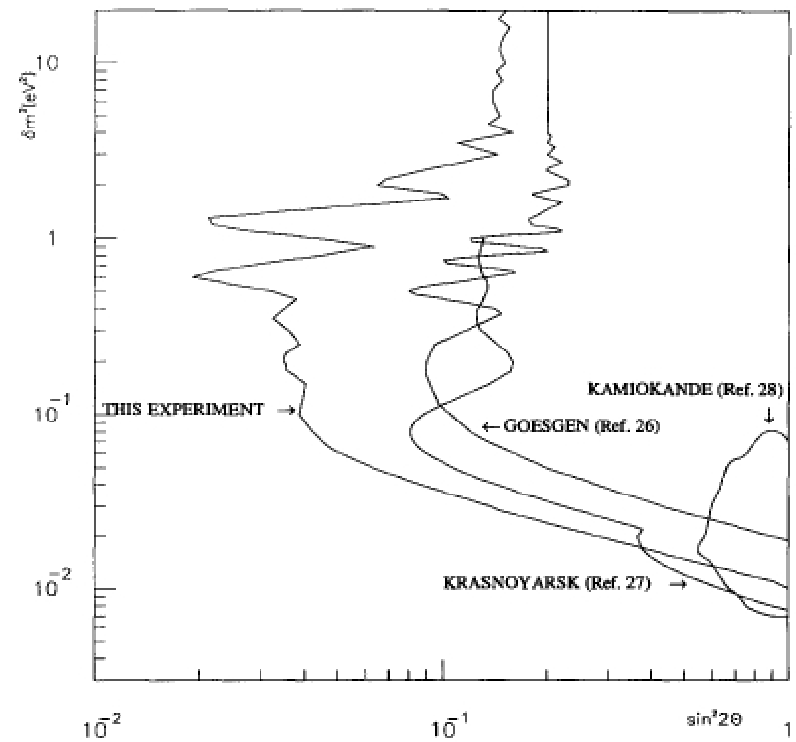
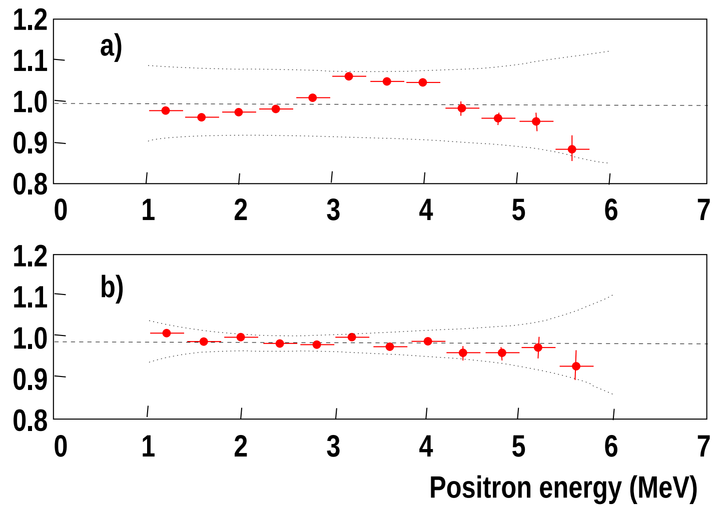


Fig. 18. The 90% C.L. exclusion contour obtained from the positron energy spectra measured at 40, 15 and 95 meters. Also shown is the hitherto excluded area in earlier reactor experiments with the region for a possible ν_e–ν_μ oscillation put forward by the KAMIOKANDE collaboration.

Bugey 90 % C.L. high δm^2 (raster scan) limit do not exclude active-sterile mixing with $\sin^2 2\theta \lesssim 0.15$ if the neutrino flux is **known with 2.8 % error**

Bugey : $\bar{\nu}_e$ flux predictions



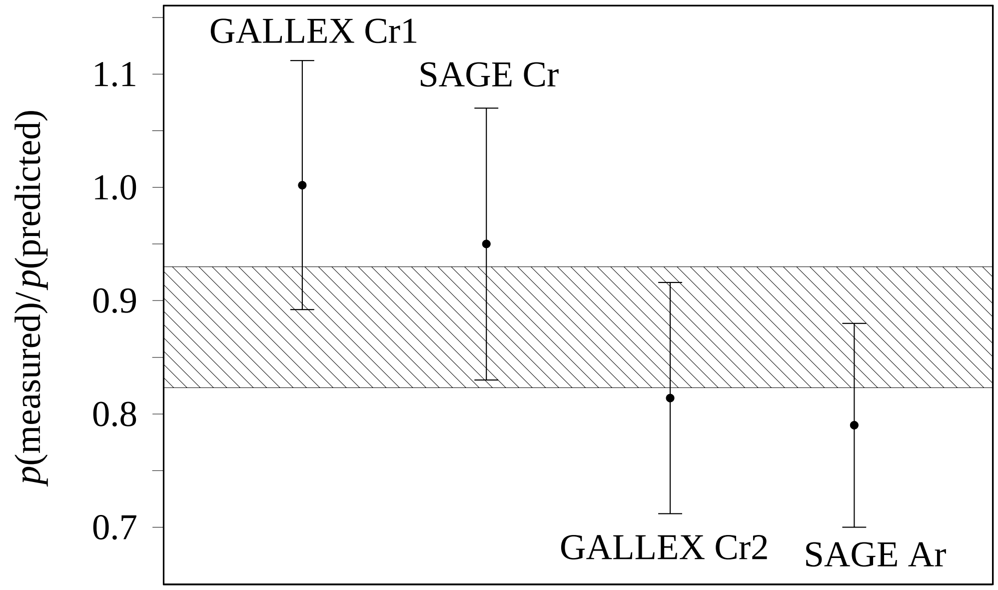
If " The ultimate check of the accuracy of the prediction consists in comparing the results in terms of $\bar{\nu}_e$ energy spectrum with the measurements performed in SBL reactor oscillation experiments." (hep-ph/0107277) **then:**

In **a)** the calculations of Klapdor and Metzinger are rejected because either show an "apparent oscillatory" shape or have bigger systematic errors.

In **b)** the predictions obtained using the β spectra measurements of Schreckenbach and Hahn are preferred.

The dashed envelopes are estimates of the overall systematics.

SBL : another 2σ discrepancy

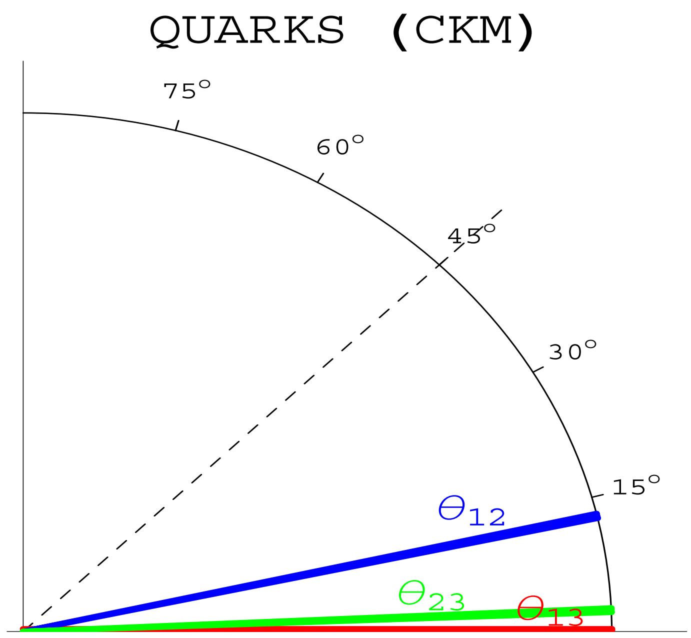


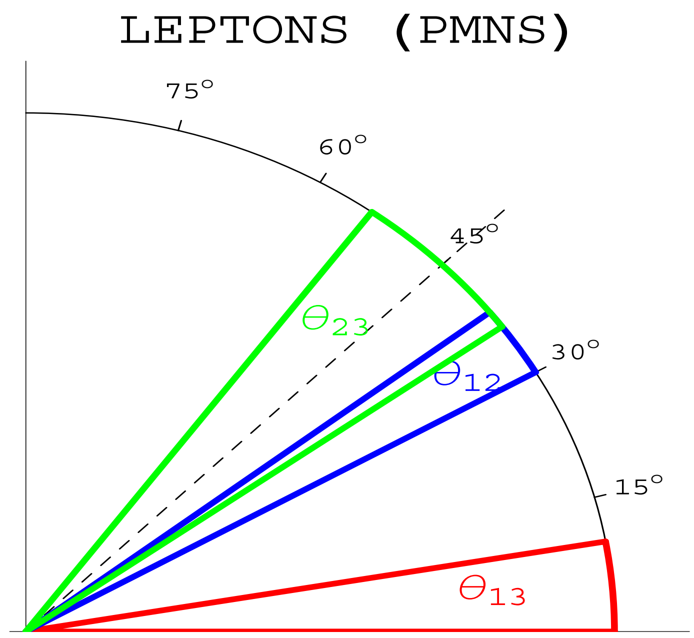
nucl-ex/0512041

combined Ge production rate : $\frac{\text{measured}}{\text{predicted}} = 0.88 \pm 0.05(1\sigma)$

radioactive source exp. at SAGE/GALLEX are consistent with active-sterile mixing and $\sin^2 2\theta \sim 0.2$

WHICH NEUTRINO MIXING ?





Experimental ν mixing angles between active ν are BI-LARGE:

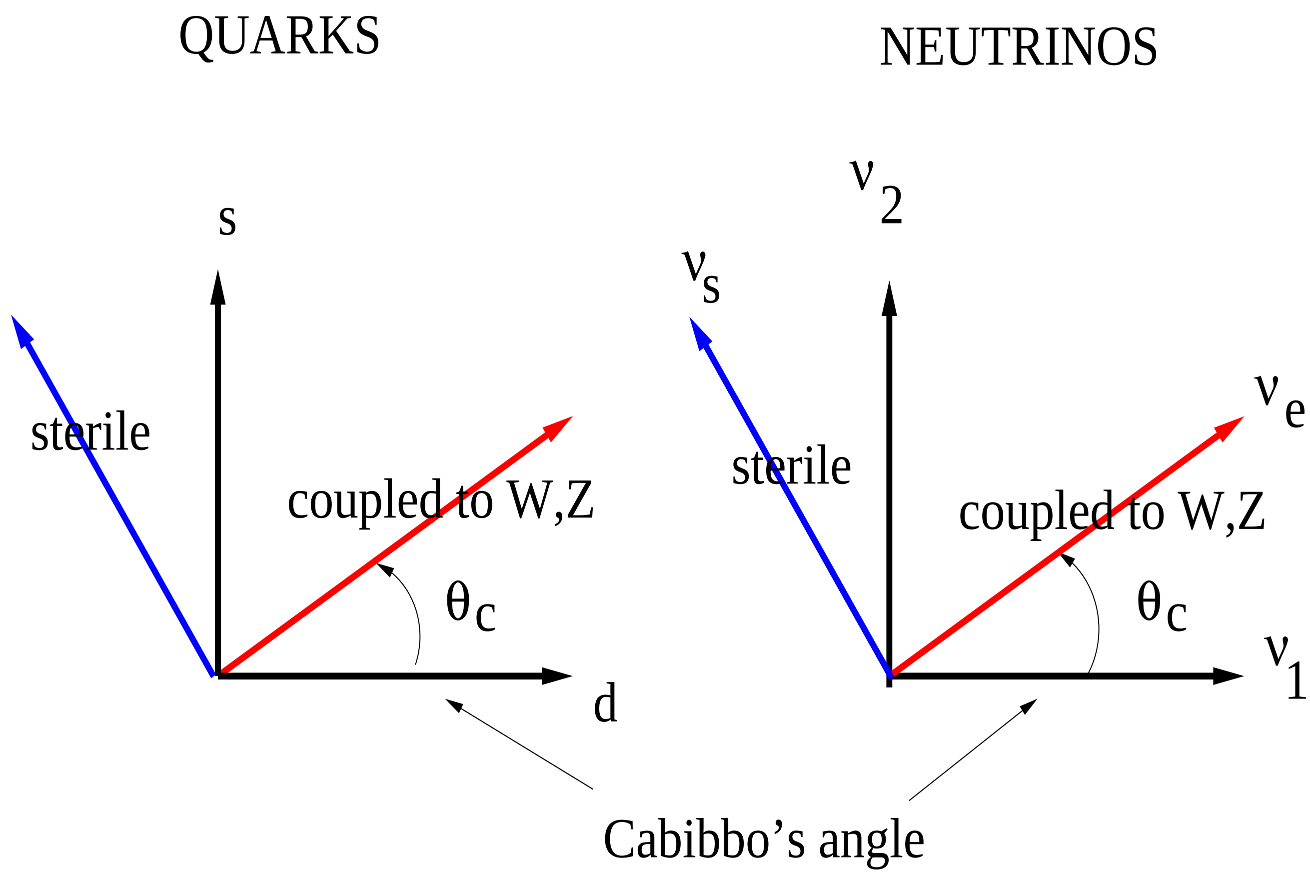
$$\theta_{12} \sim 32^o \qquad \theta_{23} \sim 45^o \qquad \theta_{13} \leq 13^o$$

Authors	Maki Nakagawa Sakata (1962)
Type of oscillation	$\nu_\mu \longrightarrow \nu_e$
Neutrino Mixing	$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} c & s \\ -s & c \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$
Reference is Quark Mixing	$\begin{pmatrix} d^{'} \\ s^{'} \end{pmatrix} = \begin{pmatrix} c & s \\ -s & c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$
Particles	fermions - elementary particles
Mixing angle	Cabibbo angle ($\theta_C = 13^o \leftrightarrow$ s = 0.22 = $\sqrt{\frac{m_d}{m_s}}$)
Mass	real
expected ν mixing angle	small

Author	B. Pontecorvo (1968)
Type of oscillation	$\nu_e \longrightarrow \nu_s$
Neutrino Mixing	$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} c & s \\ -s & c \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$
Reference Mixing	$\begin{pmatrix} K^o \\ \bar{K}^o \end{pmatrix} = \begin{pmatrix} c & s \\ -s & c \end{pmatrix} \begin{pmatrix} K_1^o \\ K_2^o \end{pmatrix}$
Particles	bosons - composite particles
Mixing angle	maximun ($\theta = \frac{\pi}{4}$)
Mass	complex
expected ν mixing angle	MAXIMUM

ACTIVE - (light)STERILE ν_e MIXING analogous to Cabibbo mixing?

Type of oscillation	$\nu_e \longrightarrow \nu_s$
Neutrino Mixing	$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} c & s \\ -s & c \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$
Reference is Quark Mixing	$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} c & s \\ -s & c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$
Particles	fermions - elementary particles
Mixing angle	$(\theta_{es} \sim \theta_C = 13^o \leftrightarrow \tan\theta_{es} = \sqrt{\frac{m_1}{m_2}})$?
Mass	real
expected ν mixing angle	small



COMPLEMENTARITY relation :

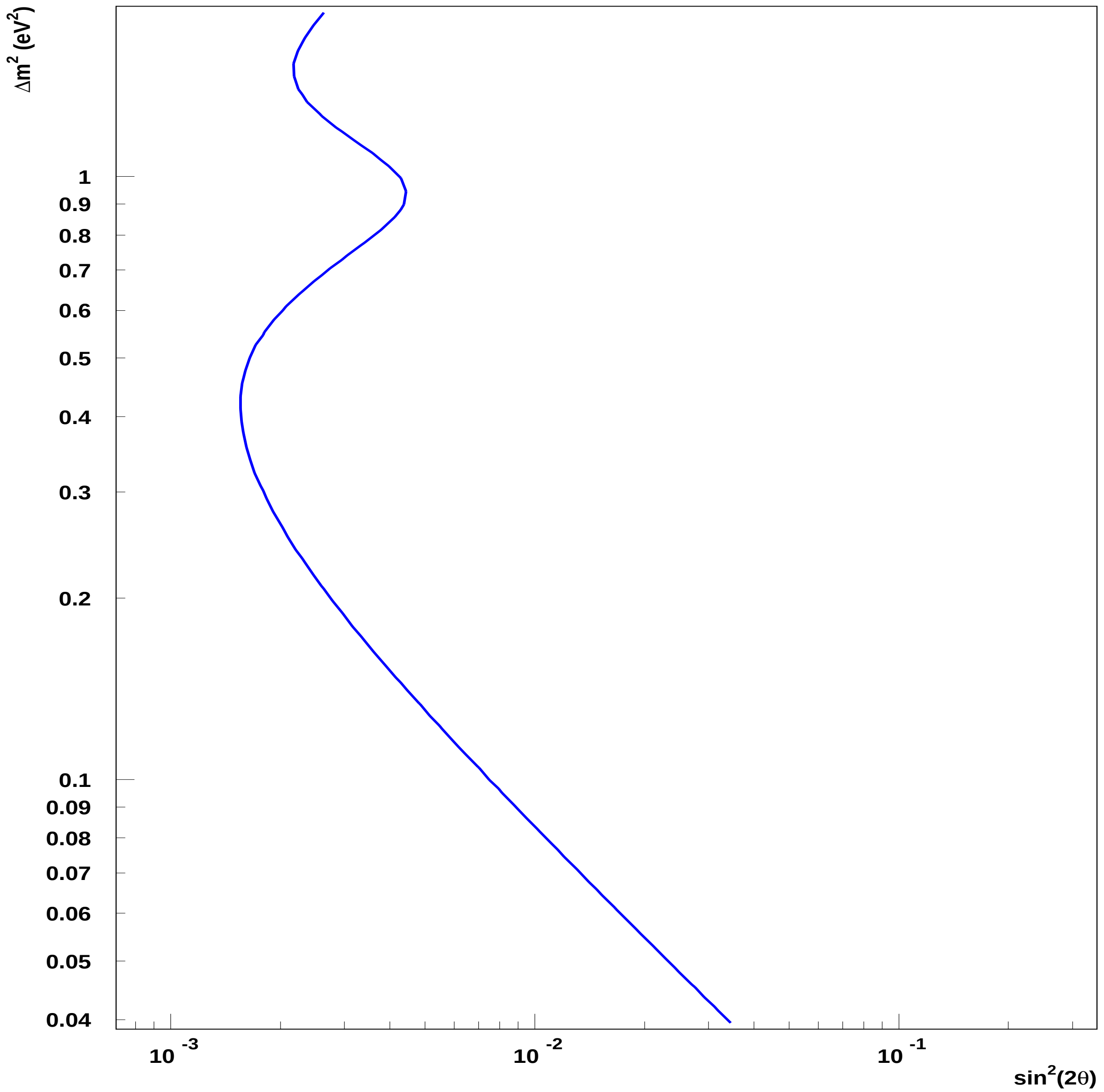
$$\theta_{12} \sim 32^o \qquad \theta_{es} \sim 13^o \qquad \theta_{12} + \theta_{es} = 45^o$$

Future ? Add SBL ν roadmaps !

experiment	status	name	start
Reactor SBL	approved	Daya Bay	2009
Reactor SBL	proposal	Double-CHOOZ	2009
Short baseline	proposal	Boone	2009?
Short baseline	approved	T2K-280 m	2009
Short baseline	approved	T2K-2km	2012
Short baseline	proposal	Noνa	2011?
Short baseline	discussions	beta-beam	2015?

- SBL searches profit of NEAR detectors of LBL studies !
- active-sterile neutrino mixing analogous to Cabibbo quark mixing ?

$90\%C.L.$ Sensitivity of T2K 2km water $\check{C}$ detector



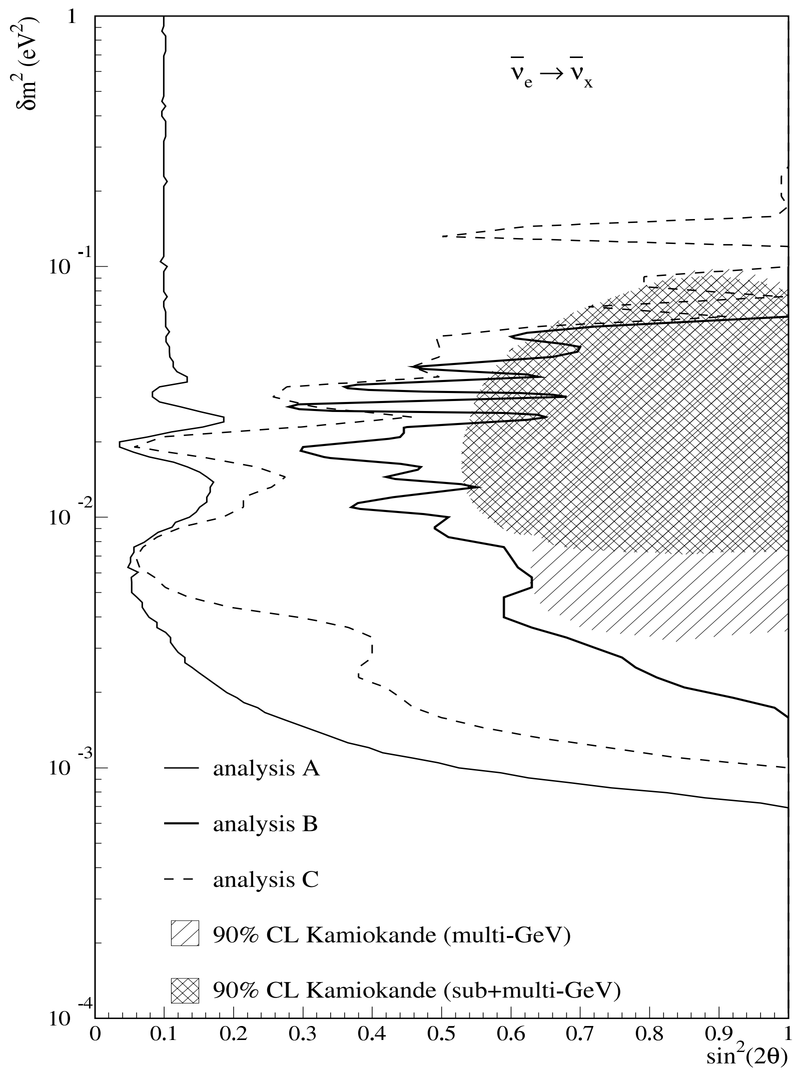
Globes result with $\sigma(syst) = 5\%$ (courtesy from M. Mezzetto)

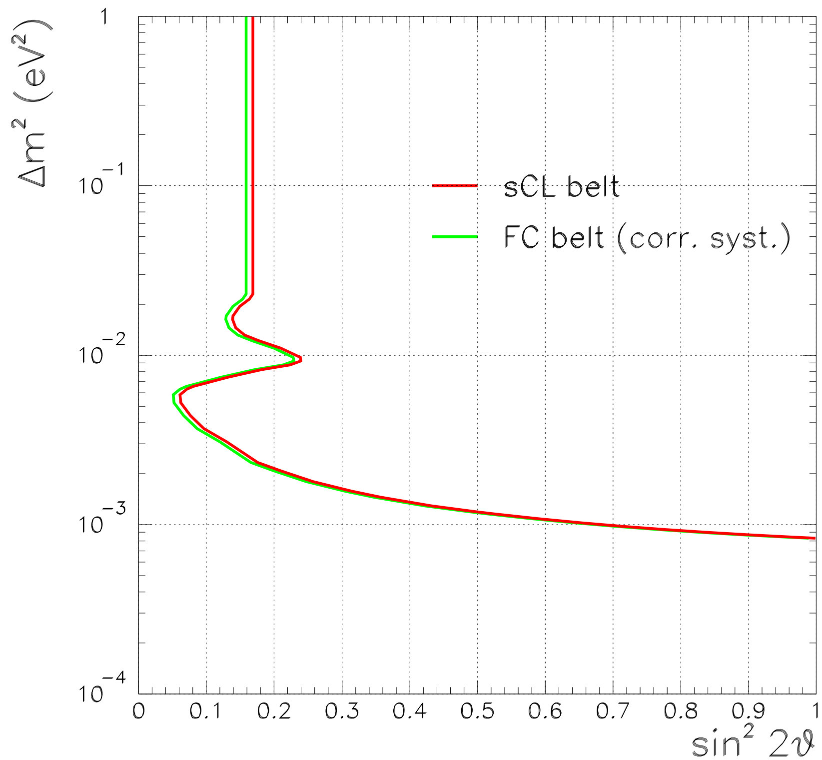
Se son rose fioriranno ...

... GOOD LUCK to MINIBOONE !!!

Backup slides

CHOOZ high δm^2 limits





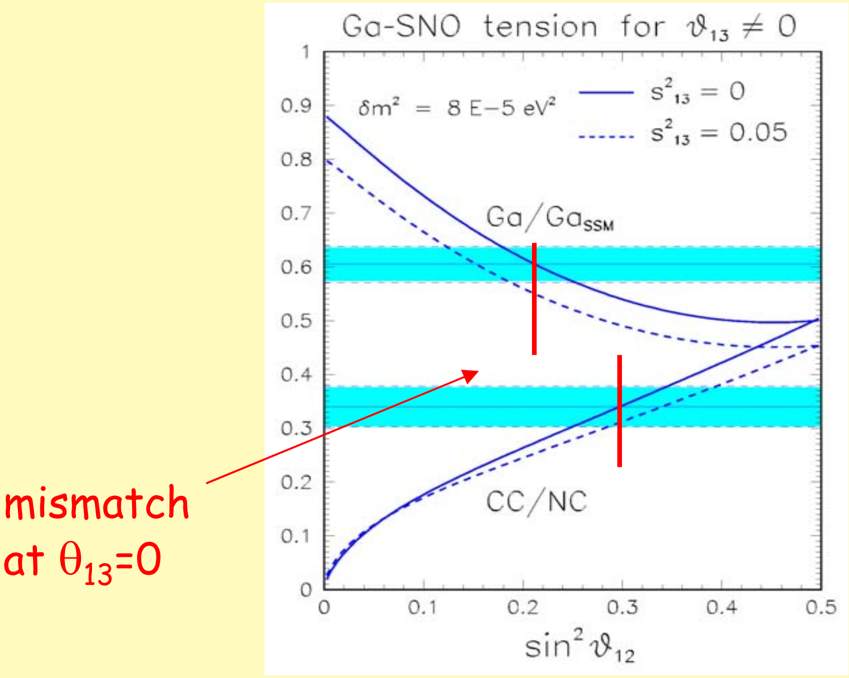
$90\% C.L.$ limit : $\sin^2 2\theta < 0.1$

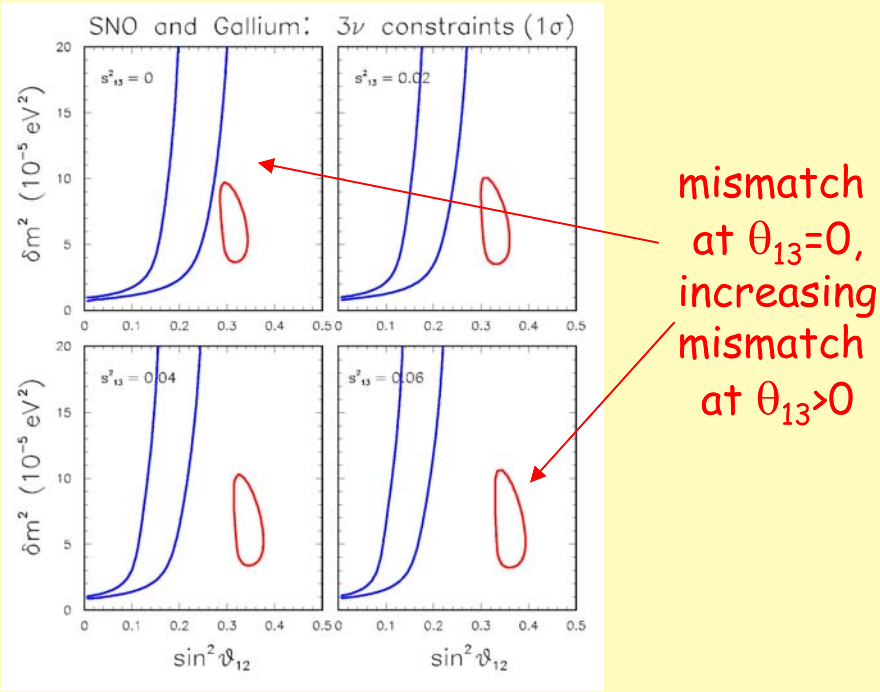
FC limit: $\sin^2 2\theta < 0.16$

hep-ex/0301017

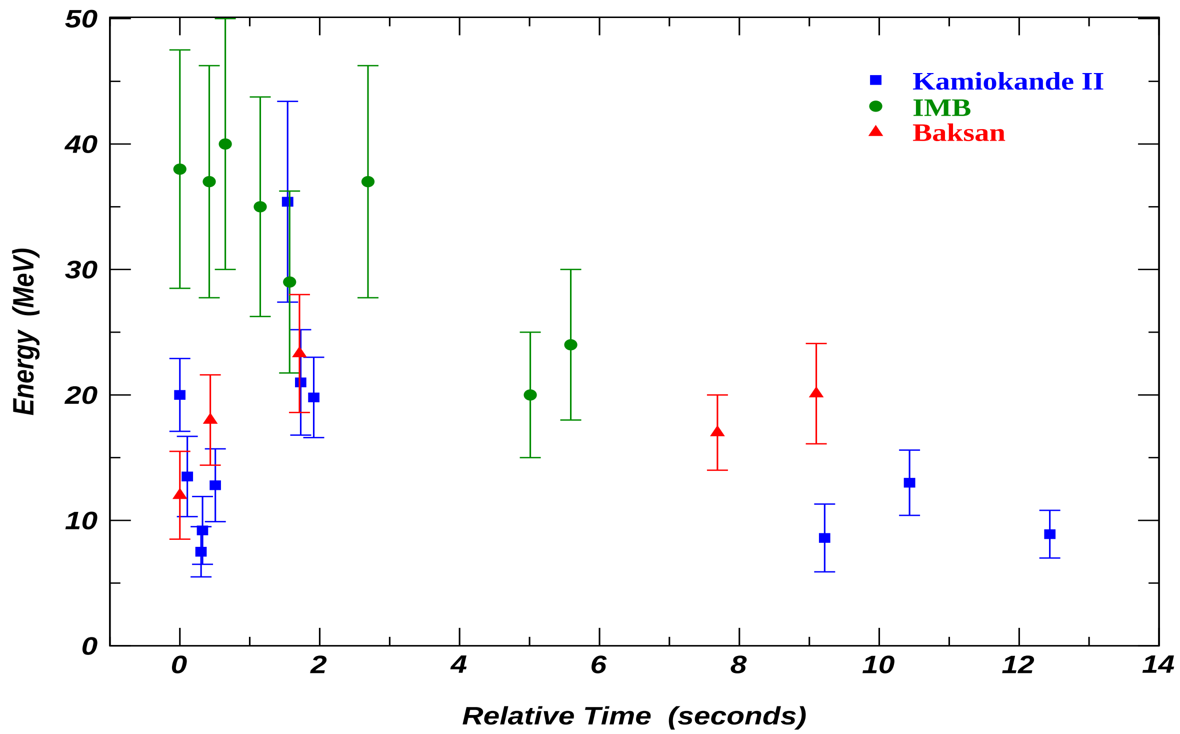
The situation with Ga cross-section renormalization (0.88±0.05 at LE), is that:

1) Ga and SNO data are no longer in good agreement with predictions for θ_{13}=0 (Ga prefers lower $\sin^2\theta_{12}$)
2) The disagreement becomes rapidly worse for increasing θ_{13}, since the Ga and SNO allowed regions become even more separated in $\sin^2\theta_{12}$.
3) Thus, there is never a very good agreement between Ga and SNO constraints, in particular for nonzero θ_{13}.





SN 1987A



Time delay of massive neutrinos:

Let us look now at the time delay in the arrival time of a non-zero mass neutrino in comparison to that of a massless one. If the mass is exactly zero, the time of flight for arriving on the Earth from the Supernova is the same for all the neutrinos. It is

$$T_0 = L_{SN}/c = 1.7 \cdot 10^5 \quad years$$

where L_{SN} is the distance of the Supernova from the Earth, and c is the light speed in vacuum. However if the mass m is not zero, then the time of flight is

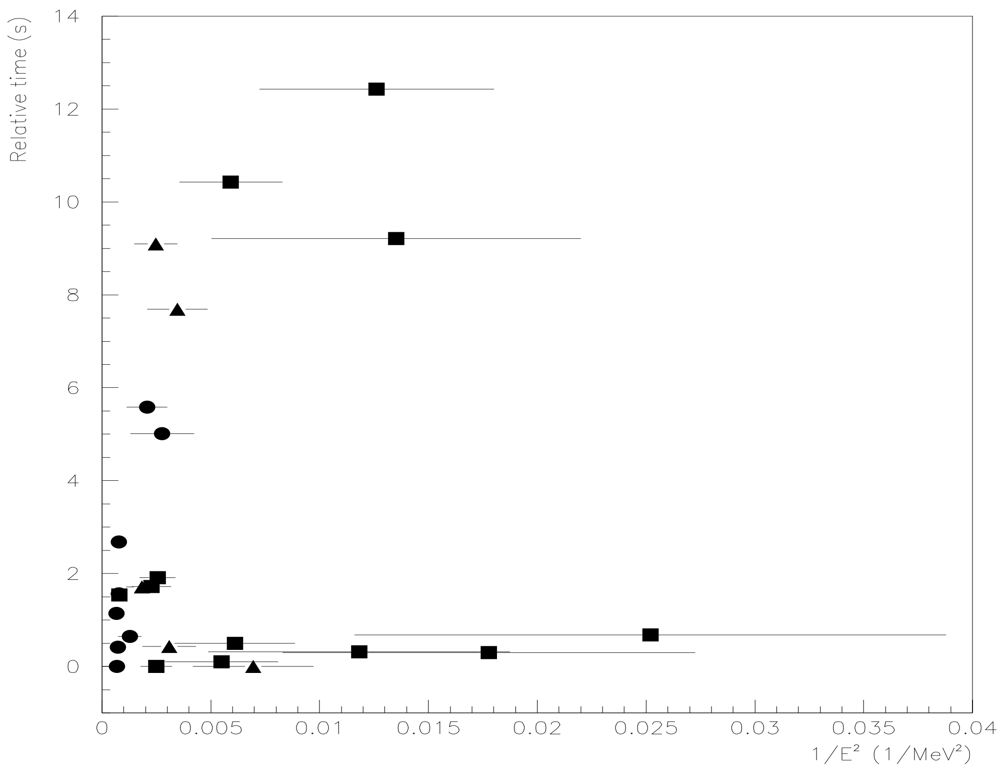
$$T_m = \frac{L_{SN}}{c \cdot \sqrt{1-(m/E)^2}} \sim \frac{L_{SN}}{c} \cdot \{1 + \ 1/2 \cdot (m/E)^2\}$$

SN 1987A

The difference of these two values, *i.e.* the delay in the arrival of a neutrino with mass m in comparison to a massless one, is

$$\Delta T_m = T_m - T_0 \approx 1/2 \cdot T_0 \cdot m^2/E^2$$

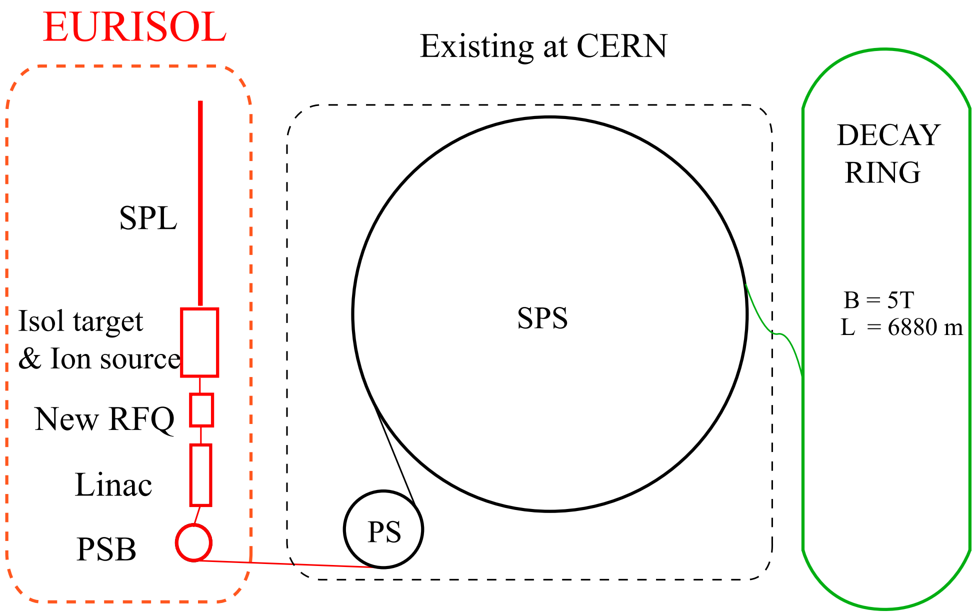
Numerically, a neutrino of energy 5 MeV should delay about one second if the mass is 3 eV and about 10 seconds if the mass is 10 eV.



$$m_1 = 3.4 \pm 0.6\,\mathrm{eV} \qquad m_2 = 22.7 \pm 3.7\,\mathrm{eV}$$

hep-ph/0212337 H. Huzita

Future β beam experiment ?

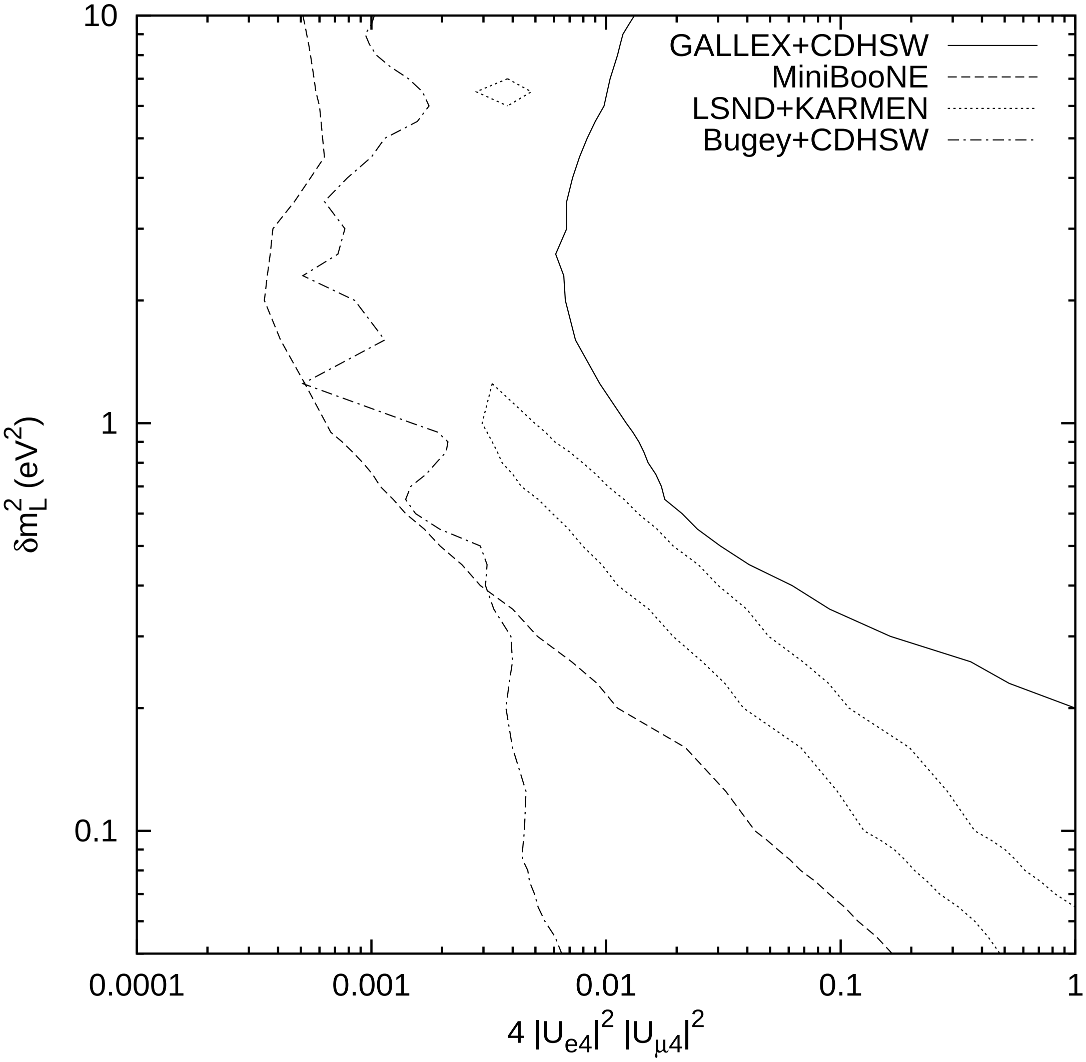


hep-ex/0410083

“Beta Beams have been introduced by Piero Zucchelli in 2001 . The idea is to generate pure, well collimated and intense ν_e and $\bar{\nu}_e$ beams by producing, collecting, accelerating radioactive ions and storing them in a decay ring. The best candidates so far are ^{18}Ne and ^{6}He for ν_e and $\bar{\nu}_e$ respectively.A baseline study for such a BetaBeam complex has been produced at CERN .

“If the MiniBoone experiment validates the LSND oscillation claim, a beta-beam experiment looking to $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillation could allow unprecedented measurements of oscillations in the region of Δm^2 relevant to astrophysics and cosmology. At the moment, no pure sources of ν_μ or ν_e are available to appearance experiments which have to explore the region characterized by $sen^2 2\theta \approx 10^{-4}$. The technology developed for the ICARUS experiment would probably be suitable for this domain of investigation.”

3+1 & CPT violation



hep-ph/0308299