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Measurement of the 3-Neutrino Mixing Matrix Using Long Baseline and Other Neutrino Sources*

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ABSTRACT

We discuss the possibility of determining the 3-neutrino mixing matrix elements using different initial flavor and energy neutrino beams and solar neutrinos neutrino oscillation solutions. The key question is the role played by identification of the specific flavor of the oscillated neutrino beam for determining the different matrix elements. We also discuss some possible long baseline beams, namely from CERN or UNK to the Gran Sasso Laboratory. Some comments are also made concerning the use of the ICARUS detector and also the possible role of solar neutrino supernova detection in determining the mixing matrix.

1. Introduction

The search for a non zero neutrino mass is among the most important issues in the study of elementary particles. Theory gives very little guidance even within the see-saw model since the symmetry breaking or heavy lepton mass scale is totally unknown.[1] If we apply this model to the Grand Unification scale we would find (see Table 1)

$$M_\nu \sim \frac{M_f^2}{10^{15}\mathrm{GeV}} \simeq 10^{-2}\mathrm{eV} \qquad \left[M_f \sim 10^2\,\mathrm{GeV}\right] \tag{1}$$

It may therefore be that one neutrino mass is above a few tens of millivolts. There are no known direct methods to measure such a low mass (even using supernova sources at Mega parsec scales). Thus, we must rely on neutrino oscillations to detect this mass scale. As is well known, there are already indications from solar neutrinos and atmospheric neutrinos that suggest the existence of neutrino mass in this range. However, it

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Table 1. Questions Concerning Neutrino Mass

1)	We know $M_\nu \ll M_{\text{leptons, quarks}}$ – But is $M_\nu \equiv 0$!
2)	In HEP $M_\nu \approx \frac{M_f^2}{M_x}$ – See-Saw Mechanism Small M_ν implies Large $M_x \rightarrow$ Ultra High Energy Scale For Example $M_x \sim M_{\text{Planck}}$, $M_f \sim 10\text{GeV}$
3)	Quark Lepton Connection – Quarks Mix, i.e. $s \rightarrow d\,(K^+ \rightarrow \pi^0\mu^\pm\nu$, for example) Do Neutrinos Mix – No Definite Evidence To Date
4)	Cosmology and Astrophysics – $M_\nu \gtrsim \text{eV} \Rightarrow$ Neutrino's important in Gravity of Universe $\sim 30\text{eV} \Rightarrow \Omega_\nu \simeq 1$ – $[M_\nu \sim$ few eV, Mix$] \Rightarrow$ Implications for Supernova Dynamics

is now possible to use long baseline neutrino beams from various high energy accelerators to underground laboratories to probe this mass range and above.[2] In this report we survey the possible future long baseline experiments, including both solar neutrinos and supernova sources to study the possibility of determining the relevant mixing matrix for 3 neutrino flavors. We will emphasize the flavor tagging in the different experiments to separate the different mixing angles.[3]

2. Three Neutrino Flavor Oscillations

We know there are three flavors for neutrinos, however, there is not yet any direct evidence that the ν_τ is active (i.e., not sterile). However, in this report we will assume the ν_τ to have normal charged current and neutral current interactions.

The three flavor CKM matrix has been cited in many references.[1] Here we give the probabilities for the $\nu \rightarrow \nu'$ transition in terms of the three angles (θ_1, θ_2, θ_3) in Table 2. since none of these angles are definitely known to be other than zero at present, we can only use the limits for neutrino oscillations or theory for guidance. In Table 3 we list some of the results of taking these neutrino oscillations results and obtaining the CKM angles. This leads to some questions concerning future experiments searching for neutrino oscillations as we have partially outlined in Table 4.

3. Long Baseline Neutrino Beams

Since the actual mass of neutrinos is currently unknown, we can think of the future search as a sort of *Neutrino Oscillation Land Map*, as shown in Figure 1. One recently proposed long baseline experiment from CERN to the ICARUS detector at

Table 2. Three flavor CKM neutrino oscillation probabilities.

			Quark Sector
$P\nu_\mu \to \nu_e$	$\simeq$	$2\sin^2\theta_1\,[1 - \cos\Delta_{12}]$	V_{us}
$P\nu_e \to \nu_\tau$	$\simeq$	$2\sin^2\theta_1\ \sin^2\theta_3\,[1 - \cos\Delta_{13}]$	V_{ub}
$P\nu_\mu \to \nu_\tau$	$\simeq$	$[\sin\theta_2 + \sin\theta_3]^2\ [1 - \cos\Delta_{23}]$	V_{cb}
		[Note, if $\sin\theta_2 = -\sin\theta_3$ we could have $P\nu_\mu \to \nu_\tau \ll P\nu_e \to \nu_\tau$	
Δ_{ij}	$=$	$\left[\frac{m_i^2 - m_j^2}{2E}\right] L$	

the Gran Sasso would make use of the fact that the proton beam to be injected into the LHC almost *points* to the Gran Sasso Laboratory, as shown in Figure 2.[2] This piece of luck must certainly be an invitation to carry out this type of physics.[2]

In Figure 3 we attempt to summarize the different scale length and neutrino mass that can be probed with the long baseline neutrino beam that accelerators and nature provides.

The key ingredient to this science is the appropriate detector for the long baseline neutrino source including solar and supernova detectors of the future.

4. Flavor Tagging with Neutrino Detectors

The issue of neutrino flavor tagging is both a source flavor and oscillated neutrino flavor determination. In some cases the neutrino is produced in a reaction that favors a neutrino flavor (i.e., *pp* reaction in the Sun gives ν_e, $\pi^+ \to \mu + \nu_\mu$ gives ν_μ neutrinos with a small – $\tilde{<}$ 1% – contamination of ν_e neutrinos). We attempt to generalize these considerations in Table 5. One of the key problems in the future is to tag ν_τ neutrinos. In Table 6 we provide an overview of the different methods to tag the ν_τ flavor. Clearly, new detectors (like ICARUS) may be important for future large mass detectors.[3]

5. The ICARUS Detector for Long Baseline Neutrino Beam from CERN to the Gran Sasso

A schematic of the ICARUS detector being built for the Gran Sasso is shown in Figure 4.[2] In our recent measurements we have achieved $\sim 50\mu$m resolution for a small detector. Simulation of ν_τ interactions in the 5000 Ton ICARUS detector are underway and show the possibility to detect ν_τ interactions.[2]

6. Supernova Burst Observatory and Neutrino Oscillations

The longest baseline neutrino beam will be from a supernova. In order to exploit this source we will need a complement of detectors on Earth to cover the possible

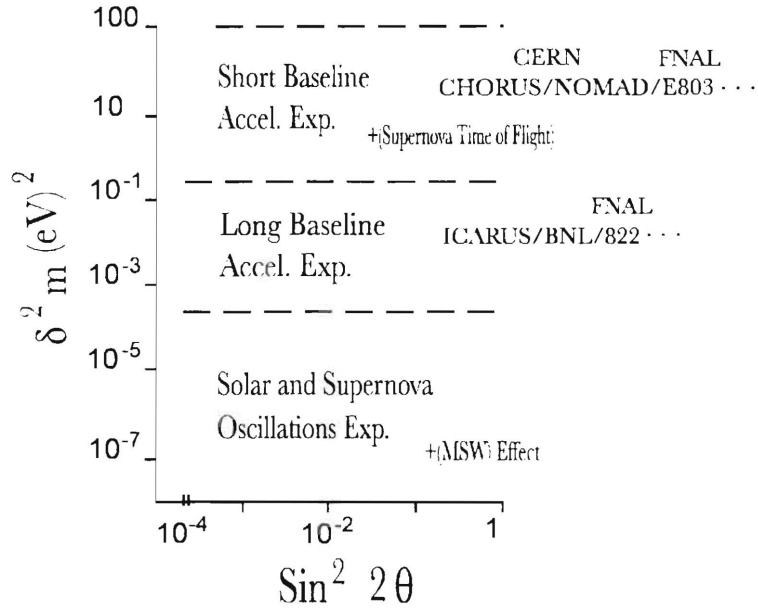

Fig. 1. Parameter space for a search for neutrino mass by neutrino oscillations.

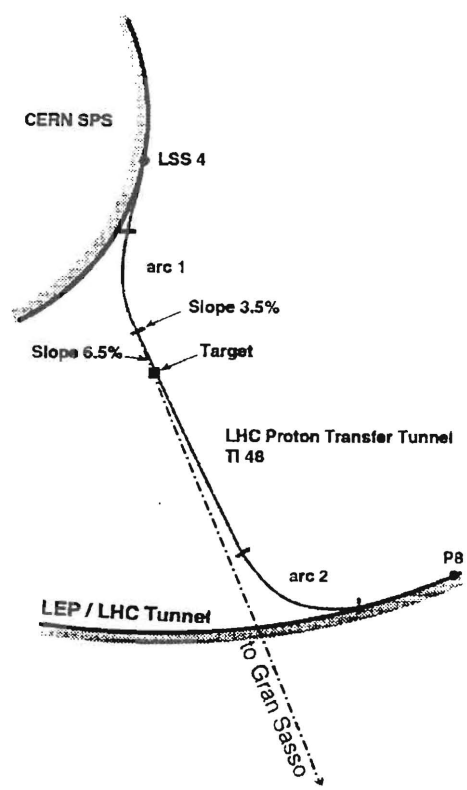

Fig. 2. Geometric characteristics of the CERN neutrino beam to Gran Sasso. (Ref. 2,3)

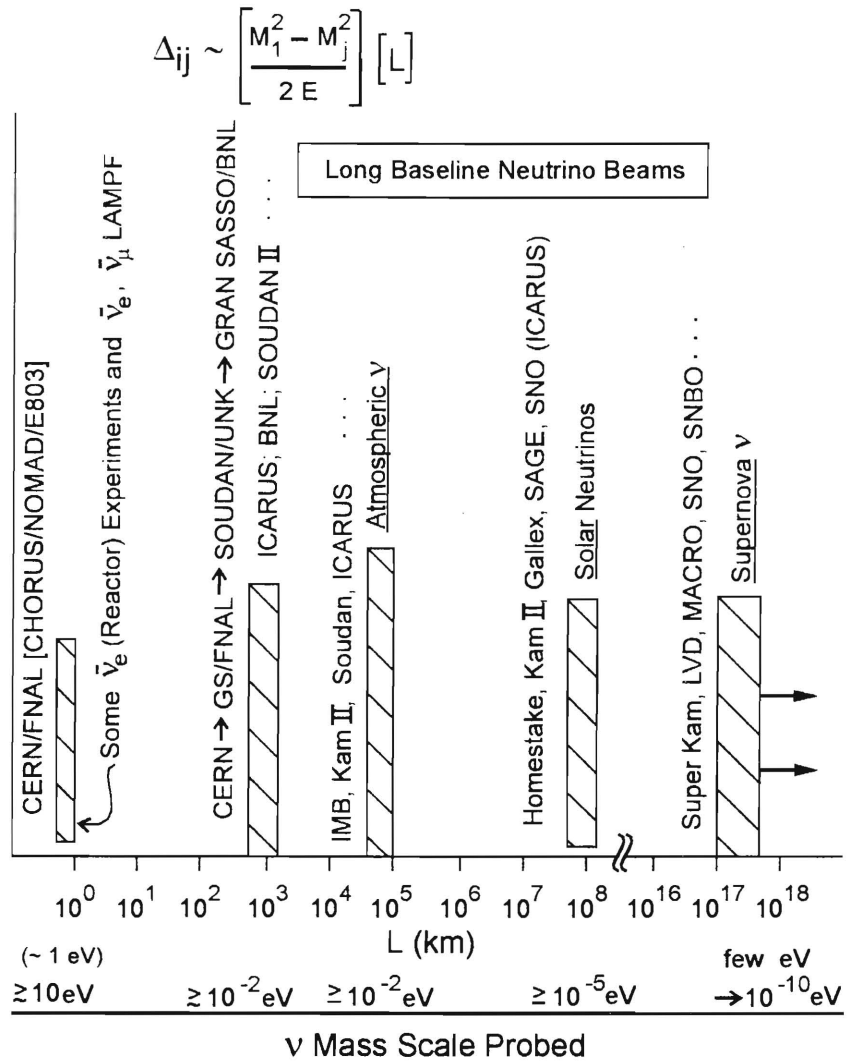

Fig. 3. Different distance scales for long baseline ν oscillation experiments and the neutrino mass range that can be probed. Several different neutrino beams or detectors are also indicated.

Table 3. Possible CKM parameters from current neutrino oscillation results.

	Source	$\sin^2 2\theta$	$\delta^2 m$ (eV)^2	CKM Angles $\nu_\mu \to \nu_e$ $2\sin^2\theta_1$	$\nu_e \to \nu_\tau$ $2\sin^2\theta_1 \ \sin^2\theta_3$	$\nu_\mu \to \nu_\tau$ $[\sin\theta_2 + \sin\theta_3]$
1)	solar ν's	8×10^{-3}	$\sim 8 \times 10^{-6}$	8×10^{-3}	8×10^{-3}	___
2)	solar ν's	0.7	$\sim 10^{-5}$	0.7	*	___
3)	Atmos. ν's	0.5	$\sim 10^{-2}$	0.5	___	0.5**
4)	Calc. or SN proc.	$\lesssim 10^{-5}$	$\gtrsim 10$	___	$\lesssim 10^{-5}$***	___

Quark Sector CKM: $\theta_1 \sim 2 \times 10^{-1}$ $\theta_2 \sim 2 - 4 \times 10^{-2}$ $\theta_3 \sim 2 \times 10^{-2}$

* assuming $\sin\theta_1 < \sin\theta_3 \ll 1$ this is unlikely

** would appear to be unlikely if $\sin\theta_{2_1}$ $\sin\theta_3 \ll 1$ as in Quark CKM results

*** this may be reasonable if the small angle solar neutrino oscillation solution is correct - in this case $\sin^2\theta_3 < 10^{-3}$

time of flight difference for a massive neutrino (i.e., 10eV) or to study the neutrino oscillations from either the MSW effect in the matter of the SN or the long baseline for vacuum oscillations.[4,11] In Table 7 we list some preliminary concepts concerning the separation of the different types of neutrino oscillations.[5]

7. Regions of Neutrino Oscillation Parameters to be Probed

There are many proposed long baseline experiments. Here we summarize those that we work with. Figure 5 shows the region of *Neutrino Oscillations Land* that will be probed by ICARUS, CHORUS, NOMAD, and E803 (at FNAL).[2,6,7] The ICARUS region assumes a neutrino beam from CERN to the Gran Sasso.[2] Recently, there has been a proposal to send a beam from the UNK accelerator in Russia to the Gran Sasso.[8] Figure 6 shows the region of the neutrino oscillation that can be covered in this case.

THe ICARUS detector can also be used for solar neutrino studies and the region of sensitivities is shown in Figure 5.[9]

8. Acknowledgements

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Table 4. Issues for Future Neutrino Oscillation Experiments.

Examples: (see text for references)

1.) Suppose we observe $\nu_\mu \to \nu_\tau$ and $\nu_\mu \to \nu_e$ . . .

What is the reason to measure $\nu_e \to \nu_\tau$

[Example $\nu_\mu \to \nu_\tau$ – CHORUS/NOMAD/E803
$\nu_\mu \to \nu_e$ – Long Baseline – ICARUS]

2.) Suppose we <u>observe (or infer)</u> $\nu_e \to \nu_\tau$

[Example : from supernova work of Fuller, Quan, et. al. (Ref. 5)
$\nu_e \to \nu_\tau$ $\sin^2 2\theta \sim 10^{-7}$ $M_{\nu_\tau} \sim$ eV Range]

How does this limit $\nu_e \to \nu_\tau$

3.) Suppose $\nu_\mu \to \nu_\tau$ is <u>not observed</u> at CERN or FNAL,

$$\delta^2 m > 30\text{eV}^2, \quad \sin^2 2\theta < 10^{-4}$$

– Are there any implications for

$$\nu_e \to \nu_\tau \quad \text{or} \quad \nu_\mu \to \nu_e$$

4.) What are the consequences of taking the small mixing angle solar neutrino oscillation as being $\nu_e \to \nu_\tau$ for long baseline experiments in the future (i.e. supernova neutrino detection)?

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2. See ICARUS Proposal, Vol. I., UCLA Report (unpublished).
3. See J.P. Revol, CERN-PPE/93-84, talk given at the Recontres de Physique de la Vallee d'Aoste (1993).
4. For an overview, see D.B. Cline, et al., Prospects for Detection of a Cosmologically Significant Neutrino Mass from a Galactic Supernova Neutrino Burst Using a Neutral Current Based Detector, to be published in Phys. Rev. D (1994), and UCLA-APH0029-2/90.
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Table 5. Neutrino flavor determination.

1) Very		
Low Energy	Incoming Beam	Outgoing Beam
(0-5 MeV)	Flavor Selection	Flavor Determination
– Solar	ν_e (Dynamics)	ν_μ, ν_τ can't be separated from each other
– Supernova	ν_e, ν_μ, ν_τ $\bar{\nu}_e$ $\bar{\nu}_\mu$ $\bar{\nu}_\tau$ separated by beam energy	can tag $\bar{\nu}_\mu$, $\bar{\nu}_\tau$ by the high energy – ν_μ, ν_τ could be changed by neutrino oscillations
– Reactor	$\bar{\nu}_e$	
– μ decay	ν_e, $\nu_{\mu i} - F_{\nu_e} \sim F_{\nu_\mu} \cdots$	
– π^+ decay	ν_μ, $\bar{\nu}_\mu$	
2) Accelerators		
Low Energy	(a) $\nu_\mu \to \mu$ (lg.flux)	can separate 2 of the
$E_\nu <$ few GeV	(b) $\nu_e \to e$ $\left(\sim 10^{-2} F_{\nu_\mu}\right)$	3 flavors ν_τ by WNC
High Energy	(a) $\nu_\mu \to \mu$ (lg.flux)	to separate ν_τ
E_ν10GeV	(b) $\nu_e \to e$ $(\sim 10^{-2})$	from $\nu_\mu \to \nu_\mu$ by
	(c) $\nu_\tau \to \tau$ $(\sim 10^{-4} - 10^{-5})$	WNC requires a high resolution detector
can select ν_μ beams and ν_e beams (K^0 decays) and ν_τ (beam dump; $D_s \to \tau\nu_\tau$)		

Table 6. Massive ν_τ detectors.

1) Direct observation of

$$\nu_\tau + N \rightarrow \tau + X$$

$\hookrightarrow$ decay] Direct observation of vertex

(a) Emulsion ($\sim$ 1 Ton) CHORUS/E803/P872 [Refs. 6, 7]

Need for small $P_{\mu_e\tau}$ [(b) ICARUS LIKE DETECTOR^{two} ($\sim$ 100 – 5000 Tons)
– observe vertex ($\sim$ 3 Ton Detector so far)

2) Indirect ν_τ Detection

$$\nu_\tau + N \rightarrow \tau + X$$

$\hookrightarrow$ decay products

(a) kinematic fit
(b) large neutral current signal
(c) hybrid – configuration of event –

(a) Nomad ($\sim$ 3 Tons) (kinematic fit) [Ref. 6]

(b) ICARUS, Soudan II, Genius ..., BNL [OBSERVE EXCESS WNC EVENTS] (Must remove ν_e Int.)

Table 7. Separation of Neutrino Oscillation Effects in a Supernova Neutrino Burst Detector [Ref. 4]

SNBO:	Super Kamiokande:	Interpretation:
Observe time-of-flight signature ?	Observe $\nu_e \leftrightarrow \nu_\tau(\mu)$ oxygen signal ?	
yes	yes	consistent with $\nu_e - \nu_\mu$ solar ν mixing solution for solar ν problem plus a massive ν_τ $(m_{\nu_\tau} > 5\,\mathrm{eV})$
no	yes	conclude there are high energy ν_e's from $\nu_e \leftrightarrow \nu_{\tau(\mu)}$ – could still have $m_{\nu_{\tau(\mu)}} > 5\,\mathrm{eV}$ – could be consistent with solar ν mixing solution
yes	no	there is a massive $\nu_{\tau(\mu)} > 5\,\mathrm{eV}$ but $\nu_e \leftrightarrow \nu_{\tau(\mu)}$ mixing negligible – neutrino mixing is <u>not</u> the solution for solar ν problem
no	no	upper limits on $\mu_{\nu_{\tau(\mu)}}$ – no solar ν mixing – $\nu_e \leftrightarrow \nu_{\tau(\mu)}$ mixing very small

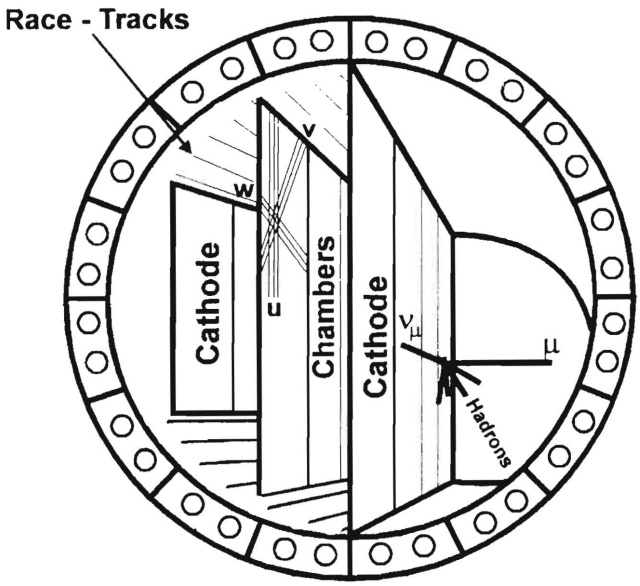

Fig. 4. The ICARUS detector for the Gran Sasso Laboratory [Ref. 2]

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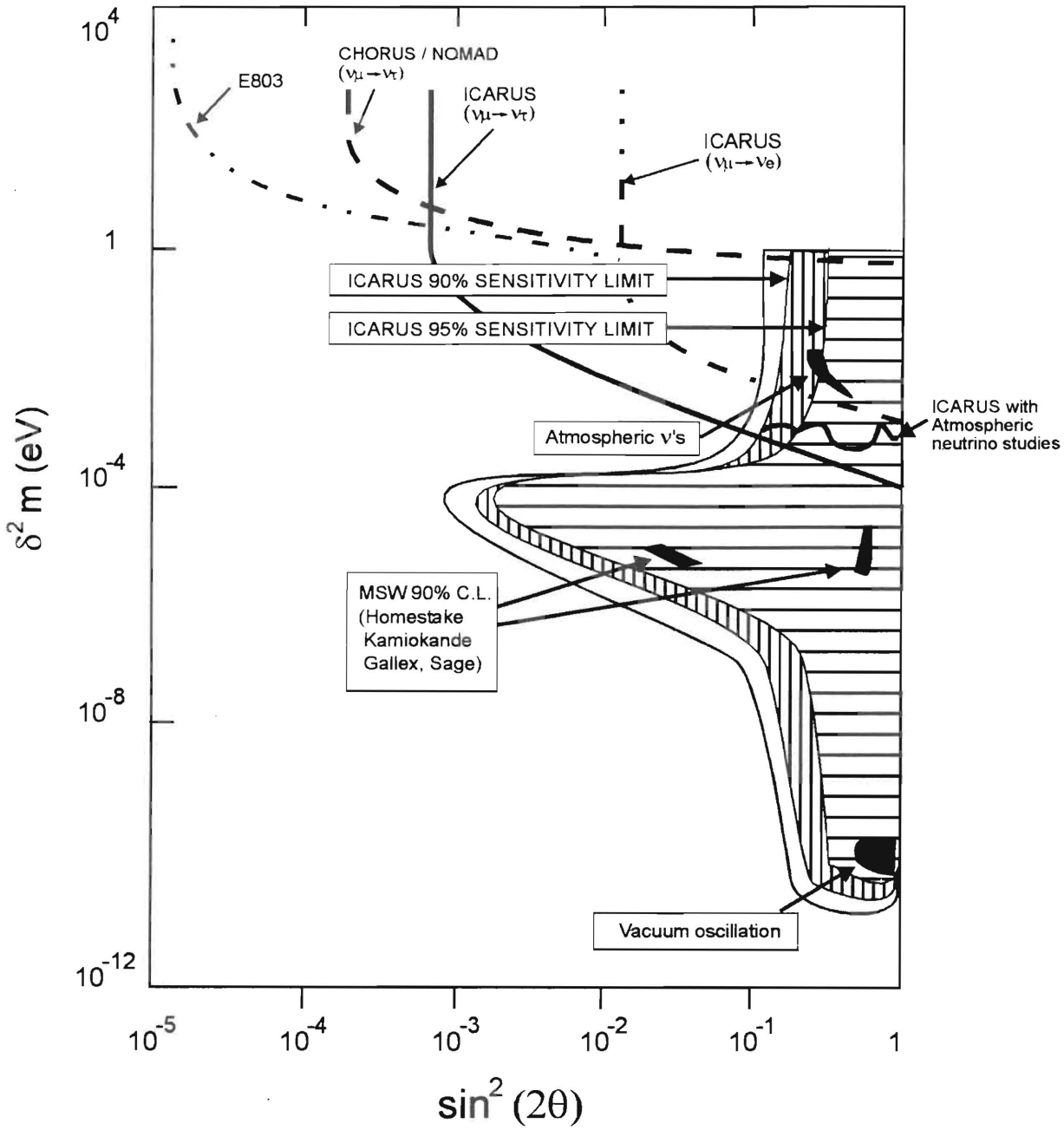

Fig. 5. Most of phase space Δm^2, $\sin^2 2\theta$ covered by CHORUS/NOMAD, ICARUS and solar neutrino experiments (MSW)[2,6,7,9,10].

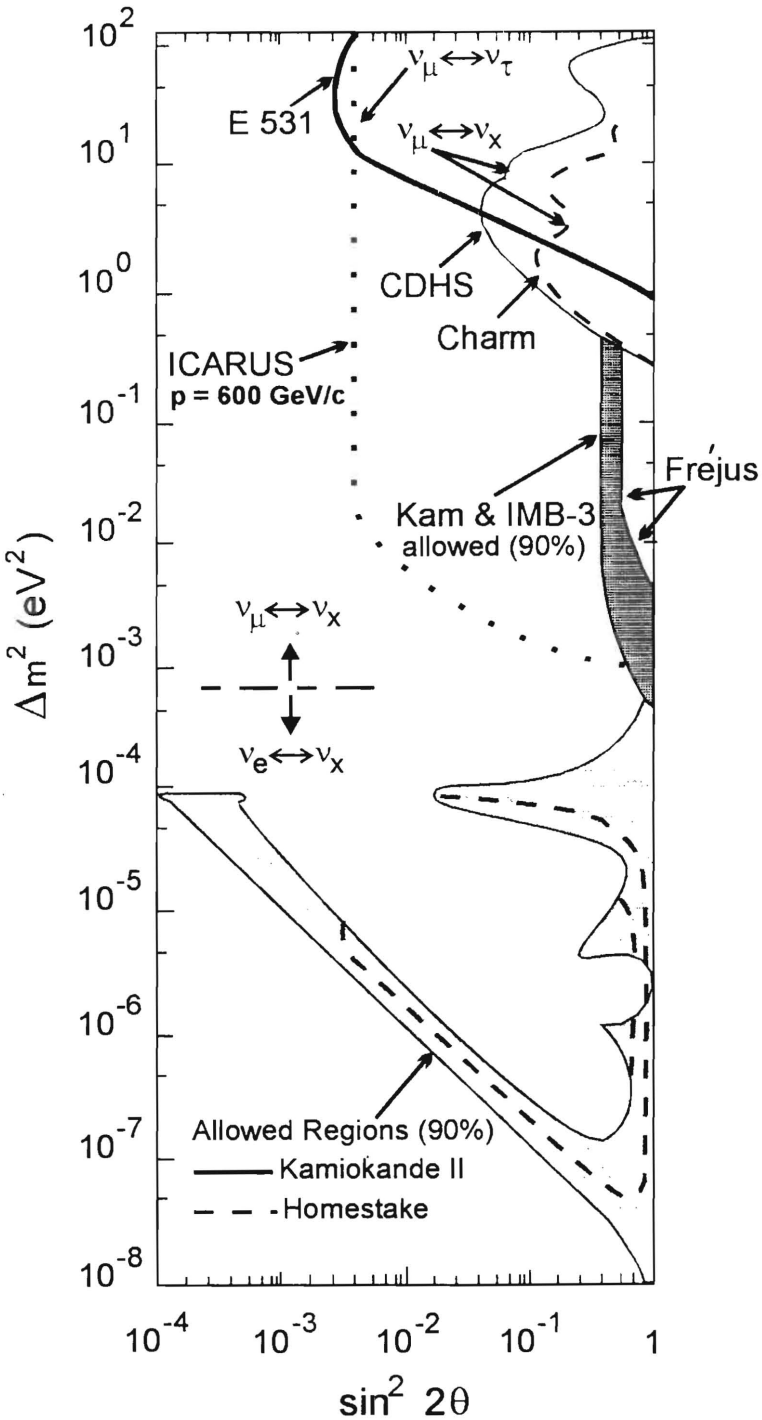

Fig. 6. Region of Neutrino Oscillation Land Map covered by a Neutrino Beam from the UNK Machine in Russia to the ICARUS Detector at the Gran Sasso.