Present Status of Neutrino Oscillation Experiments

1. Reactor, Accelerator Results
2. Solar Neutrino Problem & Neutrino Oscillation
3. Atmospheric Neutrino Deficit & Neutrino Oscillation

A. Suzuki (KEK)

Recipes of Oscillations

Oscillation probability

$$P(\nu_i \to \nu_j) = \sin^2 2\theta \cdot \sin^2\left[1.27\,\Delta m^2(\mathrm{eV})^2 \frac{R(\mathrm{m})}{E(\mathrm{MeV})}\right]$$

$\Delta m^2 = |m_1^2 - m_2^2|$
θ : mixing angle

for 2 flavor case.

Δm^2 : small

$$P \propto \left(\frac{R}{E}\right)^2 \longrightarrow \left.\begin{matrix}\text{large } R\\ \text{low } E\end{matrix}\right\}\ \begin{matrix}\text{reactor}\\ \text{solar } \nu\\ \text{atmospheric } \nu\end{matrix}$$

$\sin^2 2\theta$: small $\longrightarrow$ accelerator.

$\nu_\mu \rightsquigarrow$ $\nearrow$ $\rightsquigarrow \nu_\mu$ disappearence

$$\sin^2 2\theta < \frac{1}{\sqrt{N}}$$
$$\Delta m^2 < \frac{E}{R}\frac{1}{\sqrt[4]{N}}$$

$\nu_\mu \rightsquigarrow$ $\searrow$ $\rightsquigarrow \nu_x$ appearence

$$\sin^2 2\theta < \frac{1}{N}$$
$$\Delta m^2 < \frac{E}{R}\frac{1}{\sqrt{N}}$$

Reactor Experiments

2800 MW $5 \cdot 10^{20}\ \bar{\nu}_e / \mathrm{sec}$

$0 < E_{\bar{\nu}_e} < 10\ \mathrm{MeV}$

↓

disappearence experiment

$\bar{\nu}_e \rightarrow \bar{\nu}_x$

Present

0.01

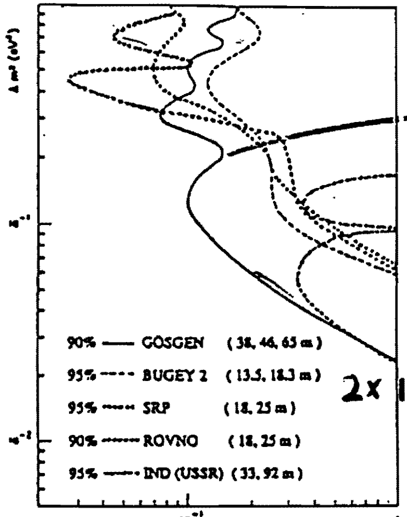


Figure 1: Present status of exclusion plots on neutrino oscillations parameters $sin^2 2\theta$ and δm^2. Regions to the right of the curves are excluded with the listed confidence levels listed in the figure.

Future $\Delta m^2 < 5 \cdot 10^{-3}$

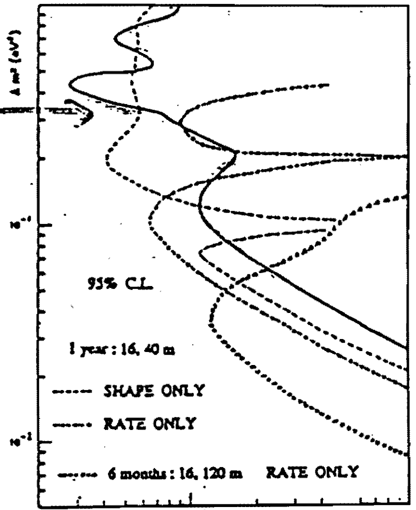


Figure 2: Expected exclusion plots on neutrino oscillations parameters $sin^2 2\theta$ and δm^2 for the new Bugey experiment. The region to the right of the continuous line correspond to the zone already excluded.

Accelerator Experiments

Present exp.

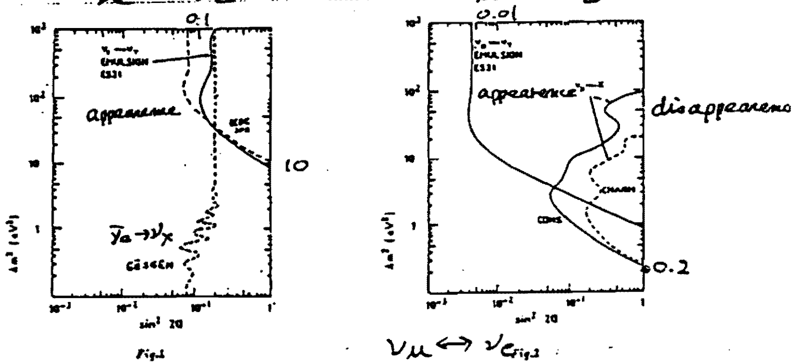
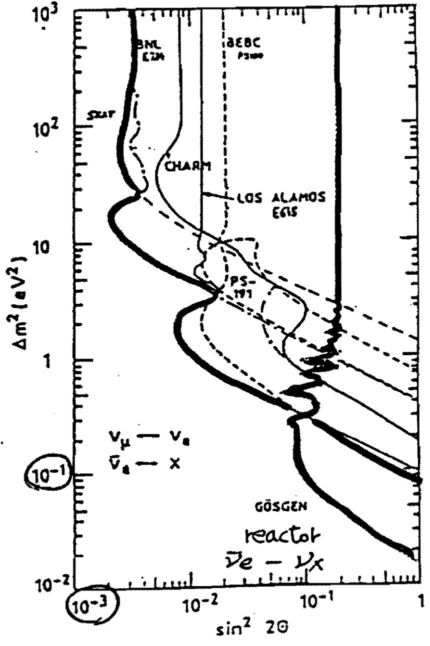


Fig.1

$\nu_\mu \leftrightarrow \nu_e$ Fig.2



All curves are limits (excluded regions being on the right of the curves), except for the PS191"banana" in Fig.2 which was the allowed region if the excess was interpreted as due to oscillations.

Future Experiments

overcome limitations of present searches

- poor knowledge of
  - flavor contamination → 10^{-3} at best
  - ν production point → middle point of decay tunnel

1. Tagged ν experiment

(Serpukhov 70 GeV PS E152)

$K^{\pm}_{\mu 2} \to \mu^{\pm} \nu_\mu (\bar{\nu}_\mu)$ $K^{\pm}_{e3} \to \pi^0 e^{\pm} \nu_e (\bar{\nu}_e)$

tagging efficiency 70 (40) % for $\nu_\mu (\nu_e)$

$\bar{\nu}_\mu (\bar{\nu}_e)$ contamination 10^{-5} ($<10^{-5}$)

$\nu_e (\nu_\mu)$ contamination $2 \cdot 10^{-4}$ (10^{-2})

small systematic error!

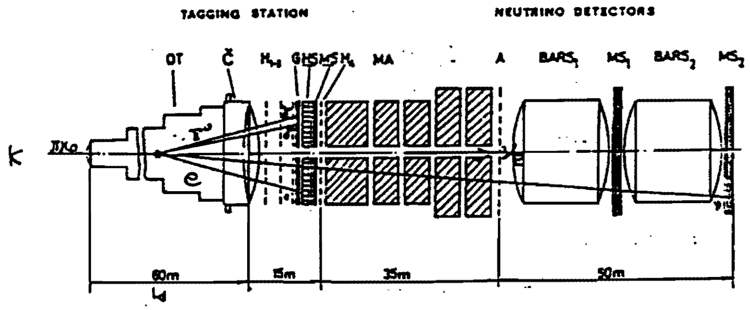


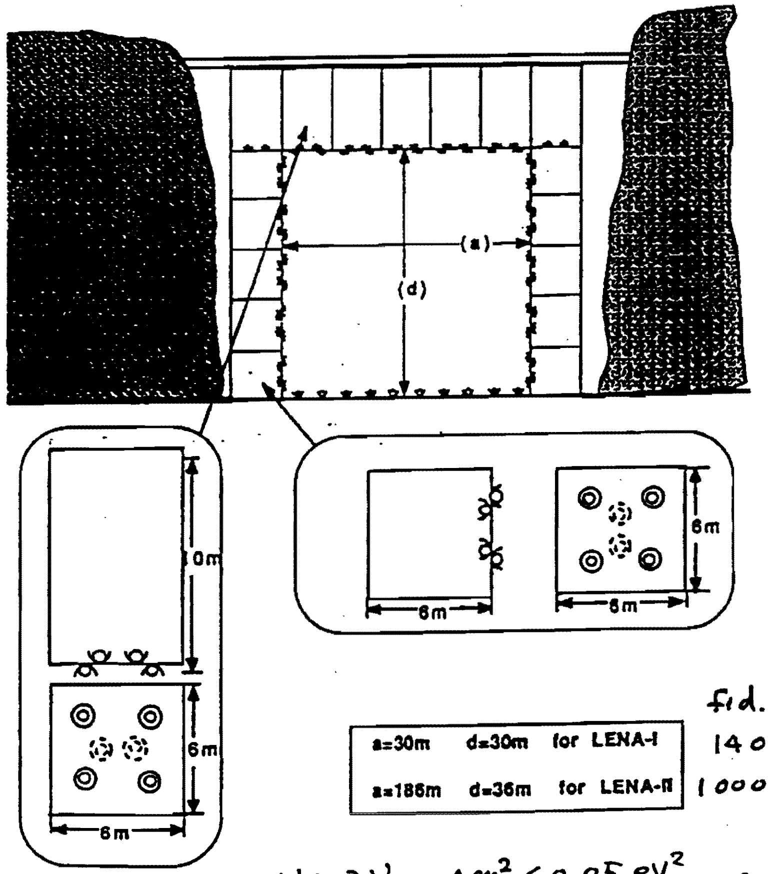
Fig. 1. Layout of the end part of the TNF at the 70 GeV PS.

May

LENA

(Lake Experiment on Neutrino Activities)

M. Koshiba, K. Nishikawa, H. Suda, Y. Watanabe



			fid. volume
a=30m	d=30m	for LENA-I	14000 m^3
a=186m	d=36m	for LENA-II	1000000 m^3

$\nu_\mu \to \nu_\tau$ $\Delta m^2 < 0.05$ eV^2

-- ν_μ ~~$\to \nu_e$ $\Delta m^2 <$~~ 0.01 eV^2 for LENA-I

FNAL injector ring s) $R = 50$ km, 100 km

(500 km, 1000 km : LENA-II)

LENA - II

τ identification
$\tau \to e\nu\nu$
(N.C. π^0 production)

μ/e separation
(N.C. single π production)

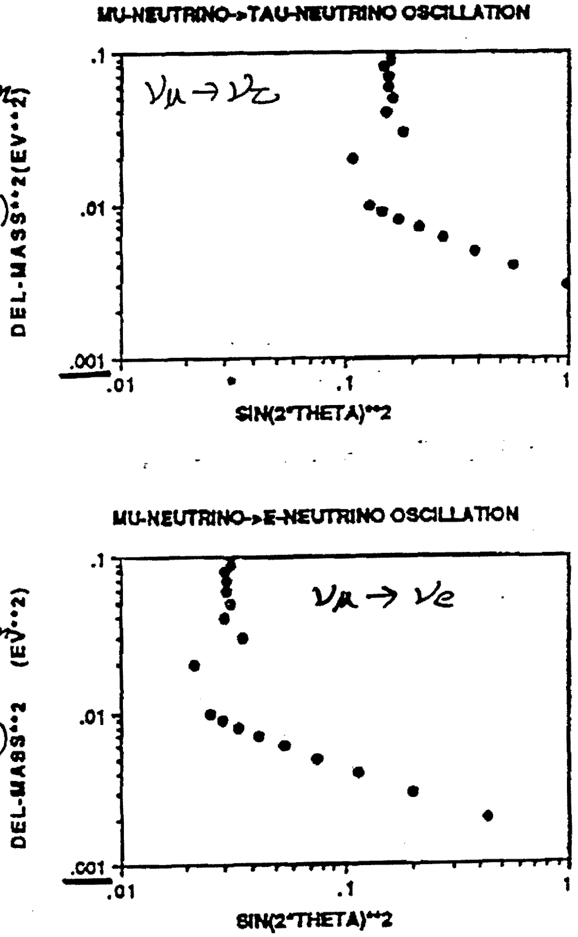
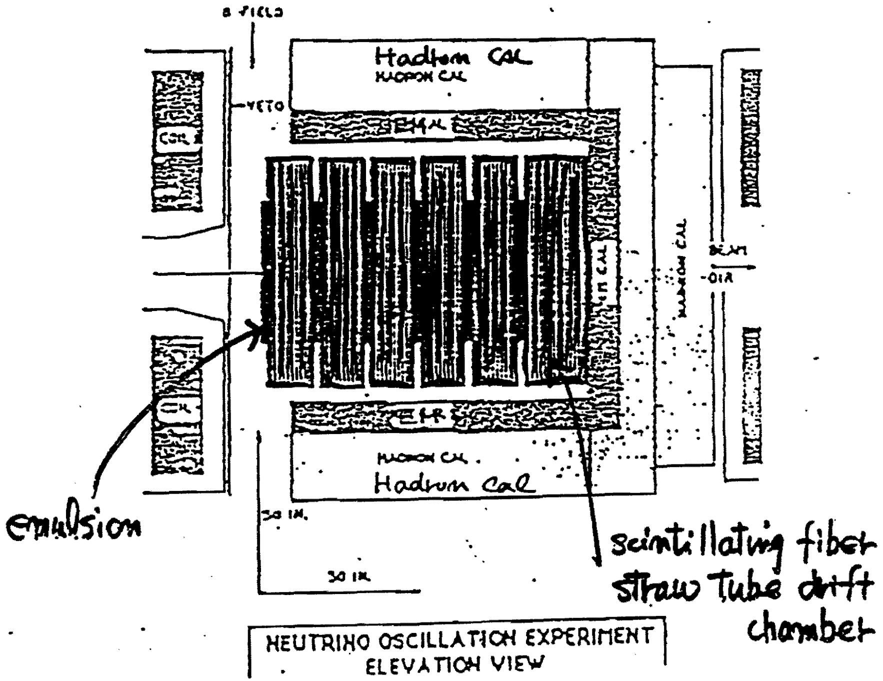


Fig.14 Accessible region of Δm^2 and mixing param LENA-II. Due to the 17% branching ratio the sensit $\nu_\mu \to \nu_\tau$ is less than that for $\nu_\mu - \nu_e$ oscillation.

Improved Limits for $\nu_\mu \to \nu_\tau$ Oscillation

(P-803)

Nagoya - Osaka - Kobe - Ohio - FNAL ----



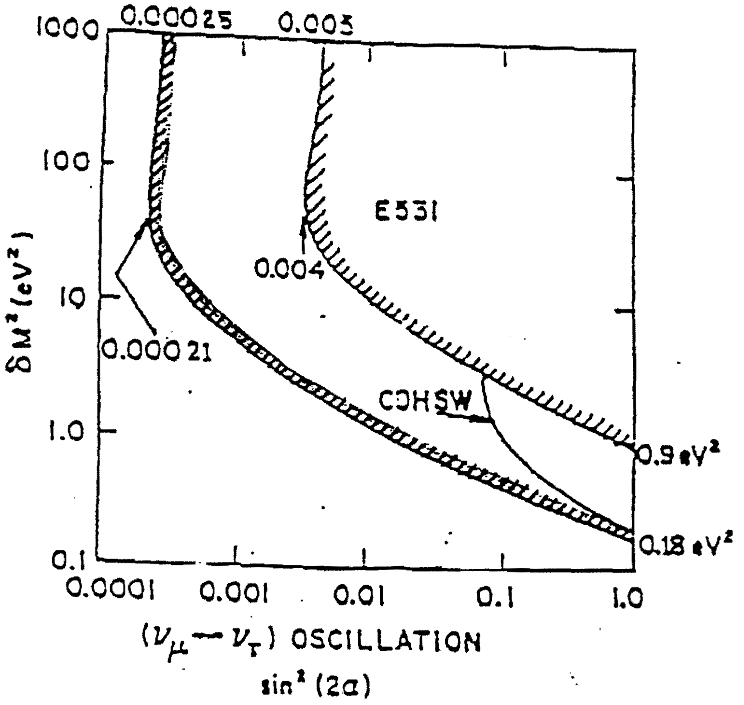
NEUTRINO OSCILLATION EXPERIMENT
ELEVATION VIEW

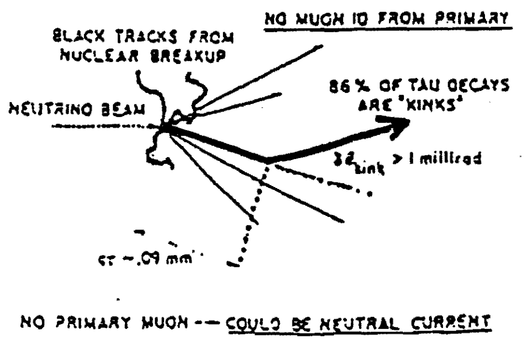
TABLE I
COMPARISON OF E-531 AND PROPOSED 150 GEV RUNNING

ITEM	E531	150 GeV
# PULSES	1×10^6	2.6×10^6
PROTONS/PULSE	1.3×10^{13}	2.0×10^{13}
AMT. EMULSION	23 liters	180 liters
FIDUCIAL VOL.	80%	90%
INT. (NC + CC)^f	3,386	185,000
INT. WITH TAGGED μ^-	1,870	132,000
INT. WITH PRIMARY τ's	0	?

$\langle E_\nu \rangle$ 30 9 GeV

$\nu_\mu \rightarrow \nu_\tau$





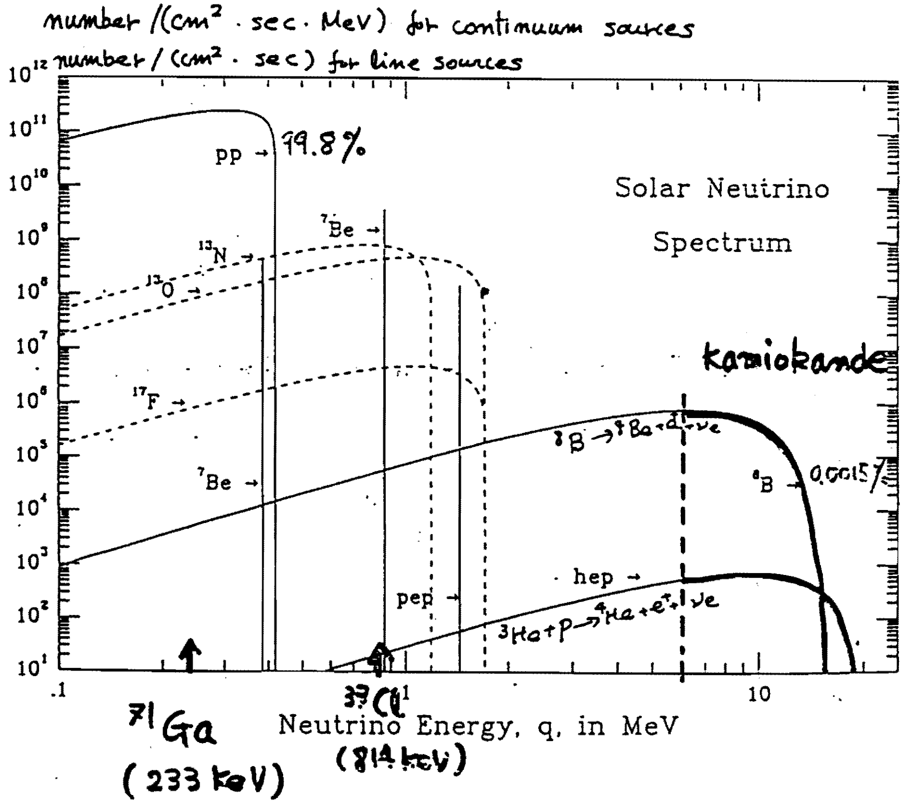
main background $\pi^- + A \rightarrow \pi^- + A$ (large P_T)

Solar Neutrino Problem

&

Neutrino Oscillations

Standard Solar Model



Solar Neutrino Problem

Chlorine Experiment (R.Davis et al.)

Reaction : $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

Detector : 615 tons of C_2Cl_4

Homestake gold mine (4200 m.w.e.)

Result : ${}^{37}Cl$ capture rate

$= \boxed{2.18 \pm 0.25 \text{ SNU}}$ for 1970-1987 runs

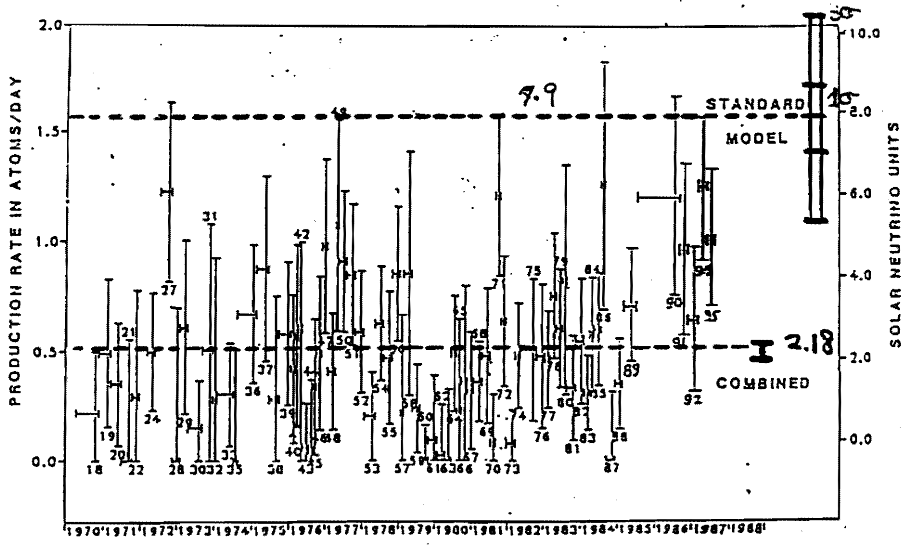
(R.Davis Neutrino '88)

: Standard Solar Model prediction

$= \boxed{7.9 \pm 2.5\ (3\sigma \text{ error})\text{ SNU}}$

(J.N.Bahcall & R.K.Ulrich '88)

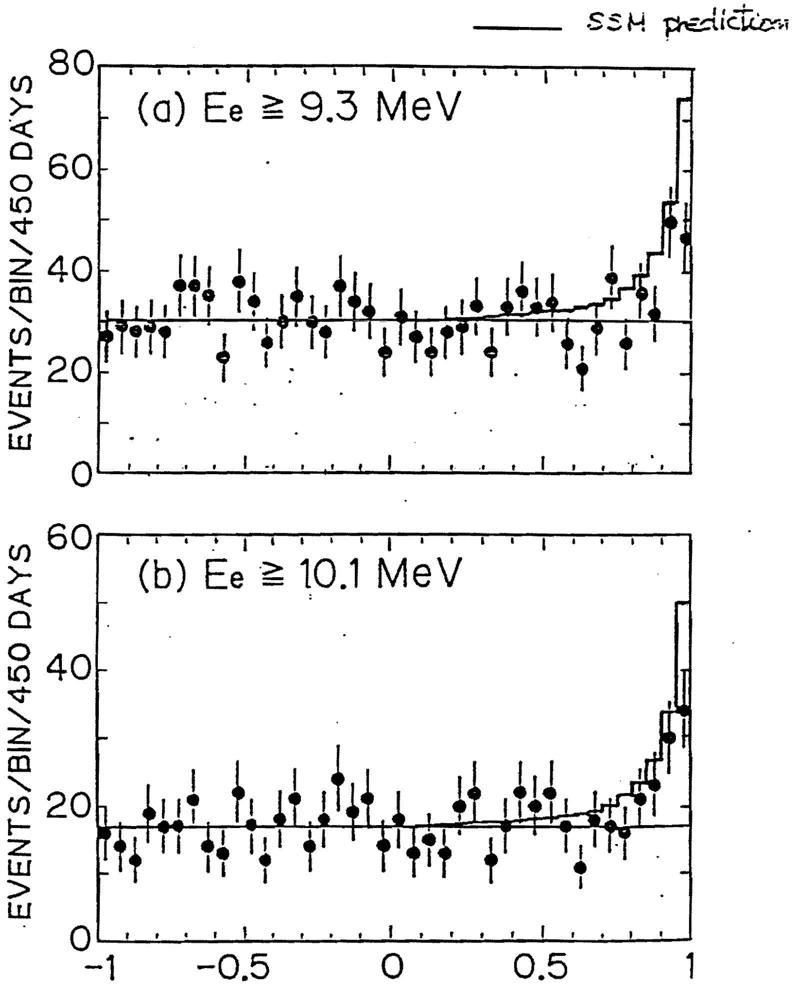
$1\ \text{SNU} = 10^{-36} \frac{\text{capture}}{\text{atom sec.}}$



Flux deficit → Solar Neutrino Problem

Selection by Directional Correlation

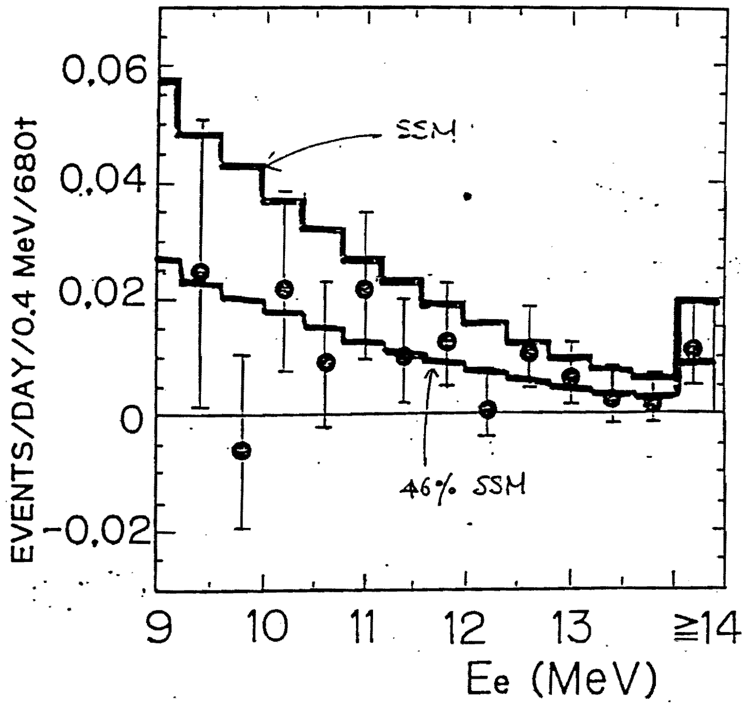
Kamiokande-II Angular Distribution



46% of 標準模型
太陽ニュートリノ問題、を確認。

Energy Distribution of Solar Neutrino Signal

$\nu_e + e \rightarrow \nu_e + e$



Possible Solutions to Solar Neutrino Problem

- Non-Standard Solar Physics
  - Reduce core temperature ← $\phi_\nu(^8B) \propto T^{18}$
    6% change for 1/3 depletion of ^8B flux
  - WIMPS in the sun

failure over 20 years

- Non-Standard Neutrino Physics
  - Neutrino decays
  - Neutrino helicity rotation
  - Oscillation in vacuum
  - Oscillation in matter (sun & earth)

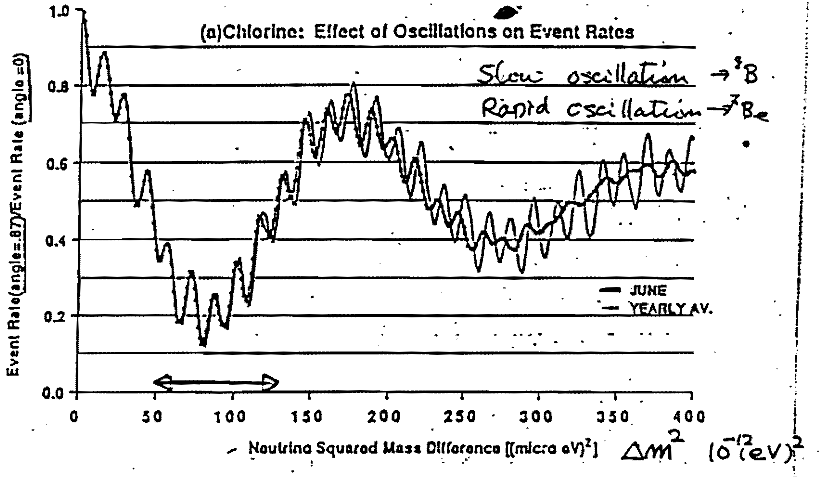
⇧

Ga ~ 50% SSM

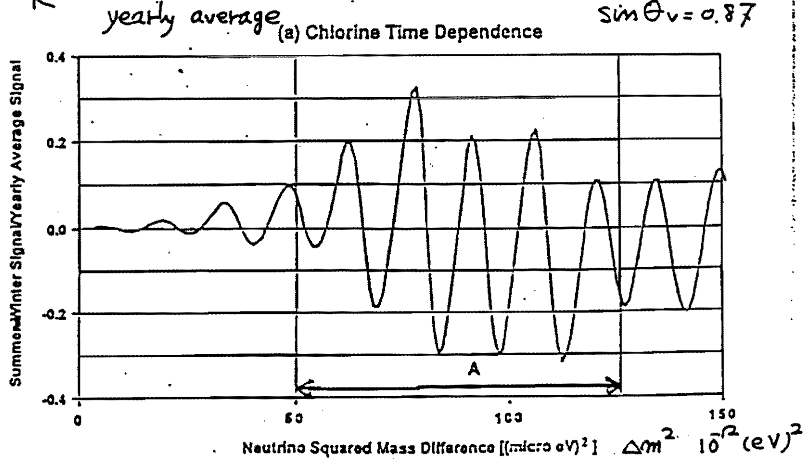
Striking Signature of "Just So" Osci.

^{37}Cl experiment

$$R = \frac{\text{Osci} (\sin\theta_\nu = 0.87)}{\text{No. Osci.}}$$



$$R = \frac{\text{Summer} - \text{Winter}}{\text{yearly average}}$$



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Golden parameters $\boxed{\sin\theta = 0.8 \quad \Delta m^2 \sim 10^{-10} (eV)^2}$

Solar Neutrino Energy Spectrum (total)

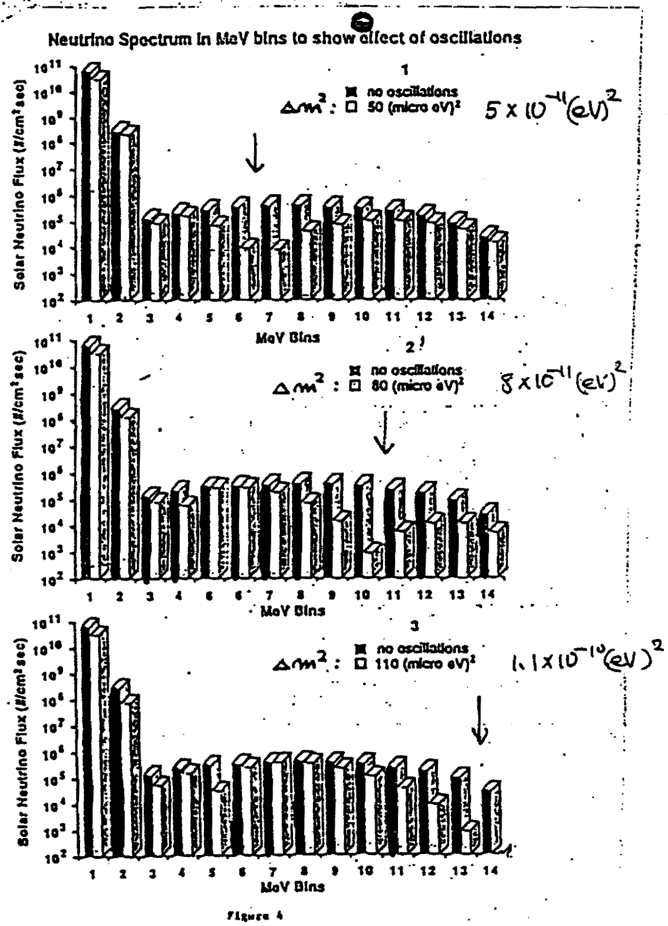


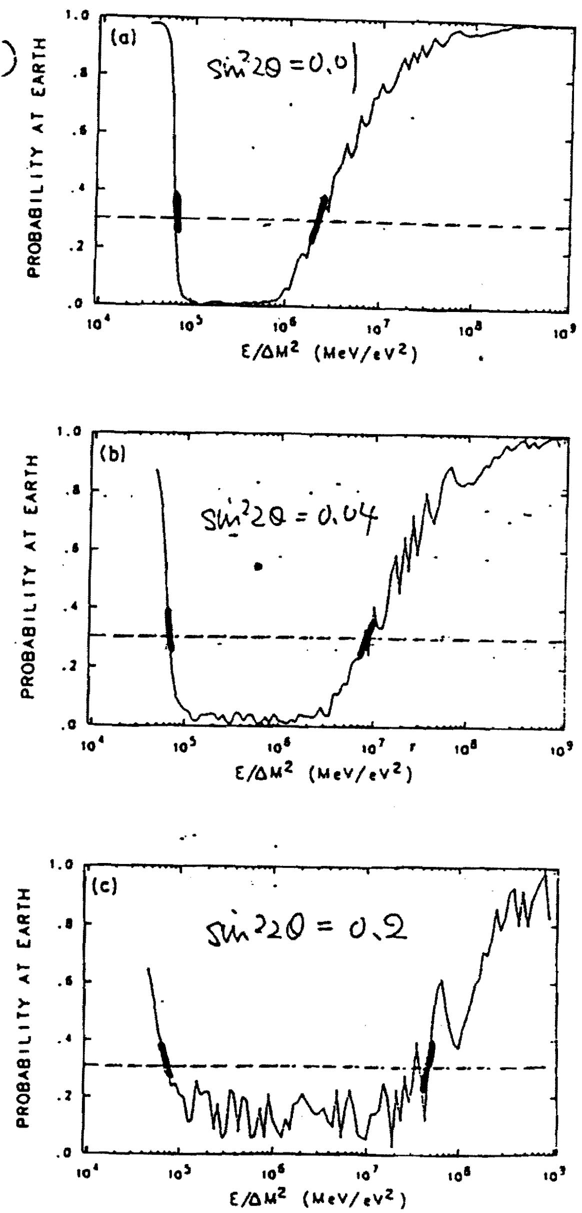
Figure 4

Rosen & Gelb
P.R. D34, 969 ('86)

$\Delta m^2 \sim 10^{-4}$

$\log_{10}\sin^2 2\theta + \log_{10}\Delta m^2 < -6.7$

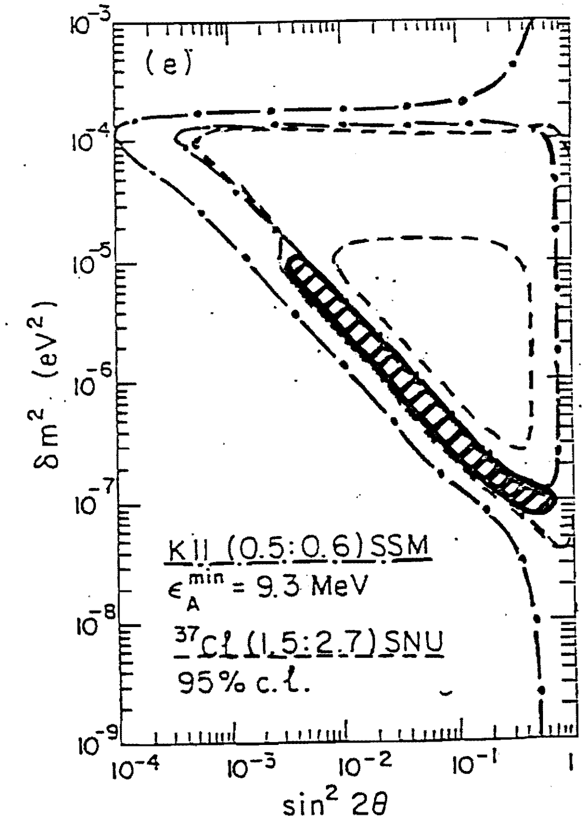
$P(\nu_e \to \nu_e)$



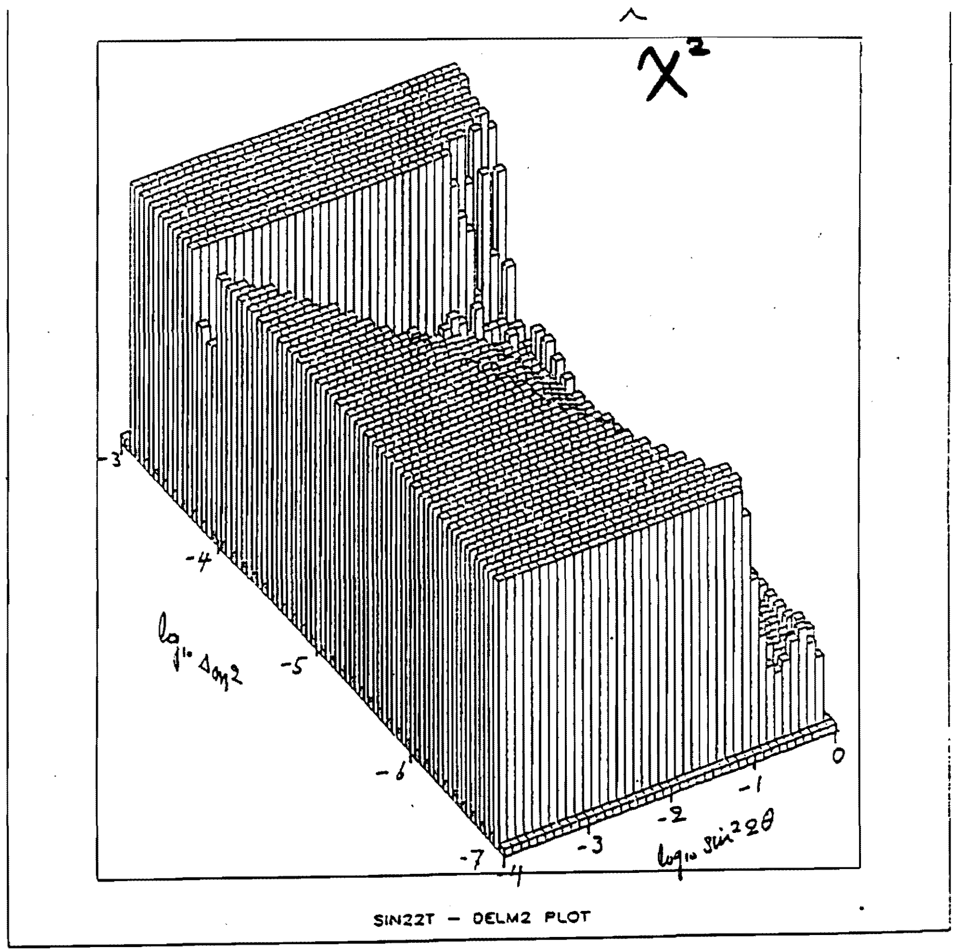
Bahcall & Haxton P.R. D? (1989)

1000 standard solar model

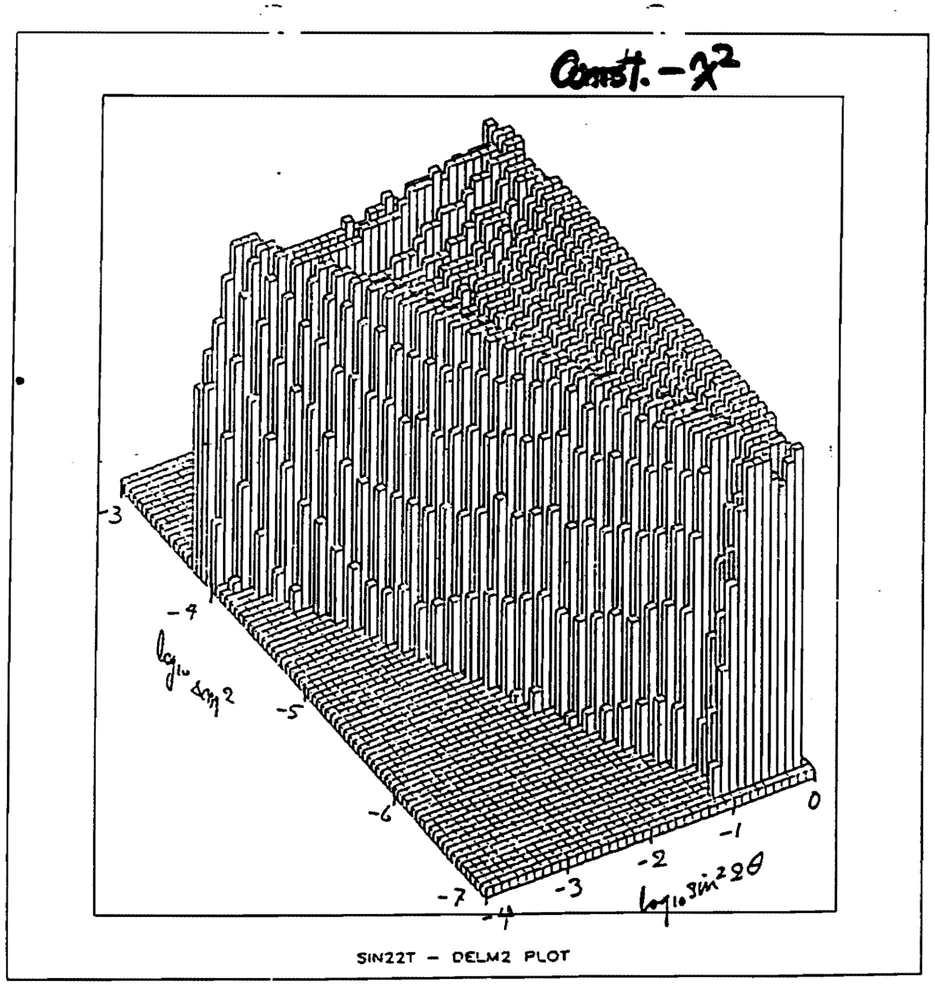
で計算.



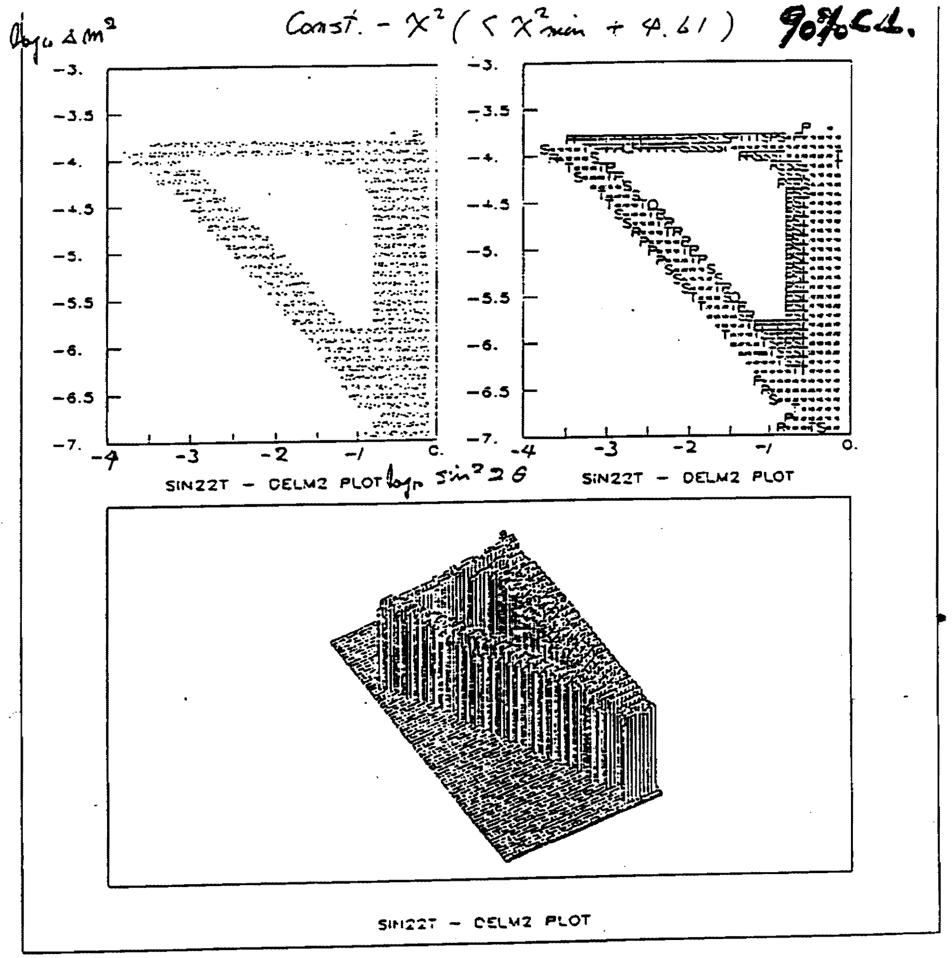
Bahcall & Haxton ('89)



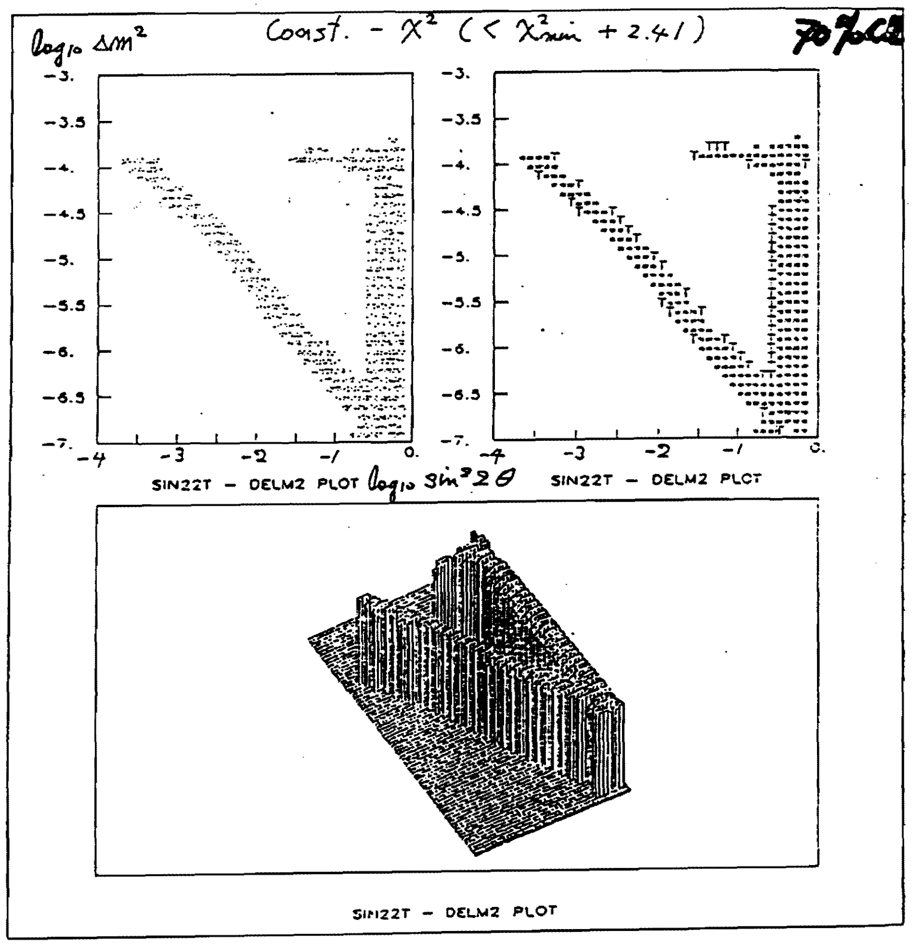
very preliminary



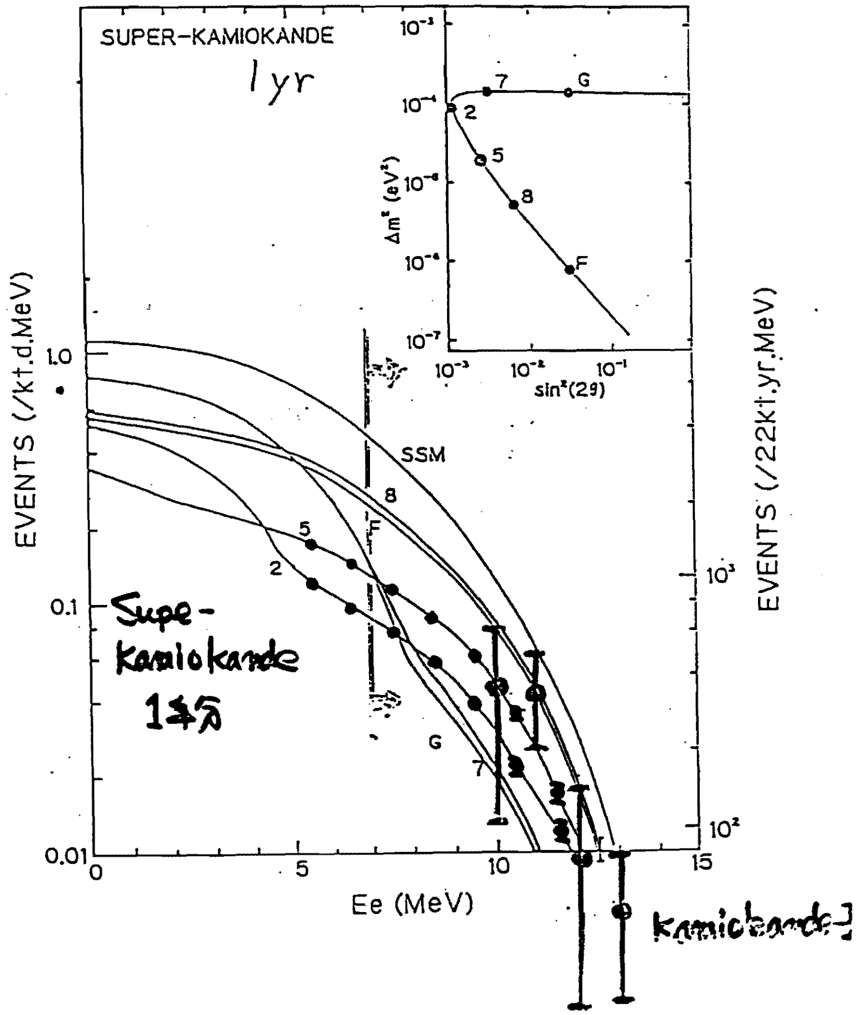
Very preliminary



Very preliminary



Very preliminary



Atmospheric Neutrino Deficit

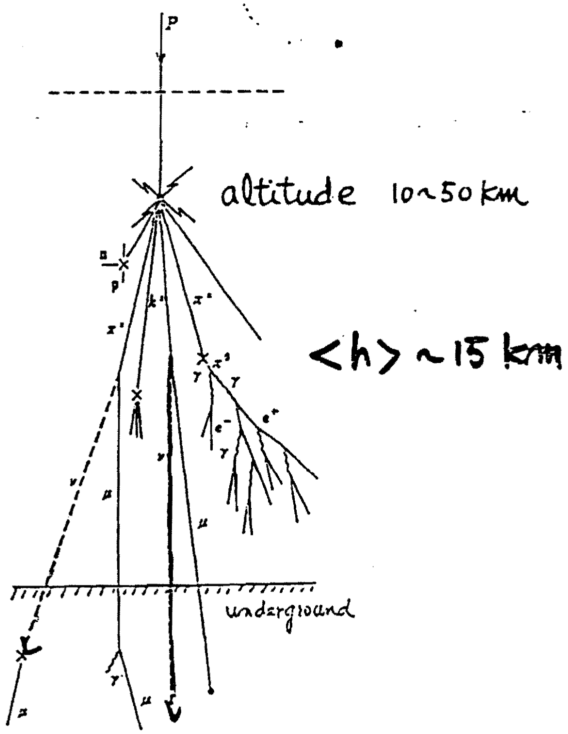
&

Neutrino Oscillations

Atmospheric Neutrino Sources

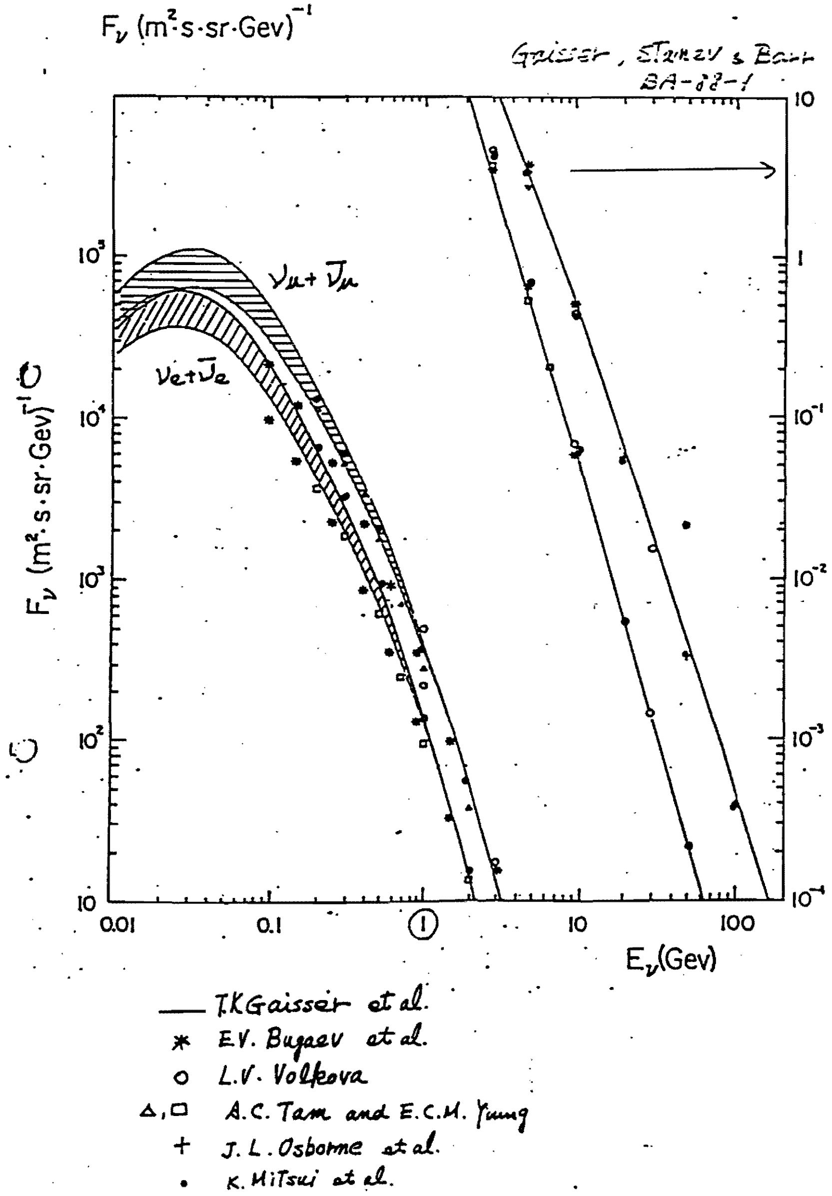
$$p + A \longrightarrow A' + \pi, K \longrightarrow \begin{cases} \mu \\ \enclose{circle}{\nu_\mu} \end{cases} \longrightarrow \begin{cases} e \\ \enclose{circle}{\nu_\mu}\enclose{circle}{\nu_e} \end{cases}$$

Figure 1.1: Illustration of atmospheric cascade.



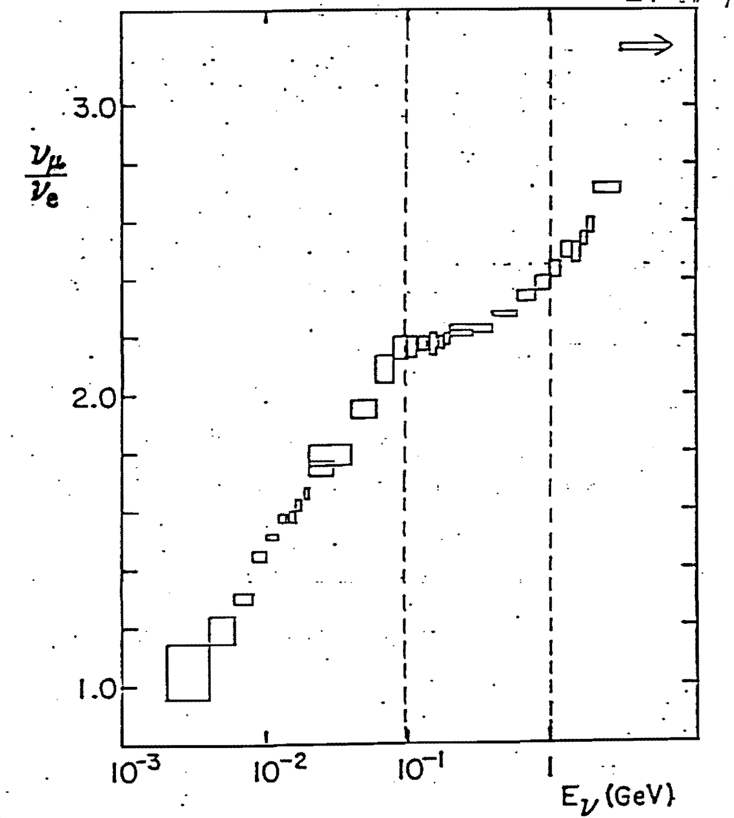
Energy Spectrum of Vertical Neutrinos

Gaisser, Stanev & Barr
BA-88-1



$(\nu_\mu+\bar\nu_\mu)\,/\,(\nu_e+\bar\nu_e)$

Gaisser, Stanev & Barr
BA-88-1



$$\begin{tikzcd}
N \arrow[r] & K^\pm\ \pi^\pm \arrow[r] & \mu^\pm\ \nu_\mu \arrow[r] & e^\pm\ \nu_\mu\ \nu_e \\
 & K^0 \arrow[ur] \arrow[r, "{(K^0\to\pi e\nu_e)\ (20\%)}"'] & \nu_e &
\end{tikzcd}$$

IMB : T.J.Haines et al., Phys.Rev.Lett. 57,1986('86)
Frejus : Ch.Berger et al., Phys. Lett. 227B,489('89)
Kamiokande : K.S. Hirata et al., Phys.Lett. 205B,416('88)

Table 1.2: Observed neutrino event numbers.

Experiment	Sensitivity (kton·yr)	ν Events (observed)	ν Events (predicted)	Ratio (obs./pred.)
IMB	3.77	401	402	1.00
observed $\mu - e$ decays		26%	34%	$\boxed{0.76}$
Frejus	1.56	188	212	0.89
fully contained		142	172	$\boxed{0.83}$
vertex contained		46	40	1.15
Kamiokande	2.87	277	337	$\boxed{0.82}$
single ring		190	250	$\boxed{0.76}$
multi ring		87	86	1.01
observed $\mu - e$ decays		94	147	$\boxed{0.64}$

Table 1.3: Results of particle type identification.

Experiment	Data	Monte Carlo
Frejus : all events (fully contained)		
charged current μ	108 (66)	125.8 (90.0)
charged current e	57 (56)	70.6 (66.8)
neutral current	23 (20)	16.0 (15.5)
Kamiokande : single ring events		
μ - like	85	144.
e - like	93	88.5

6

Monte Carlo Calculation of Atmospheric Neutrino Interactions

KAMIOKANDE

Interaction Type	Generated Events		Expected Single Ring Events	
C.C. Quasi-Elastic $(\nu N \rightarrow \ell^{\pm} N')$	44.7 %	⟹	74.8 %	93%
C.C. One-π Prod. $(\nu N \rightarrow \ell^{\pm} \pi N')$	21.1 %	⟹	18.7 %	
C.C. Multi-π Prod. $(\nu N \rightarrow \ell^{\pm} m\pi N')$	21.3 %	⟹	2.0 %	
N.C. One-π Prod. $(\nu N \rightarrow \nu \pi N')$	6.4 %	⟹	2.8 %	5%
N.C. Multi-π Prod. $(\nu N \rightarrow \nu m\pi N')$	6.2 %	⟹	1.7 %	

Table 1.4: Ratios of charged current electron to muon events.

Experiment	(e/μ)		$\frac{(e/\mu)_{obs.}}{(e/\mu)_{pred.}}$
	(observed)	(predicted)	
Frejus			
all	0.53±0.09	0.56±0.06	0.95±0.19
fully contained	0.85±0.16	0.74±0.07	1.15±0.24
Kamiokande			
single ring	1.09±0.16	0.61±0.10	1.79±0.26
$\cos\theta_z > 0$	1.21±0.25	0.62±0.01	1.95±0.40
$\cos\theta_z < 0$	0.98±0.21	0.60±0.01	1.63±0.35

Oscillation Analysis on
Atmospheric Neutrinos.

oscillation parameters

- E_ν

$$E_\nu \approx 3.5\left(1-\sqrt{1-0.8\,E_\ell\,(\mathrm{GeV})}\right)$$

$\langle y\rangle \sim 0.3 + 0.1\,E_\nu\,(\mathrm{GeV})$ for $E_\nu < 2\,\mathrm{GeV}$

$y \equiv 1 - E_\ell/E_\nu$

$300\,\mathrm{MeV} < E_\nu < 1.2\,\mathrm{GeV}$ for $E_\ell = 200 \sim 700\,\mathrm{MeV}$

- path length, L

$$L(\theta_z) = R_\otimes\left[\sqrt{(1+\langle h\rangle/R_\otimes)^2 - \sin^2\theta_z} - \cos\theta_z\right]$$

$$24\,(\mathrm{km/GeV}) \lesssim L/E \lesssim 2\cdot 10^4\,(\mathrm{km/GeV})$$

- Δm^2

$\sin^2(1.27\,\Delta m^2 L/E) \approx 0.5$ maximal osci.

for Kamiokande no $\cos\theta_z$ & E dependence

$$\Delta m^2_{ij} > 0.03\ \mathrm{eV}^2$$

$\Delta m^2_{\mu\tau} < 0.4\ \mathrm{eV}^2$ $\Delta m^2_{e\tau} < 0.03\ \mathrm{eV}^2$

(accelerator & reactor exp.)

- $P(\nu_\alpha \to \nu_\alpha) = P(\bar\nu_\alpha \to \bar\nu_\alpha)$

$P(\nu_\alpha \to \nu_\beta) = P(\bar\nu_\alpha \to \bar\nu_\beta)$

CP violation effects :

(not possible in two neutrino oscillation
not observable in leading oscillation for three neutrinos

$\Downarrow$

$$P(\bar\nu_\mu \to \bar\nu_e) - P(\nu_\mu \to \nu_e)$$
$$= -\left[P(\bar\nu_\mu \to \bar\nu_\tau) - P(\nu_\mu \to \nu_\tau)\right]$$
$$= P(\nu_e \to \nu_\tau) - P(\bar\nu_e - \bar\nu_\tau)$$
$$= -4\, s_1^2 c_1 s_2 c_2 s_3 c_3 \sin\delta\left[\sin\Delta_{12} + \sin\Delta_{23} + \sin\Delta_{31}\right]$$

$$\left(\Delta_{ij} = \tfrac{1}{2}\Delta m^2_{ij}\, L/E\right)$$

P.R.L. 45, 2084 ('80)

leading oscillation cases.

$$\sin^2 2\theta \langle \sin^2(1.27\Delta m^2 L/E)\rangle$$

$$= \left(\frac{r}{r-1}\right)\left(\frac{1-R}{1+Rr}\right) \quad \text{for } \nu_\mu \leftrightarrow \nu_e$$

$$= 1-R \quad \text{for } \nu_\mu \leftrightarrow \nu_\tau$$

$$R = (N_\mu/N_\mu^0) / (N_e/N_e^0)$$

$$0.42 < R < 0.70 \quad 90\% \text{ C.L.}$$

$\nu_\mu \rightarrow \nu_e$

$$\sin^3 2\theta > 0.39$$

$$\Delta m_{e\mu}^2 \approx 0.03 (eV)^2$$

$\nu_\mu \leftrightarrow \nu_\tau$

$$\sin^2 2\theta > 0.60$$

$$0.03 < \Delta m_{\mu\tau}^2 < 0.4 \ eV^2$$

V. Barger and K. Whismant P.L. 209B, 365 ('88)

J.G. Learned, S. Pakvasa and T.J. Weiler P.L. 207B, 79 ('88)

Implication from see-saw mechanism

$$m_{\nu_i} = m_i^2 / M_R$$

$$\Delta m_{ij}^2 \cong m_{\nu_j}^2 \quad (j>i)$$

$\nu_\mu \leftrightarrow \nu_e$

◎ $\Delta m_{e\mu}^2 \approx 0.03 \ eV^2$

$$m_{\nu_\mu} \approx 0.17 \ eV$$

$$m_{\nu_e} \approx (3\cdot 10^{-4} - 4\times 10^{-6}) eV$$

$$m_{\nu_\tau} \approx (100 - 50) eV$$

no MSW effect on solar ν

$(10^{-4} - 10^{-7}) eV^2$

$$m_t \sim m_c \sqrt{m_{\nu_\tau}/m_{\nu_\mu}} \lesssim 45 \ GeV$$

$\nu_\mu \leftrightarrow \nu_\tau$

⊙ $0.03\ \mathrm{eV}^2 \leqslant \Delta m^2_{\mu\tau} \leqslant 0.4\ \mathrm{eV}^2$

$\sin^2 2\theta > 0.60$

$m_{\nu_\tau} \approx (0.17 - 0.63)\ \mathrm{eV}$

$m_{\nu_\mu} \approx (0.3 - 2)\times 10^{-3}\ \mathrm{eV}$

$m_{\nu_e} \approx (10^{-9} - 10^{-6})\ \mathrm{eV}$

$\Delta m^2_{e\mu} \sim m^2_{\nu_\mu} \approx (0.1 - 4.0)\times 10^{-6}\ \mathrm{eV}^2$

MSW: solution to the solar ν problem

$\theta_{e\mu} = 4°$ and 36° from MSW

$\theta_{\mu\tau} > 31°$

⇩

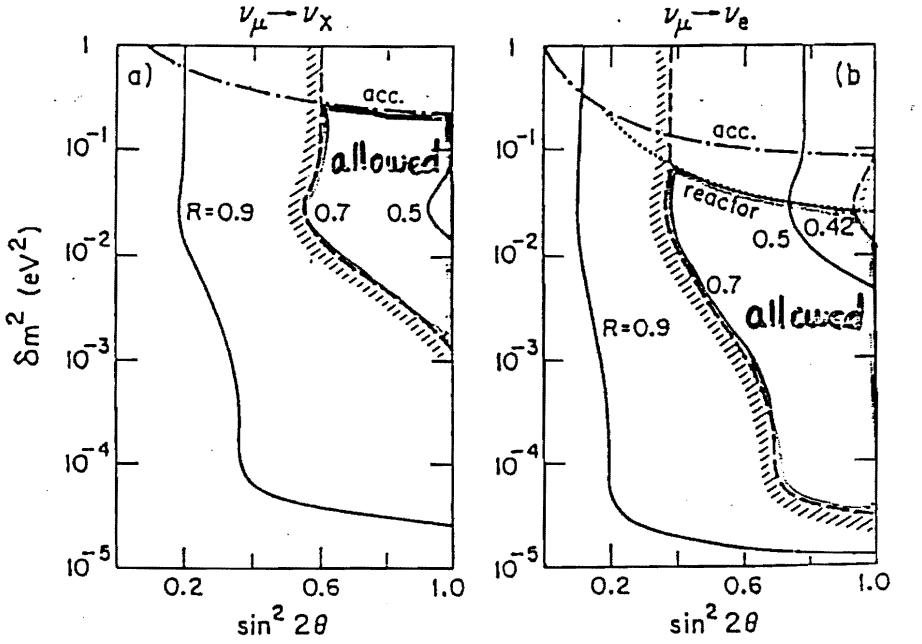
$\Delta m^2_{e\mu} \sim 10^{-6}$ $\theta_{\mu e} \sim 4°$

⇩

Ga. : (10 - 50) SNU

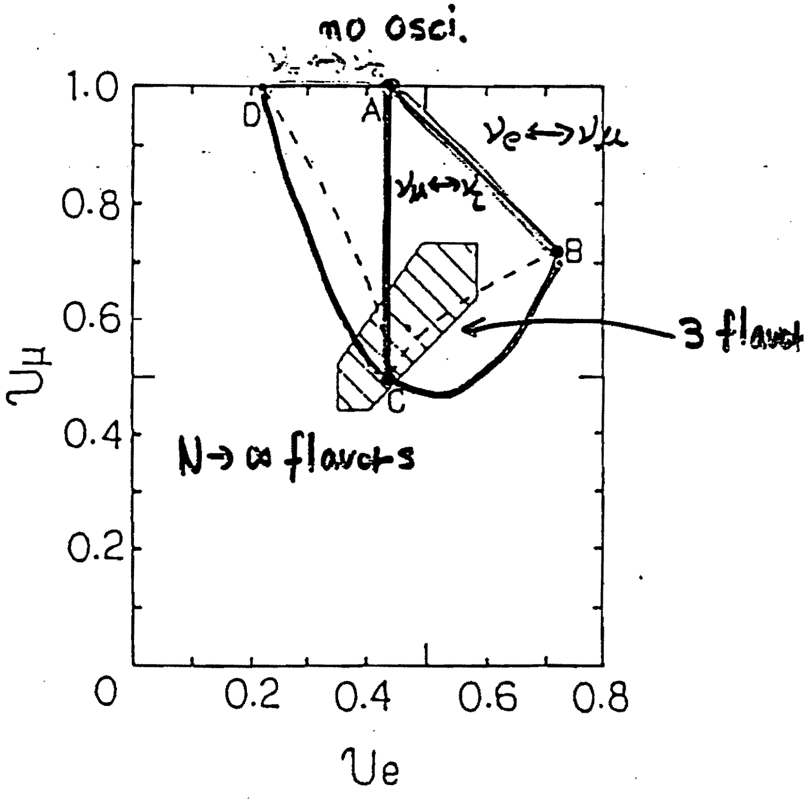
$m_t \approx (17 - 85)\ \mathrm{GeV}$

V. Barger et al., P.L. 209B, 365 ('89)



K.Hidaka, M.Honda, S.Midorikawa
Phys. Rev. Lett. 61, 1537 ('88)

$\mathcal{U}_\mu = N_\mu / N_\mu^0 \quad \mathcal{U}_e = N_e / N_\mu^0$



B. Many Flavor Neutrino Oscillations

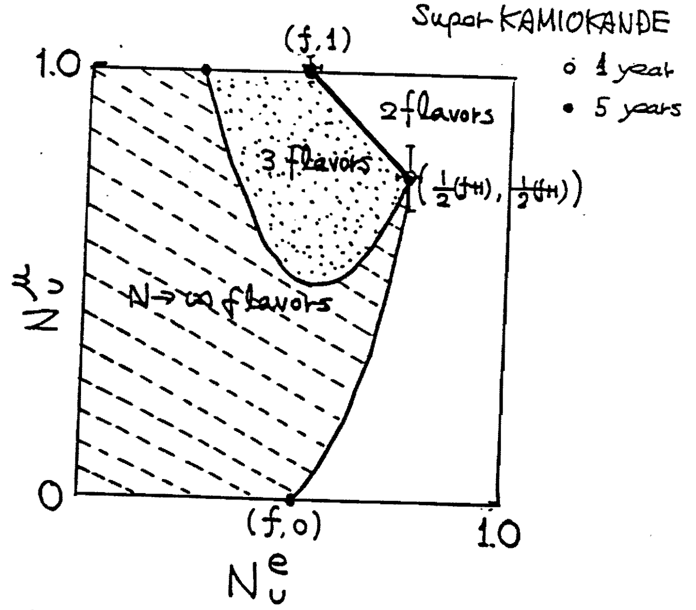
- Frampton-Glashow plot (P.R D25)

two-neutrino case

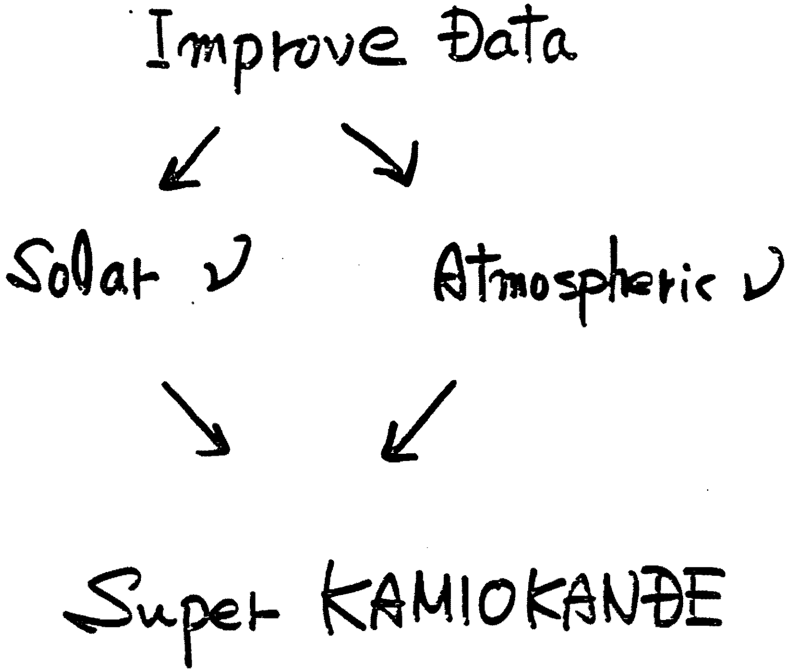
$N_D^\mu = 1 \quad N_D^e = f \quad (f \leq 1)$

$N_U^\mu = P_{\mu\mu} + f P_{e\mu} \quad N_U^e = f P_{ee} + P_{\mu e}$

no oscillation $N_U^\mu = 1 \quad N_U^e = f$
maximum oscillation $N_U^\mu = \frac{1}{2}(f+1) \quad N_U^e = \frac{1}{2}(f+1)$
oscillation $N_U^\mu + N_U^e = f + 1$



Conclusion.



Improve Data

Solar ν

Atmospheric ν

Super KAMIOKANDE

早く !!