IMPORTANCE of NEUTRINOS

1. Particle physics

   A. Probe of weak interaction

   B. ν Mass as a hint of new physics

2. Cosmology

   $m_\nu \sim 1$ to 2 eV would be significant part of dark matter

3. Astrophysics

   A. Neutrino astronomy

   B. Supernova (Type II) energetics

ν OSCILLATIONS

		Δm^2	$\sin^2 2\theta$
*** ATMOSPHERIC			
	$\nu_\mu \to \nu_\tau$ (ν_s)	10^{-2}-10^{-3} eV^2	~ 1
** SOLAR			
	$\nu_e \to \nu_\mu + \nu_\tau$ (ν_s)	10^{-5} eV^2	10^{-2}
		10^{-4} to 10^{-5} eV^2	~ 0.8
		$\sim 10^{-10}$ eV^2	$0.8 - 1$
* LSND	$\nu_\mu \to \nu_e$	$\gtrsim 1$ eV^2	$\simeq 10^{-2}$

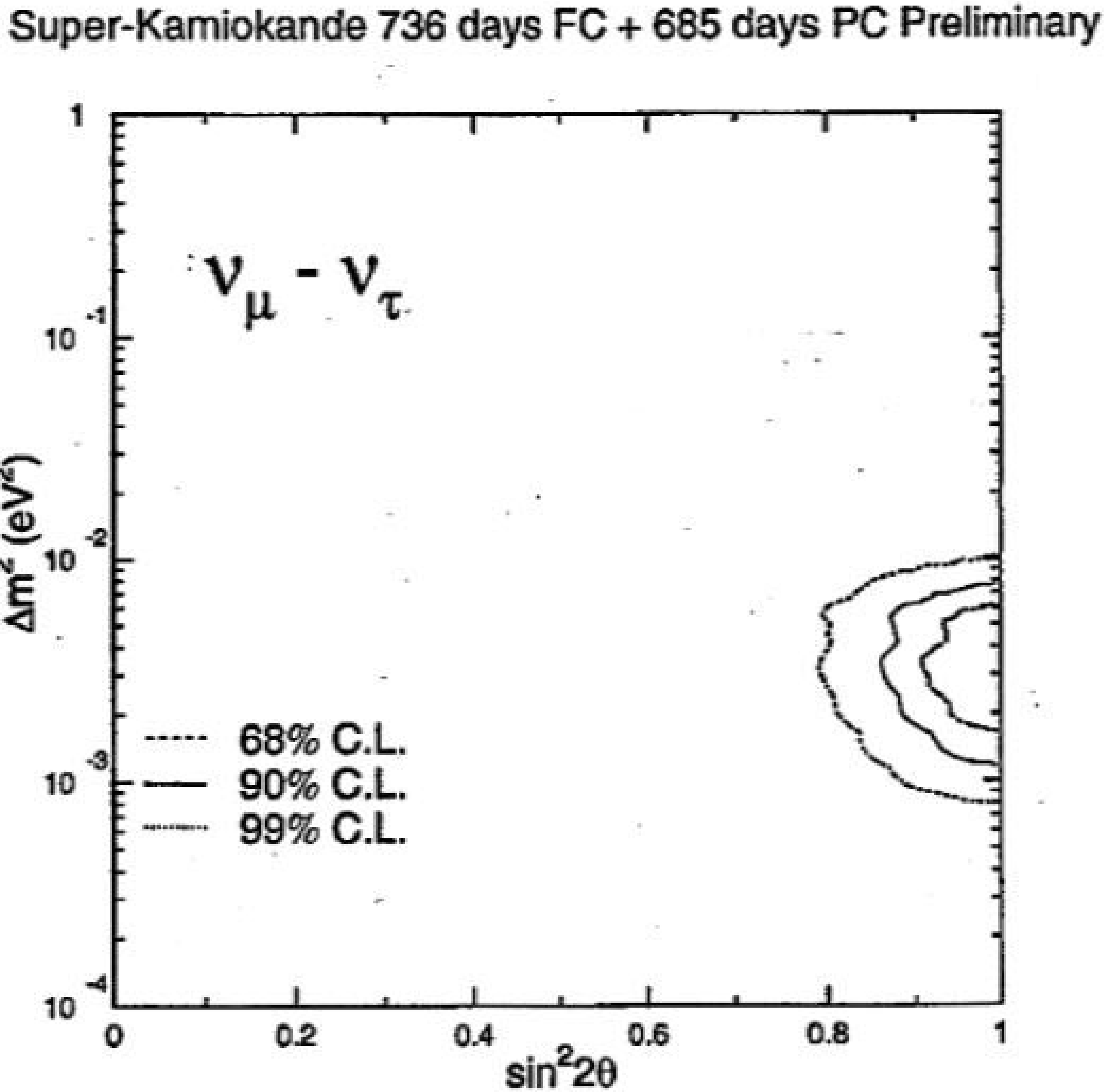
ATMOSPHERIC

Multi-GeV ν_μ ($E_\nu > 1.3$ GeV)

$$\frac{\text{UP}}{\text{DOWN}} \approx 0.5$$

UP : 2300 to 13000 km

DOWN : 30 to 100 km



Super-Kamiokande 736 days FC + 685 days PC Preliminary
$\nu_\mu - \nu_\tau$
68% C.L.
90% C.L.
99% C.L.
Δm^2 (eV^2)
$\sin^2 2\theta$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1

up-down asymmetry for massless neutrinos

Off diagonal neutral current

$\nu_\mu + ? \rightarrow \nu_\tau + ?$

ν_μ "rotates" into ν_τ in analogy with optical activity

Oscillation length $\propto \frac{1}{G_F \rho}$

~ 3000 to 6100 km

L.W. PRD 17, 2369 (1978)

M.C. Gonzalez-Garcia + 7 (1998)

Lipari Lusignoli (1999)

FUTURE $\Delta m^2 \sim 10^{-2}$ to 10^{-3} eV^2

1. $\nu_\mu \to \nu_\tau$ vs $\nu_\mu \to \nu_s$
   a. Observe ν_τ
      Super K, MINOS,
      NGS
   b. Matter affect for $\nu_\mu \to \nu_s$
      Super K
2. Oscillation into ν_e
   $\longrightarrow |U_{e3}|^2$
3. Possible CP Violation
   $\nu_\mu \longrightarrow \nu_e$
   vs. $\bar{\nu}_\mu \to \bar{\nu}_e$

SOLAR

Radiochemical Gallium Expts.

$$\frac{\text{Expt}}{\text{Theory}} = .57 \pm .06$$

Mainly expected

$$p + p \rightarrow d + e^{+} + \underline{\underline{\nu_e}}$$

$$e^{-} + {}^{7}Be \rightarrow {}^{7}Li + \underline{\underline{\nu_e}}$$

$$[\, p + {}^{7}Be \rightarrow {}^{8}B + \underline{\underline{\nu_e}} \,]$$

Luminosity constant →

$$\frac{\text{Expt}}{\text{Th}} \gtrsim 0.7$$

and 0.7 corresponds to no ^{7}Be

FORTHCOMING SOLAR ν EXPERIMENTS

SMOKING GUNS

1. Neutral current / Ch. current

SNO $\nu_x + d \to n + p + \nu$

of to $\nu_e + d \to e^- + p + p$

2. Spectrum of ^8B ν

SNO, Super K

3. Anomalous seasonal variation of monoenergetic ^7Be ν

BOREXINO

KAMLAND

4. Day-night effect. $\nu_x \to \nu_e$ in the earth at night

SNO, Super K

THEORETICAL MOTIVATION

QUARK-LEPTON SYMMETRY

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

1. Three generations
2. Mass hierarchy
3. Same weak interactions

If symmetry becomes exact ν_{Ri} must exist → ν mass

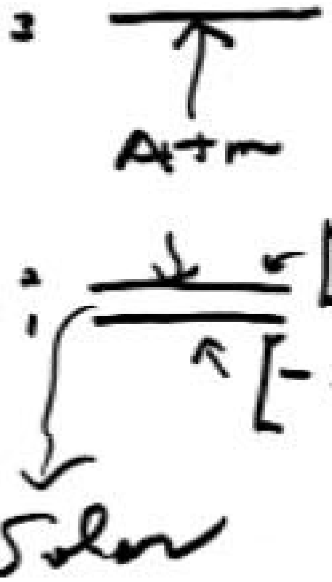
GM-R-S solution: when symmetry is broken ν_R gets mass M

$$m_\nu \sim \frac{m_D^2}{M}$$

$$\begin{matrix} L \\ R \end{matrix} \left(\begin{array}{c|c} 0 & m_D \\ m_D & M \end{array} \right)$$

3 ν Scenarios

(1)



$m_3 \cong 0.1\,eV - .03\,eV$

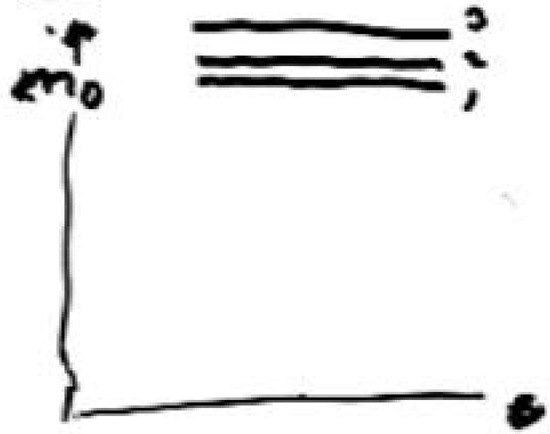
$3:\quad \frac{\nu_\mu + \nu_\tau}{\sqrt{2}} + U_{e3}\,\nu_e$

$2:\quad \left[\cos\theta\left[\frac{\nu_\mu - \nu_\tau}{\sqrt{2}}\right] + \nu_e \sin\theta\right]$

$1:\quad \left[-\sin\theta\left[\frac{\nu_\mu + \nu_\tau}{\sqrt{2}}\right] + \nu_e \cos\theta\right]$

$m_2 < .01\,eV$

(2)



Almost degenerate with $m = \underline{m_0}$

1) $m_0 = \underline{m(\nu_e)}$

2) $0\nu\,\beta\beta$ decay measures m_{ee}

$$m_{ee} = m_0\left[\pm|U_{e3}|^2 \pm \sin^2\theta \pm \cos^2\theta\right]$$

$$m_0 \gtrsim m_{ee}/\cos 2\theta$$

Conclusion

WHAT WE KNOW

1. ν's are not all massless
2. One mass eigenvalue > 0.03 eV
3. One mixing angle is large

FUTURE OSCILLATION EXPTS. ARE DESIGNED FOR

1. Do we need ν_s ?
2. To better determine Δm^2 and to determine other mixing angles.

OSCILLATION EXPTS DON'T TELL US

1. What are the masses?
2. Is the see-saw theory relevant ?