SEESAW MECHANISM
AND
ITS VARIOUS REALIZATIONS

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1. INTRODUCTION

2. TYPE I, TYPE II AND DOUBLE SEESAW

3. LARGE MIXINGS FROM TYPE II SEESAW: TWO EXAMPLES

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    A) 3 X 2
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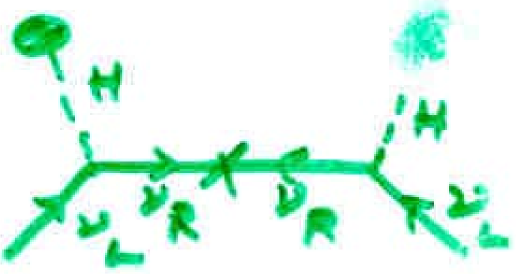
SEESAW MECHANISM FOR SMALL NEUTRINO MASSES:

STD MODEL + ν_R WITH A
LARGE MAJORANA
MASS (B-L=2)

$$\begin{array}{c|cc} & \nu_L & \nu_R \\ \hline \nu_L & 0 & M_D \\ \nu_R & M_D^T & M_R \end{array}$$



$$\Rightarrow \boxed{m_\nu \simeq -M_D^T M_R^{-1} M_D}$$

$m_{\nu D} \lesssim v_{wk} \ll M_R \Rightarrow m_\nu \ll m_{e,u,d}.$

TYPE I SEESAW

GELL-MANN, RAMOND, SLANSKY; YANAGIDA; R.N.M., SENJANOVIĆ; GLASHOW
(1979)

PHYSICS OF THE SEESAW MECHANISM

ADDING ν_R TO STD MODEL OPENS UP A WHOLE NEW LANDSCAPE OF PHYSICS !!

- RESTORES BOTH QUARK-LEPTON
- WEAK INT. BECOMES PARITY CONSERVING

$$\begin{tikzcd}
\begin{pmatrix} u_L \\ d_L \end{pmatrix} \arrow[r, leftrightarrow, "g_L"] \arrow[d, leftrightarrow, "P"'] & \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \arrow[d, leftrightarrow, "P"] \\
\begin{pmatrix} u_R \\ d_R \end{pmatrix} \arrow[r, leftrightarrow, "g_L"'] & \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}
\end{tikzcd}$$

PATI, SALAM;
R.N.M. PATI '74
SENJANOVIĆ, R.N.M. '75

- GAUGE SYM. $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- $Q = I_{3L} + I_{3R} + \frac{B-L}{2}$

A. DAVIDSON
R.N.M., MARSHAK } '79

TWO ISSUES FOR LEFT-RIGHT SYM. MODELS:

— × —

(i) HOW TO GET TO STD MODEL?

$$\begin{tikzcd}
SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X \arrow[d, "?"] \\
SU(3)_c \times SU(2)_L \times U(1)_Y \arrow[d, "\langle \Phi(2,2,0) \rangle \neq 0"] \\
SU(3)_c \times U(1)_{em}
\end{tikzcd}$$

(ii) SMALLNESS OF m_ν :

SINCE : $h_q \bar{Q}_L \Phi Q_R + h_\ell \bar{\Psi}_L \Phi \Psi_R$

$\Rightarrow$ $m_{q,\ell,\nu}$ OF SAME ORDER!!

m_ν AND SPONTANEOUS BREAKING OF PARITY:

$$\begin{tikzcd}
SU(2)_L \times SU(2)_R \times U(1)_X \arrow[d, "v_R = \langle \Delta_R^0 \rangle"] \\
SU(2)_L \times U(1)_Y \arrow[d, "v_{wk} \equiv \langle \phi \rangle"] \\
U(1)_{em}
\end{tikzcd}$$

$$\begin{array}{cc} \nu_L & N_R \\ \left(\begin{array}{cc} 0 & 0 \\ 0 & f v_R \end{array}\right) \end{array}$$

$$\begin{array}{cc} \nu_L & N_R \\ \left(\begin{array}{cc} f v_L & m_{\nu D} \\ m_{\nu D} & f v_R \end{array}\right) \end{array}$$

$$m_{\nu_D} \simeq h v_{wk} \ll f v_R$$

$$m_\nu = f \frac{v_{wk}^2}{2 v_R} - M_{\nu D}^T \frac{f^{-1}}{v_R} M_{\nu D}$$

PARITY SYM. ⇒ BOTH

THREE IMPLICATIONS

(i) ν_R MASS CONTROLLED BY B-L SYM. SCALE

(ii) $m_\nu \rightarrow 0$ AS WEAK INT. BECOMES PURE V-A.

(iii) MODIFICATION OF SEESAW (TYPE II)

PARITY SYMMETRY AND TYPE II SEESAW:

x

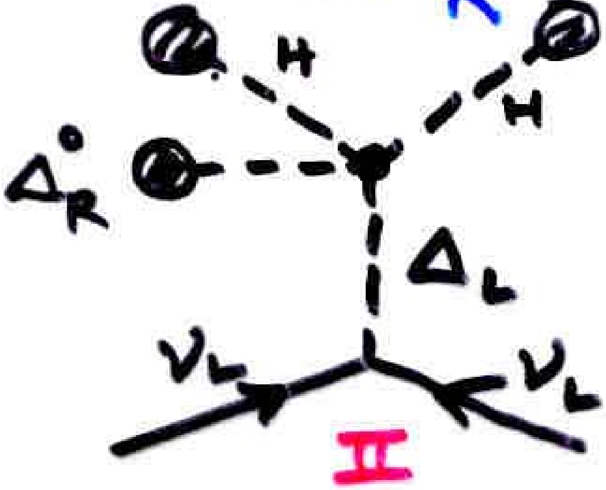
PARITY $\Rightarrow$ $\nu_R \nu_R \Delta_R \leftrightarrow \nu_L \nu_L \Delta_L$

OR $(\nu_R \chi_R)^2 \leftrightarrow (\nu_L \chi_L)^2$

TYPE II

LAZARIDIS, SHAFI; WETTERICH '80
R.N.M., SENJANOVIC '80.

$$\mathcal{M}_\nu = f\frac{v_{wk}^2}{\lambda v_R} - M_D^T (f v_R)^{-1} M_D$$



II

I

OTHER REALIZATIONS OF SEESAW:

TEV SCALE DOUBLE SEESAW

(R.N.M., VALLE '86)

TYPE I OR II SEESAW + Δm^2_{ATM}.

$\Rightarrow M_R \sim 10^{15}$ GeV

IS IT ALWAYS TRUE ?

⇒ BEYOND ν_R : ν_R , S.

(AS IN E_6)

$$\Rightarrow \begin{array}{ccc} \nu_L & \nu_R & S \\ \left(\begin{array}{ccc} 0 & m_{\nu D} & 0 \\ m_{\nu D}^T & 0 & M \\ 0 & M^T & \mu \end{array}\right) \end{array}$$

$$\Rightarrow \mathcal{M}_\nu = - m_{\nu D} M^{-1} \mu M^{T^{-1}} m_{\nu D}^T$$

⇒ $m_{\nu D}, \mu \ll M$ ⇒ $M \sim$ few TeV POSSIBLE.

(GeV)

(EXPECT TeV Z')

DOUBLE SEESAW TO TYPE III SEESAW:

BARR '03
ALBRIGHT, BARR '04

PARITY SYM:

$$\begin{pmatrix} 0 & m_{\nu D} & f v_L \\ m_{\nu D}^T & 0 & f v_R \\ f v_L & f v_R & M' \end{pmatrix} \begin{matrix} \uparrow \\ P \\ \downarrow \end{matrix}$$

$$\Rightarrow \; m_\nu = - m_{\nu D} M^{-1} M' M^{T-1} m_{\nu D}^T$$

$$- \left(m_{\nu D} + m_{\nu D}^T \right) \frac{v_L}{M}$$

$$M \equiv f v_R \sim M' \sim 10^{15}\,\mathrm{GeV}$$

SEESAW IN THE QUARK SECTOR

$SU(2)_L \times U(1)_Y$ SINGLET VECTOR LIKE QUARKS. Q
(IN LR)

$$\begin{array}{c|cc} & q_L & Q_L \\ \hline q_R & 0 & h v_R \\ Q_R & h v_L & M \end{array} \Rightarrow m_q \simeq \frac{h^2 v_L v_R}{M}$$

LESS FINE TUNING OF YUKAWAS:

DAVIDSON, WALI '87
'88.

⋮

HOW USEFUL IS SEESAW FOR UNDERSTANDING NEUTRINO MASSES AND MIXINGS ?

OF PARAMETERS : $18 + 3 = 21$

OF ν- OBSERVABLES : $\underset{m_i}{3} + \underset{\theta_{ij}}{3} + \underset{\delta_i}{3}$

⇒ MODEL BUILDING : (CP CONSERVING)

(i) SO(10) (TYPE II) (1-PAR

(ii) RADIATIVE CORRECTIONS (TYPE II) (3-)

(iii) 3 X 2 SEESAW (7)

(iv) $L_e - L_\mu - L_\tau$ AND SINGULAR SEESAW. (4-)

MINIMAL SO(10) WITH $\Delta(B-L)=2$ BREAKING:

(SUSY).

X

BABU, R.N.M. '92
BAJC, SENJANOVIĆ, VISSANI '02
GOH, R.N.M., NG '03.

SO(10) : MATTER $\psi \subset \{16\}$

HIGGS: $\{210\}$ BREAKS SO(10).

$\Delta \equiv \{126\}$ " $SU(2)_R \times U(1)_{B-L}$

$H \equiv \{10\}$ " $SU(2)_L \times U(1)_Y$

YUKAWA: $W = h\,\psi\psi H + f\,\psi\psi\bar{\Delta}$

- f UNIFIES ν's WITH q, ℓ. FLAVORS.
- 12 PARAMETERS (SOFT $\not{B}$) ALL FIXED BY (Q, e, μ, τ).

$$M_u = h\, v_u + f\, \kappa_u$$

$$M_d = h\, v_d + f\, \kappa_d$$

$$M_\ell = h\, v_d - 3 f\, \kappa_d$$

$$M_{\nu D} = h\, v_u - 3 f\, \kappa_u$$

$$M_{N_R} = f\, v_R .$$

$$\langle \phi_{10} \rangle_{u,d} = v_{u,d} \;;\; \langle \Phi_{126} \rangle_{u,d} = \kappa_{u,d} .$$

TYPE II SEESAW:

$$M_\nu = f \frac{v_{wk}^2}{\lambda v_R} - M_{\nu D} \frac{1}{f v_R} M_{\nu D}$$

FOR $\lambda \ll 1$
$v_R = M_U$; $M_\nu = m_0 f = c\,(M_d - M_\ell)$

(RELATION AT M_U).

MUST EXTRAPOLATE $m_{q,\ell}$ TO M_U!!

$$M_{d,\ell}^{(M_U)} \simeq m_{b,\tau}^{(M_U)} \begin{pmatrix} \lambda^4 & \lambda^4 & \lambda^3 \\ \lambda^4 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

PHENOMENOLOGICAL FACT:

$$m_b(M_U) \simeq m_\tau(M_U) + O(\lambda^2)$$

$$\Rightarrow M_\nu \simeq c\left(M_d - M_\ell\right)$$

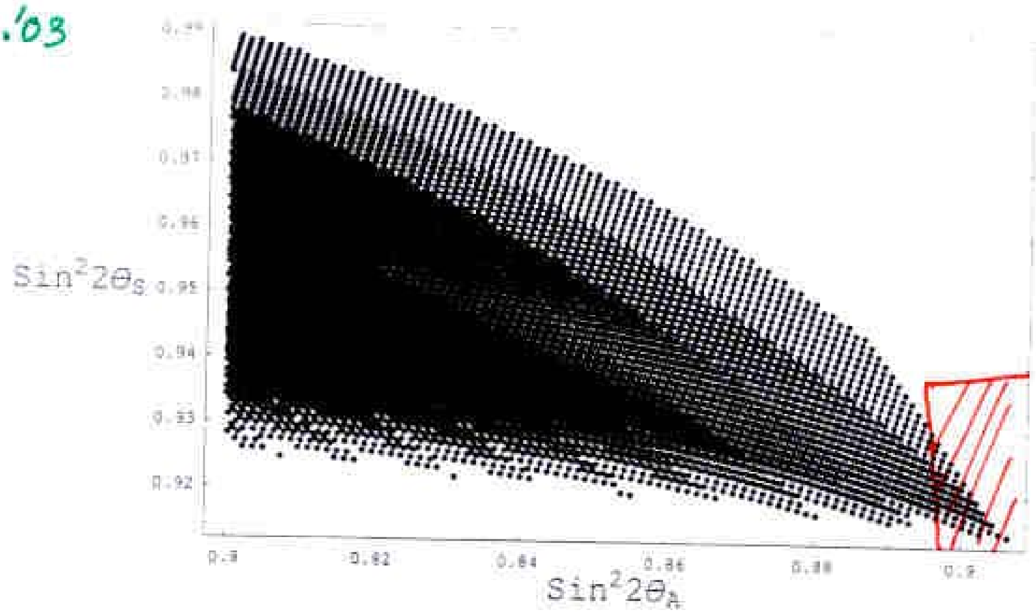
$$\simeq m_0 \begin{pmatrix} \lambda^4 & \lambda^4 & \lambda^3 \\ \lambda^4 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & \lambda^2 \end{pmatrix}$$

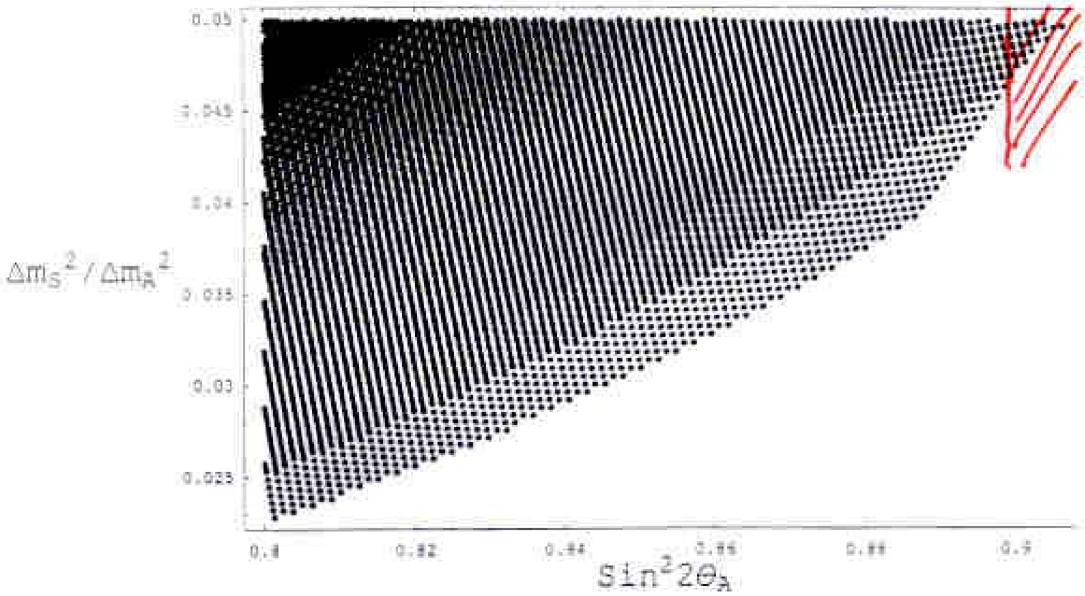
$\Rightarrow$ • θ_{12} LARGE ; • θ_{23} LARGE

• $\theta_{13} \simeq \lambda$; • $\sqrt{\frac{\Delta m^2_\odot}{\Delta m^2_A}} \simeq \lambda$.

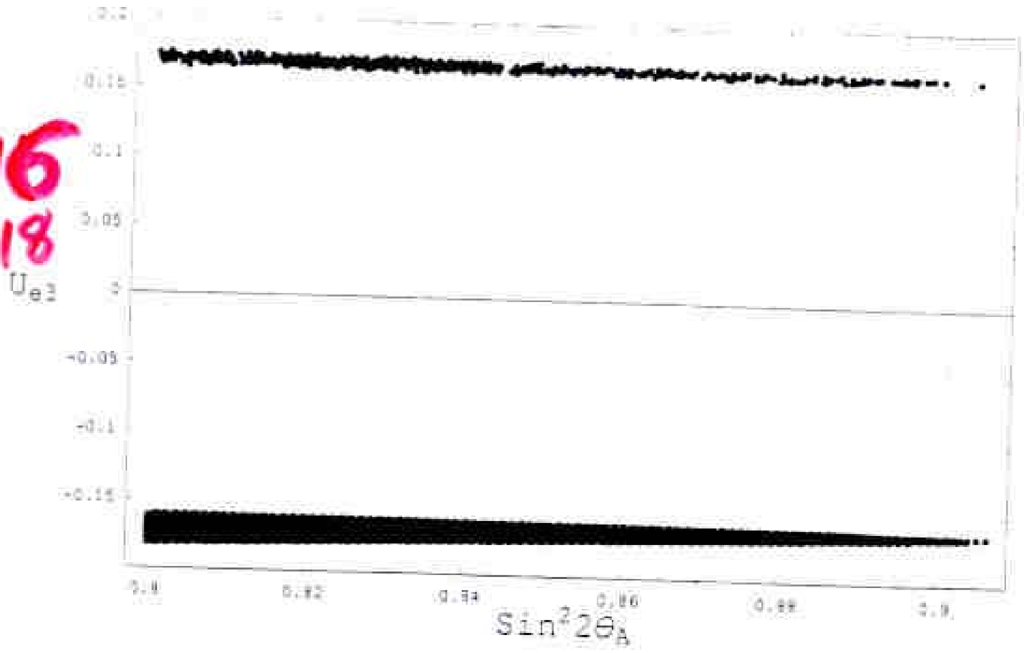
GOH, R.N.M., NG. '03

$\tan\beta = 10$





$U_{e3} \approx .16 - .18$



TESTABLE IN LBL EXPTS.

TYPE I SEESAW FOR THIS MODEL DOES NOT WORK !!

FUKUYAMA, OKADA '02
MATSUDA, KOIDE, FUKUYAMA, NISHIURA '02
DUTTA, MIMURA, R.N.M. '04

LARGE MIXING FOR QUASI-DEG. ν'S :

BALAJI, DIGHE, R.N. M., PARIDA '00
ANTUSCH, KERSTEN, LINDNER, RATZ '02
R.N.M., PARIDA, RAJASEKARAN '03 +

- Q-L UNIFICATION

⇒ AT SEESAW SCALE

$$\theta_{quark} \approx \theta_{lepton}$$

THIS CAN HAPPEN FOR THE TYPE II SEESAW CASE :

$$\mathcal{M}_\nu = f v_L - M_{\nu D} \frac{1}{f v_R} M_{\nu D}^T$$

SUPPOSE $f \simeq 1 + O(\varepsilon)$

$$\Rightarrow \boxed{m_1 \simeq m_2 \simeq m_3}$$

AND $\theta_q \simeq \theta_\ell$ AT SEESAW SCALE

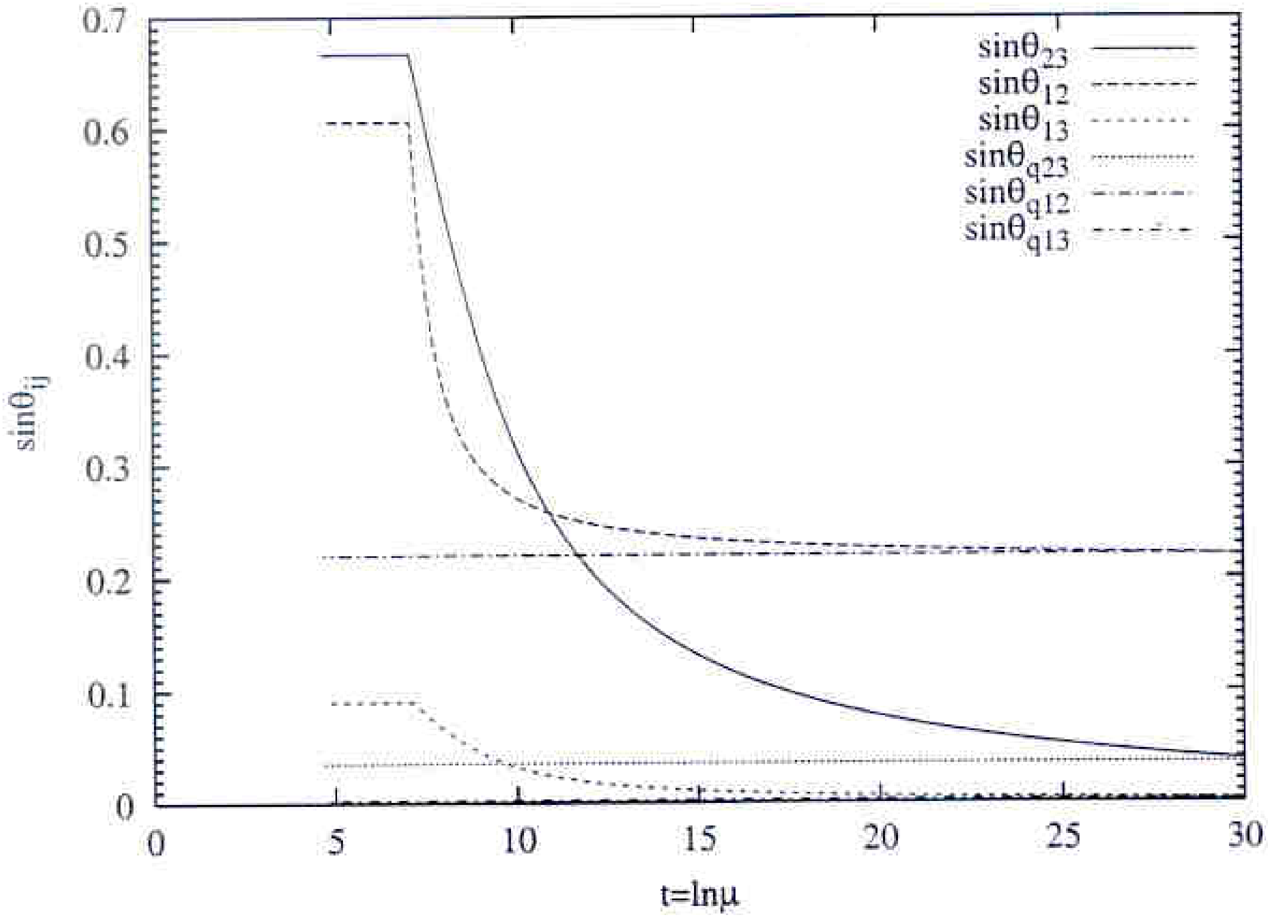
AT WEAK SCALE:

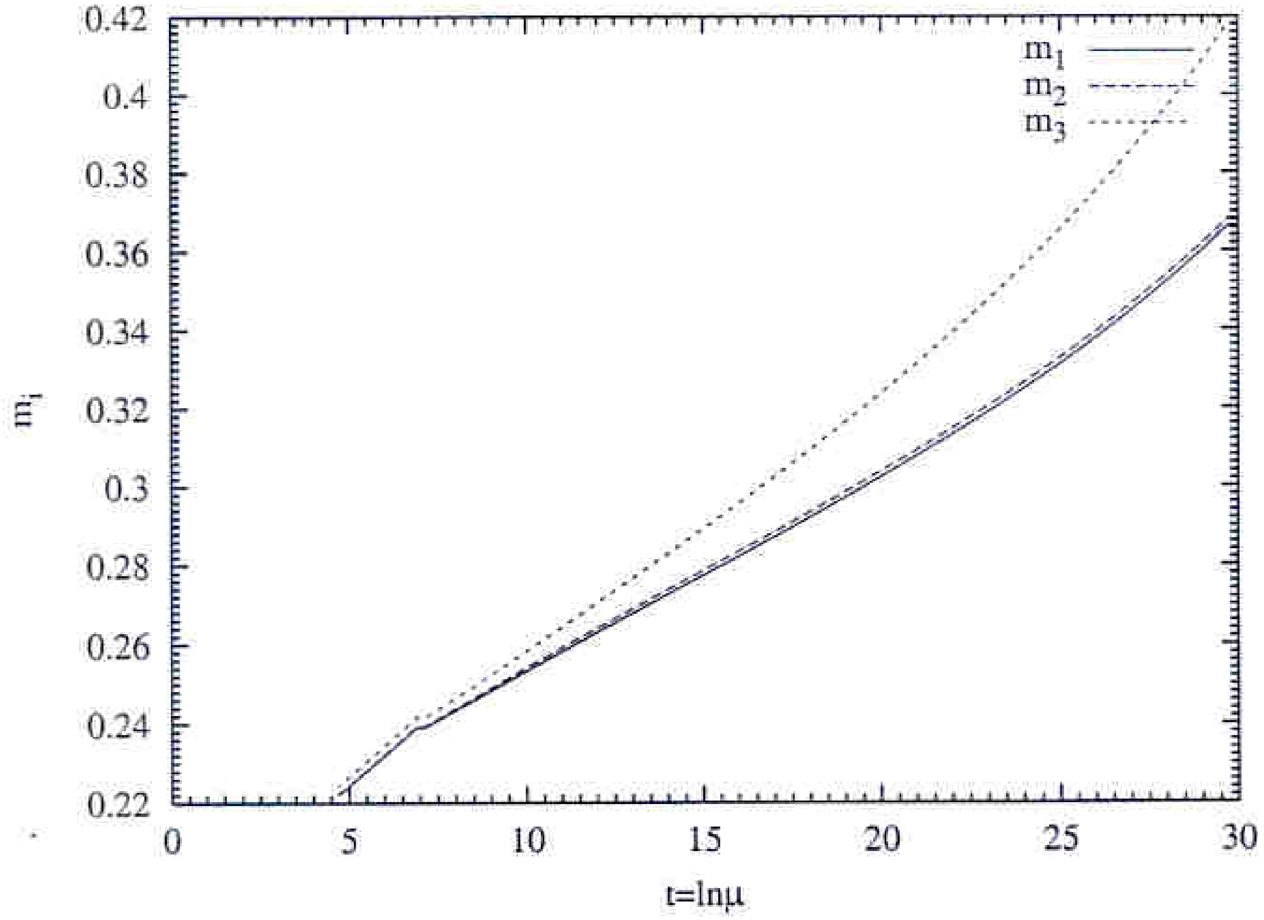
$$\mathcal{M}_\nu(M_Z) = \left(1+\delta\right) \mathcal{M}_\nu(M_U) \left(1+\delta\right)$$

$$\frac{d\theta_{ij}}{dt} \propto \frac{m_i+m_j}{m_i-m_j}\,\theta_{ij}$$

CASAS, IBARRA,
ESPINOSA, NAVARRO

LARGE SLOPE FOR $m_i \simeq m_j$





PARIDA, RAJASEKARAN, R.N.M. '03

• SEESAW WITH 2 RH NEUTRINOS : (3x2 SEESAW)

- LOCAL B-L REQUIRES 3 N_R'S FOR ANOMALY CANCELLATION

2 N_R ALTERNATIVES:

Ⓐ $M_{R3} \gg M_{R1}, M_{R2}$

SMIRNOV '93
GRIMUS & LAVOURA '00
KING '00
KING, ROSS '01

$$\Rightarrow \quad M_\nu = - \underset{3\times 2}{M_{\nu D}^T} \; \underset{2\times 2}{M_R^{-1}} \; \underset{2\times 3}{M_{\nu D}}$$

Ⓑ ONLY 2 N_R'S:

KUCHIMANCHI, R.N.M. '02
RABY '03

GAUGE GROUP: $G_{STD} \times SU(2)_H$

· GLOBAL WITTEN ANOMALY CANCELLATION REQUIRES 2 RH ν_R'S.

ADVANTAGES AND PREDICTIONS

- **LESS PARAMETERS:**

	~~CP~~	CP
3×3	21	12
3×2	14	8
		7 ($L_e - L_\mu$)

- **PREDICTIONS:**
  - INVERTED HIERARCHY
    $\Delta m^2_{23} < 0$
  - $m_{\nu_3} = 0$
- **INTERESTING COSMOLOGY:**
  - FRAMPTON, GLASHOW, YANAGIDA '02
  - RAIDAL, STRUMIA '02; ENDOH et. al. '02; AKHMEDOV, FRIGERIO, SMIRNOV '03
- **PHENOMENOLOGY:**
  CHANKOWSKI, ELLIS, POKORSKI, RAIDAL, TURCZYNSKI '04
  DUTTA, R.N.M. '03
  IBARRA, ROSS '04

ⓒ $M_{R3} \lll M_{R1}, M_{R2}$.

NATURAL IF TH. $L_e - L_\mu - L_\tau$ INV.
(R.N.M. '01)

$$\Rightarrow \quad M_{N_R} = \begin{pmatrix} 0 & M_1 & M_2 \\ M_1 & 0 & 0 \\ M_2 & 0 & 0 \end{pmatrix}$$

$$\boxed{\text{Det.}\ M_{N_R} = 0\,.}$$

SINGULAR SEESAW: $M_\nu = - M_{\nu D} M_{N_R}^{-1} M_{\nu D}^T$

HOWEVER, IF $\text{Det}\ M_{\nu D} = 0$

$\Rightarrow$ SEESAW WORKS.

LIGHT ν - SPECTRUM: (LOWEST ORDER)

2 MASSIVE

1 MASSLESS

+ 1 ν_R MASSLESS.

$\Rightarrow$ 3+1 SCENARIO FOR LSND!!

IF MINI-BOONE CONFIRMS LSND → USEFUL MODEL.

OTHER EXAMPLES:

2 + 2 EXAMPLE

CHOUBEY, BRAHMACHARI, RNM
'02

3 + 2 EXAMPLE

GOLDMAN, MCKELLAR,
STEPHENSON, GARBUTT
'04
McDONALD, MCKELLER '09