ORIGIN OF NEUTRINO MASSES AND MIXINGS

R.N. MOHAPATRA
UNIVERSITY OF MARYLAND

MAJOR THEORETICAL ISSUES IN NEUTRINO PHYSICS

i) **WHY $m_\nu \ll m_{e,u,d \ldots}$?**

IS $m_\nu \neq 0$ AN EVIDENCE FOR ν_R?

ii) **MAXIMAL MIXING;**

ATMOSPH. (+ PERHAPS SOLAR?)

iii) **ARE ν'S DEGENERATE IN MASS ?**

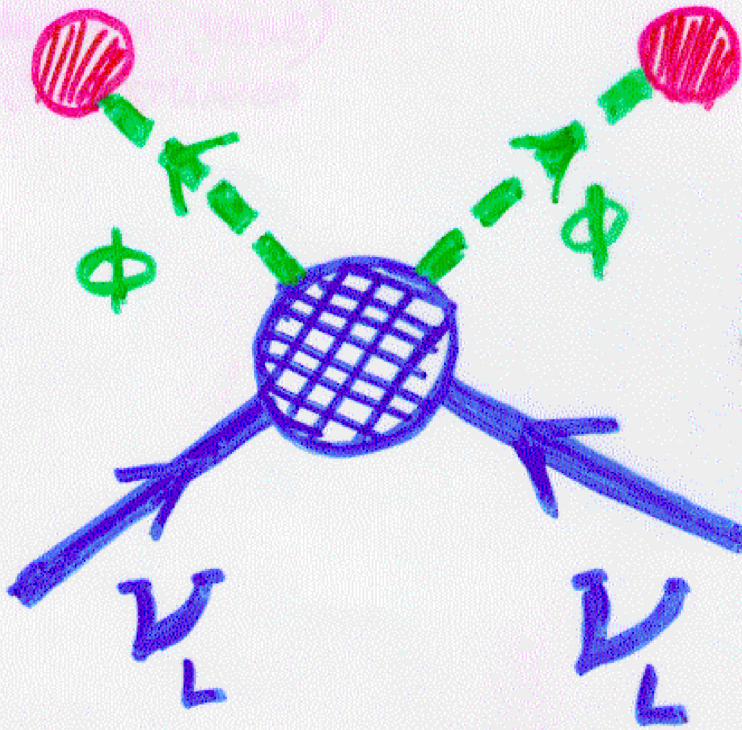
LSND $\Rightarrow m_{\nu_\mu} \simeq m_{\nu_\tau}$;

iv) **ARE THERE STERILE ν'S? IF SO, WHY ARE THEY LIGHT?**

LSND, SN r-process etc.

m_ν :

(GAUGE INV. ⇒)



$$\approx (L\Phi)^2 / M$$

- MAJORANA, $m_\nu \sim \frac{f\, v_{WK}^2}{M}$

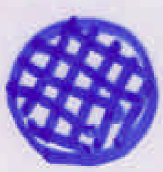
SMALL m_ν ⇒

(i) $M \gg v_{WK}$, $f \sim 1$

(ii) $f \ll 1$, $M \sim v_{WK}$

(OR BOTH)

DOES $m_\nu \neq 0$ IMPLY A ν_R ?

 = ?

STANDARD MODEL:

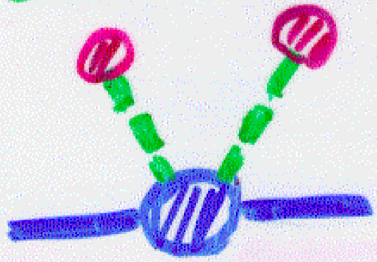
$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad u_R \qquad d_R$$

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad\qquad e_R$$

NO ν_R + B−L GLOBAL SYM

$\Rightarrow \quad m_\nu = 0$

BLACK HOLES, WORM HOLES $\Rightarrow \cancel{B-L}$



$f \sim 1$

$M \sim M_{Pl}$

$$m_\nu \lesssim \frac{v_{wk}^2}{M_{Pl}} \simeq 10^{-5}\, eV$$

(TOO SMALL !!)

BARBIERI, ELLIS, GAILLARD
AKHMEDOV, BEREZHIANI, SENJANOVIĆ

STANDARD MODEL + TRIPLET HIGGS

MA, SARKAR '97

$$m_\nu \simeq \frac{v_{wk}^2}{M_\Delta}$$

$$m_\nu \lesssim eV$$

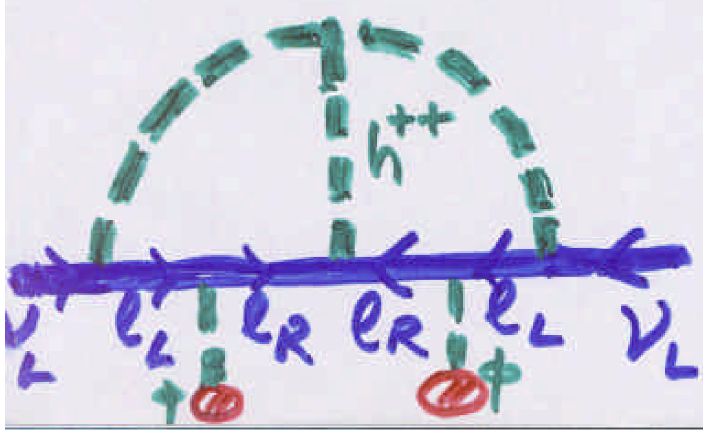
$$\Rightarrow M_\Delta \gtrsim 10^{13}\, GeV$$

INCOMPATIBLE WITH SUPERSYMMETRY + BARYOGENESIS SINCE $T_R < 10^8\, GeV$

(DELEPINE, SARKAR

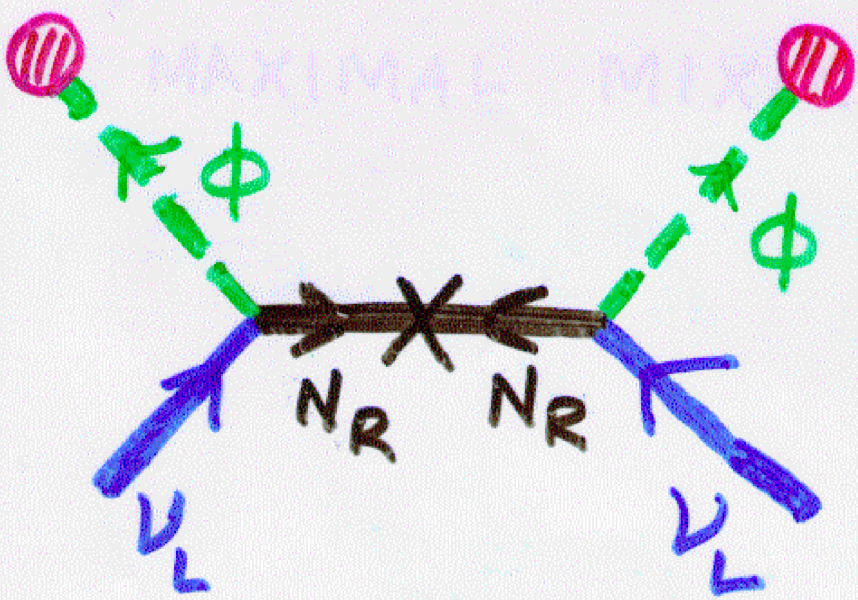
WEAK SCALE MODELS ($f \ll 1$)

(Zee '80
BABU '87)



- SMALL DUE TO 2-LO
  (OR 1-LOO
- $\frac{n_B}{n_\gamma} = 0$ (PROBLEM)
- NO UNIFICATION.

MODEL WITH ν_R:



$$m_\nu \simeq M_{\nu D}^T \frac{1}{M_R} M_{\nu D} \ll m_{\ell,q},$$

(FOR $M_R \gg v_{w}$

SEE-SAW MECHANISM

(TYPE I).

Gell-Mann, Ramond, Slansk

'7

Yanagida '79

R.N.M., Senjanović '7

ADVANTAGES OF ν_R:

- ➡ RESTORES QUARK-LEPTON SYMMETRY
- ➡ GAUGE SYM. BECOMES LEFT-RIGHT SYMMETRIC $\subset SO(10)$

$$\underset{\vec{W}_L}{SU(2)_L} \times \underset{\vec{W}_R}{SU(2)_R} \times \underset{B}{U(1)_{B-L}}$$

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \xleftrightarrow{P} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \xleftrightarrow{P} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

- $SU(2)_R \times U(1)_{B-L} \xrightarrow[V_R]{} U(1)_Y$

$$Q = I_{3L} + I_{3R} + \frac{B-L}{2}$$

$$\Rightarrow \Delta I_{3R} = \frac{1}{2}\Delta L \quad : \quad M_{N_R} \sim V_R$$

$\boxed{m_\nu \text{ PROBES THE SCALE OF } W_R}$ (PARITY BREAKING)

e.g.

SOLAR $\Rightarrow$ $m_{\nu_\mu} \sim 10^{-3}$ eV

ATMOS. $m_{\nu_\tau} \sim 10^{-1}$ eV

(IF $m_{\nu_e} \ll m_{\nu_\mu} \ll m_{\nu_\tau}$)

$$M_{W_R} \gtrsim 10^{12} \text{ GeV}$$

- $\frac{n_B}{n_\gamma}$ $\Rightarrow$ WORKS VERY WELL FOR HIGH SCALES.

- $N_R \to \ell \phi$ $\Rightarrow$ $\frac{n_\ell}{n_\gamma} \neq 0$ $\Rightarrow$ SPHALERONS $\Downarrow$ $\frac{n_B}{n_\gamma}$.

(FUKUGITA, YANAGIDA '84)

- "IMPROVES" UNIFICATION OF COUPLINGS $\Rightarrow$ SO(10) GUTS.

(CASAS et. al. 00 + ...)

MSSM $\Rightarrow$ $\alpha_s(M_Z) \sim 0.13$

EXPT. $\sim 0.118 \pm 0.004$

TWO TYPES OF SEESAW:

TYPE I:

$$M_\nu = -M_{\nu D}^T M_R^{-1} M_{\nu D}$$

$M_R \sim f V_R$, $M_{\nu D} \sim M_{\ell,u}$

$\Rightarrow$ $m_{\nu_1} \ll m_{\nu_2} \ll m_{\nu_3}$

TYPE II (TRUE IN MOST MODELS)

$$M_\nu = f \frac{V_{wk}^2}{V_R} - M_{\nu D}^T M_R^{-1} M_{\nu D}$$

$\Rightarrow$ $m_{\nu_1} \sim m_{\nu_2} \sim m_{\nu_3}$ POSSIBLE !!

OR $m_{\nu_2} \sim m_{\nu_3}$ WITH SAME CP;

NEUTRINO MIXINGS

(MAKI-NAKAGAWA-SAKATA MATRIX)

DEF.

$$\underbrace{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}}_{\text{WEAK}} = U_\nu \underbrace{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}_{\text{MASS}} ; \quad \underbrace{\begin{pmatrix}e^\circ\\ \mu^\circ\\ \tau^\circ\end{pmatrix}}_{\text{WEAK}} = U_\ell \underbrace{\begin{pmatrix}e\\ \mu\\ \tau\end{pmatrix}}_{\text{MASS}}$$

$$\boxed{U_{MNS} = U_\ell^\dagger U_\nu}$$

(i) SMA MSW:

$$U_{MNS} = \begin{pmatrix} 1 & \varepsilon & 0 \\ -\frac{\varepsilon}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ +\frac{\varepsilon}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \text{ OR } \begin{pmatrix} 1 & \frac{\varepsilon}{\sqrt{2}} & \frac{\varepsilon}{\sqrt{2}} \\ -\varepsilon & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

(ii) BIMAXIMAL

VISSANI; 97
BARGER, PAKVASA, WEILER, WHISNANT '98
JEZABEK, SUMINO '98
BALTZ, GOLDHABER, ... '98
ALTARELLI, FERUGLIO '98
(FRITZSCH, XING
KOIDE, FUSAOKA)

$$U_{MNS} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

(MSW LARGE ANGLE OR VO FOR SOLAR)

KEY QUESTION

- WHY θ_{MNS} SO DIFFERENT FROM θ_{CKM}?
- CAN THE SEESAW FORMULA PROVIDE THE ANSWER?

$$U_{MNS} = U_\ell^\dagger U_\nu$$

(i) $U_\ell \simeq 1$; $U_\nu \Rightarrow$ LARGE θ_ν

(ii) $U_\nu \simeq 1$; $U_\ell \Rightarrow$ LARGE θ_ℓ

(iii) $U_\nu \simeq 1$; $U_\ell \simeq 1$; DYNAMICS

"NATURALNESS"

"MY MODEL IS MORE NATURAL THAN YOURS"

A MORE OBJECTIVE CRITERION:

"ANY RELATION BETWEEN PARAMETERS IN A THEORY SHOULD BE GUARANTEED BY A SYMMETRY"

CASE A :

$$M_\nu = - M_{\nu D}^T M_R^{-1} M_{\nu D}$$

SO(10) LR → $M_{\nu D} \sim M_\ell$ OR M_u

- GENERIC $M_R \Rightarrow$ SMALL θ_ν

$\Rightarrow$ M_R MUST HAVE TEXTURE

RESTRICT M_R BY SYMMETRIES

(HORIZONTAL OR U(1) OR ...)

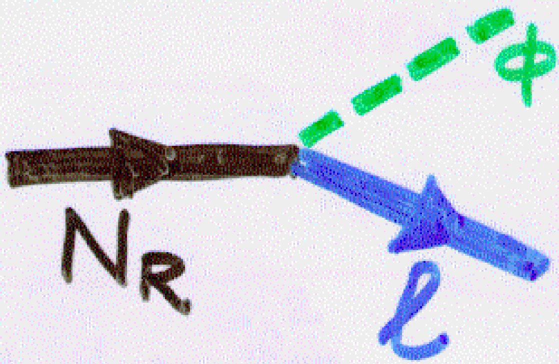
$\Rightarrow$ POSSIBLE TO GET

SMALL U_{e2} + LARGE $U_{\mu 3}$

+ SMALL U_{e3} (CHOOZ, PALO VERDE)

(ARE WE FREE TO CHOOSE ANY M_R?)

$\frac{n_B}{n_\gamma}$ AND M_R



$+ \; \cdots$

SAKHAROV CONDITION:

$$\Gamma_{N_R} < H$$

$$\downarrow$$

$$f_{ij} = \frac{M_{R,ij}}{v_R} \quad \text{CONSTRAINED!!}$$

e.g.
USUALLY $\quad M_{N_1} \ll M_{N_2} \ll M_{N_3} \quad (M_{N_1} < T_{RH})$

$\uparrow$ N_1-DECAY $\Rightarrow n_L / n_\gamma$

$$M_{R,13}/M_{R,33} < 10^{-3} \; ; \; \frac{M_{R,12}}{M_{R,22}} < 10^{-2}$$

3) LOPSIDED UNIFICATION

ALBRIGHT, BABU, BARR '98
IRGES, ELWOOD, LAVIGNAC, RAMOND
SATO, YANAGIDA '98, '98
OKAMURA, TANIMOTO '00
ALBRIGHT, BARR; BARR, DORSNER

ASSUME : $M_{\nu D}$, M_R GENERIC

BUT M_ℓ PECULIAR !

SU(5) : $\begin{pmatrix} \bar{d}_{R,i} \\ \nu_L \\ e_L \end{pmatrix} \Rightarrow M_\ell = M_d^T$

$\Rightarrow$ θ_ℓ RELATED TO $\theta_{q,R}$

(NOT OBSERVED)

$\Rightarrow$ ASYM. $M_{\ell,q}$.

c) DYNAMICALLY GENERATED LARGE MIXINGS: (BALAJI, DIGHE, PARIDA, R.N.M.'00)

AT SEESAW SCALE,

$\mu = v_R$: BOTH θ_ν & θ_ℓ SMALL.

⇒ IF TWO ν'S ARE NEARLY DEGENERATE AND SAME CP

⇒ RADIATIVE CORRECTIONS CAN MAGNIFY θ_ν AT M_Z.

WHAT ARE RADIATIVE CORRECTIONS?

BABU, LEUNG, PATALEONE; CHANKOWSKI, PLUCINIEK; ELLIS, LOLA; MA; IBARA, NAVARO, HABA et. al., TAKASUGI et. al.

$$\mathcal{M}_\nu(M_Z) = I_{RAD}\,\mathcal{M}_\nu(v_R)\,I_{RAD}$$

$$I_\alpha = 1 - \epsilon_\alpha$$

CONSIDER 2-GEN. (ν_μ, ν_τ):

AT $\mu = v_R$, SEESAW SCALE

$$M_{\nu_R} = \begin{pmatrix} m_0 & \delta \\ \delta & m_0 + \delta' \end{pmatrix};$$

$\delta \ll \epsilon \ll m$

$$\tan 2\theta = \frac{2\delta}{\delta'} \ll 1$$

(AS IN QUARK SECTOR)

EXTRAPOLATE TO WEAK SCALE:

$$M(v_{wk}) \simeq \begin{pmatrix} m_0 & \delta \\ \delta & m_0 + \delta' - \epsilon_\tau m_0 \end{pmatrix}$$

$(\epsilon_\mu \ll \epsilon_\tau)$

$$\Rightarrow \tan 2\bar{\theta} \simeq \frac{2\delta}{\delta' - \epsilon_\tau m_0}$$

IF $m_0 \epsilon_\tau \approx \delta'$, $\boxed{\bar{\theta} \text{ MAXIMAL !!}}$

- NO SYM. NEEDED;
- QUARK MIXINGS DO NOT MAGNIFY SINCE $m_b \gg m_s$, $m_t \gg m_c$

DOES IT REALLY WORK ?

YES

MSSM:

$$\varepsilon_\tau = + \frac{h_\tau^2}{16\pi^2} \ln \frac{v_R}{v_{WK}} \simeq 10^{-5} \tan^2\beta$$

$\tan\beta = 10, \quad \Delta m^2 \simeq 10^{-3}\, eV^2 \quad (m = 1 eV)$

(ATMOSPHERIC VALUE)

- REQUIRES $\boxed{\Delta m^2_{23} < 0}$
- IMPLEMENTABLE IN GUT MODELS WITH Q-L UNIFICATION
- REQUIRES SUSY WITH LARGER $\tan\beta$: (TEST)
- REQUIRE SMA MSW (TEST)

HOW NATURAL IS IT TO GET "BIMAXIMAL" MIXING ?

$$U_{MNS}(\text{Bimax}) = U_{23}(\theta = \tfrac{\pi}{4})\, U_{12}(\theta = \tfrac{\pi}{4})$$

$$M_\nu = \begin{pmatrix} \delta & F & F \\ F & A & -A \\ F & -A & A \end{pmatrix}$$

(R.N.M., NUSSINOV ALTARELLI, FERUG '9

TWO CASES:

AKHMEDOV, BRANCO, REBEL STECH '00
CHEN, MAHANTHAPPA

(i) $\delta \ll A \ll F$

$$\Delta m^2_{23} > 0$$

(ii) $\delta \ll F \ll A$

$$\Delta m^2_{23} < 0 .$$

GENERAL PROBLEM:
EITHER M_R FINE TUNED OR TOO LARG
$f_{13} \Rightarrow n_B/n_\gamma = 0 .$

BOTTOM LINE

i) SEVERAL SIMPLE MECHANISMS
TO UNDERSTAND CASE(i)
($\theta_{e\mu}$ SMALL, $\theta_{\mu\tau}$ LARGE)
EXIST.

ii) NOT EASY TO UNDERSTAND
CASE (ii) NATURALLY
IN SEE-SAW PICTURE
WITH SYM. MASS MATRICES.

- $\Delta m^2_{23} > 0$ OR < 0 (ν-FACTORY)
CAN DISCRIMINATE BETWEEN MODELS

SO(10), m_ν AND τ_{PROTON}

SO(10) - PRIME CANDIDATE FOR GUT WITH $m_\nu \neq 0$.

Q. CAN INCREASING $\tau(p \to \nu K)$ LIMIT BY A FACTOR OF TEN RULE OUT SO(10) MODELS FOR ν- MASS ?

ANS. **NO !!**

IT WILL RULE OUT ONE OR TWO OUT OF MANY INTERESTING MODELS!

SO(10), m_ν, τ_p :

$$M_\nu = - M_{\nu D}^T M_R^{-1} M_{\nu D}$$

SO(10) : $\quad M_{\nu D} \rightarrow M_u$

$$M_R = ?$$

SEVERAL SOURCES: (ACHIMAN, MERTEX '..)

$$\mathcal{L}_Y = f_{126} \psi_m \psi_m \Delta_{126} + \frac{f_{16}^{(1)}}{M} \psi_m \bar{\psi}_H \psi_m \bar{\psi}_H$$

$$+ \frac{f_{16}^{(2)}}{M} \psi_m \psi_m \psi_H \psi_H$$

$$M_R \sim f_{126} V_R + \frac{f_{16}^{(1)} V_R^2}{M} + f_{16}^{(2)} \frac{V_R^2}{M}$$

$$A(p \rightarrow \nu_\mu K) \sim f_{16}^{(2)} \frac{V_R}{M}$$

ONLY IF $f_{126} = 0$; $f_{16}^{(1)} = 0$ $\Rightarrow$ τ_p, m_ν RELATED

(BABU, PATI, WILCZEK)

ISSUE 4:

- SOLAR, ATMOS. + LSND REQUIRE 4^{th} ν_4 $(m_{\nu_4} \lesssim 10^{-3}\,\mathrm{eV})$
- LEP-SLC Z-WIDTH

  $\Rightarrow N_\nu = 3$

$\Rightarrow \nu_4 = \nu_s$ $SU(2)_L \times U(1)_Y$ SINGLET (STERILE ν)

$\Rightarrow$

m_ν TOO LARGE

$\Rightarrow$

m_{ν_s} TOO LARGE

WHY IS THE STERILE ν_s ULTRALIGHT ?

TWO CLASSES OF MODELS:

A) MIRROR UNIVERSE MODEL

OUR WORLD	MIRROR WORLD
$W^{\pm}, Z, \gamma, \ldots$	$W^{\pm\prime}, Z', \gamma', \ldots$
$u, d, e, \nu \ldots$	$u', d', e', \nu', \ldots$

GRAVITY

"STERILE UNIVERSE"

TWO VERSIONS:

FOOT & VOLKAS '95

SYMMETRIC

$M_{W,Z} = M_{W',Z'}$

BEREZHIANI, R.N.M. '95

ASYMMETRIC

$M_{W',Z'} \simeq (10-20) M_{W,Z}$

$M_{q',\ell'} \simeq (10-20) M_{q,\ell}$

BOTH VERSIONS PREDICT ULTRALIGHT STERILE ν's:

$$\nu_e, \nu_\mu, \nu_\tau \xleftrightarrow{\text{GRAVITY}} \nu_e', \nu_\mu', \nu_\tau'$$

LIGHT DUE TO B-L

LIGHT DUE TO B'-L'

ν-MASSES AND MIXINGS ARISE FROM PLANCK SCALE EFFECTS (AND ARE SMALL).

OPERATORS

$$\frac{(LH)^2}{M_{P\ell}}, \quad \frac{LH \cdot L'H'}{M_{P\ell}}, \quad \frac{(L'H')^2}{M_{P\ell}} \Rightarrow$$

DEF. $\quad \langle H' \rangle / \langle H \rangle \simeq \zeta$

$$\begin{array}{ccc} & \nu_e & \nu_s \\ M_\nu = 10^{-5}\,\text{eV} \cdot & \left(\begin{array}{cc} 1 & \zeta \\ \zeta & \lambda \zeta^2 \end{array} \right) \end{array}$$

- $\lambda \sim 1$; $\zeta \sim 20 \Rightarrow$ MSW SMALL ANGLE

WHAT IS THE MIRROR UNIVERSE REALLY LIKE ?

(R.N.M., TEPLITZ 99-00)

ASSUME : $V'_{wk} \sim 10\text{-}20\, V_{wk}$

$\Lambda'_{QCD} \sim 10\text{-}20\, \Lambda_{QCD}$.

$\Rightarrow \quad m_{\ell',q'} \sim 10\text{-}20\, m_{\ell,q}$

$m_{p',n'} \sim 10\text{-}20\, m_{p,n}$. etc

MIRROR BARYON FRACTION IN Ω_m

- $\dfrac{n_{B'}}{n_B} \sim \dfrac{1}{6}$ (ASYM. INFLATION)

$\underset{.24}{\rho_{B'}} \simeq 3 \underset{.08}{\rho_B} \Rightarrow \Omega_{B'} + \Omega_B \simeq .32$

$\Rightarrow$ MIRROR BARYONS CAN BE CDM.

$\Rightarrow$ CAN EXPLAIN MICROLENSING ANOMALY

$\Rightarrow$ RESOLVE HALO CORE DENSITY PUZZLE

(ii) SMALL m_{ν_S} DUE TO LARGE EXTRA DIMENSION

+ TeV STRING SCALE

(DIENES TALK)

STRING SYMMETRIES $\oplus$
GLOBAL B-L OF STD MODEL

$\Rightarrow$ NO ARBITRARY ν_B - MASS !

$$\bar{\nu}_L \nu_{B,R} \Rightarrow m_\nu \simeq \frac{M_{STR}}{M_{Pl}} v_{wk} \sim 10^{-4} eV$$

∞ - TOWER OF ν_S :

LOWEST STATE : $m_{\nu_S} \sim \frac{1}{R} \sim 10^{-3}$ eV

OVERALL APPRAISAL:

- HIGH SCALE SEE-SAW BY FAR THE MOST ATTRACTIVE WAY TO UNDERSTAND SMALL m_ν.
  M_R = SCALE OF PARITY VIOLATION
- ATTRACTIVE SEESAW MODELS FOR SMALL $\theta_{e\mu}$ & LARGE $\theta_{\mu\tau}$
- UNDERSTANDING "BI-MAXIMAL" IN SEESAW STILL A CHALLENGE !!
- LBL EXPTS CAN TEST MODELS WITH $\Delta m^2_{23} > 0$ OR < 0.
- STERILE $\nu_s \Rightarrow$ MIRROR UNIVERSE OR EXTRA LARGE DIMENSION ?
  (TRUELY BEYOND CONVENTIONAL GUT'S)