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Anomaly Free U(1)'s For Fermion Masses and Leptogenesis

Based on works: *Phys.Rev.D* 106 (2022) 11, 115002 (Z.T.)
(arXiv: 2209.14404)
arXiv: 2307.???? (A. Achelashvili, Z.T.)

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High Energy Seminar
Department of Physics,
OSU, Stillwater

Outline

- Intro: Shortcomings, Problems & Puzzles of SM → *New Physics*
- New U(1)Flavor model proposed:

  - Non-anomalous flavor sym. with economical setup→ texture zeros ;

  - several successful charged fermion mass patterns emerged

  - Interesting pattern for neutrino masses & mixings - predictive neutrino sector– inverted hierarchical
- Resonant Leptogenesis (by ~ TeV scale RHNs)
- Summary

Some shortcomings / puzzles of SM:

Within the SM

- **Hierarchies of Ch. fermion masses / mixings**
- **Neutrino oscillations masses / mixings - unexplained**
- **Needed amount of the baryon asymmetry can't be generated**

...

- Charged fermion masses & mixings

Observed Noticeable Hierarchies:

$$\lambda_t \sim 1 \ , \qquad \lambda_u : \lambda_c : \lambda_t \sim \lambda^8 : \lambda^4 : 1$$

$$\lambda_b \sim \lambda_\tau \sim \frac{m_b}{m_t} \qquad , \qquad \lambda_d : \lambda_s : \lambda_b \sim \lambda^4 : \lambda^2$$

With λ=0.2

$$\lambda_e : \lambda_\mu : \lambda_\tau \sim \lambda^5 : \lambda^2 : 1$$

$$V_{us} \approx \lambda \ , \qquad V_{cb} \approx \lambda^2 \ , \qquad V_{ub} = \lambda^4 - \lambda^3$$

What is origin of these hierarchies?
Is there any relation or sum rule?
Why three families?

Within SM no answer to these questions…

Extension With Flavor Symmetry

Flavor symmetry G_F distinguishing families can explain hierarchies

Simplest possibility: $G_F = U(1)_F$ (Froggatt, Nielsen'79)

$$U(1)_F \;:\qquad \phi_i \to e^{iQ(\phi_i)}\phi_i$$

$$Q(F_i) = n_i\;,\qquad Q(F_i^c) = \bar{n}_i\;,\qquad Q(H) = 0\;,\qquad Q(X) = -1$$

← *'flavon'*

With $n_i + \bar{n}_j \neq 0$: **coupling** ~~$F_i F_j^c H$~~ **forbidden!**

$$\left(\frac{X}{M_*}\right)^{n_i+\bar{n}_j} F_i F_j^c H \longrightarrow \epsilon^{n_i+\bar{n}_j} F_i F_j^c H$$

→Suppressed couplings emerge

$$\frac{\langle X\rangle}{M_*} \equiv \epsilon \ll 1$$

M_* **- cut off scale (simplest possibility $M_* \sim M_{\rm Pl}$)**

Several/multiple flavons also can be considered

Possible candidates for flavor $U(1)_F$

- **Global $U(1)_F$ is unattractive:**

  -- Spont. breaking → pseudo-Goldstones (phen. difficulties)

  --Explicit breaking → against the 'rules' (selection criteria?)

  Do gravity, non-perturbative effects respect global symmetries? Trustful setting?

- **Local $U(1)_F$:**

  Models with gauged $U(1)_F$ are highly constrained due to anomaly cancellation condition

SM is anomaly free; But extra flavor $U(1)_F$ requires additional care

-- Anomalous U(1) (of stringy origin) **(Dine, Seiberg, Witten'87)**

GS mechanism for anomaly cancellation.

Conditions:

$$\frac{A_{YY1}}{2k_Y} = \frac{A_{221}}{k_2} = \frac{A_{331}}{k_3} = \frac{A_{111}}{3k_1} = \frac{A_{GG1}}{24}$$

Anomaly coefficients: $(\mathrm{Gravity})^2 \cdot U(1)_F : A_{GG1} = \mathrm{Tr}[Q_{U(1)_F}]$

$$U(1)_Y^2 \cdot U(1)_F : A_{YY1} = \sum_i Q_Y^2(i) Q_{U(1)_F}(i)$$

$$SU(1)_L^2 \cdot U(1)_F : A_{221} = \sum_i T_2(i) Q_{U(1)_F}(i) \;, \cdots$$

String Unification conds: $k_i g_i^2 = k_1 g_A^2 = 2 g_{st}^2$

- • **Anomalous U(1)$_F$ as flavor symmetry → successful fermion hierarchies**

(Ibanez, Ross'94; Binetruy, Ramond'95; Jain, Shrock'95 …)

-- Anomaly free $U(1)_F$ [not of ‘stringy origin’] –

- Earlier Works

- Within MSSM, some anom. free $U(1)_F$ ‘s with successful $Y_{U,D,E}$

(Dudas, Pokorski, Savoy, hp/9504292)

- Within MSSM & SU(5) GUT, some examples/models of anom. free U(1)F ‘s

(Mu-Chun Chen, et al, ph/0612017, 0801.0248)

Within SU(5) GUT: Z.T. PRD 87, 075026 ; PLB 706, 398-405
based on unified GUT+U(1)-part of flavor

Within GUTs become more non-trivial [multiplet’s charges related]

Challenge to find simple anom. free $U(1)_F$ x G_{GUT}

Let’s start by $U(1)_F \times G_{SM}$ ...

Search Anomaly Free U(1) ← embedding In Non-Abelian group

1): **10[0] + 5*[0]**

2): **10[α] + 5*[-3 α]+1[5 α]**

3): **10[β] + 5*[β]+1[β]+5[-2 β]+5′*[-2 β]+1′[4 β]**

Finding 2) via SO(10)→SU(5)xU(1)″: **16= 10[1] + 5*[-3]+1[5]**
(Flipped SU(5) type) **10=5[-2]+ 5*[2]**

Finding 3) via E6->SO(10)xU(1)′→SU(5)xU(1)′:

27= 16[1] + 10[-2]+1′[4]=
10[1] + 5*[1]+1[1]+5[-2]+5′*[-2]+1′[4]

Finding 2) +3): Also possible Superposition of U(1)′ and U(1)″

All other findings, such as E7, E8, SU(N>6) give extra SU(5) states

Superposition of U(1)′ and U(1)″ : $Q_{sup}=aY'+bY''$

Three Types of Charge selection Emerge:

A: $10_0+5^*_0$

B: $10_a+5^*_{-3a}+1_{5a}$

C: $10_{a+b}+5^*_{a-3b}+1_{a+5b}+5_{-2a-2b}+5'^*_{-2a+2b}+1'_{4a}$

One family can have A-type Charges, another one B-type, etc.

Acceptable combinations: **ABB** **BBB** **ABC** **BBC**

For example, **ABB:** $\mathbf{10_0+5^*_0}$

$\mathbf{10_{\alpha} +5^*_{-3\alpha}+1_{5\alpha}}$

$\mathbf{10_{\alpha'} +5^*_{-3\alpha'}+1_{5\alpha'}}$

$\mathbf{H_q+H^*_{-q}}$

Some selection rules ('guide'):

AAB: rejected because of two 10's same 0-chage

ACC: rejected for two 5-plets

In case of ABB, α and α' should be related

α/α'=m/n, to avoid two U(1)s

Classify acceptable up type quark mass matrices...

Within GUTs charges of fermion states related →

→ Constrains & No much textures

Challenge to find simple anom. free $U(1)_F$ x G_{GUT}

Let's start by $U(1)_F \times G_{SM}$ ...

Model: SM Extension with $U(1)_F$

$U(1)_F$ - gauge symmetry

X- scalar (flavon– the SM singlet), for $U(1)_F$ breaking

$N_{1,2,\ldots}$ - SM singlet fermions – RHN's

$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$ non-trivial states

just those of SM Higgs doublet φ

three families of matter $\{q, u^c, d^c, l, e^c\}_{i=1,2,3}$

Anomaly Constrain

- SM Anomalies are intact (i.e. vanish)

  Other anomalies (direct $U(1)_F$ & mixed) must vanish:

$$(U(1)_F)^3: \qquad A_{111} = \sum_i Q_i^3$$

$$U(1)_Y \times (U(1)_F)^2: \qquad A_{Y11} = \sum_i Y_i Q_i^2$$

$$(U(1)_Y)^2 \times U(1)_F: \qquad A_{YY1} = \sum_i Y_i^2 Q_i$$

$$(SU(2)_L)^2 \times U(1)_F: \qquad A_{221} = \sum_i [Q_i(l_i) + 3Q_i(q_i)]$$

$$(SU(3)_c)^2 \times U(1)_F: \qquad A_{331} = \sum_i [2Q_i(q_i) + Q_i(u_i^c) + Q_i(d_i^c)]$$

$$(\mathrm{Gravity})^2 \times U(1)_F: \qquad A_{GG1} = \sum_i Q_i$$

anomaly free $U(1)$'s

a) hypercharge symmetry $U(1)_Y$

b) with RHN's $N_{1,2,\ldots}$ gauged $(B-L)$

Family dependent $U(1)_Y$ and (B-L) and/or their superpositions

$$\bar{a}_i Y(f) + \bar{b}_i Q_{B-L}(f)$$

Automatically anomaly free

Drawbacks:

1) By requiring top quark renormalizable Yukawa coupling $\lambda_t \sim 1$

→ also bottom and tau Yukawas allowed at renormalizable level – expectancy $\lambda_b, \lambda_\tau \sim 1$

2) only with $\bar{a}_i, \bar{b}_i$ No much/desirable texture zeros.

Modification:

$$Q_i(f) = \bar{a}_i Y(f) + \bar{b}_i Q_{B-L}(f) + \Delta Q_i(f)$$

Such that: anomalies $A_{YY1}, A_{221}, A_{331}, A_{GG1}$ stay intact.

Four RHNs - $N_{1,2,3,4}$ **and**

$$\Delta Q_i(q) = \bar{q}_3\{0,1,-1\} + \bar{q}_8\{1,1,-2\}$$
$$\Delta Q_i(u^c) = \bar{u}_3\{0,1,-1\} + \bar{u}_8\{1,1,-2\}$$
$$\Delta Q_i(d^c) = \bar{d}_3\{1,-1,0\} + \bar{d}_8\{1,1,-2\}$$
$$\Delta Q_i(l) = \bar{l}_3\{1,-1,0\} + \bar{l}_8\{1,1,-2\} \ ,$$
$$\Delta Q_i(e^c) = 0 \ ,$$
$$\Delta Q_i(N) = \bar{n}\{1,1,1,-3\} \ .$$

will be enough for our purposes

Requirements upon selection of $\bar{a}_i, \bar{b}_i \ \bar{n} \quad (\bar{q}_{3,8}, \cdots, \bar{l}_{3,8})$

(i) Top Yukawa via $q_3 u_3^c \varphi$ → $\lambda_t \sim 1$

All other Yukawas suppressed /hierarchical

→ Naturally obtain desirable pattern

(ii) Dirac and Majorana RHN couplings should naturally generate desirable neutrino oscillations

(iii) Care must be taken for canceling anomalies

$$A_{111} = \sum Q_i^3 \qquad A_{Y11} = \sum Y_i Q_i^2$$

(iv) Ratios of the states' charges should be rational

→ allow (phenomenologically required) couplings between them.

One solution – charge assignment

Normalization: $Y(l) = 1$ and $Q_{B-L}(q) = 1/3$

$$\bar{a}_i = \frac{1}{3}\{46, 43, 10\} , \quad \bar{b}_i = \frac{1}{3}\{-91, 35, 38\} ,$$

$$\{\bar{q}_3, \bar{u}_3, \bar{d}_3, \bar{l}_3\} = \frac{1}{3}\{-16, 7, -67/2, -3/2\} ,$$

$$\{\bar{q}_8, \bar{u}_8, \bar{d}_8, \bar{l}_8\} = \frac{1}{9}\{38, -41, 23/2, 51/2\} , \quad \bar{n} = -\frac{5}{3}$$

Table 1: $U(1)_F$ charge (Q) assignment for the states. $Q_X = 1$, $Q_\varphi = -7$.

	$\{q_1, q_2, q_3\}$	$\{u_1^c, u_2^c, u_3^c\}$	$\{d_1^c, d_2^c, d_3^c\}$	$\{l_1, l_2, l_3\}$	$\{e_1^c, e_2^c, e_3^c\}$	$\{N_1, N_2, N_3, N_4\}$
Q	$\{-11, -2, 0\}$	$\{26, 13, 7\}$	$\{-10, -1, -9\}$	$\{48, 6, -15\}$	$\{-61, -17, 6\}$	$\{-32, 10, 11, 5\}$

1) All anomalies vanish

2) This Q selection gives nice textures → Natural understanding of hierarchies

Yukawa couplings are fixed by $U(1)_F$ charges:

$$\left(q_1,\ q_2,\ q_3\right)\begin{pmatrix} \bar{\varepsilon}^{8} & \varepsilon^{5} & \varepsilon^{11} \\ \bar{\varepsilon}^{17} & \bar{\varepsilon}^{4} & \varepsilon^{2} \\ \bar{\varepsilon}^{19} & \bar{\varepsilon}^{6} & 1 \end{pmatrix}\begin{pmatrix} u_1^c \\ u_2^c \\ u_3^c \end{pmatrix}\varphi$$

$$\left(q_1,\ q_2,\ q_3\right)\begin{pmatrix} \varepsilon^{14} & \varepsilon^{5} & \varepsilon^{13} \\ \varepsilon^{5} & \bar{\varepsilon}^{4} & \varepsilon^{4} \\ \varepsilon^{3} & \bar{\varepsilon}^{6} & \varepsilon^{2} \end{pmatrix}\begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \end{pmatrix}\tilde{\varphi}$$

$$\left(l_1,\ l_2,\ l_3\right)\begin{pmatrix} \varepsilon^{6} & \bar{\varepsilon}^{38} & \bar{\varepsilon}^{61} \\ \varepsilon^{48} & \varepsilon^{4} & \bar{\varepsilon}^{19} \\ \varepsilon^{69} & \varepsilon^{25} & \varepsilon^{2} \end{pmatrix}\begin{pmatrix} e_1^c \\ e_2^c \\ e_3^c \end{pmatrix}\tilde{\varphi}$$

$$\frac{X}{M_{\rm Pl}} \equiv \varepsilon\ , \qquad \frac{X^*}{M_{\rm Pl}} \equiv \bar{\varepsilon}$$

Hierarhical, good fit with: $\langle\varepsilon\rangle = \langle\bar{\varepsilon}\rangle \equiv \epsilon \approx \mathbf{0.2}$

Some elements ≈ 0 → Texture zeros:

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Some elements ≈ 0 → Texture zeros:

$$\left(q_1,\ q_2,\ q_3\right)\begin{pmatrix} \overline{\varepsilon}^8 & \varepsilon^5 & \mathbf{0} \\ \mathbf{0} & \overline{\varepsilon}^4 & \varepsilon^2 \\ \mathbf{0} & \mathbf{0} & 1 \end{pmatrix}\begin{pmatrix} u_1^c \\ u_2^c \\ u_3^c \end{pmatrix}\varphi$$

$$\left(q_1,\ q_2,\ q_3\right)\begin{pmatrix} \mathbf{0} & \varepsilon^5 & \mathbf{0} \\ \varepsilon^5 & \overline{\varepsilon}^4 & \varepsilon^4 \\ \varepsilon^3 & \mathbf{0} & \varepsilon^2 \end{pmatrix}\begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \end{pmatrix}\tilde{\varphi}$$

$$\left(l_1,\ l_2,\ l_3\right)\begin{pmatrix} \varepsilon^6 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \varepsilon^4 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \varepsilon^2 \end{pmatrix}\begin{pmatrix} e_1^c \\ e_2^c \\ e_3^c \end{pmatrix}\tilde{\varphi}$$

Neutrino Dirac & Majorana Couplings

$$(l_1,\ l_2,\ l_3)\begin{pmatrix} \bar{\varepsilon}^{9} & \bar{\varepsilon}^{51} & \bar{\varepsilon}^{52} \\ \varepsilon^{33} & \bar{\varepsilon}^{9} & \bar{\varepsilon}^{10} \\ \varepsilon^{54} & \varepsilon^{12} & \varepsilon^{11} \end{pmatrix}\begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}\varphi$$

$$(N_1,\ N_2,\ N_3)\begin{pmatrix} \varepsilon^{64} & \varepsilon^{22} & \varepsilon^{21} \\ \varepsilon^{22} & \bar{\varepsilon}^{20} & \bar{\varepsilon}^{21} \\ \varepsilon^{21} & \bar{\varepsilon}^{21} & \bar{\varepsilon}^{22} \end{pmatrix}\begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}M_{\rm Pl}$$

$M_{Pl} N_4 N_4 \bar{\varepsilon}^{10}$

→ $Q = 5$

No Yukawas & mixing with N_4

Possible to forbid:

$N_4 \to -N_4$

By reflection symm.

Neutrino Dirac & Majorana Couplings

$$(l_1,\ l_2,\ l_3)\begin{pmatrix} \bar{\varepsilon}^9 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \bar{\varepsilon}^9 & \bar{\varepsilon}^{10} \\ \mathbf{0} & \varepsilon^{12} & \varepsilon^{11} \end{pmatrix}\begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}\varphi$$

$$(N_1,\ N_2,\ N_3)\begin{pmatrix} \mathbf{0} & \varepsilon^{22} & \varepsilon^{21} \\ \varepsilon^{22} & \bar{\varepsilon}^{20} & \bar{\varepsilon}^{21} \\ \varepsilon^{21} & \bar{\varepsilon}^{21} & \bar{\varepsilon}^{22} \end{pmatrix}\begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}M_{\mathrm{Pl}}$$

These zeros lead to the Prediction(s)

Quark Sector

Basis: $q^T Y_U u^c h_u$ $\qquad$ $q^T Y_D d^c h_d$

Parameterization:

$$Y_U \simeq \begin{pmatrix} a_1'\epsilon^8 & a_1\epsilon^5 & 0 \\ 0 & a_2\epsilon^4 & \epsilon^2 \\ 0 & 0 & 1 \end{pmatrix} \lambda_t^0 \ ,$$

$$Y_D \simeq \begin{pmatrix} e^{-i\eta_1} & 0 & 0 \\ 0 & e^{-i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 0 & b_1\epsilon^3 & 0 \\ b_1'\epsilon^3 & b_2\epsilon^2 & b_2'\epsilon^2 \\ 0 & 0 & 1 \end{pmatrix} \kappa_b \epsilon^2$$

$\eta_{1,2}$ do not contribute to masses. Relevant for CP

Hierarchical Yukawas → accurate analytic relations:

$$\lambda_t = \lambda_t^0[1+\mathcal{O}(\epsilon^4)] \qquad \lambda_b = \kappa_b \epsilon^2[1+\mathcal{O}(\epsilon^4)]$$

$$\frac{\lambda_u}{\lambda_t} \simeq \frac{a_1' \epsilon^8}{\sqrt{1+(a_1\epsilon/a_2)^2}} \,, \qquad \frac{\lambda_c}{\lambda_t} \simeq a_2 \epsilon^4 \sqrt{1+(a_1\epsilon/a_2)^2}$$

$$\frac{\lambda_d}{\lambda_b} \simeq \frac{b_1 b_1' \epsilon^4}{\sqrt{b_2^2+(b_1^2+b_1'^2)\epsilon^2}} \,, \qquad \frac{\lambda_s}{\lambda_b} \simeq \epsilon^2 \sqrt{b_2^2+(b_1^2+b_1'^2)\epsilon^2}$$

CKM elements:

$$|V_{us}| = \left| c_u s_d e^{i\eta_1} - s_u c_d e^{i\eta_2} \right|$$

$$|V_{cb}| = c_u \epsilon^2 \frac{|1-e^{i\eta_2} b_2'(1+b_2^2\epsilon^4)|}{\sqrt{1+\epsilon^4}\sqrt{1+b_2'^2\epsilon^4}} + \mathcal{O}(\epsilon^8) \,, \qquad \frac{|V_{ub}|}{|V_{cb}|} = \tan\theta_u = \frac{a_1}{a_2}\epsilon$$

$$\overline{\rho} + i\overline{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} = \frac{c_u c_d e^{i\eta_1} + s_u s_d e^{i\eta_2}}{c_d s_u e^{i\eta_1} - c_u s_d e^{i\eta_2}} \tan\theta_u$$

$$\tan\theta_u = \frac{a_1}{a_2}\epsilon \,, \qquad \tan 2\theta_d = \frac{2 b_1 b_2 \epsilon}{b_2^2 - (b_1^2 - b_1'^2)\epsilon^2}$$

Help to find fit

Renormalization from High scale to weak scale

$$\left.\frac{\lambda_{u,c}}{\lambda_t}\right|_{M_t} = \eta_{u,c} \left.\frac{\lambda_{u,c}}{\lambda_t}\right|_{\Lambda} , \qquad \left.\frac{\lambda_{d,s}}{\lambda_b}\right|_{M_t} = \eta_{d,s} \left.\frac{\lambda_{d,s}}{\lambda_b}\right|_{\Lambda} ,$$

$$V_{\alpha\beta}|_{M_Z} = \eta_{mix} V_{\alpha\beta}|_{\Lambda} , \quad \text{if} \quad (\alpha\beta) = (ub, cb, td, ts)$$

$$V_{\alpha\beta}|_{M_Z} = V_{\alpha\beta}|_{\Lambda} , \quad \text{if} \quad (\alpha\beta) = (ud, us, cd, cs, tb) ,$$

For: $M_t = 172.5$ GeV and $\alpha_3(M_Z) = 0.1179$

$$\eta_{u,c} \simeq 1.1262 + 0.00187 \cdot \ln\left(\frac{\Lambda}{2 \cdot 10^{16}\mathrm{GeV}}\right) ,$$

$$\eta_{d,s} \simeq 0.8916 - 0.00143 \cdot \ln\left(\frac{\Lambda}{2 \cdot 10^{16}\mathrm{GeV}}\right) ,$$

$$\eta_{mix} \simeq 0.89157 - 0.001433 \cdot \ln\left(\frac{\Lambda}{2 \cdot 10^{16}\mathrm{GeV}}\right) ;$$

- the interpolated expressions which work pretty well for $10^{15}\mathrm{GeV} < \Lambda < M_{\mathrm{Pl}}$.

Fit – Quark sector

input: $M_t = 172.5$ GeV, $m_b(m_b) = 4.18$ GeV

$$\epsilon = 0.21, \quad \{a_1, a_1', a_2\} = \{0.6974,\ 1.7065,\ 1.6606\}, \quad \{\eta_1, \eta_2\} = \{3.01985,\ -1.3954\}$$

$$\{b_1, b_1', b_2, b_2'\} = \{0.47834,\ 0.54541,\ 0.45448,\ 0.59088\}.$$

output:

$$(m_u,\ m_d,\ m_s)\,(2\ \text{GeV}) = (2.16,\ 4.67,\ 93)\,\text{MeV}, \quad m_c(m_c) = 1.27\ \text{GeV}$$

$$\mu = M_Z: \quad |V_{us}| = 0.225, \quad |V_{cb}| = 0.04182, \quad |V_{ub}| = 0.00369,$$

$$\overline{\rho} = 0.159, \quad \overline{\eta} = 0.3477$$

All results given above are in perfect agreement with experiments

Lepton Sector

$$Y_E \simeq \begin{pmatrix} c_1\epsilon^4 & 0 & 0 \\ 0 & c_2\epsilon^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \kappa_\tau \epsilon^2$$

input:

$$M_\tau = 1.777 \text{ GeV}$$

$$\text{at} \quad \mu = \Lambda \;, \qquad \{c_1, c_2\} \simeq \{0.1437, 1.335\}$$

output:

$$M_e = 0.511 \text{ MeV}, \qquad M_\mu = 105.66 \text{ MeV},$$

Neutrino Sector

No important contribution from Y_E

Y_E^{diag} basis → Lepton mixing matrix U

$$M_\nu = P U^* P' M_\nu^{\rm Diag} U^\dagger P,$$

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$P = {\rm Diag}\left(e^{i\omega_1}\ ,\ e^{i\omega_2}\ ,\ e^{i\omega_3}\right), \quad P' = {\rm Diag}\left(1\ ,\ e^{i\rho_1}\ ,\ e^{i\rho_2}\right)$$

Neutrino Dirac & Majorana Matrices

$$m_D \simeq \begin{pmatrix} A\epsilon^9 & 0 & 0 \\ 0 & B_1\epsilon^9 & C_1\epsilon^{10} \\ 0 & B_2\epsilon^{12} & C_2\epsilon^{11} \end{pmatrix} v \,, \quad M_R \simeq \begin{pmatrix} 0 & a\epsilon^2 & d\epsilon \\ a\epsilon^2 & b & c\epsilon \\ d\epsilon & c\epsilon & \epsilon^2 \end{pmatrix} \bar{c} M_{Pl} \epsilon^{20}$$

See-saw→

$$M_\nu \simeq -m_D M_R^{-1} m_D^T \simeq \begin{pmatrix} \beta & \gamma & \gamma' \\ \gamma & \alpha^2 & \alpha \\ \gamma' & \alpha & 1 \end{pmatrix} \bar{m},$$

$$M_\nu^{(2,2)} M_\nu^{(3,3)} - (M_\nu^{(2,3)})^2 = 0$$

Relations→

$$\tan^2\theta_{13} = \frac{m_3}{m_2} \left| s_{12}^2 e^{i\rho_1} + \frac{m_2}{m_1} c_{12}^2 \right|$$

$$2\delta = \pi - \rho_2 + \mathrm{Arg}\left(s_{12}^2 e^{i\rho_1} + \frac{m_2}{m_1} c_{12}^2 \right)$$

Predict inverted hierarchical neutrinos!

(Z.T. PRD 87, 075026)

$$\cos\rho_1 = \frac{m_1^2 m_2^2 \tan^4\theta_{13} - m_3^3(m_1^2 s_{12}^4 + m_2^2 c_{12}^4)}{2m_1 m_2 m_3^2 s_{12}^2 c_{12}^2}$$

$$2\delta = \pm\pi - \rho_2 + \mathrm{Arg}\left(s_{12}^2 e^{i\rho_1} + \frac{m_2}{m_1} c_{12}^2\right).$$

is incompatible with normal hierarchical neutrino masses.

(IH) in neutrino masses

$$0.001129 \text{ eV} \lesssim m_3 \lesssim 0.002833 \text{ eV}$$

$$0.1002 \text{ eV} \lesssim \sum m_i \lesssim 0.1021$$

$(0\nu\beta\beta)$ parameter

$$m_{\beta\beta} = \left|c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\rho_1} + s_{13}^2 m_3 e^{i(2\delta+\rho_2)}\right|$$

$$0.01864 \text{ eV} \lesssim m_{\beta\beta} \lesssim 0.0483 \text{ eV}$$

both parameters $\sum m_i$ and $m_{\beta\beta}$ are unequivocally determined

by the m_3's values

correlation between $\sum m_i$ and $m_{\beta\beta}$.

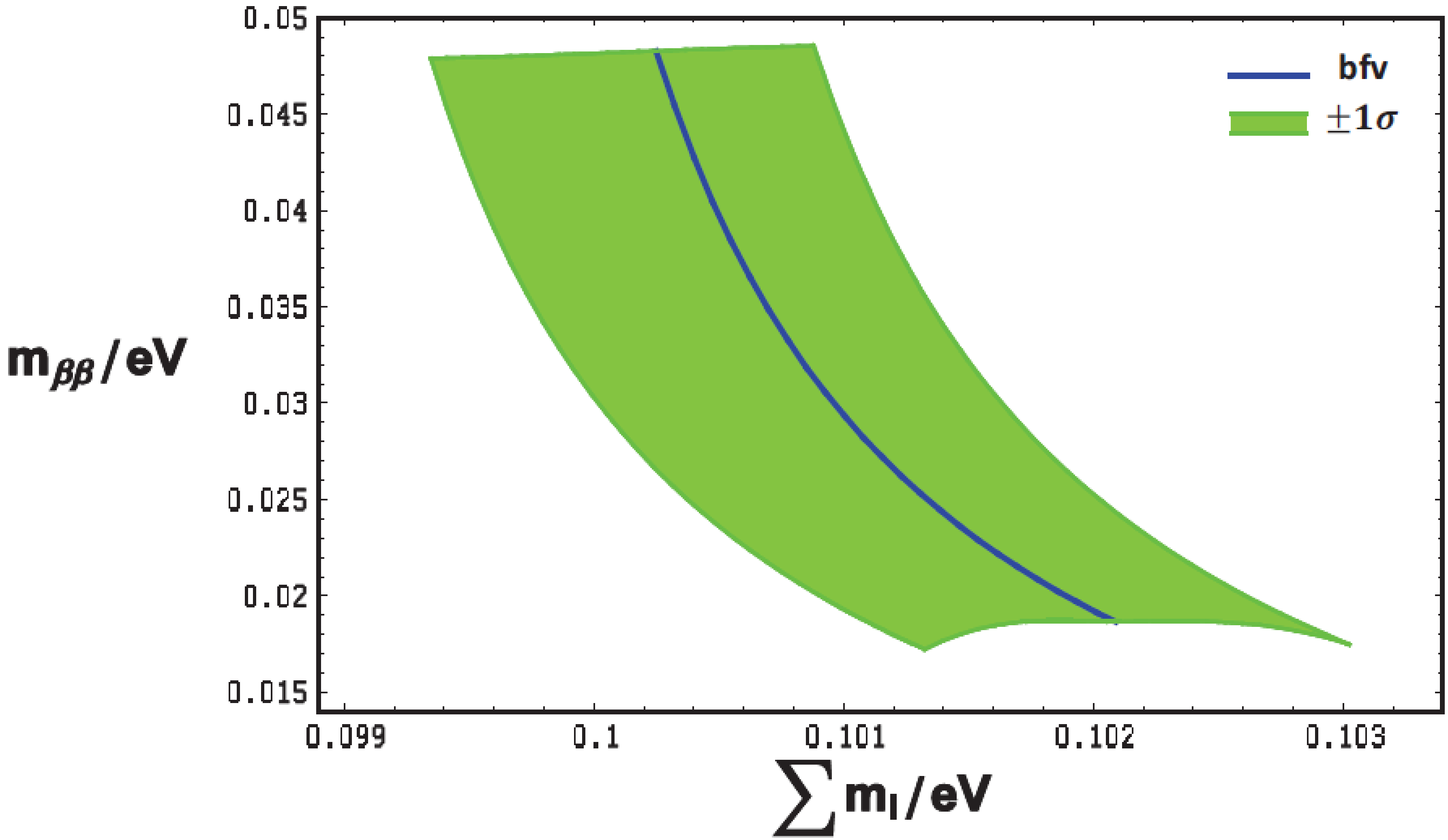


Figure 1: Correlation between $\sum m_i$ and $m_{\beta\beta}$. Solid blue line corresponds to the bfv's of the oscillation parameters [1,2]. Green area corresponds to the cases with oscillation parameters within the 1σ deviations.

All hierarchies, needed values Realized by original parameters' natural values:

With input:

$$\{A, B_1, B_2, C_1, C_2\} \simeq \{2.0236,\ 2.0236,\ 1.6189,\ 2.4283,\ -0.8094\}$$

$$\{a, b, c, d, \bar{c}\} \simeq \{3.2672e^{i1.5473}, 0.79405e^{i0.0053733}, 0.89097e^{i0.0028735}, 0.15853e^{1.5586}, 0.56333e^{2.9194}\}$$

→ Perfect Fit:

$$\{\sin^2\theta_{12}, \sin^2\theta_{23}, \sin^2\theta_{13}\} = \{0.3035,\ 0.57,\ 0.02235\}$$

$$\Delta m^2_{\rm sol} = m_2^2 - m_1^2 = 7.39 \cdot 10^{-5}{\rm eV}^2, \quad \Delta m^2_{\rm atm} = m_2^2 - m_3^2 = 2.492 \cdot 10^{-3}{\rm eV}^2$$

$$\{m_1, m_2, m_3\} = \{0.049197,\ 0.049942,\ 0.0015\}{\rm eV}$$

$$\{\delta, \rho_1, \rho_2\} = \{276^\circ,\ 91.69^\circ,\ 11.49^\circ\}, \quad \omega_{1,2,3} = 0$$

$$\{M_{N_1}, M_{N_2}, M_{N_3}\} \simeq \{1.6,\ 953.5,\ 32480\}{\rm GeV}$$

Suppressed Additional contribution to $(0\nu\beta\beta)$ parameter

$$\left|\sum_{i=1}^{3} U_{ei}^2 m_i P_i'^{*} + \frac{M_{N_1}}{1+M_{N_1}^2/\langle p^2\rangle} U_{eN_1}^2\right| =$$

$$\left| e^{-0.421i} 0.0362\,\text{eV} + \frac{e^{-0.151i} 2.76\cdot 10^{-11} M_{N_1}}{1+M_{N_1}^2/\langle p^2\rangle}\right| = 0.0368\ \text{eV}$$

$$(\text{for } \langle p^2\rangle = (200\,\text{MeV})^2)$$

With $M_{N_1} \simeq 1.6$ GeV, and mixing $|U_{eN_1}|^2 \simeq 2.76\cdot 10^{-11}$

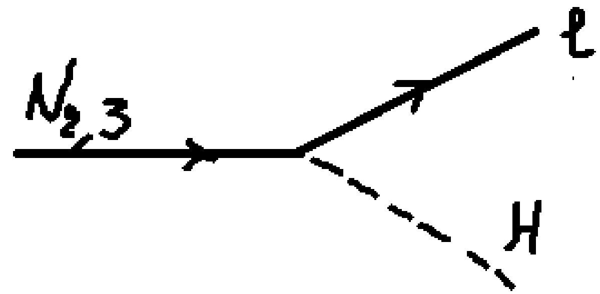
Additional contribution: within $(0.5-1.8)\%$, i.e. negligible.

for $\langle p^2\rangle = (100 - 200\,\text{MeV})^2$

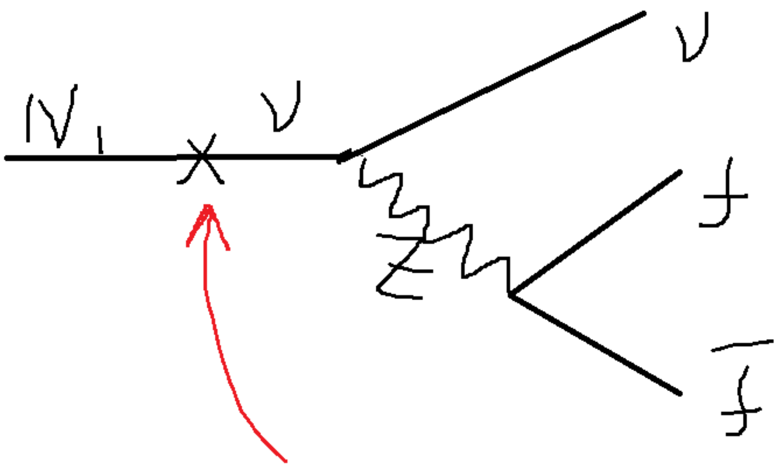
Consistency (with BBN)

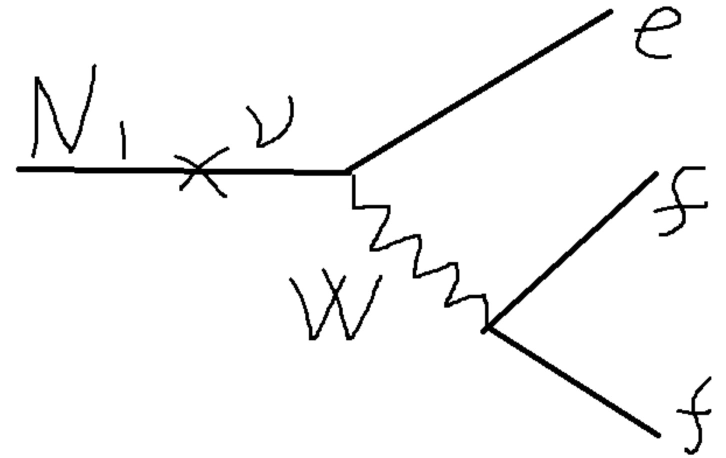
$$M_{N_{1,2,3,4}} = \{1.6,\ 2\cdot 10^3,\ 5\cdot 10^4,\ 4\cdot 10^{11}\}\ \textbf{GeV}$$

$N_{2,3}$ Decay quickly



N_1 Decays – mixing with ν's





$$|U_{iN_1}|^2 \simeq \{2.76,\ 1.29,\ 1.09\}\cdot 10^{-11}$$

$$\Gamma(N_1) = \frac{1}{\tau_{N_1}} \simeq \frac{G_F^2 M_{N_1}^5}{16\pi^3}\left(1.37|U_{1N_1}|^2 + 1.35|U_{2N_1}|^2 + 0.487|U_{3N_1}|^2\right) \simeq \frac{1}{0.0038\,\mathrm{s.}}$$

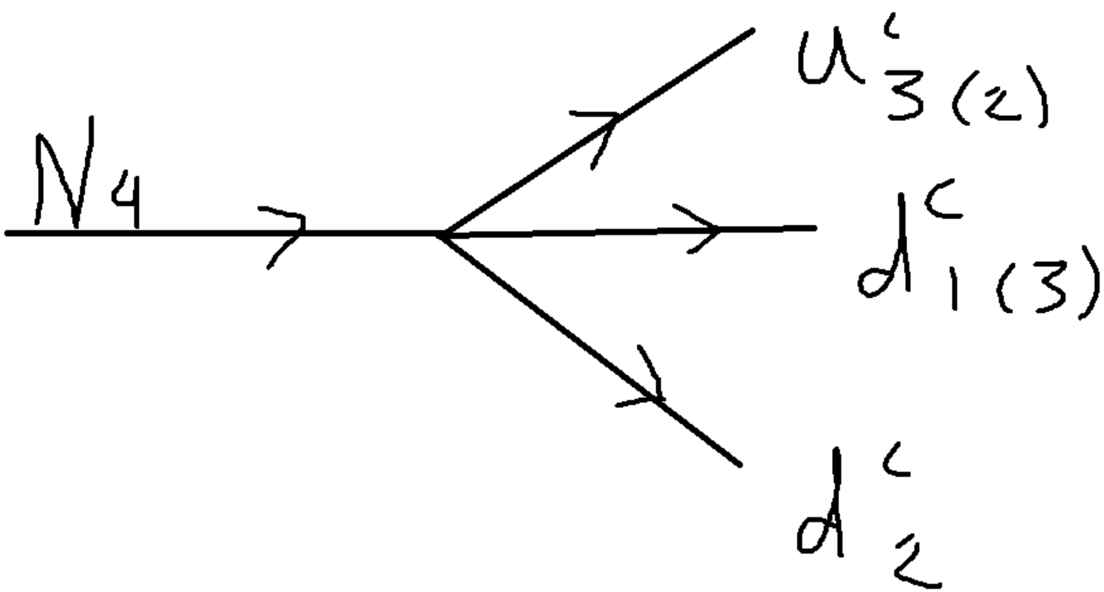
Consistency (with BBN)

N_4 Decays – due to d=6 operator couplings

$$\frac{1}{M_{Pl}^2}\left(\bar{\epsilon}(N_4 u_3^c)(d_1^c d_2^c) + \epsilon(N_4 u_2^c)(d_2^c d_3^c)\right)$$

Consistent with symmetry

$$N_4 \to -N_4$$
$$(q, u^c, d^c) \to -(q, u^c, d^c)$$



$$\Gamma(N_4) \simeq 1/(10^{-4}\mathrm{sec.})$$

Baryon Asymmetry

Generation of $\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-10}$ asymmetry

Also requires SM extension

Having extension with Right handed neutrinos→

- B-asym. Through leptogenesis

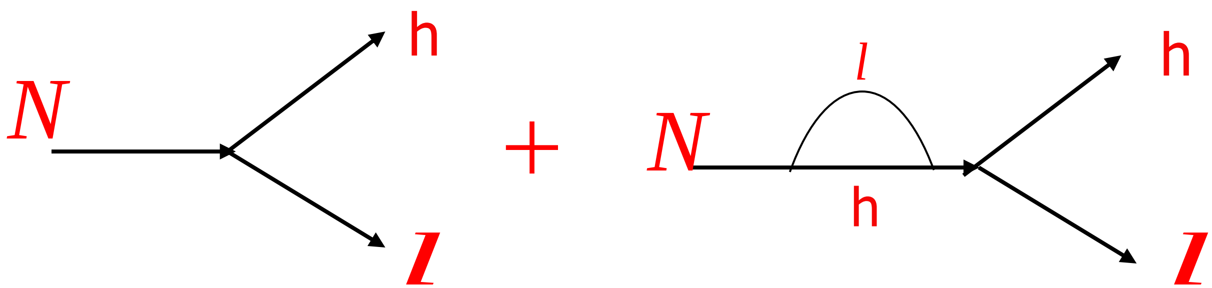
(Fukugita & Yanagida'1986)

Leptogenesis

RHNs →L, CP viol → Leptogenesis (Fikugita, Yanagida'86)

By out of equilibrium N-decays

N→h l:



In our considered model: Ligthest RHN mass < TeV

Hierarchical neutrinos for leptogenesis require $M_R \geq 10^9 \mathrm{GeV}$

(Davidson-Ibarra'02 bound)

Hierarchical RHNs will not work for the considered case …

Alternatively:

- **Quasi Degenerate RHNs → Resonant Leptogenesis**

Flanz et al'96
Pilaftsis'97
Underwood'03

- **Allows low M_R**

With degenerate N's, CP asymmetry:

$$\epsilon_1 = \frac{\mathrm{Im}(\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{21}^2}{(\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{11}(\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{22}} \frac{(M_2^2 - M_1^2)\, M_1 \Gamma_2}{(M_2^2 - M_1^2)^2 + M_1^2 \Gamma_2^2}$$

Pilaftsis & Underwood'03

Has maximum with $M_1 = M\,|1-\delta_N|, \quad M_2 = M\,|1+\delta_N|, \quad \delta_N \ll 1$

For arbitrary M !

Select parameters in M_R matrix →

- To get: quasi deg. Two RHNs

- then find: Dirac Yukawas which accommodate neutrino sector
- investigate resonant leptogenesis

It works!

M_R Diagonalization and Spectrum

$$Y_\nu^0 = \begin{pmatrix} \bar{A} & 0 & 0 \\ 0 & \bar{B}_1 & \bar{C}_1 \\ 0 & \bar{B}_2 & \bar{C}_2 \end{pmatrix}, \quad M_R^0 = \begin{pmatrix} 0 & \tilde{n}_2 & \tilde{n}_3 \\ \tilde{n}_2 & \tilde{n}_1 & \tilde{n}_4 \\ \tilde{n}_3 & \tilde{n}_4 & 1 \end{pmatrix} \bar{M}^0$$

Convenient basis:

$$Y_\nu = \begin{pmatrix} A & 0 & 0 \\ 0 & B_1 & C_1 e^{i\varphi_1} \\ 0 & B_2 & C_2 e^{i\varphi_2} \end{pmatrix},$$

$$M_R = \begin{pmatrix} 0 & n_2 & n_3 \\ n_2 & n_1 e^{i\varphi} & 0 \\ n_3 & 0 & 1 \end{pmatrix} \bar{M},$$ **With** $n_3 \ll 1$, for $n_2 \gg |n_1|, n_3^2$ →

$$M_{N_1} \simeq \left(1 - \frac{1}{2n_2}|n_1 - n_3^2|\right) \bar{M} n_2 \,, \quad M_{N_2} \simeq \left(1 + \frac{1}{2n_2}|n_1 - n_3^2|\right) \bar{M} n_2$$

$$M_{N_3} \simeq (1 + n_3^2)\, \bar{M} \,.$$

Lighter N_1 and N_2 are quasi-degenerate!

Preliminary Results

One possible parameter selection:

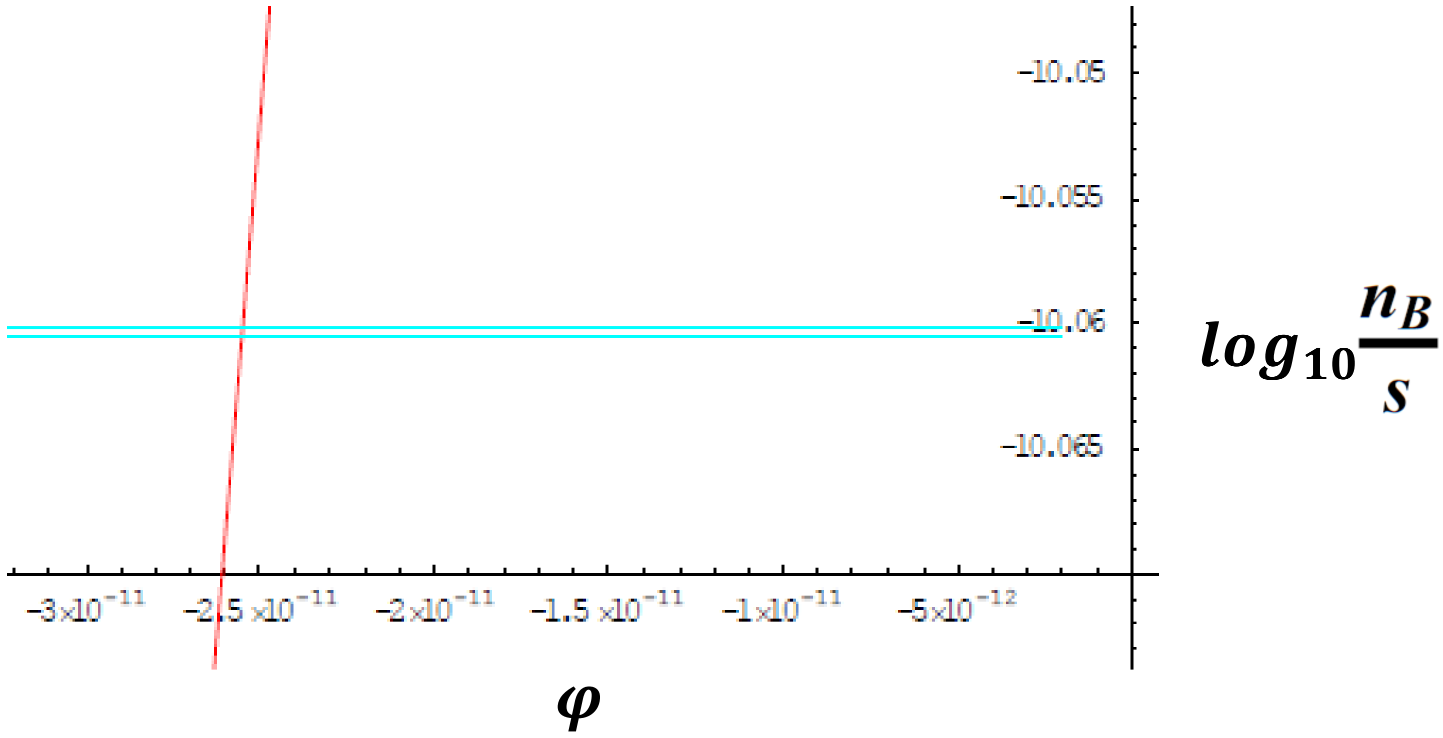
$$Y_\nu = \begin{pmatrix} 7.47\cdot 10^{-7} & 0 & 0 \\ 0 & 3.57\cdot 10^{-7} & -5.99\cdot 10^{-7} - 5.44\cdot 10^{-7} i \\ 0 & 4.33\cdot 10^{-7} & 3.89\cdot 10^{-8} + 4.49\cdot 10^{-8} i \end{pmatrix}$$

$$M_R = \begin{pmatrix} 0 & 250 & 433.013 \\ 250 & 75 - 9.38\cdot 10^{-10} i & 0 \\ 433.013 & 0 & 2500 \end{pmatrix} \times \mathbf{GeV}$$

$$M_1 \cong M_2 \cong 250\ \mathrm{GeV}$$

Preliminary Results

Baryon Asymmetry:



How natural are couplings & scales?

$U(1)_F$ symmetry gives:

$$Y_\nu \simeq \begin{pmatrix} \tilde{a}\epsilon^9 & 0 & 0 \\ 0 & \tilde{b}_1\epsilon^{10} & \tilde{c}_1\epsilon^9 \\ 0 & \tilde{b}_2\epsilon^{11} & \tilde{c}_2\epsilon^{12} \end{pmatrix}, \quad M_R \simeq \begin{pmatrix} 0 & \hat{n}_2\epsilon & \hat{n}_3\epsilon^2 \\ \hat{n}_2\epsilon & \hat{n}_1\epsilon^2 & \epsilon \\ \hat{n}_3\epsilon^2 & \epsilon & 1 \end{pmatrix} \hat{n} M_{Pl}\epsilon^{20}$$

From the neutrino sector & leptogenesis,

For $\epsilon = 0.21$ we need:

$$\tilde{a} \simeq 0.94, \quad b_1 \simeq 2.1, \quad b_2 \simeq 1.2, \quad \tilde{c}_1 \simeq 0.75, \quad \tilde{c}_2 \simeq 8$$

$$\hat{n}_1 \simeq 0.68, \quad \hat{n}_2 \simeq 0.48, \quad \hat{n}_3 \simeq 3.9$$

Natural values

$$\hat{n} \simeq 0.037$$

Scales unexplained…

$$\hat{n} M_{Pl} \simeq 9 \cdot 10^{16}\ \mathrm{GeV}$$

Accurate quasi-degeneracy of RHNs requires tunings

SUMMARY

- SM extension with $U(1)_{Flavor}$ model proposed:
- Found Non-anomalous ch. selection→ texture zeros;
- Successful ch. fermion mass hierarchies /mixings;
- Desirable Neutrino (inverted hierarchical) oscillations
- Satisfactory low scale resonant leptogenesis

-- Interesting to extent: to GUTs [like SU(5), SO(10)] – more predictive?

Thank You

Backup Slides

- Charged fermion masses & mixings

Observed Noticeable Hierarchies:

$$\lambda_t \sim 1 \ , \qquad \lambda_u : \lambda_c : \lambda_t \sim \lambda^8 : \lambda^4 : 1$$

$$\lambda_b \sim \lambda_\tau \sim \frac{m_b}{m_t} \tan\beta \ , \qquad \lambda_d : \lambda_s : \lambda_b \sim \lambda^4 : \lambda^2$$

With λ=0.2

$$\lambda_e : \lambda_\mu : \lambda_\tau \sim \lambda^5 : \lambda^2 : 1$$

$$V_{us} \approx \lambda \ , \qquad V_{cb} \approx \lambda^2 \ , \qquad V_{ub} = \lambda^4 - \lambda^3$$

What is origin of these hierarchies?
Is there any relation or sum rule?
Why three families?

Within SM no answer to these questions…

Evidences for New Physics: Neutrino Data

- **Origin of these scales and mixings?**

Unexplained in SM $\leftarrow \mathbf{m}_\nu \lesssim 10^{-4}\ \mathrm{eV}$

$$m_\nu \sim \frac{M_{EW}^2}{M_{Pl}}$$

Without New Physics

Neutrino masses via see-saw

+ RHN - ν_R

→ Oscillations

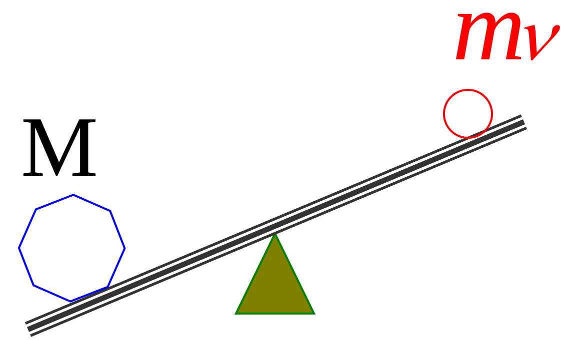
→ Leptogenesis

$\nu^c \equiv N$ □ $(1,1,0)$ ← **SM singlet**

$l\, N \langle H \rangle$ $\qquad M\, N\, N$ → **Δ L=2 Lepton number viol.**

$$\begin{pmatrix} 0 & \langle H \rangle \\ \langle H \rangle & M \end{pmatrix}$$

$$m_\nu \sim \frac{\langle H \rangle^2}{M}$$



$$M_N \simeq M$$

$$M \sim 10^{14}\ \mathrm{GeV} \ \rightarrow\ m_\nu \sim \mathrm{few} \cdot 0.01\ \mathrm{eV}$$

Some related works:

-- Within MSSM, anom. free $U(1)_F$'s with successful $Y_{U,D,E}$

Dudas, Pokorski, Savoy, hp/9504292;

-- Within MSSM & SU(5) GUT, some examples/models of anom. free $U(1)_F$'s : *Mu-Chun Chen, et al, ph/0612017, 0801.0248;*

Backup Slides for Leptogenesis

No apriory reason to expect Matter-atimatter asymmetry..

Early Universe → 50% -- 50%

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-10}$$

(with units n$\gamma = 1$)

For 10.000.000.000 Baryons ←→ 9.999.999.999 antiBaryons

How/why such asymmetry Emerges???

Sakharov Conditions (1967)
for Baryogenesis

1. B-number violation
2. C- and CP-violation
3. Out of thermal Equalibrium

(necessary conditions)

-- SM meets 3 conds. But too small asymmetry!

-- GUT ←→ sphaleron washout problem (?)

-- see Babu & Mohapatra'2012
GUT baryogenesis revamped!

Needed Physics Beyond SM (Standard Model)

-- Neutrino Sector

Are related?

interesting to try!

-- Baryon asymmetry

...

-- Neutrino mass $\nu\nu$-operator → $\Delta L \neq 0$

- Sphalerons $\Delta(B-L)=0$ → $\Delta B \neq 0$ (good!)

Remaining 2 conds. ~ details of Leptogenesis

(Fukugita & Yanagida'1986)