# Confronting Standard Model Limitations Through Non-SUSY SO(10)

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# INTRODUCTION

1. **SUSY SO(10) unifies couplings, gives $m_\nu$ by type-I seesaw,predicts Higgsino,Neutralino,wino as DM; predicts R-Parity as Gauged Discrete Sym. for the DM stabilty, Baryogenesis via Leptogenesis, and explains the origin of P-violation in weak interation. It has natural solutions to gauge hierarchy problem.**
2. **Supersymmetry appears to be indispensable for fundamental understanding of particle physics and cosmology.**
3. BUT **"We should also think outside the SUPERBOX"**: **John Ellis (CANDARK2017).**

# INTRODUCTION

1. **IN THE ABSENCE OF ANY EXPERIMENTAL CONFIRMATION OF SUSY SO FAR AND WITH FINE TUNING APPROACH TO GAUGE HIERARCHY WE (MKP, B.P. Nayak, R.SATPATHY, R. L. AWASTHI, JHEP 04 (2017)075)**
   **ATTEMPT TO SEE IF SIMILAR SOLUTIONS EXIST IN NON-SUSY SO(10) FOR $m_\nu$,DM,BAU, and UNIFICATION WITHIN SM PARADIGM.**
2. **FOR FINE TUNING:**
   **S. Weinberg, "Living in the Universe, in Universe or Multiverse", B.J. Carr ed.(2007) .**

# A MINIMAL MODEL

1. **CONSIDER SO(10) $\to$ SU(5)$\times U(1)_X \to$ SM: AFTER SECOND STEP BR.:** $X = 4T_{3R} + 3(B-L)$ **POSSIBLE WITH (i)**$45_H \oplus 16_H$ **OR (ii)** $45_H \oplus 126_H$
2. **IN BOTH CASES:** $Z_X = (-1)^{4T_{3R}+3(B-L)} = (-1)^{3(B-L)} \equiv$ **Z**$_{MP}$**, CALLED MATTER PARITY.**
3. $Z_{MP} = -1$ **in (i) SINCE** $|B-L| =$ **ODD;i,e MATTER PARITY HAS BROKEN SPONTANEOUSLY.**
4. **CHOICE (ii) RH.TRIPLET WITH** $T_{3R} = 1, B-L = -2$ **GETS VEV.** $v_R \sim M_U$**: GIVES Type-I**$\oplus$ **Type-II for** $m_\nu$**. HERE** $Z_{MP} = +1$**,SM LAGRANGIAN CONSERVES MP AS GAUGED DISCRETE SYM.**

1. **SM FERMIONS HAVE $-1$ AND SM HIGGS HAS $+1$ MATTER PARITY.**
2. **MATTER PARITY OF SO(10) REPRESENTATIONS:**

$$\begin{aligned} Z_{MP} &= \text{Even} : 10, 45, 54, 120, 126, 210; .... \\ Z_{MP} &= \text{Odd} : 16, 144, ...... \end{aligned} \tag{1}$$

3. **SM FERMIONS $\supset 16_F$ HAVE $Z_{MP} = -1$; SM HIGGS $\supset 10_H$ HAS $Z_{MP} = +1$; THE YUK. INTS. $16_F.16_F.10_H$ AND $16_F.16_F.126^\dagger_H$ CONSERVE MP.**
4. **DM FERMIONS MUST BE IN NON-STANDARD MP-EVEN REPS.**
5. **DM SCALARS MUST BE IN NON-STANDARD MP-ODD REPS.**

1. **Ref for DM in SO(10): Kadastik et.al,PRD(2009);Frigerio & Hambye,PRD(2010); MKP et. al, PRD(2010); MKP PLB(2011); Mambrini et.al PRD(2015).**

1. $$-\mathcal{L}_{\text{Yuk}} = \mathbf{Y16_F.16_F.10_H + f16_F.16_F.126_H^\dagger} + ... \qquad (2)$$

2. $$\mathbf{m}_\nu = \mathbf{fv_L} - \mathbf{M_D}\frac{\mathbf{1}}{\mathbf{fv_R}}\mathbf{M_D^T}, \qquad (3)$$

$$\begin{aligned} \mathbf{M_D} &= M_u\,(\text{UP QUARK MASS MATRIX}), \\ v_L &= \lambda v_R v_{\text{ew}}^2/M_\Delta^2 \\ M_N &= f v_R \sim f\,M_{GUT}, \end{aligned}$$

(4)

3. **REF: E. Akhmedov, M. Frigerio, JHEP 01(2007)043: Eq. quadratic in $f$, $2^3 = 8$ solutions; We find 2 distict solutions for each chosen basis**

1. $$\mathbf{M_D^{(d)}}(\mathrm{GeV}) =$$

$$\begin{pmatrix} 0.01832 + 0.00441i & 0.08458 + 0.01114i & 0.6588 + 0.27319i \\ 0.08458 + 0.01114i & 0.38538 + 1.56 \times 10^{-5}i & 3.3278 + 0.00019i \\ 0.65882 + 0.27319i & 3.32785 + 0.00019i & 81.8543 - 1.64 \times 10^{-5} \end{pmatrix} \tag{5}$$

1.

$$
\mathbf{M_D^{(u)}}(\mathrm{GeV}) =
\begin{pmatrix}
0.00054 & (1.5027 + 0.0038i)10^{-9} & (7.51 + 3.19i)10^{-6} \\
(1.5027 + 0.0038i)10^{-9} & 0.26302 & 9.63 \times 10^{-5} \\
(7.51 + 3.19i)10^{-6} & 9.63 \times 10^{-5} & 81.9963
\end{pmatrix}
\quad (6)
$$

1. $$\mathbf{f} = 10^{-6} \times \begin{pmatrix} 0.385 + 0.1291i & 0.4617 - 0.4922i & 3.509 + 1.080i \\ 0.4617 - 0.4922i & 4.626 + 0.1567i & 22.80 + 0.3317i \\ 3.509 + 1.080i & 22.80 + 0.3317i & 511.6 + 0.47i \end{pmatrix}. \quad (7)$$

1.

$$\mathbf{f} = 10^{-6} \times \begin{pmatrix} 0.3175 + 0.0904i & 0.1232 - 0.6089i & -0.4869 - 0.6918i \\ 0.1232 - 0.6089i & 3.610 - 0.0724i & 1.587 + 0.2599i \\ -0.4869 - 0.6918i & 1.587 + 0.2599i & 511.8 + 0.6524i \end{pmatrix} \quad (8)$$

1. $$\mathbf{f} = 10^{-6} \times \begin{pmatrix} -0.0690 + 0.0147i & -0.341 + 0.0164i & -4.0194 + 1.5783i \\ -0.341 + 0.0164i & -1.5745 - 0.2133i & -20.2464 - 0.3306i \\ -4.0194 + 1.5783i & -20.2464 - 0.3306i & -507.895 - 0.4034i \end{pmatrix} \tag{9}$$

1.

$$\mathbf{f} = 10^{-6} \times$$

$$\begin{pmatrix} -0.000025 + 0.000008i & -0.00019 - 0.00215i & -0.00538 - 0.00177i \\ -0.00019 - 0.00215i & -0.56091 + 0.0092i & 0.95702 - 0.27084i \\ -0.00538 - 0.00177i & 0.95702 - 0.27084i & -508.16 - 0.60957i \end{pmatrix}$$

(10)

# Fig1:Hierarchical Spectrum of RH$\nu$

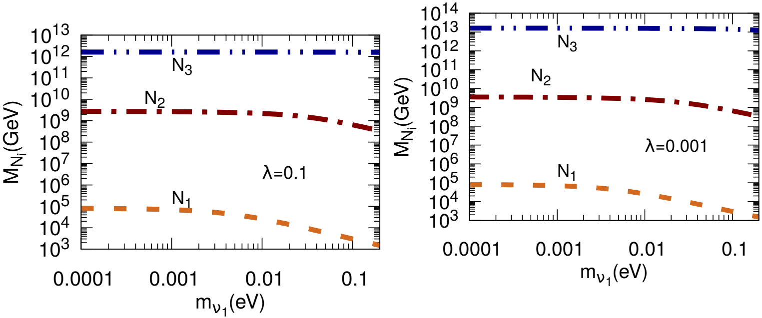

Figure: **Prediction of Hierarchical Spectrum of heavy RH neutrino masses as a function of the lightest neutrino mass and when the three neutrino masses are normally ordered. The values of $M_{\Delta_L} = 10^{12}$ GeV and $v_R = 10^{15.5}$ GeV have been kept fixed.**

# Fig2:Compact Spectrum of RH$\nu$

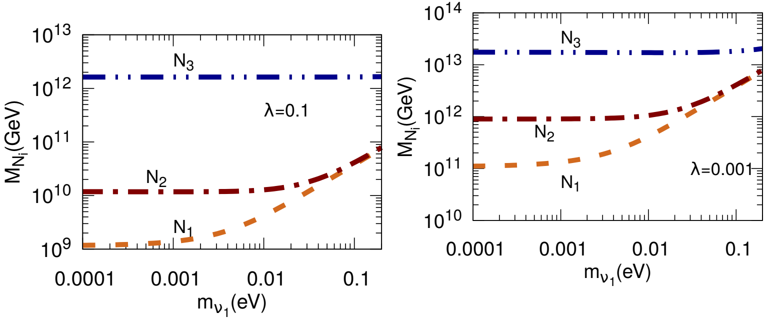

Figure: Prediction of Compact Spectrum of heavy RH neutrino masses as a function of the lightest neutrino mass when the three neutrino masses are normally ordered. The values of $M_{\Delta_L} = 10^{12}$ GeV and $v_R = 10^{15.5}$ GeV have been kept fixed.

# The CP Asymmetry

1.

$$\varepsilon_{\mathbf{i}\alpha} = \frac{\mathbf{\Gamma}(\mathbf{N_i} \to \mathbf{l}_\alpha + \mathbf{H}^*) - \mathbf{\Gamma}(\mathbf{N_i} \to \bar{\mathbf{l}}_\alpha + \mathbf{H})}{\sum_\beta \left[\mathbf{\Gamma}(\mathbf{N_i} \to \mathbf{l}_\beta + \mathbf{H}^*) + \mathbf{\Gamma}(\mathbf{N_i} \to \bar{\mathbf{l}}_\beta + \mathbf{H})\right]} . \tag{11}$$

One loop decay contributions of $N_i$ are mediated by either $N_{k\neq i}$ or $\Delta_L$[**?**], as shown in Fig. 3. The total asymmetry is sum of the two contributions

$$\varepsilon_{\mathbf{i}\alpha} = \varepsilon^{\mathbf{N}}_{\mathbf{i}\alpha} + \varepsilon^{\mathbf{\Delta}}_{\mathbf{i}\alpha}. \tag{12}$$

# fig3

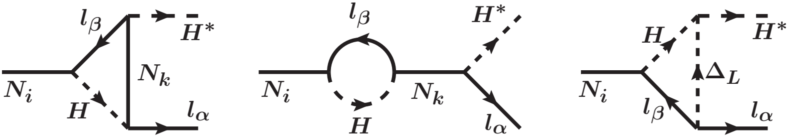

Figure: One-loop Feynman diagrams for the decay of RH neutrino $N_i$. The first and the third diagrams represent vertex corrections and the second diagram represents self-energy correction.

# Compact Spectrum: u-diagonal basis:BAU:fig6

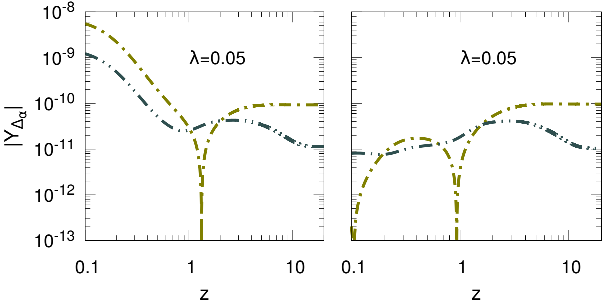

Figure: **The baryon asymmetry in $e + \mu$ flavours (double-dot-dashed blue curve) and $\tau$ flavor (dot-dashed curve) for the $u$-quark diagonal basis and compact spectrum RH$\nu$ mass scenario. Left (right) panel correspond to non-zero (zero) initial thermal abundance.**

# Hierarchical Spectrum;u-Diagonal Basis:BAU:fig9

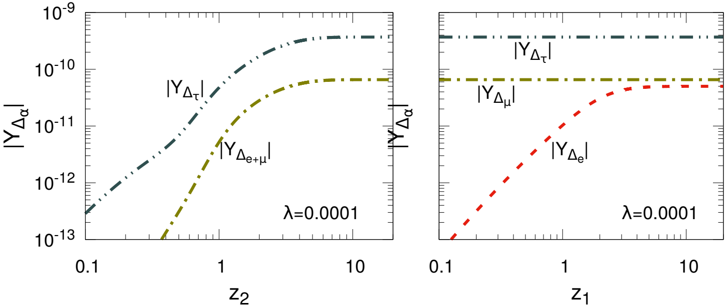

Figure: **The baryon asymmetries in $e + \mu$ and $\tau$ flavors (left panel) and separately for $e$,$\mu$ and $\tau$ flavors (right panel). Hierarchical spectrum for RH$\nu$ has been used.**

# BAU SUMMARY

1. **USING SOLUTIONS FROM BOLTZMANN Eq. WE GET BAU IN AGREEMENT WITH PLANCK2015 DATA.**
2. **THIS OCCURS IN THE CASE OF DIRAC NEUTRINO MASSES DERIVED USING UP-QUARK DIAGONAL BASIS**
3. **THE AGREEMENT OCCURS WITH BOTH COMPACT AND HIERRAECHICAL SPECTA OF RH$\nu$ MASSES.**
4. **WE HAVE USED NORMALLY ORDERED LIGHT $m_\nu$.**

# TRIPLET MAJORANA FERMION DARK MATTER

1. **PROPOSED IN SM EXTN:Cirelli,Forengo,Strumia,NPB(2006):** $\Sigma(3,0,1) \subset 45_F$ **OF SO(10)** **MASS DIFFERENCE** $m_{\Sigma^\pm} - m_{\Sigma^0} = 166$ **MeV**
2. **Extensive investigation on indirect signals and proposed collider searches: S.Mohanty et. al,IJMP(2012); A. Hryczuk et.al JCAP(2014), M. Cirelli et. al,JHEP(2014), T.Aizawa et.al,PRD(2015) and a large list of authors.**
3. **SUGGESTED MASS RANGE** $400 - 2700$ **GeV. Substantially affects** $SU(2)_L$ **gauge coupling evolution.**
4. **DIRECT SEARCH: LUX, XENON100** $> 35$ **GeV; LHC: CANDARK2017 LECTURE:(1-1000) GeV ?**

# DM MASS: NON-STD. YUK. INT.

1. WITH $A_F = 45_F, \Phi = 210_H, E = 54_H$, SO(10) GIVES
2. Non-Std. Higgs Maj.Fermion Yuk. Int:

$$-\mathcal{L}_{\mathbf{Yuk}} = \mathbf{A_F}\left(\mathbf{m_A} + \mathbf{h_p}\boldsymbol{\Phi} + \mathbf{h_e}\mathbf{E}\right)\mathbf{A_F}, \tag{13}$$

   where $m_A \simeq M_U$ and $h_i'$s are Yukawa couplings.
3. THE TRIPLET MAJORANA FERMION DM MASS CAN HAVE ANY VALUE FROM $100 - 10^{15}$ GeV BY TUNING THE PARAMETERS:

$$m_\Sigma(3,0,1) = m_A + \sqrt{2}h_p\frac{\boldsymbol{\Phi_1}}{3} + \sqrt{\frac{3}{5}}h_e < E > . \tag{14}$$

# UNIFICATION

1. **We use the fields $\Delta_L$, $\Sigma$, needed for $m_\nu$, Leptogenesis, and DM. In addition we need a color octet fermion $C_8(1,0,8) \subset 45_F$. Its mass is derived in the same way. Aizawa et al.PRD(2015: this can act as a nonthermal source of $\Sigma$.**
2. $$\frac{1}{\alpha_i(M_Z)} = \frac{1}{\alpha_i(M_U)} + \frac{a_i}{2\pi}\ln\left(\frac{M_\Sigma}{M_Z}\right) + \frac{a_i'}{2\pi}\ln\left(\frac{M_{C_8}}{M_\Sigma}\right) + \frac{a_i''}{2\pi}\ln\left(\frac{M_\Delta}{M_{C_8}}\right) + \frac{a_i'''}{2\pi}\ln\left(\frac{M_U}{M_\Delta}\right) + \Theta_i' + \Theta_i'' + \Theta_i''' - \frac{\lambda_i}{12\pi}, \qquad (15)$$

# fig10

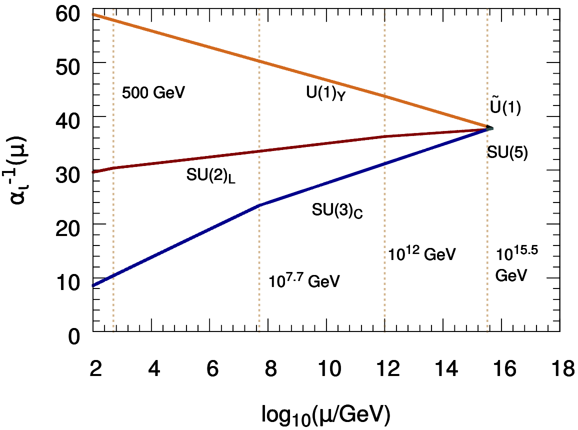

Figure: **Unification of gauge couplings of SM with** $M_U = 10^{15.56}$ **GeV,** $g_G = 0.573$**.**

# THRESHOLD EFFECTS

1. **Refs:**
   **(1).S.Weinberg PLB(1980), L. Hall, NPB(1981), B.Ovrut, H.Snitzer, PLB(1981), MKP,C.Hazra, PRD(1989) .....**
   **(2).SUPERHEAVY COMPONENTS OF A GIVEN SO(10) REP. HAVE DEDEGENERATE MASS: R. N. Mohapatra, MKP PRD(1993).**
2.

$$\begin{aligned}
\lambda_1 &= 17/5 + 4\eta_{(10)} + (0)\eta_{(45)} + 136\eta_{(126)}, \\
\lambda_2 &= 6 + 4\eta_{(10)} + 2\eta_{(45)} + 140\eta_{(126)}, \\
\lambda_3 &= 8 + 4\eta_{(10)} + 3\eta_{(45)} + 140\eta_{126}, \\
\eta_X &= \ln(M_X/M_U) \qquad (16)
\end{aligned}$$

# PROTON LIFETIME

1. $$\tau_{\mathbf{p}}^{\mathsf{expt.}} \geq \mathbf{1.4} \times \mathbf{10}^{\mathbf{34}} \quad \text{yrs.} \tag{17}$$

2. $$\tau_{\mathbf{p}}^{\mathbf{SO(10)}} \simeq \mathbf{1.8} \times \mathbf{10}^{\mathbf{34} \pm \mathbf{3.712}\eta_{\mathsf{S}} \pm \mathbf{1.012}\eta_{\mathsf{F}}} \quad \text{yrs.} \tag{18}$$

# fig11

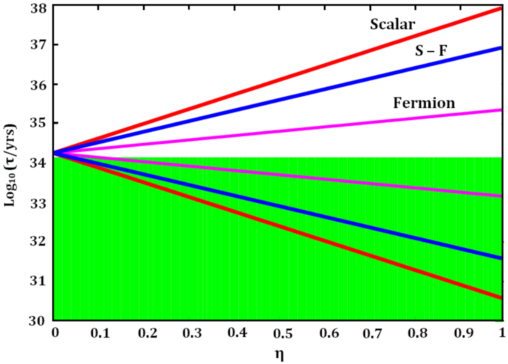

Figure: **Proton lifetime prediction for the decay mode $p \to e^+\pi^0$ shown by slanting solid lines as a function of $\eta = \eta_S(\eta_F) = |\log_{10}(M_{SH}/M_U)|(|\log_{10}(M_F/M_U)|)$ for super-heavy scalar(fermion) components.**

# Summary

1. Non-SUSY SO(10) directly breaking to SM can successfully answer the questions of $m_\nu$, BAU, DM, DM stability, Unification, and observed proton stability. It gives asymptotic parity restoration.
2. Ebedding DM in SO(10) enhances proton lifetime prediction substantially.
3. Resolution of gauge hierarchy by fine-tuning is not as natural as in SUSY SO(10).
4. In non-SUSY case there is no gravitino problem, or problem associated with Higgsino mediated proton decay.
5. Doublet-triplet splitting occurs naturally under extended survival hypothesis.

# Thank You