NEW ASPECTS OF SYMMETRY BREAKING IN GRAND UNIFIED THEORIES

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THE GRAND UNIFICATION PROGRAM

After 36 years from the first proposal by Georgi and Glashow, GUTs still attract a lot of attention for their intrinsic predictivity of spectacular phenomena

- Matter instability
- GUT Monopoles

and their potential for understanding our low-energy world through nontrivial correlations among different SM sectors

- In many extensions of the SM, gauge couplings seem to unify in a narrow window still allowed by proton decay limits and a consistent QFT description
- The Yukawa sector supports simultaneously both quark and lepton textures
- Predictive link between the tiny neutrino masses and the heavy GUT states

Still no consensus on which is the the minimal theory to be falsified the day after the discovery of proton decay

THE CONCEPT OF MINIMALITY

The concept of minimality admits a certain number of interpretations

- Minimum rank of the group
- Higgs sector dimensionality
- Naturalness of the D-T splitting
- Complexity of the gauge unification pattern
- ...
- Predictivity: i.e. the number of independent couplings

SO(10) GUTs usually score better than SU(5) models

- More predictive (SM matter falls into three 16_F rep.'s)
- Natural relief from the troubles with the simplest SU(5) models

Sticking to the SO(10) case minimality is essentially equivalent to the complexity of the Higgs sector

THE MINIMAL SO(10) HIGGS SECTOR

Just by group theoretical arguments we require the following rep.'s in order to break SO(10) to the SM

- Rank reduction: 16_H or 126_H
  breaks B-L giving mass to neutrinos but leaves an SU(5) little group

- Further SU(5) breaking: 45_H or 54_H or 210_H
  the adjoint 45_H can admit little groups different from SU(5)⊗U(1)

However since the early 1980's it has been observed that the vacuum dynamics aligns the adjoint along the SU(5)⊗U(1) direction

- non-SUSY: approximate alignment ⟶ clashes with unification constraints

[Yasuè (1981), Anastaze, Derendinger, Buccella (1983), Babu, Ma (1985)]

- SUSY: exact alignment ⟶ little group is SU(5) [Buccella, Derendinger, Savoy, Ferrara (1981)]

The subject of this talk is to provide ways out to these two issues ...

INTERMEDIATE SCALES IN THE NON-SUSY SO(10)

SUSY not mandatory for unification after we trade naturalness for predictivity

The unification ansatz in non-SUSY SO(10) predicts the existence of intermediate scales in the range $10^{10\div 14}$ GeV (ideal for neutrino masses and leptogenesis)

$$(100\ \text{GeV})^2/M_{\text{seesaw}} \gtrsim \sqrt{\Delta m^2_{\text{atm}}} \quad \Rightarrow \quad M_{\text{seesaw}} \lesssim 10^{14}\ \text{GeV}$$

The breaking of non-SUSY SO(10) to the SM can be minimally achieved with a pair of Higgs multiplets only: $45_H \oplus 16_H$ (or 126_H)

$$SO(10) \xrightarrow[\omega_Y\ \subset\ \langle 45_H\rangle]{M_G} 3_c\, 2_L\, 2_R\, 1_{B-L} \xrightarrow[\omega_R\ \subset\ \langle 45_H\rangle]{M_I} 3_c\, 2_L\, 1_R\, 1_{B-L} \xrightarrow[\chi_R\ \subset\ \langle 16_H\rangle\ \text{or}\ \langle 126_H\rangle]{M_{B-L}} 3_c\, 2_L\, 1_Y$$

$$SO(10) \xrightarrow[\omega_R\ \subset\ \langle 45_H\rangle]{M_G} 4_C\, 2_L\, 1_R \xrightarrow[\omega_Y\ \subset\ \langle 45_H\rangle]{M_I} 3_c\, 2_L\, 1_R\, 1_{B-L} \xrightarrow[\chi_R\ \subset\ \langle 16_H\rangle\ \text{or}\ \langle 126_H\rangle]{M_{B-L}} 3_c\, 2_L\, 1_Y$$

where $M_I \ll M_G$ by unification constraints

TREE LEVEL POTENTIAL

Very minimal potential analyzed long ago [Buccella, Ruegg, Savoy (1980)]

$$V_0 = V_{45_H} + V_{16_H} + V_{45_H 16_H}$$

$$V_{45_H} = -\mu^2 \, \mathrm{Tr}\, 45_H^2 + a_1 \, (\mathrm{Tr}\, 45_H^2)^2 + a_2 \, \mathrm{Tr}\, 45_H^4$$

$$V_{16_H} = -\nu^2 \, 16_H^\dagger 16_H + \lambda_1 \, (16_H^\dagger 16_H)^2 + \lambda_2 \, (16_H \, \Gamma \, 16_H)(16_H^\dagger \, \Gamma \, 16_H^\dagger)$$

$$V_{45_H 16_H} = \alpha \, (16_H^\dagger 16_H) \mathrm{Tr}\, 45_H^2 + \beta \, 16_H^\dagger 45_H^2 16_H + \tau \, 16_H^\dagger 45_H 16_H$$

From the positivity of the scalar states (1,3,0) and (8,1,0) ⊂ 45_H

[Yasuè (1981), Anastaze, Derendinger, Buccella (1983), Babu, Ma (1985)]

$$M^2(1,3,0) = 2a_2(\omega_Y - \omega_R)(\omega_Y + 2\omega_R)$$

$$M^2(8,1,0) = 2a_2(\omega_R - \omega_Y)(\omega_R + 2\omega_Y)$$

$$\Rightarrow \quad a_2 < 0 \, , \qquad -2 < \omega_Y / \omega_R < -\tfrac{1}{2}$$

The only possibility allowed by gauge coupling unification requires a splitting between ω_Y and ω_R of at least four orders of magnitude !

- This is the origin of the common knowledge that non-SUSY SO(10) GUTs with just the adjoint driving the GUT breaking are not phenomenologically viable

A TREE LEVEL ACCIDENT

Why the masses of the states (1,3,0) and (8,1,0) are so tightly correlated ?"

Enhanced global symmetries in a trivial limit of the potential $a_2 = \lambda_2 = \beta = \tau = 0$

$$V_{\rm moduli} = -\mu^2\,{\rm Tr}\,45_H^2 + a_1\,({\rm Tr}\,45_H^2)^2 - \nu^2\,16_H^\dagger 16_H + \lambda_1\,(16_H^\dagger 16_H)^2 + \alpha\,(16_H^\dagger 16_H){\rm Tr}\,45_H^2$$

$$O(45)\otimes O(32) \xrightarrow[\langle 16_H\rangle]{\langle 45_H\rangle} O(44)\otimes O(31) \Longrightarrow 44+31 = \text{75 GB}$$

Global

$$SO(10) \xrightarrow[\langle 16_H\rangle]{\langle 45_H\rangle} SM \Longrightarrow \text{33 WGB}$$

Local

$$\Big\}\ 75-33 = \text{42 PGB}$$

- The states (1,3,0) and (8,1,0) belong to this set of PGB
- Nothing would prevent the explicit breaking couplings λ_2 β and τ to enter at the quantum level !

Second law of progress in theoretical physics: [S.Weinberg (1983)]

"Do not trust arguments based on the lowest order of perturbation theory"

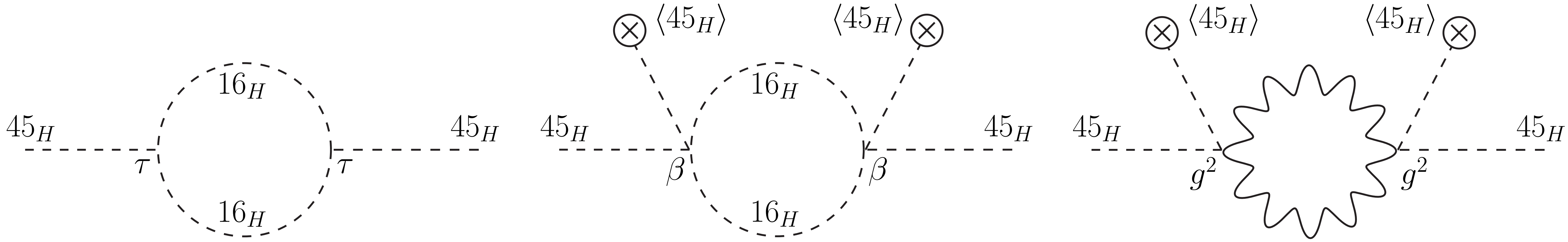
REVIVING THE MINIMAL SO(10) GUT

Explicit computation of the one-loop PGB masses using Effective-Potential methods

[Coleman, E. Weinberg (1973)]

$$M^2(1,3,0) = 2a_2(\omega_Y - \omega_R)(\omega_Y + 2\omega_R) + \frac{1}{4\pi^2}\left[\tau^2 + \beta^2(2\omega_R^2 - \omega_R\omega_Y + 2\omega_Y^2) + g^4\left(16\omega_R^2 + \omega_Y\omega_R + 19\omega_Y^2\right)\right] + \text{Log's}\,(\mu)$$

$$M^2(8,1,0) = 2a_2(\omega_R - \omega_Y)(\omega_R + 2\omega_Y) + \frac{1}{4\pi^2}\left[\tau^2 + \beta^2(\omega_R^2 - \omega_R\omega_Y + 3\omega_Y^2) + g^4\left(13\omega_R^2 + \omega_Y\omega_R + 22\omega_Y^2\right)\right] + \text{Log's}\,(\mu)$$



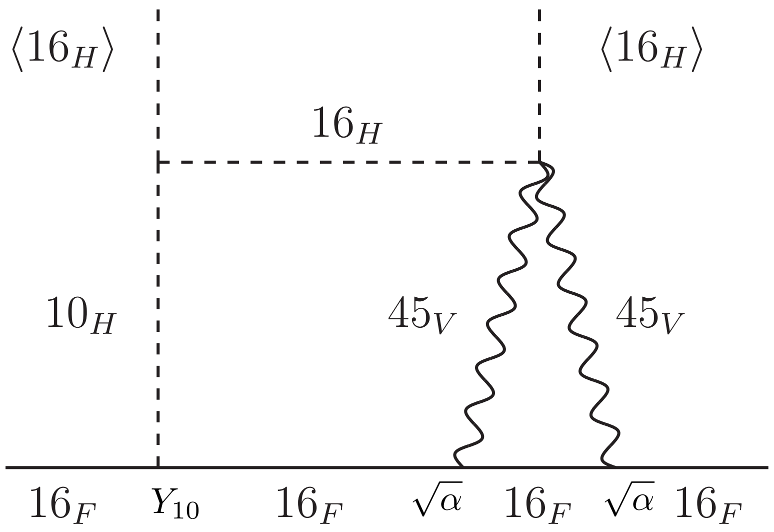
An hierarchy between ω_Y and ω_R (as required by unification), while keeping the scalar states positive (minimum condition), is now possible just by taking $|a_2|<10^{-2}$

Holds for any non-SUSY SO(10) model with one adjoint triggering the GUT breaking

WHAT ABOUT NEUTRINOS ? (NON-SUSY)

The simplest scenario featuring the Higgs scalars in $10_H \oplus 16_H \oplus 45_H$ is likely to fail when addressing the absolute neutrino mass scale

RH neutrino mass M_N (entering type-I seesaw)



- Radiative seesaw $$M_N \sim \left(\frac{\alpha}{\pi}\right) Y_{10} \frac{M_{B-L}^2}{M_G}$$

  [Witten (1980); Bajc, Senjanovic (2005)]

- New Physics at the Planck scale $$M_N \sim Y_P \frac{M_{B-L}^2}{M_P} \subset \frac{Y_P}{M_P} 16_F 16_F 16_H^* 16_H^*$$

Since $M_{B-L} \ll M_G$, M_N undershoots the natural range suggested by the the seesaw mechanism

Considering 126_H in place of 16_H the absolute neutrino mass scale would be fine

$$16_F 16_F 126_H^* \supset M_N \sim \langle 126_H^* \rangle \sim M_{B-L}$$

Work in progress...

WHAT ABOUT NEUTRINOS ? (SUSY)

Invoking TeV-scale SUSY

- The gauge running prefers M_{B-L} in the proximity of M_G
- The D=5 operator $16_F^2 \overline{16}_H^2 / M_P$ can naturally reproduce the desired range for M_N

Higgs sectors based on rep.'s up to the adjoint are therefore very interesting !

The superpotential does not support a renormalizable breaking to a SUSY-SM

[Buccella, Derendinger, Savoy, Ferrara (1981)]

$$W = 45_H^2 + 16_H \overline{16}_H + 16_H 45_H \overline{16}_H$$

- D-Flatness: $|\langle 16_H \rangle| = |\langle \overline{16}_H \rangle|$
- F-Flatness: $\langle 45_H \rangle \propto \langle 16_H \overline{16}_H \rangle$

The little group is SU(5) due to the alignment of the adjoint along the spinors

New physics at the Planck scale, parametrized by effective M_P-suppressed operators, allows for the adjoint misalignment

[Babu, Barr (1995)]

THE GUT SCALE LITTLE HIERARCHY

The hierarchy induced in the Higgs spectrum by $M_G / M_P \approx 10^{-2}$ factors splits the GUT-scale thresholds over several orders of magnitude

- Fast proton decay via neutrino mass operators

$$W_Y \supset \frac{1}{M_P} 16_F \; g \; 16_F 16_H 16_H + \frac{1}{M_P} 16_F \; f \; 16_F \overline{16}_H \overline{16}_H \supset \frac{\langle 16_H \rangle}{M_P} \left(Q \; g \; L \; \overline{T} + Q \; f \; Q \; T \right)$$

$$M_T \approx M_G \quad \longrightarrow \quad \Gamma^{-1}(\overline{\nu} K^+) \sim (0.6 - 3) \times 10^{33} \text{ yrs}$$ [Babu, Pati, Wilczek (2000)]

$$M_T \approx \frac{M_G}{M_P} M_G \quad \longrightarrow \quad \Gamma^{-1}(\overline{\nu} K^+)^{\text{NR}} = \left(\frac{M_G}{M_P} \right)^2 \Gamma^{-1}(\overline{\nu} K^+) \ll \Gamma^{-1}(\overline{\nu} K^+)^{\text{exp}} > 0.670 \times 10^{33} \text{ yrs}$$

- Upset of the one-step unification pattern favoured by the MSSM

Unification could be preserved close to the Planck scale

- Unwelcome for RH neutrino masses $M_N \approx M_G^2 / M_P$

Is it possible to overcome the SU(5) lock at the renormalizable level while keeping only spinorial and adjoint rep.'s ? ⟶ Flipped embeddings ...

DIGRESSION: FLIPPED EMBEDDINGS

$G \supset H \otimes U(1)_X \supset [K \otimes U(1)_Z] \otimes U(1)_X$ G Simple H K Simple or Semi-simple

- Standard breaking chain $G \to H \to K \otimes U(1)_Z$
- Flipped breaking chain $G \to H \otimes U(1)_X \to K \otimes U(1)_{\tilde{Z}}$ $\tilde{Z} = \alpha Z + \beta X \,, \quad \beta \neq 0$

Requiring that the rep.'s of G decompose in submultiplets with the same quantum numbers under both $K \otimes U(1)_Z$ and $K \otimes U(1)_{\tilde{Z}}$ fixes **α** and **β** [Barr (1989)]

Basic example: Flipped SU(5) [De Rujula, Georgi, Glashow (1980); Barr (1982)]

$G \equiv SO(10)$ $H \equiv SU(5)$ $K \equiv SU(3)_C \otimes SU(2)_L$ $\tilde{Z} \equiv Y$ $\alpha = -\frac{1}{5} \,, \quad \beta = +\frac{1}{5}$

$$16 \equiv \begin{cases} (u^c \oplus \ell)_{\overline{5}_{-3}} \\ (d^c \oplus Q \oplus \nu^c)_{10_{+1}} \\ (e^c)_{1_{+5}} \end{cases}$$

- Flipping: corresponds to a **π** rotation in the $SU(2)_R$ space !
- Notice the SM-singlet in the 10 of Flipped SU(5)

HYPERCHARGE EMBEDDINGS IN SO(10)⊗U(1)$_X$

$$SO(10)\otimes U(1)_X \supset SU(5)\otimes U(1)_Z\otimes U(1)_X \supset SU(3)_C\otimes SU(2)_L\otimes \underbrace{U(1)_{Y'}\otimes U(1)_Z\otimes U(1)_X}_{U(1)_Y}$$

$$Y = \alpha Y' + \beta Z + \gamma X$$

Given the anomaly-free X charge matter assignment $(X_{16}, X_{10}, X_1) = (+1, -2, +4)$ there are only three solutions which accommodate the SM quantum numbers over a 16⊕10⊕1 matter representation

$\alpha = 1\ \beta = 0\ \gamma = 0$
- Standard

$\alpha = -\frac{1}{5}\ \beta = \frac{1}{5}\ \gamma = 0$
- Flipped SU(5) [De Rujula, Georgi, Glashow (1980); Barr (1982)]

$\alpha = -\frac{1}{5}\ \beta = -\frac{1}{20}\ \gamma = \frac{1}{4}$
- Flipped SO(10) [Kephart, Nakagawa (1984); Rizos, Tamvakis (1988)]

- The active role of the U(1)$_X$ generator in the SM hypercharge identification gives the opportunity of breaking the gauge symmetry at the renormalizable level and by means of only rep.'s up to the adjoint

MINIMAL FLIPPED SO(10)⊗U(1) SUSY HIGGS SECTOR

- Spinor decomposition

$SO(10)$	$SO(10)_f$
$(\overline{3},1;+\frac{1}{3})_{\overline{5}}$	$(\overline{3},1;+\frac{1}{3})_{\overline{5}}$
$(1,2;-\frac{1}{2})_{\overline{5}}$	$(1,2;+\frac{1}{2})_{\overline{5}}$
$(3,2;+\frac{1}{6})_{10}$	$(3,2;+\frac{1}{6})_{10}$
$(\overline{3},1;-\frac{2}{3})_{10}$	$(\overline{3},1;+\frac{1}{3})_{10}$
$(1,1;+1)_{10}$	$(\mathbf{1},\mathbf{1};\mathbf{0})_{\mathbf{10}} \equiv e$
$(\mathbf{1},\mathbf{1};\mathbf{0})_{\mathbf{1}}$	$(\mathbf{1},\mathbf{1};\mathbf{0})_{\mathbf{1}} \equiv \nu$

- Preserve a SM little group
- Connected by an $SU(2)_R$ rotation

Full rank reduction

To keep D-Flatness

$$2 \times \left(16_H \oplus \overline{16}_H\right) \oplus 45_H$$

Renormalizable agent

Renormalizable superpotential $\quad W_H = \frac{\mu}{2}\,\mathrm{Tr}\,45^2 + \rho_{ij}16_i\overline{16}_j + \tau_{ij}16_i 45\overline{16}_j \qquad i,j=1,2$

Imposing D- and F-flatness at the GUT scale:

- A nontrivial vacuum requires ρ and τ to be hermitian
- The inspection of the gauge spectrum reveals the following little group

SM for misaligned $16 \oplus \overline{16}$ pairs

TOWARDS A REALISTIC FLAVOR

The flipped SO(10) embedding offers also the possibility of triggering the EW symmetry breaking without a 10_H

Simplified Yukawa sector with just one pair of Higgs spinors + Z_2 matter parity

$$W_Y = Y_U\, 16_F 10_F 16_H + \frac{1}{M_P}\left[Y_E\, 10_F 1_F \overline{16}_H \overline{16}_H + Y_D\, 16_F 16_F \overline{16}_H \overline{16}_H\right]$$

	$SO(10)$	$SO(10)_f$
16_F	$(D^c \oplus L)_{\overline{5}} \oplus (U^c \oplus Q \oplus E^c)_{10} \oplus (N^c)_1$	$(D^c \oplus \Lambda^c)_{\overline{5}} \oplus (\Delta^c \oplus Q \oplus S)_{10} \oplus (N^c)_1$
10_F	$(\Delta \oplus \Lambda^c)_5 \oplus (\Delta^c \oplus \Lambda)_{\overline{5}}$	$(\Delta \oplus L)_5 \oplus (U^c \oplus \Lambda)_{\overline{5}}$
1_F	$(S)_1$	$(E^c)_1$
$\langle 16_H \rangle$	$(0 \oplus \langle H_d \rangle)_{\overline{5}} \oplus (0 \oplus 0 \oplus 0)_{10} \oplus (\nu_H)_1$	$(0 \oplus \langle H_u \rangle)_{\overline{5}} \oplus (0 \oplus 0 \oplus e_H)_{10} \oplus (\nu_H)_1$
$\langle \overline{16}_H \rangle$	$(0 \oplus \langle H_u \rangle)_5 \oplus (0 \oplus 0 \oplus 0)_{\overline{10}} \oplus (\nu_H)_1$	$(0 \oplus \langle H_d \rangle)_5 \oplus (0 \oplus 0 \oplus e_H)_{\overline{10}} \oplus (\nu_H)_1$

$$Q = (U,\ D) \quad L = (N,\ E) \quad \Lambda = (\Lambda^0,\ \Lambda^-) \quad \Lambda^c = (\Lambda^{c+},\ \Lambda^{c0}) \quad \langle H_u \rangle = (0,\ v_u) \quad \langle H_d \rangle = (v_d,\ 0)$$

- The SM fermions span necessarily over a reducible 16⊕10⊕1 matter rep.
- All the fermions, but the up-quarks, need Planck-suppressed contributions
- The top/bottom hierarchy is due to an $M_f/M_P \sim 10^{-2}$ factor $\longrightarrow$ $\tan\beta \sim 1$

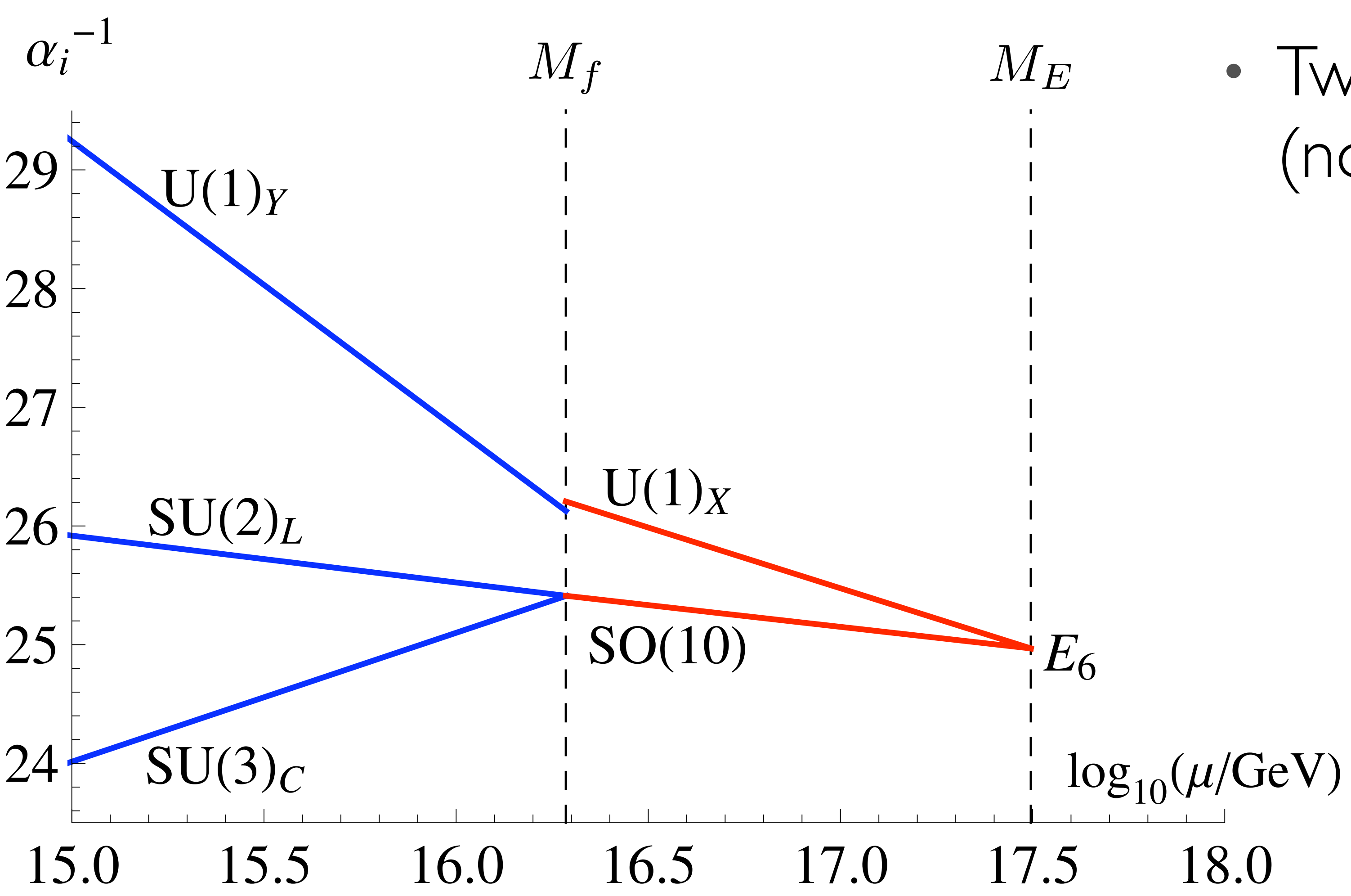
A UNIFIED E_6 SCENARIO

The flipped SO(10)⊗U(1) model can be naturally embedded in an E_6 GUT with one 78_H and two pairs of $27_H \oplus \overline{27}_H$ in the Higgs sector

$$W_H = \frac{\mu}{2}\mathrm{Tr}\,78^2 + \rho_{ij}27_i\overline{27}_j + \tau_{ij}27_i 78\overline{27}_j + \alpha_{ijk}27_i 27_j 27_k + \beta_{ijk}\overline{27}_i\overline{27}_j\overline{27}_k \qquad i,j=1,2$$

SUSY vacuum

- The little group is SU(5) for misaligned $27_H \oplus \overline{27}_H$ pairs
- Needs effective adjoint interactions near the Planck scale in order to reach the SM



- Two-loop MSSM with TeV scale SUSY (no GUT-scale thresholds)

CONCLUSIONS

A longstanding result claims that non-SUSY SO(10) GUTs with just the adjoint triggering the GUT breaking can not provide a successful gauge unification

- We argued that this result is an artifact of the tree-level potential and showed that quantum corrections have a dramatic impact
- A model featuring $10_H \oplus 126_H \oplus 45_H$ in the Higgs sector has all the ingredients to be a viable minimal non-SUSY SO(10) candidate

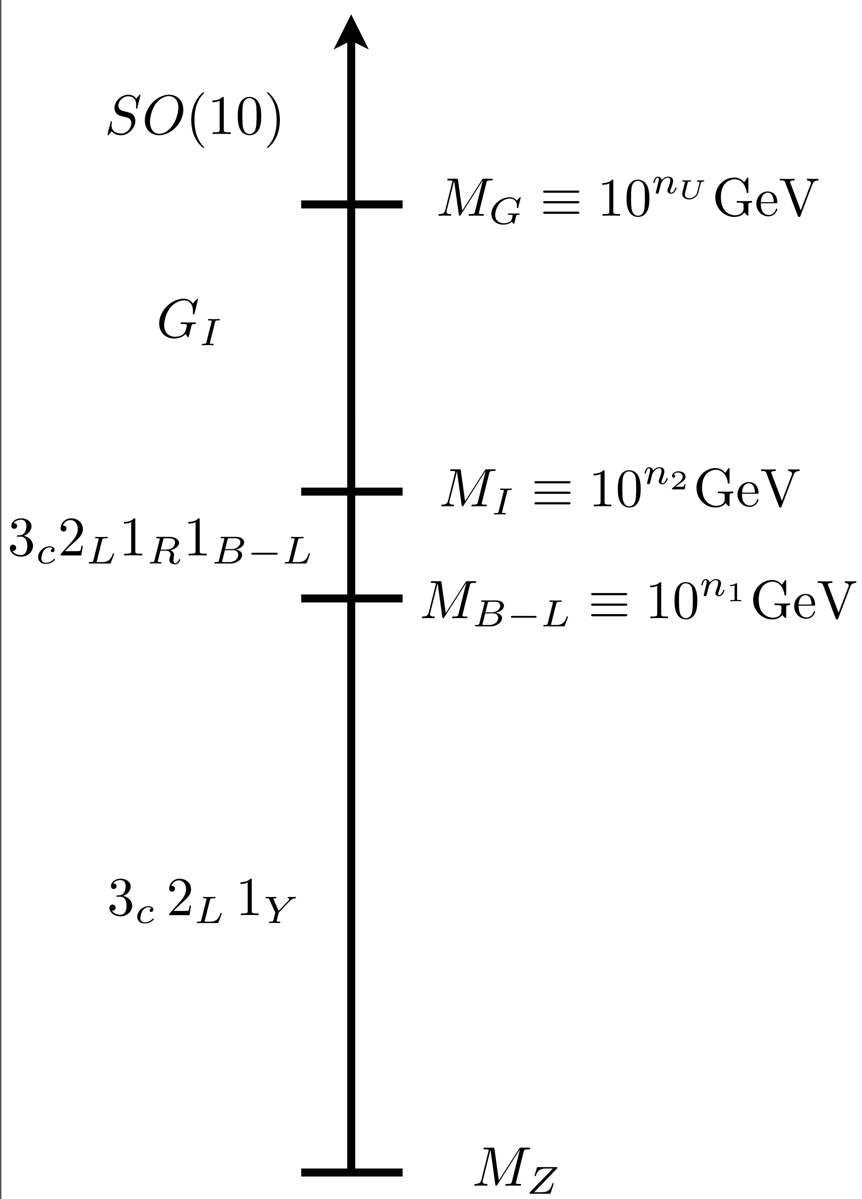
SUSY SO(10) GUTs with rep.'s up to the adjoint do not provide a phenomenolgically viable breaking to the SM (GUT-scale Little Hierarchy due to NR operators)

- The flipped SO(10) embedding offers the option of breaking the gauge symmetry to $SU(3)_C \otimes U(1)_Q$ at the renormalizable level and by means of a simple Higgs sector: $2 \times (16_H \oplus \overline{16}_H) \oplus 45_H$
- We made the case for a two-step breaking of an E_6 GUT realised in the vicinity of the Planck scale via an intermediate flipped $SO(10) \otimes U(1)$ stage

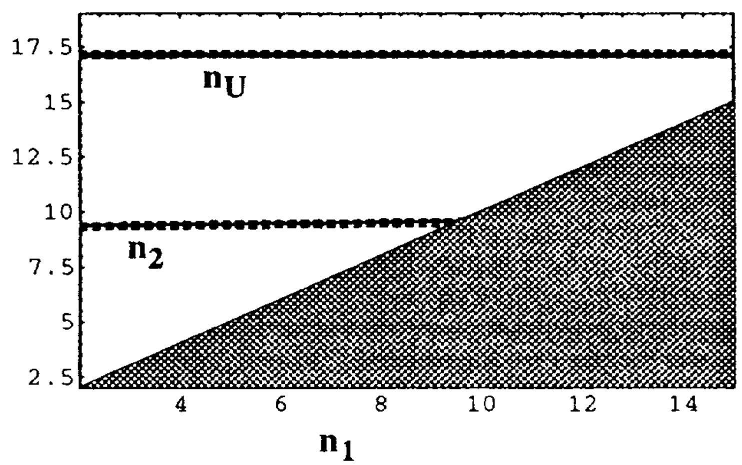
BACKUP SLIDES

IMPACT OF THE FULL TWO-LOOP ANALYSIS

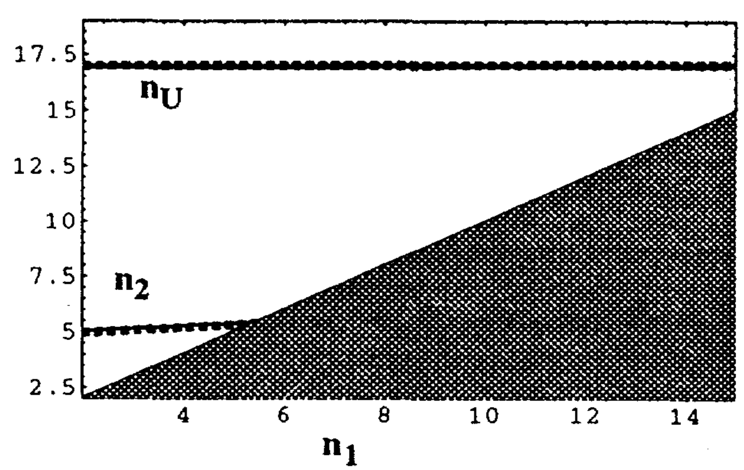
General RG analysis of gauge coupling unification based on the Extended Survival Hypothesis (no detailed thresholds!)



[Deshpande, Keith, Pal (1993)]

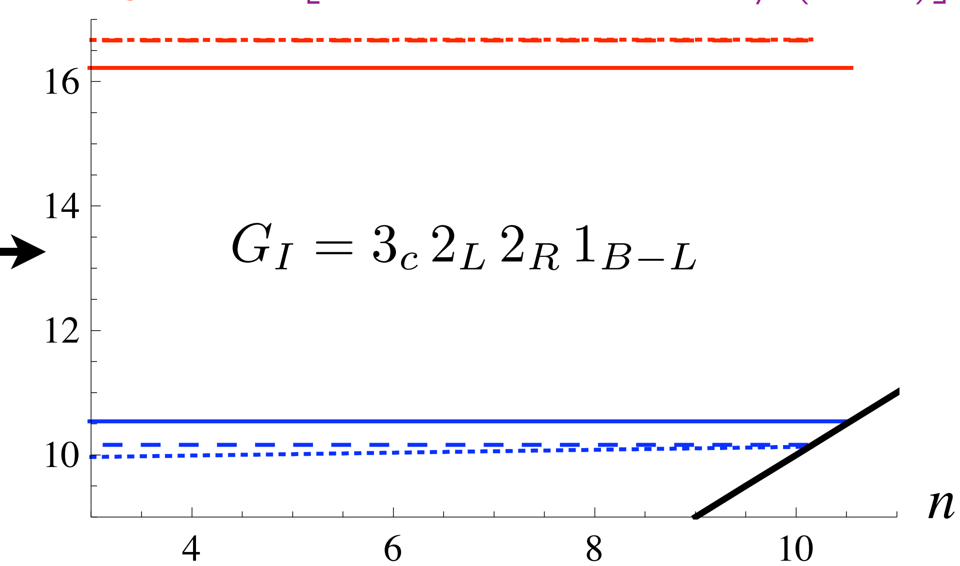


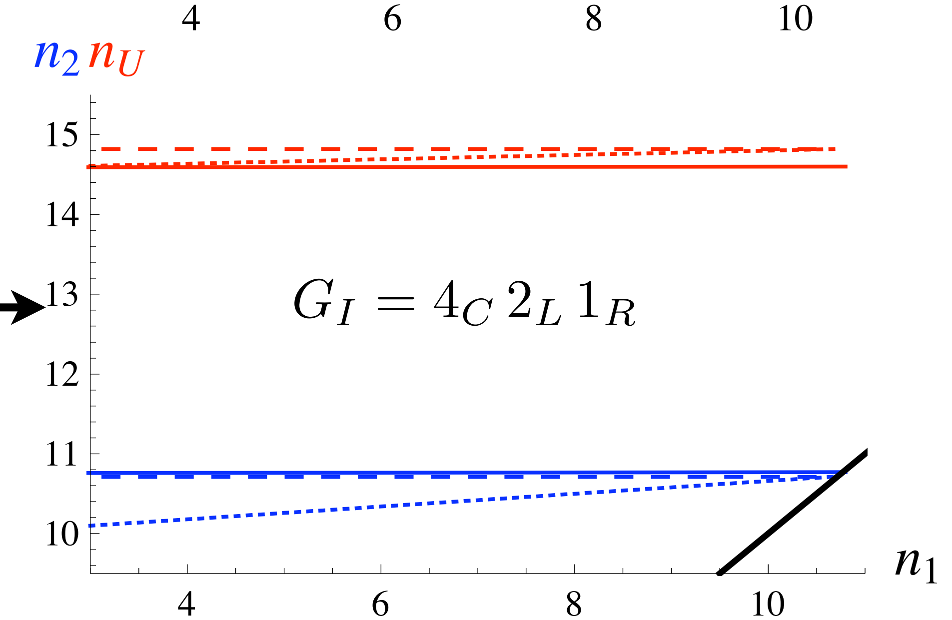
Chain VIIIb



Chain XIIa

[Bertolini, DL, Malinsky (2009)]





- U(1) mixing makes the B-L scale essentially free (upper bound given by M_I)
- Two-loop effects tend to raise the M_I scale and lower the GUT scale
- Sharp disagreement for chain XIIa: the M_I scale is raised by 5 orders of magnitude !

MINIMAL FLIPPED SO(10)⊗U(1) SUSY HIGGS SECTOR

The most general renormalizable superpotential made of $2 \times (16_H + \overline{16}_H) \oplus 45_H$ is

$$W_H = \frac{\mu}{2}\,\mathrm{Tr}\,45^2 + \rho_{ij} 16_i \overline{16}_j + \tau_{ij} 16_i 45 \overline{16}_j \qquad i,j = 1,2 \qquad \tau_{ij} \longrightarrow \tau_i \delta_{ij}$$

We require D- and F-flatness at the GUT scale

- The vacuum manifold reads

$$\begin{aligned} e_{1,2} &= r_{1,2} \cos\alpha_{1,2}\; e^{i\phi_{e_{1,2}}} \\ \nu_{1,2} &= r_{1,2} \sin\alpha_{1,2}\; e^{i\phi_{\nu_{1,2}}} \\ \overline{e}_{1,2} &= r_{1,2} \cos\alpha_{1,2}\; e^{-i\phi_{e_{1,2}}} \\ \overline{\nu}_{1,2} &= r_{1,2} \sin\alpha_{1,2}\; e^{-i\phi_{\nu_{1,2}}} \end{aligned}$$

$$\begin{aligned} 8\mu\,\omega^+ &= \tau_1 r_1^2 \sin 2\alpha_1 e^{i(\phi_{e_1}-\phi_{\nu_1})} + \tau_2 r_2^2 \sin 2\alpha_2 e^{i(\phi_{e_2}-\phi_{\nu_2})} \\ 8\mu\,\omega^- &= \tau_1 r_1^2 \sin 2\alpha_1 e^{i(\phi_{\nu_1}-\phi_{e_1})} + \tau_2 r_2^2 \sin 2\alpha_2 e^{i(\phi_{\nu_2}-\phi_{e_2})} \\ 4\sqrt{2}\mu\,\omega_R &= \tau_1 r_1^2 \cos 2\alpha_1 + \tau_2 r_2^2 \cos 2\alpha_2\,, \\ 4\sqrt{2}\mu\,\omega_Y &= -\tau_1 r_1^2 - \tau_2 r_2^2 \end{aligned}$$

Where $r_{1,2}$ and $\alpha_{1,2}$ are fixed in terms of superpotential paremeters ...

The inspection of the gauge boson spectrum reveals the following little groups

- SU(5)⊗U(1) for aligned $16 \oplus \overline{16}$ pairs $\quad \alpha_1 = \alpha_2 \quad \text{and} \quad \phi_{\nu_1} - \phi_{\nu_2} = \phi_{e_1} - \phi_{e_2}$
- SM for misaligned $16 \oplus \overline{16}$'s pairs $\quad \alpha_1 \neq \alpha_2 \quad \text{and/or} \quad \phi_{\nu_1} - \phi_{\nu_2} \neq \phi_{e_1} - \phi_{e_2}$

MASS MATRICES (CHARGED FERMIONS)

After the EW symmetry breaking the mass matrices for the matter fields sharing the same unbroken $SU(3)_C \otimes U(1)_Q$ quantum numbers are

$$\hat{\nu}_H \equiv \nu_H / M_P$$
$$\hat{e}_H \equiv e_H / M_P$$

$$(U)(U^c) \qquad M_u = Y_U v_u$$

$$(D, \Delta)(\Delta^c, D^c) \qquad M_d = \begin{pmatrix} Y_D \hat{\nu}_H v_d & Y_D \hat{e}_H v_d \\ Y_U e_H & Y_U \nu_H \end{pmatrix} \sim \mathcal{O}\begin{pmatrix} v & v \\ M_f & M_f \end{pmatrix}$$

$$\begin{pmatrix} d^c \\ \tilde{\Delta}^c \end{pmatrix} \equiv U_d \begin{pmatrix} \Delta^c \\ D^c \end{pmatrix} \qquad M_d \to M_d U_d^\dagger \equiv M'_d \sim \mathcal{O}\begin{pmatrix} v & v \\ 0 & M_f \end{pmatrix}$$

$$(\Lambda^-, E)(E^c, \Lambda^{c+}) \qquad M_e = \begin{pmatrix} Y_E \hat{\nu}_H v_d & Y_U e_H \\ Y_E \hat{e}_H v_d & Y_U \nu_H \end{pmatrix} \sim \mathcal{O}\begin{pmatrix} v & M_f \\ v & M_f \end{pmatrix}$$

$$\begin{pmatrix} e \\ \tilde{\Lambda}^- \end{pmatrix} \equiv U_e^* \begin{pmatrix} \Lambda^- \\ E \end{pmatrix} \qquad M_e \to U_e M_e \equiv M'_e \sim \mathcal{O}\begin{pmatrix} v & 0 \\ v & M_f \end{pmatrix}$$

Up to a tiny $\mathcal{O}(v/M_f)$ rotation $(D)(d^c)$ and $(e)(E^c)$ correspond to the light d.o.f. , while $(\Delta)(\tilde{\Delta}^c)$ and $(\tilde{\Lambda}^-)(\Lambda^{c+})$ get a super-heavy mass

MASS MATRICES (NEUTRINOS)

$(\Lambda^0, N, \Lambda^{c0}, N^c, S)$

$$M_\nu = \begin{pmatrix} 0 & 0 & Y_U e_H & 0 & Y_U v_u \\ 0 & 0 & Y_U \nu_H & Y_U v_u & 0 \\ Y_U e_H & Y_U \nu_H & Y_D \hat{v}_d v_d & 2Y_D \hat{v}_d \nu_H & 2Y_D \hat{v}_d e_H \\ 0 & Y_U v_u & 2Y_D \hat{\nu}_H v_d & Y_D \hat{\nu}_H \nu_H & 2Y_D \hat{\nu}_H e_H \\ Y_U v_u & 0 & 2Y_D \hat{e}_H v_d & 2Y_D \hat{e}_H \nu_H & Y_D \hat{e}_H e_H \end{pmatrix} \sim \mathcal{O} \begin{pmatrix} 0 & 0 & M_f & 0 & v \\ 0 & 0 & M_f & v & 0 \\ M_f & M_f & 0 & v & v \\ 0 & v & v & M_f^2/M_P & 2M_f^2/M_P \\ v & 0 & v & 2M_f^2/M_P & M_f^2/M_P \end{pmatrix}$$

Working in the one family approximation, for the lightest neutrino we get

$$m_\nu \sim \frac{(\nu_H^2 + e_H^2)^2 + 2e_H^2\nu_H^2}{3e_H^2\nu_H^2(e_H^2+\nu_H^2)} M_P v_u^2 \xrightarrow{e_H \sim \nu_H \sim M_f} m_\nu \sim \frac{v_u^2}{M_f^2/M_P} \sim 0.1 \text{ eV}$$

$$\nu \sim \frac{\nu_H}{\sqrt{\nu_H^2+e_H^2}}\Lambda^0 - \frac{e_H}{\sqrt{\nu_H^2+e_H^2}} N \qquad \tilde{\Lambda}^0 \sim \frac{\nu_H}{\sqrt{\nu_H^2+e_H^2}}\Lambda^0 + \frac{e_H}{\sqrt{\nu_H^2+e_H^2}} N$$

Setting $v_u \sim v_d \sim 0$ and working in the basis $(\nu, \tilde{\Lambda}^0, \Lambda^{c0}, N^c, S)$ the heavy spectrum reads

$$M'_\nu \sim \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & M_f & 0 & 0 \\ 0 & M_f & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{M_f^2}{M_P} & 2\frac{M_f^2}{M_P} \\ 0 & 0 & 0 & 2\frac{M_f^2}{M_P} & \frac{M_f^2}{M_P} \end{pmatrix} \longrightarrow$$

$$\begin{aligned} m_{\nu_{M_1}} &\sim -M_f^2/M_P & \nu_{M_1} &\sim \tfrac{1}{\sqrt{2}}(N^c - S)\,, \\ m_{\nu_{M_2}} &\sim 3\cdot M_f^2/M_P & \nu_{M_2} &\sim \tfrac{1}{\sqrt{2}}(N^c + S)\,, \\ m_{\nu_{PD_1}} &\sim -M_f & \nu_{PD_1} &\sim \tfrac{1}{\sqrt{2}}(\tilde{\Lambda}^0 - \Lambda^{c0})\,, \\ m_{\nu_{PD_2}} &\sim M_f & \nu_{PD_2} &\sim \tfrac{1}{\sqrt{2}}(\tilde{\Lambda}^0 + \Lambda^{c0})\,, \end{aligned}$$

COMPARATIVE SUMMARY

SUSY vacua left invariant by the SM-singlet VEVs in various combinations of the lowest-dimensional representations in standard vs flipped SO(10) and E(6)

	Standard $SO(10)$		Flipped $SO(10)\otimes U(1)$	
Higgs superfields	R	NR	R	NR
$16 \oplus \overline{16}$	$SO(10)$	$SU(5)$	$SO(10)\otimes U(1)$	$SU(5)\otimes U(1)$
$2\times\left(16 \oplus \overline{16}\right)$	$SO(10)$	$SU(5)$	$SO(10)\otimes U(1)$	SM
$45 \oplus 16 \oplus \overline{16}$	$SU(5)$	SM	$SU(5)\otimes U(1)$	$\text{SM}\otimes U(1)$
$45 \oplus 2\times\left(16 \oplus \overline{16}\right)$	$SU(5)$	SM	**SM**	SM
$2\times 45 \oplus 16 \oplus \overline{16}$	$SU(5)$	SM	$SU(5)\otimes U(1)$	$\text{SM}\otimes U(1)$

Higgs superfields	R	NR
$27 \oplus \overline{27}$	E_6	$SO(10)$
$2\times\left(27 \oplus \overline{27}\right)$	E_6	$SU(5)$
$78 \oplus 27 \oplus \overline{27}$	$SO(10)$	$\text{SM}\otimes U(1)$
$78 \oplus 2\times\left(27 \oplus \overline{27}\right)$	$\mathbf{SU(5)}$	SM
$2\times 78 \oplus 2\times\left(27 \oplus \overline{27}\right)$	$SU(5)$	SM