UNIFICATION WITHOUT SUPERSYMMETRY: WHERE DO WE STAND?

Planck 2011 - Lisboa, 1st June 2011

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THE GRAND UNIFICATION PROGRAM

Potential understanding of our low-energy world

- Charge quantization
- Rationale for the SM quantum numbers
- Handle on flavor and neutrino masses

Intrinsic predictivity of new phenomena

- Matter instability
- GUT Monopoles

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Main hint:

• In many extensions of the SM, gauge couplings seem to unify in a narrow window still allowed by proton decay limits and a perturbative QFT description

THE GRAND UNIFICATION PROGRAM

∆α*i*(*MZ*) = *O*(10%) =⇒ ∆*M^G* = *O*(100%) (1)

I. INTRODUCTION

Main hint:

• In many extensions of the SM, gauge couplings seem to unify in a narrow window still allowed by proton decay limits and a perturbative QFT description $\overline{}$

STILL LOOKING FOR "THE" THEORY

After 37 years from Georgi and Glashow there is still no consensus on which is the the minimal theory

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- GG SU(5): fails on the unification side and for neutrino masses
	- Minimal extensions: add a 15_H or a 24_F [Dorsner, Fileviez Perez (2005),

Bajc, Nemevsek, Senjanovic (2007)]

- Minimal SUSY SU(5): proton decay close to the experimental bound
	- But not ruled out [Bajc, Fileviez Perez, Senjanovic (2002), Emmanuel-Costa, Wiesenfeldt (2003), Martens, Mihaila, Salomon, Steinhauser (2010)]

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- SO(10) GUTs usually score better than SU(5) models
	- More predictive in the Yukawa sector (SM matter $+$ RH neutinos into 3 16 s)
	- Natural relief from the tensions with the simplest SU(5) models

INTERMEDIATE SCALES IN THE NON-SUSY SO(10)

2021 - 2021 - 2021 - 2021 - 2021 - 2021 - 2021 - 2021 - 2021 - 2021 - 2021 - 2021 - 2021 - 2021 - 2021 - 2021

−−→ χR

3c2L1^Y (8)

−−→ ωY

catz predicts the existence of intermediate scales in the range The unification ansatz predicts the existence of intermediate scales in the range $10^{10 \div 14}$ GeV

SO (10) MUSIC AND A CARD OF THE MUSIC AND THE MUSIC AND A

−−→ ωR

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सन्दर्भ
सन्दर्भ

2L1R4^C

$$
(100~{\rm GeV})^2/M_{\rm seesaw} \gtrsim \sqrt{\Delta m^2_{\rm atm}} \quad \Rightarrow \quad M_{\rm seesaw} \lesssim 10^{14}~{\rm GeV}
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 $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \longleftarrow SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \longleftarrow SO(10)$

INTERMEDIATE SCALES IN THE NON-SUSY SO(10)

The unification ansatz predicts the existence of intermediate scales in the range 1010÷14 GeV

[Chang, Mohapatra, Gipson, Marshak, Parida (1985)]

INTERMEDIATE SCALES IN THE NON-SUSY SO(10) *SO*(10) *^M^G* −−−−−−−−→ 4*^C* 2*^L* 1*^R ^M^I* −−−−−−−−→ 3*^c* 2*^L* 1*^R* 1*^B*−*^L MB*−*^L* −−−−−−−−−−−−−−−→ 3*^c* 2*^L* 1*^Y* (36) *SO*(10) *^M^G* −−−−−−−−→ *^M^I* −−−−−−−−→ *MB*−*^L*

3*^c* 2*^L* 1*^R* 1*^B*−*^L*

3*^c* 2*^L* 1*^R* 1*^B*−*^L*

χ*^R* ⊂ "16*H*# or "126*H*#

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S annication ansatz predicts the existence of intermed
10÷14 GeV $10^{10 \div 14}$ GeV The unification ansatz predicts the existence of intermediate scales in the range 3*^c* 2*^L* 1*^Y* (37) the dynamics of a set of Higgs sectors in the renormalizable non-supersymmetric *SO*(10) grand unified theory (GUT)

ω*^R* ⊂ "45*H*#

ω*^Y* ⊂ "45*H*#

^M^I −−−−−−−−→ ω*^R* ⊂ "45*H*#

Hereonaury required to break SO(10) to the SM $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ *C* 2^{*C*} **C** 2^{*C*} 2^{*C*} **C** $\frac{1}{2}$ 2^{*C*} $\frac{1}{2}$ 2*C* ω*B*−*^L* ⊂ "45*H*# **∂** 16_H minimally required to break SO(10) to the SM χ*^R* ⊂ "16*H*# or "126*H*# *SO*(10) breaking patterns passing through intermediate 421 or 3221 gauge symmetries (or their 3211 intersection), but it also exhibit the neighborhood in a potential to predict society to the Standard Model (SM) for the Stan

3*^c* 2*^L* 2*^R* 1*^B*−*^L*

ω*^Y* ⊂ "45*H*#

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SO(10) *^M^G* −−−−−−−−→

*Y*¹⁰

ω*^R* ⊂ "45*H*#

ω*^R* ⊂ "45*H*#

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

$$
SO(10) \xrightarrow{M_G} \xrightarrow{M_G} 4_C 2_L 1_R \xrightarrow{M_I} \xrightarrow{M_I} 3_c 2_L 1_R 1_{B-L} \xrightarrow{M_{B-L}} 3_c 2_L 1_Y
$$

 $M_z > M_{\rm B}$ > by unification $M_I > M_{B-L}$ by unification $\overline{}$ \mathfrak{r} **c**¹ W *O* M ^{*G*} $\gg M$ _{*I*} $> M$ _{*B*−*L* (by unification constraints}

INTERMEDIATE SCALES IN THE NON-SUSY SO(10) *SO*(10) *^M^G* −−−−−−−−→ 4*^C* 2*^L* 1*^R ^M^I* −−−−−−−−→ 3*^c* 2*^L* 1*^R* 1*^B*−*^L MB*−*^L* −−−−−−−−−−−−−−−→ *SO*(10) *^M^G* −−−−−−−−→ *^M^I* −−−−−−−−→ *MB*−*^L* 3*^c* 2*^L* 1*^Y* (36)

3*^c* 2*^L* 1*^R* 1*^B*−*^L*

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The unification ansatz predicts the existence of intermediate scales in the range $10^{10 \div 14}$ GeV the dynamics of a set of Higgs sectors in the renormalizable non-supersymmetric *SO*(10) grand unified theory (GUT) C diffication ansatz
10÷14 GeV $10^{10 \div 14}$ GeV 3*^c* 2*^L* 2*^R* 1*^B*−*^L* 3*^c* 2*^L* 1*^Y* (37)

ω*^R* ⊂ "45*H*#

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^M^I −−−−−−−−→ ω*^R* ⊂ "45*H*#

 $45H \oplus 16H$ minimally required to break SO(10) to the SM *SO*(10) breaking patterns passing through intermediate 421 or 3221 gauge symmetries (or their 3211 intersection), *A*5_H ⊕ 16_H minimally required to break SO(10) to the SM $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ *C* 2^{*C*} **C** 2^{*C*} 2^{*C*} **C** $\frac{1}{2}$ 2^{*C*} $\frac{1}{2}$ 2*C* ω*B*−*^L* ⊂ "45*H*# **∂** 16_H minimally required to break SO(10) to the SM χ*^R* ⊂ "16*H*# or "126*H*#

3*^c* 2*^L* 2*^R* 1*^B*−*^L*

ω*^Y* ⊂ "45*H*#

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SO(10) *^M^G* −−−−−−−−→

ω*^R* ⊂ "45*H*#

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

$$
SO(10) \xrightarrow{M_G} \xrightarrow{M_G} 4_C 2_L 1_R \xrightarrow{M_I} \xrightarrow{M_I} 3_c 2_L 1_R 1_{B-L} \xrightarrow{M_{B-L}} 3_c 2_L 1_Y
$$

 W where M *G* $\gg M$ ^{*I*} $> M$ *B*−*L* by unification constraints $M_z > M_{\rm B}$ > by unification $M_I > M_{B-L}$ by unification $\overline{}$ \mathfrak{r} **c**¹ **OUTHERM** △ 2012 → 2014 →

*Y*¹⁰

Local: *SO*(10) "45*H*# −−−−→ "16*H*# **O** 33 WGB (42) WGB (42 Local: *SO*(10) "45*H*# −−−−→ SM → 33 WGB (42) WGB **NO GO !?**

The dynamics of the Higgs sector does not support gauge coupling unification [Yasuè (1981), Anastaze, Derendinger, Buccella (1983), Babu, Ma (1985)] ⊺ne dynami

Luca Di Luzio (SISSA, Trieste) - Unification without supersymmetry: where do we stand ? - Planck 2011 - 3/8 *M^G* ∼ SISS, (*^M^B*−*^L* [⊂] ¹⁶² *^F* (16[∗] *H*) ²*/M^P* (3)

4 (χ[†] (χ[†] (χ[†] (χ[†] (χ[†] (χ[†] (χ⁺) ⁺Γ*j*χ−)(χ*†* THE LOCKING STATES

² +

*^H*16*^H* + λ¹ (16*†*

λ2

^H + *a*¹ (Tr 45²

*^H*16*H*)

*V*Φ^χ = α (χ*†*χ)Tr Φ² + β χ*†*Φ²χ + τ χ*†*Φχ *.* (8)

H)

2 + α (16†16)

[−]Γ*j*χ+)

*H*16*H*)Tr 45²

² (11)

^H (10)

² [−] ^ν² ¹⁶*†*

 $\frac{1}{2}$

⁼ [−]*µ*² Tr 45²

*A*5_H ⊕ 16_H potential analysed long ago [Buccella, Ruegg, Savoy (1980)] (1980)

H)

λ1

^H + *a*¹ (Tr 45²

 $+$

² ^χ*†*

^V^χ ⁼ [−]ν²

*V*⁴⁵*^H*

*^V*moduli ⁼ [−]*µ*² Tr 45²

$$
V_0 = V_{45_H} + V_{16_H} + V_{45_H16_H}
$$

 $V_{45_H} = -\mu^2 \text{ Tr } 45_H^2 + a_1 (\text{Tr } 45_H^2)^2 + a_2 \text{ Tr } 45_H^4$ *^H* (14) $V_{16_H} = - \nu^2 \, 16_H^\dagger 16_H + \lambda_1 \, (16_H^\dagger 16_H)^2 + \lambda_2 \, (16_H \, \Gamma \, 16_H) (16_H^\dagger \, \Gamma \, 16_H^\dagger)$ H) $V_{45_H 16_H} = \alpha (16_H^{\dagger} 16_H) \text{Tr} 45_H^2 + \beta 16_H^{\dagger} 45_H^2 16_H + \tau 16_H^{\dagger} 45_H 16_H$ *H*16*H*)Tr 45²

4 (χ[†] (χ[†] (χ[†] (χ[†] (χ[†] (χ[†] (χ⁺) ⁺Γ*j*χ−)(χ*†* THE LOCKING STATES $v_{\rm eff}$ if the product of sigma matrices given in σ sigma matrices given in σ The parameters (couplings and VEVs) of the scalar potential are constrained by the requirements of boundedness T I IF I $\bigcap C$ VINI $\bigcap C$ TATFC and the absence of tachyonic states, enssuring that the vacuum is stable and the stationary points correspond to

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*V*¹⁶*^H* ⁼ [−]ν² ¹⁶*†* 45H ⊕ 16H potential analysed long ago [Buccella, Ruegg, Savoy (1980)] *H*
FBuccella, Ruegg, Savoy (1980) $F = F \cdot \mathbf{F} \$ $\mathbf{F}_{\mathbf{a}}$ in $\mathbf{F}_{\mathbf{a}}$ the former implies in Appendix B the former implies in $\mathbf{F}_{\mathbf{a}}$ *^a*¹ *>* [−]¹³

H)

λ1

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C. Constraints on the potential parameters

and the absence of tachyonic states, ensuring that the vacuum is stated and the state and the state and the sta

*V*⁴⁵*^H*

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Appendix B.

(corresponding to an extra *Z*² symmetry Φ → −Φ) one recovers the results in [24], namely

$$
V_0 = V_{45_H} + V_{16_H} + V_{45_H16_H}
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$$
V_0 \tV_{45H} + V_{16H} + V_{45H} + V_{45H
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From the positivity of the scalar states $(1,3,0)$ and $(8,1,0) \subset 45$ _H tensorial indices have been suppressed; and interested reader reader can find more information on the tensorial structure of the tensorial structure of the tensorial structure of the tensorial structure of the tensorial st *V* Scalar states (1,3,0) and (8,1,0) Scalar states $2 + 2$ **1 H**₁ (1701), Anastaze, From the positivity of the scalar states (1,3,0) and $(8,1,0) \subset 45_H$ r
[Yasuè (1981), Anastaze, Derendinger, Buccella (1983), Babu, Ma (1985)] M ² and the positivity of the scalar states (1.3.0) and (8.1.0) \subset 45 μ *M*2(8, 1,0, 1,0) and (0, 1,0) and (0, 1,0) and (D, 1,0) and (D, 1,0) and the 2008 of the 2008 of 2008 and 2008 a *^M*²(8*,* ¹*,* 0) = 2*a*2(ω*^R* [−] ^ω*^Y*)(ω*^R* + 2ω*^Y*)*,* (27) $(9, 1, 0)$ and $(8, 1, 0)$ ⊂ 45_H

$$
M^{2}(1,3,0) = 2a_{2}(\omega_{B-L} - \omega_{R})(\omega_{B-L} + 2\omega_{R})
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\n
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M^{2}(8,1,0) = 2a_{2}(\omega_{R} - \omega_{B-L})(\omega_{R} + 2\omega_{B-L})
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\n
$$
\implies a_{2} < 0, \quad -2 < \omega_{B-L}/\omega_{R} < -\frac{1}{2}
$$

Luca Di Luzio (SISSA, Trieste) - Unification without supersymmetry: where do we stand? - Planck 2011 - 4/8 α *Δ D Lazio* (*SiSSI i*, *i i CSIC*) α *^a*² *<* ⁰ *,* [−]¹ [≤] ^ω*^Y /*ω*^R* ≤ −² ³ and β *>* 0 *.* (30) nonsupersymmetry: where do we stand ? - Planck 2011 - 4/8 nonsupersymmetry: where do we stand ? - Planck 2011 - 4/8

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 \overline{M} *^H*45*H*16*^H* (16) Gauge dinneation requires an nierarchy between **w**el and **w**r : Gauge unification requires an hierarchy between $\omega_{\texttt{B-L}}$ and $\omega_{\texttt{R}}$! of the flipped SU(5) ⊗ U(1)^Z setting. Hence, the large hierarchy (of about four orders of Gauge unification requires an hierarchy between $\omega_{\text{B-L}}$ and ω_{R} !

> Luca Di Luzio (SISSA, Trieste) - Unification without supersymmetry: where do we stand? - Planck 2011 - 4/8 $\frac{1}{2}$ **b**² ∴ ∞ ¹ ≤ ∞ 200 ≤ ∞ 1 × 200 ≤ ∞ 1 × 200 ≤ 1 × 200 × 1 × 200 × 1 × 30 × 1 × 200 × 1 × 30 × 1 × 200 × 1 × 200 × 1 × 200 × 1 × 200 × 1 × 200 × 1 × 200 × 1 × 200 × 1 × 200 × 1 × 200 × 1 × 200 × 1 × 200 × 1 × nonsupersymmetry: where do we stand ? - Planck 2011 - 4/8 nonsupersymmetry: where do we stand ? - Planck 2011 - 4/8

\land TREE LEVEL ACCIDENT $t = \frac{1}{2}$

Global symmetries of the potential in the limit $a_2 = \lambda_2 = \beta = \tau = 0$

 $V_{\text{moduli}} = -\mu^2 \text{Tr } 45_H^2 + a_1 (\text{Tr } 45_H^2)^2 - \nu^2 16_H^{\dagger} 16_H + \lambda_1 (16_H^{\dagger} 16_H)^2 + \alpha (16_H^{\dagger} 16_H) \text{Tr } 45_H^2$ This issue can be somewhat alleviated by considering 126*^H* in place of 16*^H* in the Higgs sector, since in such a case

$\frac{1}{1-\epsilon}$ $\frac{1}{2}$ T_{max} PGB are left in the spectrum. The spectrum of σ and the spectrum theorem the spectrum. The spectrum theorem the spectrum theorem the spectrum. The spectrum theorem the spectrum theorem the spectrum theorem th \land TREE LEVEL ACCIDENT $t = \frac{1}{2}$

MB−L

−−−−−−−−−−−→

3^c 2^L 1^Y (15)

 $= 2$

SO(10) ^M^G

SO(10) ^M^G

where ρ is the gauge group label. Neglecting for the abelian components, t al symmetries of the potential in the limit $a_2 = \lambda_2 = \beta = \tau = 0$ Glot al symmetries $f + I$ o_rue botential in t $\mathbf{H} = \mathbf{H}$ Ξ IIIIIII $u_2 = \lambda_2$ $\beta=\tau=0$!45^H " !45^H " !16H" or !126H" *Global symmetries of the potential in the limit* $a_2 = \lambda_2 = \beta = \tau = 0$

3^c 2^L 1^R 1B−^L

GB in the scalar spectrum. The gauge SO(10) symmetry is at the same time broken down to the small group. The small group is at the same time broken down to the SM gauge group. The same time broken down to the SM gauge grou

MI

−−−−→

explicitly breaking terms a2, λ2, β and τ.

SO(10) ^M^G

−−−−→

3c 2L 2R 1B−l 2

explicitly breaking terms a2, λ2, β and τ.

 $\beta_{\rm i} = -\mu$ $(45_H^2 + a_1 (\text{Tr }45_H^2)^2 - \nu^2 16_H^{\dagger} 16_H + \lambda_1 (16_H^{\dagger} 16_H)^2 + \alpha (16_H^{\dagger} 16_H)$ $(45H + a_1 (\text{Tr }45H)^2 - \nu^2 16H \text{Tr }40H + \lambda_1 (\text{Tr }46H)^2 + \alpha (\text{Tr }46H) \text{Tr }45H$ $\mathbf{v}_{\mathbf{f}}$ $\frac{1}{\sqrt{2}}$ \sim 11/ $\frac{1}{2}$ 11 $\frac{1}{2}$ 11 $\frac{1}{2}$ 11 \overline{I} $-V$ $V_{\rm {mo}}$ $\mu = -\mu^2$ Tr 45² 45_H^2 a_1 (Tr 45^2 , $^{12} - \nu^2 16^{\dagger} 16 \nu + \lambda_1 6$ $\sim 16_H 16_H + \lambda_1$ c_{1}^{+} 1 c_{2}^{+} $(1c_{1}^{+}$ 1 c_{1}^{+} \sqrt{n} $1r_{2}^{2}$ $V_{\text{moduli}} = -\mu^2 \text{Tr } 45_H^2 + a_1 (\text{Tr } 45_H^2)^2 - \nu^2 16_H^{\dagger} 16_H + \lambda_1 (16_H^{\dagger} 16_H)^2 + \alpha (16_H^{\dagger} 16_H) \text{Tr } 45_H^2$ This issue can be somewhat alleviated by considering 126*^H* in place of 16*^H* in the Higgs sector, since in such a case

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

\n
$$
SO(10) \xrightarrow{\langle 45_H \rangle} SM \implies 33 \text{ WGB}
$$

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

$\frac{1}{1-\epsilon}$ $\frac{1}{2}$ A TREE LEVEL ACCIDENT A TREE LEVEL ACCIDENT *^a*¹ *>* [−]¹³ ⁸⁰ *a*² *,* λ¹ *>* 0 *.* (24) while the absence of tachyons in the physical spectrum yields while the absence of tachyons in the physical spectrum yields in the physical spectrum yields and *^a*² *<* ⁰ *,* [−]² *<* ^ω*^Y /*ω*^R <* [−]¹ $t = \frac{1}{2}$

 $= 2$

SO(10) ^M^G

² *.* (25)

SO(10) ^M^G

where ρ is the gauge group label. Neglecting for the abelian components, t al symmetries of the potential in the limit $a_2 = \lambda_2 = \beta = \tau = 0$ *V* $a_2 = \lambda_2 = \beta = \tau = 0$ netries of the potential in the limit $a_2 = \lambda_2 = \beta = \tau = 0$ Global symmetries of the potential in the limit $a_2 = \lambda_2 = \beta = \tau = 0$

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$$
 75 - 33 = 42 PGB

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- $radant I$ χ^R %= 0 respectively. Hence, this setting gives rise to 20 + 21 = 41 GB. The gauged SO(10) is simultaneously broken The absence of the terms λ_2 β and ℓ is just a thee level accident: • The absence of the terms λ_2 β and τ is just a tree level accident ! \bullet The absence of the terms λ_2 β and τ is just a tree level accident \vdash *flip about the commonly pair* and is journal to set the large movement.

we shall see later in Sect. In Sect. In Sect. 2013, the scalar spectrum can change significantly at the general spectrum can change significantly at the scalar spectrum can change significantly at the quantum can change si

M^B−*^L/M^P* suppression factor inherent to the *d* = 5 effective mass and yields *M^N* ∼ *M^B*−*^L*, what might be, at least

A TREE LEVEL ACCIDENT \land TRFF | FVFI *A*CCIDENT $\frac{1}{1-\epsilon}$ $\frac{1}{2}$ *^a*¹ *>* [−]¹³ ⁸⁰ *a*² *,* λ¹ *>* 0 *.* (24) while the absence of tachyons in the physical spectrum yields while the absence of tachyons in the physical spectrum yields in the physical spectrum yields and *^a*² *<* ⁰ *,* [−]² *<* ^ω*^Y /*ω*^R <* [−]¹ \land TREE LEVEL ACCIDENT $t = \frac{1}{2}$

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In the achieved. In the a by gauge coupling unification (see chains VIIIb and XIIb in [36]) cannot be achieved. • Nothing prevents these couplings from entering at the quantum level!

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ONE LOOP PGB MASSES: RESULTS *R* − Ω Ω Ω 14 1 € Ω ΓΩ Ω Η ΤΩ *^R* [−] ^ω*R*ω*^Y* + 2ω² *^Y*) + *^g*⁴ " *^R* + ω*^Y* ω*^R* + 19ω²

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#\$ + Log's (*µ*) (72)

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1

1

!

τ ² + β²(2ω²

 $\frac{1}{2}$

 $|L\tilde{c}|$ $\sqrt{2}$ tation of the one-loop PGB masses with Effective-Potential methods $\overline{}$ $\overline{}$ Explicit computation of the one-loop PGB masses with Effective-Potential methods

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$$

+
$$
\frac{1}{4\pi^{2}} \left[\tau^{2} + \beta^{2} (2\omega_{R}^{2} - \omega_{R}\omega_{B-L} + 2\omega_{B-L}^{2}) + g^{4} (16\omega_{R}^{2} + \omega_{B-L}\omega_{R} + 19\omega_{B-L}^{2}) \right] + \text{Log's}(\mu)
$$

$$
M^{2}(8,1,0) = 2a_{2}(\omega_{R} - \omega_{B-L})(\omega_{R} + 2\omega_{B-L})
$$

+
$$
\frac{1}{4\pi^{2}} \left[\tau^{2} + \beta^{2}(\omega_{R}^{2} - \omega_{R}\omega_{B-L} + 3\omega_{B-L}^{2}) + g^{4} \left(13\omega_{R}^{2} + \omega_{B-L}\omega_{R} + 22\omega_{B-L}^{2} \right) \right] + \text{Log's}(\mu)
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$$

- *Menological vacua open up at the quantum level! Menological vacua open up at the quantum level!* • For $|a_2|$ <10⁻² the phenomenological vacua open up at the quantum level!
- Inherent to all the non-SUSY SO(10) models with a dominant $\langle 45_H \rangle$

WHAT ABOUT NEUTRINOS ?

The $45H \oplus 16H \oplus 10H$ scenario fails when addressing the neutrino mass scale

schematically addressing the neutrino spectrum: in nonsupersymmetric models, the *B* − *L* breaking scale *MB*−*^L* turns out to be On the other hand, the simplest scenario featuring the Higgs scalars in 10*^H* ⊕ 16*^H* ⊕ 45*^H* of *SO*(10) fails when generally smaller than the GUT scale and magnitude. The scale of magnitude of magnitude. The scale of the rightneutrino masses *^M^N* [∼] *^M*² *^B*−*L/M^P* emerging first at the *^d* = 5 level from an operator of the form 16² On the other hand, the simplest scenario featuring the Higgs scalars in 10*^H* ⊕ 16*^H* ⊕ 45*^H* of *SO*(10) fails when addressing the neutrino spectrum: in nonsupersymmetric models, the *B* − *L* breaking scale *MB*−*^L* turns out to be generally smaller than the GUT scale *MG*, by a few orders of magnitude. Thus, the scale of the right-handed (RH) neutrino masses *^M^N* [∼] *^M*² *^B*−*L/M^P* emerging first at the *^d* = 5 level from an operator of the form 16² addressing the neutrino spectrum: in nonsupersymmetric models, the *B* − *L* breaking scale *M^B*−*^L* turns out to be generally smaller than the GUT scale R WHAT ABOUT NEUTRINOS ? (with *M^P* typically identified with the Planck scale) undershoots by orders of magnitude the range of about 10¹² to WUT INEUTININUS : $\sum_{i=1}^n \sum_{i=1}^n \sum_{j=1}^n \sum_{j$

10¹⁴ GeV naturally suggested by the seesaw implementation.

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structure.

structure.

10¹⁴ GeV naturally suggested by the seesaw implementation.

and the most common choice is a 10H dimensional multiplet with the Yukawa interaction \mathcal{A}

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L^Y = 16^F Y1010H16^F . (1)

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The $45_H \oplus 16_H \oplus 10_H$ scenario fails when addressing the neutrino mass scale the neutrino mass scale eι J tr *Ino* ∞ ma *B*−*L M* IIIdSS SCAIC \overline{O} m *M*² *B*−*L* ss scal *B*−*L M^N* ∼ $+$ ا ب
ا <u>ገe</u> $n \in I$ neutri<mark>r</mark> *B*−*L Ino mass scale S*CCTIQETO TQUES VVITCIT $\overline{1}$ and $\overline{1}$ and $\overline{1}$ and $\overline{1}$ and $\overline{1}$ and $\overline{1}$ and $\overline{1}$ and only support via ble viables not only support via $\overline{1}$ *SO*(10) breaking patterns passing through intermediate 421 or 3221 gauge symmetries (or their 3211 intersection),

I. INTRODUCTION

the dynamics of a set of Higgs sectors in the renormalizable non-supersymmetric *SO*(10) grand unified theory (GUT)

• Radiative seesaw
\n(1980); Bajc, Senjanovic (2005)]
\n
$$
M_R \sim \left(\frac{\alpha}{\pi}\right) Y_{10} \frac{M_{B-L}^2}{M_G} \quad \subset \quad 10_H
$$
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10_H
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45_V \succeq \succeq 45_V
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 τt / 101 R . the neutrino masses can be generated at the renormalizable level by the term $\frac{1}{2}$ $\implies m_{\nu} \sim m_{t}^{2}/M_{R} \gg 1$ eV ideavy! $\begin{bmatrix} \nu & \nu & \nu \end{bmatrix}$ is scenario, the contract in principal in principle, c.f. in principal in princip the neutrino masses can be generated at the renormalizable level by the term $\frac{1}{2}$ $m_\nu \sim m_\tau^2/M_R \gg 1 \; \text{eV}$ = 1 loo heavy! \mathcal{L} and \mathcal{L} , the involves arises a challenging one-loop and \mathcal{L} $\frac{1}{\sqrt{1-\frac{1$ *^H*. This lifts the problematic \dot{H} ² \Rightarrow $m_{\nu} \sim m_{\tilde{t}} / M_R \gg 1 \text{ eV}$ and H and H in principle, acceptable. This scenario, though via ble in principle, c.f. $\frac{1}{2}$ M_{B-L} ≪ M_G =⇒ M_R ≪ 10^{14} GeV =⇒ $m_\nu \sim m_t^2/M_R$ ≫ 1 eV (Too heavy!

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I. INTRODUCTION

M^R ∼

the dynamics of a set of Higgs sectors in the renormalizable non-supersymmetric *SO*(10) grand unified theory (GUT)

[Witten (1980); Bajc, Senjanovic (2005)] • Radiative seesaw 16^F 16^F 16^F 16^F 10^H 45^V 45^V "16H# 16^H "16H# *B*−*L M^G* 10*^H* 16*^H* 45*^H* 45*^V* (4) *^Y*¹⁰ [√]^α (5) !α *Y*¹⁰ *M*² *B*−*L M^G M^N* ∼ *Y^P* 10*^H* 16*^H* 45*^H* 45*^V* (4) *^Y*¹⁰ [√]^α (5) *M^N* ∼ !α *M^N* ∼ *Y^P M*² 10*^H* 16*^H* 45*^H* 45*^V* (4) *^Y*¹⁰ [√]^α (5) *M^R* ∼ #α π \$ *Y*¹⁰ *M*² *B*−*L M^G* ⊂ (4) *M*² *B*−*L* On the other hand, the simplest scenario featuring the Higgs scalars in 10*^H* ⊕ 16*^H* ⊕ 45*^H* of *SO*(10) fails when addressing the neutrino spectrum: in nonsupersymmetric models, the *B* − *L* breaking scale *M^B*−*^L* turns out to be generally smaller than the GUT scale *MG*, by a few orders of magnitude. Thus, the scale of the right-handed (RH) neutrino masses *^M^N* [∼] *^M*² *^B*−*^L/M^P* emerging first at the *^d* = 5 level from an operator of the form 16² *^F* (16[∗] *^H*)²*/M^P* (with *M^P* typically identified with the Planck scale) undershoots by orders of magnitude the range of about 10¹² to ⊂ *M^P* 16*^F* 16*^F* 16[∗] *H*16[∗] *^H* (7) 10*^H* 16*^H* 45*^H* 45*^V* 126*^H* 45*^H* 54*^H* 210*^H* '16*H*(= 0 (8)

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 126 fail as mentioned in the introduction. The failure of gauge coupling unification in the operator, obtained with a 10*^H* ⊕ 16*^H* ⊕ 16*^H* ⊕ 45*^H* Higgs sector, can naturally reproduce the desired range for *M^N* . Let us recall that the extra 16*^H* is mandatory in this context in order to retain SUSY as a good symmetry below the within the MSSM prefers *M^B*−*^L* in the proximity of *M^G* and, hence, the Planck-suppressed *d* = 5 RH neutrino mass operator, obtained with a 10*^H* ⊕ 16*^H* ⊕ 16*^H* ⊕ 45*^H* Higgs sector, can naturally reproduce the desired range for *M^N* . Let us recall that the extra 16*^H* is mandatory in this context in order to retain SUSY as a good symmetry below the within the MSSM prefers *M^B*−*^L* in the proximity of *M^G* and, hence, the Planck-suppressed *d* = 5 RH neutrino mass operator, obtained with a 10*^H* ⊕ 16*^H* ⊕ 16*^H* ⊕ 45*^H* Higgs sector, can naturally reproduce the desired range for *M^N* . Let us recall that the extra 16*^H* is mandatory in this context in order to retain SUSY as a good symmetry below the *W*ithout SUSY it is natural to consider a 126_H in place of 16_H '16*H*(∼ *M^B*−*^L* \$ *M^G* (10)

- level, a supersymmetric breaking of the *SO*(10) gauge group to the SM. This is due to the constraints on the vacuum $M_R \sim Y_{126} M_{B-I}$, $\subset Y_{126} 10_F 10_F 120_H$ 16*^H* and 16*^H* vacuum expectation values (VEV), make the the adjoint vacuum aligned to '16*H*(. As a consequence, level, a supersymmetric breaking of the *SO*(10) gauge group to the SM. This is due to the constraints on the vacuum better: $M_B \sim Y_{126}$ M_{B-L} \subset Y_{126} $16_F16_F126_H^*$ 16*^H* and 16*^H* vacuum expectation values (VEV), make the the adjoint vacuum aligned to '16*H*(. As a consequence, $\sum_{i=1}^{n}$ and $\sum_{i=1}^{n}$ and $\sum_{i=1}^{n}$ and $\sum_{i=1}^{n}$ $\sum_{i=1}^{n}$ and $\sum_{i=1}^{n}$ $\sum_{i=1}^{n}$ singleted in $\sum_{i=1}^{n}$ singleted in $\sum_{i=1}^{n}$ singleted in $\sum_{i=1}^{n}$ singleted in $\sum_{i=1}^{n}$ singleted *Y₁ V₁ V₁ V₁ V₁ 10 10 100^{*}* • RH neutrino mass scale much better: $M_R \sim Y_{126} M_{B-L}$ ⊂ $Y_{126} 16_F 16_F 126_F^*$ *^H* (11)
- sector with 126*^H* ⊕ 126*^H* in place of 16*^H* ⊕ 16*^H* suffers from the same "*SU*(5) lock", since the GUT-scale '126*H*(ially prodictive This issue might be addressed by giving up renormalizability. However, this option may be rather problematic sector with 126*^H* ⊕ 126*^H* in place of 16*^H* ⊕ 16*^H* suffers from the same "*SU*(5) lock", since the GUT-scale '126*H*(exhibits an *SU*(5) little group as well. T ung up T sector with 126*^H* ⊕ 126*^H* in place of 16*^H* ⊕ 16*^H* suffers from the same "*SU*(5) lock", since the GUT-scale '126*H*(α potentially predictive α • Renormalizable Yukawa sector potentially predictive

since it introduces a delicate interplay between physics at two different scales, *M^G* \$ *M^P* , with the consequence of 993); Bajc, i^xieito, Senjanovic, vissani (2005); Joshipura, Patel (2011)] -since it introduces a delicate interplay between physics at two different scales, *M^G* \$ *M^P* , with the consequence of , i*ieifo, Senjahovic, vissani (2005*)*; joshipura, Patei (2011)] This is supported by giving up renormalizability. However, this option may be rather problematic may be rather proble 1 patra (1993); Bajc, Melfo, Senjanovic, Vissani (2005); Joshipura, Patel (2011) splitting the GUT-scale thresholds over several orders of magnitude around *MG*. This may affect proton decay as $\frac{28}{3}$. Tonapad a (1775), Baje, Pieno, Senjanović, Pissani (2000), jošnipara, Pater (2011) 16*^F* 16*^F* 126[∗] *^H* ⊃ *M^N* ∼ '126[∗] *^H*(∼ *M^B*−*^L* (12) [Babu, Mohapatra (1993); Bajc, Melfo, Senjanovic, Vissani (2005); Joshipura, Patel (2011)]

10¹⁴ GeV naturally suggested by the seesaw implementation.

#α

∼

10¹⁴ GeV naturally suggested by the seesaw implementation.

B^{*B*−</sub>*L*₂}

M^P

\$

On the other hand, the simplest scenario featuring the Higgs scalars in 10*^H* ⊕ 16*^H* ⊕ 45*^H* of *SO*(10) fails when

*M*²

B−*L*

and the most common choice is a 10H dimensional multiplet with the Yukawa interaction \mathcal{A}

\$ *^M^B*−*^L* [⊂] ¹⁶²

(with *M^P* typically identified with the Planck scale) undershoots by orders of magnitude the range of about 10¹² to

L^Y = 16^F Y1010H16^F . (1)

^F (16[∗]

H)

²*/M^P* (5)

(with *M^P* typically identified with the Planck scale) undershoots by orders of magnitude the range of about 10¹² to

setting with 16*^H* ⊕ 16*^H* relying on a *d* = 5 RH neutrino mass operator. The models with 126*^H* ⊕ 126*^H* are also prone persymmetry: where do we stand ? - Planck 2011 - //8 $\,$ setting with 16*^H* ⊕ 16*^H* relying on a *d* = 5 RH neutrino mass operator. The models with 126*^H* ⊕ 126*^H* are also prone etry: where do we stand ? $\,$ - $\,$ Planck 2011 $\,$ - $\,$ //8 $\,$ $\,$ well as the SUSY gauge unification, and force the *B* − *L* scale below the GUT scale. The latter is harmful for the thout supersymmetry: where do we stand ? = Planck 2011 = 7/8 Luca Di Luzio (SISSA, Trieste) - Unification without supersymmetry: where do we stand ? - Planck 2011 - 7/8

- This result is an artifact of the tree-level potential and quantum corrections have a dramatic impact
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	- Compute the scalar spectrum (work in progress...)
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	- Compute the scalar spectrum (work in progress...)
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- If compatible
	- Compute the proton decay branching ratios ...

BACKUP SLIDES

SO(10) AS A THEORY OF FERMION MASSES AND MIXINGS On the other hand, the simplest scenario featuring the Higgs scalars in 10*^H* ⊕ 16*^H* ⊕ 45*^H* of *SO*(10) fails when **SO(10) AS A THEORY OF FERMIONI MASSES ANID MIXINICS** SO(10) AS A THEORY OF FERMION MASSES AND MIXINGS IN MASSES AND MIXINGS I than the GUT scale spoils the gauge coupling unification of the MSSM.

M^e = \$1*,* 2*,* 2%

M^e = \$1*,* 2*,* 2%

and the gauge unification constraints. In particular, such a minimal grand unified scenarios not only support viable

generally smaller than the GUT scale *MG*, by a few orders of magnitude. Thus, the scale of the right-handed (RH) **B**−**B**−20H emerging first at the first and θ and θ and θ and θ are form θ the form θ of θ and θ are θ the form θ of θ and θ are θ the form θ of θ and θ are θ the form $\$ On the other hand, the simplest scenario featuring the Higgs scalars in 10*^H* ⊕ 16*^H* ⊕ 45*^H* of *SO*(10) fails when addressing the neutrino spectrum: in nonsupersymmetric models, the *B* − *L* breaking scale *M^B*−*^L* turns out to be *M^R* = \$10*,* 1*,* 3% *Y*¹²⁶ *M^L* = ! *M^R* = \$10*,* 1*,* 3% *Y*¹²⁶ *M*_L of scalars. A study in that direction has been done in $[28]$. Earlier works considering a study and α Renormalizable Yukawa sector with $10_H \oplus 126_H$

· SO(10) Yukawa (with *M^P* typically identified with the Planck scale) undershoots by orders of magnitude the range of about 10¹² to

but it also exhibits all the needed ingredients for a potential lying realistic description of the Standard Model (SM)

addressing the neutrino spectrum: in nonsupersymmetric models, the *B* − *L* breaking scale *M^B*−*^L* turns out to be

 $16_F (Y_{10}10_H + Y_{126}126_H^*) 16_F$ $10_H = (1, 2, 2) + (6, 1, 1)$ $126_H^* = (15, 2, 2) + (10, 1, 3) + (10, 3, 1) + (6, 1, 1)$ neutrino Dirac-mass matrix are given, respectively, by $\frac{1}{2}$

¹⁰ *Y*¹⁰ − 3 \$15*,* 2*,* 2%

¹⁰ *Y*¹⁰ − 3 \$15*,* 2*,* 2%

¹²⁶ *Y*¹²⁶

one [25, 26], compatible with the results of the neutrino oscillation experiments (for a

An obvious attempt to loosen the corset of the minimal theory is to add the minimal theory is to add the 120-plet

 $\frac{1}{2}$

¹²⁶ *Y*¹²⁶

• Effective mass sum rule \pm ffective mass sum rule \sum is understood. Given a fermion \overline{C} field that transforms according to the representation \overline{C}

 $M_u = \langle 1, 2, 2 \rangle_{10}^u Y_{10} + \langle 15, 2, 2 \rangle_{126}^u Y_{126}$ $M_d = \langle 1, 2, 2 \rangle_{10}^d \, Y_{10} + \langle 15, 2, 2 \rangle_{126}^d \, Y_{126}$ $M_e = \langle 1, 2, 2 \rangle_{10}^d \, Y_{10} - 3 \, \langle 15, 2, 2 \rangle_{126}^d \, Y_{126}$ *M* $M_R = \langle 10, 1, 3 \rangle Y_{126}$ $M_{\nu} = M_L M_D = \langle 1, 2, 2 \rangle_{10}^u Y_{10} - 3 \langle 15, 2, 2 \rangle_{126}^u Y_{126}$ $M_L = \langle \overline{10}, 3, 1 \rangle$ Y_{126} *^M^B*−*^L* & *^M^G* ⁼[⇒] *^M^R* & ¹⁰¹⁴ GeV =[⇒] *^m*^ν [∼] *^m*² *M*^B $\frac{1}{20}$ $\frac{1$ *M^G* (*M^I > M^B*−*^L* (6) *^M^B*−*^L* & *^M^G* ⁼[⇒] *^M^R* & ¹⁰¹⁴ GeV =[⇒] *^m*^ν [∼] *^m*² *M*^B_{*C*} $\frac{1}{20}$ $\frac{1}{20}$ *M^G* (*M^I > M^B*−*^L* (6) Y_{126} τ tively. The coefficients kd, κ , \k Y_{126} \mathbf{V} ${\cal M}_\nu = M_L - M_D M_R^{-1} M_D^T$ $\frac{T}{D}$ $M_P = \langle 10, 1, 3 \rangle Y_{126}$ $\overline{}$ $\mathcal{M}_u = \langle 1, 2, 2 \rangle_{10}^a Y_{10} + \langle 15, 2, 2 \rangle_{126}^a Y_{126}$