A non-SUSY SO(10) model for the physics below MGUT

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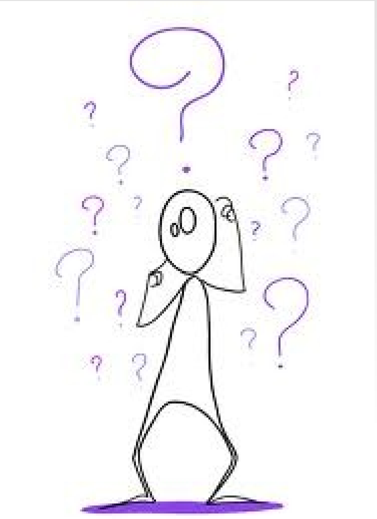
Introduction

- Absence of new-physics signals casts some doubts on the relevance of our concept of <u>naturalness</u>



"Let us consider a theory valid up to a maximum energy and make all its parameters dimensionless by measuring them in units of Λ . The naturalness criterion states that one such parameter is allowed to be much smaller than unity only if setting it to zero increases the symmetry of the theory. If this does not happen, the theory is unnatural"

G. Giudice, arXiv:0801.2562

- It worked in the past

Naturalness

- Electromagnetic energy of an electron as a sphere of radius r: α/r

this must be smaller than the

total energy $E=m_e \rightarrow r > \alpha/m_e \gg$ atomic radius

Either the different contributions to the total energy mysteriously cancel with a high precision, or some new physics sets in before the energy scale r^{-1}, modifying the EM contribution to the electron mass at short distances and preserving naturalness

the positron has to be included in a consistent relativistic quantum theory

- Mixing in the K^0 and $\overline{K^0}$ system

$$\frac{m_{K_L^0} - m_{K_S^0}}{m_{K_L^0}} = \frac{G_F^2 f_K^2}{6\pi^2} \sin^2\theta_C \Lambda^2 = 7 \times 10^{-15}$$

$$\Downarrow$$

$\Lambda < 2$ GeV

before reaching this energy scale a new particle (the c-quark with mc ≈ 1.2 GeV) modifies the short-distance behavior of the theory

For the Higgs mass...

$$\delta m_H^2 = \frac{3 G_F}{4\sqrt{2}\pi^2}\left(4 m_t^2 - 2 m_W^2 - m_Z^2 - m_H^2\right)\Lambda^2 \longrightarrow \Lambda \leq O(1)\, TeV$$

New physics expected at these energies

L
H
C

NO-New physics seen so far

Which direction?

Building models where naturalness is restored not so far from the weak scale

Models with large fine tunings that disregard the naturalness principle in part or even completely

This scenario will be analyzed in the following

A possible BSM model

non-SUSY SO(10)

Unification of couplings at a large scale compatible with proton decay

A Yukawa sector compatible with all data on flavour physics, fermion masses and mixings

Agreement with leptogenesis as the origin of the baryon asymmetry

An axion suitable to solve the strong CP problem and account for the observed Dark Matter

The SO(10) model

G.Altarelli & D.M.,JHEP 1308 (2013) 021

- All these different phenomena can be satisfied with a single intermediate scale

$$M_I \sim 10^{11}\,GeV$$

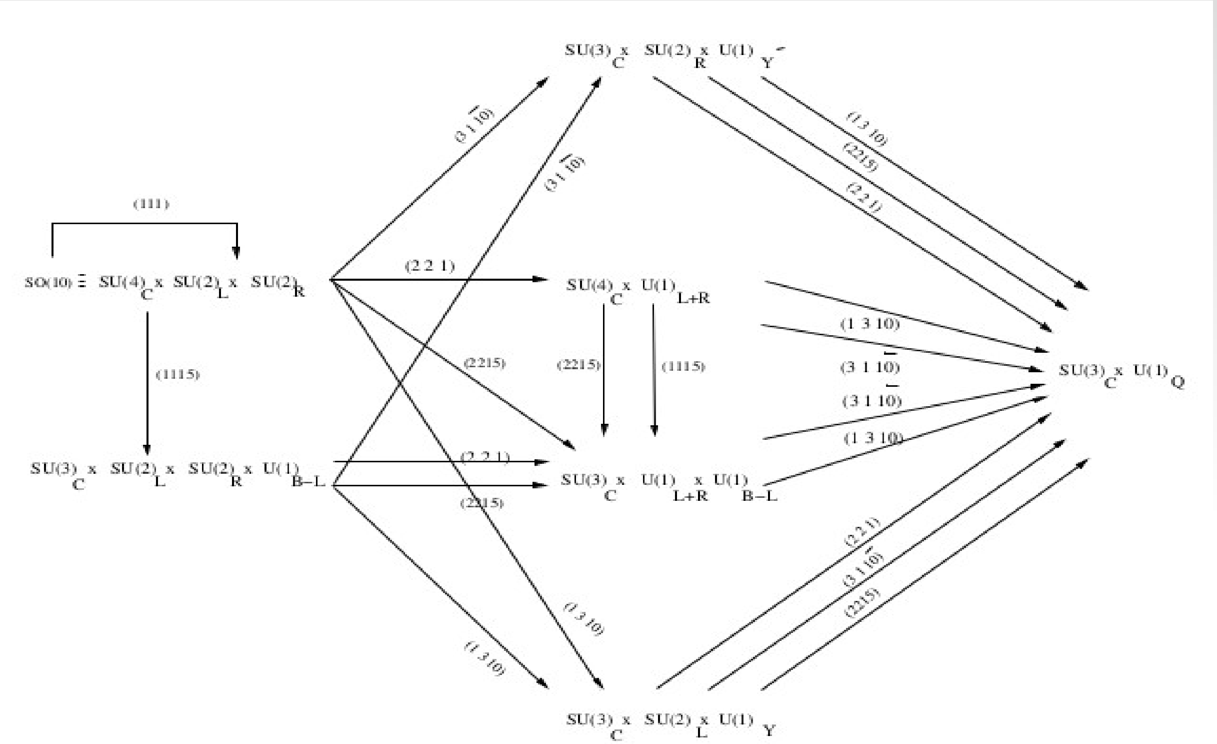
See-saw and leptogenesis compatible with M_I

M_I also suitable for the axion to reproduce the correct Dark Matter abundance

- To be honest with you, I only consider:
  - LO evolutions
  - Crude threshold matching
  - And "who cares" about fine-tuning

The SO(10) model

- The prize to pay:
  - Very large Higgs representations and more VEV's than in the SM



- Can we do everything with more parameters?
  - NO!
    Mass matrices, for example, are strongly correlated

The SO(10) model

- SM fermions in the 16 representation

3 (up) + 3 (up-bar) +
3 (down) + 3 (down-bar) +
1 (e) + 1 (e-bar) +
1(nu-L)+ 1(nu-R)

X 3 generations

- Gauge bosons in the 45

- Higgses in … representations

Breaking chain

SO(10)

M_{GUT}

210

breaking SO(10)

PS=SU(4)xSU$_L$(2)xSU$_R$(2)

M_I

$\overline{126}$ - 45

for breaking Pati-Salam and give fermion masses

for a viable axion candidate

SM=SU(3)xSU(2)xU(1)

M_Z

10

for breaking SM and give fermion masses

Babu and Mohapatra, Phys. Rev. Lett. 70, 2845 (1993)

M_{GUT} and M_I from gauge coupling unification

- The role of the $\overline{126}$ in the coupling evolution

PS quantum numbers

$$\overline{126} = (6,1,1) \oplus (\overline{10},3,1) \oplus (10,1,3) \oplus (15,2,2)$$

colored states: must be at M_{GUT}

useful for see-saw type-II; not used here

contain color singlet: used for breaking PS → SM

vev at the EW scale: involved in the evolutions SM->PS and PS->M_{GUT}

M_{GUT} and M_I from gauge coupling unification

- The role of the 10 in the coupling evolution

$$10 = (6,1,1) \oplus (1,2,2)$$

colored states:
must be at M_{GUT}

vev at the EW scale:
involved in the evolutions
SM-> M_{GUT}

- Where are the dangerous colored states?

Extended survival hypothesis

Extended survival hypothesis

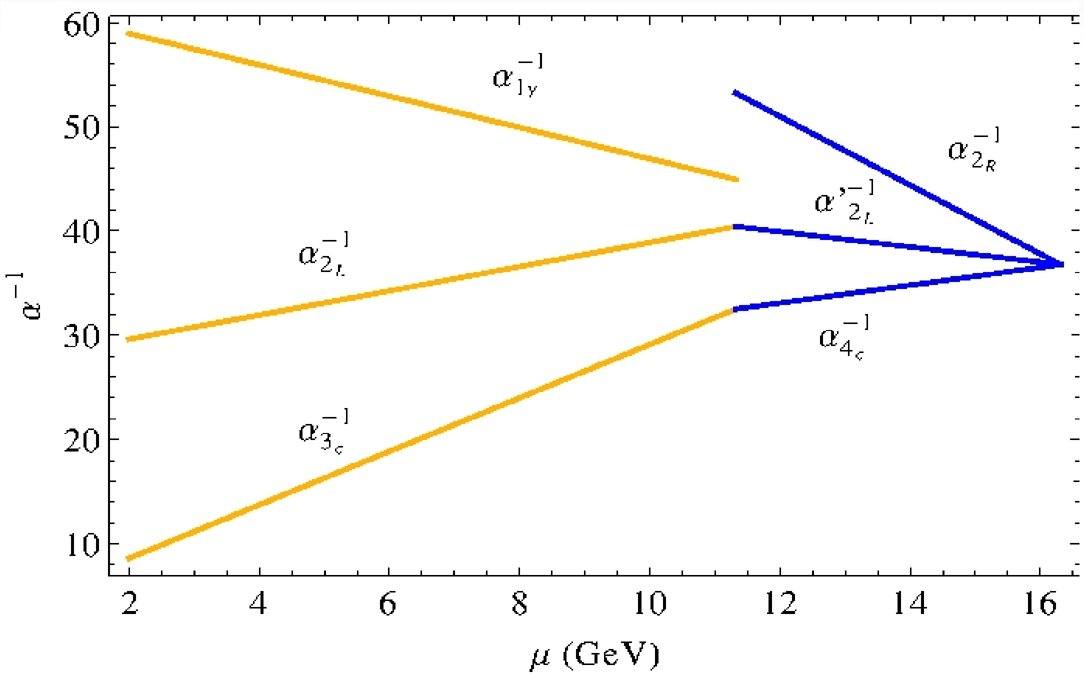
- which is the assumption that at any scale, the only scalar multiplets present are those that develop VEVs at smaller scales

	210	$\overline{126}$	45	10
M_{GUT}	All components	(6,1,1) ($\overline{10}$,3,1)	(1,3,1) (6,2,2) (15,1,1)	(6,1,1)
M_I	–	(10,1,3) (15,2,2)	(1,1,3)	–
EW	-	-	-	(1,2,2)

M_{GUT} and M_I from gauge coupling unification

- To 1-loop accuracy

$$\alpha_i^{-1}(M_2)=\alpha_i^{-1}(M_1)-\frac{a_i}{2\pi}\log\frac{M_2}{M_1}$$



a_3	a_{2L}	a_Y	a_4	a'_{2L}	a_{2R}
-7	-19/6	41/10	-7/3	2	28/3

$$M_I=(1.3\pm0.2)\cdot10^{11}\,GeV$$

$$M_{GUT}=(1.9\pm0.6)\cdot10^{16}\,GeV$$

$$\alpha_{GUT}\sim0.027$$

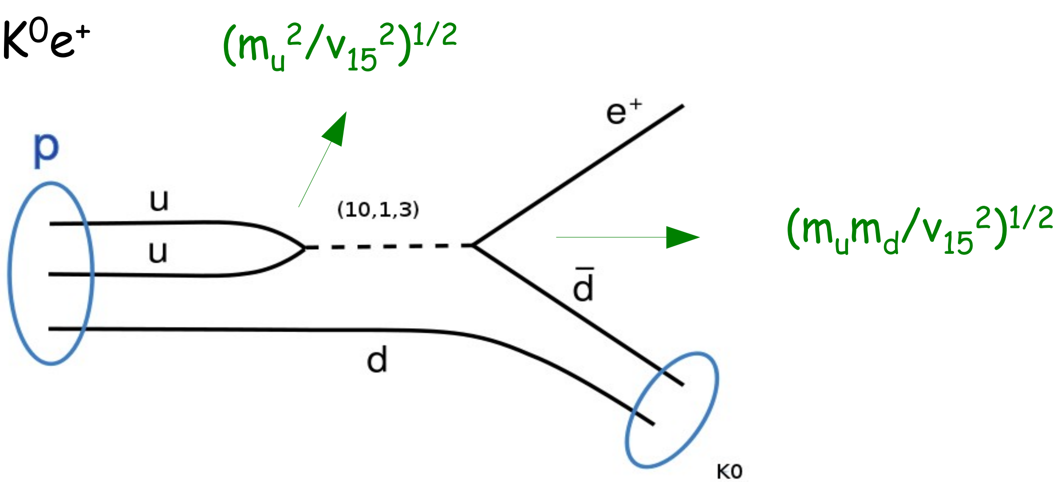
Proton decay

- naïve estimate

$$\tau \sim \frac{M_{GUT}^4}{\alpha_{GUT}^2 m_p^5} \sim 5 \cdot 10^{36}\, y \gg \tau^{\exp} \equiv 10^{34}\, y$$

- from colored scalar triplet (10,1,3) of 126 with masses around M_I

p-> $K^0 e^+$



$$\Gamma \sim \frac{m_u^2 m_d m_s \sin^2\theta_C}{v_{15}^4} \left(\frac{m_p^5}{M_T^4} \right)$$

$$M_T \geq 10^{10-11}\, GeV \sim M_I$$

The Yukawa sector

- Yuwaka Lagrangian

$$L_Y = 16_F \left(h\,10 + f\,\overline{126} \right) 16_F$$

h,f complex
symmetric matrices

- The role of the 10 in the Yukawa sector

decomposition under
SU(3)xSU(2)xU(1)

$$10 = (6,1,1) \oplus (1,2,2) \longrightarrow (1,2,2) = \left(1,2,\frac{1}{2}\right) \oplus \left(1,2,-\frac{1}{2}\right) \equiv H_u \oplus H_d$$

- if $H^*_u = H_d$ (as in the SM), in the limit $V_{cb}=0$ we would get $m_t/m_b \sim 1$ → contradiction with the experimental fact $m_t/m_b \ll 1$ B.Bajc et al.,Phys. Rev. D73, 055001 (2006)

- one assumes a 10 with complex components → H_u different from H_d

$$k_{u,d} = \langle (1,2,2)_{u,d} \rangle_{10}$$

The Yukawa sector

- An extra U(1) symmetry a la Peccei-Quinn is needed to avoid extra Yukawa coupling and keep the parameter space at an acceptable level:

$$16_F \rightarrow e^{i\alpha} 16_F \,, 10 \rightarrow e^{-2i\alpha} 10, \overline{126} \rightarrow e^{-2i\alpha} \overline{126}$$

  - The role of the $\overline{126}$ in the Yukawa sector

$$\overline{126} = (6,1,1) \oplus (\overline{10}, 3,1) \oplus (10,1,3) \oplus (15,2,2)$$

$$v_R = \langle (10,1,3) \rangle_{126} \neq 0$$

$$v_{u,d} = \langle (15,2,2)_{u,d} \rangle_{126}$$

Mass matrices

$$M_u = h k_u + f v_u \qquad M_d = h k_d + f v_d \qquad M_{\nu_D} = h k_u - 3 f v_u$$

$$M_l = h k_d - 3 f v_d \qquad M_\nu^M = f v_R \longrightarrow$$ for see-saw type-I

- Rewritten in a suitable form for a fit:

Joshipura and Patel, Phys.Rev.D83, 095002 (2011)

$$M_u = r_v \left(\frac{3+s}{4} M_d + \frac{1-s}{4} M_l \right)$$

$$M_\nu^D = r_v \left(\frac{3(1-s)}{4} M_d + \frac{1+3s}{4} M_l \right)$$

$$M_\nu^M = r_R^{-1} \left(M_d - M_l \right)$$

$$r_v = k_u / k_d$$
$$s = v_u / r_v v_d$$

M_d = down-quark mass matrix

M_l = charged lepton mass matrix

Including leptogenesis

- The important novelty of our approach is the introduction of the baryon-to-photon number ratio as a fit observable

$$\eta_B = (5.7 \pm 0.6) \times 10^{-10}$$

Iocco et al.,
Phys. Rept.472, 1 (2009)

- To compute η_B: implementing the Boltzmann equations

The procedure is really time-expensive

- Alternative way:

W.Buchmuller, P.Di Bari and M.Plumacher,
Annals Phys.315, 305 (2005)

1- we work with a given number of flavors and active RH neutrinos
2-we implement simplified solutions of the Boltzmann equations
3-we check a posteriori that the assumptions in step (1) are correct

Including leptogenesis

4- in the case of a positive answer, we use the heavy spectrum and the Dirac mass matrix obtained from the fit to solve numerically the Boltzmann equations and get a more precise determination of η_B

We start assuming:

$$10^9 < M_{\nu_1} < 10^{12}\,GeV$$

τ Yukawa coupling is in equilibrium: two-flavour approach

Blanchet and Di Bari,
JCAP 0703, 018 (2007)
Abada et al.,
JHEP 0609, 010 (2006)

$$(M_{\nu_2} - M_{\nu_1})/M_{\nu_1} \sim O(1)$$

N_1 and N_2 contribute to leptogenesis

Davidson, Nardi, Nir,
Phys.Rept.466, 105 (2008)

Di Bari, Riotto,
Phys.Lett. B671 (2009) 462-469;
JCAP 1104 (2011) 037

Including leptogenesis

Blanchet and Di Bari,
JCAP 0703, 018 (2007)

$$\varepsilon_{i\alpha} = \frac{3}{16\pi (h^\dagger h)_{ii}} \sum_{j\neq i} \left\{ \mathrm{Im}\left[h^\star_{\alpha i} h_{\alpha j} (h^\dagger h)_{ij}\right] \frac{\xi(x_j/x_i)}{\sqrt{x_j/x_i}} + \frac{2}{3(x_j/x_i - 1)} \mathrm{Im}\left[h^\star_{\alpha i} h_{\alpha j} (h^\dagger h)_{ji}\right] \right\}, \quad (9)$$

Dirac mass matrices

where $x_i \equiv (M_i/M_1)^2$ and

Majorana masses

$$\xi(x) = \frac{2}{3} x \left[(1+x) \ln\left(\frac{1+x}{x}\right) - \frac{2-x}{1-x}\right]. \quad (10)$$

decay terms

$z=M_1/T$

$$\frac{dN_{N_i}}{dz} = -D_i \left(N_{N_i} - N_{N_i}^{\mathrm{eq}}\right)$$

N_{Δ_α}'s and the N_i's are the abundances per number of N_1's

$$\frac{dN_{\Delta_\alpha}}{dz} = \sum_i \varepsilon_{i\alpha} D_i \left(N_{N_i} - N_{N_i}^{\mathrm{eq}}\right) - N_{\Delta_\alpha} \sum_i P^0_{i\alpha} W_i^{\mathrm{ID}}$$

washout term

$B/3-L_\alpha$

Flavor projectors

Fit results

- We have to estimate 15 real parameters:
  12 in Md, 2 contained in s and one in r_ν
- 15 observables at the GUT scale:
  6 quark masses, 4 in the CKM, 3 in the PMNS, η_B, $\Delta m_{sol}/\Delta m_{atm}$

Obs.	fit	pull	Obs.	fit	pull
mu	0.49	0.03	|Vus|	0.225	0.038
md	0.78	0.75	|Vcb|	0.042	-0.208
ms	32.5	-1.5	|Vub|	0.0038	-0.659
mc	0.287	-1.49	J	3.1×10^{-5}	0.589
mb	1.11	-2.77	$\sin^2\theta_{12}$	0.318	0.611
mt	71.4	0.7	$\sin^2\theta_{23}$	0.353	-1.548
r	0.031	0.1	$\sin^2\theta_{13}$	0.0222	-0.758
η_B	5×10^{-10}	-0.001			

Fit results

$$\chi^2_{min} = 17.4$$

- All data reproduced within 3σ
- The largest contribution from the atmospheric angle

This tendency to drift toward smaller values is due to the stringent requirements imposed by η_B (otherwise χ^2 ~0.95)

predictions

Light ν masses (eV)	Heavy ν masses (10^{11} GeV)	Phases (°)	m_{ee} (eV)	Σm_i (eV)
0.0046	1.00	δ=88.6	5×10^{-4}	0.065
0.0098	1.09	ϕ_1=-33.2		
0.0504	21.4	ϕ_2=15.7		

compact RH spectrum

The request for an axion candidate

- An extra U(1) symmetry a la Peccei-Quinn is needed to avoid extra Yukawa coupling and keep the parameter space at an acceptable level:

$$16_F \to e^{i\alpha} 16_F \, , 10 \to e^{-2i\alpha} 10, \overline{126} \to e^{-2i\alpha} \overline{126}$$

- It is expected that the $U(1)_{PQ}$ be broken by $\langle \overline{126} \rangle \neq 0$ at the scale of $SU(2)_R$ breaking, otherwise the 10 would drive the U(1) breaking to give $M_{PQ} \approx M_W$, which is ruled out by experiments

- $\langle \overline{126} \rangle \neq 0$ is not enough, since a linear combination of $U(1)_{PQ}$, T3R and B-L remains unbroken

↳ Add another Higgs representation

The request for an axion candidate

- 16 Mohapatra and Senjanovic, Z.Phys. C17, 53 (1983)
- another 126 B.Bajc et al.,Phys. Rev. D73, 055001 (2006)
- 45 → our choice to break the degeneracy

$(1,1,3) \in 45$ with vanishing B-L and α' different from α

⇩

little impact on the coupling constant evolutions

Axions as dark matter particles

- The axion mechanism gives a solution to the strong CP problem without need to impose an additional constraint in the fitting procedure

Kim and Carosi,
Rev. Mod. Phys. 82 (2010) 557

- mass: $$m_a = \frac{(m_u/m_d)^{\frac{1}{2}}}{1+z} \frac{f_\pi m_\pi}{F_a} \Rightarrow m_a \sim (4.3-4.7)\times 10^{-5}\, eV$$

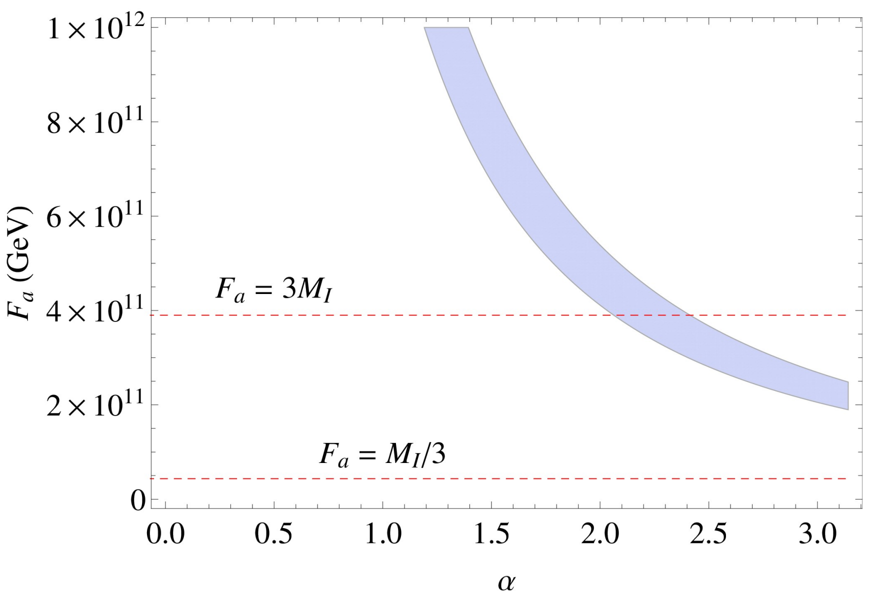
F_a ~ MI

- energy density of cold axions:

$$\Omega_c h^2 \sim 0.7 \left(\frac{F_a}{10^{12}\, GeV}\right)^{7/6} \left(\frac{\alpha}{\pi}\right) = \underbrace{0.1192 \pm 0.0062}_{\text{PLANCK+WP+BICEP2+BAO}}$$

arXiv:1403.6462

α=initial misalignment angle



Conclusions

- Non-susy SO(10) gives a viable GUT scenario for beyond SM physics
- A particular breaking chain with $M_I \sim 10^{11}$ GeV is needed to accommodate all compelling phenomena that demand new physics below M_{GUT}
- Price to pay: very large level of fine-tuning !
- Competitive scenarios: non-renormalizable couplings (smaller Higgs representations)

A comment on leptogenesis

- Additional decay channels involving the RH gauge bosons and the color singlets in the (10,1,3)
- Let us consider the W_R

$$\Gamma_{N_1} = \frac{\left(M^{dag}_{\nu_D} M_{\nu_D}\right)_{11}}{4\pi v_u^2} M_{\nu_1}(1+X)$$

Dilution factor

$$M_{\nu_1} > M_{W_R}$$

NO because 2-body decays

$N \to l\, W_R$ are too fast $\to X \sim O(10^4\text{-}10^5)$

$$M_{\nu_1} < M_{W_R}$$

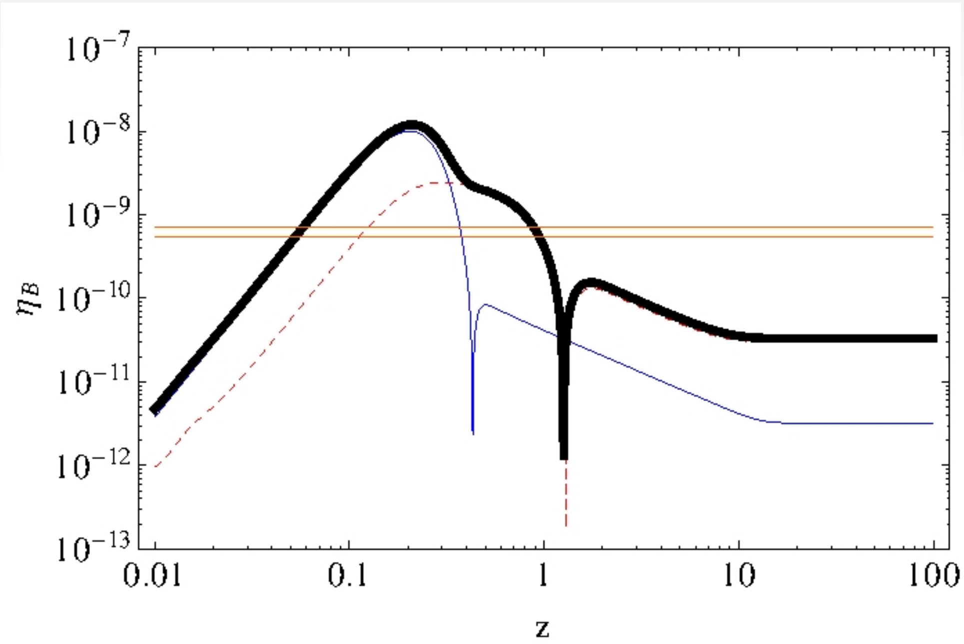
3-body decays $\to \Gamma_3 < H$ implies

$$M_{\nu_1} > 2\cdot 10^{11} / \left(M_{W_R} / M_{\nu_1}\right)^4$$

Satisfied for $M_{WR} \sim M\nu_1 \sim M_I$

A comment on leptogenesis

- Leptogenesis not-included in the fit



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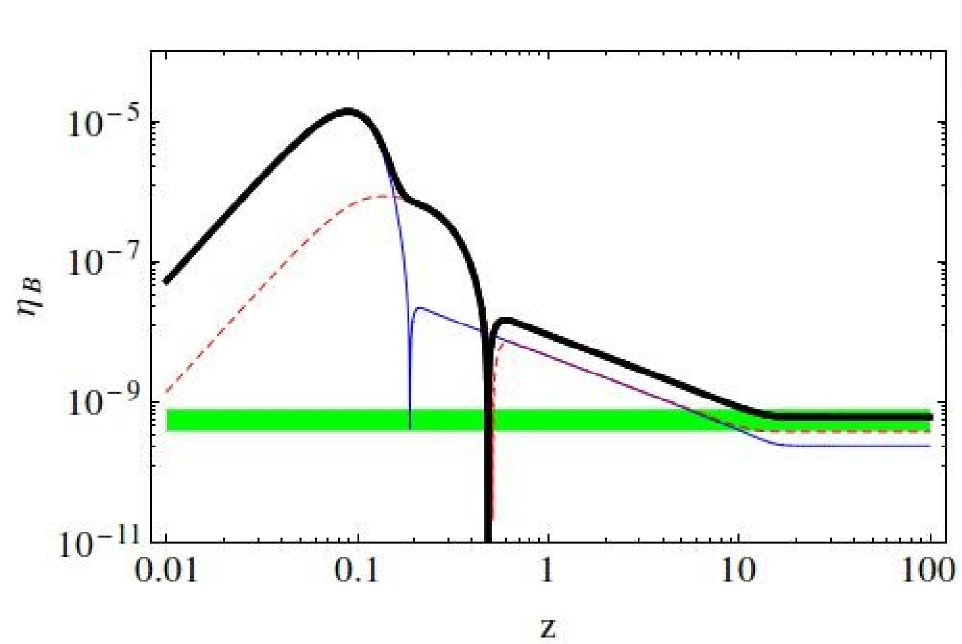

Other breaking chains

$SO(10) \to 3_c 2_L 2_R 1_X \to SM$

$(1,2,2,0)$ in 126 + $(1,1,3,0)$ in 45 $\Rightarrow$ $M_I \sim 10^9$ GeV

[or $(1,2,2,-1/2)$ in 16]

$SO(10) \to 3_c 2_L 2_R 1_X \times P \to SM$

$M_I \sim (0.4-1)\ 10^{11}$ GeV $\tau \sim 10^{-1/-2}\ \tau_{exp}$

$3_c 2_L 2_R 1_X$ not a suitable intermediate scale