MPI Heidelberg, November 30 2009

35 years of GUTs - where do we stand?

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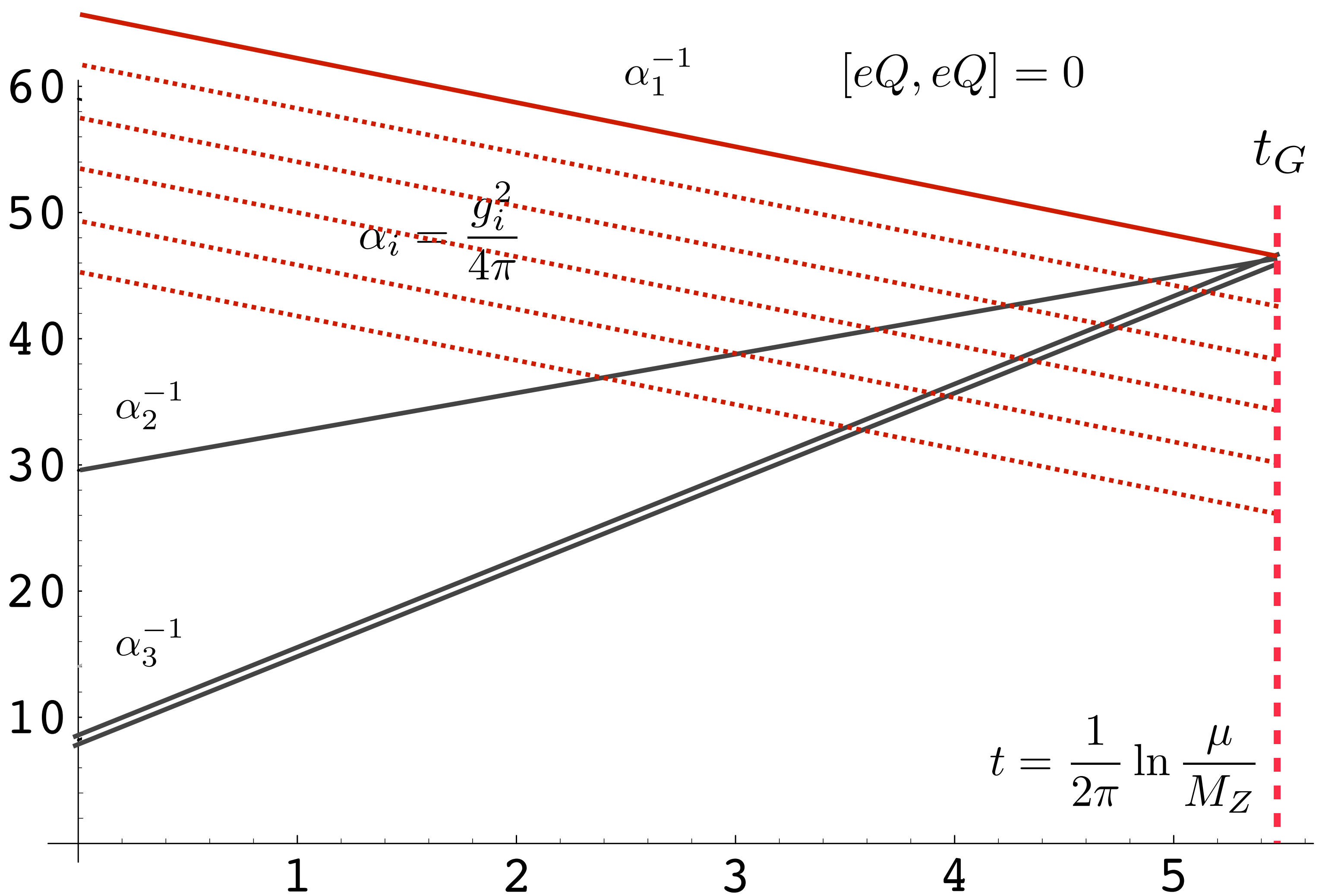
based on Phys.Rev.D80:015013,2009 and arXiv:0912.xxxx[hep-ph]

Outline

- Grand Unified Theories - a brief intro
- Simplest Grand unified models and their status
- Minimal non-SUSY SO(10)
- No-go? No, go!
- Quantum resuscitation of the cadaver

Grand Unified Theories - a brief intro

- Convergence of the running gauge couplings at very high energies



$M_G \sim 10^{16}\text{GeV}$

If not an accident the gauge interactions unify
and a new dynamics pops up there

Grand Unified Theories - a brief intro

- Neutrino masses in the SM: $L = \begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix} = (1, 2, -\frac{1}{2})$

  - d = 5 Weinberg operator: $\mathcal{L}_{eff} \ni \frac{c}{\Lambda} LHLH$

- Neutrino oscillation parameters:

$$\Delta m^2_\odot = (8.0 \pm 0.3) \times 10^{-5}\,\mathrm{eV}^2 \qquad |\Delta m^2_A| = (2.5 \pm 0.3) \times 10^{-3}\,\mathrm{eV}^2$$

$$\boxed{\Lambda \sim (10^{12} - 10^{14})\ \mathrm{GeV}}$$

"New physics" scale governing neutrino masses (seesaw)

Remarkably close to the unification scale!

O.K., let's take the gauge unification idea seriously...

Grand Unified Theories - a brief intro

Consequences:

- GUT-scale predictions for one of the gauge couplings, e.g.: $\sin^2\theta_W = \frac{3}{8}$

- Quarks and leptons share the GUT multiplets

  - Yukawas spanned over the GUT multiplets $\Rightarrow$ insight into flavour

  - gauge transitions violate B and L $\Rightarrow$ "exotic" processes

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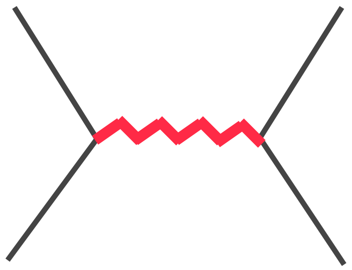
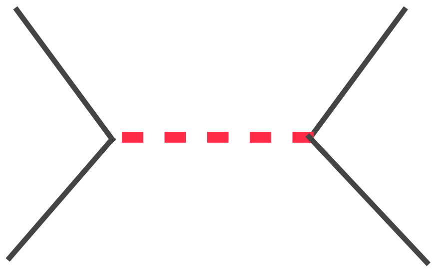
- d = 6 proton decay:

$$\frac{f_1}{M_G^2}\overline{Q}u^c\overline{Q}e^c, \quad \frac{f_2}{M_G^2}u^c\overline{Q}d^c\overline{L} \qquad \frac{f_3}{M_G^2}QQQL, \quad \frac{f_4}{M_G^2}u^cu^cd^ce^c$$

vector-induced



scalar-induced



current SK limit: $\tau(p^+ \to \pi^0 e^+) \gtrsim 10^{33}\,\text{years} \Rightarrow$ $M_G \gtrsim 10^{15.5}\,\text{GeV}$

Grand Unified Theories - a brief intro

- Minimality is an invaluable guiding principle

  - overall predictivity

  - in particular for flavour (not dictated by symmetry but by Higgs structure)

- Minimal GUT gauge group:

  - rank 4 or higher
  - must have complex representations
  - correct multiplet patterns

  $\Rightarrow$ SU(5)

  unique rank = 4 option

Minimal SU(5) model

- Gauge fields: $24_G = (8,1,0) \oplus (1,3,0) \oplus (1,1,0) \oplus (3,2,-\frac{5}{6}) \oplus (\overline{3},2,+\frac{5}{6})$

  G^μ $\quad A^\mu$ $\quad B^\mu$ $\quad (X^\mu, Y^\mu)$

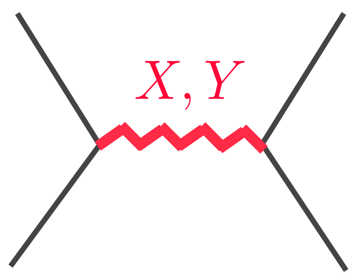
- Matter fields: $\overline{5}_F = (1,2,-\frac{1}{2}) \oplus (\overline{3},1,+\frac{1}{3})$ $\quad 10_F = (1,1,+1) \oplus (3,2,+\frac{1}{6}) \oplus (\overline{3},1,-\frac{2}{3})$

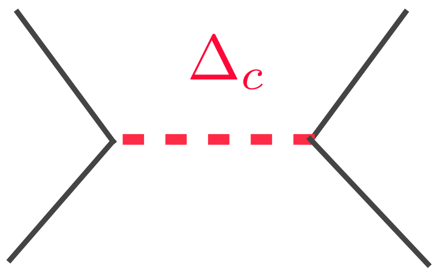
  L $\quad d^c$ $\quad e^c$ $\quad Q$ $\quad u^c$

- Higgs fields: $\overline{5}_H = (1,2,-\frac{1}{2}) \oplus (\overline{3},1,+\frac{1}{3})$ $\quad 24_H = (1,1,0) \oplus \ldots$

  H $\quad \Delta_c$ $\quad$ SU(5)-breaking SM singlet

- Proton decay:



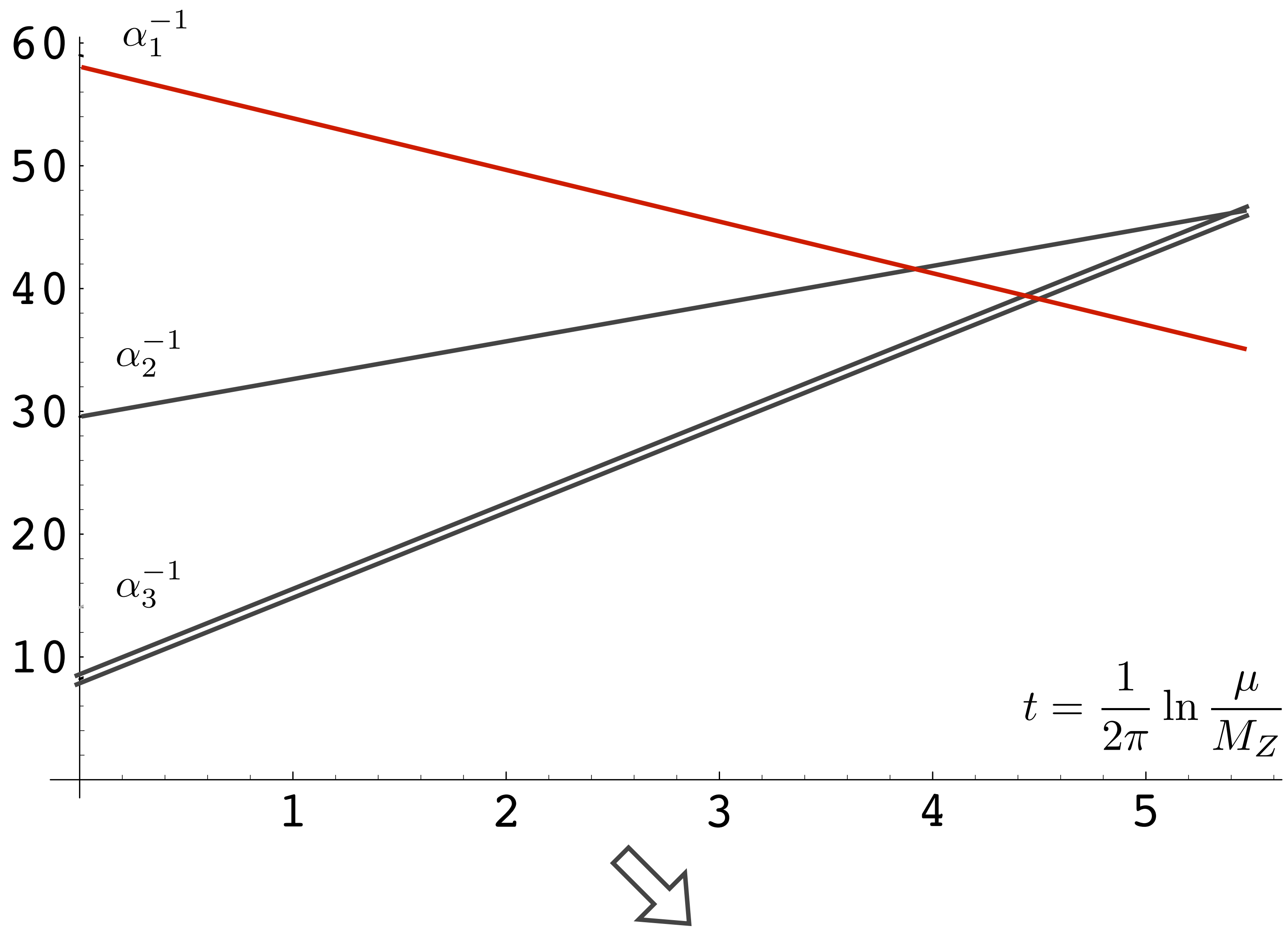


$\overline{10}_F \not{D} 10_F + \overline{\overline{5}}_F \not{D} \overline{5}_F$ $\qquad Y_5 \overline{5}_F 10_F \overline{5}_H + Y_{10} 10_F 10_F * \overline{5}_H^\dagger$

- Flavour structure: $M_u = M_u^T$ $\quad M_d = M_l^T$ $\quad$ b-tau unification (?)

Minimal SU(5) model

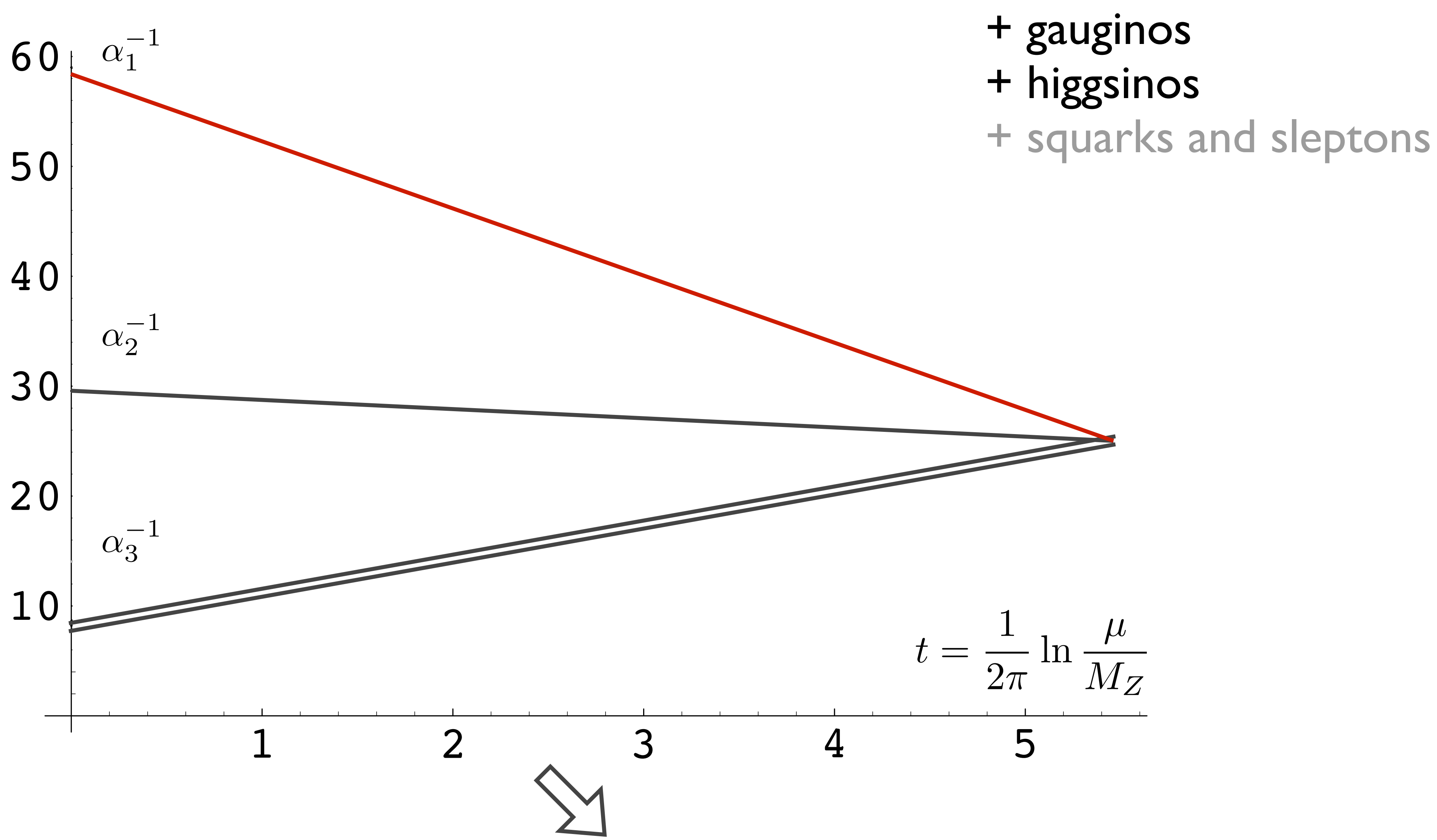
- Gauge coupling unification in minimal SU(5) GUT: $Y \in SU(5)$



no unification ?

Minimal SUSY SU(5) GUT

- Gauge coupling unification in minimal SUSY SU(5) GUT: $Y \in SU(5)$



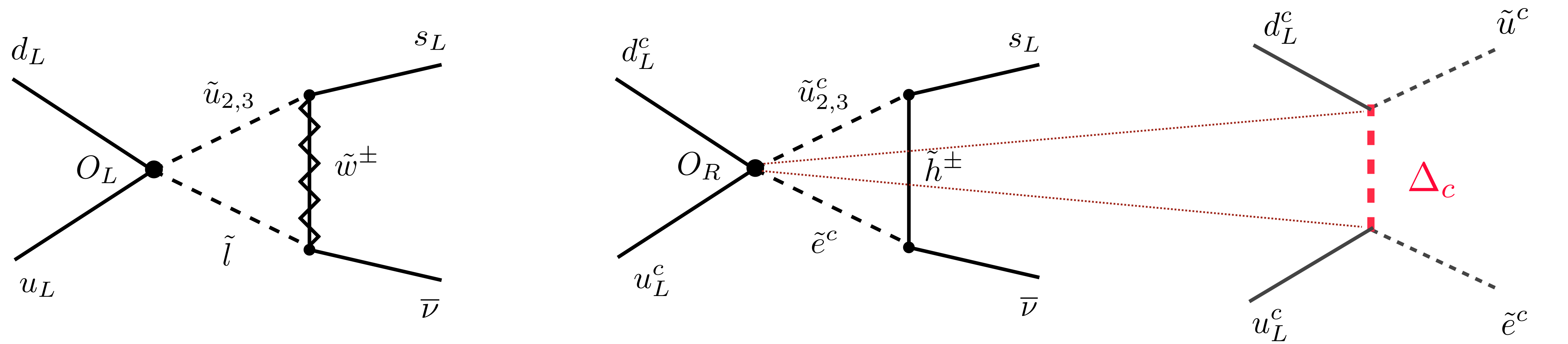
supersymmetric GUTs !

- Good also for hierarchies

Minimal SUSY SU(5) GUT

- SUSY SU(5) : simpler than non-SUSY (up to an extra Higgs doublet)

  - d=5 proton decay operators in SUSY:



$$W_L \sim \frac{c_L}{M_{\Delta_c}} \hat{Q}\hat{Q}\hat{Q}\hat{L} \qquad W_R \sim \frac{c_R}{M_{\Delta_c}} \hat{u}^c\hat{u}^c\hat{d}^c\hat{e}^c \qquad c_L,\, c_R \sim Y_u Y_d^\dagger,\, Y_u^\dagger Y_d$$

$$\Gamma(p^+ \to K^0 e^+) \propto \frac{\alpha_G^2}{(4\pi)^4} \frac{m_p^5}{M_{\Delta_c}^2 M_{\rm SUSY}^2} |V_{\rm CKM} Y_u Y_d^\dagger V_{\rm CKM}^\dagger|^2$$

- yields at best 10^{30} years;
- perhaps viable with non-renormalizable operators invoked (?) Bajc, Fileviez-Perez, Senjanovic, 2002

Interlude

- Both SUSY as well as non-SUSY minimal SU(5) very sick...

  - the only rank = 4 option though !

- How about rank = 5 ?

  - admits adding one more Cartan to the four SM ones

  - a very natural candidate: B - L

  - left-right symmetric models à la

$$SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \to SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

  - $SU(2)_R$ requires RH neutrino, seesaw natural

  - rank = 5 admits more than a single breaking step like e.g.

$$SU(4)_C \otimes SU(2)_L \otimes SU(2)_R \qquad SU(3)_c \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L}$$

  - these emerge as subgroups of SO(10)

SO(10) basics

- Anomaly-free

$$16_F = (3,2,+\tfrac{1}{6}) \oplus (1,2,-\tfrac{1}{2}) \oplus (\bar{3},1,+\tfrac{1}{3}) \oplus (\bar{3},1,-\tfrac{2}{3}) \oplus (1,1,+1) \oplus (1,1,0)$$

$$10_H = (1,2,-\tfrac{1}{2}) \oplus (1,2,+\tfrac{1}{2}) \oplus (\bar{3},1,+\tfrac{1}{3}) \oplus (3,1,-\tfrac{1}{3})$$ - N.B. doublets in pairs

- Strongly correlated Yukawa's: a chance to understand some aspects of flavour

$16_F 16_F 10_H \ni$ Dirac masses for everybody driven by a single coupling!

- RH neutrinos automate, renormalizable type I+II seesaw natural

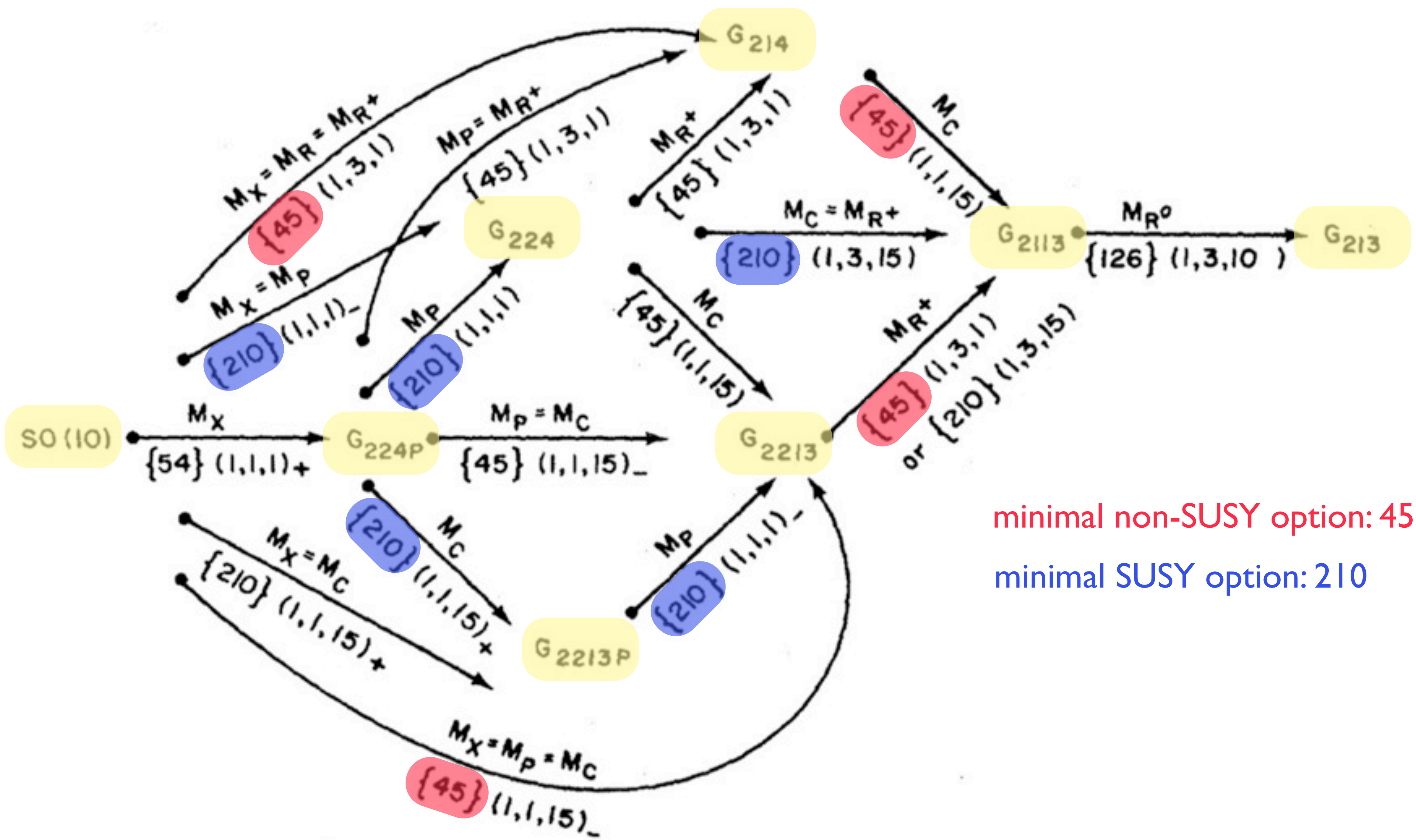
$$\overline{126}_H \ni (1,2,-\tfrac{1}{2}) \oplus (1,2,+\tfrac{1}{2}) \oplus (1,1,0) \oplus (1,3,+1) \oplus \ldots$$

$16_F 16_F \overline{126}_H \ni$ LH and RH Majorana neutrino masses, extra Dirac contributions

- SO(10) SSB: $\overline{126}_H$ breaks large portion of the GUT symmetry, but not SU(5)

SO(10) basics

- SO(10) breaking chains (omitting the SU(5) options) :



minimal non-SUSY option: 45

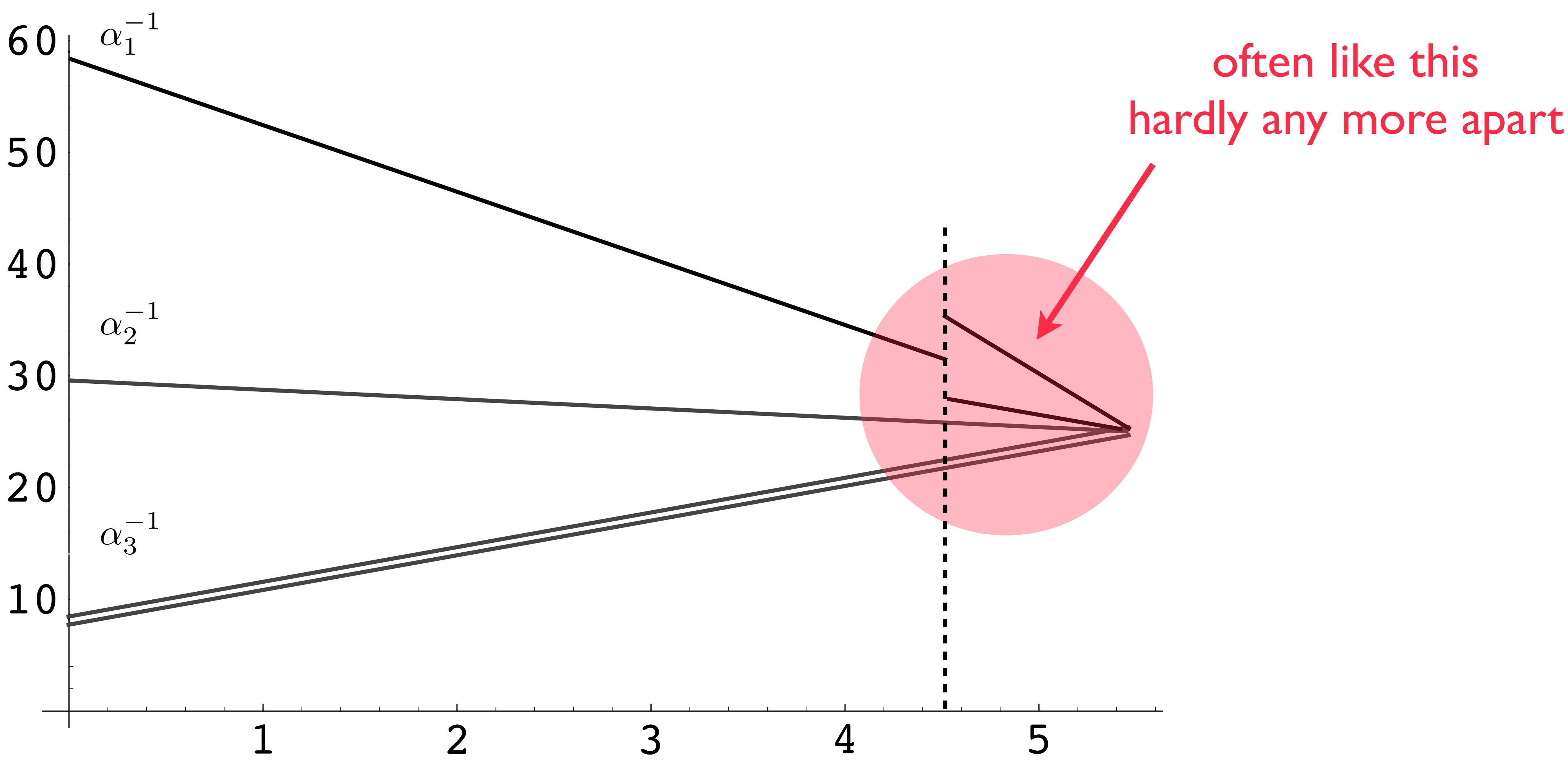
minimal SUSY option: 210

Chang, Mohapatra, Gipson, Marshak, Parida 1985

SO(10) basics

- N.B. in SUSY the extra freedom in running is not very pronounced

Example: $SO(10) \to SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \to \mathrm{SM}$



"SUSY likes desert"

Minimal SUSY SO(10) GUT

- **Structure**

T.E. Clark, T.K. Kuo, N. Nakagawa 1982
C.S. Aulakh, Rabindra N. Mohapatra 1983
C.S. Aulakh, B. Bajc, A. Melfo, G. Senjanovic and F. Vissani 2004

Matter: $3 \times 16_F$

Higgses: $10_H \oplus \overline{126}_H \oplus 126_H \oplus 210_H$ - D-flatness, realistic breaking pattern

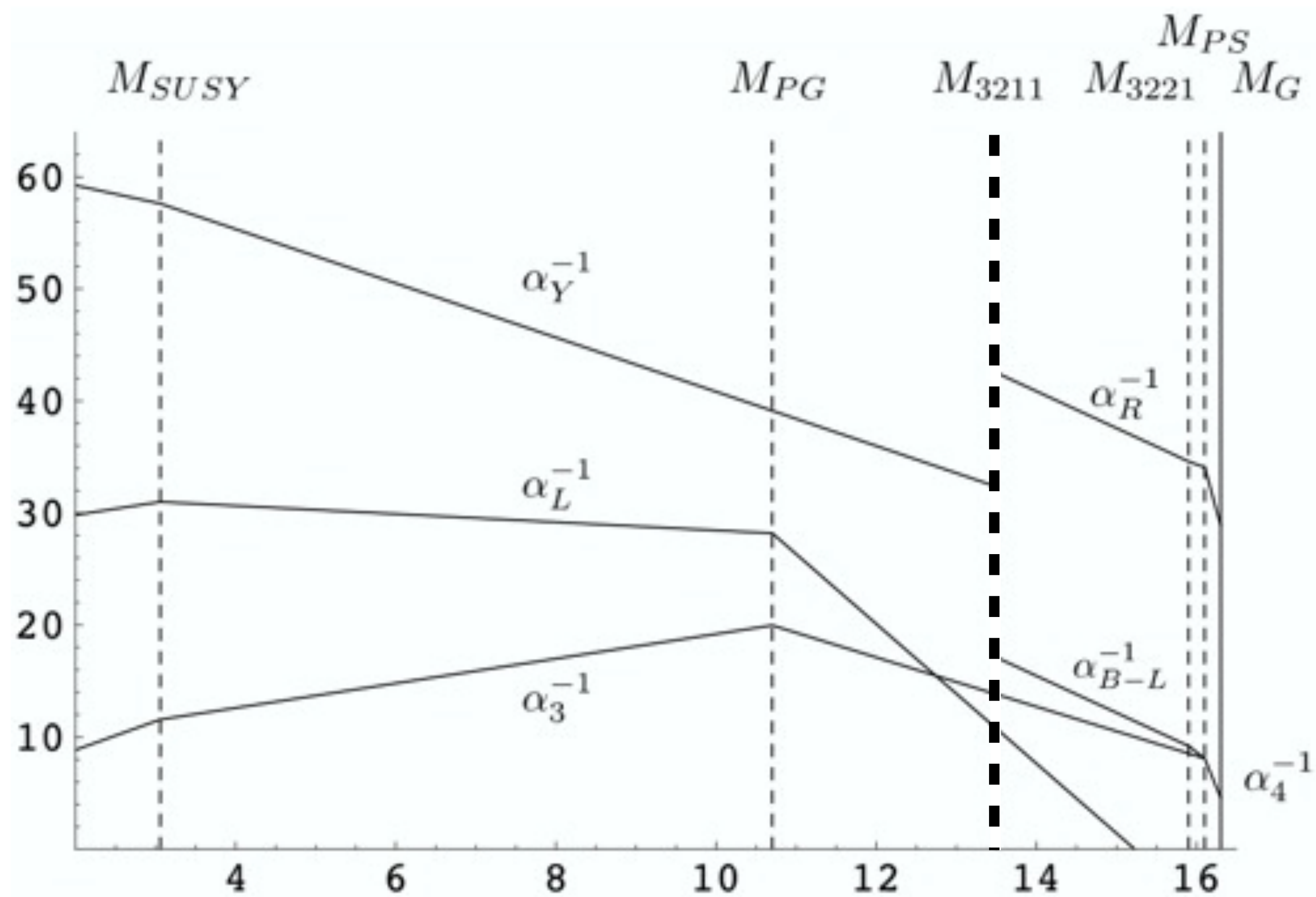
- **Proton decay** - in a better shape than in SU(5) - many triplets around

- **Neutrino challenge:**

High B - L scale ⇒ neutrinos too light

Low B - L scale ⇒ thresholds

hints: C. Aulakh, 2005
complete analysis: S. Bertolini, MM, T. Schwetz 2006



Minimal non-SUSY SO(10)

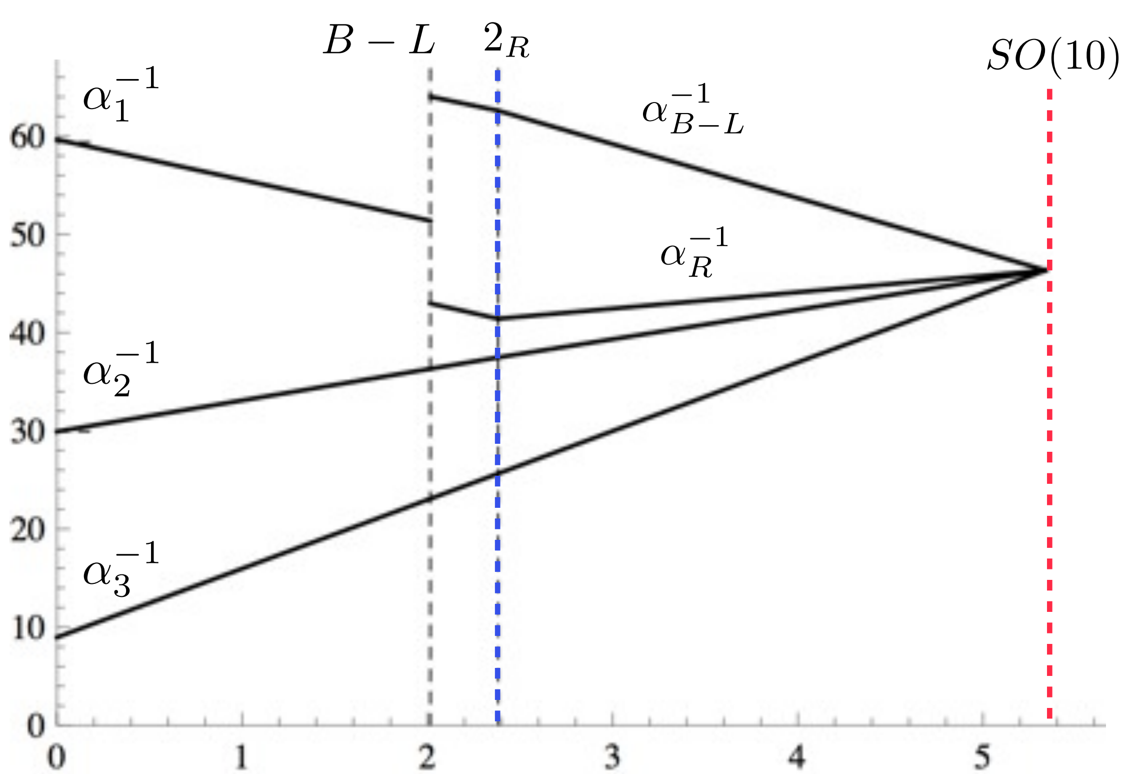
I won't be concerned about naturalness as long as predictivity is at stakes.

- Unlike minimal SU(5), minimal SO(10) can live and is simpler without SUSY

  - smaller representations, minimal model $45_H \oplus 16_H \oplus 10_H$ or $45_H \oplus \overline{126}_H \oplus 10_H$

  - only d=6 or higher proton decay

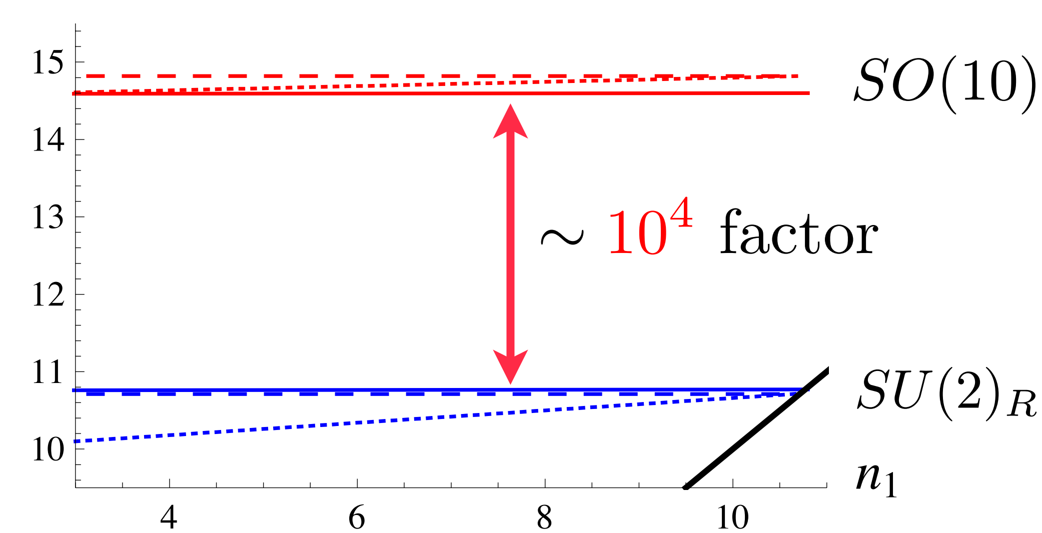
- Typical "multi-stage" breaking pattern



"non-SUSY doesn't like desert"

- a more realistic example:

$$SO(10) \to 3_c 2_L 2_R 1_{B-L} \to 3_c 2_L 1_R 1_{B-L} \to \ldots$$



- gap between GUT and intermediate SSB

Chang, Mohapatra, Gipson, Marshak, Parida 1985
recent reassessment: Bertolini, MM, Di Luzio 2009

Minimal non-SUSY SO(10)

(the 45+16 variant)

- The gap from the minimal non-SUSY SO(10) perspective:

The minimal Higgs sector dynamics does not support it !!!

$$\langle 45_H \rangle = \begin{pmatrix} \omega_Y & & & & \\ & \omega_Y & & & \\ & & \omega_Y & & \\ & & & \omega_R & \\ & & & & \omega_R \end{pmatrix} \otimes \tau_2$$

triggers the following chains:

$\omega_Y \gg \omega_R$ $\quad SO(10) \stackrel{45}{\rightarrow} SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \stackrel{45}{\rightarrow} SU(3)_c \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L} \stackrel{16}{\rightarrow} SM$

$\omega_R \gg \omega_Y$ $\quad SO(10) \stackrel{45}{\rightarrow} SU(4)_C \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L} \stackrel{45}{\rightarrow} SU(3)_c \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L} \stackrel{16}{\rightarrow} SM$

$\omega_R = \pm\omega_Y$ $\quad SO(10) \stackrel{45}{\rightarrow} SU(5) \otimes U(1) \stackrel{16}{\rightarrow} SM$ - this one we know is not realistic though!

- tachyons in the scalar spectrum unless $\frac{1}{2} \leq |\omega_Y/\omega_R| \leq 2$

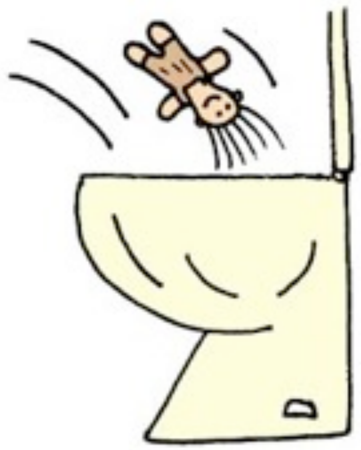
$$\begin{aligned} m^2_{(8,1,0)} &= 2a_2(\omega_R - \omega_Y)(\omega_R + 2\omega_Y) \\ m^2_{(1,3,0)} &= 2a_2(\omega_Y - \omega_R)(\omega_Y + 2\omega_R) \end{aligned}$$

Only the (flipped) SU(5) vacuum allowed !

Yasue, Ma & co., Buccella & co. back in 1980's

Status of the Minimal non-SUSY SO(10)

- This "textbook" result implies no-go also for the Minimal non-SUSY SO(10)



Is that really a no-go?

- "Second Weinberg's law of progress in particle physics":

"Never trust arguments based on the lowest order of perturbation theory."

S.Weinberg (an essay from 1983)

No-go? No! Go!

Resuscitating the Minimal non-SUSY SO(10)

- There is something peculiar about the "tachyons":

$$
\begin{aligned}
m^2_{(8,1,0)} &= 2a_2(\omega_R-\omega_Y)(\omega_R+2\omega_Y)\\
m^2_{(1,3,0)} &= 2a_2(\omega_Y-\omega_R)(\omega_Y+2\omega_R)
\end{aligned}
$$

PGB's of an enhanced global symmetry of the scalar potential, but quite interesting...

$$
V = \tfrac{1}{2}m^2_{16}16^\dagger 16 + \lambda(16^\dagger 16)^2 + \tfrac{1}{2}m^2_{45}\mathrm{Tr}(45^2) + a_1[\mathrm{Tr}(45^2)]^2 + \alpha 16^\dagger 16 \mathrm{Tr}(45^2)
$$

$$
+a_2\mathrm{Tr}(45^4) + \beta\, 16^\dagger.45.45.16 + \tau\, 16^\dagger.45.16 + \ldots
$$

individual rotations of 16 and 45 preserved

individual rotations of 16 and 45 broken explicitly

How come that β and τ do not enter the PGB masses when turned on ???

- the τ - term obviously "does not have enough legs"
- the β - term is accidentally zero (resembles the SM gauge mass term)

IRRELEVANT AT THE QUANTUM LEVEL!

S.Bertolini, MM, L.Di Luzio, arXiv:0912.xxxx[hep-ph]

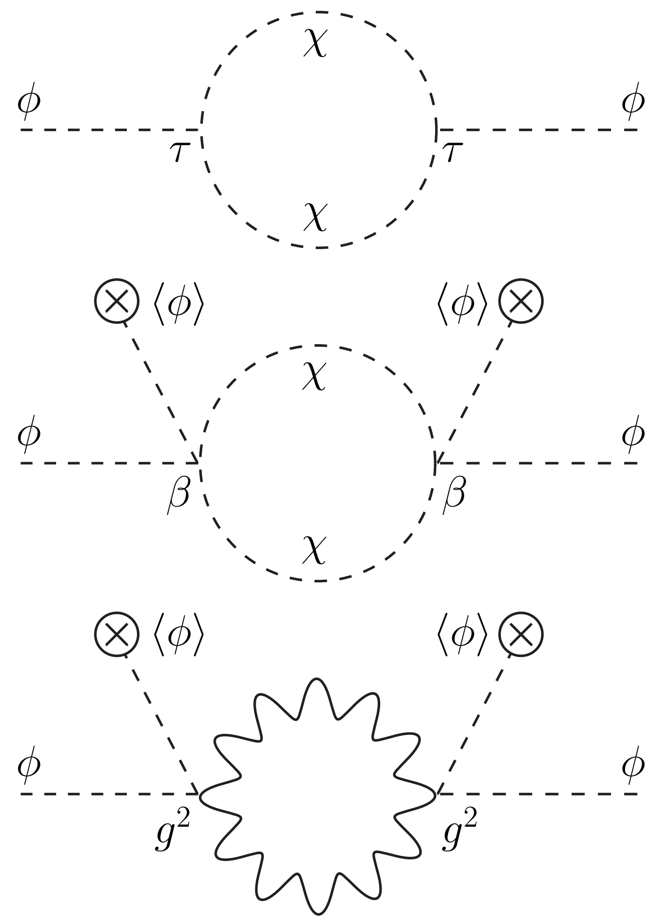
Resuscitating the Minimal non-SUSY SO(10)

- We have performed a one-loop analysis of the minimal SO(10) vacuum

  - Coleman-Weinberg effective potential minimization:

$$\Delta m^2_{(1,3,0)} = \frac{1}{4\pi^2}\left[\tau^2 + \beta^2(2\omega_R^2 - \omega_R\omega_Y + 2\omega_Y^2) + g^4\left(16\omega_R^2 + \omega_Y\omega_R + 19\omega_Y^2\right)\right] + \text{logs}\,,$$

$$\Delta m^2_{(8,1,0)} = \frac{1}{4\pi^2}\left[\tau^2 + \beta^2(\omega_R^2 - \omega_R\omega_Y + 3\omega_Y^2) + g^4\left(13\omega_R^2 + \omega_Y\omega_R + 22\omega_Y^2\right)\right] + \text{logs}\,,$$



  - radiative corrections to PGB masses non-trivial & large

  - compete with the tree-level parts for $a_2 \lesssim \mathcal{O}(10^{-1})\beta, \tau$

NO TACHYONS even in the $\omega_R \gg \omega_Y$ or $\omega_Y \gg \omega_R$ regimes !

THE GAP IS SUPPORTED AT THE QUANTUM LEVEL !!!

  - unexpected bonus : the "gap" shrinks a bit

S.Bertolini, MM, L.Di Luzio, arXiv:0912.xxxx[hep-ph]

Conclusions

Grand unifications are beatiful but the minimal (predictive) models tend to fail:

- Minimal SU(5) killed by unification constraints
- Minimal SUSY SU(5) killed by proton decay
- Minimal SUSY SO(10) killed by flavour + unification constraints
- Minimal non-SUSY SO(10) cursed 25 years ago for "technical reasons"
- The first quantum level analysis of its vacuum brings it back to life!

"True love's kiss to the Sleeping Beauty... just 75 years too early ?!"

Thank you for your kind attention!