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Intermediate scales in the non-SUSY SO(10) grand unification - a reapprisal

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based on **arXiv:0903.4049[hep-ph], to appear soon in PRD**

Grand Unified Theories

- GUTs provide a very attractive framework for understanding some of the striking SM features

  - Weinberg angle (from gauge coupling unification)
  - hypercharge quantization and anomalies

- GUTs are physical - a lot of testable "smoking gun" signals

  - d>4 operators driven by intermediate scales (proton decay, neutrinos, n-nbar...)
  - monopoles

- Understanding of the flavour structure (Yukawas) accented

  i.e. correlations between Yukawas to see deeper into :

  - proton decay (depends on the position of the GUT scale and the shape of Yukawas)
  - neutrino physics (the same, B-L scale instead)

Viability of the simplest GUTs

Inspecting the Yukawa sector in detail it was possible to draw conclusions about the viability of the simplest GUTs...

- Minimal SUSY SU(5):

  - d=5 proton decay issue, viable only with non-renormalizable operators invoked

  Bajc, Fileviez-Perez, Senjanovic, 2002

- Minimal SUSY SO(10) with 10+126:

  - proton decay OK, troublesome abs. neutrino mass scale, higher than desired by seesaw

  Aulakh, 2005, Bertolini, M.M., Schwetz 2006

How about non-supersymmetric ?

I won't be concerned about naturalness if the price to be paid was loss of predictivity.

- Minimal non-SUSY SU(5):

  - fails badly due to the multi-sigma defect in the gauge coupling convergence & scales

- Minimal non-SUSY SO(10):

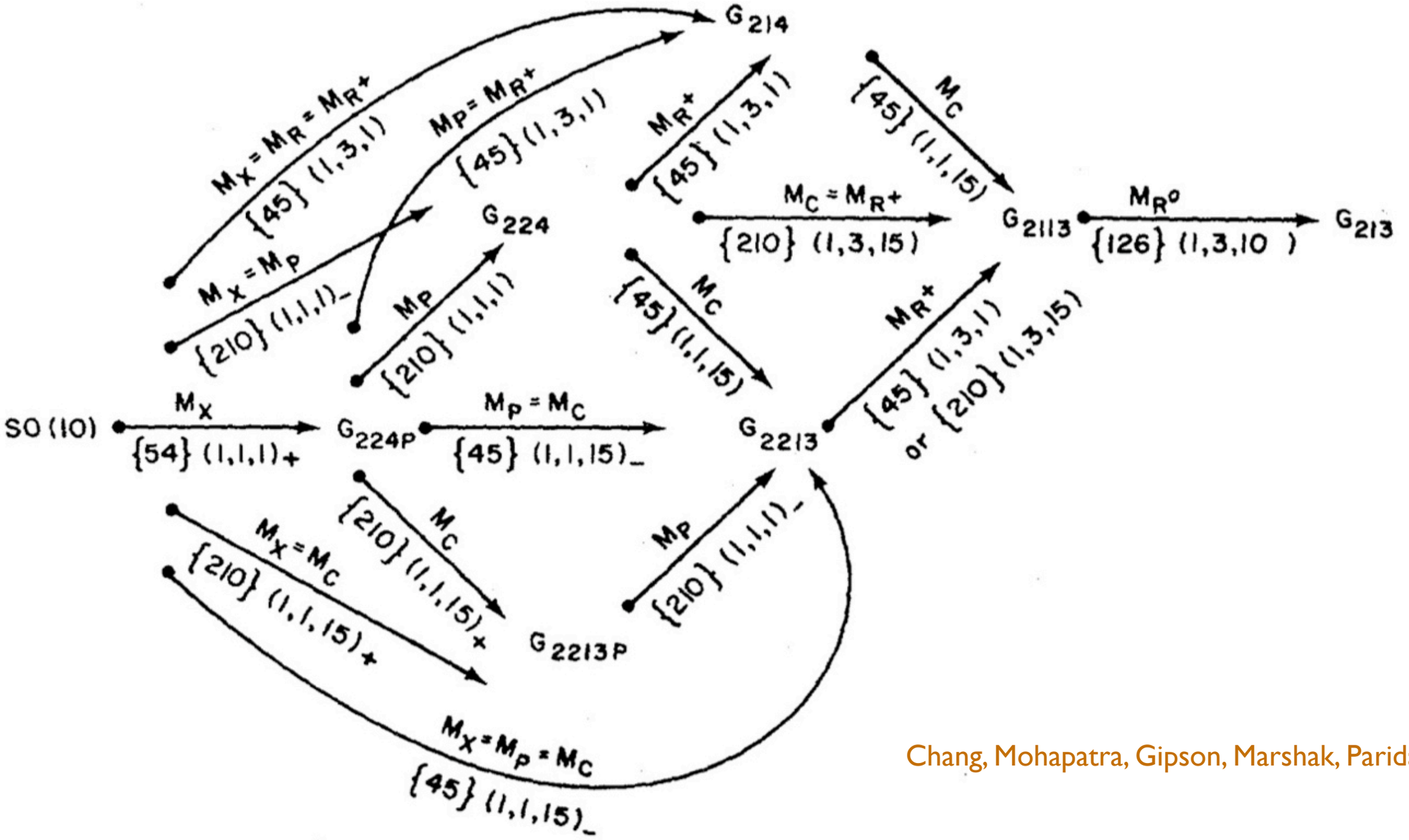
  - multiple intermediate scales, B-L typically lower than desired, need not be an issue though

  N.B. the intermediate as well as the GUT scale thresholds can change the game!

  - study in detail the intermediate scales (with some 'mild' thresholds assumption) and identify potentially viable (yet simple enough to be tractable) scenarios

Intermediate scales in non-SUSY SO(10)

In general, though simple to formulate, this is a rather complicated task...



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

Intermediate scales in non-SUSY SO(10)

Obviously, there has been a lot done in the past - some of the most recent works:

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

Two-loop analysis of all the breaking chains
with up to four intermediate scales,
minimal survival hypothesis (MSH)

N.B. MSH makes sense only at one loop; yet can be a convenient guide also at two loops, but must be relaxed in a full-fledged study

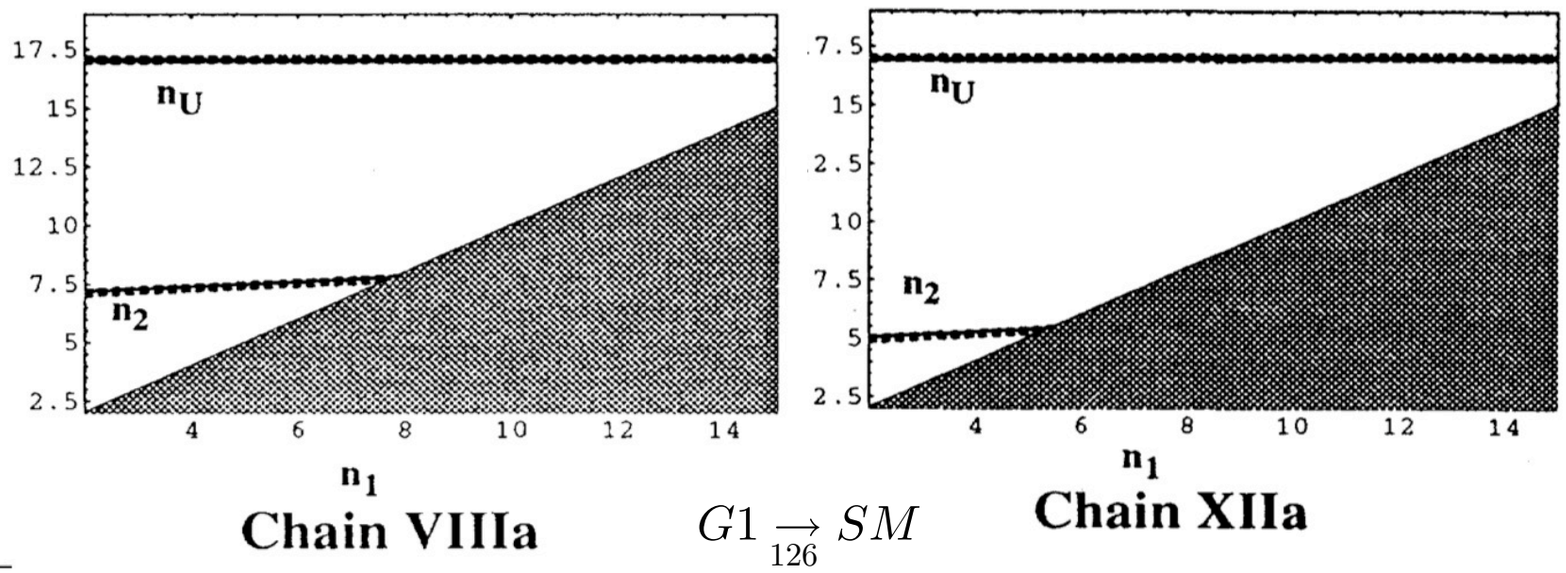
Deshpande, Keith, Pal (1993)

Chain	G2	G1
I:	$\xrightarrow[210]{} \{2_L 2_R 4_C\}$	$\xrightarrow[45]{} \{2_L 2_R 1_X 3_c\}$
II:	$\xrightarrow[54]{} \{2_L 2_R 4_C P\}$	$\xrightarrow[210]{} \{2_L 2_R 1_X 3_c P\}$
III:	$\xrightarrow[54]{} \{2_L 2_R 4_C P\}$	$\xrightarrow[45]{} \{2_L 2_R 1_X 3_c\}$
IV:	$\xrightarrow[210]{} \{2_L 2_R 1_X 3_c P\}$	$\xrightarrow[45]{} \{2_L 2_R 1_X 3_c\}$
V:	$\xrightarrow[210]{} \{2_L 2_R 4_C\}$	$\xrightarrow[45]{} \{2_L 1_R 4_C\}$
VI:	$\xrightarrow[54]{} \{2_L 2_R 4_C P\}$	$\xrightarrow[45]{} \{2_L 1_R 4_C\}$
VII:	$\xrightarrow[54]{} \{2_L 2_R 4_C P\}$	$\xrightarrow[210]{} \{2_L 2_R 4_C\}$
VIII:	$\xrightarrow[45]{} \{2_L 2_R 1_X 3_c\}$	$\xrightarrow[45]{} \{2_L 1_R 1_X 3_c\}$
IX:	$\xrightarrow[210]{} \{2_L 2_R 1_X 3_c P\}$	$\xrightarrow[45]{} \{2_L 1_R 1_X 3_c\}$
X:	$\xrightarrow[210]{} \{2_L 2_R 4_C\}$	$\xrightarrow[210]{} \{2_L 1_R 1_X 3_c\}$
XI:	$\xrightarrow[54]{} \{2_L 2_R 4_C P\}$	$\xrightarrow[210]{} \{2_L 1_R 1_X 3_c\}$
XII:	$\xrightarrow[45]{} \{2_L 1_R 4_C\}$	$\xrightarrow[45]{} \{2_L 1_R 1_X 3_c\}$

$$SO(10) \overset{M_U}{\to} G_2 \overset{M_2}{\to} G_1 \overset{M_1}{\to} SM$$

Update of the study above with the LEP data at hand,
two intermediate scales, mostly one-loop, MSH

Sample results: $M_i \equiv 10^{n_i}\,\mathrm{GeV}$

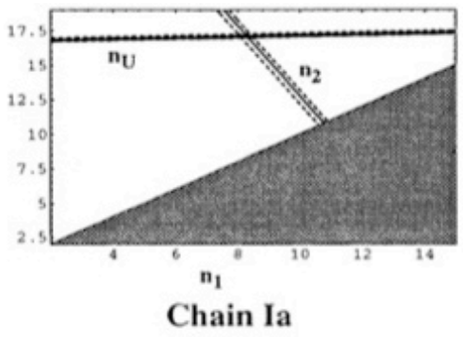


$G1 \underset{126}{\to} SM$

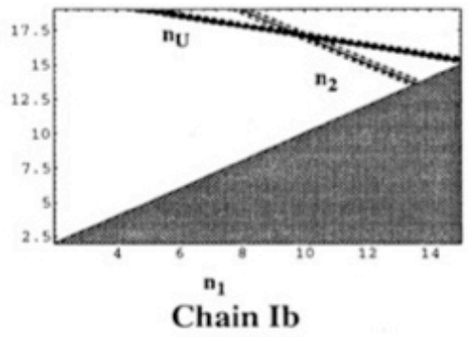
Intermediate scales in non-SUSY SO(10)

a-chains: $G1 \underset{126}{\rightarrow} SM$ b-chains: $G1 \underset{16}{\rightarrow} SM$

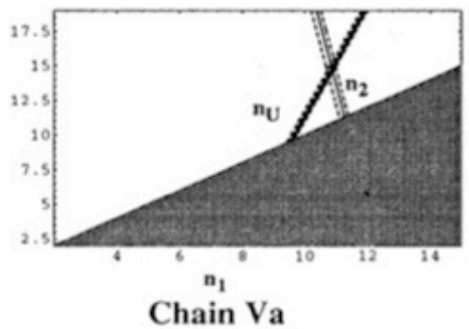
and 8 more...



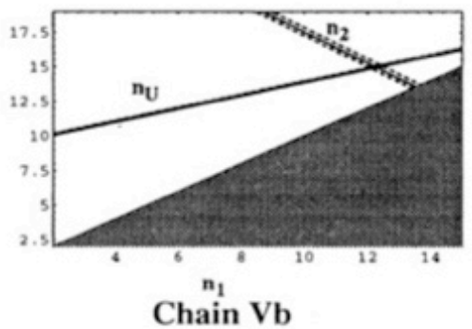
Chain Ia



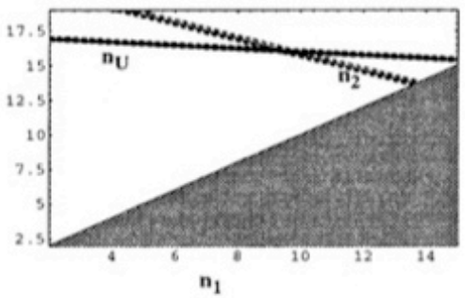
Chain Ib



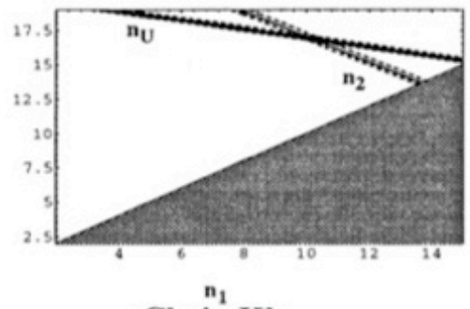
Chain Va



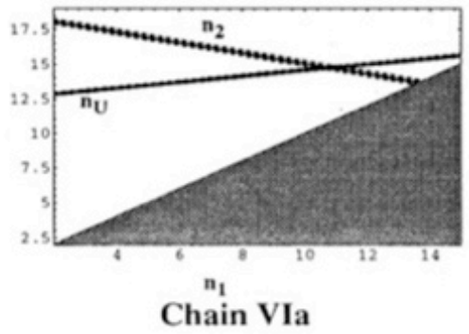
Chain Vb



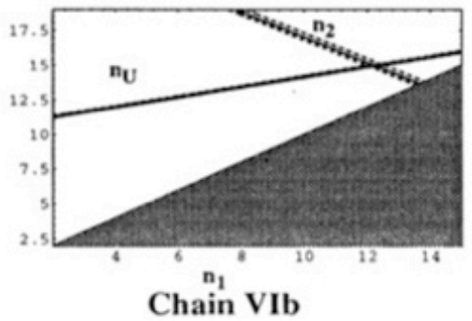
Chain IIa



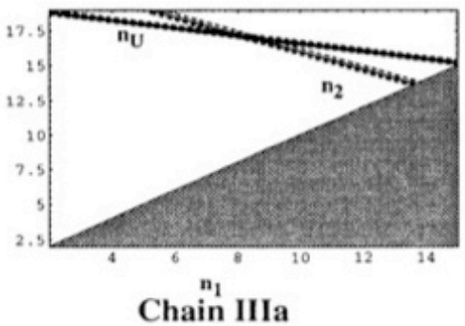
Chain IIb



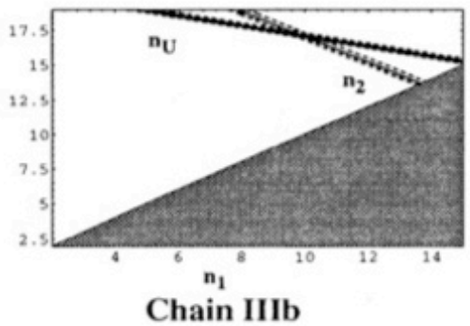
Chain VIa



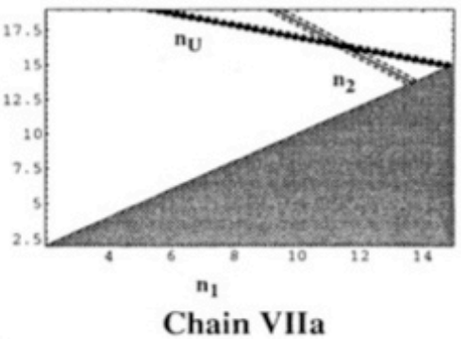
Chain VIb



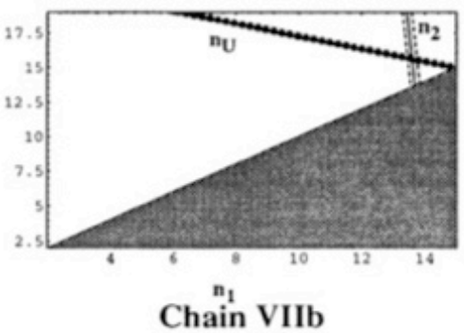
Chain IIIa



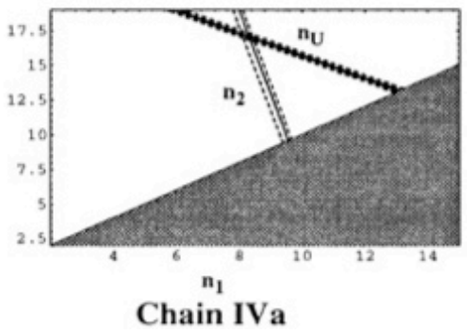
Chain IIIb



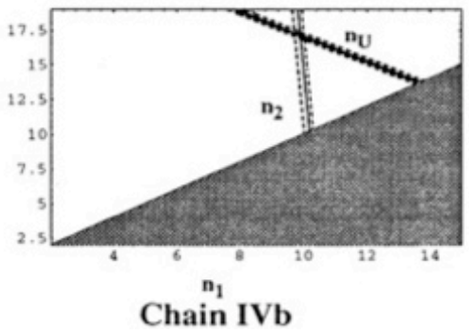
Chain VIIa



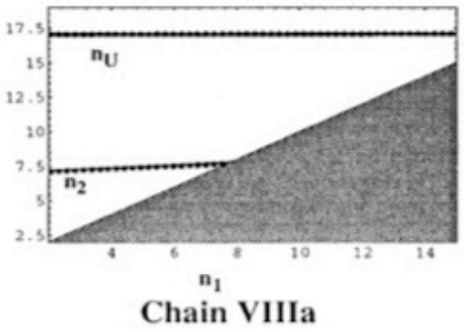
Chain VIIb



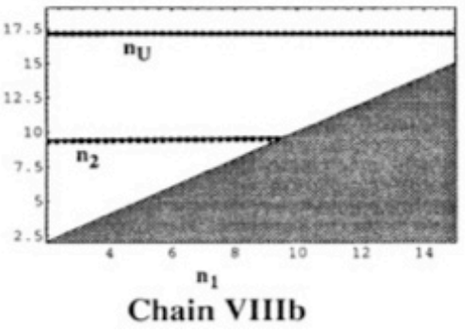
Chain IVa



Chain IVb



Chain VIIIa



Chain VIIIb

Deshpande, Keith, Pal (1993)

Intermediate scales in non-SUSY SO(10) - a reapprisal

- Reapprisal motivated namely by:

S. Bertolini, L. Di Luzio, M. Malinsky, to appear soon in PRD

- some obvious defects of the existing analyses, even at one loop (!)

  - mixing of multiple U(1) factors has never been taken into account

  - need to bring down further multiplets for a potentially realistic flavour structure (namely a-chains with 126 in the Higgs sector)

  - numerical mistakes within a 'training' sample of beta-functions

- need to update the charts with the latest values of the gauge couplings at M_Z

- we have added an extended discussion of the role of Yukawa's (at two loop)

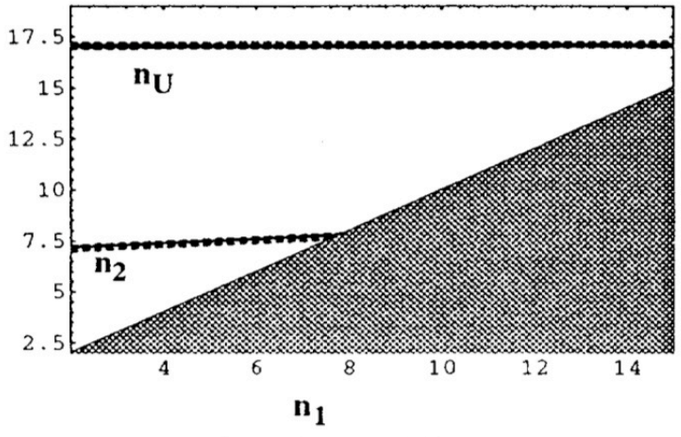
- need to master the machinery before approaching a specific model in detail

As we shall see, the reassessment reveals discrepancies just in the most interesting chains with the adjoint 45 responsible for both SO(10) as well as the G2 breaking !

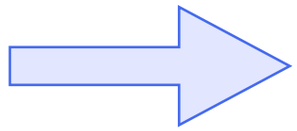
Intermediate scales in non-SUSY SO(10) - a reapprisal

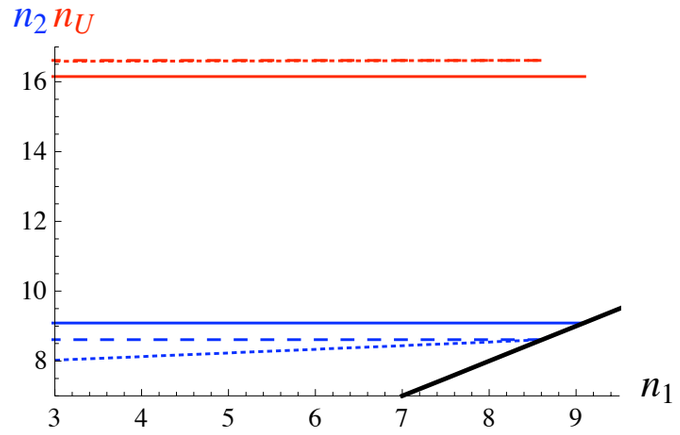
- The U(1) mixing effects in chains VIII-XII make the M_1 scale essentially free

  - this was to be anticipated because of the minimal survival hypothesis



Chain VIIIa

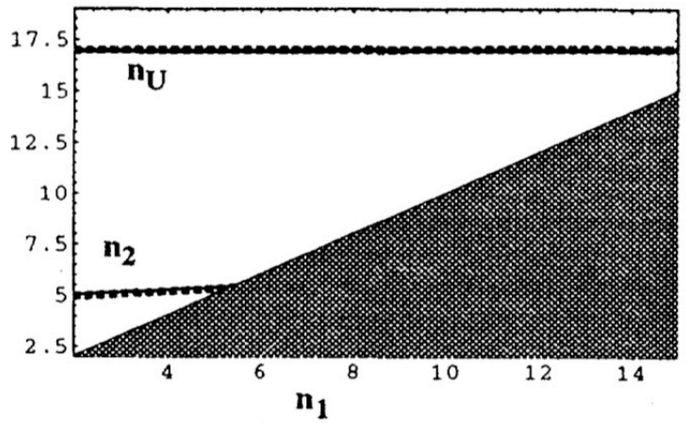




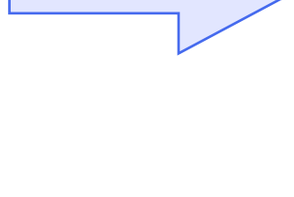
- The two-loop effects tend to rise the B-L scale and lower the GUT scale

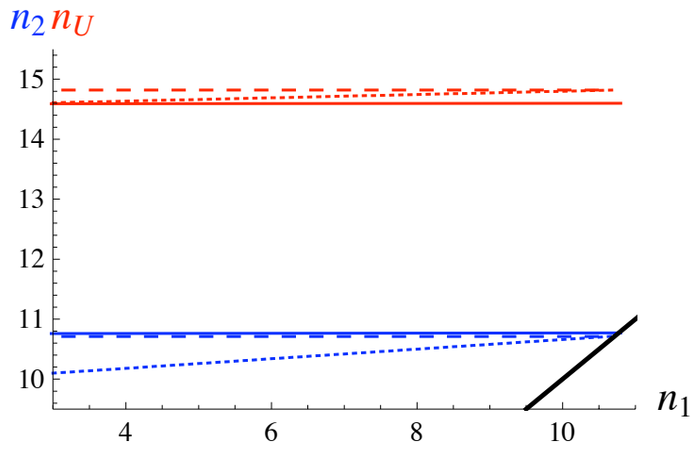
  - better for the seesaw, worse for the proton, but often still OK

- In chain XIIa we found six orders of magnitude discrepancy in the B-L scale!



Chain XIIa





Status of the minimal potentially realistic scenario

It is very interesting that it is namely the simplest scenario with 45 that gets most improved...

VIIIa,b: $SO(10) \overset{45}{\rightarrow} SU(3)_c \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \overset{45}{\rightarrow} SU(3)_c \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L} \overset{126,\,16}{\rightarrow} SM$

126: n_U around 16.2, $n_I < 9.5$

16: n_U around 16.2, $n_I < 10.8$

- the scenario with 16 in the Higgs sector looks particularly promising

XIIa,b: $SO(10) \overset{45}{\rightarrow} SU(4)_C \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L} \overset{45}{\rightarrow} SU(3)_c \otimes SU(2)_L \otimes U(1)_R \otimes U(1)_{B-L} \overset{126,\,16}{\rightarrow} SM$

126: n_U around 14.6, $n_I < 11$

16: n_U around 14.8, $n_I < 12.5$

- both these scenarios look promising
- chain XIIa brought back from oblivion by lifting the B-L scale by a factor of 10^6

So far we have entirely ignored the details of the Higgs sector though!
work in progress...

Conclusions

- flavour considerations provide strong constraints on simplest GUTs
  - minimal SUSY SU(5) & minimal SUSY SO(10) very sick

- non-SUSY GUTs are still viable & potentially predictive, i.e. interesting
  - in particular, it is far from obvious whether minimal non-SUSY SO(10) is OK or not
  - to get a consistent picture one has to master the running to a high degree

- the new RGE analysis brings back some of the previously disfavoured chains!
  - the first full-fledged two-loop assessment, passing various consistency checks
  - differs substantially from the existing results, sometimes by a factor of a million

- in particular, the simplest chains are in a much better shape than before!
  - one has to dive into a detailed & often tedious study of the vacuum & thresholds

Thank you for your kind attention!