Yukawa sector in SO(10)

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Outline

- GUTs and neutrino mass
- Intermediate scales
- The see-saw and the Yukawa sector
- Non supersymmetric models
- The minimal SUSY model
- Departing from the minimal

GUTs and neutrino mass

SO(10): all fermions in 16 representation

SU(5) fermions: in 5 and 10 representations

$\Rightarrow \nu_R$ is a singlet

- adding a singlet to the theory gives a lot of new parameters
- SU(5) breaks directly to SU(3)xSU(2)xU(1)

  - no intermediate scales

... and m_ν calls for intermediate scales

The (B-L) breaking scale

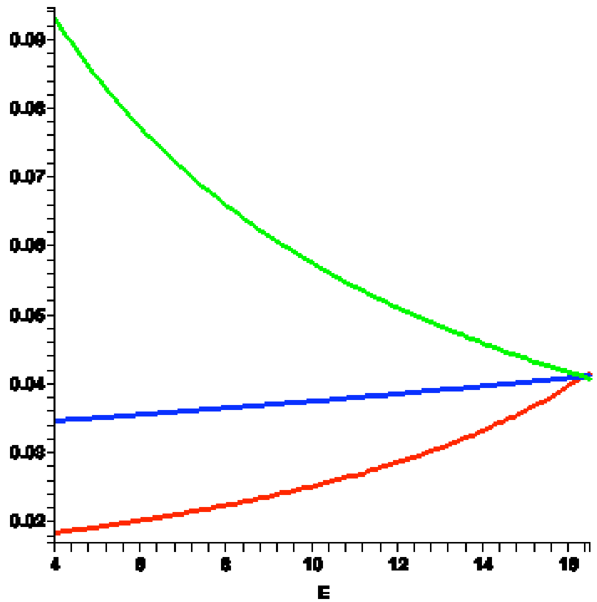
Best idea for small m_ν: the see-saw mechanism

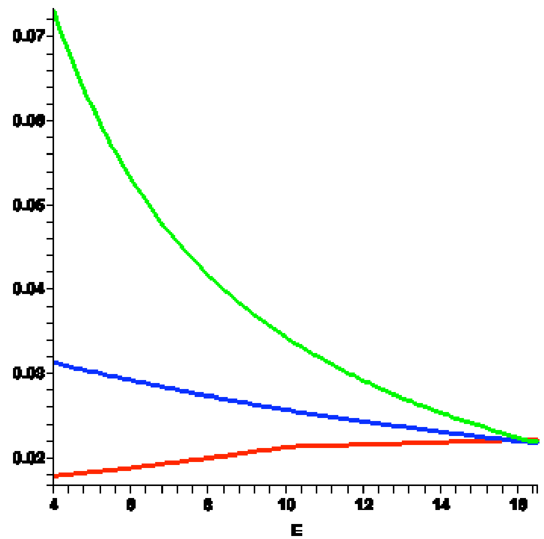
give ν_R a mass by breaking B-L
at a large scale M_R

$$\langle\Delta\rangle \nu_R^T i\sigma_2 \nu_R \qquad \langle\Delta\rangle = M_R$$

$$m_\nu = \frac{M_W^2}{M_R} \qquad \begin{aligned} m_\nu &\sim 0.01 eV \\ M_R &\sim 10^{13} GeV \end{aligned}$$

An intermediate scale would be convenient
(not indispensable)





SUSY: ONE-STEP UNIFICATION

$$\frac{1}{\alpha_i(M_W)} = \frac{1}{\alpha_U} - \frac{b_i}{2\pi}\ln(M_G/M_W)$$

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

NON-SUSY: INTERMEDIATE SCALE

$$\frac{1}{\alpha_i(M_W)} = \frac{1}{\alpha_U} - \frac{b_i}{2\pi}\ln(M_R/M_W) - \frac{b'_i}{2\pi}\ln(M_G/M_R)$$

M_R determined by the particle content

SO(10) symmetry

Many possible intermediate scales

$$SO(10)$$

$$M_X \Downarrow \langle p \rangle$$

GUT scale

$$SU(4)_C \times SU(2)_L \times SU(2)_R$$

$$M_{PS} \Downarrow \langle a \rangle$$

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$M_R \Downarrow \langle \sigma \rangle$$

see-saw scale

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

three types of see-saw

TYPE I (renormalizable version)

- An $SU(2)_R$ triplet with $(B-L)=2$ gets a vev at a large scale M_R

$$\langle\Delta^c\rangle \Rightarrow \nu^c \text{ mass} \sim M_R$$

gives a mass to the right-handed neutrino

- At EW scale, neutrino gets a Dirac mass

$$m_D$$

$$\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \quad \rightsquigarrow \quad m_\nu \sim \frac{m_D^2}{M_R} \sim \frac{M_W^2}{M_R}$$

Type II

Senjanovic, Mohapatra 1980

In Left-Right theories, terms like:

$$\Delta\, H^2 \Delta^c \;+\; m_\Delta \Delta^2$$

H : bidoublet

Δ : Left-handed triplet

Δ^c : Right-handed triplet

Provide a small vev for the Left-handed triplet after EW breaking

$$\langle \Delta \rangle \sim \frac{\langle H \rangle^2 \langle \Delta^c \rangle}{m_\Delta^2} \sim \frac{M_W^2}{M_R}$$

Mass for ν from $L^T \tau_2 \langle \Delta \rangle L$

vev of Δ^c induces a small vev for Δ after EW breaking

In SUSY SO(10) , triplets are in 126:
mixing with 54 or 210 can give such terms in the potential.

TWO TYPES OF SEE-SAW ARE OF SAME MAGNITUDE:
BUT VERY DIFFERENT PARAMETERS INVOLVED

Yukawa sector

Pati-Salam fourth color:

$$U = \begin{pmatrix} u \\ u \\ u \\ \nu \end{pmatrix} \quad D = \begin{pmatrix} d \\ d \\ d \\ e \end{pmatrix} \dots$$

SO(10):

$$\Psi_{16} = \begin{pmatrix} U \\ D \\ D^c \\ U^c \end{pmatrix}$$

- All fermions in one (spinorial) representation
- Couple to:

$$\Psi\, C\, \Gamma^a \Psi\, H_a \qquad \underline{10}$$

$$\Psi\, C\, \Gamma^a \Gamma^b \Gamma^c \Psi\, D_{abc} \qquad \underline{120} \text{ (antisym.)}$$

$$\Psi\, C\, \Gamma^a \Gamma^b \Gamma^c \Gamma^d \Gamma^e \Psi\, \Sigma_{abcde} \qquad \underline{126}$$

SU(4)C x SU(2)L x SU(2)R Decomposition

$$H_{10} = (6,1,1) + (1,2,2)$$

$$D_{120} = (\overline{10},1,1) + (10,1,1) + (6,3,1) + (6,1,3) + (1,2,2) + (15,2,2)$$

$$\overline{\Sigma}_{\overline{126}} = \underset{\Delta_R}{(10,1,3)} + \underset{\Delta_L}{(\overline{10},3,1)} + (6,1,1) + (15,2,2)$$

- 126 can give type I and type II see-saw
- (15,2,2) in 126 can contain the SM Higgs
- is 126 enough for all fermion masses ? no..

One doublet is not enough:

Lazarides, Shafi Wetterich 1981

Clark, Kuo Nakagawa 1982

$$M_U = y_{10} \langle 1,2,2 \rangle^u_{10} \quad + y_{126} \langle 15,2,2 \rangle^u_{126}$$

$$M_D = y_{10} \langle 1,2,2 \rangle^d_{10} \quad + y_{126} \langle 15,2,2 \rangle^d_{126}$$

$$M_E = y_{10} \langle 1,2,2 \rangle^d_{10} \quad -3\, y_{126} \langle 15,2,2 \rangle^d_{126}$$

- only 10 : $m_d = m_l$
- only 126: $3\, m_d = m_l$

} at the GUT scale, for all generations

- 126 required for neutrino mass - but what else?
  - is there a difference between choosing 10 or 120 ?

Notice: same question for SUSY or non-SUSY models

non-susy: 126 + 10

Bajc, A.M, Vissani, Senjanovic 2005

(2nd and 3rd generations only)

$$M_U = y_{10} \langle 1, 2, 2 \rangle_{10}^{u} \; + y_{126} \langle 15, 2, 2 \rangle_{126}^{u}$$
$$M_D = y_{10} \langle 1, 2, 2 \rangle_{10}^{d} \; + y_{126} \langle 15, 2, 2 \rangle_{126}^{d}$$
$$M_E = y_{10} \langle 1, 2, 2 \rangle_{10}^{d} \; - 3\, y_{126} \langle 15, 2, 2 \rangle_{126}^{d}$$
$$M_{\nu_D} = y_{10} \langle 1, 2, 2 \rangle_{10}^{u} \; - 3\, y_{126} \langle 15, 2, 2 \rangle_{126}^{u}$$

$$M_{\nu_L} = y_{126} \langle \overline{10}, 3, 1 \rangle_{126}^{d}$$
$$M_{\nu_R} = y_{126} \langle 10, 1, 3 \rangle_{126}^{d}$$

see-saw, type I and II:

$$M_N = -M_{\nu_D} M_{\nu_R}^{-1} M_{\nu_D} + M_{\nu_L}$$

approx.

$$\theta_q = V_{cb} = 0$$

$$\frac{\langle 2,2,1\rangle^u_{10}}{\langle 2,2,1\rangle^d_{10}} = \frac{m_c(m_\tau - m_b) - m_t(m_\mu - m_s)}{m_s m_\tau - m_\mu m_b} \approx \frac{m_t}{m_b}$$

- real 10: $m_t = m_b$
- need a complex 10 - PQ symmetry → axion as Dark Matter

$$10^{10}\mathrm{GeV} \leq M_{PQ} \leq 10^{13}\mathrm{GeV}$$

$$\mathbf{16} \to e^{i\alpha}\mathbf{16}$$

$$\mathbf{10} \to e^{-2i\alpha}\mathbf{10}$$

$$\overline{\mathbf{126}} \to e^{-2i\alpha}\overline{\mathbf{126}}$$

Breaks PQ at the right-handed neutrino mass scale...

But cannot break completely: combination $U(1)_{PQ},\, U(1)_{B-L},\, T_{3R}$ remains

SUSY or not: 126 + 10

Bajc, Vissani, Senjanovic 2002

$$M_D = y_{10}\,\langle 1,2,2\rangle^d_{10} + y_{126}\,\langle 15,2,2\rangle^d_{126}$$
$$M_E = y_{10}\langle 1,2,2\rangle^d_{10} - 3\,y_{126}\,\langle 15,2,2\rangle^d_{126}$$

Type II see-saw: $M_N = M_{\nu_L} = y_{126}\,\langle 10,1,3\rangle^d_{126}$

$\theta_D = 0$ (small mixing in M_D)

$m_s = m_\mu = 0$

$$M_N \propto \begin{pmatrix} 0 & 0 \\ 0 & m_b - m_\tau \end{pmatrix}$$

unless $m_b = m_\tau$, neutrino mixing vanishes

large $\theta_{atm} \leftrightarrow b - \tau$ unification

Full 3-gen. analysis:
- connection still true

θ_{13} close to exp. limit

Matsuda, Koide, Fukuyama, Nishiura 2002

Goh, Mohapatra, Ng, 2003

non-susy: 126 + 120

(2nd and 3rd generations only)

$$M_U = y_{120}(\langle 1,2,2\rangle^u_{120} + \langle 15,2,2\rangle^u_{120}) \quad + y_{126}\,\langle 15,2,2\rangle^u_{126}$$

$$M_D = y_{120}(\langle 1,2,2\rangle^d_{120} + \langle 15,2,2\rangle^d_{120}) \quad + y_{126}\,\langle 15,2,2\rangle^d_{126}$$

$$M_E = y_{120}(\langle 1,2,2\rangle^d_{120} - 3\langle 15,2,2\rangle^d_{120}) \; - 3\,y_{126}\,\langle 15,2,2\rangle^d_{126}$$

$$M_{\nu_D} = y_{120}(\langle 1,2,2\rangle^u_{120} - 3\langle 15,2,2\rangle^u_{120}) \;\; - 3\,y_{126}\,\langle 15,2,2\rangle^u_{126}$$

y_{120} antisymmetric

$$\frac{\langle 1,2,2\rangle^u_{120} + \langle 15,2,2\rangle^u_{120}}{\langle 1,2,2\rangle^d_{120} + \langle 15,2,2\rangle^d_{120}} \sim \frac{m_t}{m_b}$$

- real 120: $m_t = m_b$
- complex 120: interesting connections with neutrino masses and mixings

SUSY or not: 126 + 120

Bajc, A.M, Vissani, Senjanovic 2005

(2nd and 3rd generations only)

Most general charged fermion matrix:

$$M_f = \mu_f \begin{pmatrix} \sin^2\theta & i\sin\theta\cos\theta + i\epsilon_f \\ -i\sin\theta\cos\theta - i\epsilon_f & \cos^2\theta \end{pmatrix}$$

$$|\epsilon_f| \propto m_2^f/m_3^f \ll 1$$

to leading order in $|\epsilon_f|$

$$|\mu_f| = m_3^f$$
$$\sin 2\theta |\epsilon_f| = m_2^f/m_3^f$$

- •neutrino masses
- •relation m_b, m_τ
- •quark mixing V_{cb}

•neutrino masses

$$M_N^{II} \propto Y_{126} \propto \begin{pmatrix} \sin^2\theta & \\ & \cos^2\theta \end{pmatrix}$$

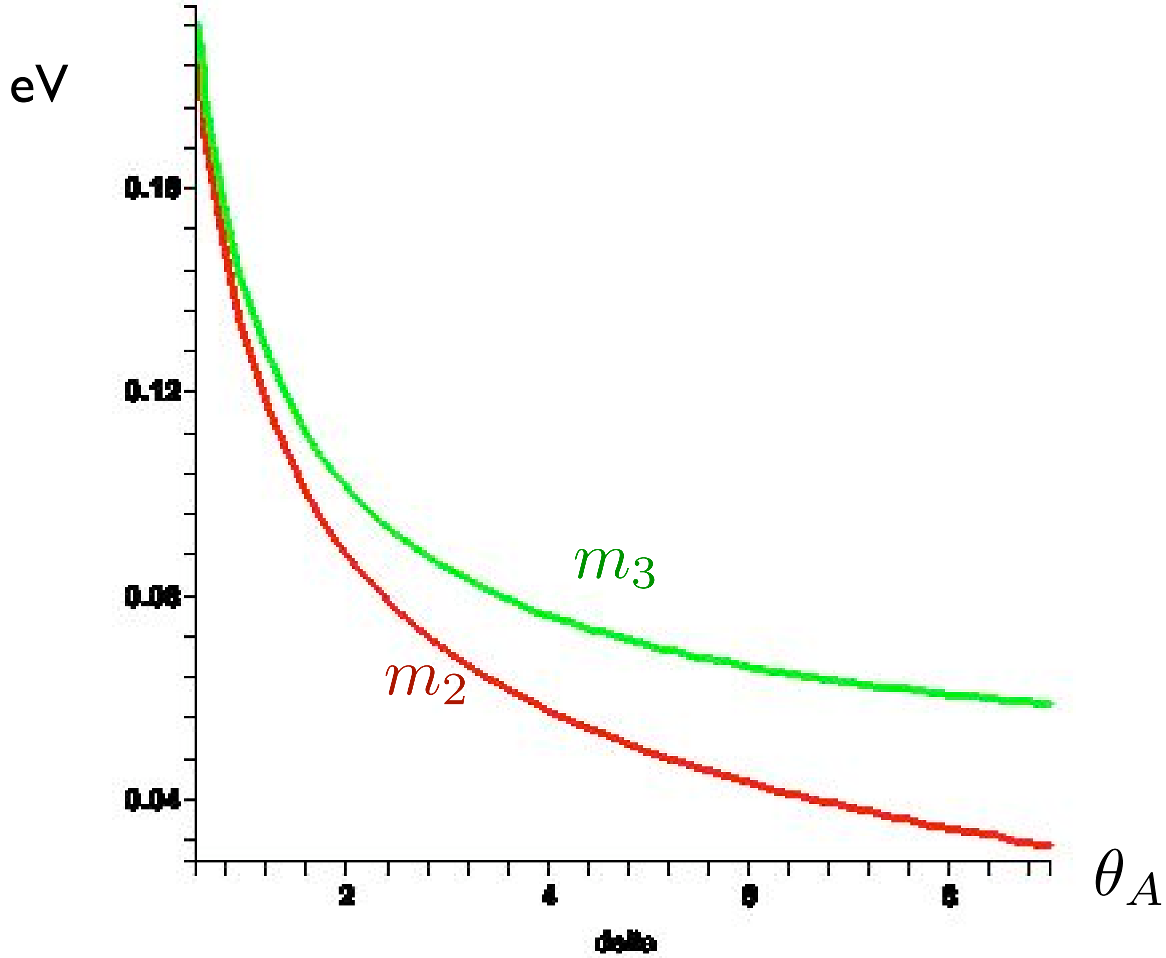
$$M_N^{I} \propto (Y_{126} + cY_{120})^T Y_{126}^{-1} (Y_{126} + cY_{120}) \;\propto \begin{pmatrix} \sin^2\theta & \\ & \cos^2\theta \end{pmatrix}$$

So $\theta \sim \theta_A$ to leading order in $|\epsilon_E|$

and for neutrino masses:

$$\frac{m_3^2 - m_2^2}{m_3^2 + m_2^2} = \frac{\cos 2\theta_A}{1 - \sin^2 2\theta_A/2} + \mathcal{O}(|\epsilon|)$$

- large θ_A gives degenerate neutrinos



99% CL

$36^\circ < \theta_{23} < 54^\circ$

central value

$$|\Delta m^2_{23}| \ = \ (2.5 \pm 0.2)\, 10^{-3}\, \mathrm{eV}^2$$

- relation m_b, m_τ *at the GUT scale*

$$\frac{m_\tau}{m_b} = 3 + 3\sin 2\theta_A \ \mathrm{Re}[\epsilon_E - \epsilon_D] + \mathcal{O}(|\epsilon^2|)$$

- but $m_\tau \sim 2m_b$ .... include

-running (large Yukawa coupling)
-correction of higher order in ϵ
-3 generations

•quark mixing

$$|V_{cb}| = |\Re(\xi) - i\cos 2\theta_A\, \Im(\xi)| + \mathcal{O}(|\epsilon^2|)$$

$$\xi = \cos 2\theta_A(\epsilon_D - \epsilon_U)$$

since: $\sin 2\theta|\epsilon_f| = m_2^f/m_3^f$

$$\sin 2\theta_A \simeq 1 \qquad \cos 2\theta_A \simeq 0$$

then: $\epsilon_D \simeq \frac{m_s}{m_b} \gg \frac{m_c}{m_t} \simeq \epsilon_U \quad \Rightarrow \quad |V_{cb}| \simeq \cos 2\theta_A \frac{m_s}{m_b}$

- large neutrino mixing implies small quark mixing
- even too small...

$$|V_{cb}| \sim 1/25$$

$$m_s/m_b < 1/20$$

$$\cos 2\theta_A < 1/3$$

126 + 10 or 126 + 120 ?

- In non-supersymmetric models, both posible in principle
  - 10 and 120 need to be complex
  - can have a PQ symmetry - axion as DM
- SUSY requires 126 + 10 for $m_b = m_\tau$
- Type II (even Type I) see-saw can give relations between neutrino and charged fermions masses and mixings
- Detailed models can be even more predictive: symmetry breaking and unification constraints
- 10 + 120 ? radiative see-saw - works for split-SUSY

Bajc, Senjanovic 2005

Unification: non-SUSY

Deshpande, Keith, Pal 1993

$m_\nu \geq m_t^2/M_R$ ➡ $M_R \geq 10^{13}$ GeV

		$\log(M_R/GeV)$
I :	$SO(10) \xrightarrow[210]{} \{2_L 2_R 4_C\} \xrightarrow[45]{} \{2_L 2_R 1_X 3_c\} \xrightarrow[h]{} \{2_L 1_Y 3_c\}$	8.2-10.6
II :	$SO(10) \xrightarrow[54]{} \{2_L 2_R 4_C P\} \xrightarrow[210]{} \{2_L 2_R 1_X 3_c P\} \xrightarrow[h]{} \{2_L 1_Y 3_c\}$	8.6 - 13.6
III :	$SO(10) \xrightarrow[54]{} \{2_L 2_R 4_C P\} \xrightarrow[45]{} \{2_L 2_R 1_X 3_c\} \xrightarrow[h]{} \{2_L 1_Y 3_c\}$	8.0 - 13.6
IV :	$SO(10) \xrightarrow[54]{} \{2_L 2_R 1_X 3_c P\} \xrightarrow[210]{} \{2_L 2_R 1_X 3_c\} \xrightarrow[h]{} \{2_L 1_Y 3_c\}$	8.2-10.8
V :	$SO(10) \xrightarrow[210]{} \{2_L 2_R 4_C\} \xrightarrow[45]{} \{2_L 1_R 4_C\} \xrightarrow[h]{} \{2_L 1_Y 3_c\}$	11.0-11.2
VI :	$SO(10) \xrightarrow[54]{} \{2_L 2_R 4_C P\} \xrightarrow[45]{} \{2_L 1_R 4_C\} \xrightarrow[h]{} \{2_L 1_Y 3_c\}$	12.2 - 13.6
VII :	$SO(10) \xrightarrow[54]{} \{2_L 2_R 4_C P\} \xrightarrow[210]{} \{2_L 2_R 4_C\} \xrightarrow[h]{} \{2_L 1_Y 3_c\}$	11.3 - 13.6
VIII :	$SO(10) \xrightarrow[45]{} \{2_L 2_R 1_X 3_c\} \xrightarrow[45]{} \{2_L 1_R 1_X 3_c\} \xrightarrow[h]{} \{2_L 1_Y 3_c\}$	2.0-7.7
IX :	$SO(10) \xrightarrow[54]{} \{2_L 2_R 1_X 3_c P\} \xrightarrow[45]{} \{2_L 1_R 1_X 3_c\} \xrightarrow[h]{} \{2_L 1_Y 3_c\}$	2.0-10.0
X :	$SO(10) \xrightarrow[210]{} \{2_L 2_R 4_C\} \xrightarrow[210]{} \{2_L 1_R 1_X 3_c\} \xrightarrow[h]{} \{2_L 1_Y 3_c\}$	-
XI :	$SO(10) \xrightarrow[54]{} \{2_L 2_R 4_C P\} \xrightarrow[210]{} \{2_L 1_R 1_X 3_c\} \xrightarrow[h]{} \{2_L 1_Y 3_c\}$	2.0-13.5
XII :	$SO(10) \xrightarrow[45]{} \{2_L 1_R 4_C\} \xrightarrow[45]{} \{2_L 1_R 1_X 3_c\} \xrightarrow[h]{} \{2_L 1_Y 3_c\}$	2.0-5.3

Unification: non-SUSY

Deshpande, Keith, Pal 1993

$m_\nu \geq m_t^2/M_R$ ➡ $M_R \geq 10^{13}$ GeV

		$\log(M_R/GeV)$
[redacted]		
II :	$SO(10) \xrightarrow[54]{} \{2_L 2_R 4_C P\} \xrightarrow[210]{} \{2_L 2_R 1_X 3_c P\} \xrightarrow[h]{} \{2_L 1_Y 3_c\}$	8.6 - 13.6
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[redacted]		

Unification: SUSY

- One-step: no intermediate scales
  - $m_\nu \propto M_W^2 / M_{GUT}$ can be too small

- Potentials very constrained: no survival principle
  - calculate all the masses

- See-saw + SUSY = MSSM with R-parity
  - R-parity is in the center of SO(10)
  - R-parity $\equiv$ Matter parity = $(-1)^{3(B-L)}$
  - See-saw: break (B-L) with a (B-L)-even field in order to give ν_R a mass

Aulakh, A.M, Rasin, Senjanovic 1998

...get R-parity preserved
and the stable LSP is a DM candidate

What is the minimal renormalizable SUSY- GUT ?

- Based on SO(10)

- With a see-saw for neutrino mass: $\overline{126}$ (+ 126)

- Yukawa sector: 10 + $\overline{126}$ needed: the <u>light</u> Higgs must be a combination of doublets in 10 and 126

  - need a mixing $\langle\Phi\rangle\, H_{10}\, \overline{\Sigma}_{\overline{126}}$ can use 210

- Symmetry breaking down to LR
  (126, $\overline{126}$ break down to MSSM)

  - 210 can do that too

Babu, Mohapatra, 1993

$$\Phi_{210}\,,\ H_{10}\,,\ \overline{\Sigma}_{\overline{126}}\,,\ \Sigma_{126}$$

minimal SO(10)

Clark, Kuo, Nakagawa,1982

Aulakh, Bajc, A.M, Vissani, Senjanovic,2003

$$\Psi_{16}, H_{10}, \Sigma_{126}, \overline{\Sigma}_{\overline{126}}, \Phi_{210}$$

$$\begin{aligned} W_H &= m_\Phi \Phi^2 + m_\Sigma \Sigma\overline{\Sigma} + \lambda \Phi^3 + \eta \Phi \Sigma \overline{\Sigma} + m_H H^2 + \Phi H (\alpha \Sigma + \bar{\alpha} \overline{\Sigma}) \\ &+ y_{10} \Psi C \Gamma \Psi H + y_{126} \Psi C \Gamma^5 \Psi \overline{\Sigma} \end{aligned}$$

- 26 real parameters: same as MSSM
- light Higgs made up of 126, 10 and 210 doublets
  - rich enough Yukawa structure
- Type I and II see-saw
  - possibility of connecting large θ_A with $b-\tau$ unification
- symmetry can be broken down to MSSM (+R-parity)
  - stable LSP

symmetry breaking

$$SO(10)$$

$$M_X \Downarrow \langle p \rangle$$ in 210

$$SU(4)_C \times SU(2)_L \times SU(2)_R$$

$$M_{PS} \Downarrow \langle a \rangle$$ in 210

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$M_R \Downarrow \langle \sigma \rangle$$ in 126

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

symmetry breaking

$$H \equiv \mathbf{10} = (6,1,1) + (1,2,2)$$

$$\begin{aligned}\Phi \equiv \mathbf{210} &= (15,1,1) + (1,1,1) + (15,1,3) \\ &+ (15,3,1) + (6,2,2) + (10,2,2) + (\overline{10},2,2) \\ \Sigma \equiv \mathbf{126} &= (\overline{10},1,3) + (10,3,1) + (6,1,1) + (15,2,2) \\ \overline{\Sigma} \equiv \overline{\mathbf{126}} &= (10,1,3) + (\overline{10},3,1) + (6,1,1) + (15,2,2)\end{aligned}$$

doublets: vev $\sim M_W$

SM singlets: vev $\sim M_{GUT}$

type II see-saw: vev $\sim M_W^2/M_{GUT}$

- Find the symmetry breaking conditions
- Calculate masses for all states
- Find the composition of the light Higgs doublets

Bajc, A.M, Vissani, Senjanovic 2004

Aulakh, Girdaar, 2004

Fukuyama, et. al. 2004

An overconstrained model

After fine-tune of the SM Higgs mass:
8 parameters left in the heavy Higgs sector

$$m, \alpha, \overline{\alpha}, |\lambda|, |\eta|, \phi = \arg\lambda = -\arg\eta$$

$$x = \Re(x) + i\Im(x)$$

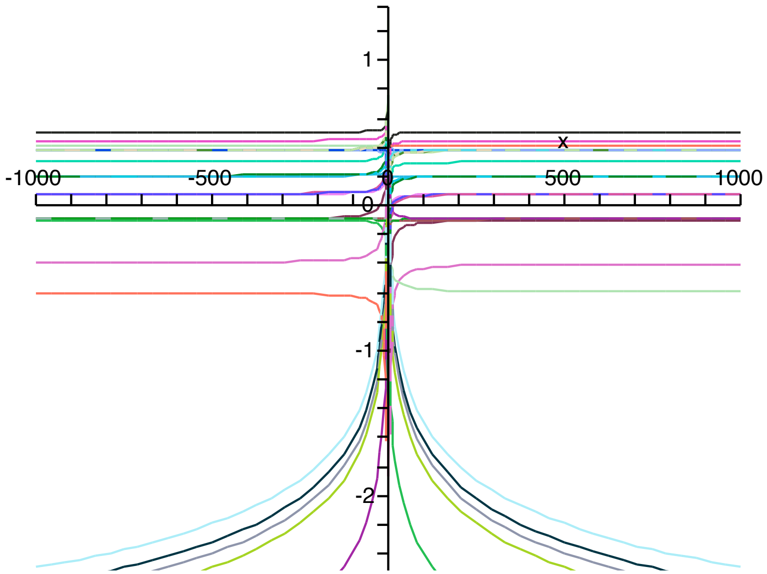
ratio of masses

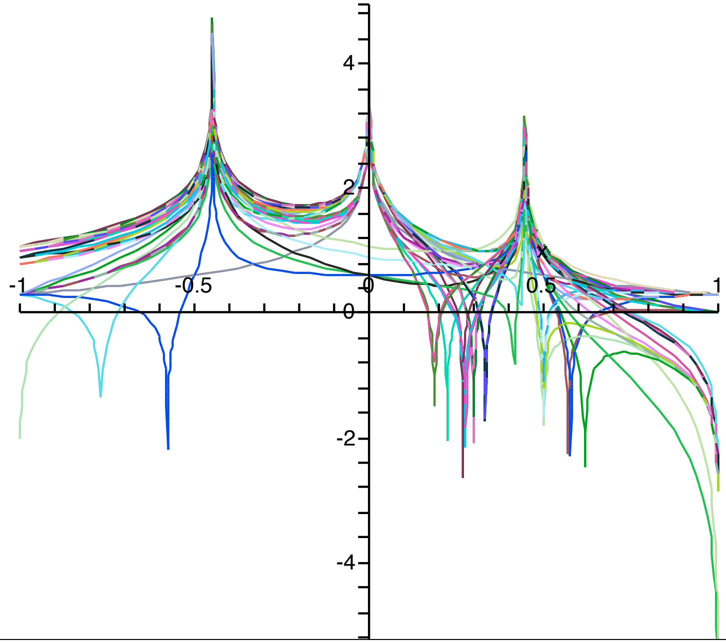
Vevs and masses of all states have form:

$$\sim \frac{m}{\lambda} f(x)$$

$$\frac{m}{\sqrt{\lambda\eta}} f(x)$$

- variation with parameters quite smooth, with x non -trivial





$$Log[M_i/10^{16}]$$

$x \rightarrow \infty$

x real < 1

- Light states spoil unification: keep x < 1

Fermion mass fitting

- The light Higgs is a combination no longer arbitrary

$$H_{u,d} = r^{\mathbf{10}}_{u,d} H^{\mathbf{10}}_{u,d} + r^{\overline{\mathbf{126}}}_{u,d} H^{\overline{\mathbf{126}}}_{u,d} + r^{\mathbf{126}}_{u,d} H^{\mathbf{126}}_{u,d} + r^{\mathbf{210}}_{u,d} H^{\mathbf{210}}_{u,d}$$

  - $r^{\mathbf{I}}_{u,d}$ known functions of the parameters

- Assume type II see-saw

$$m_\nu = y_{126}\, v_\Delta \qquad v_\Delta = \frac{(\alpha r^{\mathbf{10}}_u + \sqrt{6}\eta r^{\overline{\mathbf{126}}}_u) r^{\mathbf{210}}_u}{m_\Delta}$$

  - neutrino mass depends on the same parameters

General analysis (type I and II)

Bertolini, Frigerio, Malinsky, 2005-2006

Aulakh,Garg, Girdaar, 2005-2006

Mohapatra, Goh, Ng, Dutta, Mimura...

Babu, Macesanu

Wang, Yang

- Do the complete fit with all fermion masses and all parameters
- Parameter space for type I and type II getting smaller
- Include unification constrains, threshold effects - even worse

too small neutrino mass: model seems to be ruled out !

Summary

- SO(10): ideal framework for small neutrino mass
- Models can provide connections between fermion masses and mixings, for example
  - $b - \tau$ unification $\Longleftrightarrow$ large θ_{atm} (10+126)
  - large neutrino $\Longleftrightarrow$ small quark mixings (120+126)
  - large θ_{atm} $\Longleftrightarrow$ degenerate neutrinos (120+126)
- Non supersymmetric models are alive and well
- Minimal SUSY GUT is in trouble
  - ✶ lack of intermediate scales
- Next-to-minimal SUSY GUT may not be predictive ...
  - ✶ but work is in progress