Proton Decay in $SO(10)$ with Stabilized Doublet–Triplet Splitting

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Outline

- **Motivation/“Evidence” favoring SO(10) GUT**
- **Doublet-Triplet Splitting Issues:**
  - **Dimopoulos-Wilczek Mechanism**
  - **Stability of VEV structure**
  - **Absence of pseudo-Goldsone bosons**
  - **GUT threshold corrections and unification**
- **Proton decay**
  - **d=5 and d=6 proton decay rates**
  - **Correlation between the two**
- **Conclusions**

Motivations/Evidence favoring SO(10)

- Electric charge quantization
  - $Q_p = -Q_e$ to better than 1 part in 10^{21}
- Miraculous cancellation of anomalies
- Quantum numbers of quarks and leptons
- Existence of ν_R and thus neutrino mass via seesaw
- Unification of gauge couplings with low energy SUSY
- $b-\tau$ unification
- Baryon asymmetry of the universe via leptogenesis

Miraculous cancellation of anomalies

- $SU(3)_C^2 \times U(1)_Y$: $\frac{1}{2}\left[2 \times (\frac{1}{6}) + 1 \times (\frac{-2}{3}) + 1 \times (\frac{1}{3})\right] = 0$

- $SU(2)_L^2 \times U(1)_Y$: $\frac{1}{2}\left[3 \times (\frac{1}{6}) + 1 \times (\frac{-1}{2})\right] = 0$

- $(\text{gravity})^2 \times U(1)_Y$:
$$\left[3 \times 2 \times (\tfrac{1}{6}) + 3 \times (\tfrac{-2}{3}) + 3 \times (\tfrac{1}{3}) + 2 \times (\tfrac{-1}{2}) + 1 \times 1\right] = 0$$

- $U(1)_Y^3$:

$$\left[3 \times 2 \times (\tfrac{1}{6})^3 + 3 \times (\tfrac{-2}{3})^3 + 3 \times (\tfrac{1}{3})^3 + 2 \times (\tfrac{-1}{2})^3 + 1 \times (1)^3\right] = 0$$

Suggests $SO(10)$ embedding

$SO(10)$ is automatically anomaly free

Structure of matter multiplets

$$Q = \begin{pmatrix} u_1 & u_2 & u_3 \\ d_1 & d_2 & d_3 \end{pmatrix} \sim (3, 2, \frac{1}{6})$$

$$u^c = \begin{pmatrix} u_1^c & u_2^c & u_3^c \end{pmatrix} \sim (\overline{3}, 1, \frac{-2}{3})$$

$$d^c = \begin{pmatrix} d_1^c & d_2^c & d_3^c \end{pmatrix} \sim (\overline{3}, 1, \frac{1}{3})$$

$$L = \begin{pmatrix} \nu \\ e^- \end{pmatrix} \sim (1, 2, \frac{-1}{2})$$

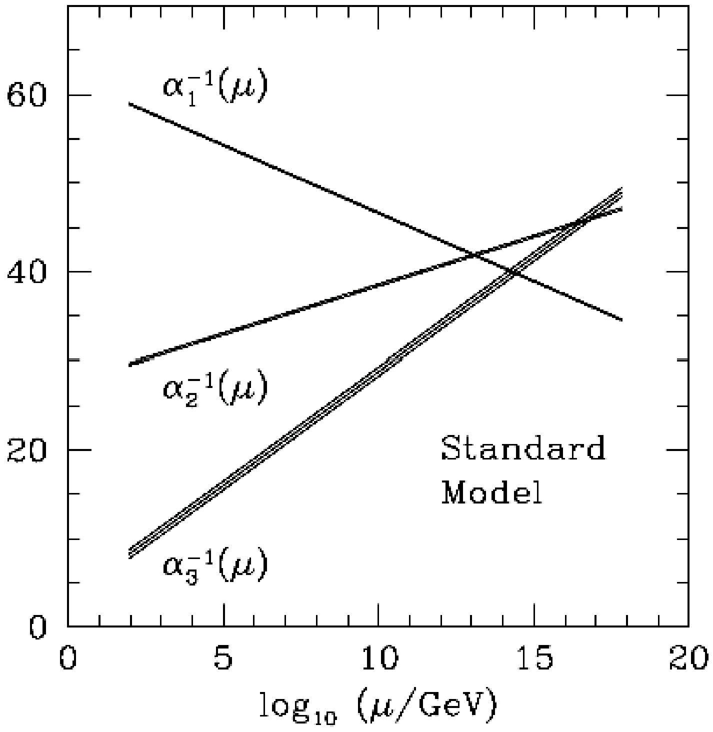
$$e^c \sim (1, 1, +1)$$

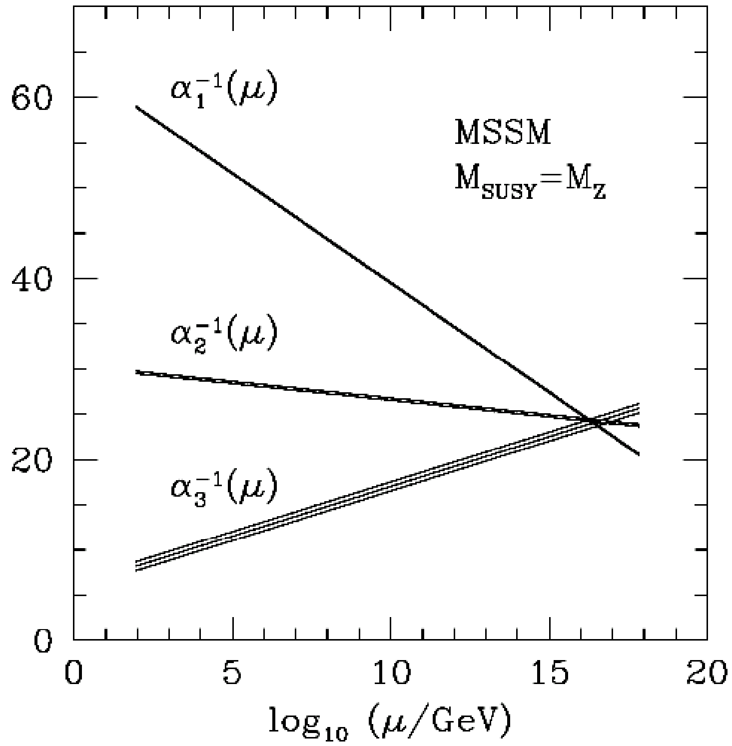
$$\nu^c \sim (1, 1, 0)$$

Matter Unification in 16 of SO(10)

u_1	:	$\vert\uparrow\downarrow\uparrow\uparrow\downarrow>$
u_2	:	$\vert\uparrow\downarrow\uparrow\downarrow\uparrow>$
u_3	:	$\vert\uparrow\downarrow\downarrow\uparrow\uparrow>$
d_1	:	$\vert\downarrow\uparrow\uparrow\uparrow\downarrow>$
d_2	:	$\vert\downarrow\uparrow\uparrow\downarrow\uparrow>$
d_3	:	$\vert\downarrow\uparrow\downarrow\uparrow\uparrow>$
u_1^c	:	$\vert\downarrow\downarrow\uparrow\downarrow\downarrow>$
u_2^c	:	$\vert\downarrow\downarrow\downarrow\uparrow\downarrow>$
u_3^c	:	$\vert\downarrow\downarrow\downarrow\downarrow\uparrow>$
d_1^c	:	$\vert\uparrow\uparrow\uparrow\downarrow\downarrow>$
d_2^c	:	$\vert\uparrow\uparrow\downarrow\uparrow\downarrow>$
d_3^c	:	$\vert\uparrow\uparrow\downarrow\downarrow\uparrow>$
ν	:	$\vert\uparrow\downarrow\downarrow\downarrow\downarrow>$
e	:	$\vert\downarrow\uparrow\downarrow\downarrow\downarrow>$
e^c	:	$\vert\downarrow\downarrow\uparrow\uparrow\uparrow>$
ν^c	:	$\vert\uparrow\uparrow\uparrow\uparrow\uparrow>$

Evolution of gauge couplings



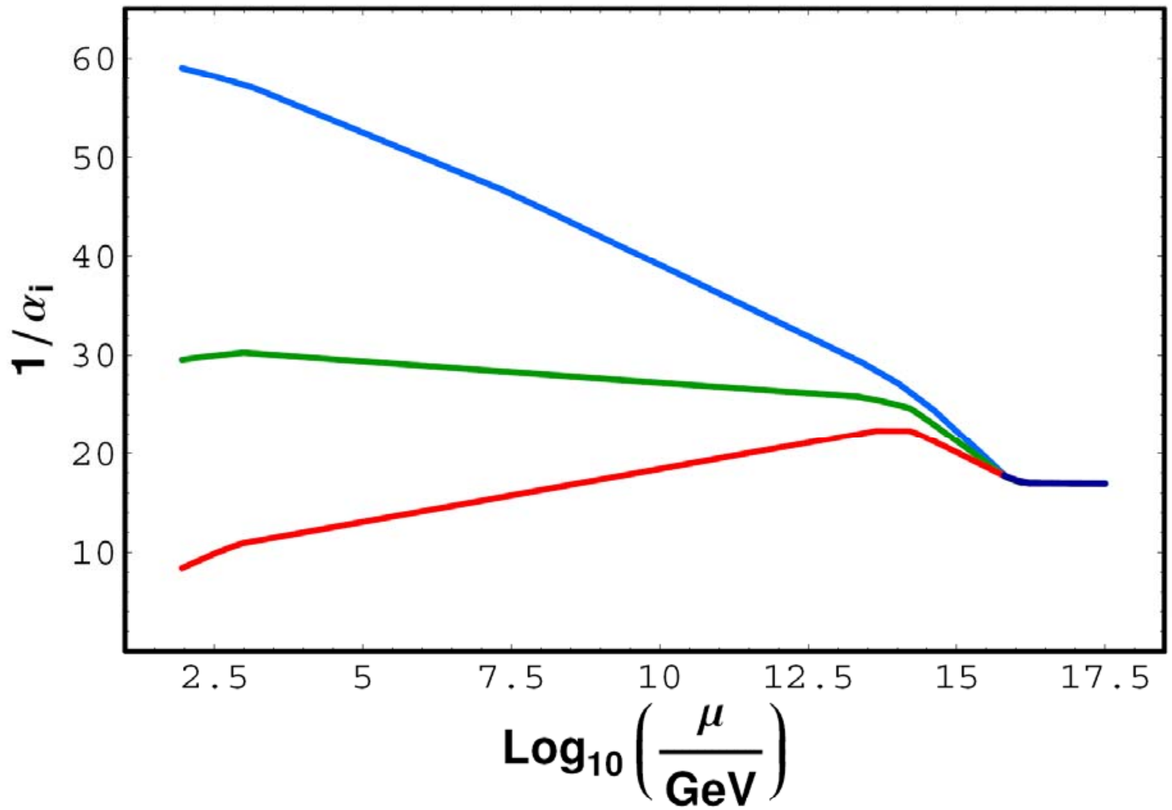


Standard Model

Supersymmetry

Unifcation far off

$\alpha_3(M_Z) \simeq 0.13$ predicted



Gauge coupling evolution in our SO(10) model

GUT gauge groups

- SU(5)
- SO(10)
- E_6
- E_8
- …

- $[SU(3)]^3$
- $[SU(5)]^2$
- $[SU(3)]^4$
- …

Minimal SUSY SU(5) GUT

Matter multiplets: $\{\mathbf{10}+\bar{\mathbf{5}}+\mathbf{1}\}$

$$\mathbf{10}:\begin{pmatrix} 0 & u_3^c & -u_2^c & u_1 & d_1 \\ -u_3^c & 0 & u_1^c & u_2 & d_2 \\ u_2^c & -u_1^c & 0 & u_3 & d_3 \\ -u_1 & -u_2 & -u_3 & 0 & e^c \\ -d_1 & -d_2 & -d_3 & -e^c & 0 \end{pmatrix}$$

$$\bar{\mathbf{5}}:(d_1^c, d_2^c, d_3^c, e, -\nu_e)$$

$$\mathbf{1}:\nu^c$$

Higgs: $\mathbf{24}_H, \quad \{\mathbf{5}_H, \quad \bar{\mathbf{5}}_H\}$ ⇨ Contain color triplets $\{H_C, \quad \bar{H}_C\}$

Yukawa Couplings $Y_u^{ij}\mathbf{10}_i\mathbf{10}_j\mathbf{5}_H + Y_d^{ij}\mathbf{10}_i\bar{\mathbf{5}}_j\bar{\mathbf{5}}_H$

$$M_\ell = M_d^T \Rightarrow m_b = m_\tau, m_s = m_\mu, m_d = m_e$$

MSSM Higgs doublets have color triplet partners in GUTs

$$H(1,2,1/2) \oplus H_c(3,1,-1/3) = \mathbf{5} \text{ of } SU(5)$$

$$\bar{H}(1,2,-1/2) \oplus \bar{H}_c(\bar{3},1,1/3) = \bar{\mathbf{5}}$$

$H, \ \bar{H}$ **must remain light**

$H_c, \bar{H}_c$ **must have GUT scale mass to prevent rapid proton decay**

Doublet-triplet splitting

Even if color triplets have GUT scale mass, d=5 proton decay is problematic

Doublet-triplet splitting in SU(5)

$$W_{D-T} = \bar{\mathbf{5}}_H(\lambda \mathbf{24}_H + M)\mathbf{5}_H$$

$$< 24_H >= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -3/2 & 0 \\ 0 & 0 & 0 & 0 & -3/2 \end{pmatrix} V$$

$$M_{H_c} = \lambda V + M \sim O(M_{GUT}); \; M_H = -\frac{3}{2}\lambda V + M$$

FINE-TUNED TO $O(M_W)$

The GOOD

(1) Predicts unification of couplings

(2) Uses economic Higgs sector

The BAD

(1) Unnatural fine tuning

(2) Large proton decay rate

Realistic SO(10) model without fine-tuning

Quarks and leptons: $\{16_i\}$

Babu, Pati, Wilczek (1998)
Barr, Raby (1997)
Babu, Pati, Tavartkiladze (2007)

Economic Higgs system

$\{45_H + 16_H + \overline{16}_H\} \Rightarrow$ breaks symmetry to SM

$\{10_H + 10'_H\} \Rightarrow$ EW symmetry breaking

$\{16'_H + \overline{16}'_H\} \Rightarrow$ avoids pseudoGoldstones

$\{2 \text{ singlets} : S, Z\} \Rightarrow$ Fixes VEVs

Small Higgs representation $\Rightarrow$ Small threshold effects for gauge couplings

A Z_2-assisted anomalous $\mathcal{U}(1)$ symmetry guarantees stability

Dimopoulos-Wilczek mechanism

$$W_{D-T} = \lambda(\mathbf{10}_H \mathbf{45}_H \mathbf{10}'_H) + \ldots$$

$$\langle 45_H \rangle = \begin{pmatrix} a & 0 & 0 & 0 & 0 \\ 0 & a & 0 & 0 & 0 \\ 0 & 0 & a & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix} \otimes i\tau_2 \quad \propto (B-L)$$

Dimopoulos, Wilczek (1981)
Babu, Barr (1993)

⇨ B-L VEV gives mass to triplets only

⇨ If 10_H only couples to fermions, no d=5 proton decay

⇨ Doublets from 10_H and $10'_H$ light

4 doublets, unification upset

⬇

Add mass term for *10'$_H$*

$$W_{D-T} = \lambda(\mathbf{10}_H \mathbf{45}_H \mathbf{10}'_H) + M \mathbf{10}'_H \mathbf{10}'_H$$

Issues to be addressed with DW mechanism

- Can the VEV pattern for 45_H be realized?
- Is the VEV structure stable?
- Are there flat directions?
- Are there pseudo-Goldstone bosons?
- Are threshold corrections small?
- Is $d = 5$ proton decay consistent with data?

We now have a complete model where all issues are successfully addressed

Complete SO(10) Model

Z_2-assisted anomalous $\mathcal{U}(1)$

	$A(45)$	$H(10)$	$H'(10)$	$C(16)$	$\bar{C}(\overline{16})$	Z	S	$C'(16)$	$\bar{C}'(\overline{16})$	16_i
$\mathcal{U}(1)$	0	1	-1	$\frac{k+4}{2k}$	$-\frac{1}{2}$	$\frac{2}{k}$	$\frac{2}{k}$	$\frac{k-4}{2k}$	$-\frac{k+8}{2k}$	$-\frac{1}{2}+a_i$
Z_2	$-$	$+$	$-$	$+$	$+$	$-$	$+$	$+$	$+$	P_i

Superpotential:

$$\begin{aligned} W(A) &= M_A \mathrm{tr} A^2 + \frac{\lambda_A}{M_*}\left(\mathrm{tr} A^2\right)^2 + \frac{\lambda'_A}{M_*}\mathrm{tr} A^4 \\ W(A,C,C') &= C\left(\frac{a_1}{M_*}ZA + \frac{b_1}{M_*}C\bar{C} + c_1 S\right)\bar{C}' + C'\left(\frac{a_2}{M_*}ZA + \frac{b_2}{M_*}C\bar{C} + c_2 S\right)\bar{C} \\ W(DT) &= \lambda_1 HAH' + \lambda_{H'}\frac{S^k}{M_*^{k-1}}(H')^2 + \lambda_2 H\bar{C}\bar{C} \end{aligned}$$

Fixing the VEVs

$$\begin{aligned} \langle A \rangle &= i\sigma_2 \otimes \text{Diag}\,(a,\ a,\ a,\ 0,\ 0) \\ \langle C \rangle &= \left\langle \overline{C} \right\rangle = c, \quad \left\langle C' \right\rangle = \left\langle \overline{C}' \right\rangle = 0 \\ \langle S \rangle &= s, \quad \langle Z \rangle = z \end{aligned}$$

$$F_A = 0 \Rightarrow a^2 = \frac{M_A M_*}{2(6\lambda_A + \lambda'_A)}$$

$$\mathcal{U}(1)\ \text{Dterm} \Rightarrow c^2 + z^2 + s^2 = \frac{k}{2}\xi \quad (\xi = \frac{g_A^2 M_P^2}{192\pi^2}\text{Tr}Q)$$

$$F_{C'} = 0 \Rightarrow -\frac{3a_1}{M_*} za + \frac{b_1}{M_*} c^2 + c_1 s = 0$$

$$F_{\overline{C'}} = 0 \Rightarrow \frac{3a_2}{M_*} za + \frac{b_2}{M_*} c^2 + c_2 s = 0\ .$$

$$F_S = 0 \Rightarrow \left\langle C' \right\rangle = 0$$

$$F_Z = 0 \Rightarrow \left\langle \overline{C'} \right\rangle = 0$$

$$\Rightarrow s = \frac{c^2}{M_*} \frac{b_1 a_2 - b_2 a_1}{a_1 c_2 - a_2 c_1}\ , \qquad z = \frac{c^2}{3a} \frac{b_1 c_2 - b_2 c_1}{a_1 c_2 - a_2 c_1}$$

All the VEVs are fixed, in desired directions

Doublet-Triplet Mass Matrix

$$M_{D,T} = \begin{array}{c} \\ \bar{5}_H \\ \bar{5}_{H'} \\ \bar{5}_C \\ \bar{5}_{C'} \end{array} \begin{array}{c} \begin{array}{cccc} 5_H & 5_{H'} & 5_{\bar{C}} & 5_{\bar{C}'} \end{array} \\ \begin{pmatrix} 0 & \eta_{D,T} a & \lambda_2 c & 0 \\ -\eta_{D,T} a & M_{H'} & 0 & 0 \\ 0 & 0 & 0 & \kappa_{D,T} Y_1 \\ 0 & 0 & \kappa_{D,T} Y_2 & M' \eta \end{pmatrix} \end{array}$$

with $\quad \eta_D = 0 \;, \quad \eta_T = \lambda_1 \;, \quad \kappa_D = 3 \;, \quad \kappa_T = 2$

$M_{H'} = \lambda_{H'} s^k / M_*^{k-1}$, $Y_{1,2} = 2 a_{1,2} z a / (M_*) \sim M_{\mathrm{GUT}}^2 / M_*$

$M' \subset Z^2 S C' \bar{C}' / M^2$, $\eta = 1$ or 0

All color triplets heavy, one pair of Higgs doublets light

H_u is in 5_H, H_d in $\bar{5}_H + 16'_H \Rightarrow \tan\beta \neq \frac{m_t}{m_b}$

Stability of doublet mass

$$M_{D,T} = \begin{array}{c} \\ \bar{5}_H \\ \bar{5}_{H'} \\ \bar{5}_C \\ \bar{5}_{C'} \end{array} \begin{array}{c} \begin{array}{cccc} 5_H & 5_{H'} & 5_{\bar{C}} & 5_{\bar{C}'} \end{array} \\ \begin{pmatrix} 0 & \eta_{D,T} a & \lambda_2 c & 0 \\ -\eta_{D,T} a & M_{H'} & 0 & 0 \\ 0 & 0 & 0 & \kappa_{D,T} Y_1 \\ 0 & 0 & \kappa_{D,T} Y_2 & M' \eta \end{pmatrix} \end{array}$$

Zeros in first column protected by $\mathcal{U}(1) \times Z_2$ symmetry

Mass for doublet needs negative charge VEV

All GUT scale VEVs have positive $\mathcal{U}(1)$ charge

Superpotential must be holomorphic

$A^n(C\overline{C})^m$ type terms would destabilize $(B-L)$ VEV

Such terms forbidden by $\mathcal{U}(1)$ symmetry

$$W_\mu = \frac{1}{\tilde{M}} H C' C' S \Rightarrow \mu \sim 10^2 \text{ GeV}$$

This shows all order stability of doublet mass

Spectrum of doublets and triplets

$$\frac{M_{D_1} M_{D_2} M_{D_3}}{M_{T_1} M_{T_2} M_{T_3} M_{T_4}} = \frac{9}{4 M_{\text{eff}} \cos\gamma}$$

with $\tan\gamma = \frac{\lambda_2 c}{3 Y_2}$, $\frac{1}{M_{\text{eff}}} = \left(M_T^{-1}\right)_{11} = \frac{M_{H'}}{\lambda_1^2 a^2}$

M_{eff} controls $d = 5$ proton decay: $\mathcal{A}(d = 5) \propto 1/M_{\text{eff}}$

$M_{\text{eff}} \sim 10^{19}$ realized naturally, as $M_{H'} \ll M_{\text{GUT}}$

Spectrum heavy states from 45

$M_{e^c_A} = M_3 = \frac{1}{2} M_8 \equiv \frac{1}{2} M_\Sigma$, with $M_\Sigma = \frac{2\lambda'_A}{6\lambda_A + \lambda'_A} M_A$.

$M_3 : M(1,3,0)$, $M_8 : M(8,1,0)$, $M_{e^c} : M(1,1,1)$

Remaining states are in $10 + \overline{10}$ of $SU(5)$

Spectrum from 10 + 10-bar

$$M(\Psi^{10}) = \begin{array}{c} \\ \Psi^{10}_A \\ \Psi^{10}_C \\ \Psi^{10}_{C'} \end{array} \begin{array}{c} \begin{array}{ccc} \overline{\Psi}^{\overline{10}}_A & \overline{\Psi}^{\overline{10}}_{\bar{C}} & \overline{\Psi}^{\overline{10}}_{\bar{C}'} \end{array} \\ \begin{pmatrix} M_\Psi & 0 & X_1 \\ 0 & 0 & \kappa_\Psi Y_1 \\ X_2 & \kappa_\Psi Y_2 & M'\eta \end{pmatrix} \end{array} ,$$

with $\Psi = (u^c, q, e^c)\ , \quad \kappa_\Psi = (2,1,0)\ , \quad M_\Psi = (0,0,M_\Sigma/2)$

$$X_{1,2} = 4a_{1,2}zc/M_*$$

$$\mathcal{U}^c_1\mathcal{U}^c_2 = Y_1Y_2(4+\tilde{p}^2)\ , \quad \mathcal{Q}_1\mathcal{Q}_2 = Y_1Y_2(1+\tilde{p}^2)\ , \quad \mathcal{E}^c_1\mathcal{E}^c_2 = Y_1Y_2\hat{p}^2$$

with $\tilde{p}^2 = \dfrac{|X_1|^2}{|Y_1|^2} = \dfrac{|X_2|^2}{|Y_2|^2}\ , \quad \hat{p}^2 = \tilde{p}^2 \left| 1 - \dfrac{M_\Sigma M'}{2X_1X_2}\eta \right|$

Gauge boson spectrum

$$M^2(X,Y) = g^2a^2 \equiv M_X^2 \ , \quad M^2(X',Y') = M_X^2(1+p^2)$$

$$M^2(V_{u^c,\bar{u}^c}) = M_X^2(4+p^2) \ , \quad M^2(V_{e^c,\bar{e}^c}) = M_X^2 p^2 \ , \quad \text{with} \quad p^2 = \frac{4c^2}{a^2}$$

Note: $p = \tilde{p}$ in the model

$\Rightarrow$ Apparent $N=4$ SUSY in $\{10+\overline{10}\}$ spectrum

$\Rightarrow$ Threshold corrections from $\{10+\overline{10}\}$ cancels

$\Rightarrow$ Model almost as predictive as minimal SUSY $SU(5)$

Threshold corrections

$$\alpha^{-1}(\Lambda) = \alpha_i^{-1}(M_Z) - \frac{b_i}{2\pi} \ln \frac{\Lambda}{M_Z} + \Delta_{i,w}^{(2)} + \Delta_i^{\mathrm{GUT}} ,$$

Weak scale threshold

Case 1 : $\tan\beta = 3$, $m_0 \simeq 300$ GeV, $m_{1/2} \simeq 352.4$ GeV

$\Rightarrow \Delta_{i,w}^{(2)} \simeq (0.2602,\ 0.349,\ 1.207)$

Case 2 : $\tan\beta = 3$, $m_0 \simeq 930$ GeV, $m_{1/2} \simeq 146.8$ GeV

$\Rightarrow \Delta_{i,w}^{(2)} \simeq (0.4021,\ 0.2264,\ 0.9483)$;

Case 3 : $\tan\beta = 3$, $m_0 \simeq 1.97$ TeV, $m_{1/2} \simeq 146.8$ GeV ,

$\Rightarrow \Delta_{i,w}^{(2)} \simeq (0.6431,\ 0.4739,\ 1.209)$.

GUT scale threshold

Hisano, Murayama, Yanagida (1993)
Hisano, Moroi, Tobe, Yanagida (1995)

$$\ln \frac{M_{\text{eff}} \cos\gamma}{M_Z} = \frac{5\pi}{6} \Big(3(\alpha_2^{-1} + \Delta_{2,w}^{(2)} - \frac{1}{6\pi}) - 2(\alpha_3^{-1} + \Delta_{3,w}^{(2)} - \frac{1}{4\pi}) - (\alpha_1^{-1} + \Delta_{1,w}^{(2)}) \Big)$$

$$- \ln \frac{4\kappa^{5/2}}{9} + \ln \frac{(4+p^2)^{3/2}(1+\tilde{p}^2)^2}{(4+\tilde{p}^2)^{3/2}(1+p^2)^2} + \ln \frac{p}{\hat{p}}$$

$$\ln \frac{\left(M_X^2 M_\Sigma\right)^{1/3}}{M_Z} = \frac{\pi}{18} \Big(5(\alpha_1^{-1} + \Delta_{1,w}^{(2)}) - 3(\alpha_2^{-1} + \Delta_{2,w}^{(2)} - \frac{1}{6\pi}) - 2(\alpha_3^{-1} + \Delta_{3,w}^{(2)} - \frac{1}{4\pi}) \Big)$$

$$+ \frac{1}{6} \ln \kappa - \frac{1}{6} \ln \frac{(4+p^2)(1+\tilde{p}^2)^2}{(4+\tilde{p}^2)(1+p^2)^2} - \frac{1}{3} \ln \frac{p}{\hat{p}} ,$$

Very similar to minimal SUSY $SU(5)$ threshold

A single new parameter beyond $SU(5)$

$\Rightarrow$ better $\alpha_3(M_Z)$

M_{H_C} of $SU(5)$ replaced by $M_{\text{eff}} \cos\gamma$

$\Rightarrow d = 5$ proton decay under control

Correlation between d=5 and d=6 proton decay

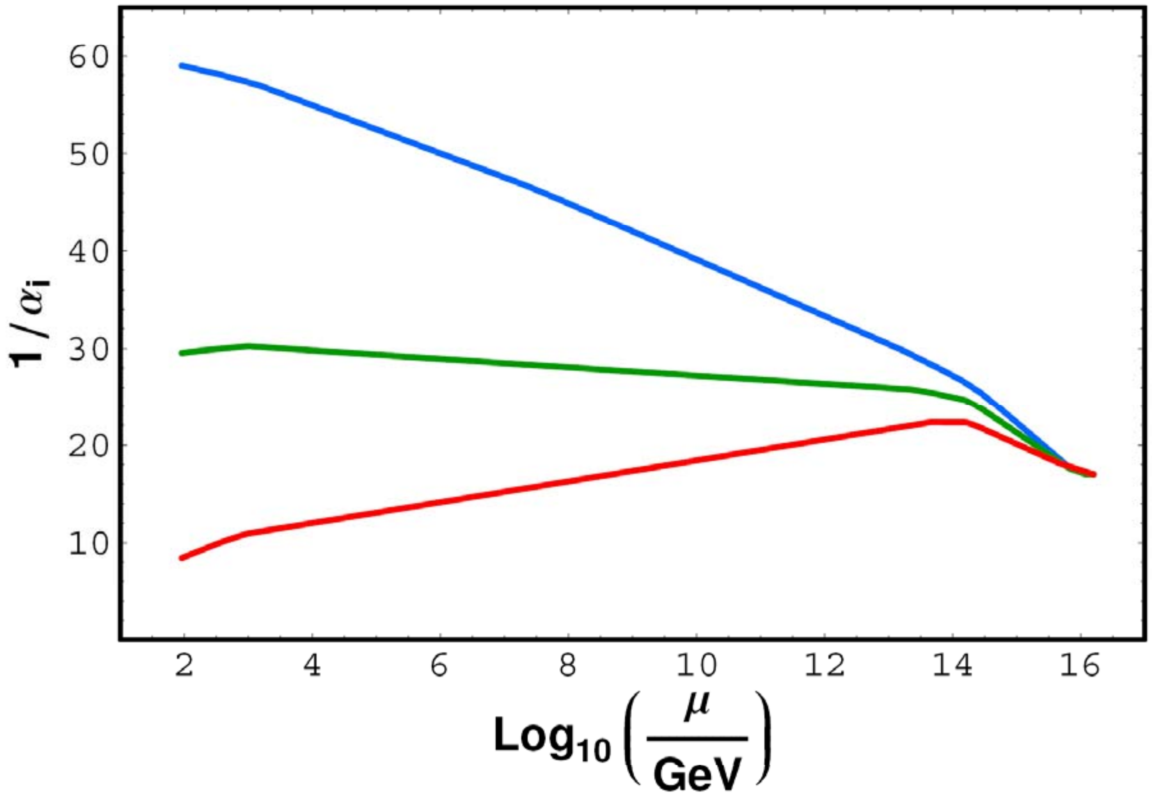
$$M_{\text{eff}} \simeq 10^{18}\text{GeV} \cdot \left(\frac{10^{16}\text{GeV}}{M_X}\right)^3 \left(\frac{3}{\tan\beta}\right) \left(\frac{1/25}{r}\right) \frac{\exp[2\pi(\Delta^{(2)}_{2,w} - \Delta^{(2)}_{3,w} - \delta\alpha_3^{-1})]}{1.42 \cdot 10^{-2}} .$$

$$r \equiv M_\Sigma / M_X \ll 1, \quad r = (1/25 - 1/200)$$

$$\alpha_3^{-1}(M_X) = \alpha_3^{-1}(M_Z) + \Delta^{(2)}_{3,w} - \frac{1}{4\pi} + \frac{3}{2\pi} \ln \frac{M_X}{M_Z}$$

$$- \frac{1}{2\pi} \ln \frac{M_X^4}{M_{T_1} M_{T_2} M_{T_3} M_{T_4}} + \frac{3}{2\pi} \ln r - \frac{1}{2\pi} \ln \frac{M_X^2}{\mathcal{U}_1^c \mathcal{U}_2^c} - \frac{1}{\pi} \ln \frac{M_X^2}{\mathcal{Q}_1 \mathcal{Q}_2} .$$

$$\alpha_G = (1/19 - 1/22)$$



60
50
40
30
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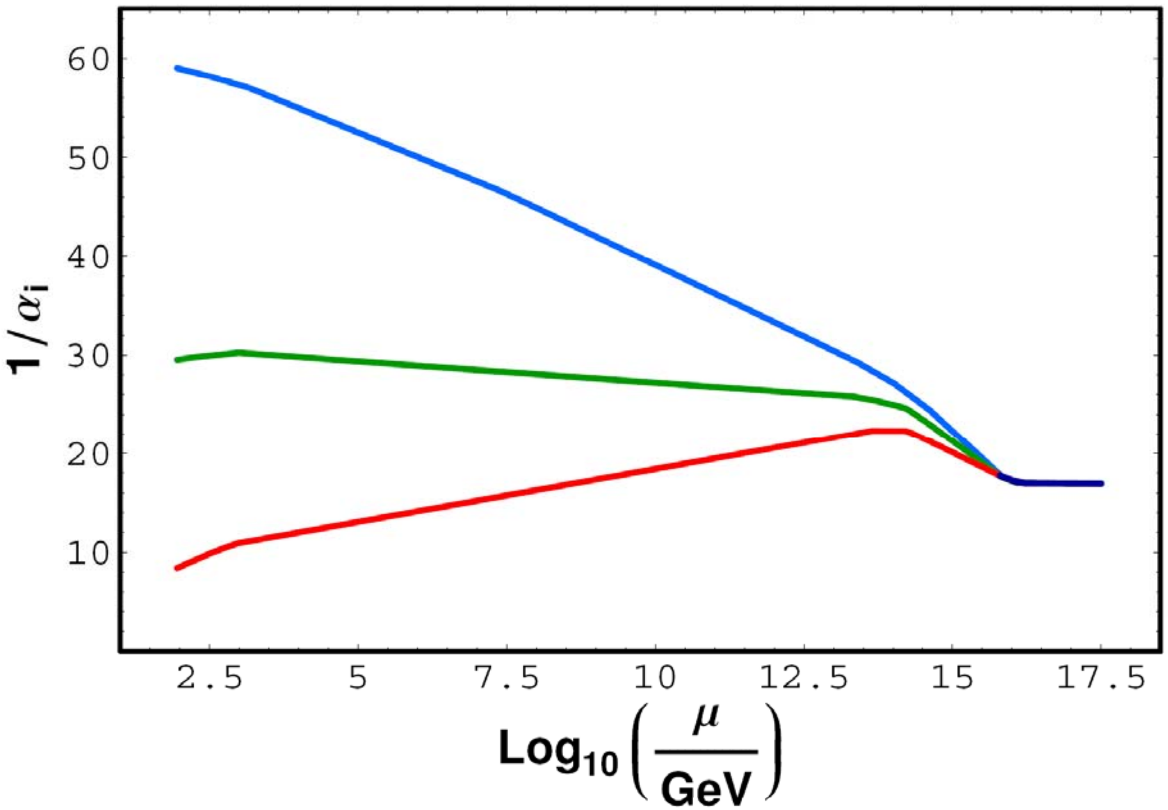
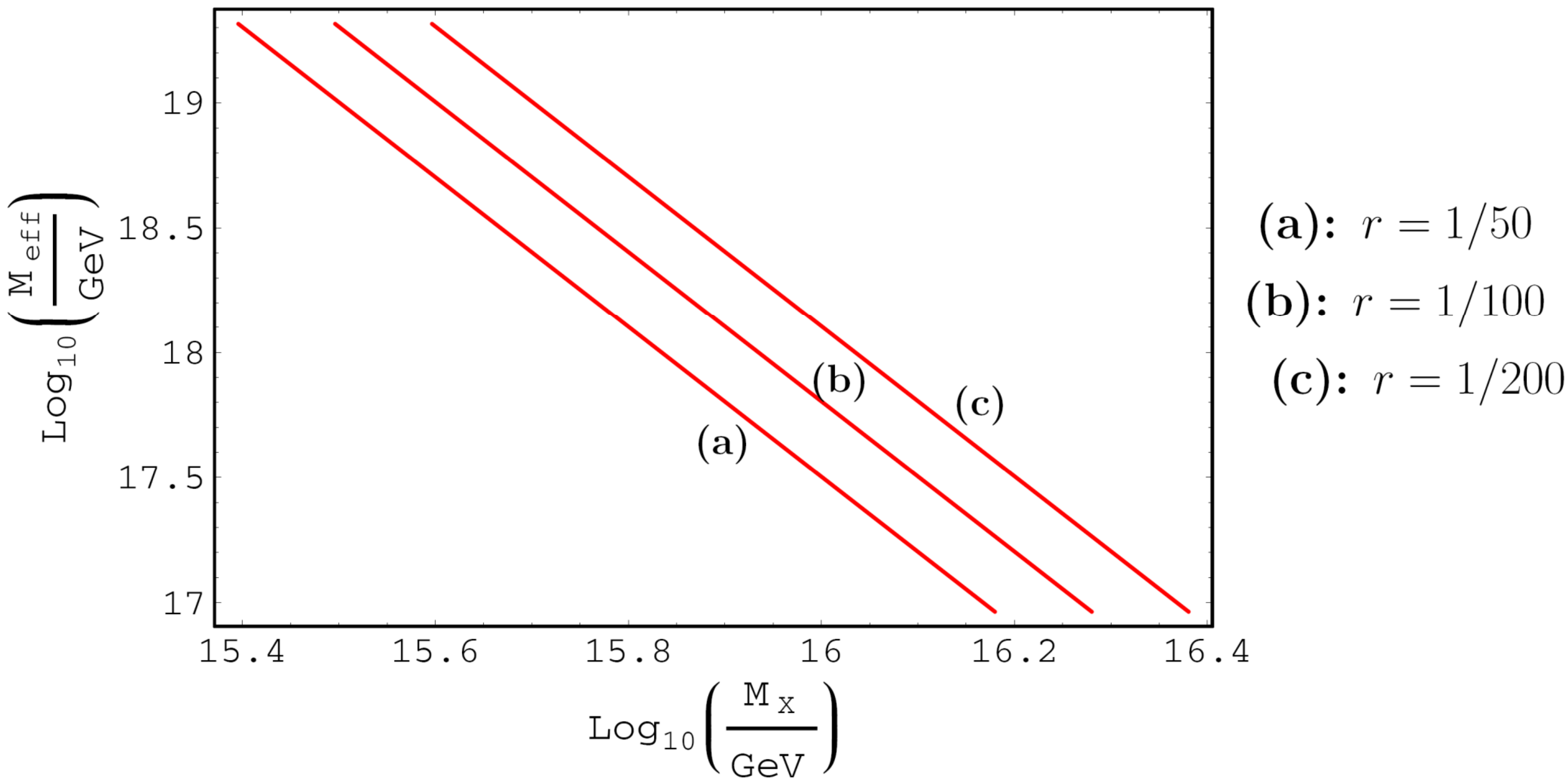
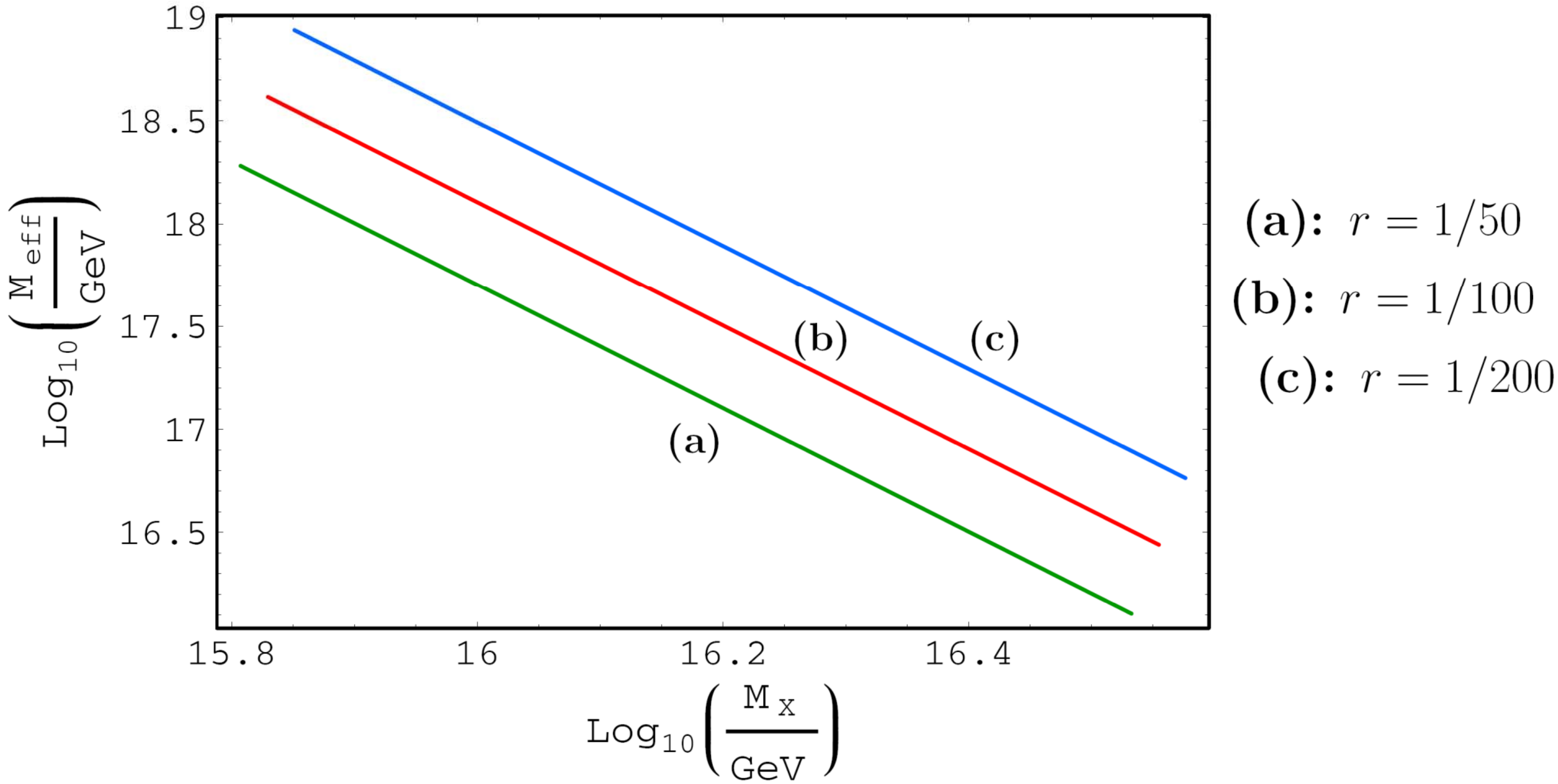
12
14
16
$1/\alpha_i$
$\mathrm{Log}_{10}\left(\frac{\mu}{\mathrm{GeV}}\right)$



Gauge coupling evolution in our SO(10) model



Light SUSY spectrum, $\alpha_3(M_Z) \simeq 0.1176$, $\tan\beta = 3$.



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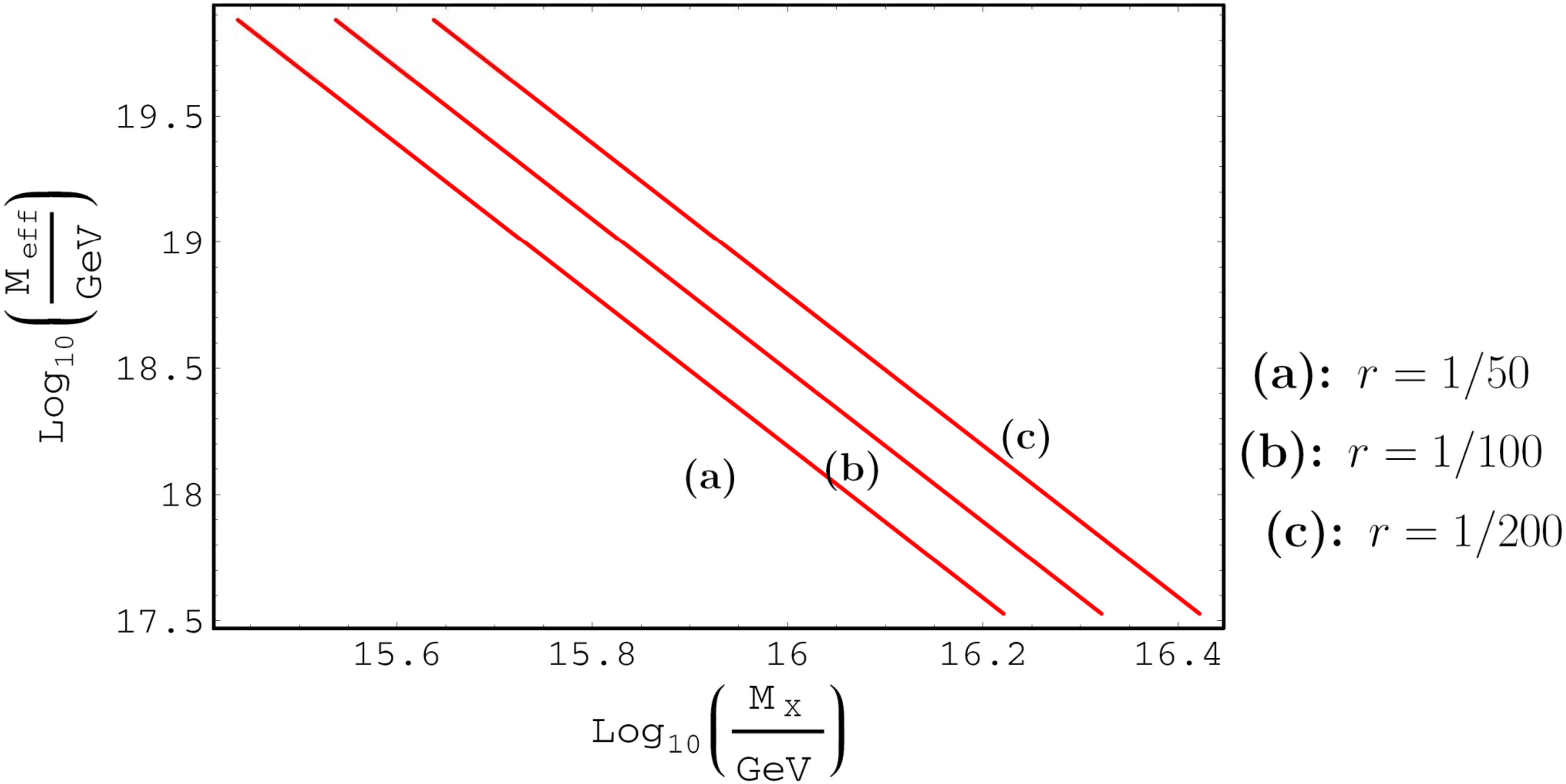
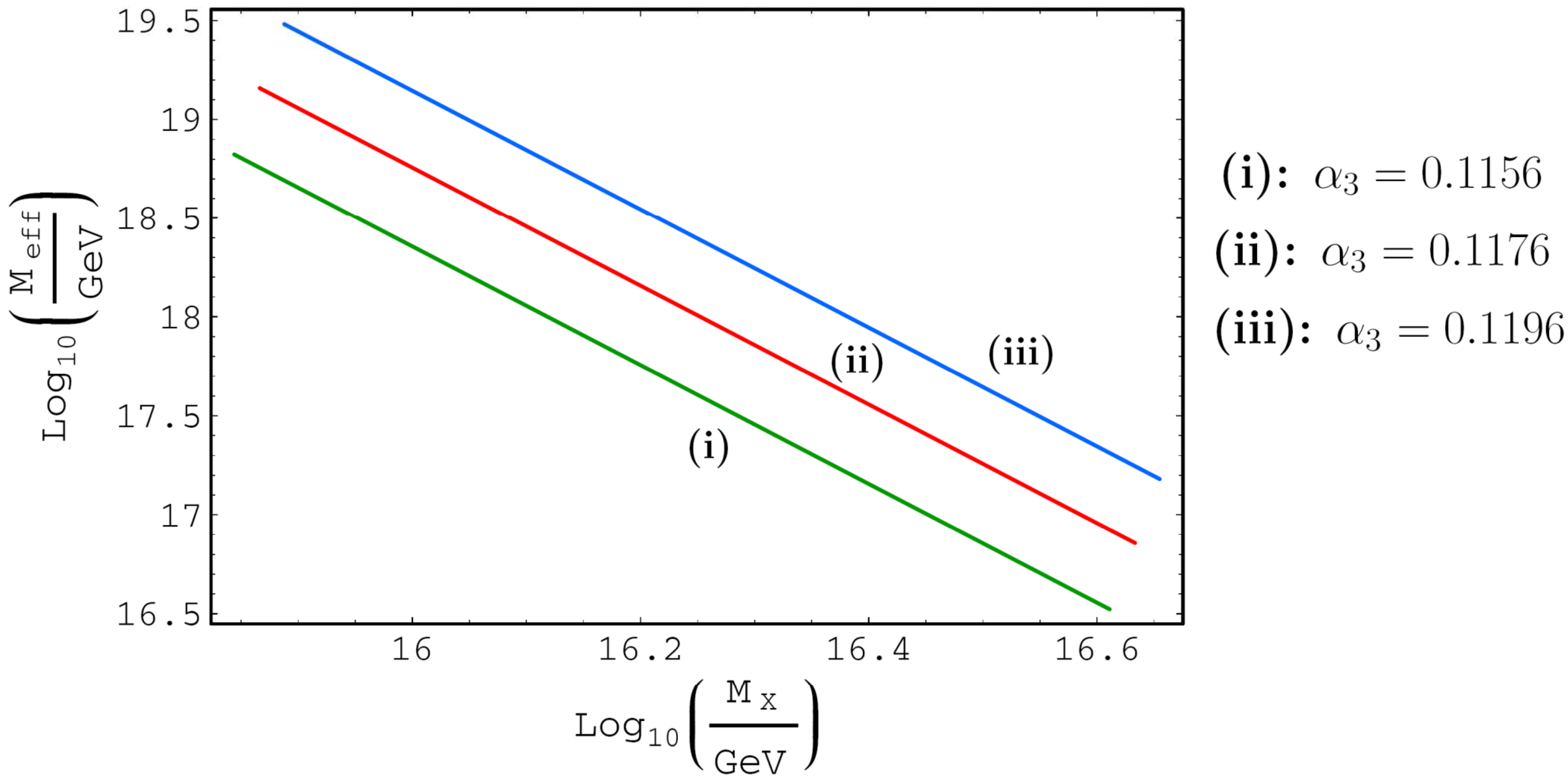
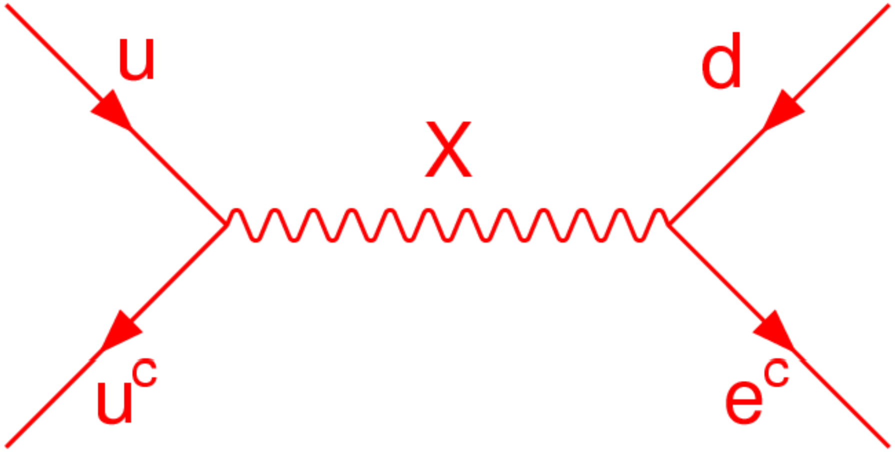


Medium-heavy SUSY spectrum, $\alpha_3(M_Z) \simeq 0.1176$, $\tan\beta = 3$.



Medium-heavy SUSY spectrum, $r = 1/200$, $\tan\beta = 3$.

Gauge boson induced d=6 proton decay

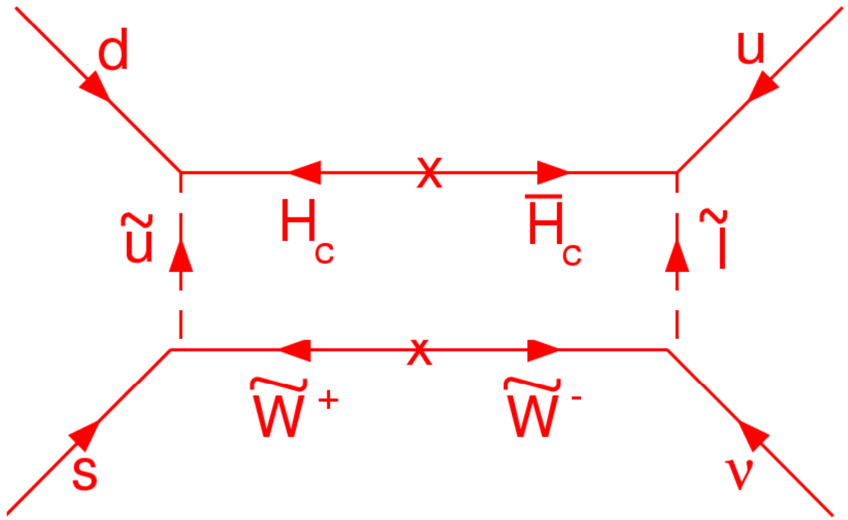


$$p \to e^{+}\pi^{0},\ \tau_{p}^{-1} \approx \left[\frac{g^{2}}{M_{X}^{2}}\right]^{2} m_{p}^{5} \approx [10^{36\pm1} yr]^{-1}$$

Higgsino mediated d=5 proton decay

Sakai, Yanagida (1982)

Weinberg (1982)



$$p \rightarrow \bar{\nu} K^{+}$$

$$\tau_p^{-1} \approx [\frac{f^2}{M_{H_c} M_{SUSY}}]^2 (\frac{\alpha}{4\pi})^2 m_p^5 \approx [10^{28} - 10^{32} yr]^{-1}$$

Proton Decay in the present SO(10) model

$$\tau_p^{d=5}(p \to \bar{\nu} K^+) \simeq 2.3 \cdot 10^{33}\,\text{yrs} \times \left(\frac{0.01\,\text{GeV}^3}{\tilde{\beta}}\right)^2 \left(\frac{1.74}{A_S^t}\right)^2 \left(\frac{1.34}{A_L}\right)^2 \times$$

$$\times \left(\frac{M_{\text{eff}}}{1.51 \cdot 10^{19}\,\text{GeV}}\right)^2 \left(\frac{m_{\tilde{q}}}{1.8\,\text{TeV}}\right)^4 \left(\frac{125\,\text{GeV}}{M_{\tilde{W}}}\right)^2 .$$

Analysis similar to BPW (1998)

$\Rightarrow M_{\text{eff}} > 1.2 \times 10^{19}$ GeV

d = 6 Proton decay

$$\Gamma(p \to e^+\pi^0) \simeq \frac{m_p}{64\pi f_\pi^2}(1+D+F)^2\bar{\alpha}^2\left(\frac{g_5^2 A_R}{M_X^2}\right)^2\left(5+\frac{2}{1+p^2}+\frac{1}{(1+p^2)^2}\right) ,$$

$$\Gamma(p \to \bar{\nu}\pi^+) \simeq \frac{m_p}{32\pi f_\pi^2}(1+D+F)^2\bar{\alpha}^2\left(\frac{g_5^2 A_R}{M_X^2}\right)^2\left(1+\frac{1}{1+p^2}\right)^2 .$$

For $p \lesssim 1/3$, $\Gamma(p \to e^+\pi^0) \simeq \Gamma(p \to \bar{\nu}\pi^+)$,

$p \sim 1$, $\Gamma(p \to e^+\pi^0) \sim 1.4 \cdot \Gamma(p \to \bar{\nu}\pi^+)$.

$p \gg 1$, $\Gamma(p \to e^+\pi^0) \simeq 2.5\Gamma(p \to \bar{\nu}\pi^+)$.

$$\tau_p(p \to e^+\pi^0) = (0.8 - 7.6) \cdot 10^{34} \text{ years} ,$$

$$\tau_p(p \to \bar{\nu}\pi^+) = (0.83 - 18) \cdot 10^{34} \text{ years} .$$

Summary and Conclusions

- New $SO(10)$ model with natural doublet–triplet mass splitting has been proposed
- Mass hierarchy stable to all orders
- No pseudo-Goldstone bosons
- GUT scale threshold effects surprisingly small
- Better values of $\alpha_3(M_Z)$ predicted
- $d = 5$ proton decay adequately but not fully suppressed
- $d = 5$ and $d = 6$ proton decay rates correlated
- Both $p \to \overline{\nu} K^+$ and $p \to e^+ \pi^0$ should be within reach of HyperKamiokande and DUSEL experiments