Quarks and Leptons as Nambu-Goldstone Fermions Under $E_7/SO(10)$

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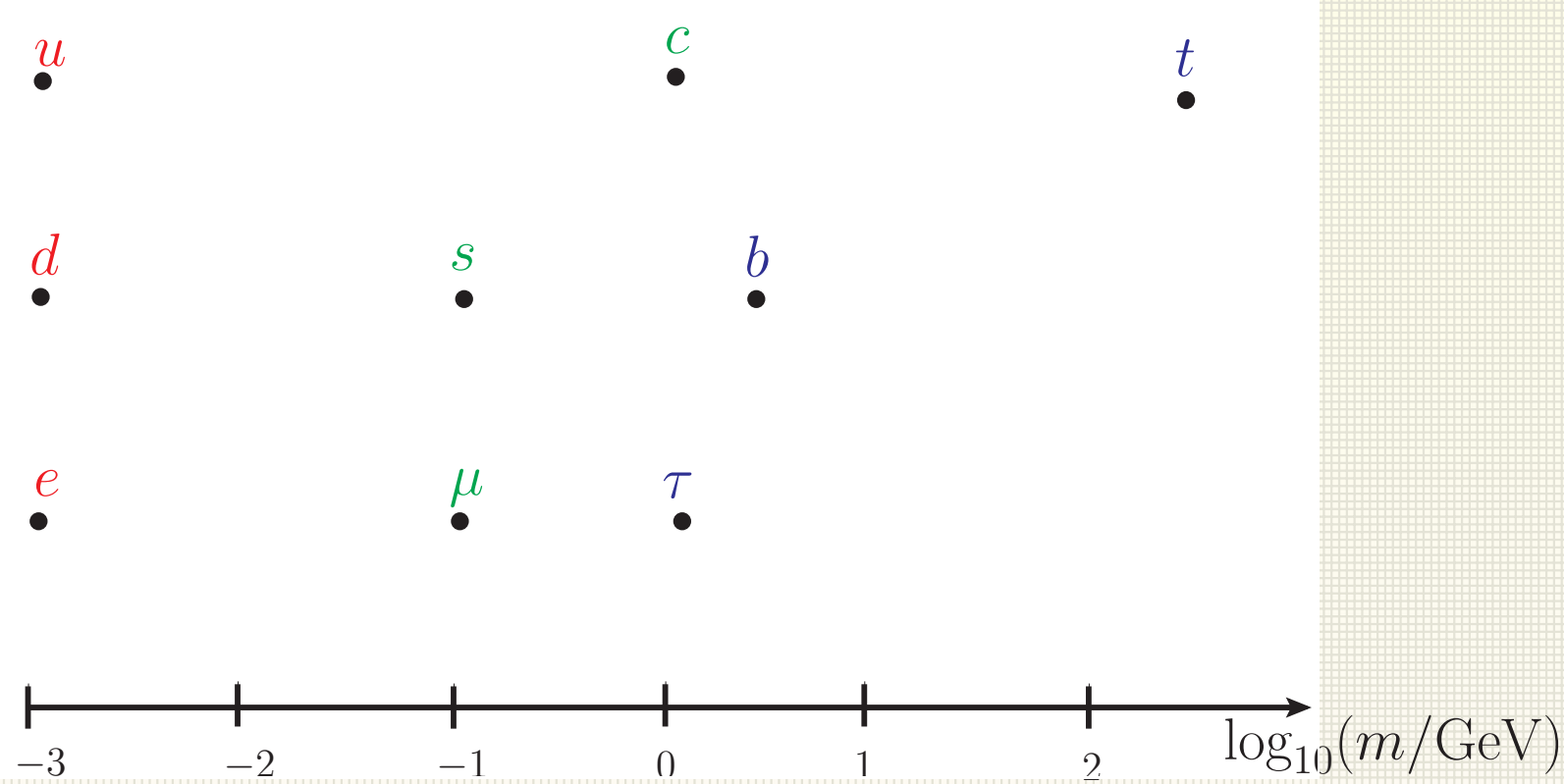
Outline

Hierarchy of Yukawa couplings?



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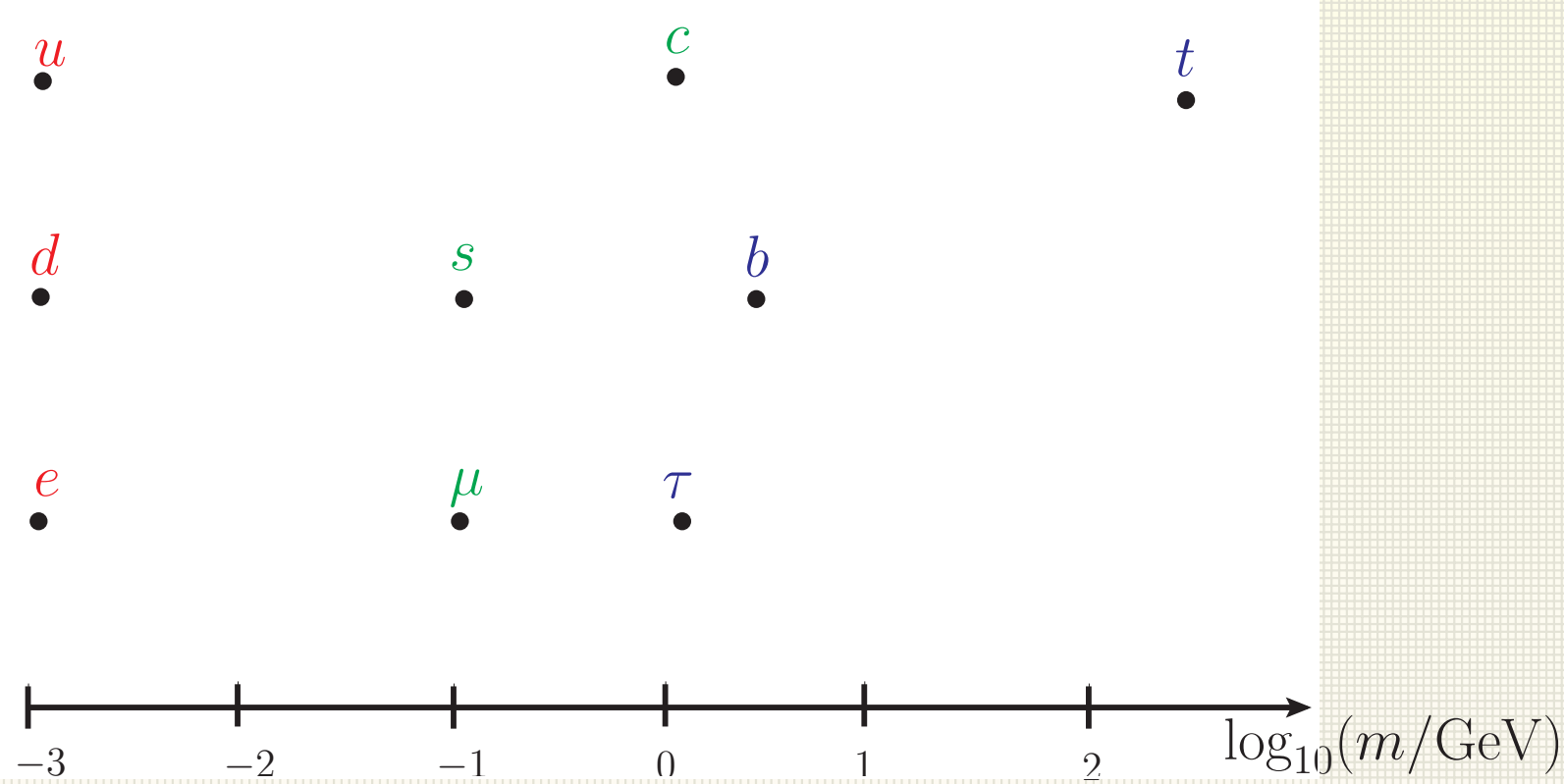

Ad-hoc $\Rightarrow$ dynamical?

Field content of standard model

Gauged adjoint and light chiral fundamentals

- Gauge some group $H \subset G$ in real representation
- Where do light chiral fields in fundamental of H come from?

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Hint from pions

- Take $SU(2)/U(1)$ toy model
- Broken X and $Y \Rightarrow Z = X + iY$, $Z^* = X - iY$
- $SU(2) \sim S^3 \Longrightarrow S^3/U(1) \sim \mathbb{CP}^1$

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- $SU(2) \sim S^3 \Longrightarrow S^3/U(1) \sim \mathbb{CP}^1$
- Gauge $U(1)$, toy pions in fundamental complex representation
- Need fermionic analogue

Strategy

Coset spaces

- Assuming gravity mediation
- $M_\Lambda > M_P\ (\sim M_{GUT}) \gg M_{SUSY}$

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$\Rightarrow$ Need SUSY nonlinear σ model!

Formulation of SUSY nonlinear σ model

Supergravity action

- In supergravity component Lagrangian,

$$\Delta\mathcal{L}_{NGB}^{NL} = -\left(\partial^{\mu}\pi_i\right) g^{ij} \left(\partial_{\mu}\pi_j\right)$$

$$\Delta\mathcal{L}_{NGF}^{NL} = c^{ijkl} \left(\bar{\psi}_i\gamma^{\mu}\psi_j\right) \left(\bar{\psi}_k\gamma_{\mu}\psi_l\right)$$

- g^{ij} and c^{ijkl} exhibit shift symmetry for d.o.f.'s in nonlinear realization.

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Complex extension of G

- Symmetry breaking is no $G \to H$, but $G^{\mathrm{C}} \to H$
- If G/H Kähler, then $G/H \simeq G^{\mathrm{C}}/H$
- Otherwise, need extra "quasi-Nambu-Goldstone bosons" to preserve supersymmetry

Restrictions on G/H

Non-compactness

- Shown by Bagger and Witten, Phys. Lett. B **118** 103 (1982) for $\mathbb{CP}^1$.
- Gauging on compact coset induces finite D-term, breaking SUSY

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No $U(1)$'s in H

- Shown by Kugo and Yanagida, Prog. Theor. Phys **124**, 555 (2010).
- Kähler transformation in flat space

$$K(\Phi, \Phi^\dagger) \to K(\Phi, \Phi^\dagger) + F(\Phi) + F^\dagger(\Phi^\dagger)$$

Restrictions on G/H (cont'd)

No $U(1)$'s in H (cont'd)

- Under supergravity,

$$L = \left[\Sigma\Sigma^\dagger e^{-K(\Phi,\Phi^\dagger)}\right]_D + \left[\Sigma^3 W(\Phi)\right]_F$$

- For finite W, $\Sigma \to \Sigma e^F$ not sufficient, breaking G-invariance of theory, giving $O(m_{3/2})$ masses to N-G fields
- $F^{(\dagger)}$ must vanish
- If $H \supset U(1)$, global G transformation induces local $U(1)$, generating Fayet-Iliopoulos D-term $-g\mathrm{tr}V$.
- $H \not\supset U(1)$, then Lagrangian G-invariant

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Summary: G/H **Kähler and non-compact,** $H \not\supset U(1)$

Choosing $G = E_7$

Formal motivations for E_7

- Appears in $N = 8$ supergravity
- Nonlinear realization gives the "simplest field theory" [Arkani-Hamed, Cachazo, Kaplan arXiv:0808.1446]

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GUT-like representations

- $SU(5) \supset (5 + 5^*)_H \bigoplus 10 \bigoplus 5^*$
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  - $E_7/[SU(5) \times U(1)^3] \rightarrow (10 \bigoplus 5^*) \times 3 + 5_H$
  - $E_7/[SO(10) \times U(1)^2] \rightarrow (10 \bigoplus 5^*) \times 2 + (5 + 5^*)_H$

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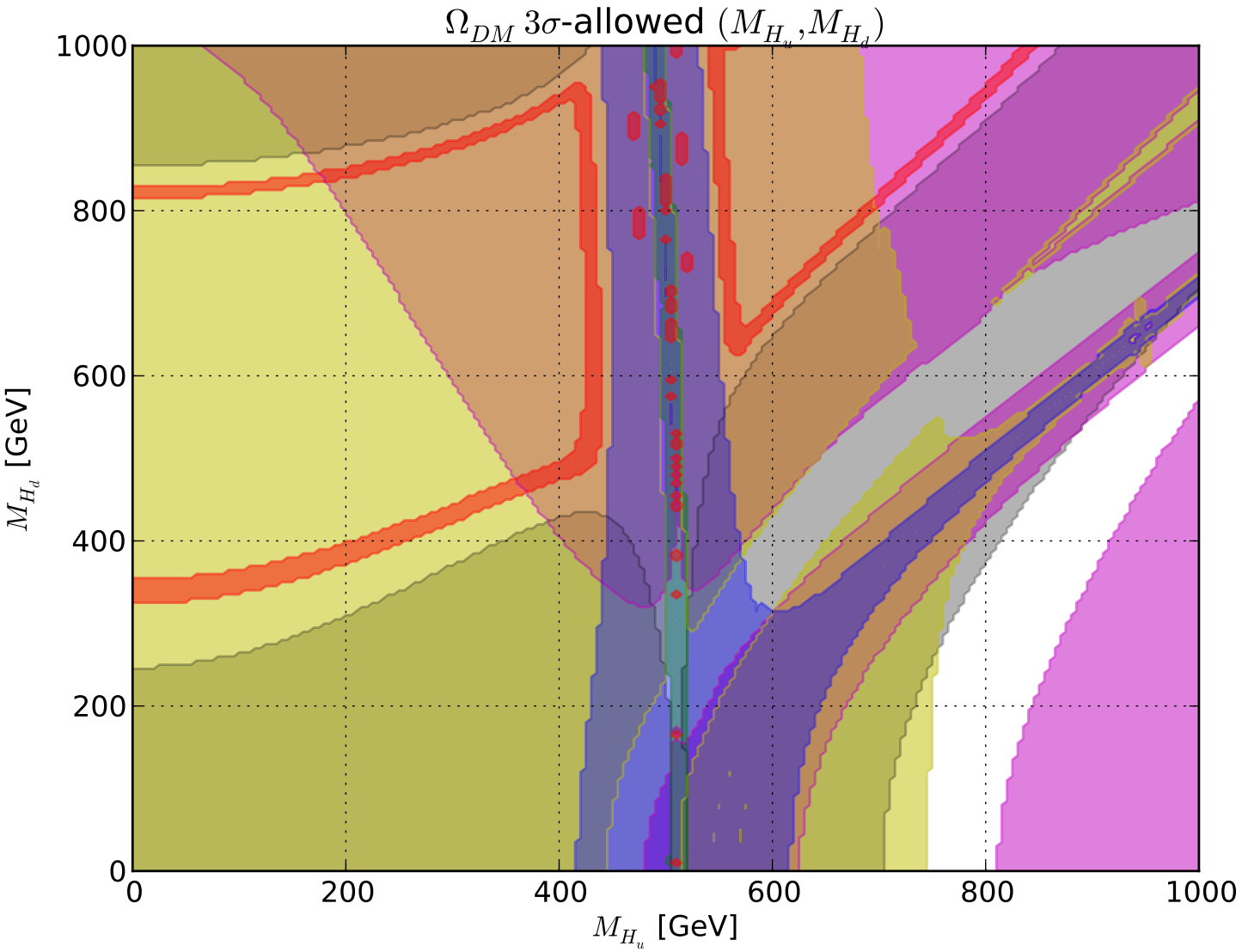
- E_6 too small, E_8 gives mirror families

Light 5^*, Light 10 (3rd generation)



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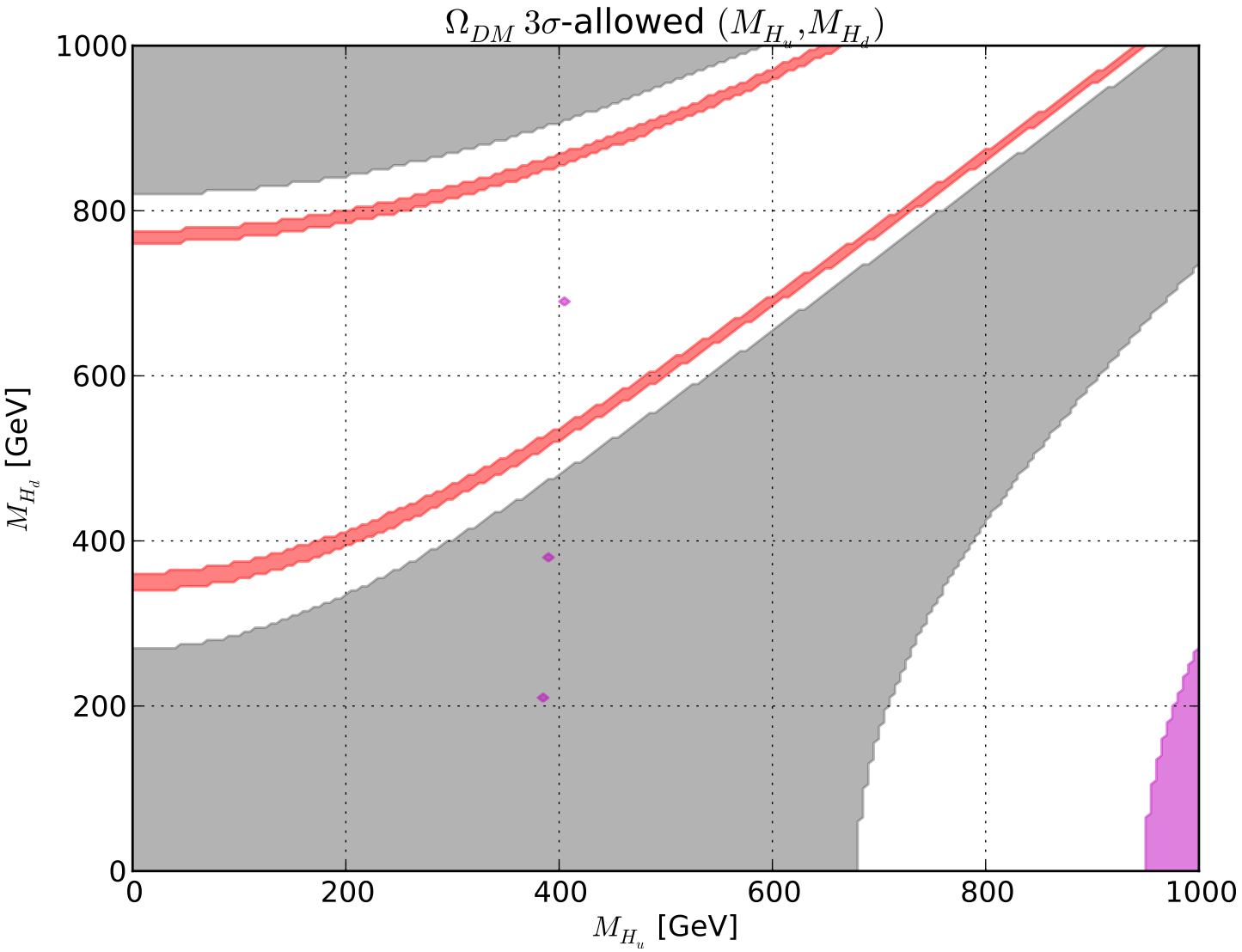
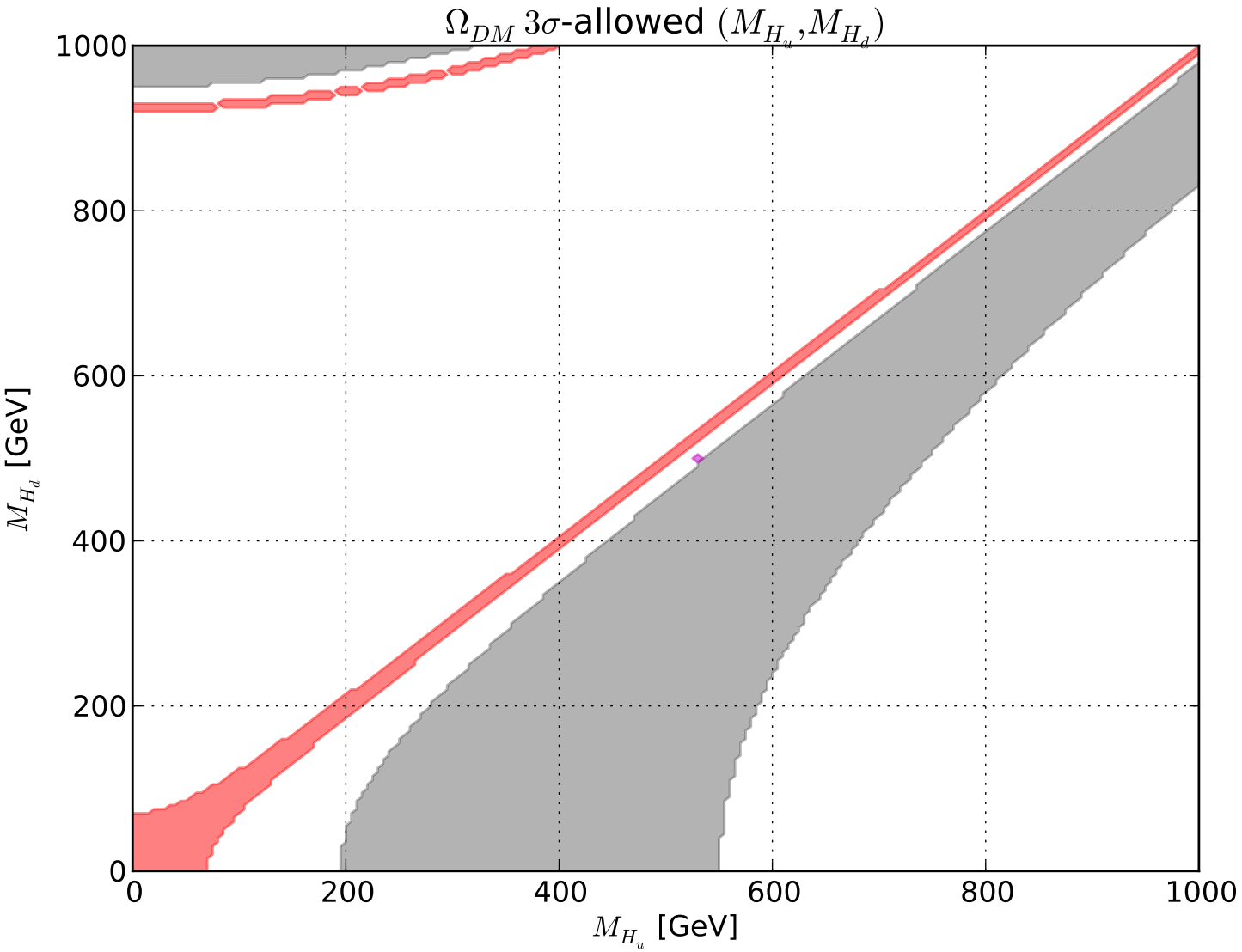


Heavy 5^*, Heavy 10 ($M_{input} = M_P$)



GUT-less $E_7/SO(10)$ model

- Global symmetry must be gauged anyway $\Rightarrow$ gauge $SU(3)_C \times SU(2)_L \times U(1)_Y \subset SO(10)$
- Don't need universal M_a
- *Explicitly* break $U(1)^2$ for coupling to supergravity, gives two "novinos" N_1, $N_2 \sim M_P$

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- Superpotential:

$$W = W_Y + W_S + W_H$$

where

$$\begin{aligned} W_Y &= Y_u \cdot 10 \cdot 10 \cdot 5_H + Y_d \cdot 10 \cdot 5^* \cdot 5^*_H \\ W_S &= M_\nu \cdot 1 \cdot 1 + M_N \cdot N \cdot N \\ W_H &= \mu \cdot 5_H \cdot 5_H* \end{aligned}$$

GUT superpotential

Additions to superpotential

$$\Delta W = W_\Sigma + W_{H'}$$

where

$$\begin{aligned} W_\Sigma &= M_\Sigma \mathrm{Tr}\,\Sigma^2 + \lambda \mathrm{Tr}\,\Sigma^3 \\ W_{H'} &= \lambda_{\mathbf{1}} \cdot 5_H \cdot \Sigma \cdot 5_H^* \end{aligned}$$

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Outstanding issues

- Set right boundary conditions for Ω_{DM}
- Evade LHC bounds?

Making $M_{GUT} \approx M_P$

$$\Sigma \sim 24 \supset (8,1) \oplus (1,3) \oplus (1,1) \oplus (3,2) \oplus (3^*,2)$$

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Choose: $\sim 10^{12}$ GeV

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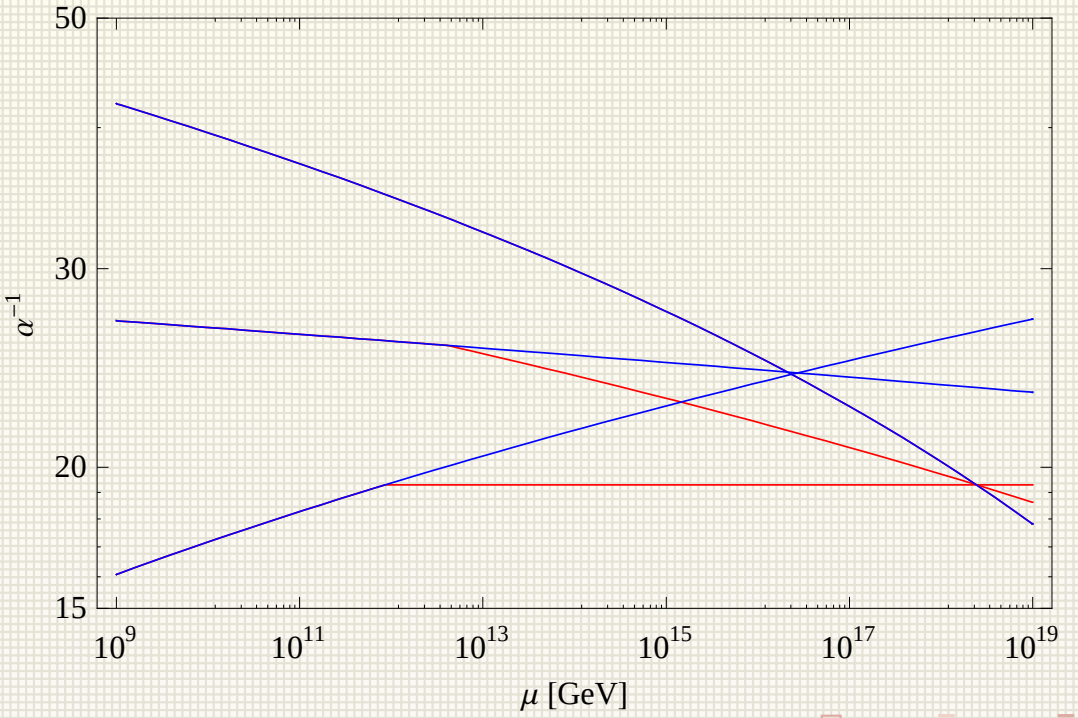

Solving the double-triplet splitting problem

Missing partner mechanism

- 50 of $SU(5)$ contains color $(3,1)$, not weak $(1,2)$
- Explicit triplet Higgs $5_H + 5_H^*$ to $50 + 50^*$ coupling

$$W_T = \lambda_T \cdot 5_H \cdot \langle 75 \rangle \cdot 50 + \text{c.c.}$$

- Huge threshold corrections?

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Product group unification

- $SU(5)_G \to SU(5)_G \times SU(3)_H \times U(1)_H$
- Diagonal

$$SU(3)_c \subset SU(3)_G \times SU(3)_H$$

$$U(1)_Y \subset U(1)_G \times U(1)_H$$

Product group unification (1/2)

Breaking

$$\bar{Q}(m+\lambda\Sigma)Q+\frac{1}{2}m_{\Sigma}\mathrm{Tr}(\Sigma^2)+hHQ\bar{q}+c.c.$$

where

$$Q\sim(5^*,3,1)\ ,\ q\sim(1,3,1)$$

and

$$\langle Q\rangle\sim vI_3\ ,\ \langle\Sigma\rangle\sim\mathrm{diag}(3,3,-2,-2,-2)$$

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Gaugino mass splitting

Modified soft breaking

$$\begin{aligned}\Delta\mathcal{L}_{SSB}= & -\frac{1}{2}M_G\lambda_G\lambda_G-\frac{1}{2}M_{H3}\lambda_{H3}\lambda_{H3}\\ & -\frac{1}{2}M_{H1}\lambda_{H1}\lambda_{H1}+c.c.\end{aligned}$$

Product gauge unification (2/2)

Gaugino mass splitting

- Re-weighted SM gaugino soft masses:

$$M_3 \Longrightarrow g_3^2 \left(\frac{M_{H3}}{g_{H3}^2} + \frac{M_G}{g_G^2} \right)$$

$$M_1 \Longrightarrow g_1^2 \left(\frac{M_{H1}}{15 g_{H1}^2} + \frac{M_G}{g_G^2} \right)$$

- Changes in low-energy phenomenology:

$$M_3 = M_{1/2} \Longrightarrow M_3 \sim 2 \times M_{1/2}$$

$$M_1 \sim M_{1/2}$$

MSSM analysis

Soft masses

- $m_{3/2} = m_{0(3)} = 1\,\text{TeV}$
- $m_{0(1,2)} = 0$
- $A_0 = 0,\ m_{H_u} = m_{H_d} = 0$
- $M_{input} = M_P$

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Uncertainties in $\tan\beta$

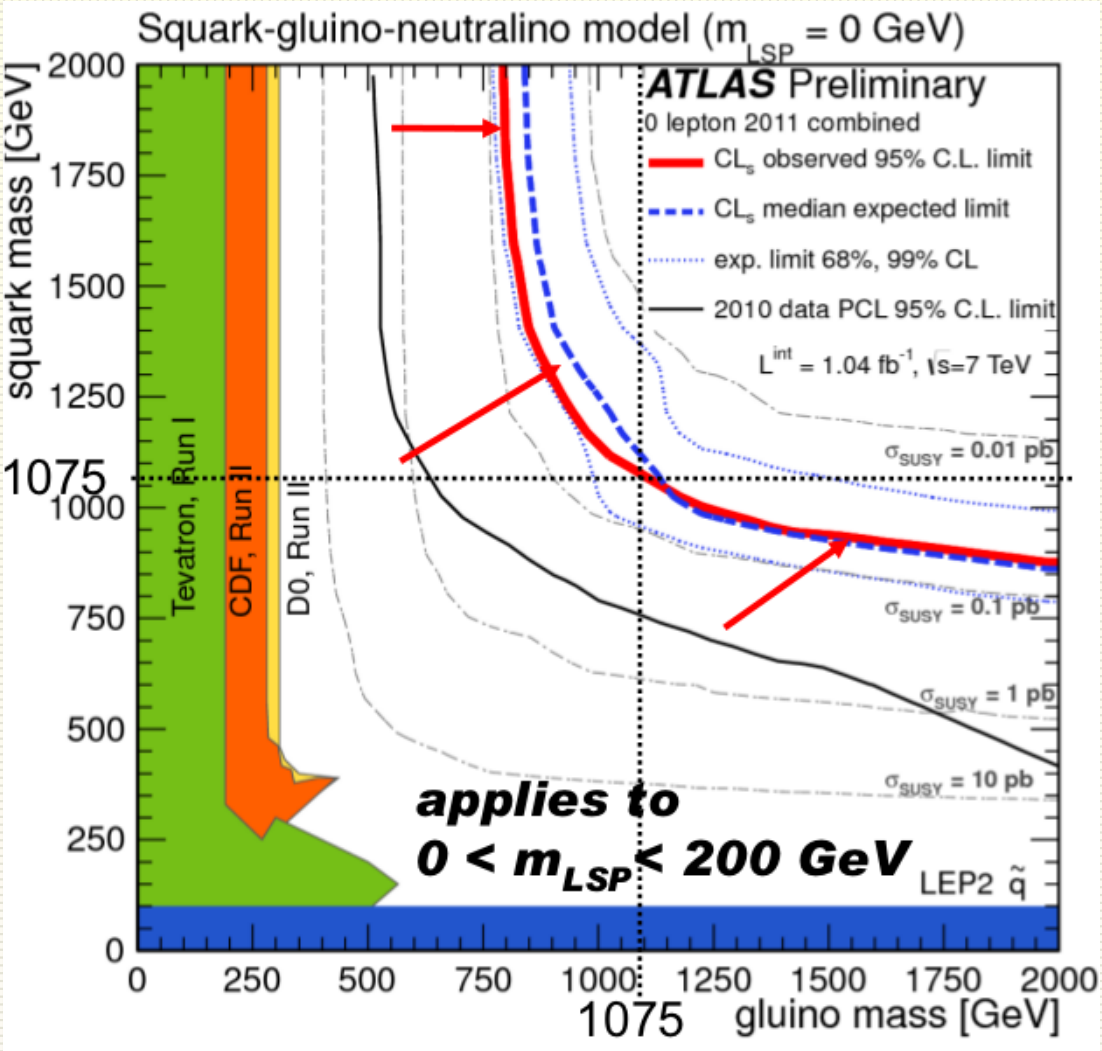
- With finite μ term, b commonly of the same order (connected through hidden sector)
- Spectrum unaffected, except for small shift in $\tilde{t}$, $\tilde{b}$ masses
- Direct detection cross section varies from $4 \times 10^{-47}\,\text{cm}^2$ ($\tan\beta = 10$) to $4 \times 10^{-46}\,\text{cm}^2$ ($\tan\beta = 50$) due to $\tilde{H}_d$ contribution to χ_1^0.

Spectra

Choose SPS1a for comparison since slepton/light gaugino spectra similar:

Field	SPS1a	$M_3 = M_{1/2}$	M_3 =500 GeV
$\tilde{\chi}_1^0$	100	100	100
$\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$	180	230	230
$\tilde{l}_{R(1,2)}$	140	120	120
$\tilde{l}_{L(1,2)}$	200	200	200
H_0, A_0, $H^\pm$	400	970	1100
$\tilde{\chi}_2^\pm$, $\tilde{\chi}_{3,4}^0$	380	960	1100
$\tilde{\tau}$,$\tilde{\nu}_\tau$	200	1000	1000
$\tilde{t}_1$	550	920	1200
$\tilde{g}$	600	789	1250
$\tilde{q}_{1,2}$	550	680	1100

Newest model-independent constraints



Constraint on model points

Jets + missing E_T

$\geq$ 3-jet signal region only 10 ± 2 SM events at 165pb^{-1}:

	SPS1a	$M_3 = M_{1/2}$	M_3 =500 GeV
Prod. σ	4.5 pb	0.6 pb	16 fb
Efficiency	12%	28%	29%
$\mathfrak{L}(2\sigma)$	7 pb^{-1}	15 pb^{-1}	10 fb^{-1}

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Multiplicities

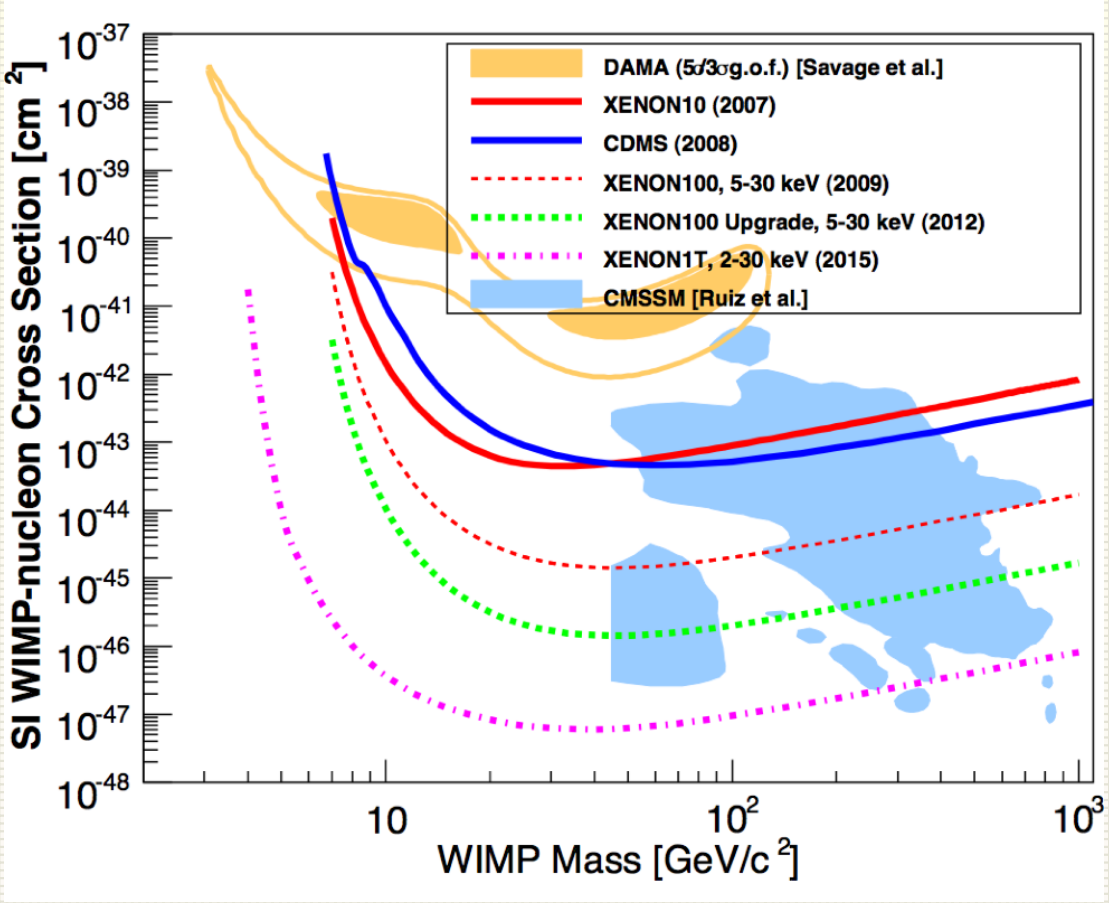
Mistag rates: τ-jet (8%), b-jet (5%)

	SPS1a	$M_3 = M_{1/2}$	M_3 =500 GeV
b-jets	18%	5%	5%
τ-jets	8%	9%	9%
$n_l \geq 2$	8%	14%	14%

Dark matter phenomenology

Detection

- $\sigma_{\chi N}$ excludable by XENON100/1T
- χ_1^0 mostly bino, $< \sigma v >_{\chi\chi}$ is p-wave suppressed



Summary

Created consistent $E_7/SO(10)$ coset model with distinctive collider signatures

Can be ruled out by DM direct detection in 1–5 years depending on $\tan\beta$

Can be ruled out by LHC Higgs search in $\sim 10\ \mathrm{fb}^{-1}$ (by end of 2011 at $\sim 80\ \mathrm{pb}^{-1}$/day)