Explicit Supersymmetry Breaking in the $B - L$ MSSM

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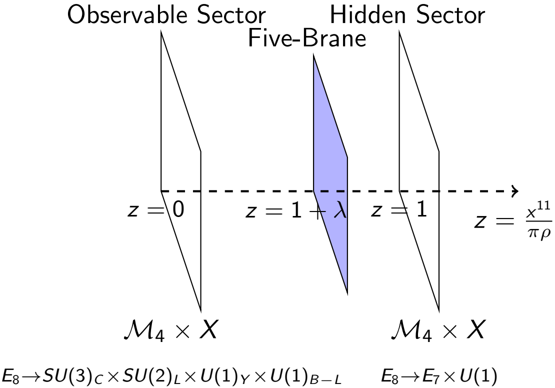
Vacuum Configuration

- We start from 11D Horava-Witten theory;
- First compactify each 10D sector on a 6D Calabi-Yau threefold X: 11D$\rightarrow$ 5D;
- Integrate over the 11th dimension, to obtain a 4D effective theory, with unbroken SUSY at M_U.



Calabi-Yau

- The Calabi–Yau manifold X is chosen to be a torus-fibered threefold with fundamental group $\pi_1(X) = \mathbb{Z}_3 \times \mathbb{Z}_3$;
- Hodge data: $h^{1,1} = h^{1,2} = 3$;
- Degree-two Dolbeault cohomology group

$$H^{1,1}(X, \mathbb{C}) = \text{span}_{\mathbb{C}}\{\omega_1, \omega_2, \omega_3\} \ ,$$

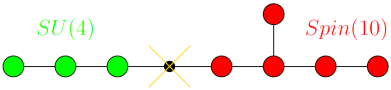
  where $\omega_i = \omega_{ia\bar{b}}$ are harmonic $(1,1)$-forms;
- Kähler form of the CY is an element of the Kähler cone $\mathcal{K} = H^2_+(X, \mathbb{R}) \subset H^2(X, \mathbb{R})$

$$\omega = a^i \omega_i, \quad \text{where } a^i > 0 \ .$$

  The real, positive coefficients a^i are the three $(1,1)$ Kähler moduli of the Calabi–Yau threefold.

Observable Sector

- We turn on a holomorphic vector bundle $V^{(1)}$ on X with structure group $SU(4) \subset E_8$, which breaks the E_8 group to $Spin(10)$ [Braun,He,Ovrut,Pantev, arXiv:hep-th/0512177]



- Turning on two *flat* Wilson lines, each associated with a different $\mathbb{Z}_3$ factor of the $\mathbb{Z}_3 \times \mathbb{Z}_3$ holonomy of X, breaks the

$$Spin(10) \to SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L} \ .$$

✔ We obtain the particle spectrum of the $B-L$ MSSM.

- $B-L$ symmetry breaking by right-handed sneutrino VEV:

$$U(1)_Y \times U(1)_{B-L} \longrightarrow U(1)_Y$$

Vacuum Constraints

- Having fixed the gauge bundle $V^{(1)}$ on the observable sector, we are left to find a hidden sector bundle $V^{(2)}$ and set the five-brane position.
- Not all configurations are allowed. The choices need to satisfy a series of vacuum constraints:
  1. Effective theory anomaly-free if

  $$c_2(TX) - \mathrm{ch}_2(V^{(1)}) - \mathrm{ch}_2(V^{(2)}) - [W] = 0,$$

  where W is the five-brane class.
  2. The five brane class needs to be effective

  $$[W]_i \geq 0 \ , \quad i = 1, \ldots, h^{1,1} = 3.$$

  3. Dimensional reduction constraint: size 11th dimension$>$Calabi-Yau scale

  $$\pi \rho \widehat{R} V^{-1/3} > (vV)^{1/6} \ , \quad V = \frac{1}{6} d_{ijk} a^i a^j a^k (\text{Calabi-Yau volume}) \ .$$

Vacuum Constraints

4. Genus-one corrected (to order $\kappa_{11}^{4/3}$) gauge kinetic functions are positive:

$$f^{(1)} = V + \frac{\epsilon'_S \hat{R}}{2V_{1/3}} \left(\tfrac{2}{3}a^1 - \tfrac{1}{3}a^2 + 4a^3 + (\tfrac{1}{2} - \lambda)^2 W_i a^i\right) > 0$$

$$f^{(2)} = V - \frac{\epsilon'_S \hat{R}}{2V_{1/3}} \left(\tfrac{2}{3}a^1 - \tfrac{1}{3}a^2 + 4a^3 + (1 - (\tfrac{1}{2} + \lambda)^2) W_i a^i\right) > 0 \ ,$$

where ϵ'_S is an expansion parameter.

5. Fix $M_U = 3.16 \times 10^{16}\text{GeV}$, $\alpha_{\text{GUT}} = \frac{g_{\text{GUT}}^2}{4\pi} = \frac{1}{26.5}$ on the observable sector, such that all parameters agree with observations. Example:

$$\epsilon'_S = \frac{2\pi^2}{(8\pi^2)^{4/3}} \alpha_{\text{GUT}}^2 \frac{M_P^2}{M_U^2} V^{5/3}, \quad v = \frac{1}{V M_U^6} \ .$$

6. DUY theorem $\Rightarrow N = 1$ SUSY unbroken at unification, in both observable and hidden sectors if both $V^{(1)}$ and $V^{(2)}$ are slope stable.

Proposed Hidden Sector Bundle

- In [Ashmore,Dumitru,Ovrut, arXiv:2003.05455], we build a hidden sector bundle $V^{(2)}$ with $U(1)$ structure group, from a single line bundle $L = \mathcal{O}_X(l^1, l^2, l^3)$, $l^i \in \mathbb{Z}$.
- Hidden sector gauge group: $E_7 \times U(1)$.
- We embed the $A_{U(1)}$ connection associated with L into the hidden E_8 via

$$U(1) \hookrightarrow S(U(1) \times U(1)) \subset SU(2) \hookrightarrow E_8 \ .$$

- The hidden-sector bundle

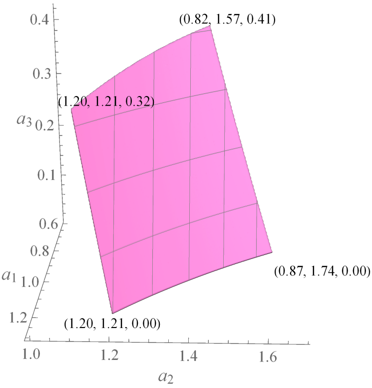
$$V^{(2)} = L \oplus L^{-1} \ .$$

- DUY: The connection solves the HYM equation and $N = 1$ SUSY is preserved if

$$\mu(L) = \mu(L^{-1}) = 0 \ .$$

A Possible Solution

- In [Ashmore,Dumitru,Ovrut, arXiv:2003.05455], we show $L = \mathcal{O}_X(2,1,3)$ solves all the vacuum constraints when we fix the five-brane near the hidden wall $z = 0.95$, $z \in [0,1]$.
- We find a finite solution region inside the Kahler moduli space.
- In the absence of a moduli stabilization mechanism, the real parts of the moduli fields $\mathrm{Re}S = V = \frac{1}{6} d_{ijk} a^i a^j a^k$ and $\mathrm{Re}T^i = \hat{R} a^i / V^{1/3}$ can take any values for (a^1, a^2, a^3) inside this region.



Low Energy Spectrum

In addition [Ashmore,Dumitru,Ovrut, arXiv:arXiv:2012.11029] ...

- Gauginos in the $\underline{\mathbf{133}}$ of E_7 can form a condensate and break SUSY at low energy (non-perturbative effect).
- For $L = \mathcal{O}_X(2,1,3)$ we obtain the right spectrum to allow for Gaugino Condensation:

$U(1) \times E_7$	Cohomology	χ
$(0, \underline{\mathbf{133}})$	$H^*(X, \mathcal{O}_X)$	0
$(0, \underline{\mathbf{1}})$	$H^*(X, \mathcal{O}_X)$	0
$(-1, \underline{\mathbf{56}})$	$H^*(X, L)$	8
$(1, \underline{\mathbf{56}})$	$H^*(X, L^{-1})$	-8
$(-2, \underline{\mathbf{1}})$	$H^*(X, L^2)$	58
$(2, \underline{\mathbf{1}})$	$H^*(X, L^{-2})$	-58

A Realistic Model for SUSY Breaking

- The hidden sector coupling RGE:

$$\frac{4\pi}{g^{(2)}_{E_7}}(p) = \frac{4\pi}{g^{(2)}_{E_7}}(M_U) - \frac{b}{2\pi}\ln\left(\frac{\langle M_U\rangle}{p}\right) \ .$$

- The beta function b depnds on the number of chiral fields in $(1, \underline{\mathbf{56}})$:

$$b = 3 \times T(\mathbf{133}) - |\chi((1, \underline{\mathbf{56}}))| \times T(\mathbf{56}) = 54 - 6|\chi((1, \underline{\mathbf{56}}))| \ .$$

- The gaugino condensate forms at the scale Λ at which the hidden sector gauge coupling becomes strong ($\frac{4\pi}{g^{(2)}_{E_7}}(\Lambda) \approx 0$). Only possible if $b > 0$.

$$\text{for } L = \mathcal{O}_X(2,1,3) \quad \Rightarrow \quad b = 6 > 0.$$

- Condensate forms at the energy scale $\Lambda \equiv \Lambda(S,T) = M_U e^{\frac{-2\pi}{b}\frac{\mathrm{Re} f_2}{\mathrm{Re} f_1 \alpha_{\mathrm{GUT}}}}$.

Soft SUSY breaking Lagrangian

- The condensate generates a superpotential in the effective theory $\hat{W}_{\text{mod}}(S,T) \sim \Lambda^3(S,T)$.
- Observable and hidden sectors couple gravitationally in 4D $N = 1$ Supergravity. Example: the gravitino mass:

$$m_{3/2} \sim \frac{|\Lambda^3|}{M_P^2} \sim M_{\text{soft}};$$

- All soft susy breaking terms can be computed across the Kahler moduli solution space (a^1, a^2, a^3).
- In [Ashmore,Dumitru,Ovrut, arXiv:arXiv:2012.11029] we find phenomenologically viable solutions only when $M_{\text{soft}} \in$[1TeV,100TeV].

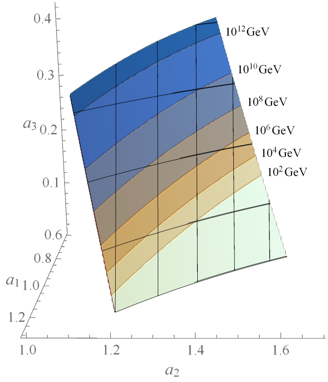


Figure: M_{soft} across the Kahler moduli solution space.

Conclusions

So far we found a vacuum configuration which satisfies a series of constraints:

- $N = 1$ SUSY at the compactification scale; Effective theory is anomaly-free;
- Size 11th dimension $>$ Calabi-Yau size scale;
- Gauge couplings unify at $M_U = 3.16 \times 10^{16}$GeV at the predicted value;
- We attached a SUSY breaking mechanism via gaugino condensation in the hidden sector; We showed that SUSY can be broken at energies ranging from 1TeV to 10^{10}TeV;

Further work:

- Moduli stabilization mechanism missing;
  $\Rightarrow$ Solution: Can be achieved in the presence of a gaugino condensate and flux or via a double gaugino condensate on the hidden wall;
- Expansion coefficients are large;
  $\Rightarrow$ Solution: Bundle deformations:
  [Ashmore,Dumitru,Ovrut,arXiv:2106.09087].