Supersymmetry breaking

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Abstract. We review the various mechanisms of supersymmetry breaking and its transmission to the observable sector. We argue that hybrid models where gauge dominates over gravity mediation, but gravity provides the main contributions to the Higgs sector masses and the neutralino mass, are able to combine the advantages and reduce the disadvantages of the two transmission mechanisms.

Keyword. Supersymmetry breaking.

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1. Introduction

Supersymmetric extensions of the Standard Model are currently the best candidates for new physics at low energy. Indeed, they provide (a) a technically natural solution to the hierarchy problem, i.e. of why $M_W \ll M_{GUT}, M_P$, if the scale of supersymmetry breaking $M_{SUSY} \sim M_W$, (b) accurate gauge coupling unification in the minimal supersymmetric extension of the Standard Model (MSSM).

It has a natural candidate for dark matter, if $R$-parity is conserved. If supersymmetry is made local, it predicts Einstein gravity $\rightarrow$ supergravity (SUGRA). It is an essential ingredient in any stable string construction.

The most important and still open question of supersymmetric extensions of the Standard Model concerns the mechanism of spontaneous breaking of supersymmetry. In this talk we review the basic mechanisms of supersymmetry breaking, their achievements and problems and some recent progress.

2. Supersymmetry breaking: Early model building attempts

There are two possible contributions to SUSY breaking. (1) Matter or $F$-term $\langle F \rangle \neq 0$: (off-shell) matter multiplets are $(z_i, \psi_i, F_i)$. The prototype examples are: O’Raifeartaigh model(s) (O’R) $\rightarrow F$-breaking. (2) Gauge or $D$-term $\langle D_a \rangle \neq 0$: gauge multiplets are $(\lambda_a, A^a_\mu, D_a)$. This happens only for Abelian gauge factors $U(1)_a$. The prototype examples are: Fayet–Iliopoulos model(s) (FI) $\rightarrow D$-breaking.
O’R models have (at least) three chiral multiplets:

\[ W = X_1 g_1(\phi) + X_2 g_2(\phi). \] (1)

For generic functions \( g_1(\phi), \) the SUSY conditions \( F_i = 0, \) where \( -F_{X_1} = g_1(\phi), -F_{X_2} = g_2(\phi), -F_{\phi} = X_1 g'_1(\phi) + X_2 g'_2(\phi) \) cannot be satisfied and SUSY is necessarily broken. There is a flat direction, since \( F_{\phi} = 0 \) fixes only a linear combination of \( X_1 \) and \( X_2. \)

There is also a continuous \( R \)-symmetry

- fields : \( X_1 \ X_2 \ \phi \)
- \( R \)-charge : \( 2 \ 2 \ 0 \)

FI models have (at least) an extra gauge group \( U(1)' \) and two charged fields \( \phi_\pm, \) with \( W = m\phi_+\phi_- \) and \( D = |\phi_+|^2 - |\phi_-|^2 + \xi, \) where \( \xi \) (positive in what follows) is the FI term.

(i) \( m^2 > g^2 \xi \rightarrow \langle \phi_\pm \rangle = 0, \) SUSY broken, \( U(1)' \) unbroken.
(ii) \( m^2 < g^2 \xi \rightarrow \langle \phi_+ \rangle = 0, \langle \phi_- \rangle \neq 0, \) both SUSY and \( U(1)' \) broken.

There is a continuous \( R \)-symmetry

- fields : \( \phi_+ \ \phi_- \)
- \( R \)-charge : \( 1 \ 1 \)

Obs: The existence of a \( U(1) \) \( R \)-symmetry seems to play a role in breaking SUSY. Indeed, if we break it in the FI model

\[ W' = m\phi_+\phi_- + \frac{\lambda}{\Lambda} (\phi_+\phi_-)^2 \] (2)

then a new SUSY minimum appears for

\[ \langle \phi_+\phi_- \rangle = -\frac{m\Lambda}{2\lambda} \] (3)

Coupling MSSM to the SUSY breaking sector \( \rightarrow \) soft breaking terms giving large masses to the superpartners of quarks, leptons and gauge fields.

2.1 Early attempts of model building

No low-energy SUSY breaking model with renormalizable interactions and tree/one-loop mediation of SUSY breaking was found (Fayet). Most of the subsequent efforts involved non-perturbative dynamics (DSB models), in combination with loop (gauge) mediation to the MSSM and gravity mediation to MSSM.

More recently, it was emphasized that local but very long-lived metastable vacua are generic in vector-like gauge theories in strong coupling [1]. They evade the criteria of supersymmetry breaking that we discuss below.
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3. Dynamical SUSY breaking (DSB)

Gauge coupling unification and the hierarchy problem favour a low (TeV) scale of supersymmetry breaking. Witten [2] suggested that in a GUT or SUGRA theory,

$$M_{SUSY} \leq M_{GUT}, \ M_P$$

points towards a dynamical SUSY breaking mechanism. If there is a (‘hidden’) supersymmetric sector, undergoing strong dynamics in analogy to QCD, then strong infra-red dynamics + dimensional transmutation lead to

$$M_{SUSY} = M_P e^{-8\pi^2/b_0 g^2(M_P)},$$

where $g = $ gauge coupling of the UV free theory and $b_0$ is its one-loop beta function.

Obs: Equation (4) can also be realized by Euclidian stringy instanton effects [3]

$$M_{SUSY} \sim M_P e^{-A(E_p)},$$

where $A(E_p)$ is the area of the cycle wrapped by a Euclidian $E_p$ brane in the internal space.

4. Criteria for SUSY breaking

(a) The Witten index criterion [5]: A necessary condition for SUSY breaking is

$$\text{Tr}(-1)^F = 0,$$

where

$$\text{Tr}(-1)^F = \sum_E (n_B - n_F)(E) = (n_B - n_F)(0)$$

is the number of bosonic states minus the number of fermionic states of zero energy. If $\text{Tr}(-1)^F \neq 0 \rightarrow $ SUSY unbroken. On the other hand, if $\text{Tr}(-1)^F = 0$, the Witten index cannot decide if supersymmetry is broken or not.

(b) The Affleck–Dine–Seiberg sufficient condition [4]: If (1) there is no flat direction in the classical scalar potential and (2) there exists a spontaneously broken global symmetry then supersymmetry is necessarily broken.

(Heuristic) Proof: (2) implies the existence of a Goldstone boson. Unbroken supersymmetry asks for the existence of a bosonic massless partner, which generically correspond to a non-compact flat direction. This contradicts (1). This criterion is particularly useful in searching for DSB models.

(c) The Nelson–Seiberg necessary condition [6]: In a theory with generic superpotential, the existence of a spontaneously broken, continuous $R$-symmetry, is a necessary condition for SUSY breaking.

Proof: Consider an effective theory with $n$ chiral fields $\phi_i$ of $R$-charges $r_i$. There are $n - 1$ $R$-invariants $\chi_i = \phi_i^{1/r_i} / \phi_1^{1/r_1}$. Then $W = \phi_1^{2/r_1} W(\chi_i)$. If $\phi_1 \neq 0$, the SUSY conditions

$$\partial_{\phi_i} W = \partial_{\chi_i} W = 0$$

are \( n \) equations for \( n - 1 \) variables, which cannot generically be solved (exception: \( r_1 = 2, r_i = 0 \)). For non-generic superpotentials, the result is not true.

All the criteria above are very useful, especially in models with DSB. However they all have loopholes in their arguments and are therefore not rigorous theorems.

5. Gravity and gauge mediation

5.1 Gravity mediation

In the gravity trasmission scenario, supersymmetry is broken in a ‘hidden’ sector which communicates with our sector (MSSM) via non-renormalizable interactions (e.g. SUGRA interactions)

\[
\text{MSSM} \leftrightarrow \text{Hidden Sector} \quad \text{nonren.int.} \quad T_i, \langle F_i \rangle \neq 0.
\]

Let us define the strength of supersymmetry breaking by

\[
F^2 = \sum_i |F_i|^2,
\]

then the strength of the supersymmetry breaking in the observable sector \( \bar{M}_{\text{SUGRA}} \), in the case of Minkowski 4d spacetime is controlled by the mass of the gravitino

\[
\bar{M}_{\text{SUGRA}} \sim m_{3/2}, \quad m_{3/2} = \frac{F}{\sqrt{3}M_P}. \tag{9}
\]

- Flavour changing neutral current (FCNC) effects are generically problematic in SUGRA theories: there are additional contributions, involving exchange of superpartners, not protected by the GIM mechanism.

Solutions for FCNC problem:

(i) Flavour universality in the family (flavour) space:

\[
(m_0^2)_{ij} \simeq m_0^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}.
\]

(ii) Alignment in the family space: \( (m_0^2)_{ij} \) are aligned to Yuk. \( Y_{ij} \): the unitary transformations diagonalizing fermion mass matrices diagonalize also the corresponding scalar mass matrices.

If none of the solutions (i) and (ii) are at work, then squark and slepton masses have to be heavier than 50 TeV or so! It is widely believed that universality and the alignment are not generic features of gravity mediation. This has to be addressed in a quantum theory of gravity like string theory.

- Gravity mediation provides a natural solution for the \( \mu \)-problem via the Giudice–Masiero mechanism [7].
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5.2 Gauge mediation

A simple way of getting flavour universality: breaking supersymmetry in a sector coupling to ‘messengers’, which are charged under the SM gauge interactions → transmission of SUSY breaking through SM gauge loops = gauge mediation [8]

\[
\text{SUSY breaking } \leftrightarrow \text{ Messenger } \leftrightarrow \text{ MSSM}
\]

\[
X = \langle X \rangle + \theta^2 F_X \rightarrow XM \bar{M} \rightarrow \text{ soft terms}
\]

Messengers are typically vector-like and charged under SM gauge groups. If \( SU(5) \) complete multiplets (say \( N \) pairs \( 5 + \bar{5} \)), they preserve MSSM gauge coupling unification.

- MSSM soft terms:
  1. Gaugino masses → 1-loop
     \[
     M_{1/2} \sim N \frac{g^2}{16\pi^2} \left( \frac{F_X}{\langle X \rangle} \right).
     \]
  2. Scalar (squarks, sleptons) masses: two-loops
     \[
     m_{0}^2 \sim N \left( \frac{g^2}{16\pi^2} \right)^2 \left( \frac{F_X}{\langle X \rangle} \right)^2.
     \]

We would like to discuss here some subtleties for the case where messengers are charged under an anomalous Abelian gauge group, a generic feature of string compactifications with \( D \)-branes. The messengers are defined to couple directly only to \( X_a \) via couplings as

\[
W_m = q_i (\lambda_{ija} X_a + M_{ij}) \tilde{q}_j,
\]

where \( \lambda_{ija} \) and \( M_{ij} \) are fixed by eventual hidden sector \( U(1) \) gauge invariance constraints. It is convenient in what follows to consider matrices in the messenger space \( \lambda_a \) and \( M \). Non-renormalizable couplings to \( X_a \) are also possible, but they do not change the conclusions of the present discussion. Let us start the discussion for simplicity with one field \( S \). The important things for the contributions to the soft terms from the messengers are encoded in their mass matrix and in particular in the value of its eigenvalues and supertrace. The scalar mass matrix for a couple of messengers generically coupled to a superfield \( X \) with a coupling \( \lambda \), and with charges \( q, \tilde{q} \) under \( U(1)_X \) is

\[
M_{ij}^2 = \left( \frac{\lambda^2 \langle S \rangle^2}{\lambda F_S} + q g_X^2 D \right) \left( \frac{\lambda F_S}{\lambda^2 S^2 + \tilde{q} g_X^2 D} \right),
\]

where \( D \) is the \( D \)-term of \( U(1)_X \), \( g_X^2 \) its coupling constant and \( F_S \) the \( F \)-term of the field \( S \).

It is well-known (but sometimes overlooked) that in the presence of \( D \)-term contributions in the hidden sector, that are generic in string theory constructions, there are some constraints and ingredients to take into account.

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(a) The absence of the one-loop induced Fayet–Iliopoulos term for the hypercharge imposes the condition

\[ \xi_Y \sim \text{Tr} \left( Y \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 + M_0^2} \right) = 0, \]  

where \( X \) is the \( U(1) \) generator of the hidden sector, \( M_0^2 \) the scalar messenger mass, and \( \xi_Y \) the corresponding FI term. Notice that condition (15) is stronger than the absence of the logarithmically divergent piece [7a]

\[ (\text{Tr} Y M_0^2)_{\text{mess}} = (\text{Tr} Y X)(D) = 0, \]  

equivalent to the absence of mixing between hypercharge and \( U(1)_X \). A sufficient (but \textit{a priori} not necessary) solution to (15) is to consider vector-like (with respect to the SM gauge group) messenger fields with equal \( U(1)_X \) charge \( q = \tilde{q} \)

\[ \begin{pmatrix} U(1)_Y \\ U(1)_X \end{pmatrix} \]

\[ M \quad y \\ \tilde{M} \quad \tilde{y} \]

where we displayed only the Abelian charges of the messenger fields \( M, \tilde{M} \). Notice that having vector-like messenger fields with respect to all gauge groups, i.e. charges \((y, q)\) for \( M \) and \((-y, -q)\) for \( \tilde{M} \) does generate a FI term for the hypercharge which phenomenologically, if non-zero, has to be very small. Some recently proposed string models with supersymmetry breaking and gauge mediation fall unfortunately into this category and are therefore phenomenologically unacceptable.

(b) If \( (\text{Str} M^2)_{\text{mess}} \neq 0 \), there are new contributions to the scalar masses (but not to the gaugino masses) [9,12]. They can generate phenomenological problems [12] or, on the contrary, in a well-defined theory containing gravity, can generate an original compressed low-energy spectrum, with squarks lighter than sleptons at high energy [9]. These new terms are proportional to

\[ (\text{Str} M^2)_{\text{mess}} = (\text{Str} X) g_X^2 (D). \]  

By assuming (17) \( q = \tilde{q} \), the two eigenvalues of (14) are given by

\[ m_\pm^2 = \left( (\lambda(S))^2 + qg_X^2 D \right) - \lambda F_S, \quad m_\pm^2 = \left( (\lambda(S))^2 + qg_X^2 D \right) + \lambda F_S, \]

whereas the fermion mass is given by

\[ m_f = \lambda(S). \]

The supertrace is then

\[ (\text{Str} M^2)_{\text{mess}} = 2qg_X^2 D \neq 0. \]  

By standard gauge-mediation type diagrams, gaugino masses are induced at one-loop, whereas scalar masses are induced at two-loops. However, as explained above, in the presence of a non-vanishing supertrace for the messengers, the computation of the scalar masses is slightly different compared to the standard gauge-mediation.
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models, as shown by Poppitz and Trivedi [12]. In particular the result is not anymore UV finite, and there is a logarithmically divergent term.

Whenever we are interested in a predominantly standard gauge mediation spectrum, in addition to the well-known condition $M_{\text{GM}} \gg m_{3/2}$, where

$$ M_{\text{GM}} \sim \frac{g^2}{16\pi^2} \sum_a \text{Tr}(\hat{\lambda}_a M^{-1})F_a $$

(22)

is the typical scale of the soft terms in standard gauge mediation and $m_{3/2}$ is the gravitino mass, the vanishing of the two additional contributions (15), (18) has to be imposed. On the more quantitative level, standard gauge mediation contributions dominate over non-standard ones (18) for

$$ M_{\text{GM}}^2 \gg (\text{Tr } X)(D). $$

(23)

Whereas a small value of the induced FI term for the hypercharge (15) and some of the non-standard contributions (18) can be allowed, their complete absence entails the following simple constraints:

$$ \text{Tr } X = 0, \text{ Tr } \left( Y \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 + M_0^2} \right) = 0. $$

(24)

Problems of gauge mediation:

(c) It is very difficult to generate $\mu$, $B\mu$ of correct size for electroweak symmetry breaking.

(d) Basically there are no explicit complete model with supersymmetry breaking in the ground state and viable mediation to the observable sector. Recently, new constructions based on metastable vacua provided viable models, even with purely renormalizable interactions (e.g. Shih et al).

6. Hybrid models

In several recent works (moduli stabilization + uplift with FI model, metastable vacua) messengers are very heavy ($m_M \sim 10^{15}$ GeV). Then $m_{3/2} \sim M_{\text{GMSB}}$ and SUGRA and GMSB contributions are comparable.

- Hybrid models have new particle spectra and signatures.

  E.g. Hybrid models with non-standard (negative) gauge mediation contributions generated by messengers under anomalous Abelian gauge symmetries [9] have (generically) sleptons heavier than squarks and a compressed particle spectrum at low energy.

- Hybrid models could combine advantages of both SUSY breaking mechanisms if

$$ M_{\text{GMSB}} \sim \text{TeV} \sim 10^{-30}m_{3/2}. $$

(25)

This is naturally realized if the messenger mass matrix is [10]
\[ M = \lambda_1 X + \lambda_2 \Sigma, \] (26)

where \( \Sigma \) is the SU(5) GUT adjoint breaking \( SU(5) \to SU(3) \times SU(2) \times U(1) \). If \( \lambda_2 \sim 0.1 \) and \( \langle X \rangle \ll \langle \Sigma \rangle \), then messenger masses are of order \( 10^{15} \text{ GeV} \), we get (25), and there is a splitting between doublet and triplet messengers \( M_\text{tr}/M_\text{d} = -2/3 \).

Since \( \langle \Sigma \rangle \sim V Y \), where \( Y \) is the hypercharge generator, we get a very peculiar spectrum. For 5–5 messenger spectrum we get

\[
\begin{align*}
\frac{M_3}{\alpha_3} & = -\frac{3}{2} \frac{M_2}{\alpha_2}, \\
M_1 & \sim m_{3/2}, \quad \mu, B \sim 500 \text{ GeV}, \\
m^2_{\text{scalars}} & \sim \text{TeV}^2.
\end{align*}
\]

\[
(27)
\]

\[ \bullet \] Lightest neutralino is mostly bino and is much lighter than the other superpartners.

This is independent of the messenger representations and happens because GMSB contributions to the neutralino mass vanishes

\[
(M_1)_{\text{GMSB}} \sim \text{Tr}(Y^2/M) \sim \text{Tr Y} = 0.
\]

Even if this is gauge mediation, the LSP is the neutralino!

\[ \bullet \] Due to the SU(5) messenger doublet-triplet splitting \( M_3 = -\frac{3}{2} M_2 \), we get specific values for quarks versus lepton scalar masses from generalized gauge mediation diagrams.

Compared to minimal gauge mediation, the ratio of various masses depend on the GUT representation of the messengers. For e.g. for 10–\bar{10} messenger spectrum we get

\[
\frac{M_3}{\alpha_3} = \frac{7}{12} \frac{M_2}{\alpha_2}.
\]

\[
(29)
\]

In strings and D-brane models with controllable instantonic effects, hybrid models seem very generic, whereas minimal gauge mediation models seem very difficult to realize [11]. The reason is related to the various constraints of moduli stabilization and gauge invariance in effective string theory models, which very often contain anomalous gauge symmetries with Green–Schwarz mechanism of anomaly cancelation.

7. Metastable supersymmetry breaking


Heuristic argument: Global SUSY breaking (especially DSB) in the ground state asks for continuous \( R \)-symmetry. This is problematic:

(a) spontaneously broken \( \to \) massless axion,

(b) unbroken \( \to \) no gaugino masses.
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In 2006, Intriligator–Seiberg–Shih constructed simple DSB long-lived metastable vacua in SQCD with gauge group $SU(N_c)$ and number of flavours $N_c + 1 < N_f < 3N_c/2$.

In the ‘electric’ theory, there are (antiquarks) quarks $(\bar{Q}_j)Q^i$, with mass terms

$$ W_{mass} = m\delta^i_j\bar{Q}^i\bar{Q}_j. \quad (30) $$

There is a dual ‘magnetic’ theory with gauge group $SU(N_f - N_c)$, $N_f$ flavours of (antiquarks) quarks $(\bar{q}_j)q^i$, elementary mesons $M^i_j$ and superpotential

$$ W = h\bar{q}M\bar{q} - h\mu^2 \text{Tr} M, \quad (31) $$

where $\mu^2 = mA$ and $A$ is the dynamical scale of the electric theory. For $N_f < 3N_c/2$, the magnetic theory is IR free and admits a perturbative description.

By neglecting gauge interactions, this is a O'R sector breaking SUSY by the rank reduction.

ISS analysis holds if $\mu \ll A_m$, where $A_m$ denotes the Landau pole in the magnetic theory. After adding gauge interactions, the ISS vacuum becomes metastable. A non-perturbative superpotential arises

$$ W_{np} = (N_f - N_c)\left(\frac{hN_f\det M}{A_m^{3N_f-2N_c}}\right)^{1/(N_f - N_c)} \quad (32) $$

such that the full theory has $N_c$ SUSY minima at

$$ hM = e^{2(N_f - N_c)/N_c}A_m = \frac{\mu}{e^{(3N_f - 2N_c)/N_c}}. \quad (33) $$

The lifetime of the false vacuum is of order $e^{S_b}$, where the bounce action is

$$ S_b = \frac{1}{e^{(3N_f - 2N_c)/N_c}} \gg 1. \quad (34) $$

Several groups did use the ISS model for gauge mediation SUSY breaking to MSSM. As it stands, the model has an unbroken approximate $R$-symmetry in the ISS vacuum → no gaugino masses. Variations of the model with metastable vacua and without $R$-symmetry do exist.

$$ W'_{m} = \frac{1}{m_X}(Q\bar{Q})(Q\bar{Q}) \rightarrow W'_{m} = \frac{1}{m_X}MM. \quad (35) $$

An interesting proposal: The SM gauge group is part of the flavour symmetry of the ISS model → the ISS fields break SUSY and are messengers at the same time (Kitano, Ooguri and Ookouchi; Csaki et al).

Smoking gun: Some ISS/messenger fields are light, in the TeV range (masses through radiative corrections).
7.1 Small R-symmetry breaking and metastable vacua

Strategy:
- Start with a SUSY breaking (R-symmetric) O’R or FI model.
- Add a term in the Lagrangian breaking explicitly R-symmetry, with a small coefficient $\epsilon \rightarrow$ a new SUSY vacuum appears for large vev’s $\Phi \sim 1/\epsilon$.
- For $\epsilon \ll 1$, the old SUSY breaking vacuum is still locally stable.
- The lifetime of the false vacuum is very large ($\tau \sim \exp(1/\epsilon^m)$), with $m = 3, 4$.

O’R example: (Intriligator–Seiberg–Shih [13]): There is some tension here between the smallness of the parameter $\epsilon$ and the required magnitude of the induced gaugino masses, which vanish in the $\epsilon \rightarrow 0$ limit.

8. Conclusions and prospects

We reviewed the main mechanisms of supersymmetry breaking and transmission to the observable sector in supersymmetric extensions of the Standard Model. It was argued that, whereas both gravity and gauge mediations have advantages and problems, in a hybrid scenario where they compete with each other, advantages can add up whereas they can mutually solve their problems. We also discuss some subtleties concerning gauge contributions in string effective models where messengers are charged under anomalous gauge symmetries with $D$-term contributions to their masses. We also show a simpler hybrid model with gauge mediation dominance where the LSP is the lightest neutralino, which is naturally much lighter than the rest of superpartners. Most of the recent progress in the field was stimulated by the recently discovered long-lived metastable non-supersymmetric vacua in vector-like supersymmetric gauge theories.

LHC will start in 2008 the hunt for physics BSM and particularly low-energy SUSY. I would classify the SUSY spectrum in three categories:
- generic SUGRA mediation $\rightarrow$ all soft terms of the same order $m_{\text{soft}} \sim m_{3/2}$, but numerically different.
- gauge mediation $\rightarrow$ flavour universality and some correlation between the different soft terms. Very likely that this will be a metastable vacuum, in which case ‘there are reasons of anxiety’ (Coleman, 1977), but potential new low-energy physics beyond MSSM.
- some flavour symmetry governing both Yukawas and SUSY breaking $\rightarrow$ correlation/alignment between fermion masses and soft terms for different families.
- some combination of all this $\leftrightarrow$: hybrid models with interesting spectra, that deserve further studies.
- a string SUSY breaking (Scherk–Schwarz, non-BPS configurations, intersecting branes, fluxes).

In some of these cases, string theory/extra dims. could be accessible to LHC $\rightarrow$ the dream of string theorists. In any case, in a couple of years, we will probably know how SUSY was broken in nature!
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References

[7a] The quadratic divergence cancels since Tr $Y = 0$