Gravity Mediation: soft breaking terms in $N = 1$ supergravity

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Based on:

Outline

- The goals of supersymmetric models
- Some “basic problems”
- How to hide the hidden sector
- Gaugino condensation
- Gravity mediation
- Solution to “basic problems”
- Embedding in heterotic string theory
- Modulus mediation
- The hidden wall in M-theory
- Mirage mediation
Goals of SUSY

Supersymmetric model building tries to achieve the following goals:

- explain the hierarchy between Planck scale and weak scale
- give soft supersymmetric breaking terms that are phenomenologically consistent
- explain $SU(2) \times U(1)$ breakdown as a consequence of supersymmetry breakdown
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The last problem needs the consideration of supergravity!
MSSM

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- $Q, U, D$ for quarks and partners
- $L, E$ for leptons and partners
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with superpotential

$$W = QHD + Q\bar{H}U + LHE + \mu H\bar{H}.$$ 

Also allowed are

$$UDD + QLD + LLE.$$
Proton stability in supersymmetric models requires a new symmetry, R-parity, that forbids dangerous operators (even of dimension 4):

- UDD and QLD are forbidden
- H and L can be distinguished
- superpartners of known particles are odd under R-parity
- superpartners are produced in pairs
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- the good news is a stable particle (LSP)

But there is also bad news.
If we consider the MSSM and postulate R-parity we get an enhancement to a continuous R-symmetry. This symmetry forbids gaugino masses, and leads to a harmful axion in the case of spontaneous breakdown (by Higgs fields).
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This needs new structure beyond the MSSM!
Hidden sectors

This also seems to be true for the unsatisfactory tree level mass relations:

\[ StrM^2 = 0 \]

(Ferrara, Girardello, Palumbo, 1979)

- gaugino masses vanish at level of renormalizable couplings (dimension 5 operators are required)
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\[ \] gaugino masses vanish at level of renormalizable couplings (dimension 5 operators are required)

So the supersymmetry breakdown has to be somehow remote from the particles of the MSSM

a “hidden sector”

interacting weakly with the “observable sector”.
How to hide the hidden sector?

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This was the reason for me to learn supergravity

- after all gravity exists
- the question of the vacuum energy can be solved
- Moreover, “dynamical” SUSY breakdown did not seem to work in the case of global supersymmetry
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At that time supergravity was still quite young

(Cremmer, Julia, Scherk, van Nieuwenhuizen, Ferrara, Girardello, 1979)
How to obtain the small scale

Hidden sector gaugino condensation: $(\lambda\lambda) = \Lambda^3$

$$\Lambda \sim \mu \exp(-1/g^2(\mu)) << M_{\text{Planck}}$$

leads to gravitino mass

$$m_{3/2} \sim \Lambda^3 / M_{\text{Planck}}^2$$

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SUSY breakdown requires nontrivial gauge kinetic function:

\[
F_i = \exp(-K/2)D_i W + f_i(\lambda\lambda) + \ldots
\]

(Ferrara, Girardello, HPN, 1983)
Hidden sector gaugino condensation

Four-Fermi-terms

\[ \frac{h}{M^2} (\lambda \lambda) (\chi \chi) \]

lead to gaugino masses

\[ m_{1/2} = \frac{h}{M^2} (\Lambda^3) \sim m_{3/2}. \]
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Other soft terms are induced by radiative corrections.

In this simple scheme the gaugino mass might be the dominant soft parameter in the low energy spectrum.
Soft terms

Soft mass terms can be of the type

- $\phi \phi^*$ for complex scalar field $\phi$
- $\phi^2 + \phi^*2$ (as in F-term breaking)

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- $\phi\phi^*$ for complex scalar field $\phi$
- $\phi^2 + \phi^{*2}$ (as in F-term breaking)

as well as

- trilinear terms $\phi^3 + \phi^{*3}$
- gaugino masses $\chi\bar{\chi}$

which are forbidden by the (continous) R-symmetry

(Girardello, Grisaru, 1982)
Some “basic problems”

Remember, spontaneously broken SUSY needs to overcome some basic obstacles:

- positive $m^2$ for all scalar masses
  $(StrM^2 = 0$ for F-term breakdown at tree level)$
- question of nonvanishing gaugino masses (tree level)
- the appearance of a harmful R-axion
- The cosmological constant $E_{\text{vac}}$ is too large
Observe that (continuous) R-symmetry is broken explicitly through the presence of a nonvanishing gravitino mass

\[ m_{3/2} = \exp(-K) W \]

- positive \( m^2 \) for scalar masses
- nonvanishing gaugino masses
- no R-axion
- the cosmological constant \( E_{\text{vac}} \) might vanish (e.g. as a result of some fine-tuning)
Thus spontaneously broken supergravity solves the problems. The scheme consists of

- an observable sector containing the spectrum of the MSSM and
- a hidden sector that is responsible for supersymmetry breakdown,

coupled only through interactions of gravitational strength.

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- an **observable sector** containing the spectrum of the MSSM and
- a **hidden sector** that is responsible for supersymmetry breakdown,

coupled only through **interactions of gravitational strength**.

*(HPN, 1982)*

This is the scheme called gravity mediation (msugra)
Scale of Susy breakdown

The size of the soft terms is set by the gravitino mass

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\]

The soft terms could be smaller than \(m_{3/2}\), but at most by a few orders of magnitude

We therefore expect \(m_{3/2}\) to be in the (multi) TeV range and thus \(F_{\text{SUSY}}\) at the intermediate scale

\[
F_{\text{SUSY}} \sim 10^{11}\text{GeV}.
\]
Completing the action

Early 1982 the general coupling of N=1 supergravity to matter and gauge fields had not been worked out. In spring this was finally done (Cremmer, Ferrara, Girardello, van Proeyen, 1982)

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Early 1982 the general coupling of N=1 supergravity to matter and gauge fields had not been worked out. In spring this was finally done (Cremmer, Ferrara, Girardello, van Proeyen, 1982)

and brought a surprise:

\[ StrM^2 = 2(N - 1)m_{3/2}^2 \]

in the presence of \( N \) chiral supermultiplets.

Masses of the scalar partners of quarks and leptons could be lifted even at tree level
Explicit models were considered by

(Barbieri, Ferrara, Savoy; Arnowit, Chamseddine, Nath, 1982)

The models assumed minimal kinetic terms for the scalar fields and a superpotential

\[ W = h(z) + g(y_i), \]

where \( z \) denotes a hidden sector chiral superfield and \( y_i \) those of the observable sector.
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Supersymmetry was broken in the way suggested by Polonyi

\[ W = mM(z + \beta M) \text{ with } \beta = 2 - \sqrt{2} \text{ for } E_{\text{vac}} = 0 \]
Explicit models II

Susy is broken in the hidden sector with a gravitino mass

\[ m_{3/2} = m \exp \left( \frac{1}{2} (\sqrt{3} - 1)^2 \right) \]

so \( m \) should be chosen in the TeV range.
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The scalar masses of the \( y_i \) are all lifted to a common value of

\[ m_0 = m_{3/2}. \]

The masses are degenerate because of the choice of common (minimal) kinetic terms.
General scheme

Parametrizing the hidden sector by:

\[ \langle z_i \rangle = b_i M \quad \text{and} \quad \langle h_i \rangle = a_i^* m M \]

we can derive a general formula for the soft terms.

(HPN, Srednicki, Wyler, 1982)
General scheme

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The vacuum energy can be cancelled by an appropriate choice of the \( a_i \) and \( b_i \) and all the soft terms can be computed.

The A-parameter (the coefficient of the trilinear scalar interactions) is given by

\[ A = b_i^* (a_i + b_i) \]
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in the scalar sector.

The soft gaugino masses are generated at tree level if the theory has a nontrivial gauge kinetic function

\[ m_{1/2} = \frac{\partial f}{\partial z_i} m_{3/2} \]

(Ferrara, Girardello, HPN, 1983)
String theory

This scheme has a natural embedding in the heterotic $E_8 \times E_8$ string theory.

- $SU(3) \times SU(2) \times U(1)$ from first $E_8$
- hidden sector **gaugino condensation** from subgroup of second $E_8$
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- hidden sector gaugino condensation from subgroup of second $E_8$

An important role is played by the antisymmetric tensor field of 10d supergravity

- its field strength stabilizes the gaugino condensate

(Derendinger, Ibanez, HPN; Dine, Rohm, Seiberg, Witten, 1985)
Flux and Chern-Simons terms

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Need modification

$$H = dB + \alpha' (\omega^{YM} - \omega^L)$$

with $\omega^{YM} = AF + \frac{2}{3} A^3$ and $\omega^L = \omega R + \frac{2}{3} \omega^3$

such that $dH = \text{Tr} F^2 - \text{Tr} R^2$.

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The 4d potential contains the “perfect square” structure

$$\left( dB + \alpha'(\omega^\text{YM} - \omega^\text{L}) - \alpha'(\lambda \lambda) \right)^2$$
Chern-Simons terms

Observe that

- \( dB \) is quantized in units of the string scale, \( (\text{Rohm, Witten, 1985}) \)
- \( \omega^{YM} \) and \( (\lambda\lambda) \) are both \( \alpha' \) corrections.
Chern-Simons terms

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- $\omega^{YM}$ and $(\lambda\lambda)$ are both \textit{“$\alpha'$ corrections”}.

This led to the conjecture that

- the gaugino condensate is compensated by a Chern-Simons term,  
  \[(\text{Derendinger, Ibanez, HPN, 1986})\]

avoiding the quantization constraint.
Modulus Mediation

In such a scheme, the fields responsible for the breakdown of supersymmetry are moduli fields like

- the dilaton $S$
- or the Kähler moduli $T$.

This is why this scheme is often called modulus mediation.
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It is the natural embedding of gravity mediation in the framework of string theory.
Further support for this conjecture comes from Heterotic M-theory (Horava, Witten, 1996)

with gravity multiplet in the bulk and $E_8 \times E_8$ on the branes
Chern-Simons terms im M-theory

- three index tensor field $C_{NMP}$ lives in bulk
- again field strength $G = dC + \text{Chern} – \text{Simons}$
- gauge supermultiplets live on the boundaries (branes)
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$$G = (dC) + \alpha' \sum_i \delta(x_{11} - x_{11}^i) \left( \omega_i^{YM} - \frac{1}{2} \omega_i^L \right)$$
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\begin{align*}
G &= (dC') + \alpha' \sum_i \delta(x_{11} - x^i_{11}) \left( \omega^{YM}_i - \frac{1}{2} \omega^L_i \right) \\
\text{and} \quad dG &= \text{Tr} F^2_1 + \text{Tr} F^2_2 - \text{Tr} R^2
\end{align*}
Chern-Simons terms im M-theory (II)

- Flux $dC$ lives in the bulk
- Gauge fields and gauginos live on the branes
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and this suggest a local compensation on the boundary

$$\left( \alpha' (\omega_i^{YM} - \omega_i^L) - \alpha' (\lambda_i \lambda_i) \right)^2$$

(HPN, Olechowski, Yamaguchi, 1997)
Chern-Simons terms in M-theory (II)

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This suggests that

- supersymmetry is broken on a hidden brane
- the hidden sector becomes a hidden wall
The hidden wall

This suggestion of susy breakdown on a hidden wall fits perfectly in the picture of other string theories with D-branes and fluxes, e.g.

- moduli stabilization by $H_3$ and $F_3$ fluxes in Type IIB theory  
  (Giddings, Kachru, Polchinski, 2002)
- $T$ modulus fixed by gaugino condensation  
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So the message is:

- supersymmetry breaks at a hidden brane and is
- mediated by bulk moduli to the observable sector.
Signals of the scheme

Are there some model independent properties of the soft mass terms?

We always have

\[ W = \text{something} - \exp(-X) \]

where “something” is small and \( X \) is moderately large
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Are there some model independent properties of the soft mass terms?

We always have

\[ W = \text{something} - \exp(-X) \]

where “something” is small and \( X \) is moderately large

In fact

\[ X \sim \log(M_{\text{Planck}}/m_{3/2}) \]

providing a “little” hierarchy.

(Choi, Falkowski, HPN, Olechowski, 2005)
Mixed Modulus Anomaly Mediation

The contribution from “Modulus Mediation” is therefore suppressed by the factor

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Numerically this factor is given by: \[ X \sim 4\pi^2. \]
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Thus loop corrections known as “Anomaly Mediation” become competitive, leading to a Mixed Modulus-Anomaly-Mediation scheme.

For reasons that will be explained later we call this scheme MIRAGE MEDIATION

(Loaiza, Martin, HPN, Ratz, 2005)
The little hierarchy

\[ m_X \sim \langle X \rangle m_{3/2} \sim \langle X \rangle^2 m_{\text{soft}} \]

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- moduli and gravitino are heavy
- relieves the Susy flavour and CP problems
- distinct pattern of soft breaking terms.

(Endo, Yamaguchi, Yoshioka, 2005; Choi, Jeong, Okumura, 2005)
Mirage Unification

Mirage Mediation provides a characteristic pattern of soft breaking terms.
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To see this, let us consider the gaugino masses

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as a sum of two contributions of comparable size.
Mirage Unification

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as a sum of two contributions of comparable size.

- $M_{\text{anomaly}}$ is proportional to the $\beta$ function, i.e. negative for the gluino, positive for the bino

- thus $M_{\text{anomaly}}$ is non-universal below the GUT scale
Evolution of couplings
The Mirage Scale

\[ \text{log}_{10}(\mu/\text{GeV}) \]

\[ M_1 \]

\[ M_2 \]

\[ M_3 \]

(Lebedev, HPN, Ratz, 2005)
The Mirage Scale (II)

The gaugino masses coincide

- above the GUT scale
- at the mirage scale

\[ \mu_{\text{mirage}} = M_{\text{GUT}} \exp\left(-\frac{8\pi^2}{\alpha}\right) \]
The Mirage Scale (II)

The gaugino masses coincide

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\[ \mu_{\text{mirage}} = M_{\text{GUT}} \exp(-8\pi^2/\alpha) \]

where \( \alpha \) denotes the “ratio” of the contribution of modulus vs. anomaly mediation. We write the gaugino masses as

\[ M_a = M_s (\alpha + b_ag_a^2) = \frac{m_3/2}{16\pi^2} (\alpha + b_ag_a^2) \]

and \( \alpha \to 0 \) corresponds to pure anomaly mediation.
Constraints on the mixing parameter

\[ \alpha \]

- \( \tan \beta = 30 \)
- \( m_t = 172 \text{ GeV} \)
- \( \text{sgn } \mu = +1 \)

- TACHYONS
- \( \tilde{\tau}_L \text{ LSP} \)
- ALLOwed
- \( m_h < 114 \text{ GeV} \)

(Löwen, HPN, Ratz, 2006)
Constraints on $\alpha$

$L_{\tan\beta=5}$ $m_t=172\text{ GeV}$ $\text{sgn}\mu=+1$

$\tilde{t}_1, \text{LSP}$

$TACHYONS$

$\tilde{m}_h < 114\text{ GeV}$

ALLOWED

$(\text{Löwen, HPN, Ratz, 2006})$
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The scale of soft masses is set by the gravitino mass.
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Gravity Mediation has a natural embedding in heterotic string theory:

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These schemes are known under the name of Modulus and/or Mirage Mediation.
Conclusion

The general scheme

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We are waiting for

- LHC to confirm this picture.