Outline

- **Basic questions:** moduli stabilization and scale of Supersymmetry breakdown
- A large hierarchy creates a *little* hierarchy
- **Mirage Mediation**
- Distinct “compressed” pattern of soft terms
- Some remarks on *fine tuning*
- Robust prediction for gaugino masses
- **The Gaugino Code**
- Identification of string schemes
- Conclusions and outlook
Two Basic Questions

- origin of the small scale?
- stabilization of moduli?
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- stabilization of moduli?

Recent progress in

- moduli stabilization via fluxes in warped compactifications of Type IIB string theory  
  (Dasgupta, Rajesh, Sethi, 1999; Giddings, Kachru, Polchinski, 2001)

- generalized flux compactifications of heterotic string theory  
  (Becker, Becker, Dasgupta, Prokushkin, 2003; Gurrieri, Lukas, Micu, 2004)

- combined with gaugino condensates and “uplifting”  
  (Kachru, Kallosh, Linde, Trivedi, 2003)
Mediation schemes

Supersymmetry is broken in a hidden sector and we have a variant of so-called gravity mediation

- tree level dilaton/modulus mediation
  
  (Derendinger, Ibanez, HPN, 1985; Dine, Rohm, Seiberg, Witten, 1985)

- radiative corrections in case of a sequestered hidden sector (e.g. anomaly mediation)
  
  (Randall, Sundrum, 1999)
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  (Randall, Sundrum, 1999)

The importance of the mechanism to adjust the cosmological constant has only been appreciated recently

(Choi, Falkowski, HPN, Olechowski, Pokorski, 2004)
Fluxes and gaugino condensation

Is there a general pattern of the soft mass terms?

We always have (from flux and gaugino condensate)

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

where “something” is small and \( X \) is moderately large.
Fluxes and gaugino condensation

Is there a general pattern of the soft mass terms?

We always have (from flux and gaugino condensate)

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

where “something” is small and $X$ is moderately large.

In fact in this simple scheme

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

providing a “little” hierarchy.

(Choi, Falkowski, HPN, Olechowski, Pokorski, 2004)
The contribution from “Modulus Mediation” is therefore suppressed by the factor

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

Numerically this factor is given by: \( X \sim 4\pi^2 \).
Mixed Modulus Anomaly Mediation

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Numerically this factor is given by: \( X \sim 4\pi^2 \).

Thus the contribution due to radiative corrections e.g. “Anomaly Mediation” becomes competitive, leading to a Mixed Modulus-Anomaly-Mediation scheme.

For reasons that will be explained later we call this scheme \textbf{MIRAGE MEDIATION}

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

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

is a generic signal of such a scheme

- moduli and gravitino are heavy
- gaugino mass spectrum is compressed

(Choi, Falkowski, HPN, Olechowski, 2005; Endo, Yamaguchi, Yoshioka, 2005; Choi, Jeong, Okumura, 2005)

- such a situation occurs if SUSY breaking is e.g. “sequestered” on a warped throat

(Kachru, McAllister, Sundrum, 2007)
Mirage Unification

Mirage Mediation provides a characteristic pattern of soft breaking terms.

To see this, let us consider the gaugino masses

\[ M_{1/2} = M_{\text{modulus}} + M_{\text{anomaly}} \]

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

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

\[ \alpha_i \]

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The Mirage Scale

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

\( M_1 \)

\( M_2 \)

\( M_3 \)

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

The gaugino masses **coincide**

- above the GUT scale
- at the mirage scale

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

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

\[ M_a = M_s (\rho + b_a g_a^2) = \frac{m_{3/2}}{16\pi^2} (\rho + b_a g_a^2) \]

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

\[
\begin{align*}
\tan \beta &= 5 & \text{sign } \mu &= 1 & m_t &= 172 \text{ GeV} \\
\frac{m_{3/2}}{\sqrt{2}} &\leq 1 \text{ TeV} & m_h &< 114 \text{ GeV} \\
\theta_1 &\text{ LSP} \\
\text{TACHYONS} \\
\text{ALLOWED}
\end{align*}
\]

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

\begin{align*}
\tan \beta &= 30 \\
\text{sign } \mu &= 1 \\
m_t &= 172 \text{ GeV}
\end{align*}

TACHYONS

\[ m_{3/2} \text{ (TeV)} \]

\[ \tilde{\chi}_1 \text{ LSP} \]

\[ m_h \lesssim 114 \text{ GeV} \]

ALLOWED

(Löwen, HPN, Ratz, 2006)
The “MSSM hierarchy problem”

The scheme predicts a rather high mass scale

- heavy gravitino
- rather high mass for the LSP-Neutralino
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- rather high mass for the LSP-Neutralino

One might worry about a fine-tuning to obtain

the mass of the weak scale around 100 GeV from

\[
\frac{m_Z^2}{2} = -\mu^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1},
\]

and there are large corrections to \( m_{H_u}^2 \).....

(Choi, Jeong, Kobayashi, Okumura, 2005)
Evolution of Higgs masses

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

\[ m_{H_i}^2/\text{TeV}^2 \]

\[ m_{H_u}^2 \]

\[ m_{H_d}^2 \]
Evolution of Squark masses

\[ m_{\tilde{q}_L}^2 / \text{TeV}^2 \]

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

- tachyonic region

\[ m_{\tilde{q}_L}^{(0)}, m_{\tilde{q}_L}^{(1)}, m_{\tilde{q}_L}^{(2)}, m_{\tilde{q}_L}^{(3)} \]
Evolution of Squark masses

\[
\begin{align*}
\log_{10}(\frac{\mu}{\text{GeV}}) & \quad m_{\tilde{u}_R}^2/\text{TeV}^2 \\
\end{align*}
\]

\[
\begin{align*}
\log_{10}(\frac{\mu}{\text{GeV}}) & \quad m_{\tilde{u}_R}^{(1)}/\text{TeV}^2 \\
\end{align*}
\]

\[
\begin{align*}
\log_{10}(\frac{\mu}{\text{GeV}}) & \quad m_{\tilde{u}_R}^{(2)}/\text{TeV}^2 \\
\end{align*}
\]

\[
\begin{align*}
\log_{10}(\frac{\mu}{\text{GeV}}) & \quad m_{\tilde{u}_R}^{(3)}/\text{TeV}^2 \\
\end{align*}
\]

tachyonic region

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The “MSSM hierarchy problem”?

The influence of the various soft terms is given by

\[ m_Z^2 \simeq -1.8 \mu^2 + 5.9 M_3^2 - 0.4 M_2^2 - 1.2 m_{H_u}^2 + 0.9 m_{q_L}^{(3)} + \]

\[ + 0.7 m_{u_R}^{(3)} - 0.6 A_t M_3 + 0.4 M_2 M_3 + \ldots \]
The “MSSM hierarchy problem”?

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\[ m_Z^2 \simeq -1.8 \mu^2 + 5.9 \, M_3^2 - 0.4 \, M_2^2 - 1.2 \, m_{H_u}^2 + 0.9 \, m_{q_{L(3)}}^2 + \]
\[ + 0.7 \, m_{u_{R(3)}}^2 - 0.6 \, A_t \, M_3 + 0.4 \, M_2 \, M_3 + \ldots \]

Mirage mediation improves the situation

- especially for small \( \rho \)
- because of a reduced gluino mass and a “compressed” spectrum of supersymmetric partners

(Choi, Jeong, Kobayashi, Okumura, 2005)

- explicit model building required

(Kitano, Nomura, 2005; Lebedev, HPN, Ratz, 2005; Pierce, Thaler, 2006; Dermisek, Kim, 2006; Ellis, Olive, Sandick, 2006; Martin, 2007)
Explicit schemes I

The different schemes depend on the mechanism of uplifting:

- uplifting with anti D3 branes

  \( \rho \sim 5 \) in the original KKLT scenario leading to a mirage scale of approximately \( 10^{11} \) GeV

This scheme leads to pure mirage mediation:
- gaugino masses and
- scalar masses

both meet at a common mirage scale

(Kachru, Kallosh, Linde, Trivedi, 2003)
Constraints on $\rho$

$m_{3/2}$ (TeV) vs $\rho$

- TACHYONS
- $\tilde{t}_1$ LSP
- $m_h < 114$ GeV
- ALLOWED

- $\tan \beta = 30$
- sign $\mu = 1$
- $m_t = 172$ GeV

(Löwen, HPN, Ratz, 2006)
The Mirage Scale

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

\[ M_i/\text{GeV} \]

\[ M_3 \]

\[ M_2 \]

\[ M_1 \]

(Lebedev, HPN, Ratz, 2005)
Explicit schemes II

- uplifting via matter superpotentials

  - allows a continuous variation of $\rho$
  - leads to potentially \textit{new contributions} to sfermion masses

(Lebedev, HPN, Ratz, 2006)
Explicit schemes II

- uplifting via matter superpotentials
  - allows a continuous variation of $\rho$
  - leads to potentially new contributions to sfermion masses
- gaugino masses still meet at a mirage scale
- soft scalar masses might be dominated by modulus mediation
- similar constraints on the mixing parameter

(Lebedev, HPN, Ratz, 2006)
Constraints on the mixing parameter

\[
\rho \sim 0 \rightarrow 2 \rightarrow 4 \rightarrow 6 \rightarrow 8 \rightarrow 10
\]

\[
\frac{3}{2} / \frac{1}{2} \text{LParen} / \text{TeV} \text{RParen} = 1
\]

\[
\tan \beta = 5 \quad \text{sign} \, \mu = 1 \quad m_t = 175 \text{ GeV}
\]

Below LEP

No EWSB

\( \tilde{g}_{\text{LSP}} \)

\( \tilde{\chi} \)

\( \chi \)

Below LEP

(V. Löwen, 2007)
Constraints on the mixing parameter

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(V. Löwen, 2007)
Constraints on the mixing parameter

\[
\begin{align*}
\tan \beta &= 30 \\
\eta &= 4 \\
\eta' &= 6
\end{align*}
\]
Explicit schemes III

- This “relaxed” mirage mediation is rather common for schemes with F-term uplifting
  (Intriligator, Seiberg, Shih; Gomez-Reino, Scrucca; Dudas, Papineau, Pokorski;
  Abe, Higaki, Kobayashi, Omura; Lebedev, Löwen, Mambrini, HPN, Ratz, 2006)

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Explicit schemes III

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Main message

- predictions for gaugino masses are more robust than those for sfermion masses

- mirage (compressed) pattern for gaugino masses rather generic
Obstacles to D-term uplifting

In supergravity we have the relation

\[ D \sim \frac{F}{W} \]

which implies that KKLT AdS minimum cannot be uplifted via D-terms.

(Choi, Falkowski, HPN, Olechowski, 2005)
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Moreover in these schemes we have

\[ F \sim m_{3/2}M_{\text{Planck}} \quad \text{and} \quad D \sim m_{3/2}^2. \]

So if \( m_{3/2} \ll M_{\text{Planck}} \) the D-terms are irrelevant.

(Choi, Jeong, 2006)
The string signatures

So far we have only considered Type IIB string theory compactifications. But there are also:

- Type IIA string theory
- Heterotic string theory
- M-theory on manifolds with $G_2$ holonomy
- Heterotic M-theory
The string signatures

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- Type IIA string theory
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- Heterotic M-theory

Questions:

- are there distinct signatures for the various schemes?
- can they be identified with LHC data?

(Choi, HPN, 2007)
Some important messages

Please keep in mind:

- the lifting mechanism plays an important role for the pattern of the soft SUSY breaking terms
- predictions for gaugino masses are more robust than those for sfermion masses
- dilaton/modulus mediation suppressed in many cases
- mirage pattern for gaugino masses rather generic
What to expect from the LHC

At the LHC we scatter

- protons on protons, i.e.
- quarks on quarks and/or
- gluons on gluons

Thus LHC will be a machine to produce strongly interacting particles. If TeV-scale susy is the physics beyond the standard model we might expect LHC to become a

GLUINO FACTORY

with cascade decays down to the LSP neutralino.
The Gaugino Code

First step to test these ideas at the LHC:

look for pattern of gaugino masses

Let us assume the

- low energy particle content of the MSSM
- measured values of gauge coupling constants

\[ g_1^2 : g_2^2 : g_3^2 \simeq 1 : 2 : 6 \]

The evolution of gauge couplings would then lead to unification at a GUT-scale around \( 10^{16} \) GeV
Formulae for gaugino masses

\[
\left( \frac{M_a}{g_a^2} \right) \text{ TeV} = \tilde{M}_a^{(0)} + \tilde{M}_a^{(1)}|_{\text{anomaly}} + \tilde{M}_a^{(1)}|_{\text{gauge}} + \tilde{M}_a^{(1)}|_{\text{string}}
\]

\[
\tilde{M}_a^{(0)} = \frac{1}{2} F^I \partial_I f_a^{(0)}
\]

\[
\tilde{M}_a^{(1)}|_{\text{anomaly}} = \frac{1}{16\pi^2} b_a \frac{F^C}{C} - \frac{1}{8\pi^2} \sum_m C_a^m F^I \partial_I \ln(e^{-K_0/3} Z_m)
\]

\[
\tilde{M}_a^{(1)}|_{\text{string}} = \frac{1}{8\pi^2} F^I \partial_I \Omega_a
\]
The Gaugino Code

Observe that

- evolution of gaugino masses is tied to evolution of gauge couplings
- for MSSM $M_a/g_a^2$ does not run (at one loop)

This implies

- robust prediction for gaugino masses
- gaugino mass relations are the key to reveal the underlying scheme

3 CHARACTERISTIC MASS PATTERNS

(Choi, HPN, 2007)
mSUGRA Pattern

Universal gaugino mass at the GUT scale

- mSUGRA pattern:
  
  \[ M_1 : M_2 : M_3 \approx 1 : 2 : 6 \approx g_1^2 : g_2^2 : g_3^2 \]

  as realized in popular schemes such as gravity-, modulus-, gauge- and gaugino-mediation

This leads to

- LSP \( \chi_1^0 \) predominantly Bino

  \[ M_{\text{gluino}} / m_{\chi_1^0} \approx 6 \]

  as a characteristic signature of these schemes.
Anomaly Pattern

Gaugino masses below the GUT scale determined by the $\beta$ functions

- anomaly pattern:

\[ M_1 : M_2 : M_3 \simeq 3.3 : 1 : 9 \]

at the TeV scale as the signal of anomaly mediation.

For the gauginos, this implies

- LSP $\chi_1^0$ predominantly Wino

\[ M_{\text{gluino}}/m_{\chi_1^0} \simeq 9 \]

Pure anomaly mediation inconsistent, as sfermion masses are problematic in this scheme (tachyonic sleptons).
Mirage Pattern

Mixed boundary conditions at the GUT scale characterized by the parameter $\rho$ (the ratio of anomaly to modulus mediation).

- $M_1 : M_2 : M_3 \simeq 1 : 1.3 : 2.5$ for $\rho \simeq 5$
- $M_1 : M_2 : M_3 \simeq 1 : 1 : 1$ for $\rho \simeq 2$

The mirage scheme leads to

- LSP $\chi_1^0$ predominantly Bino
- $M_{\text{gluino}}/m_{\chi_1^0} < 6$
- a “compact” gaugino mass pattern.
Uncertainties

String thresholds

\[ \tilde{M}_a^{(1)} |_{\text{string}} = \frac{1}{8\pi^2} F^I \partial_I \Omega_a \]

Kähler corrections

\[ \tilde{M}_a^{(1)} |_{\text{anomaly}} = \frac{1}{16\pi^2} b_a \frac{F^C}{C} - \frac{1}{8\pi^2} \sum_m C^m a F^I \partial_I \ln(e^{-K_0/3} Z_m) \]

Intermediate thresholds

\[ \tilde{M}_a^{(1)} |_{\text{gauge}} = \frac{1}{8\pi^2} \sum_\Phi C^\Phi a \frac{F^X \Phi}{M_\Phi} \]
Various string schemes

- **Type IIB with matter on D7 branes:** mirage mediation  
  (Choi, Falkowski, HPN, Olechowski, 2004)

- **Type IIB with matter on D3 branes:** anomaly mediation?

- **Heterotic string with dilaton domination:** mirage mediation  
  (Löwen, HPN, 2008)

- **Heterotic string with modulus domination:** string thresholds might dominate and spoil anomaly pattern  
  (Ibanez, HPN, 1986)

- **M theory on \(G_2\) manifolds:**  
  Kähler corrections might spoil mirage pattern  
  (Acharya, Bobkov, Kane, Kumar, Shao, 2007)
Summary

In the calculation of the soft masses we get the most robust predictions for gaugino masses.

- **Modulus Mediation:** \((f_{WW} \text{ with } f = f(\text{Moduli}))\)

If this is suppressed we might have loop contributions, e.g.

- **Anomaly Mediation** as simplest example.
Summary

In the calculation of the soft masses we get the most robust predictions for **gaugino masses**

- **Modulus Mediation**: \((fW W \text{ with } f = f(\text{Moduli}))\)

If this is suppressed we might have loop contributions, e.g.

- **Anomaly Mediation as simplest example**

How much can it be suppressed?

\[
\log\left(\frac{m_{3/2}}{M_{\text{Planck}}}\right)
\]

So we might expect a mixture of tree level and loop contributions.
Conclusion

Gaugino masses can serve as a promising tool to disentangle various string schemes

- rather robust predictions
- 3 basic and simple patterns (mSugra, anomaly, mirage)
- mirage pattern rather generic
- main uncertainties from “string threshold corrections”

With some luck we might test these ideas at the LHC!