

Strings meet LHC

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Based on work with K. Choi, A. Falkowski, M. Olechowski, S. Pokorski,
hep-th/0411066, hep-th/0503216, hep-ph/0702146

O. Lebedev, Y. Mambrini, V. Loewen, M. Ratz, hep-th/0603047, hep-0612035

Outline

- Basic questions: moduli stabilization and Susy breakdown: Fluxes and Gaugino Condensation
- A large and a little hierarchy
- Mirage Mediation
- Distinct pattern of soft terms
- Some remarks on fine tuning
- Explicit schemes KKLT and LNR
- Robust prediction for gaugino masses
- The Gaugino Code
- 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)

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.

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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)

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 the contribution due to “Anomaly Mediation” (suppressed by a loop factor) becomes 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

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

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.

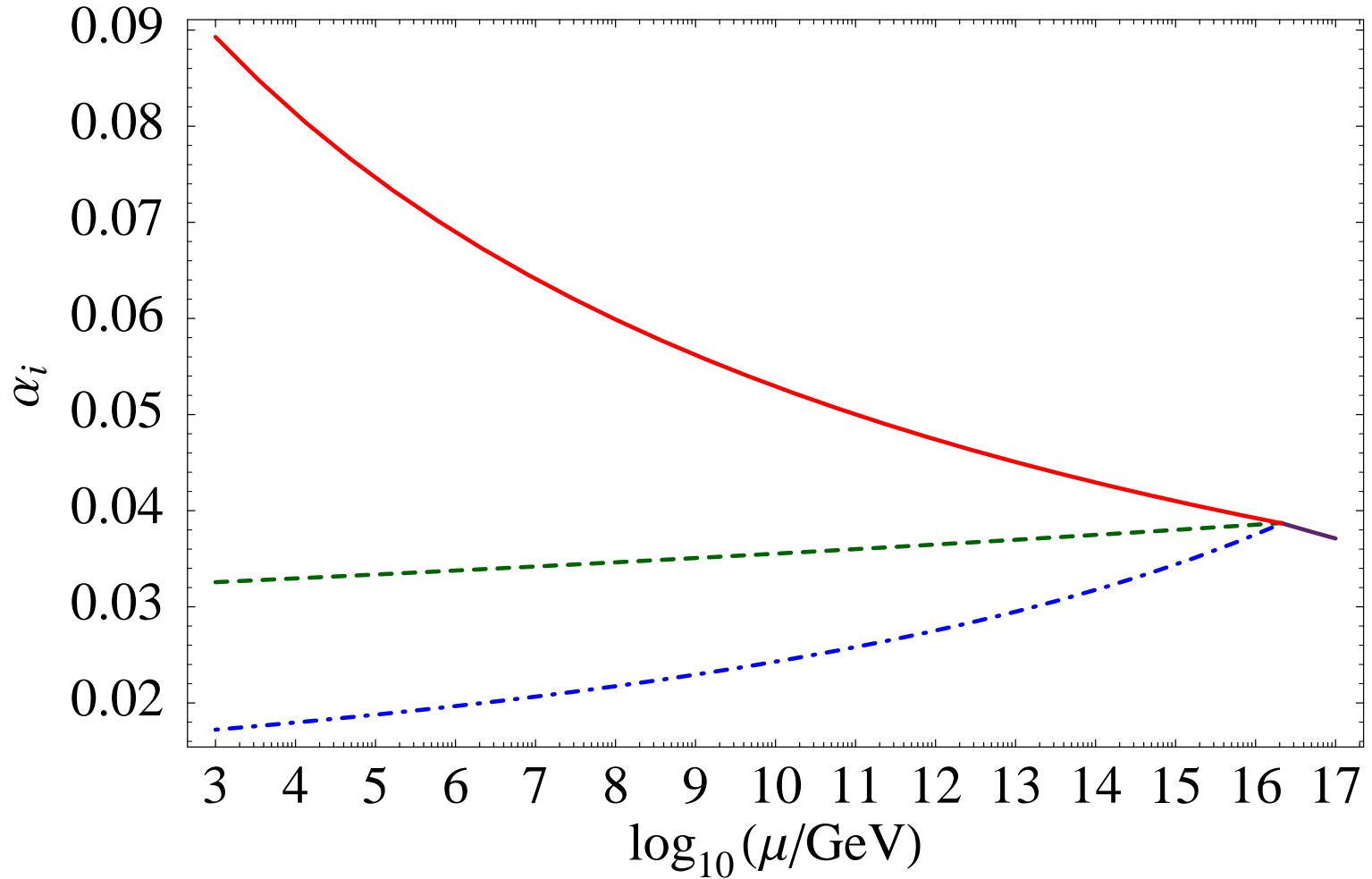
To see this, let us consider the gaugino masses

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

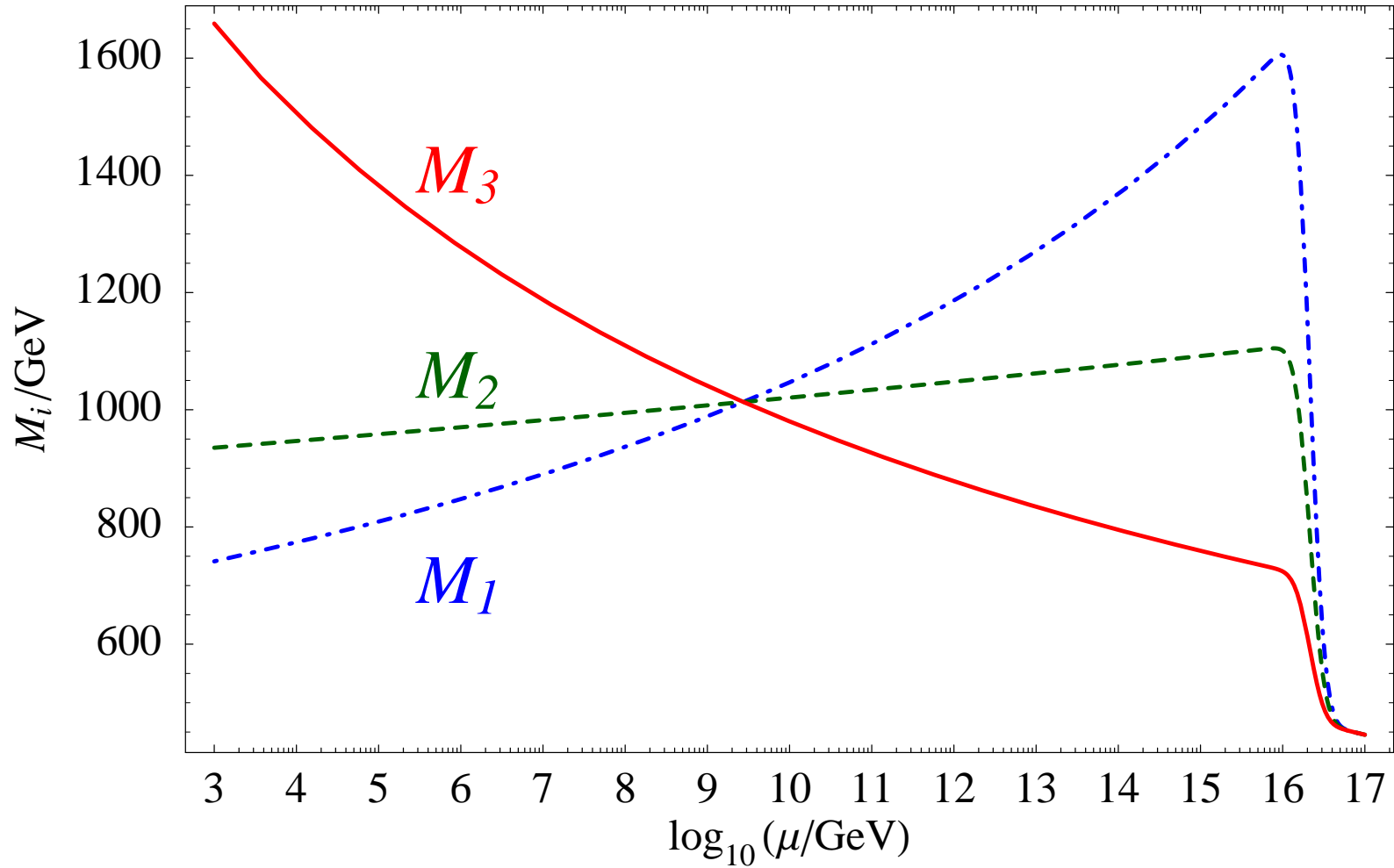
as a sum of two contributions of comparable size.

- M_{anomaly} is proportional to the β function,
i.e. **negative** for the gluino, **positive** for the bino
- thus M_{anomaly} is non-universal below the GUT scale

Evolution of couplings



The Mirage Scale



(Lebedev, HPN, Ratz, 2005)

The Mirage Scale (II)

The gaugino masses coincide

- above the GUT scale
- at the mirage scale

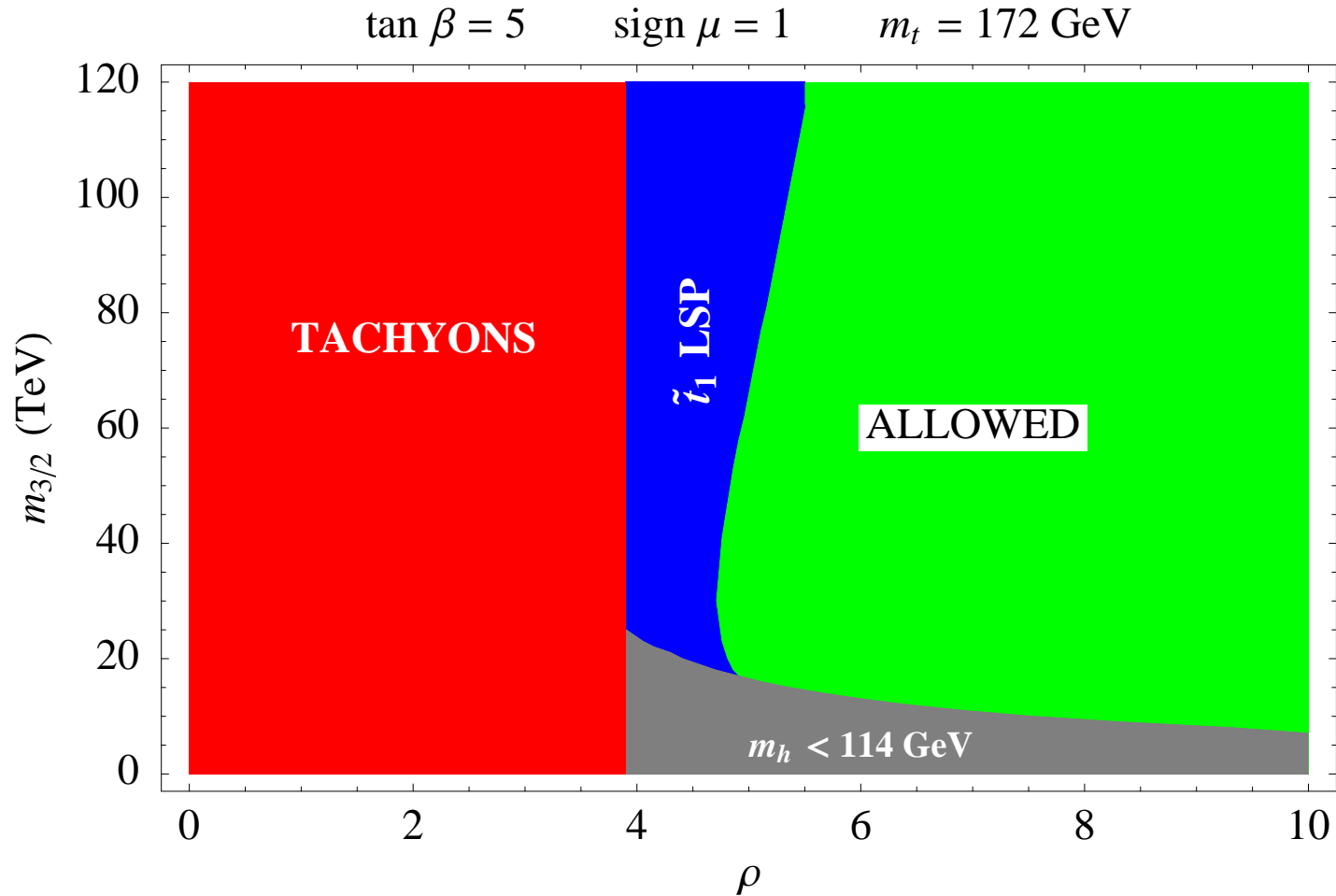
$$\mu_{\text{mirage}} = M_{\text{GUT}} \exp(-8\pi^2/\rho)$$

where ρ denotes the “ratio” of the contribution of **modulus** vs. **anomaly mediation**. We write the gaugino masses as

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

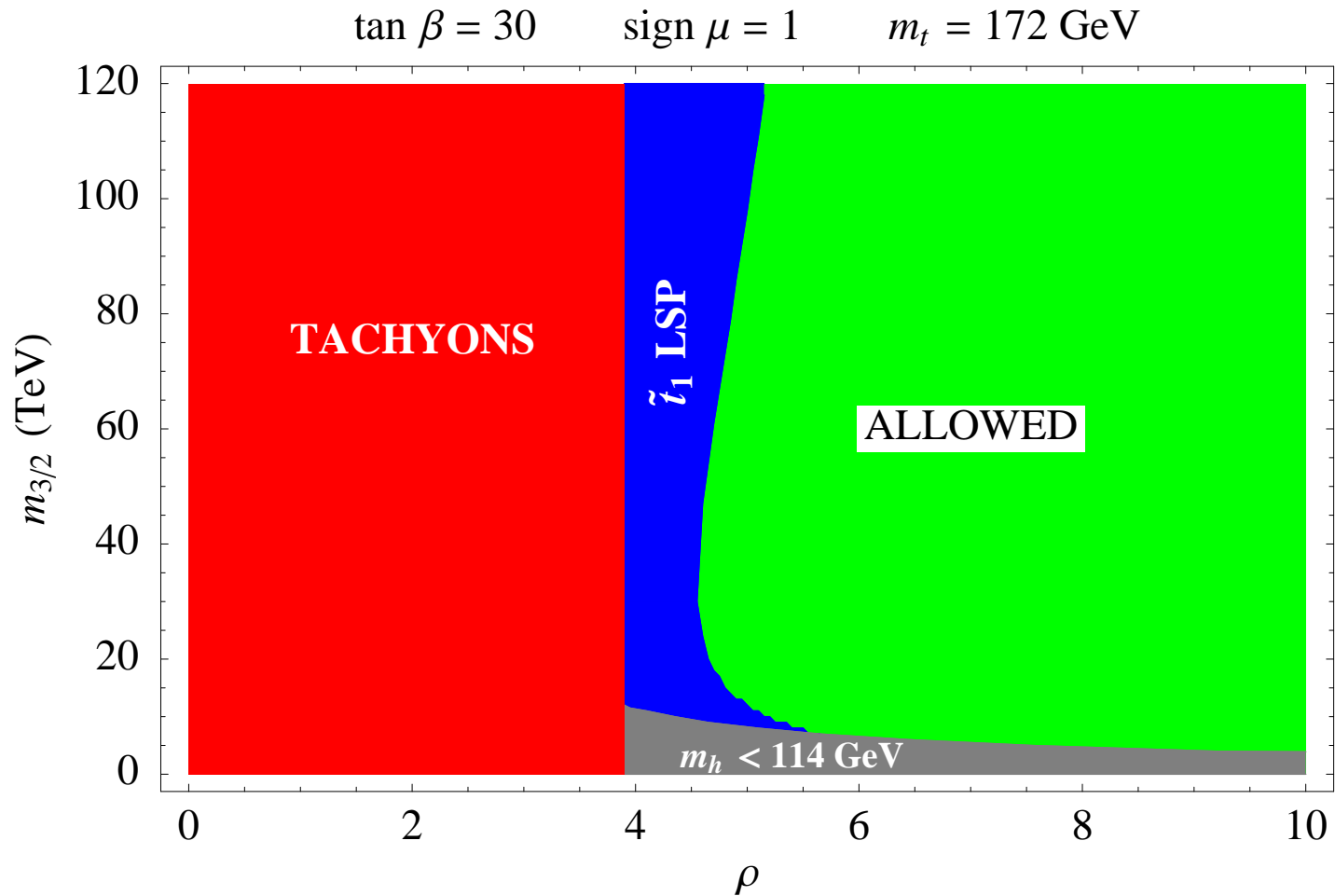
and $\rho \rightarrow 0$ corresponds to pure anomaly mediation.

Constraints on the mixing parameter



(Löwen, HPN, Ratz, 2006)

Constraints on ρ



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The “MSSM hierarchy problem”

The scheme predicts a rather high mass scale

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Thus we 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)

The “MSSM hierarchy problem”?

The influence of the various soft terms is given by

$$m_Z^2 \simeq -1.8 \mu^2 + 5.9 M_3^2 - 0.4 M_2^2 - 1.2 m_{H_u}^2 + 0.9 m_{q_L^{(3)}}^2 + \\ + 0.7 m_{u_R^{(3)}}^2 - 0.6 A_t M_3 + 0.4 M_2 M_3 + \dots ,$$

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Mirage mediation improves the situation

- especially for **small ρ**
- 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**

(Kachru, Kallosh, Linde, Trivedi, 2003)

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

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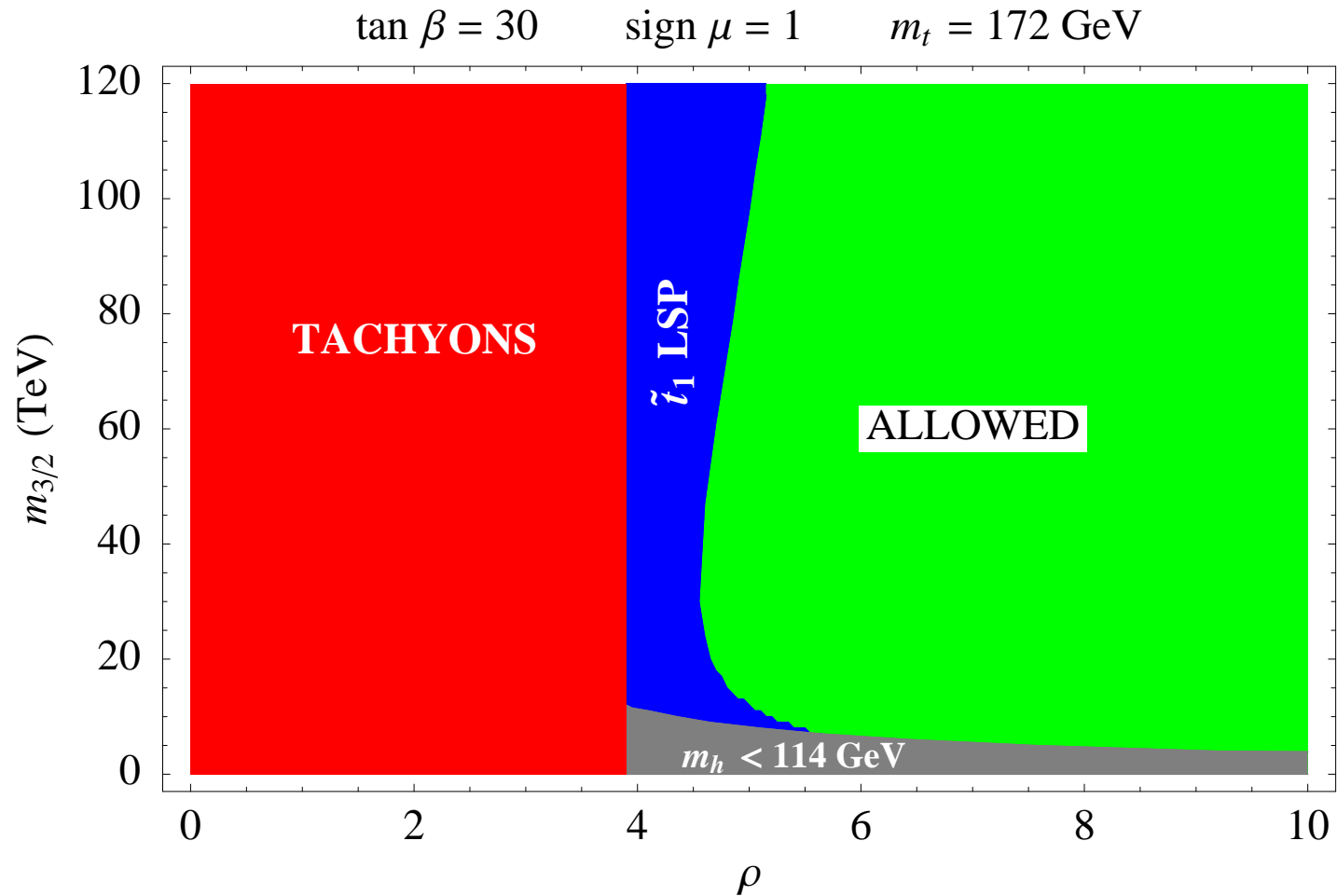
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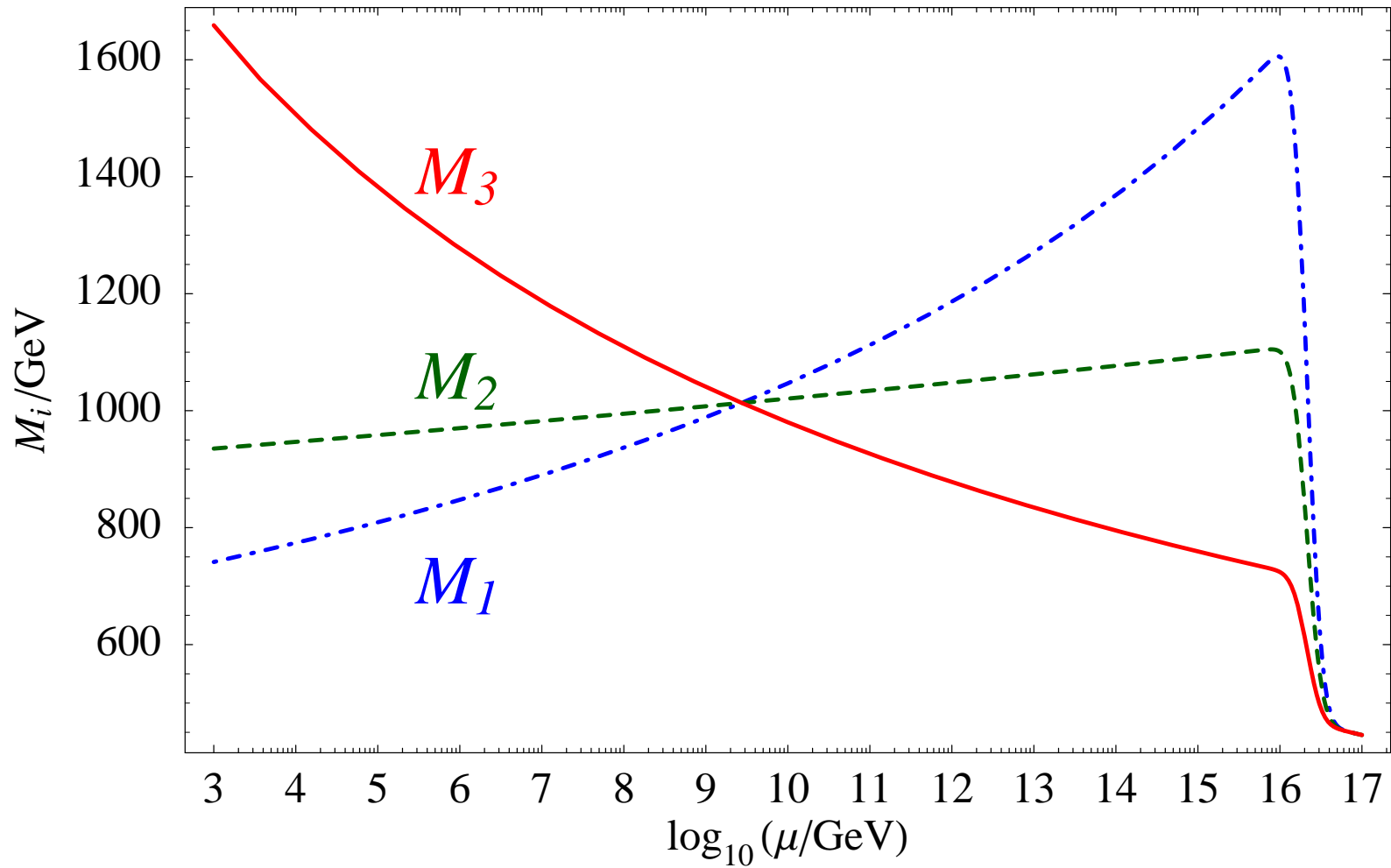
- $\rho \sim 5$ in the original KKLT scenario leading to
- a **mirage scale** of approximately 10^{11} GeV
- This scheme leads to **pure mirage mediation**:
 - gaugino masses and
 - scalar masses
- **both meet at a common mirage scale**

Constraints on ρ



(Löwen, HPN, Ratz, 2006)

The Mirage Scale



(Lebedev, HPN, Ratz, 2005)

Explicit schemes II

- **uplifting via matter superpotentials**

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- allows a continuous variation of ρ
- leads to potentially **new contributions** to sfermion masses

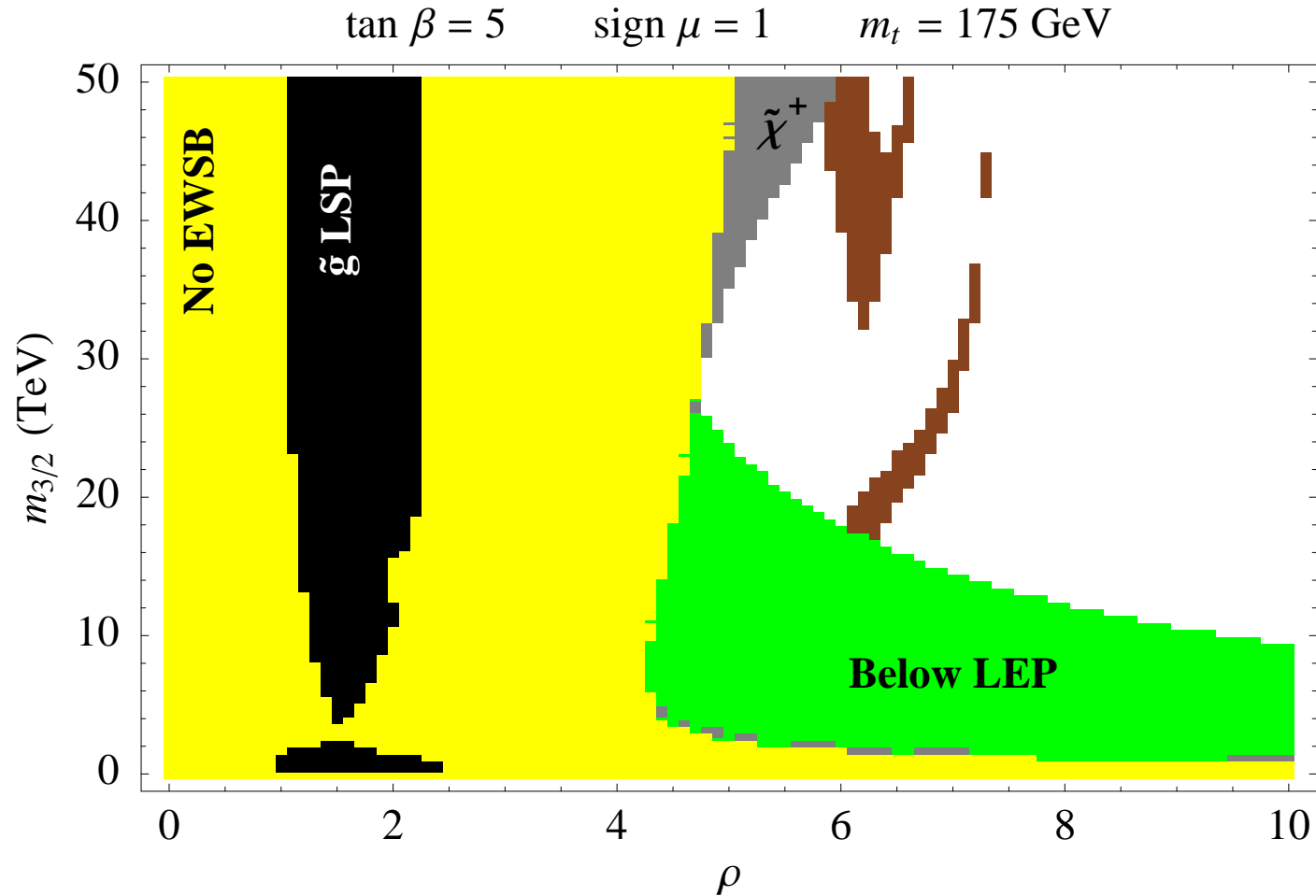
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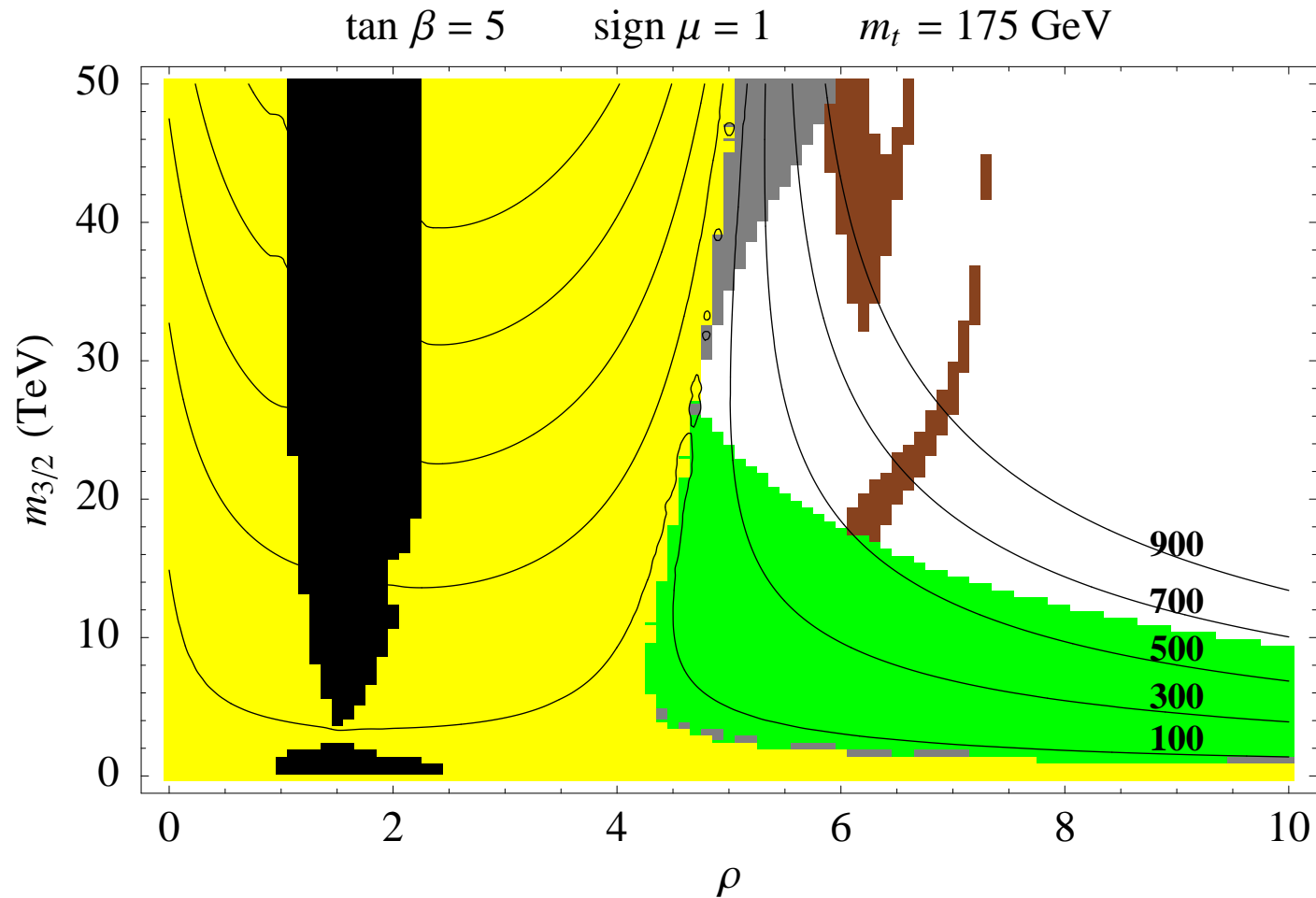
- allows a continuous variation of ρ
 - leads to potentially **new contributions** to sfermion masses
- **gaugino masses still meet at a mirage scale**
 - **soft scalar masses might be dominated by modulus mediation**
 - similar constraints on the mixing parameter

Constraints on the mixing parameter



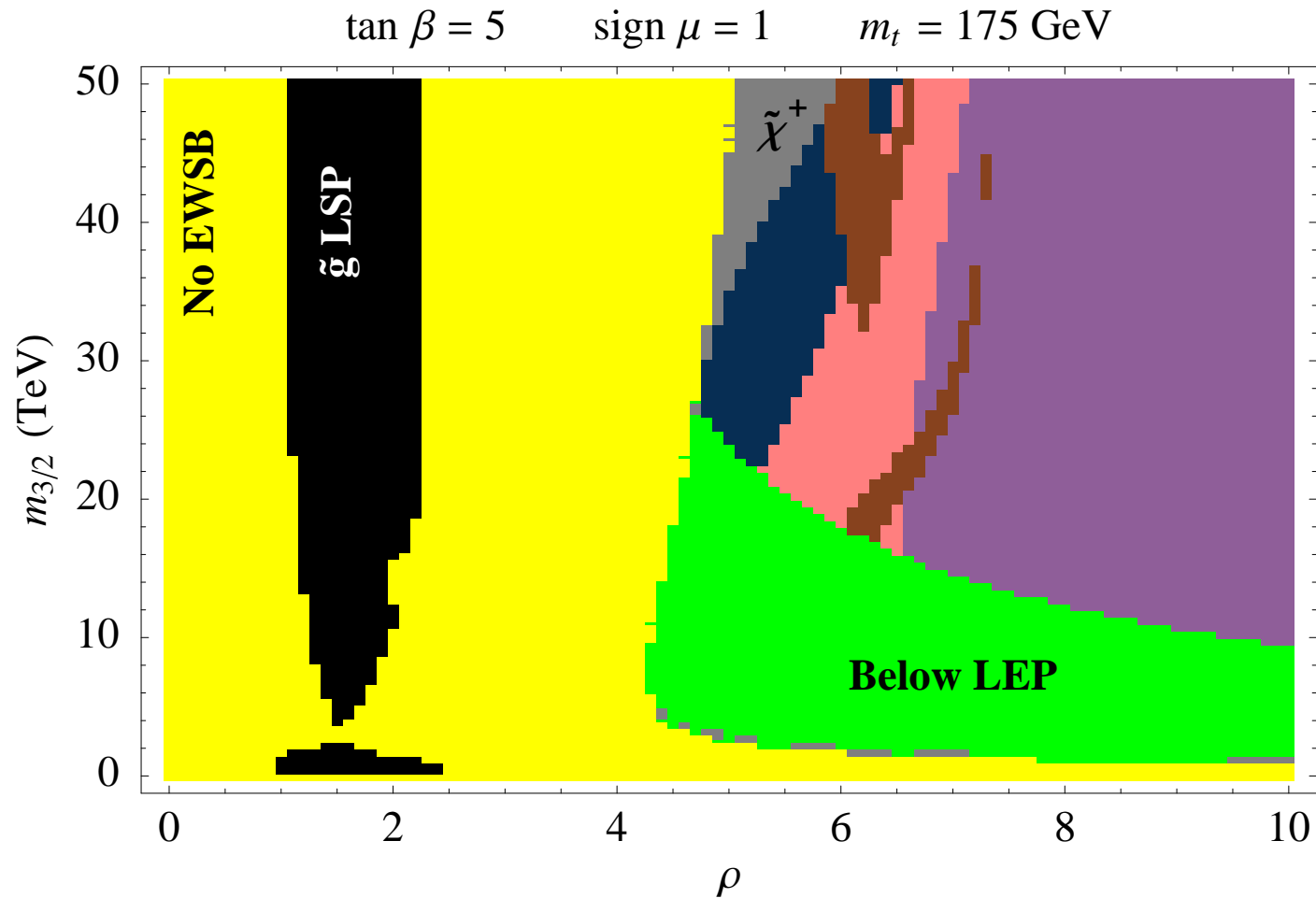
(V. Löwen, 2007)

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Explicit schemes III

- This “relaxed” mirage mediation is rather common for schemes with F-term uplifting
(Gomez-Reino, Scrucra; Dudas, Papineau, Pokorski; Abe, Higaki, Kobayashi, Omura; Lebedev, Löwen, Mambrini, HPN, Ratz ,2006)
- although “pure” mirage mediation is possible as well

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Main message

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

mirage 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.

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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 Gaugino Code

How can we 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

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:

$$M_1 : M_2 : M_3 \simeq 1 : 2 : 6 \simeq g_1^2 : g_2^2 : g_3^2$$

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

This leads to

- LSP χ_1^0 predominantly Bino
- $M_{\text{gluino}}/m_{\chi_1^0} \simeq 6$

as a characteristic signature of these schemes.

Anomaly Pattern

Gaugino masses below the GUT scale determined by the β 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 χ_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 ρ (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 χ_1^0 predominantly Bino
- $M_{\text{gluino}}/m_{\chi_1^0} < 6$
- a “compact” gaugino mass pattern.

Summary

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

- **Modulus Mediation:** (fWW with $f = f(\text{Moduli})$)

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

- **Anomaly Mediation**

Summary

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

- **Modulus Mediation:** (fWW with $f = f(\text{Moduli})$)

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

- **Anomaly Mediation**

How much can it be suppressed?

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

So we might expect

a mixture of tree level and loop contributions.

Conclusion

Mirage Mediation naturally appears in string theory models with background fluxes and gaugino condensation. It

- relieves cosmological problems of moduli and gravitino
- reduces the fine tuning of the weak scale
- gives a consistent neutralino dark matter candidate

Mirage mediation

- avoids the problems of conventional schemes like anomaly and modulus mediation
- is the correct way to implement anomaly mediation
- gives a consistent picture with very few parameters

Conclusion

The **source of Mirage Mediation** is the appearance of a small parameter

$$X^{-1} \sim \log(m_{3/2}/M_{\text{Planck}})$$

that leads to a (heavy) superpartner spectrum exhibiting

- a little hierarchy $m_X \sim \langle X \rangle m_{3/2} \sim \langle X \rangle^2 m_{\text{soft}}$
- a rather heavy gravitino mass
- and an **unusual relation** between the gaugino masses.

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Mirage Mediation provides a distinct pattern of soft terms that could be tested at the LHC!