The Gaugino Code

Hans Peter Nilles

Bethe Center for Theoretical Physics

Universität Bonn

Outline

- Mediation schemes in string theory
- Recent progress
- Mirage Mediation
- Distinct “compressed” pattern of soft terms
- Some remarks on the MSSM hierarchy problem
- Robust prediction for gaugino masses
- The Gaugino Code
- Identification of string schemes
- Uncertainties
- Conclusions and outlook

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)

  (Ibanez, HPN, 1986; Randall, Sundrum, 1999)

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)

  (Ibanez, HPN, 1986; Randall, Sundrum, 1999)

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

(Choi, Falkowski, HPN, Olechowski, Pokorski, 2004)

Basic Questions

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

Basic Questions

- origin of the small scale?
- 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; Löwen, HPN, 2008)

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)

Mixed Mediation Schemes

The contribution from "Modulus Mediation" is therefore suppressed by the factor

$$X \sim \log(M_{\rm Planck}/m_{3/2}) \sim 4\pi^2.$$

Mixed Mediation Schemes

The contribution from "Modulus Mediation" is therefore suppressed by the factor

$$X \sim \log(M_{\mathrm{Planck}}/m_{3/2}) \sim 4\pi^2.$$

Thus the contribution due to radiative corrections becomes competitive, leading to mixed mediation schemes.

The simplest case for radiative corrections leads to anomaly mediation competing now with the suppressed contribution of modulus mediation.

For reasons that will be explained later we call this scheme

MIRAGE MEDIATION

(Loaiza, Martin, HPN, Ratz, 2005)

The little hierarchy

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

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.

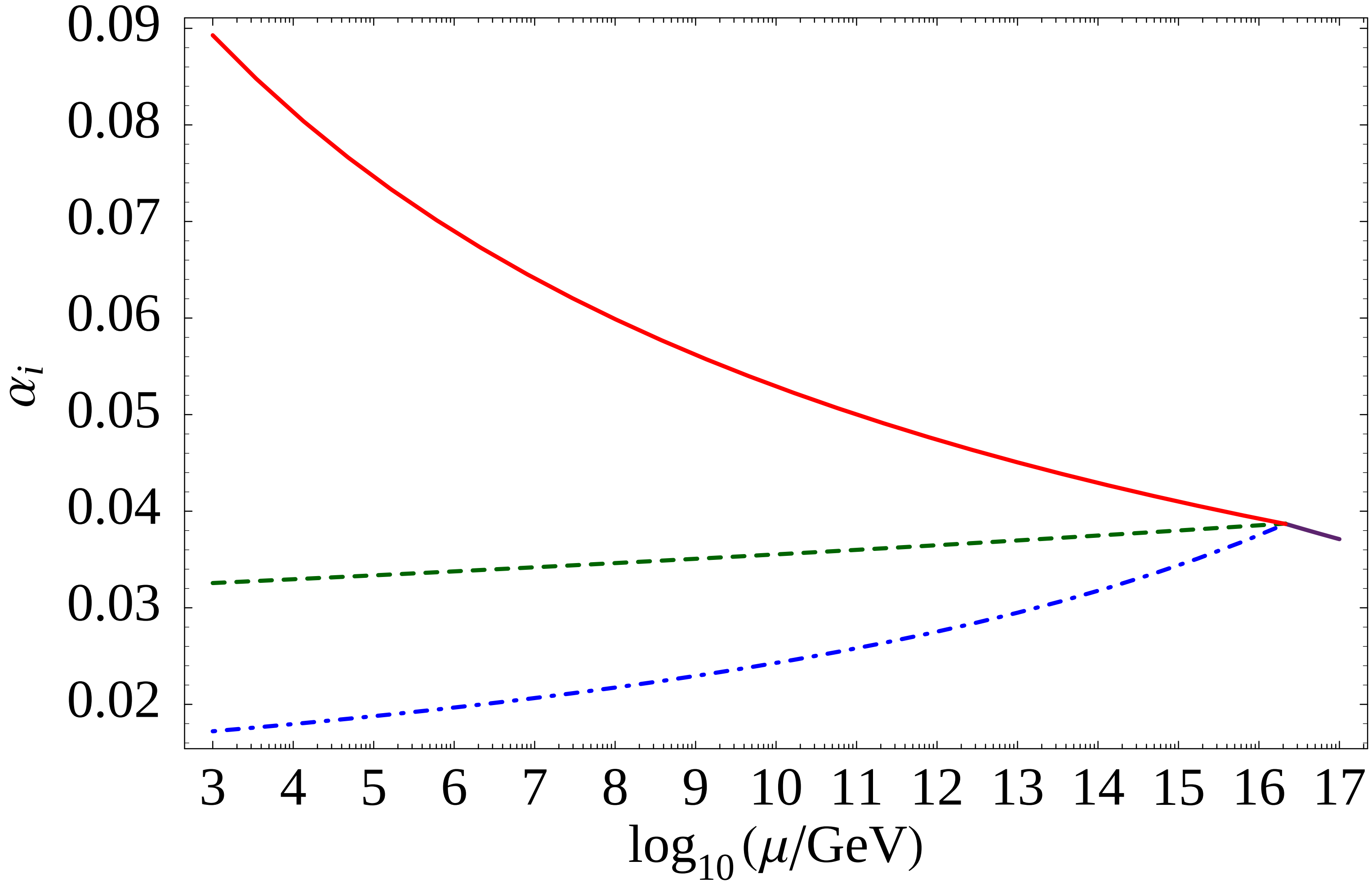
To see this, let us consider the gaugino masses

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

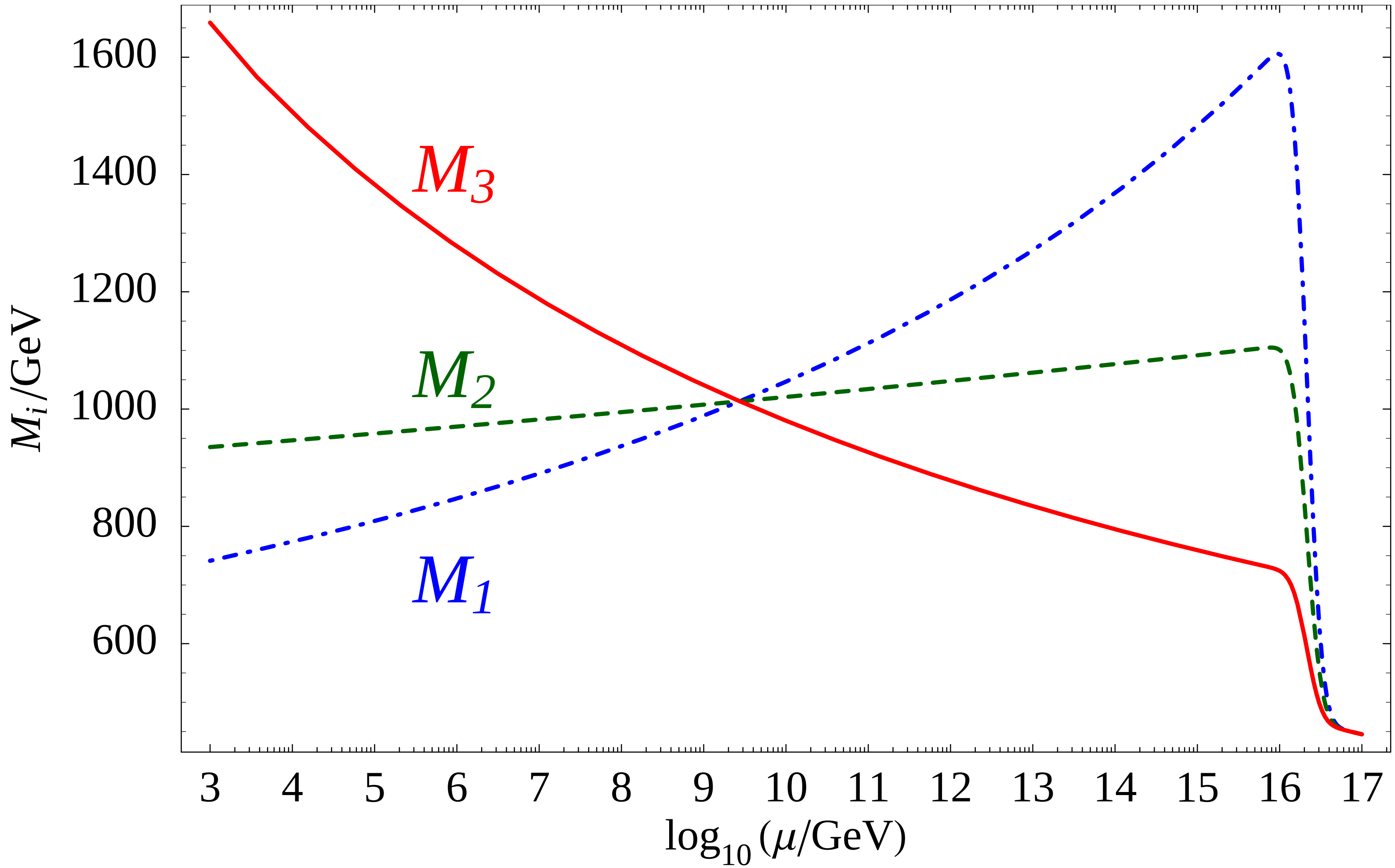
as a sum of two contributions of comparable size.

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

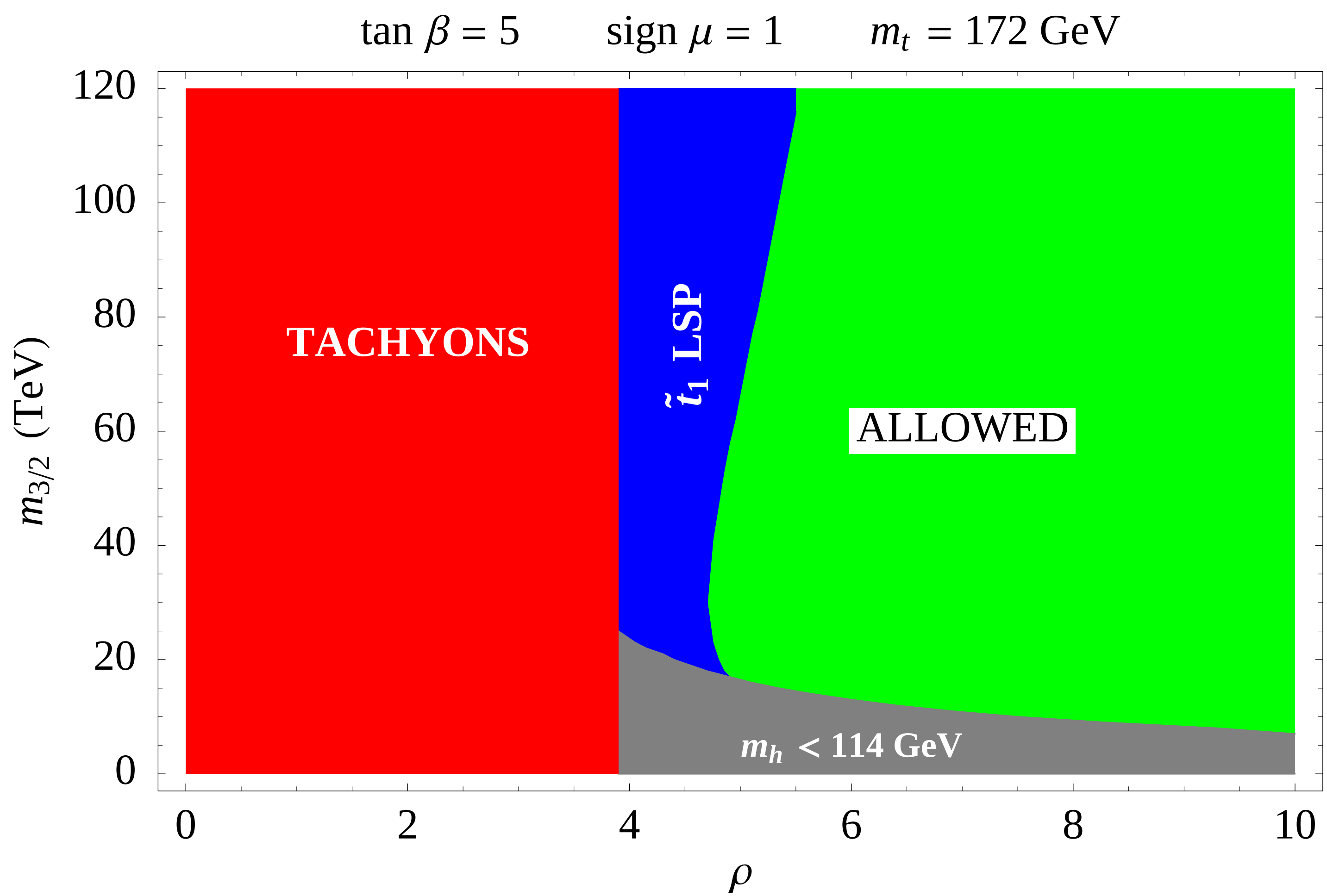
- above the GUT scale
- at the mirage scale $\mu_{\text{mirage}} = M_{\text{GUT}} \exp(-8\pi^2/\rho)$

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

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

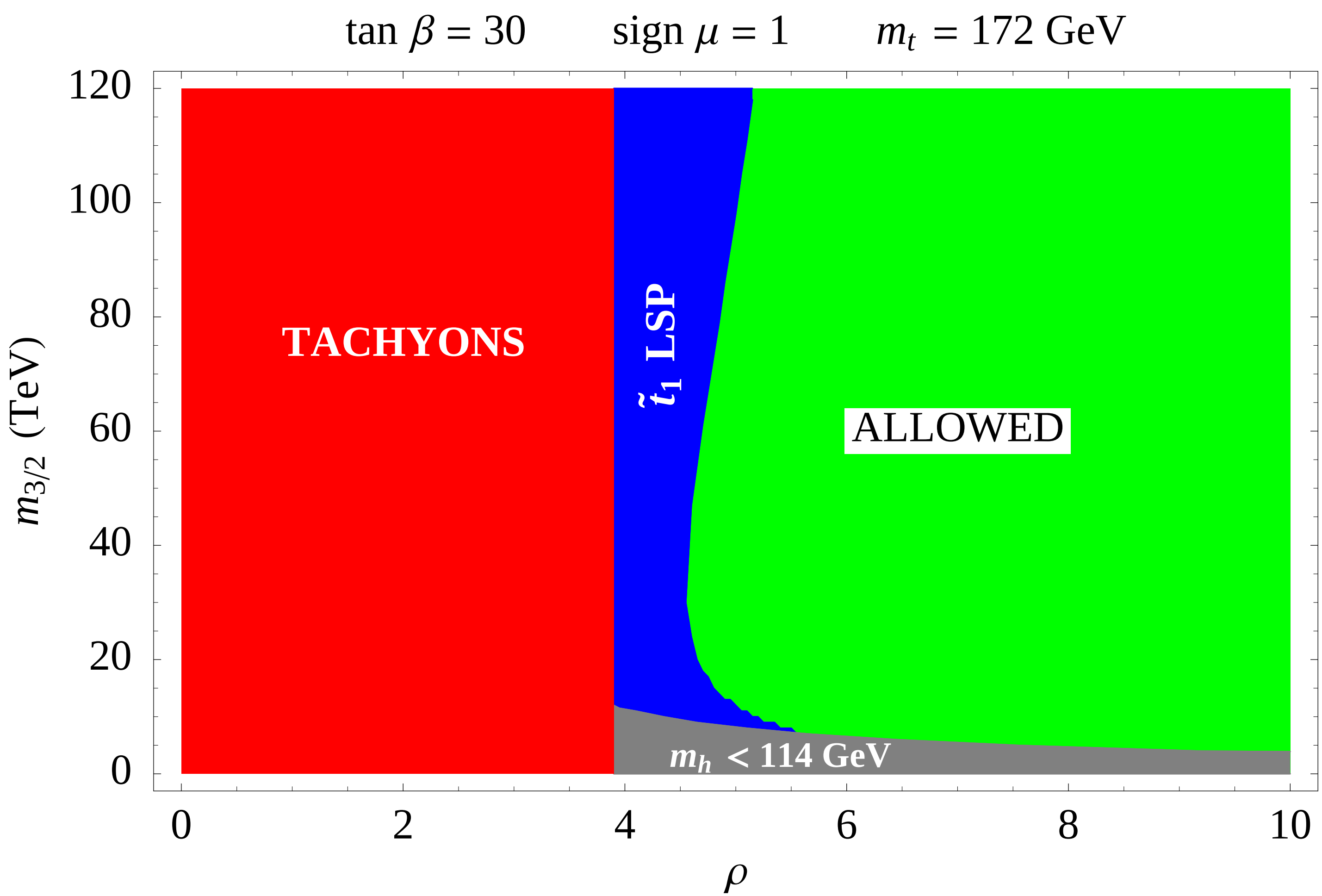
and $\rho \to 0$ corresponds to pure anomaly mediation.

Constraints on the mixing parameter



(Löwen, HPN, Ratz, 2006)

Constraints on ρ



(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

The "MSSM hierarchy problem"

The scheme predicts a rather high mass scale

- heavy gravitino
- 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)

The "MSSM hierarchy problem"?

The influence of the various soft terms is given by

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

The “MSSM hierarchy problem”?

The influence of the various soft terms is given by

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

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

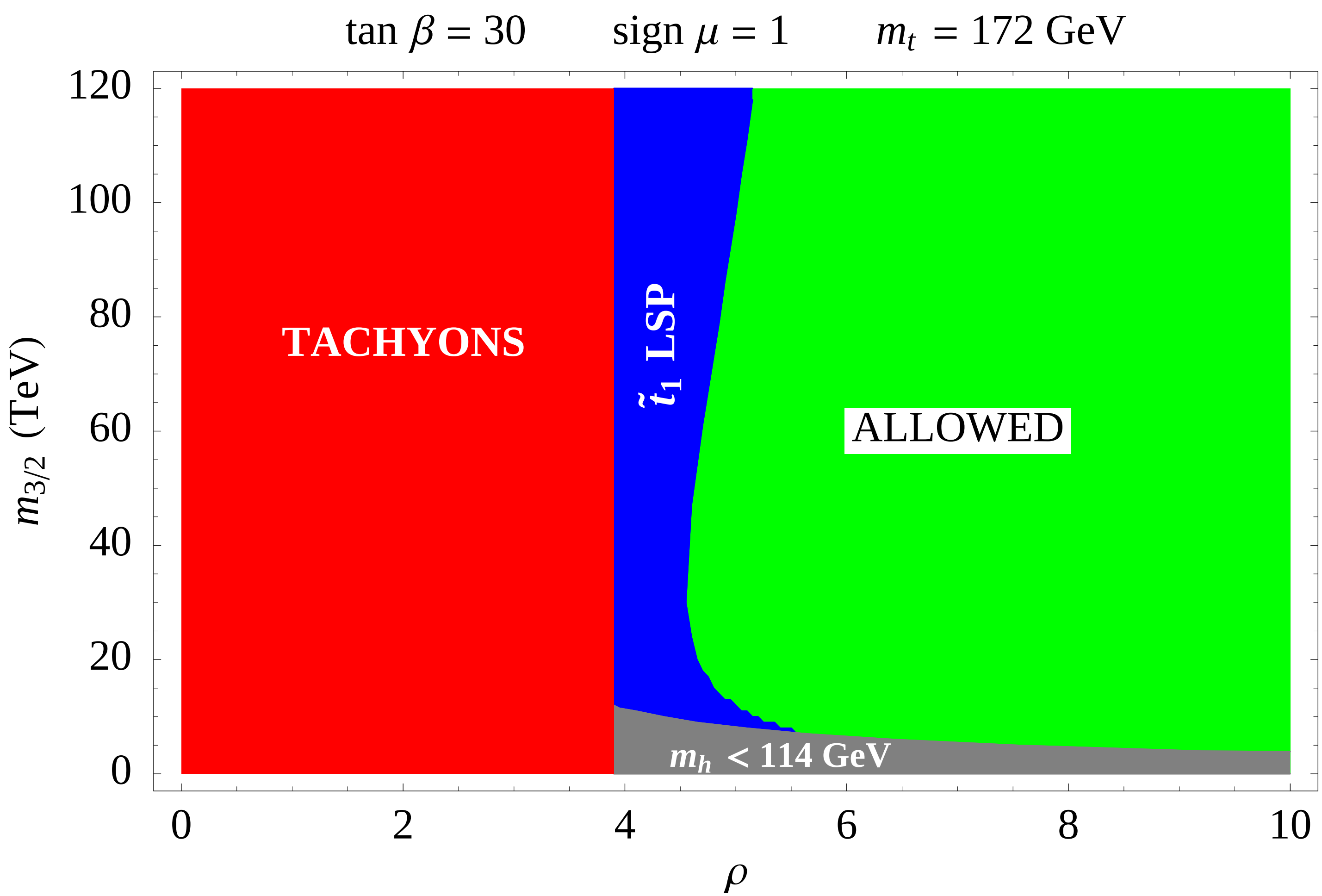
The different schemes depend on the mechanism of uplifting:

- uplifting with anti D3 branes

  (Kachru, Kallosh, Linde, Trivedi, 2003)

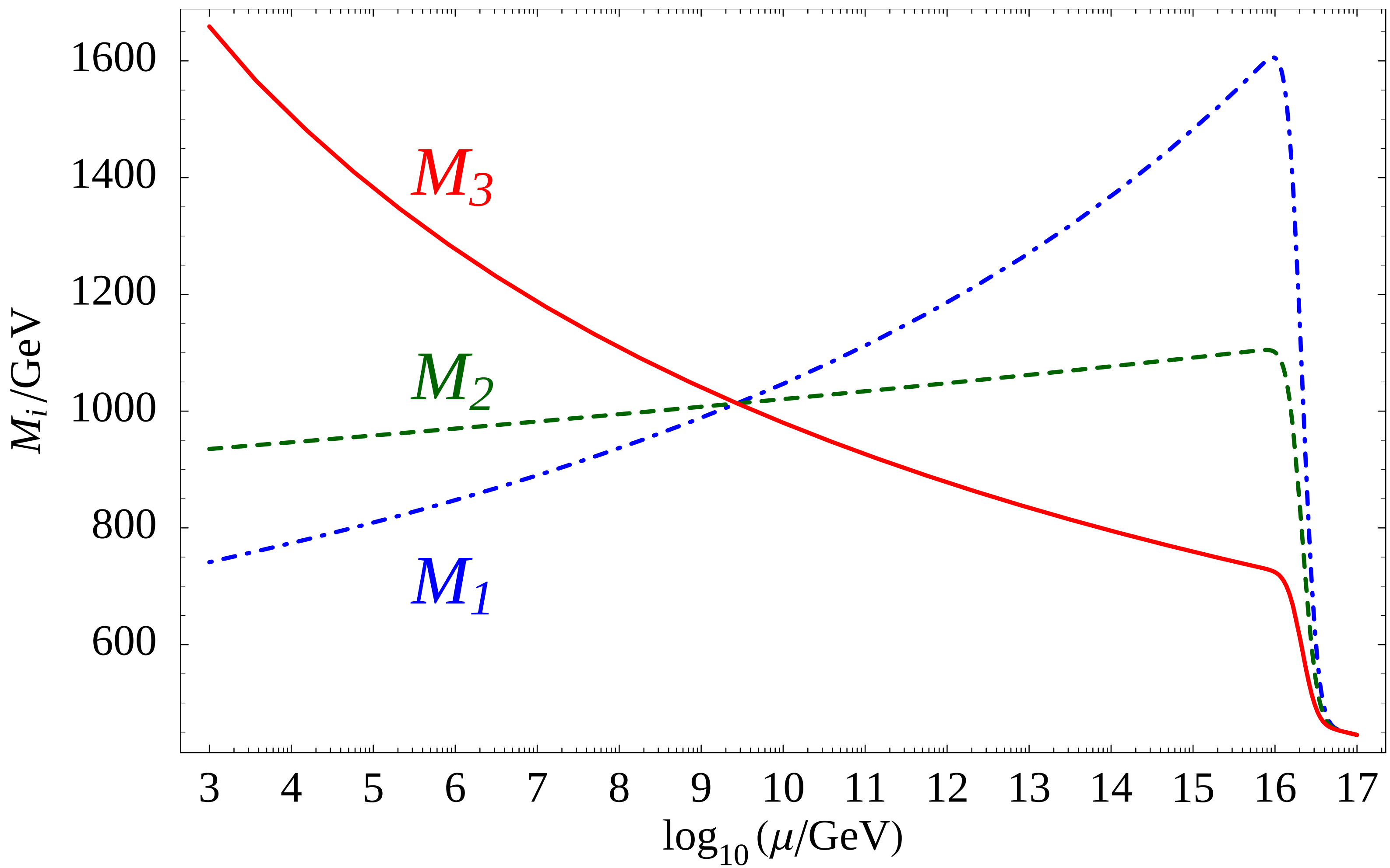
  - $\rho \sim 5$ in the original KKLT scenario leading to
  - a mirage scale of approximately 10^{11} GeV
- This scheme leads to pure mirage mediation:
  - gaugino masses and
  - scalar masses
- both meet at a common mirage scale

Constraints on ρ



(Löwen, HPN, Ratz, 2006)

The Mirage Scale



(Lebedev, HPN, Ratz, 2005)

Explicit schemes II

- uplifting via matter superpotentials

(Lebedev, HPN, Ratz, 2006)

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

Explicit schemes II

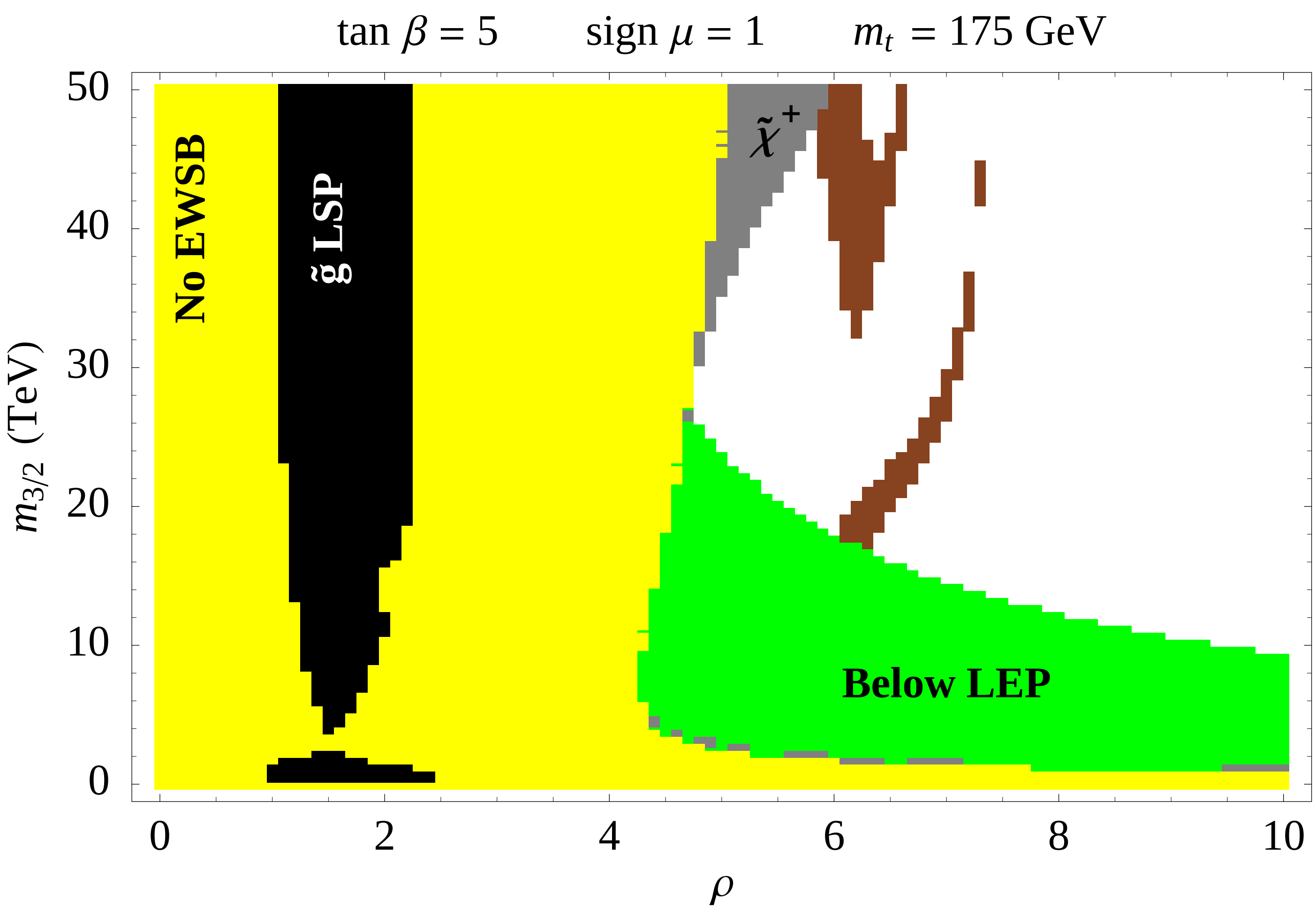
- uplifting via matter superpotentials

  (Lebedev, HPN, Ratz, 2006)

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

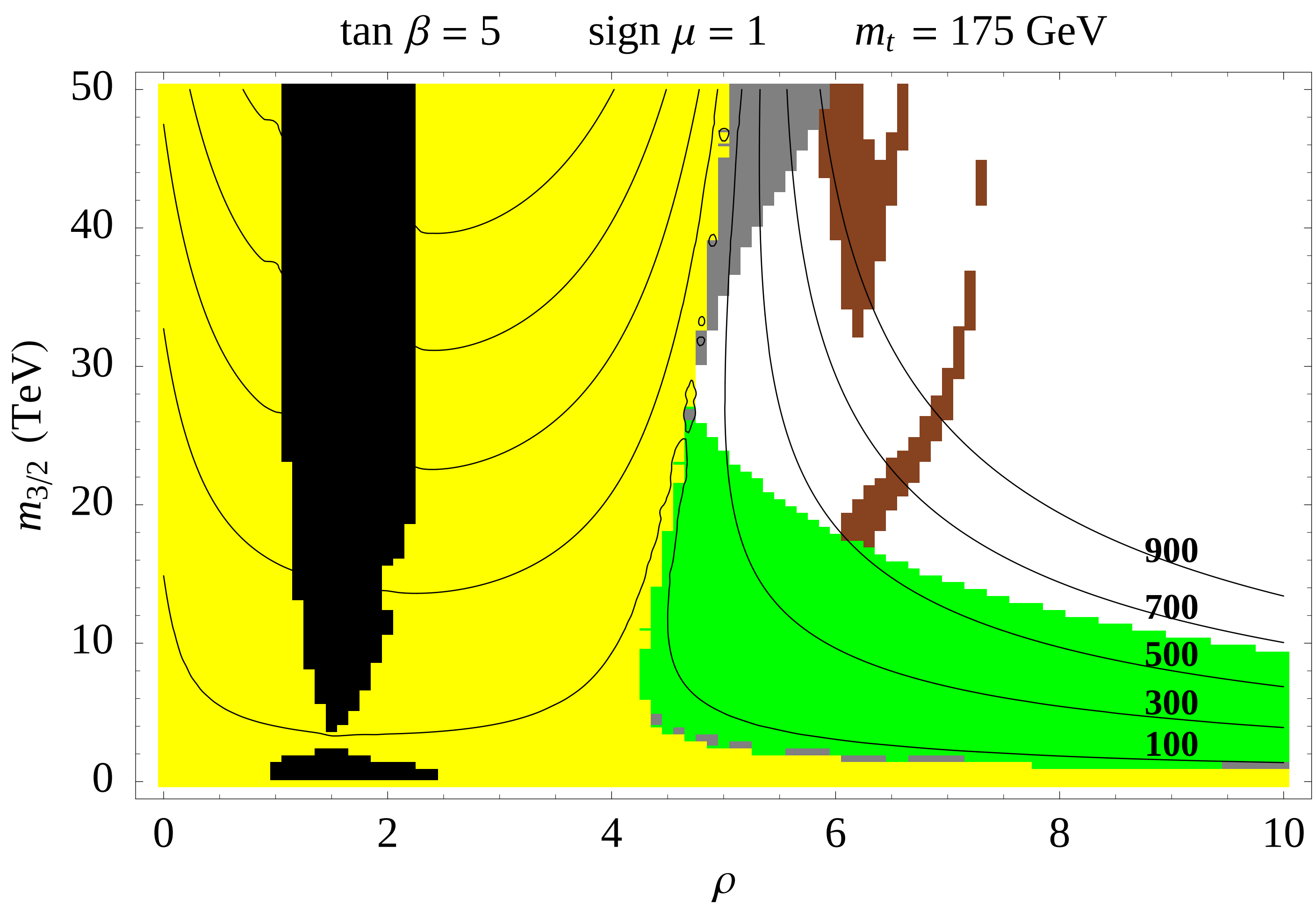
- gaugino masses still meet at a mirage scale
- soft scalar masses might be dominated by modulus mediation
- similar constraints on the mixing parameter

Constraints on the mixing parameter



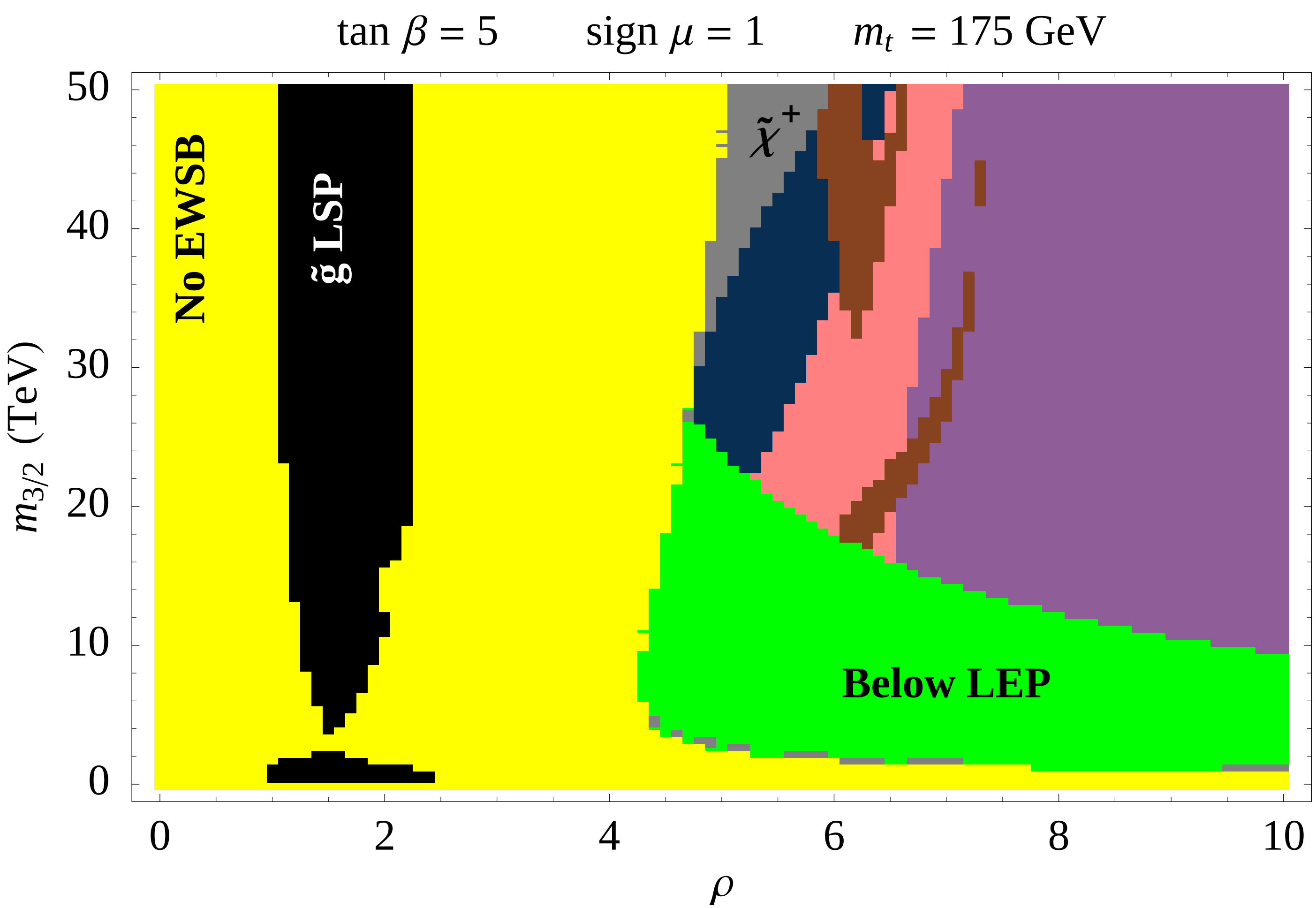
(V. Löwen, 2007)

Constraints on the mixing parameter



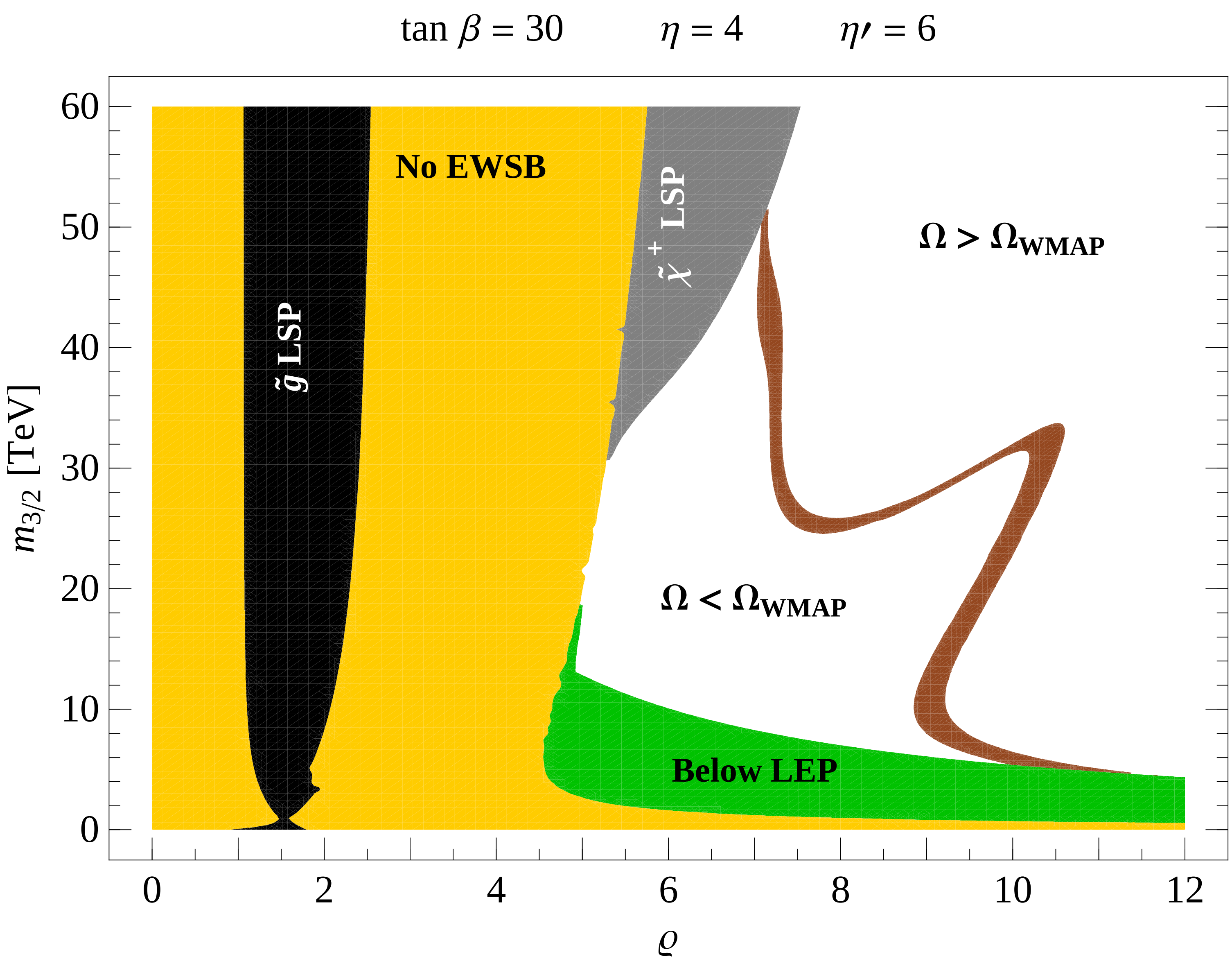
(V. Löwen, 2007)

Constraints on the mixing parameter



(V. Löwen, 2007)

Constraints on the mixing parameter



Explicit schemes III

- This “relaxed” mirage mediation is rather common for schemes with F-term uplifting

  (Intriligator, Shih, Seiberg; Gomez-Reino, Scrucca; Dudas, Papineau, Pokorski; Abe, Higaki, Kobayashi, Omura; Lebedev, Löwen, Mambrini, HPN, Ratz ,2006)

- although “pure” mirage mediation is possible as well

Explicit schemes III

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

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)

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)

Moreover in these schemes we have

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

So if $m_{3/2} \ll M_{\mathrm{Planck}}$ the D-terms are irrelevant.

(Choi, Jeong, 2006)

The string signatures

Schemes to consider:

- Type IIB string theory
- Type IIA string theory
- Heterotic string theory
- M-theory on manifolds with G_2 holonomy
- Heterotic M-theory

The string signatures

Schemes to consider:

- Type IIB string theory
- Type IIA string theory
- Heterotic string theory
- M-theory on manifolds with G_2 holonomy
- Heterotic M-theory

Questions:

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

(Choi, HPN, 2007)

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

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

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

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

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

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:

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

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

This leads to

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

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
- $M_{\rm gluino}/m_{\chi_1^0} \simeq 9$

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
- $M_{\rm gluino}/m_{\chi_1^0} < 6$
- a “compact” gaugino mass pattern.

Uncertainties

String thresholds

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

Kähler corrections

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

Intermediate thresholds

$$\tilde{M}_a^{(1)}|_{\rm gauge} = \frac{1}{8\pi^2} \sum_\Phi C_a^\Phi \frac{F^{X_\Phi}}{M_\Phi}$$

Various String Schemes

- Type IIB with matter on D7 branes:
  mirage mediation
- Type IIB with matter on D3 branes:
  anomaly mediation?
- Heterotic string with dilaton domination:
  mirage mediation
- Heterotic string with modulus domination:
  string thresholds might spoil anomaly pattern
- M theory on "G_2 manifold":
  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: (fWW with $f = f(\mathrm{Moduli})$)

If this is supressed 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: (fWW with $f = f(\mathrm{Moduli})$)

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

- Anomaly Mediation as simplest example

How much can it be suppressed?

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

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
- Is pure modulus mediation possible?
- Main uncertainties from “string threshold corrections”

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

Conclusion

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

- predicts heavy moduli and a heavy 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

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

that leads to a (heavy) superpartner spectrum exhibiting

- a little hierarchy $m_X \sim \langle X \rangle m_{3/2} \sim \langle X \rangle^2 m_{\mathrm{soft}}$
- a rather heavy gravitino mass
- and a mirage pattern of the gaugino masses.

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 $\quad m_X \sim \langle X \rangle m_{3/2} \sim \langle X \rangle^2 m_{\text{soft}}$
- a rather heavy gravitino mass
- and a mirage pattern of the gaugino masses.

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