The Gaugino Code

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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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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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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.

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

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 Modulus Anomaly Mediation

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

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

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

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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

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.

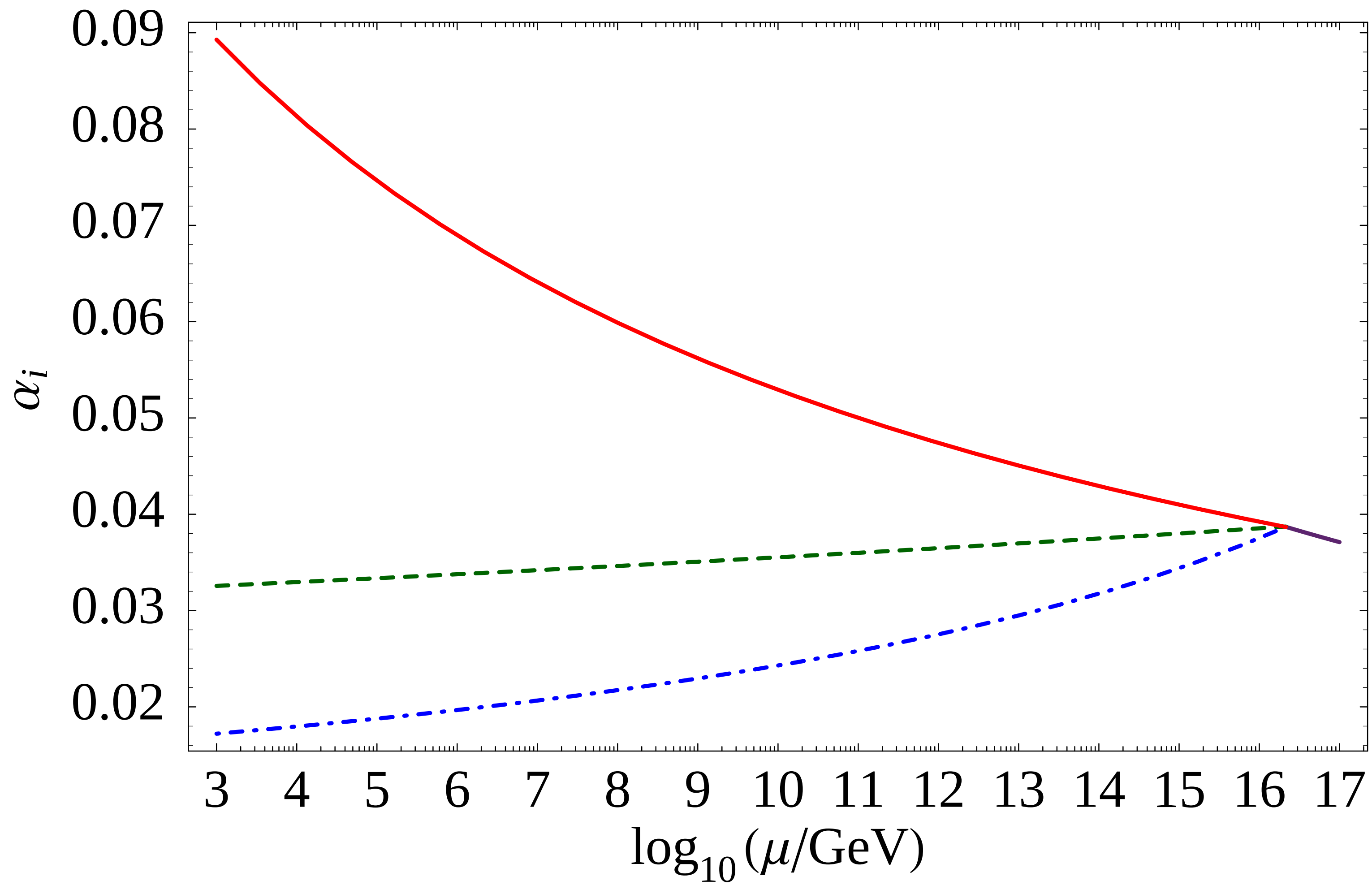
To see this, let us consider the gaugino masses

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

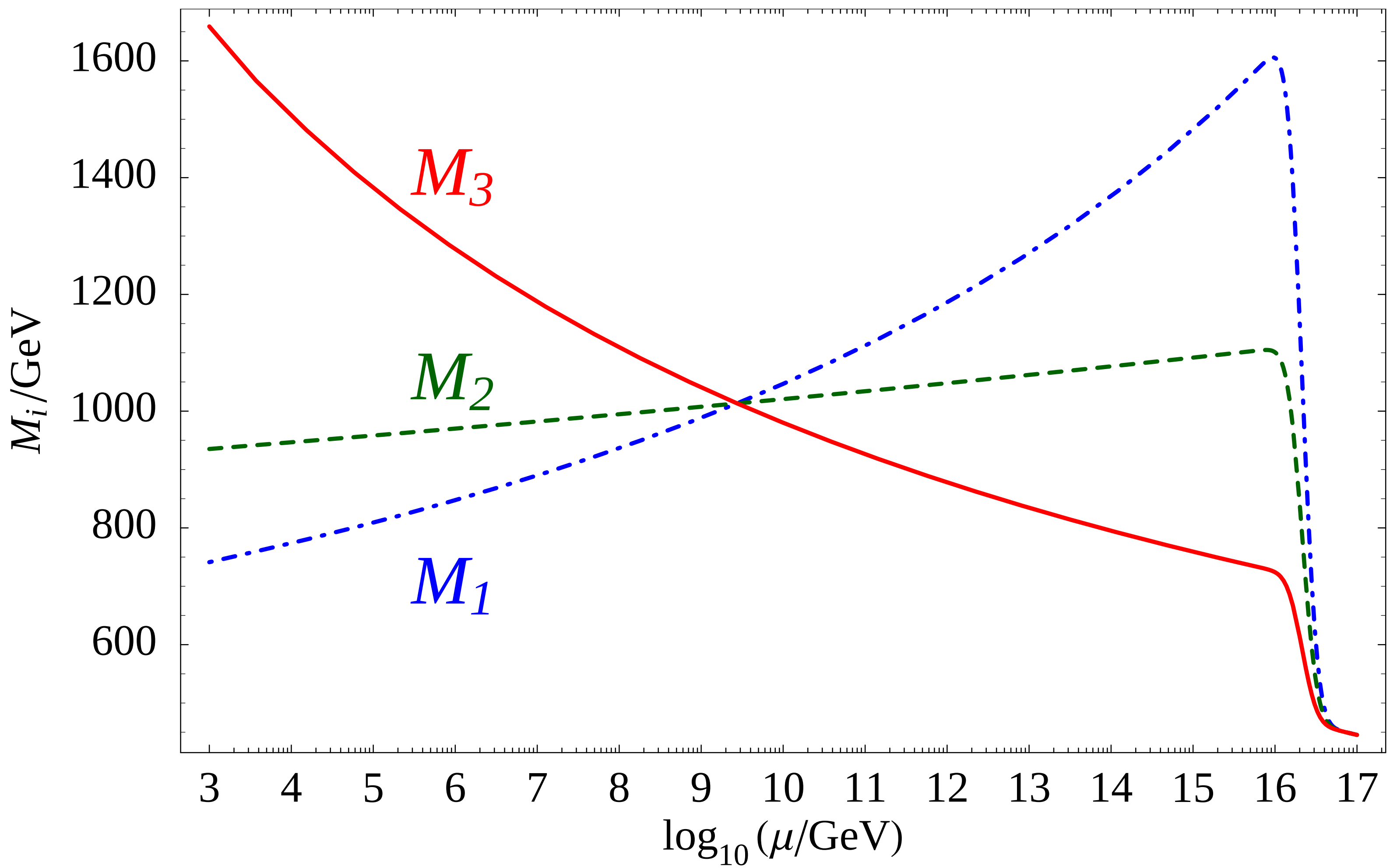
as a sum of two contributions of comparable size.

- 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

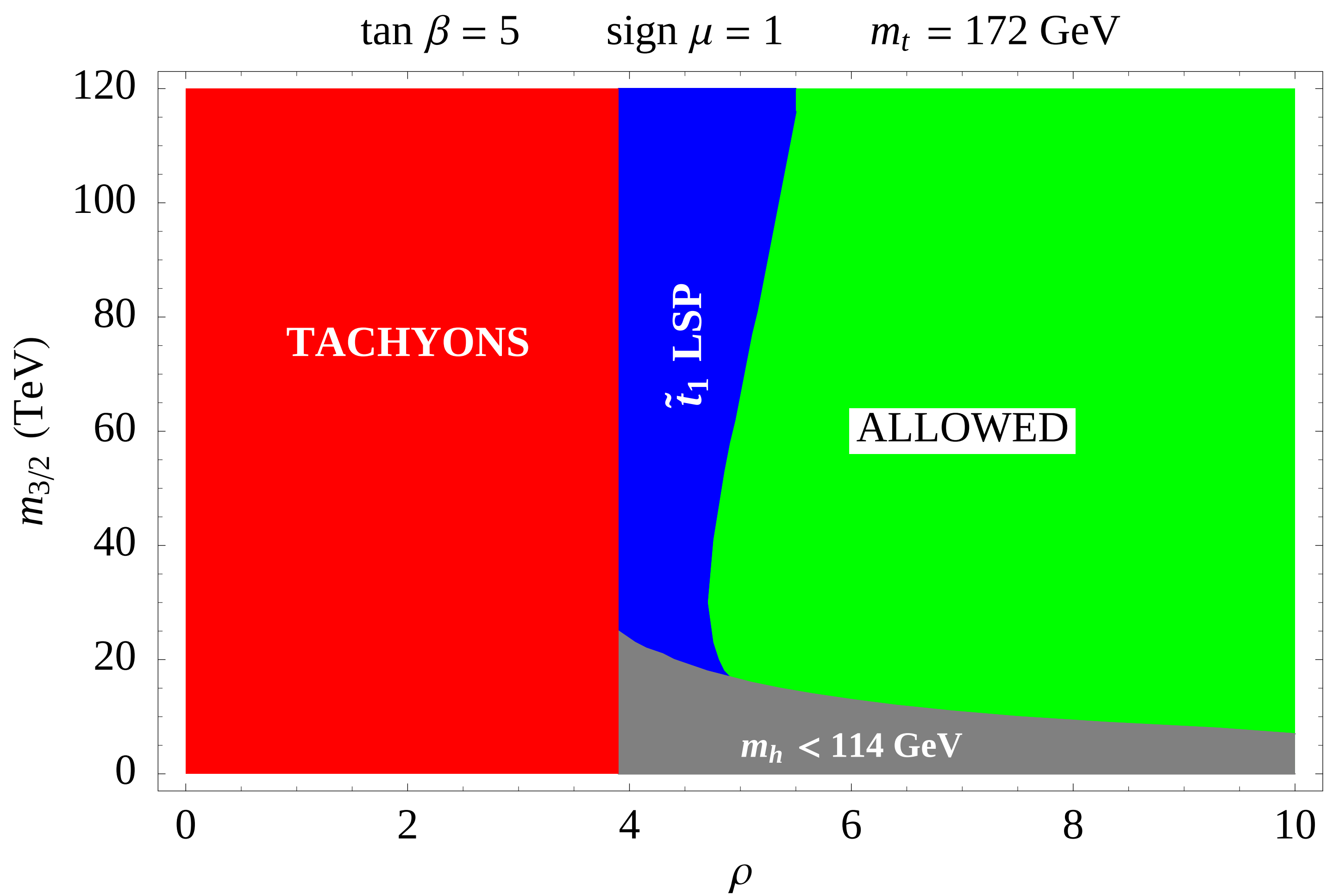
- above the GUT scale
- at the mirage scale $\mu_{\text{mirage}} = M_{\text{GUT}} \exp(-8\pi^2/\rho)$

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

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

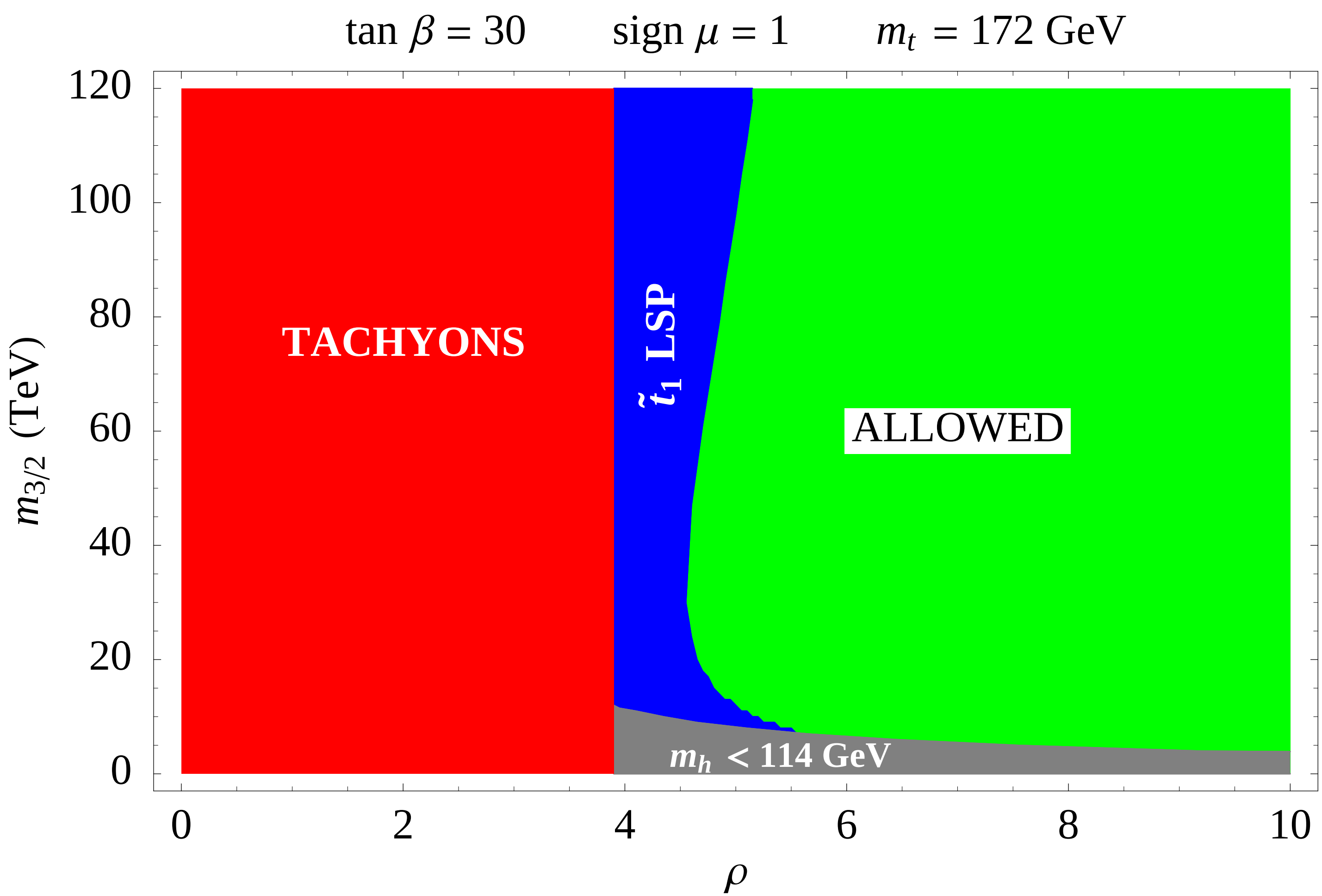
and $\rho \to 0$ corresponds to pure anomaly mediation.

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

- heavy gravitino
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One might worry about a fine-tuning to obtain

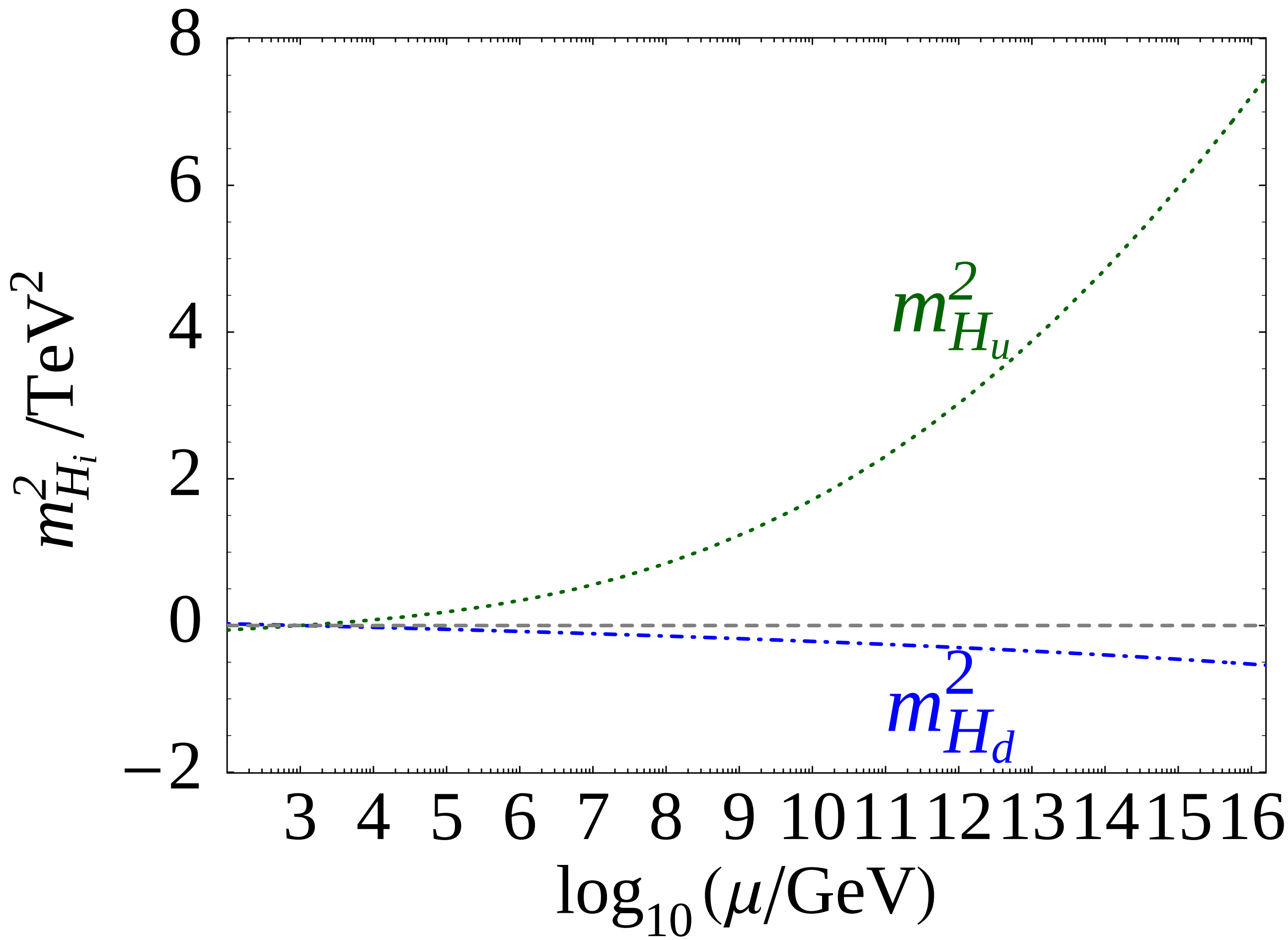
- the mass of the weak scale around 100 GeV from

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

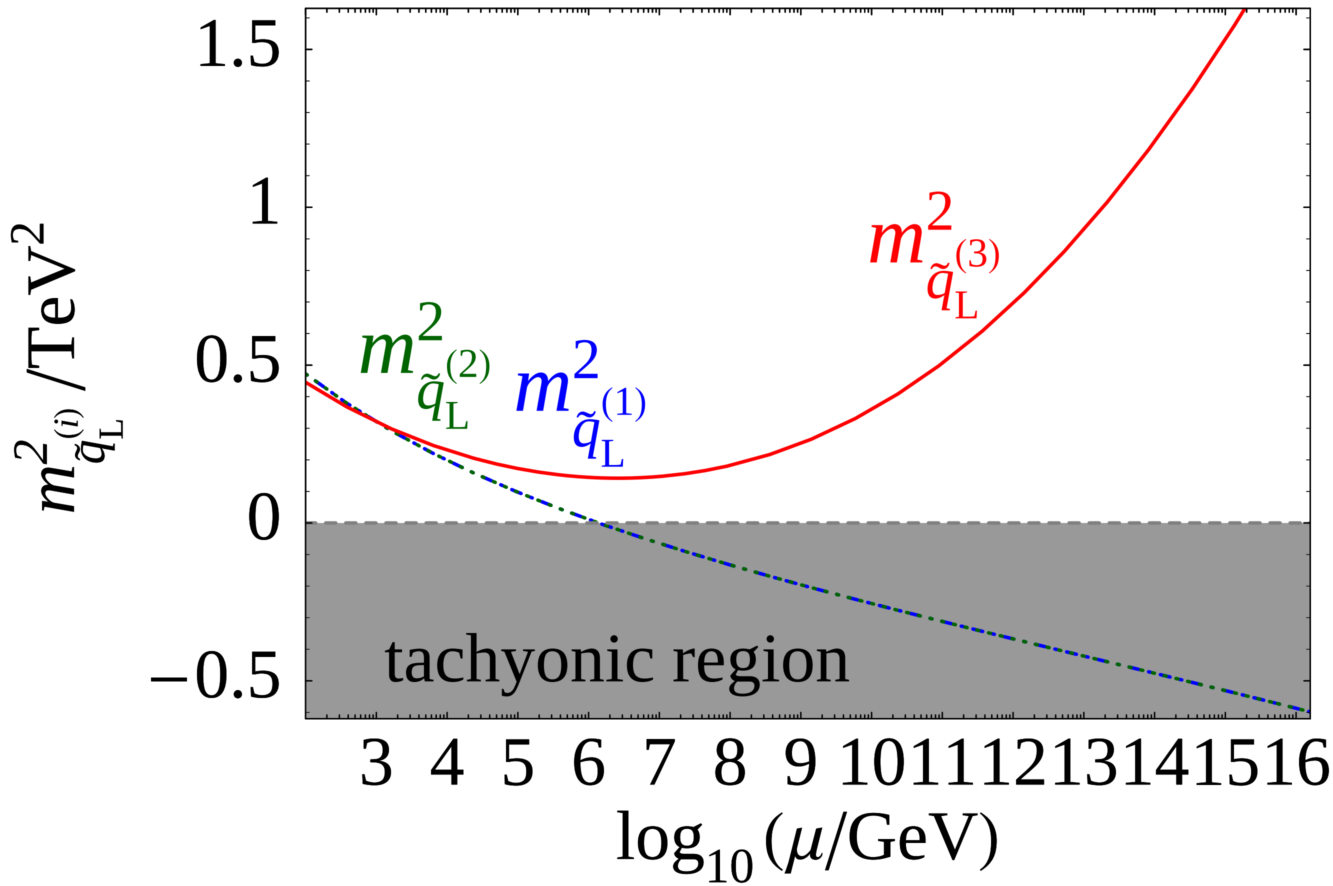
and there are large corrections to $m_{H_u}^2$......

(Choi, Jeong, Kobayashi, Okumura, 2005)

Evolution of Higgs masses



Evolution of Squark masses



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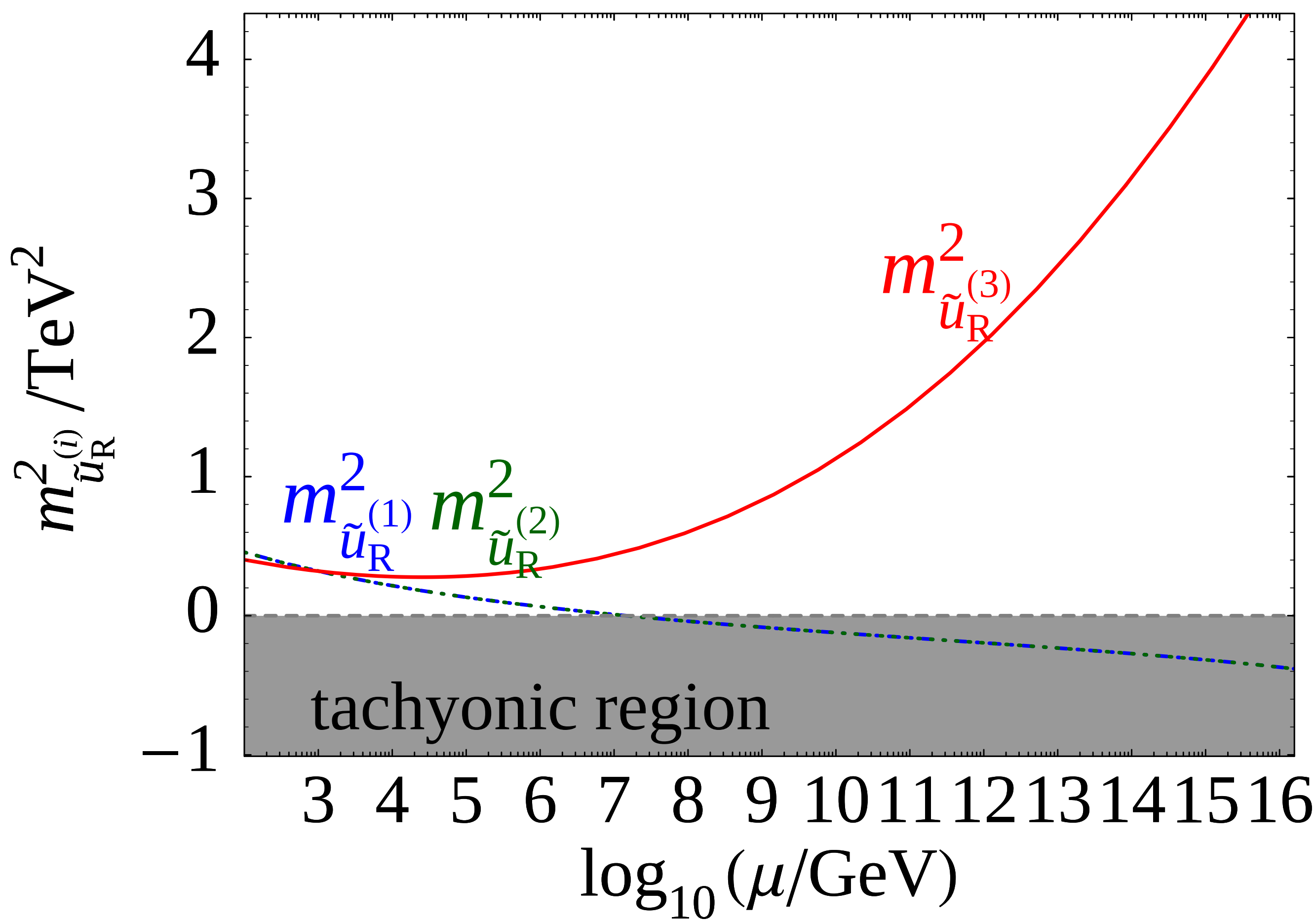

The "MSSM hierarchy problem"?

The influence of the various soft terms is given by

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

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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

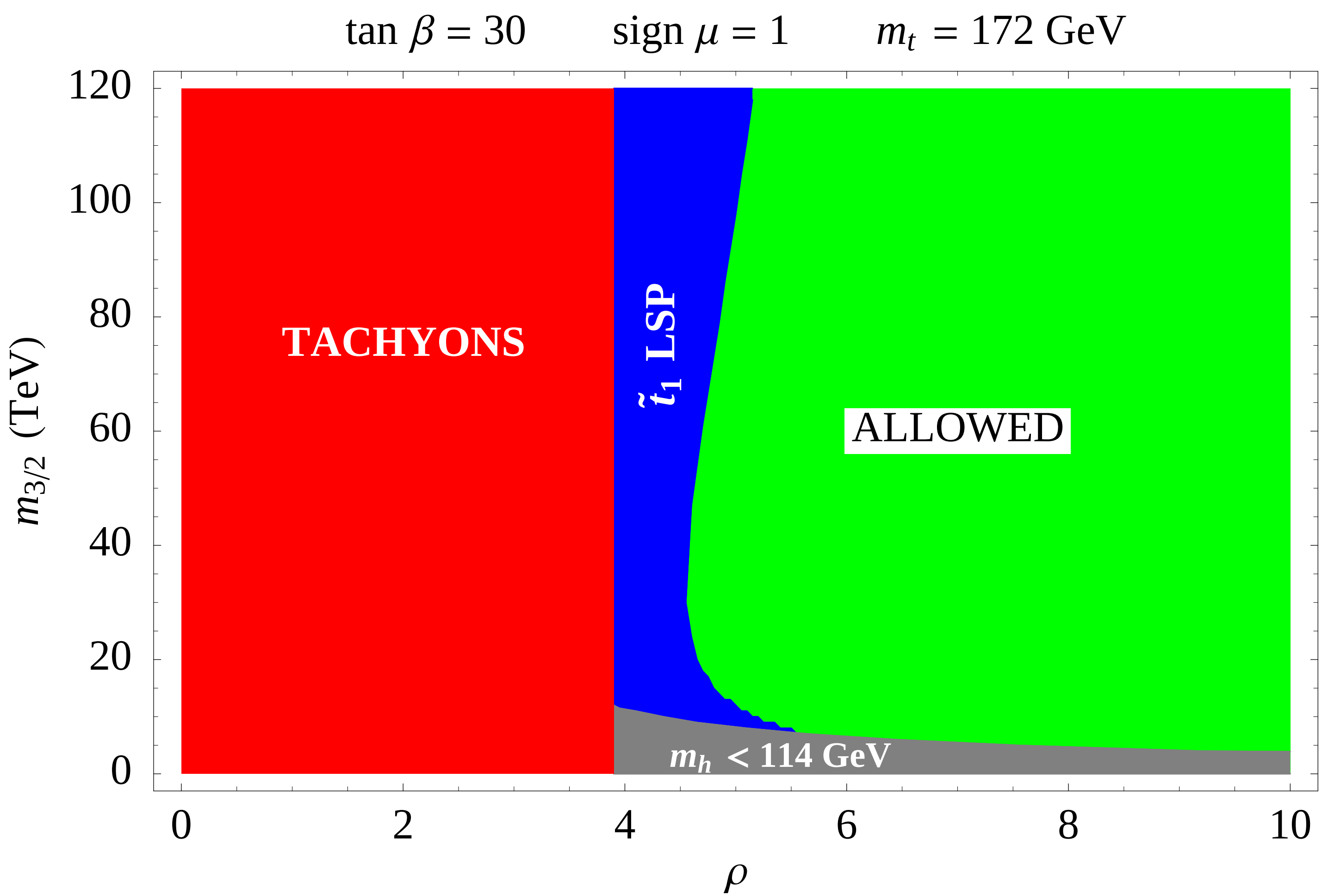
The different schemes depend on the mechanism of uplifting:

- uplifting with anti D3 branes

  (Kachru, Kallosh, Linde, Trivedi, 2003)

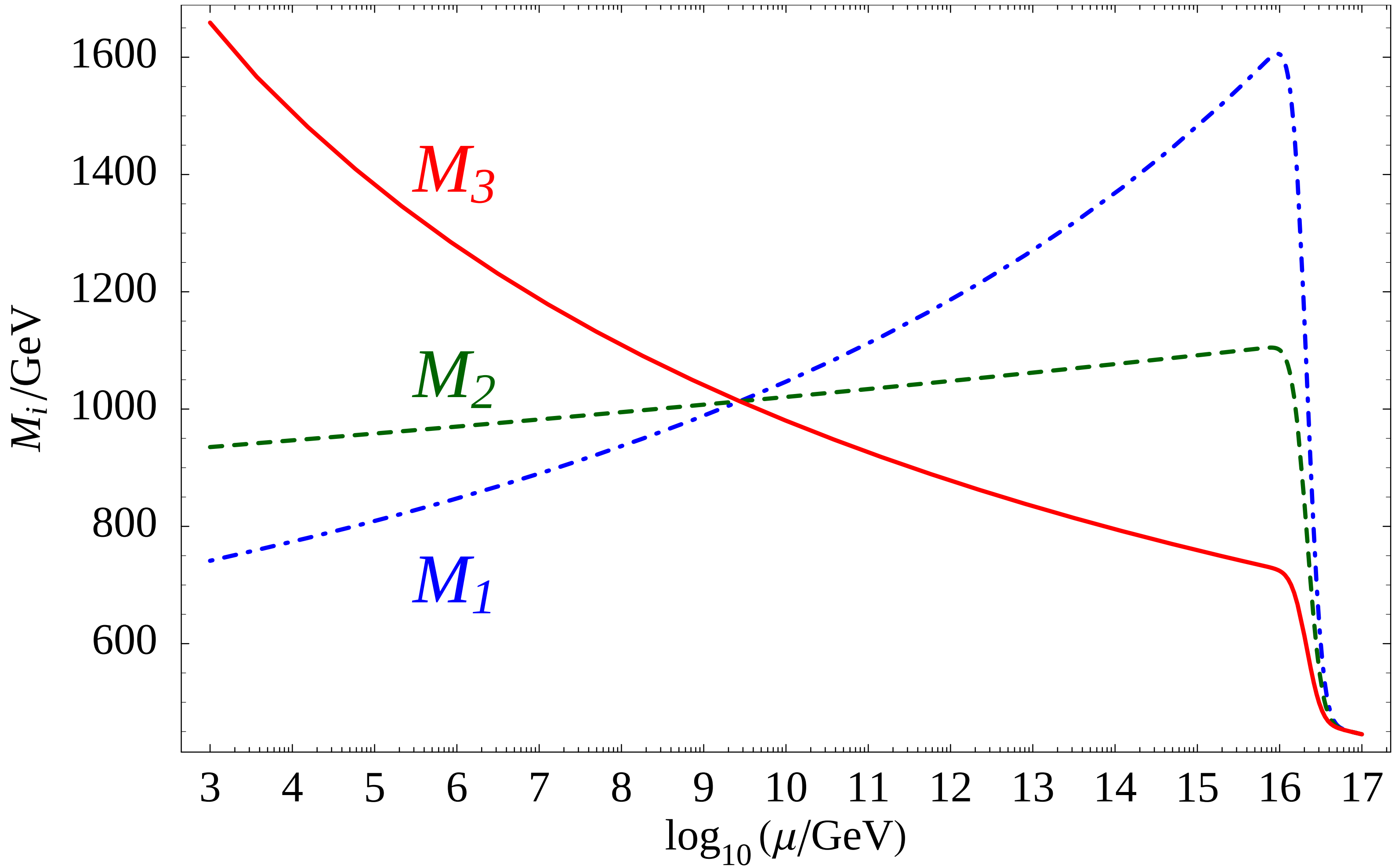
  - $\rho \sim 5$ in the original KKLT scenario leading to
  - a mirage scale of approximately 10^{11} GeV
- This scheme leads to pure mirage mediation:
  - gaugino masses and
  - scalar masses
- both meet at a common mirage scale

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
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- uplifting via matter superpotentials

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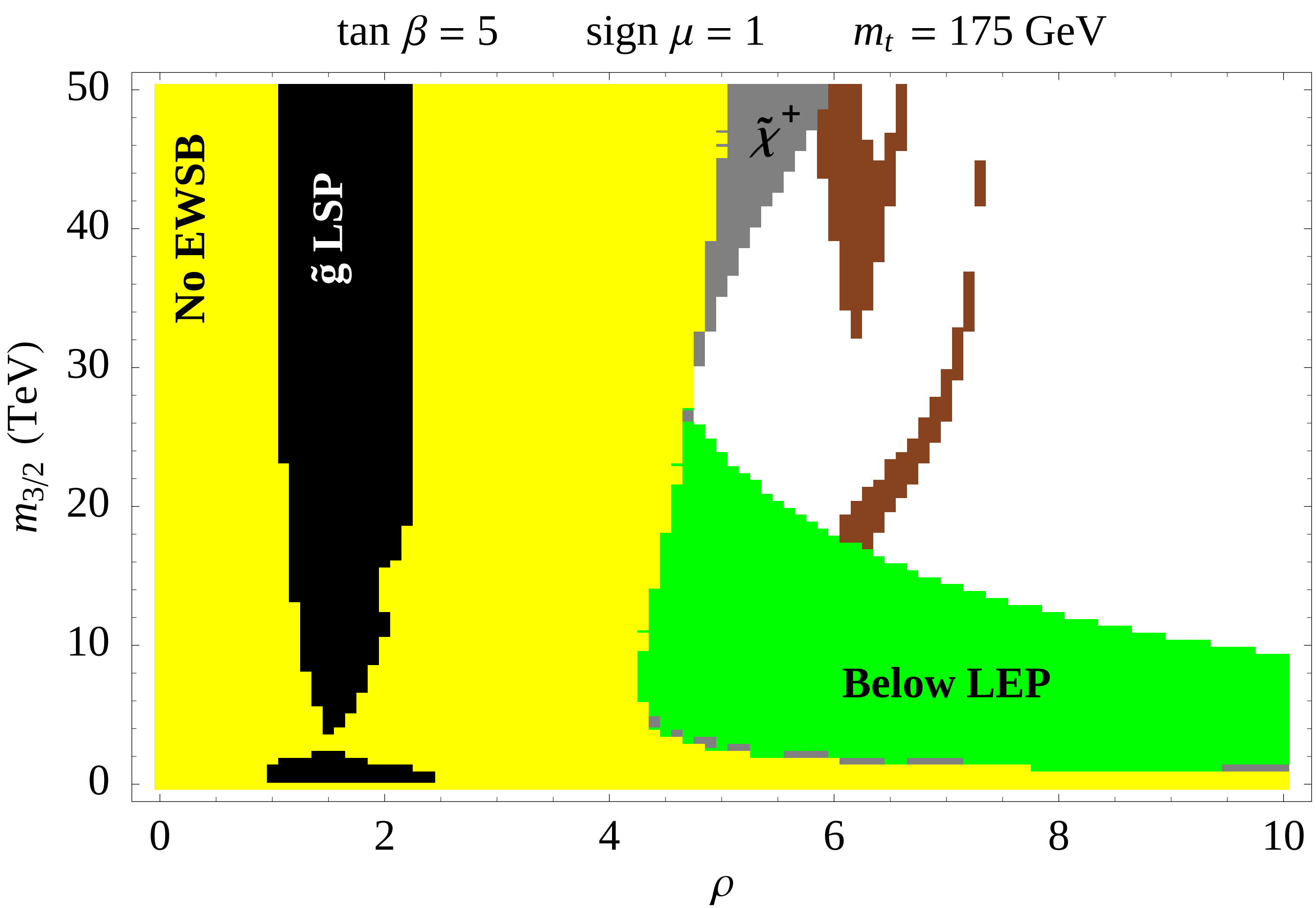
  - allows a continuous variation of ρ
  - leads to potentially new contributions to sfermion masses
- gaugino masses still meet at a mirage scale
- soft scalar masses might be dominated by modulus mediation
- similar constraints on the mixing parameter

Constraints on the mixing parameter



(V. Löwen, 2007)

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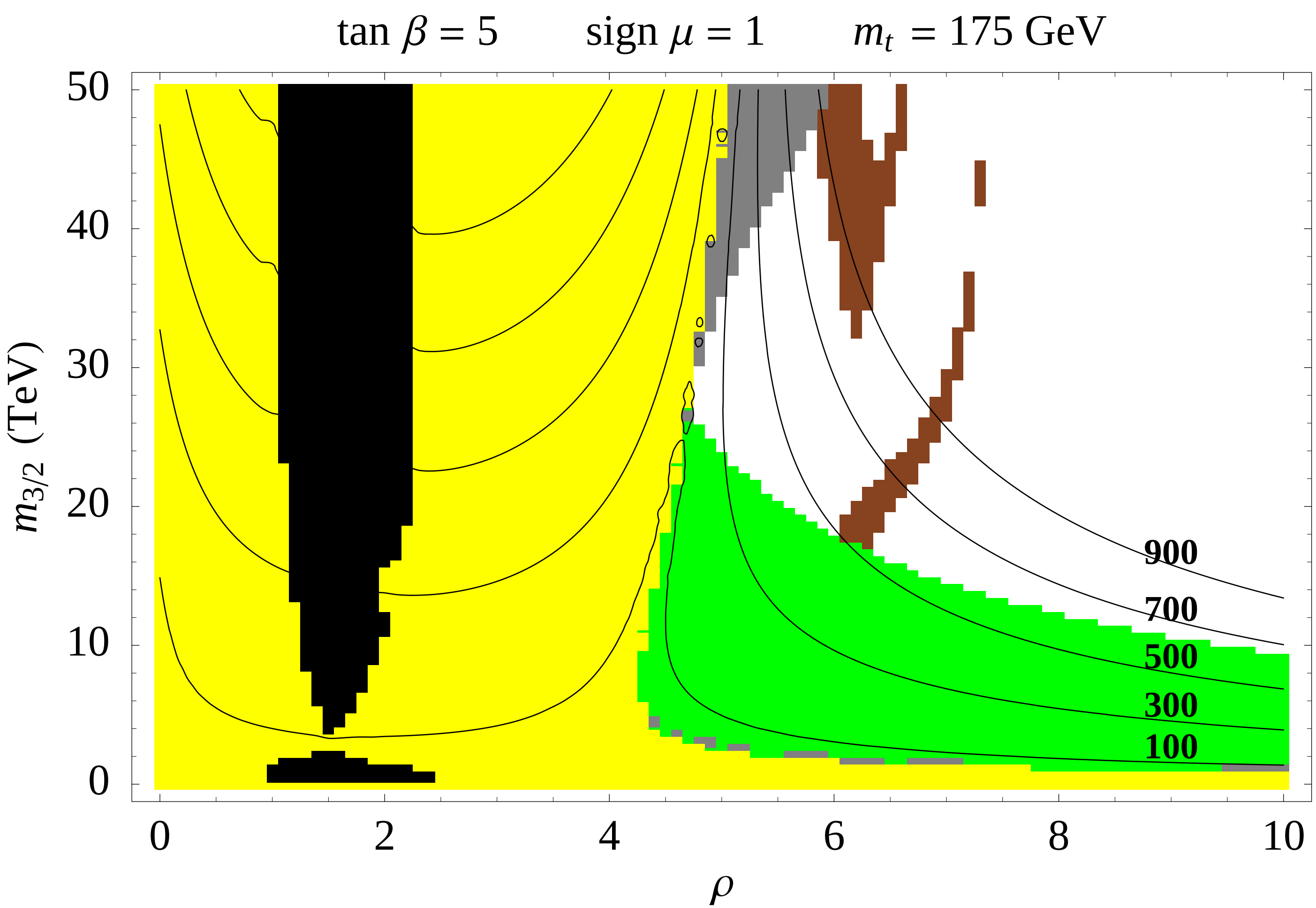

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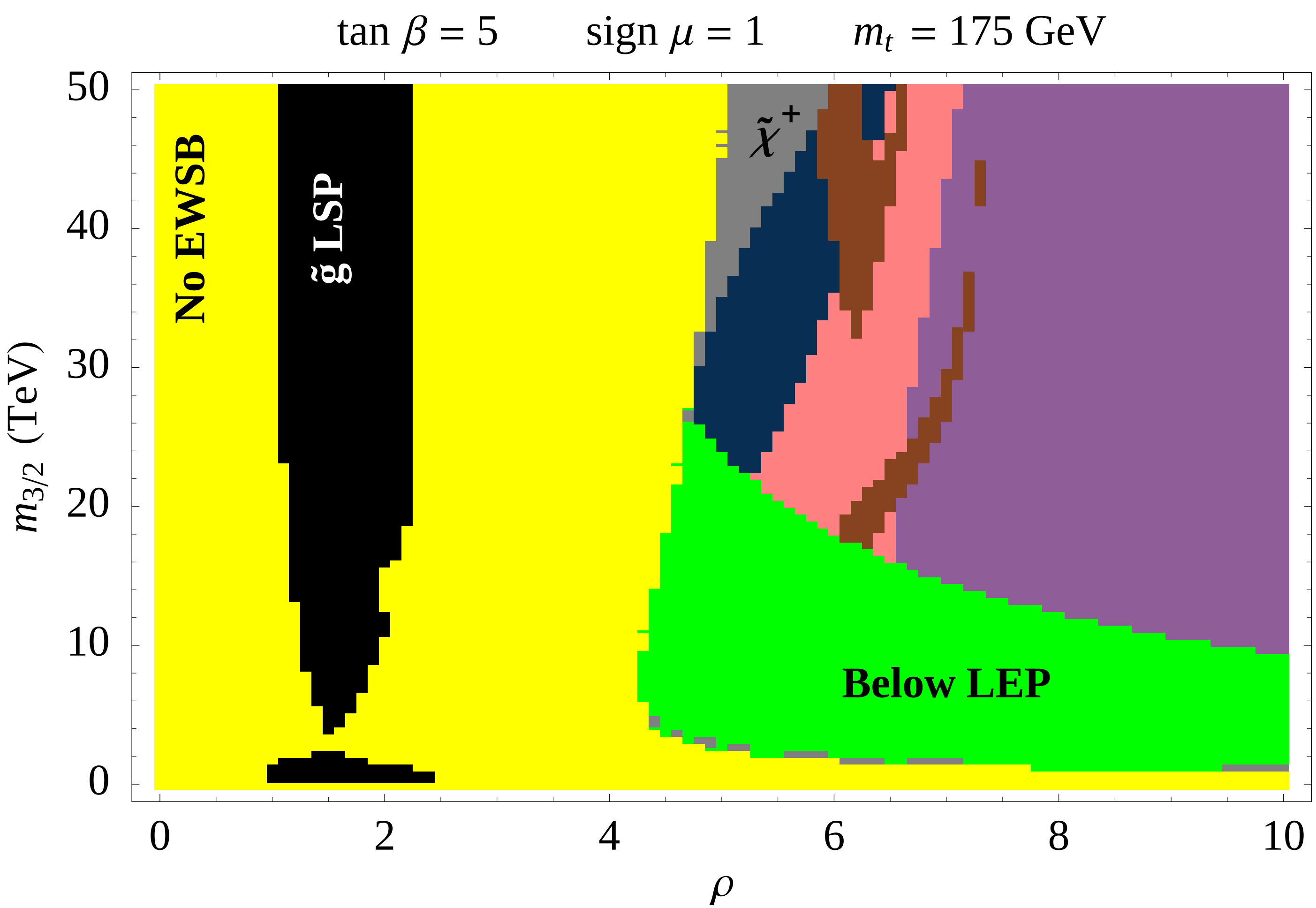

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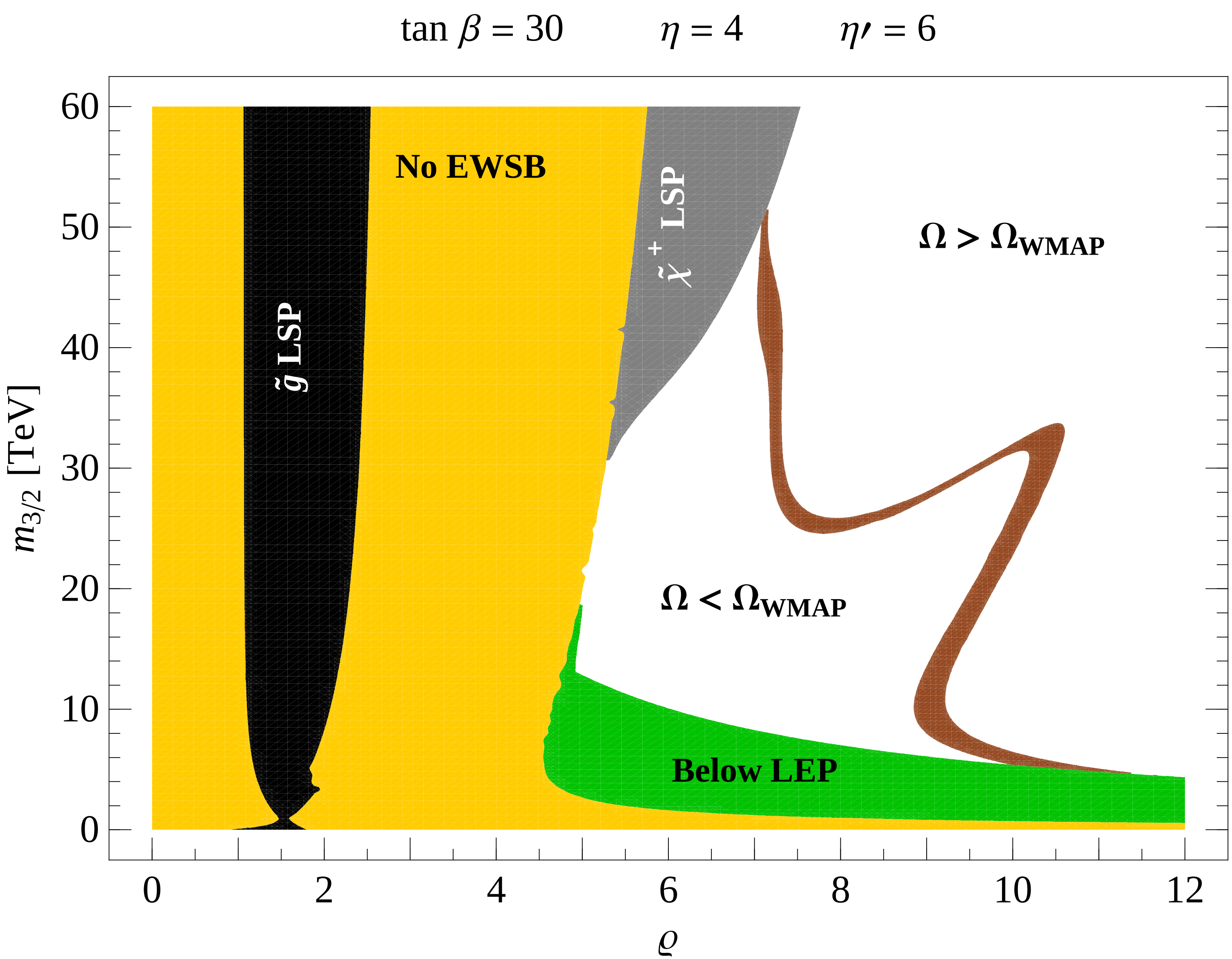

Explicit schemes III

- 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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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

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

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

(Choi, Jeong, 2006)

The string signatures

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

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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 uplifting 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

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

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

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

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

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
- $M_{\mathrm{gluino}}/m_{\chi_1^0} \simeq 6$

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 (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: (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.

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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
- main uncertainties from “string threshold corrections”

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