Hidden Susy from Precision Gauge Unification

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Input from string theory

- The MSSM is not a generic prediction of string theory,
- .... but it can be embedded.
- We obtain some lessons from the successful models.
- Relevant issues among others: the μ-problem, the top-mass and the flavour structure.
- Geometry of extra dimensions plays a crucial role.

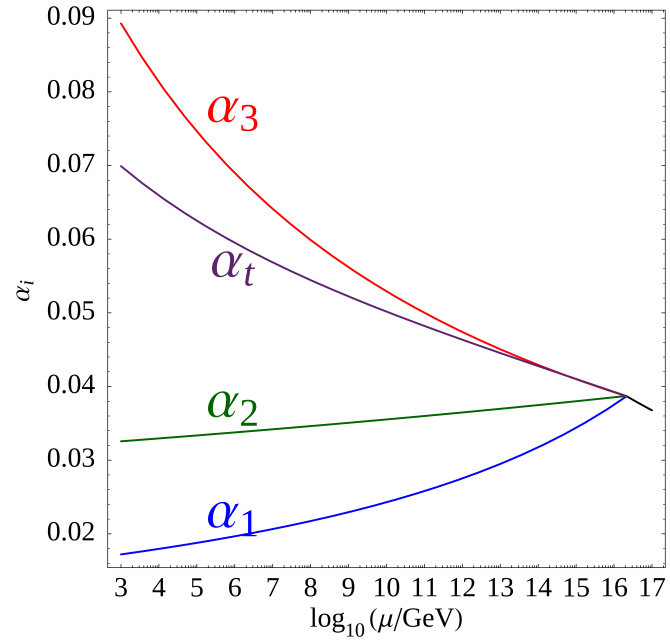
Lessons from geometry

- some fields localized others not
- specific pattern for susy breakdown

(Krippendorf, Nilles, Ratz, Winkler, 2012)

Unification

- Higgs doublets live in bulk: $d = 10$
- heavy top quark lives in bulk as well
- first two families localized at fixed points: $d = 4$



- $\mu-$term protected by a discrete symmetry
- natural incorporation of gauge-Yukawa unification
- we expect precision gauge unification (PGU)

Lesson 1: The Higgs system

Some generic properties of the heterotic "MiniLandscape"

- exactly two Higgs multiplets (no triplets). Potentially additional Higgs pairs removed with other vector-like exotics
- μ protected by an R-symmetry

(Lebedev et al., 2008; Kappl et al., 2009)

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(Lebedev et al., 2008; Kappl et al., 2009)

This last pair is “localized” in the untwisted sector

- R-symmetry from Lorentz group in extra dimensions
- solution to μ problem (Minkowski vacuum)
- gauge-Higgs unification

Lesson 2: the top quark

Majority of models of the “MiniLandscape” have the top-quark in the untwisted sector

- maximal overlap with Higgs field in untwisted sector
- only one trilinear Yukawa coupling for the top quark (others Yukawa couplings suppressed)

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- maximal overlap with Higgs field in untwisted sector
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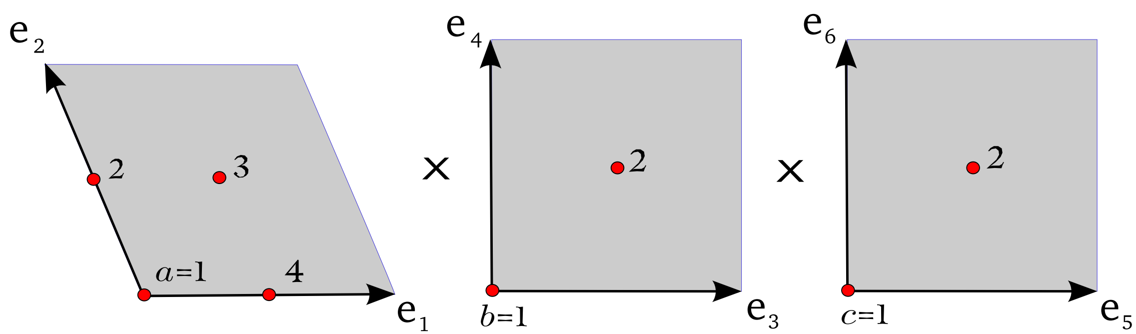
The top quark is a bulk field as well:

- unification of gauge coupling and top quark Yukawa coupling (gauge-top unification)
- other fields of 3rd family reside in different sectors (and are quite model dependent)
- 3rd family is a “patchwork family”

Lesson 3: the first two families

The first two families live at fixed points ($d = 4$):



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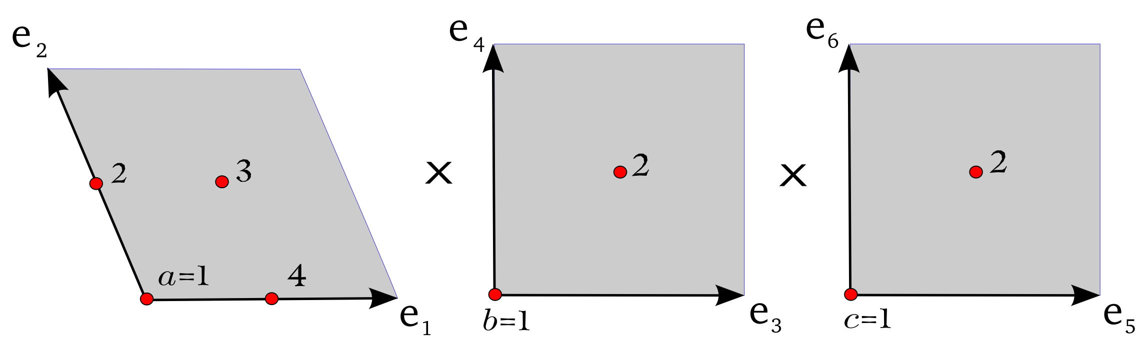

- they exhibit a D_4 family symmetry (absence of FCNC)
- no trilinear Yukawa couplings
  (suppressed masses compared to top quark)
- mass pattern is generated via a Frogatt-Nielsen mechanism (dictated by the pattern of Wilson lines)

Lesson 4: Pattern of Susy breakdown

Expect some version of "Mirage Mediation":

(Choi, Falkowski, Nilles,Olechowski, 2005)

- scalar masses of order of the gravitino mass $m_{3/2}$
- gaugino masses and A-parameters suppressed by $\log(M_{\text{Planck}}/m_{3/2}) \sim 4\pi^2$
- compressed pattern of gaugino masses

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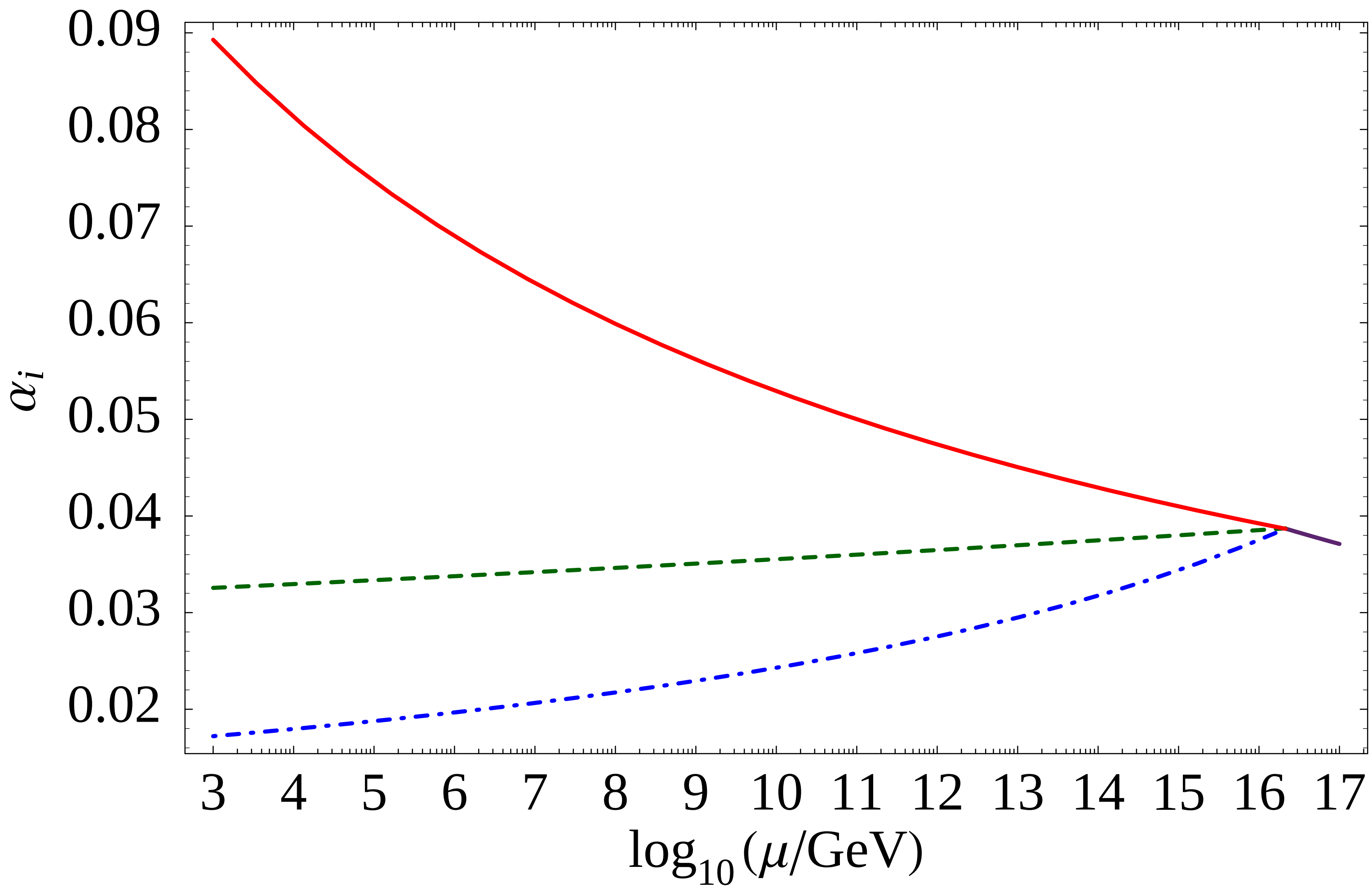
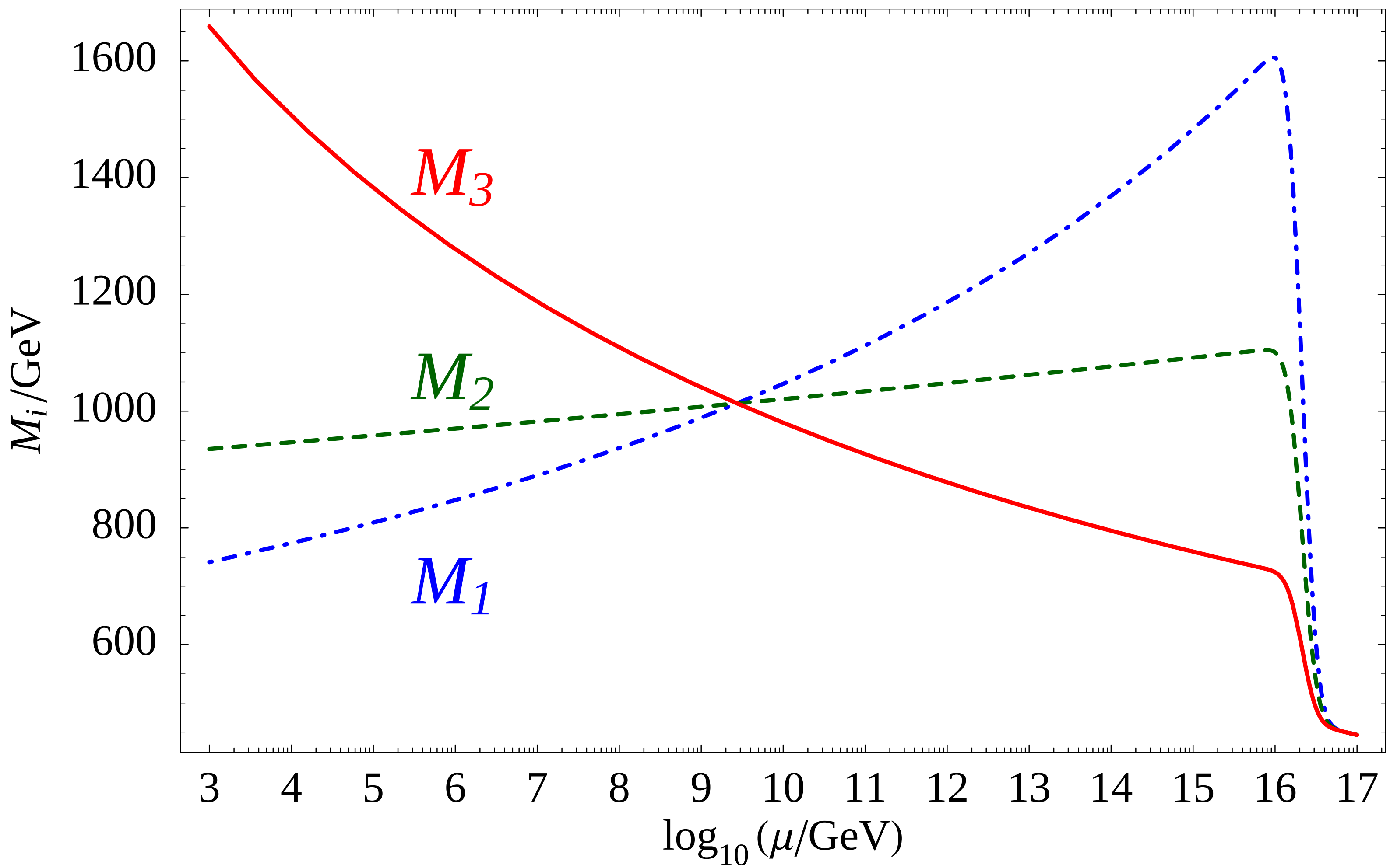
Various sectors enjoy extended Susy
and therefore a stronger protection (via loops $\sim 1/(4\pi)^2$)

- untwisted sector (bulk): $N = 4$
- fixed tori: $N = 2$ and fixed points: $N = 1$

Evolution of couplings

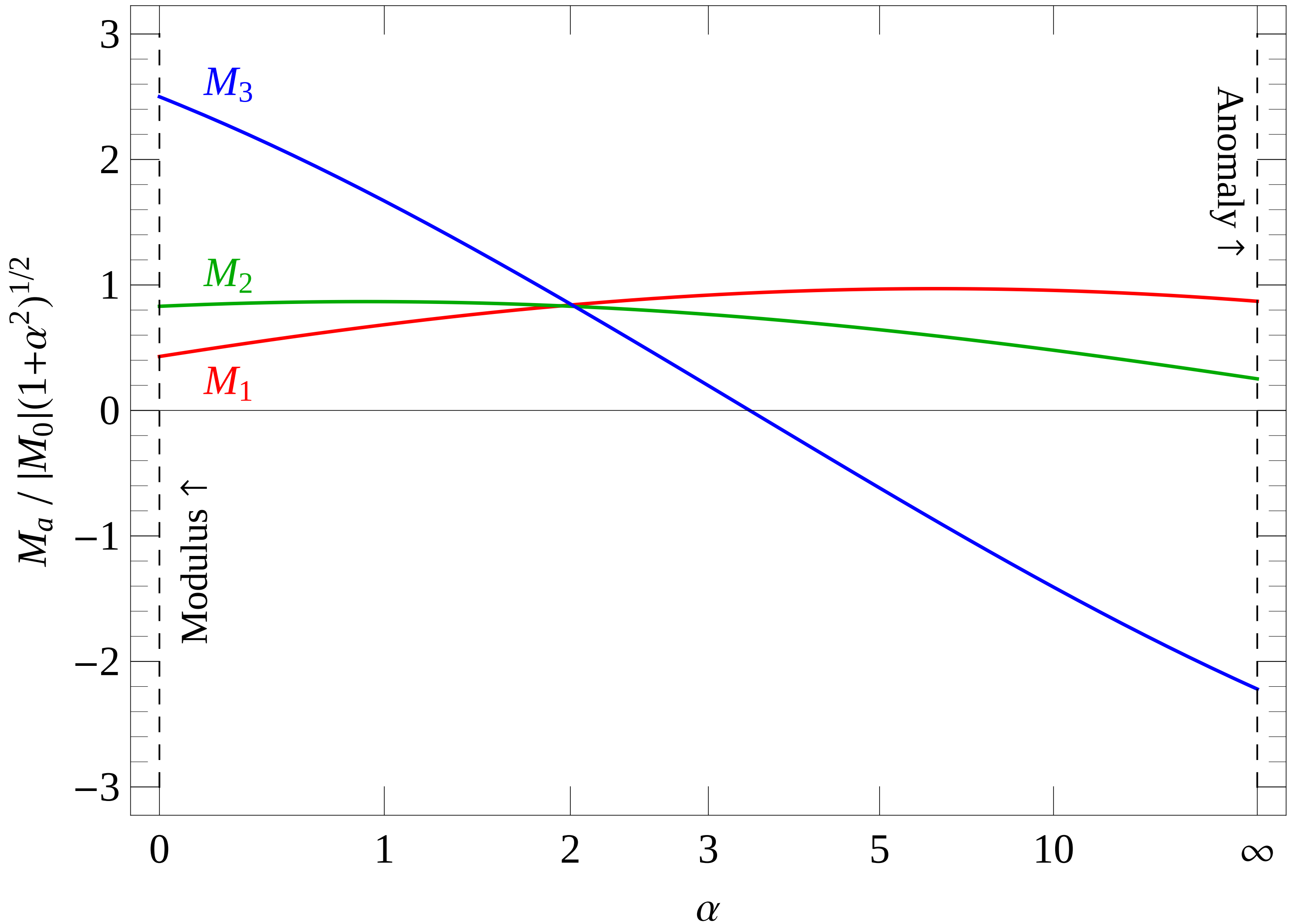


The Mirage Scale



(Lebedev, HPN, Ratz, 2005)

Gaugino Masses



Soft terms

While normal scalar masses are less protected

- this is not true for the top- and Higgs-multiplets
- they live in the untwisted sector (bulk)
- all other multiplets live in twisted sectors (branes)

This protection can be understood as a remnant of

- extended supersymmetry in higher dimensions
- $N = 4$ supersymmetry from $N = 1$ in $D = 10$ via torus compactification
- Higgs und stops remain in the TeV-range

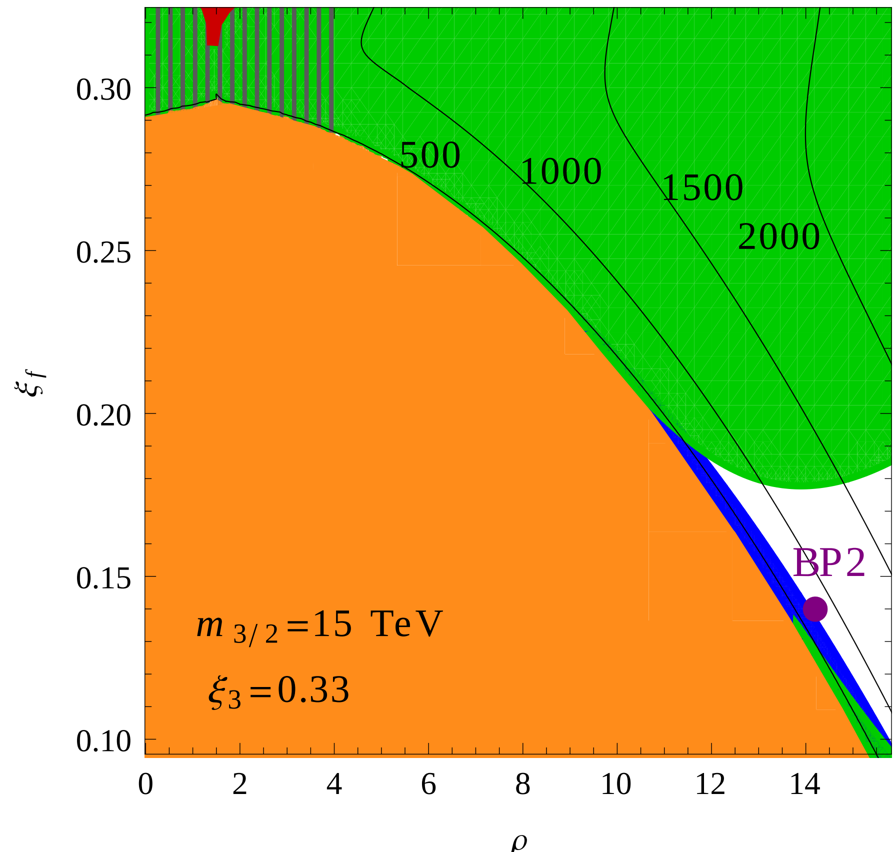
(Krippendorf, Nilles, Ratz, Winkler, 2012)

The overall pattern

This provides a specific pattern for the soft masses with a large gravitino mass in the multi-TeV range

- normal squarks and sleptons in multi-TeV range
- top squarks $(\tilde{t}_L, \tilde{b}_L)$ and $\tilde{t}_R$ in TeV-range (suppressed by $\log(M_{\rm Planck}/m_{3/2}) \sim 4\pi^2$)
- A-parameters in TeV range
- gaugino masses in TeV range
- mirage pattern for gaugino masses (compressed spectrum)
- heavy moduli (enhanced by $\log(M_{\rm Planck}/m_{3/2})$ compared to the gravitino mass)

Model with 3 TeV gluino

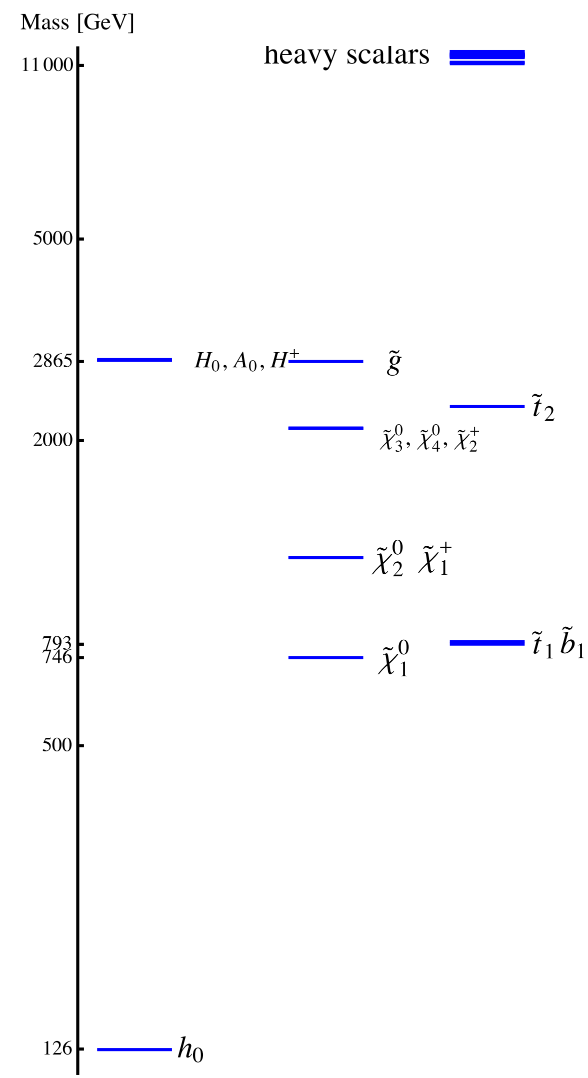


Parameter scan for a gluino mass of 3 TeV.

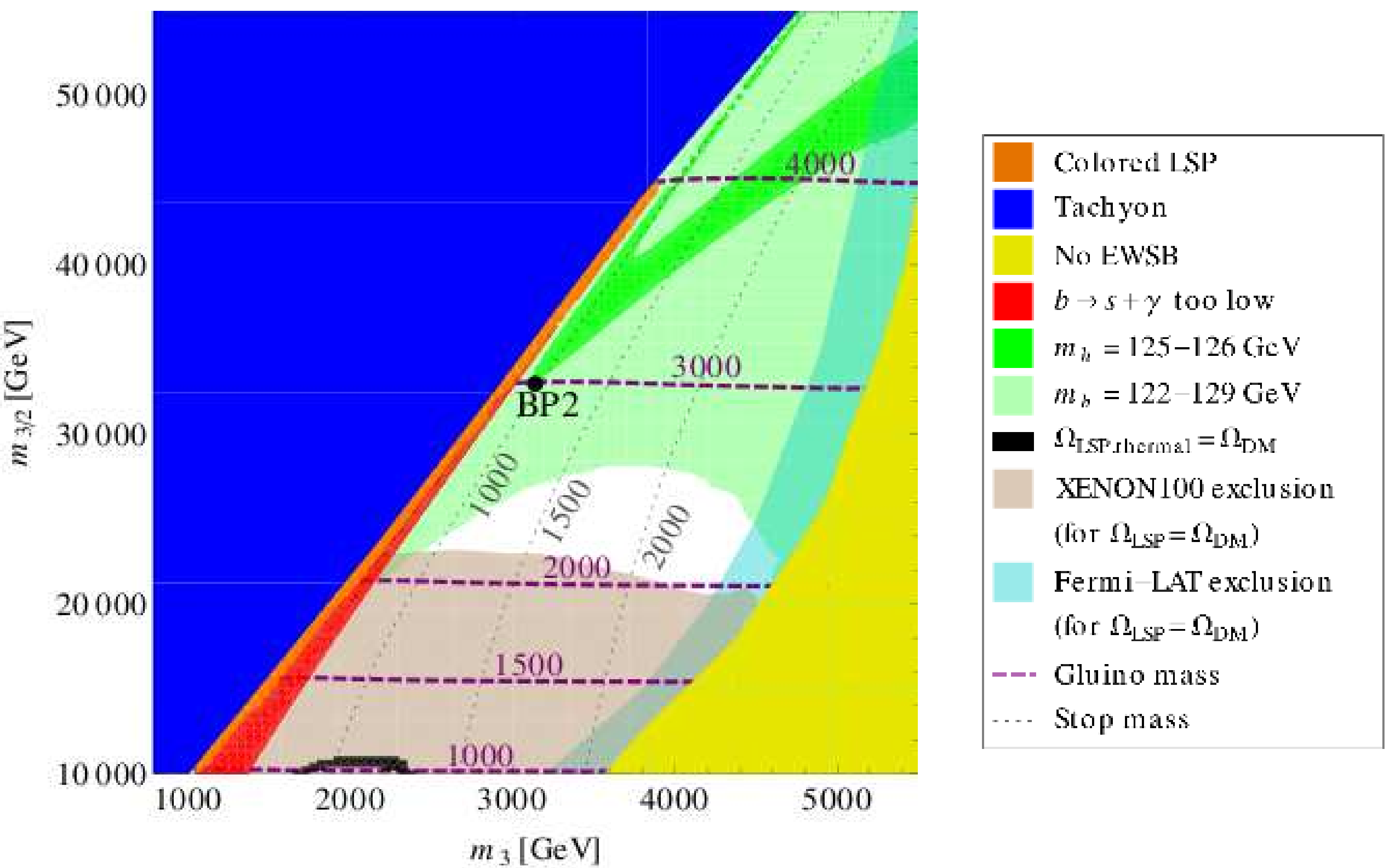
The coloured regions are excluded while the hatched region indicates the current reach of the LHC.

The contours indicate the mass of the lightest stop.

Spectrum of model with a 3 TeV gluino



Parameter Scan



Messages

- large gravitino mass (multi TeV-range)
- heavy moduli: $m_{3/2} \log(M_{\rm Planck}/m_{3/2})$
- mirage pattern for gaugino masses rather robust
- sfermion masses are of order $m_{3/2}$
- the ratio between sfermion and gaugino masses is limited
- heterotic string yields “Natural Susy”. There is a reduced fine-tuning because of
  - mirage pattern,
  - and light stops,
- and this is a severe challenge for LHC searches.

The quest for “Precision Susy”

Two important arguments for supersymmetry

- solution to the hierarchy problem
- gauge coupling unification

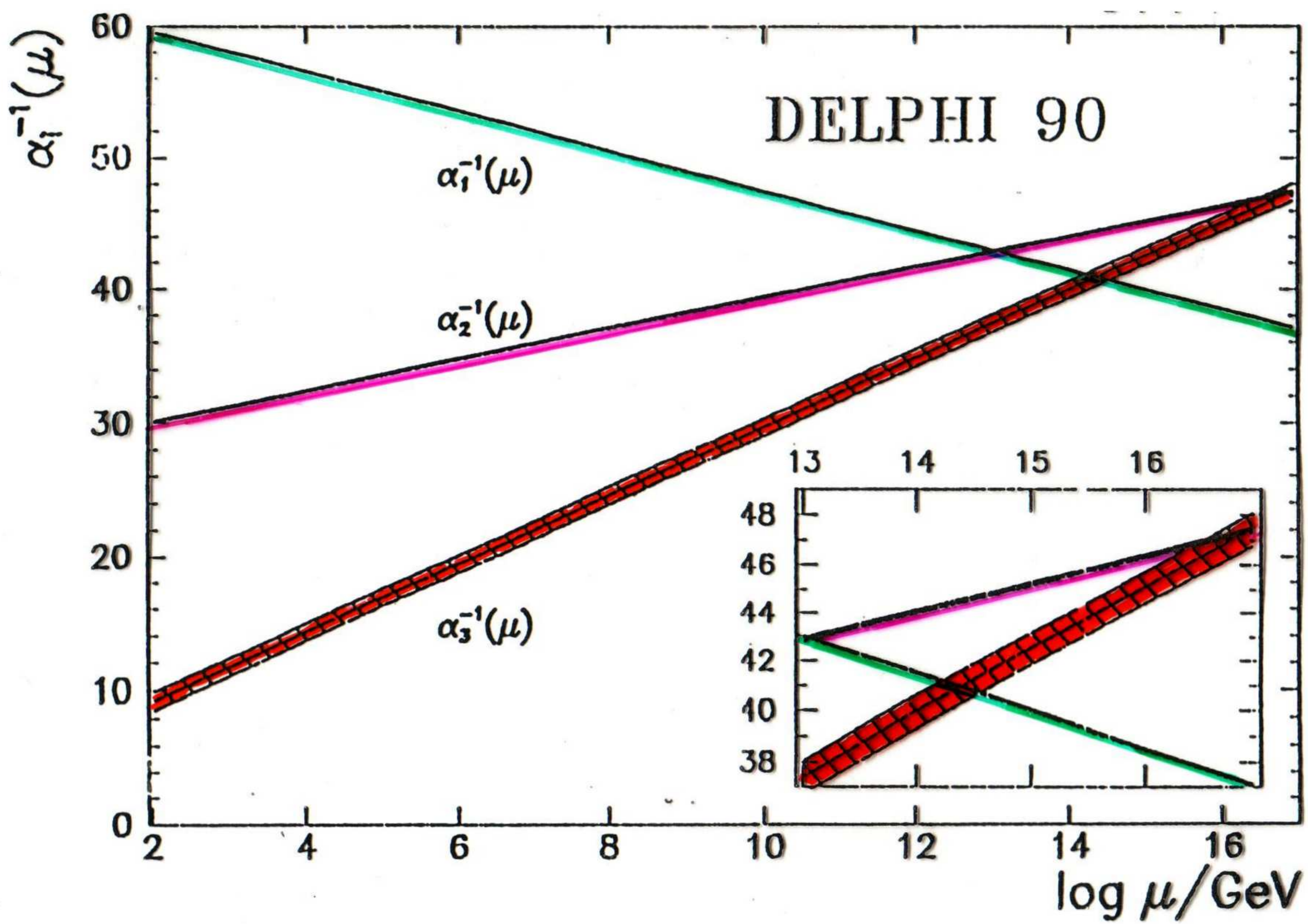
We want to take these two arguments as serious as possible and reanalyze the MSSM within the previously described scheme. We make two assumptions:

- demand precision gauge unification
- require a small μ parameter for a reduced fine tuning

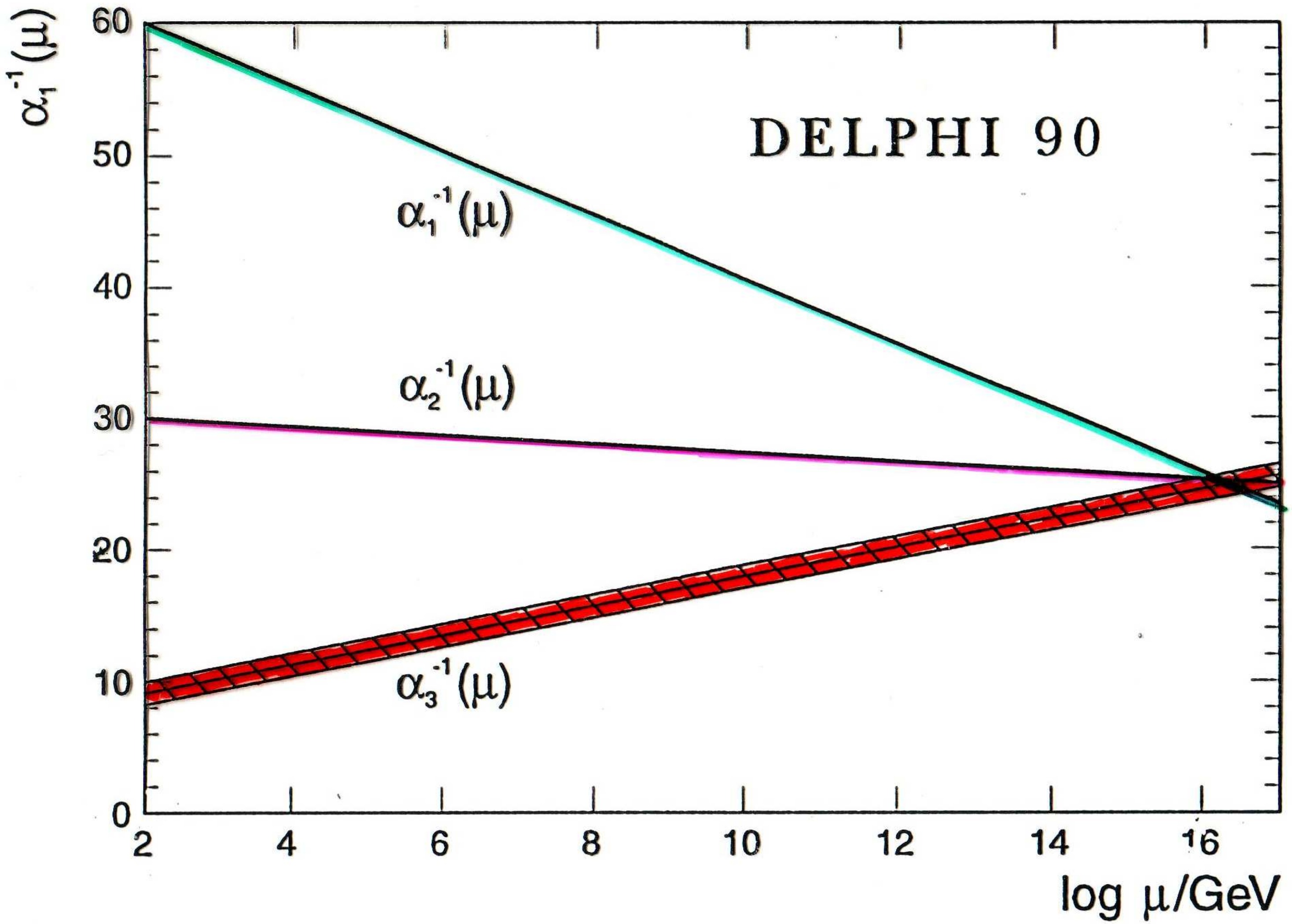
What are the consequences for the spectrum?

(Krippendorf, Nilles, Ratz, Winkler, 2013)

Standard Model



MSSM



DELPHI 90
$\alpha_1^{-1}(\mu)$
$\alpha_2^{-1}(\mu)$
$\alpha_3^{-1}(\mu)$
0
10
20
30
40
50
60
2
4
6
8
10
12
14
16
log μ/GeV

Precision gauge unification

$$\frac{1}{g_i^2(M_{\text{GUT}})} = \frac{1}{g_i^2(M_Z)} - \frac{b_i^{\text{MSSM}}}{8\pi^2}\ln\left(\frac{M_{\text{GUT}}}{M_Z}\right) + \frac{1}{g_{i,\text{Thr}}^2}$$

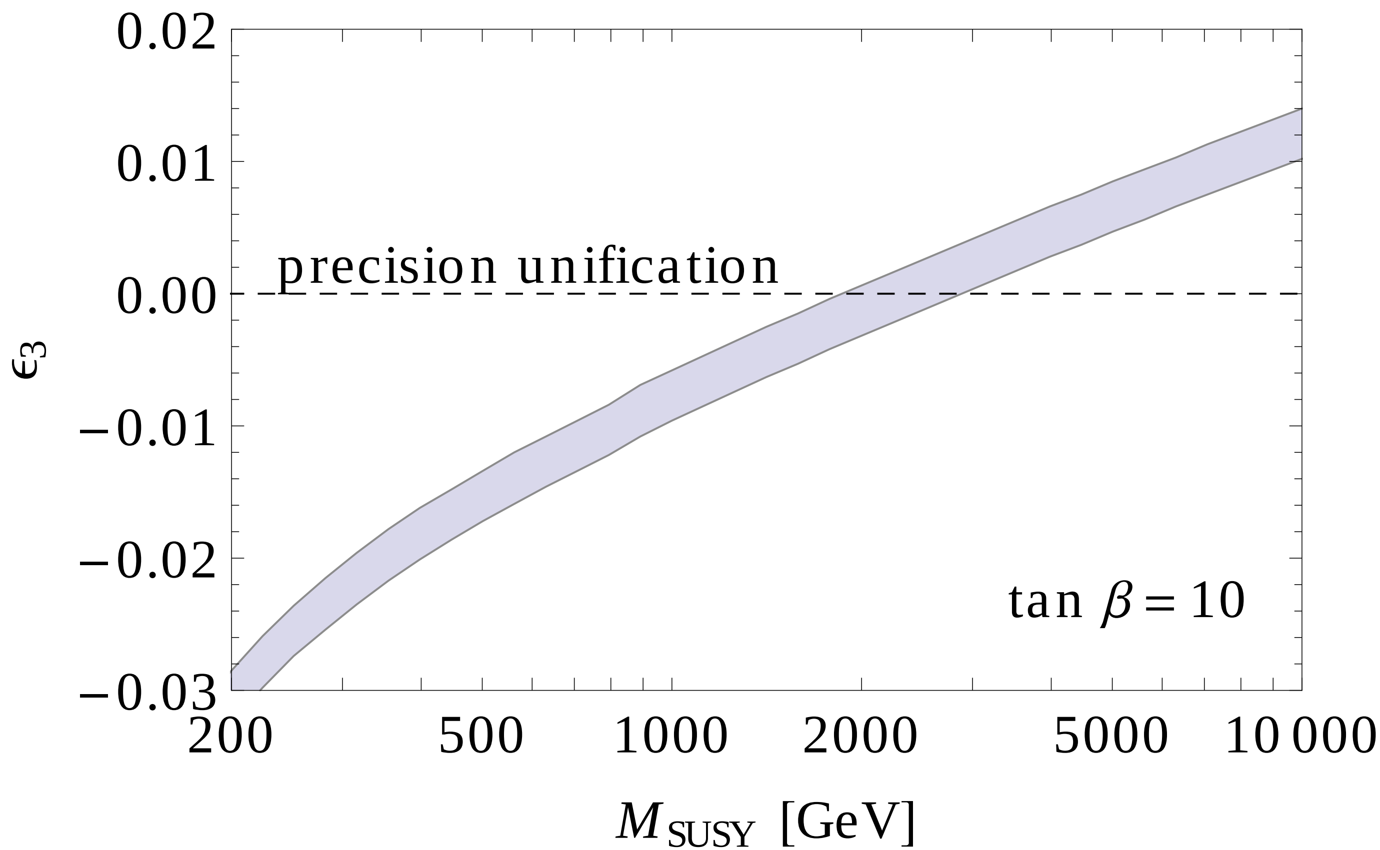
Low scale thresholds:

$$\frac{1}{g_{i,\text{Thr}}^2} = \frac{b_i^{\text{MSSM}} - b_i^{\text{SM}}}{8\pi^2}\ln\left(\frac{M_{\text{SUSY}}}{M_Z}\right)$$

The measure for gauge unification:

$$\epsilon_3 = \frac{g_3^2(M_{\text{GUT}}) - g_{1,2}^2(M_{\text{GUT}})}{g_{1,2}^2(M_{\text{GUT}})}$$

Unification versus M_{SUSY}



M_{SUSY} should thus be in the few-TeV range.

The Susy-Scale

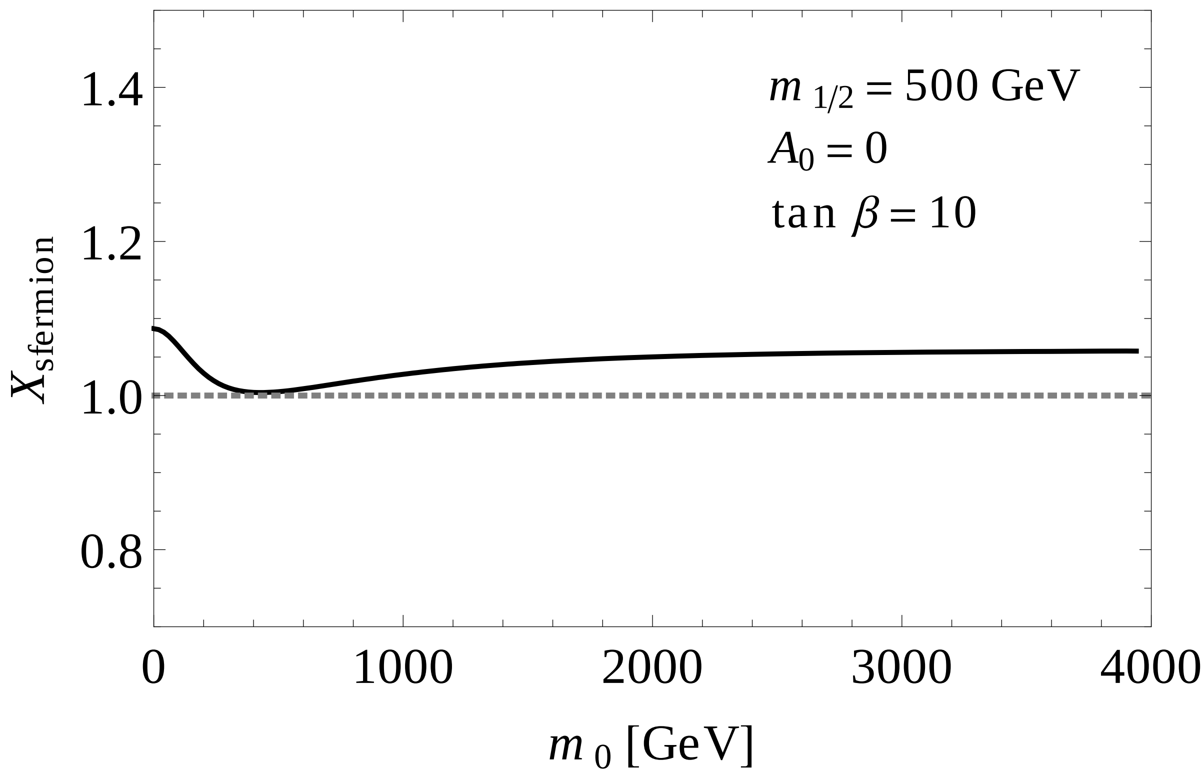
If all supersymmetric partners have the same mass M, then $M_{SUSY} = M$.
For non-universal masses we have an effective scale:

$$M_{\text{SUSY}} \sim \frac{m_{\widetilde{W}}^{32/19}\, m_{\tilde{h}}^{12/19}\, m_{H}^{3/19}}{m_{\tilde{g}}^{28/19}}\, X_{\text{sfermion}}$$

with

$$X_{\text{sfermion}} = \prod_{i=1\ldots3} \left(\frac{m_{\widetilde{L}^{(i)}}^{3/19}}{m_{\widetilde{D}^{(i)}}^{3/19}} \right) \left(\frac{m_{\widetilde{Q}_{\mathrm{L}}^{(i)}}^{7/19}}{m_{\widetilde{E}^{(i)}}^{2/19}\, m_{\widetilde{U}^{(i)}}^{5/19}} \right)$$

Effect of sfermions



Within this class of models the effect of sfermions is small

Universal MSSM

Consider universal gaugino masses (at the GUT scale).

$$M_1 : M_2 : M_3 = 1 : 2 : 6$$

The effective Susy scale reads:

$$M_{\mathrm{SUSY}} \;\simeq\; 0.3 \left(m_{\tilde{h}}^{12} \, m_{1/2}^{4} \, m_{H}^{3} \right)^{1/19} \; X_{\mathrm{sfermion}}$$

leading to a large Higgsino mass:

$$m_{\tilde{h}} \;\simeq\; 20 \text{ TeV} \times \left(\frac{\text{TeV}}{m_{1/2}} \right)^{1/3} \left(\frac{\text{TeV}}{m_H} \right)^{1/4}$$

with a severe fine-tuning problem.

Compressed Spectra

Consider mirage mediation:

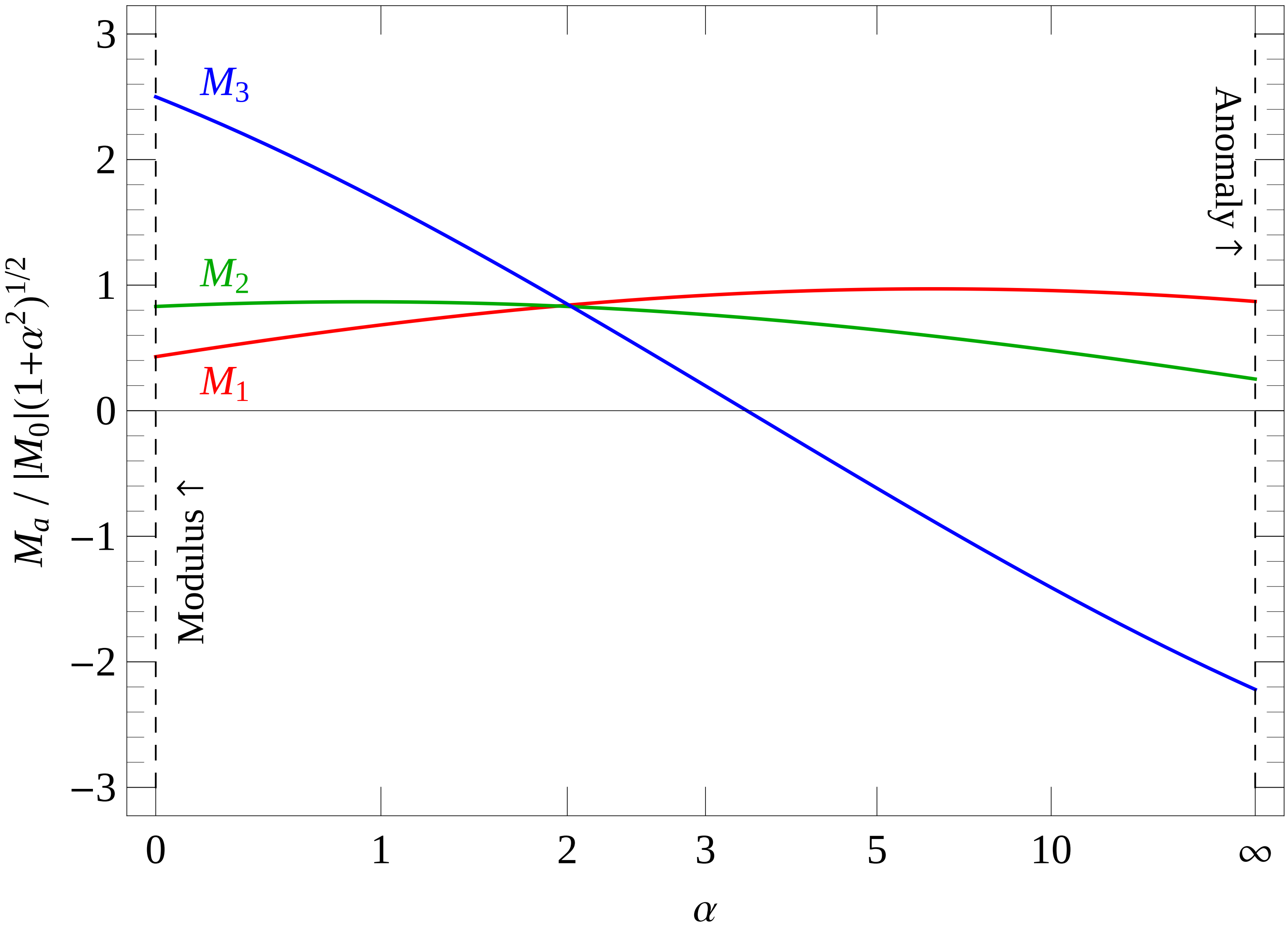
$$M_i \;=\; \frac{m_{3/2}}{16\,\pi^2}\left(\varrho + b_i^{\mathsf{MSSM}}\,g^2\right)$$

which leads to

$$M_1 : M_2 : M_3 = (\varrho + 3.3) : 2(\varrho + 0.5) : 6(\varrho - 1.5)$$

There is a
strong compression of gaugino masses for small ϱ
(and even an unphysical region where the gluino is the lightest gaugino).

Mirage mediation



Key observation

Recall the formula for M_{SUSY}:

$$M_{\text{SUSY}} \sim \frac{m_{\widetilde{W}}^{32/19}\, m_{\widetilde{h}}^{12/19}\, m_{H}^{3/19}}{m_{\widetilde{g}}^{28/19}}\, X_{\text{sfermion}}$$

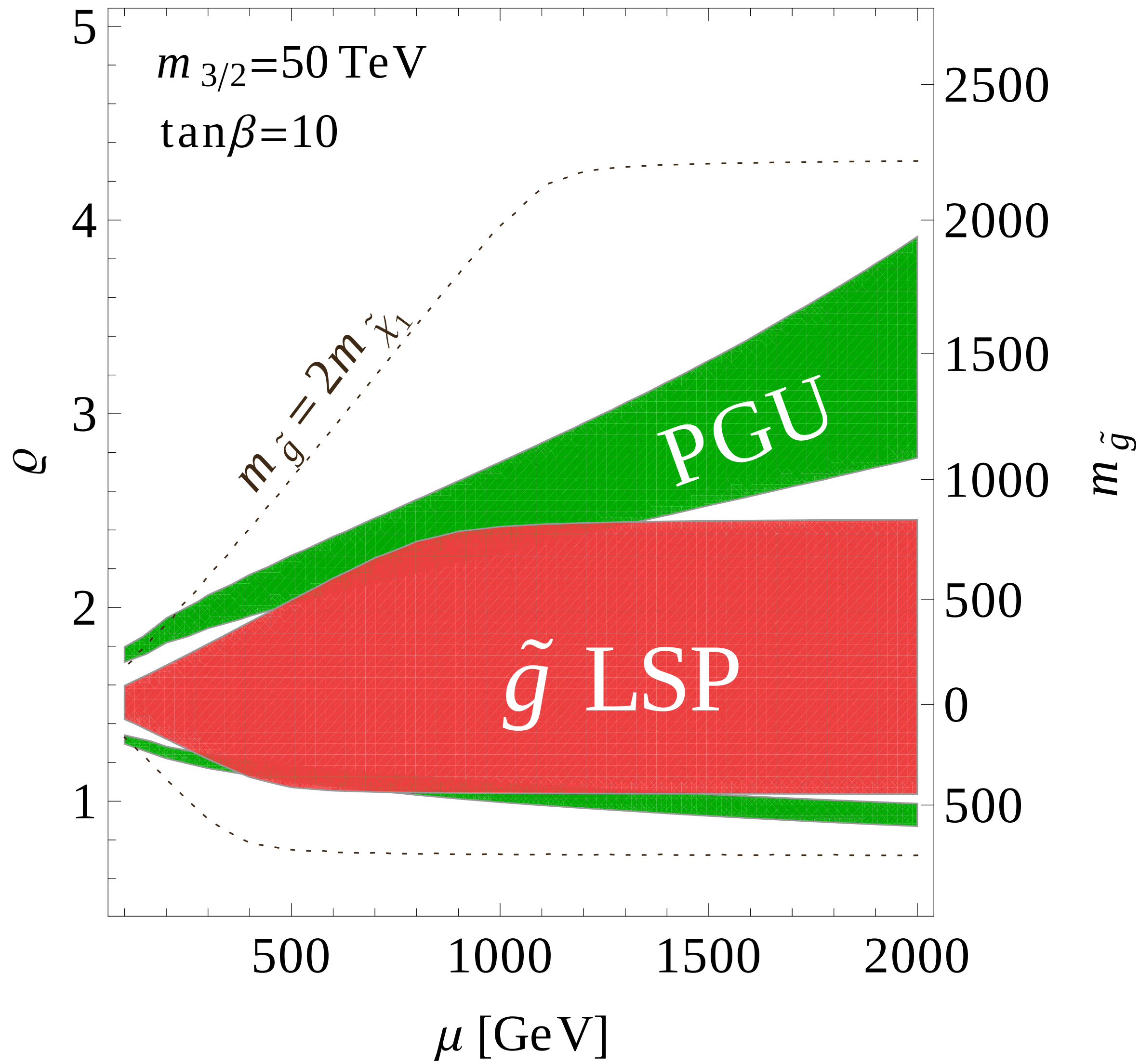
An increase of the gluino reduces M_{SUSY} and vice versa.

A highly compressed gaugino spectrum reduces M_{SUSY}

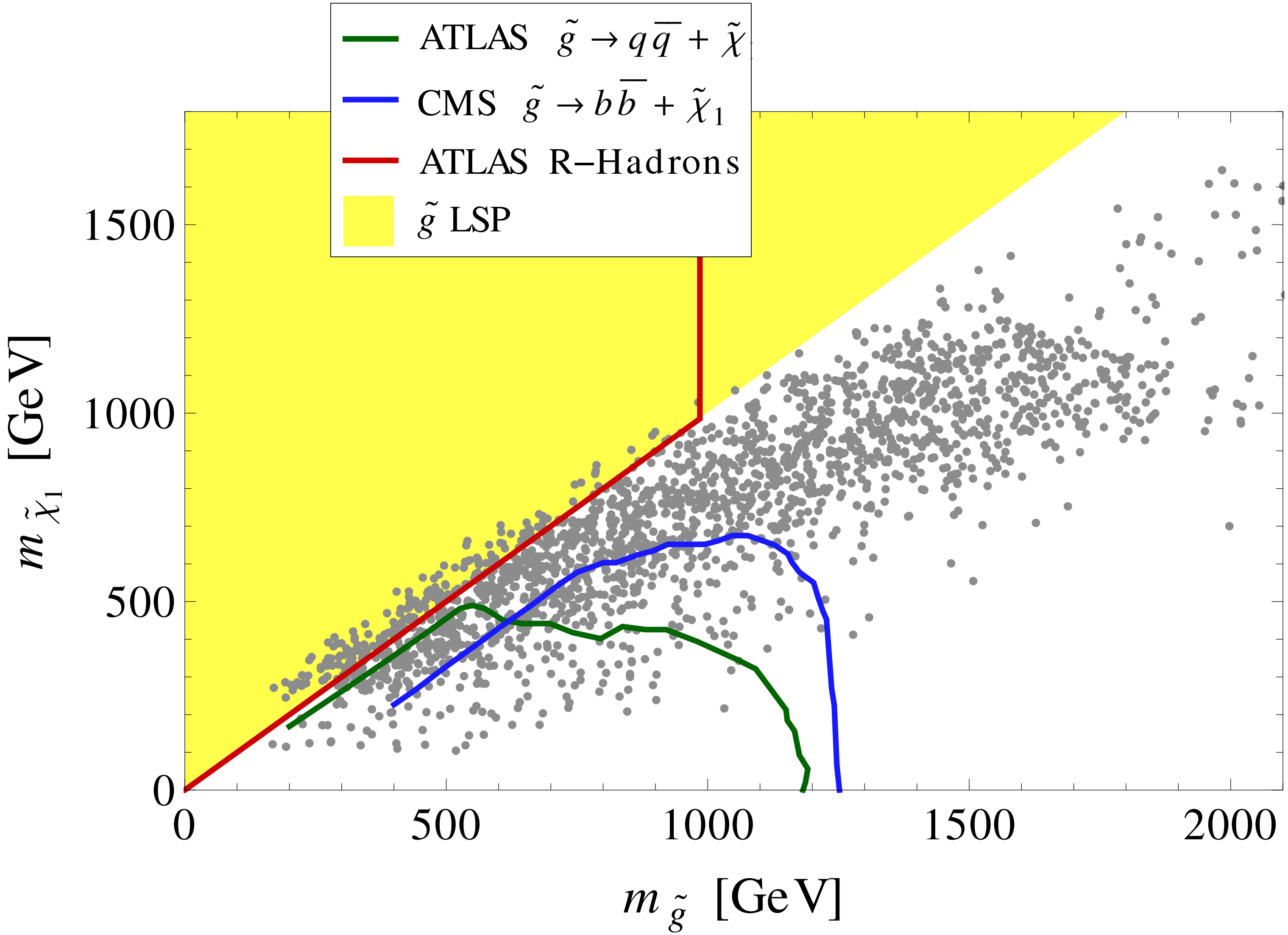
$$M_1 : M_2 : M_3 = (\varrho + 3.3) : 2(\varrho + 0.5) : 6(\varrho - 1.5)$$

It allows PGU for a smaller μ and therefore less fine tuning.

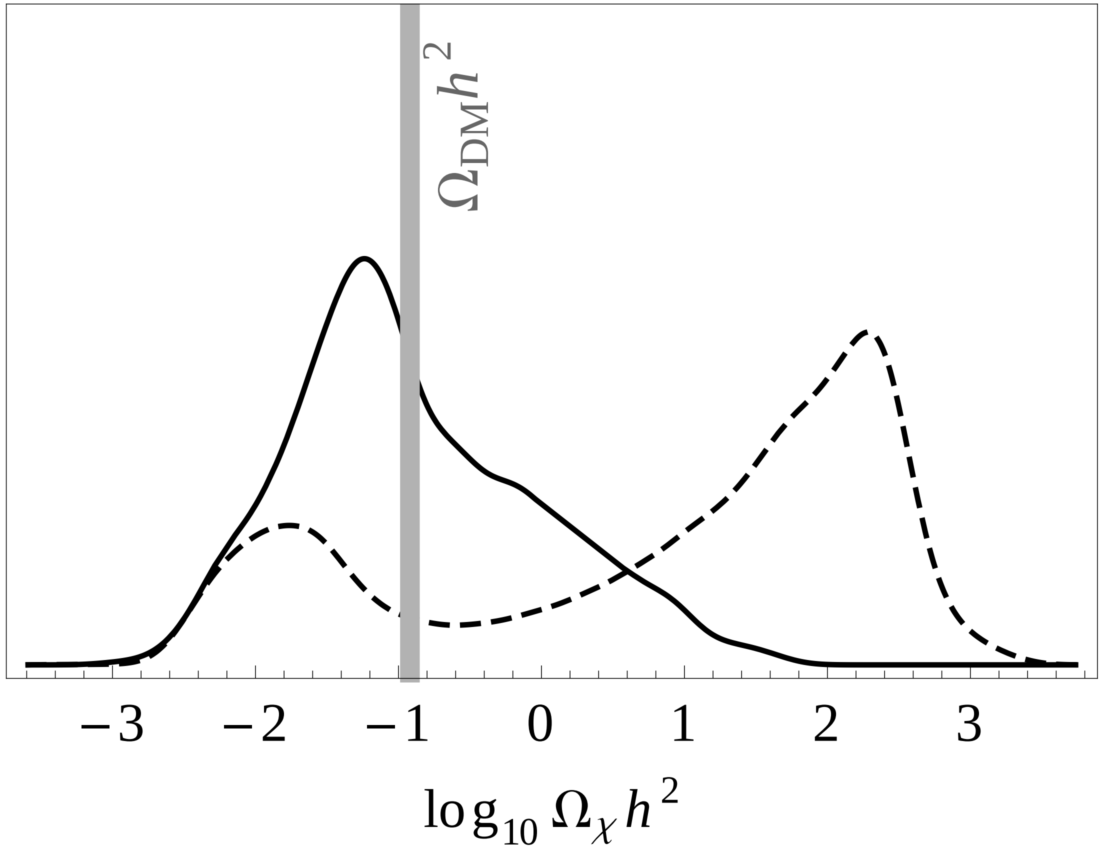
ϱ versus μ



LHC Limits are weak

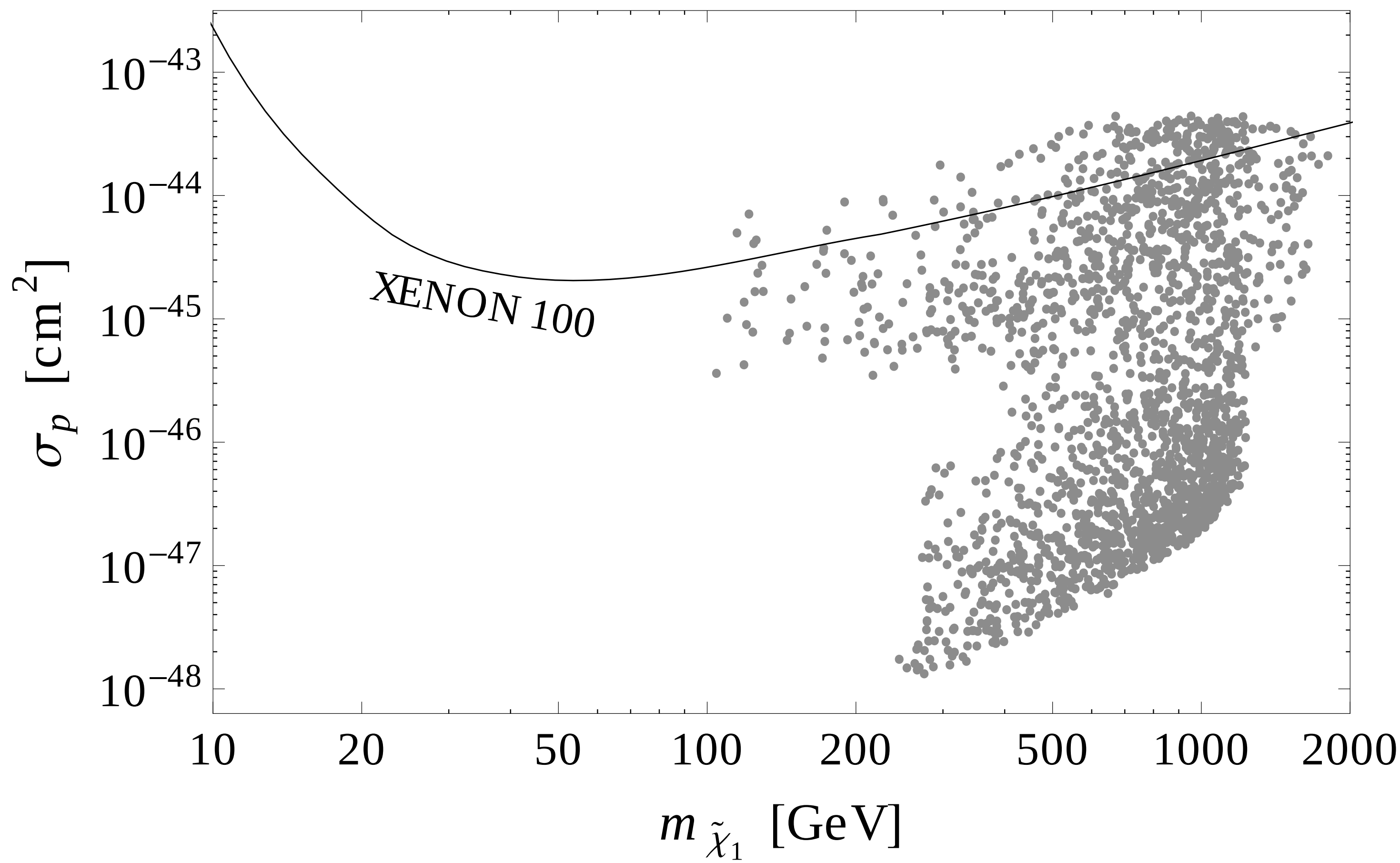


Relic Density



Distribution of thermal neutralino relic density for the benchmark sample with (solid) or without (dashed) the assumption of precision gauge coupling unification.

Limits from direct detection



Direct detection experiments might check the scheme.

Conclusions

String pattern favours “Natural Susy”

- mirage pattern + remnants of extended Susy

We request

- precision gauge unification
- reduced fine tuning

Consequences:

- ultra-compressed gaugino spectrum and small μ
- a challenge for the LHC?
- correct relic density (direct detection possible)

The LHC shows us where to go