Strings, MSSM and LHC

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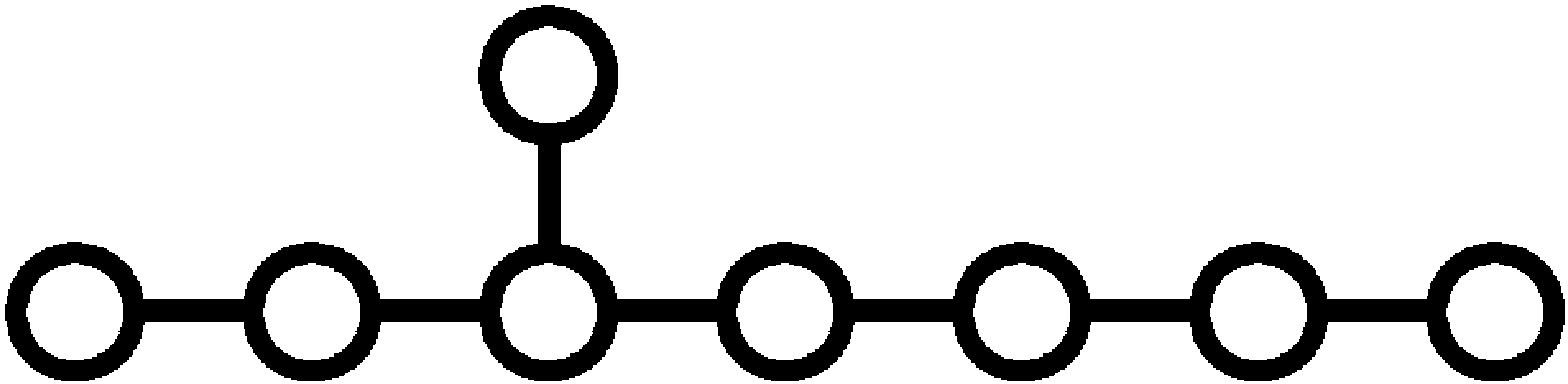
Strings and the (MS)SM

- The MSSM is not a generic prediction of string theory.
- We have to see whether it can be embedded.
- After that we can hope to learn 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.

Where to look?

- Some useful rules include Grand Unification....
- Strings give a hint for exceptional groups

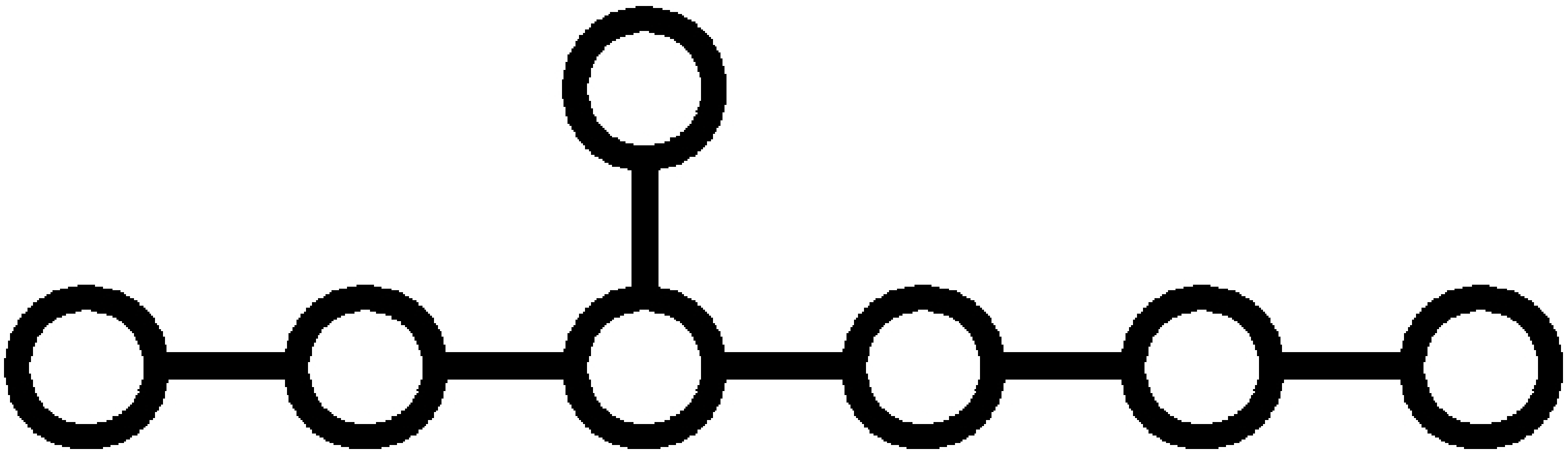
Maximal Group E_8



E_8 is the maximal group.

There are, however, no chiral representations in $d = 4$.

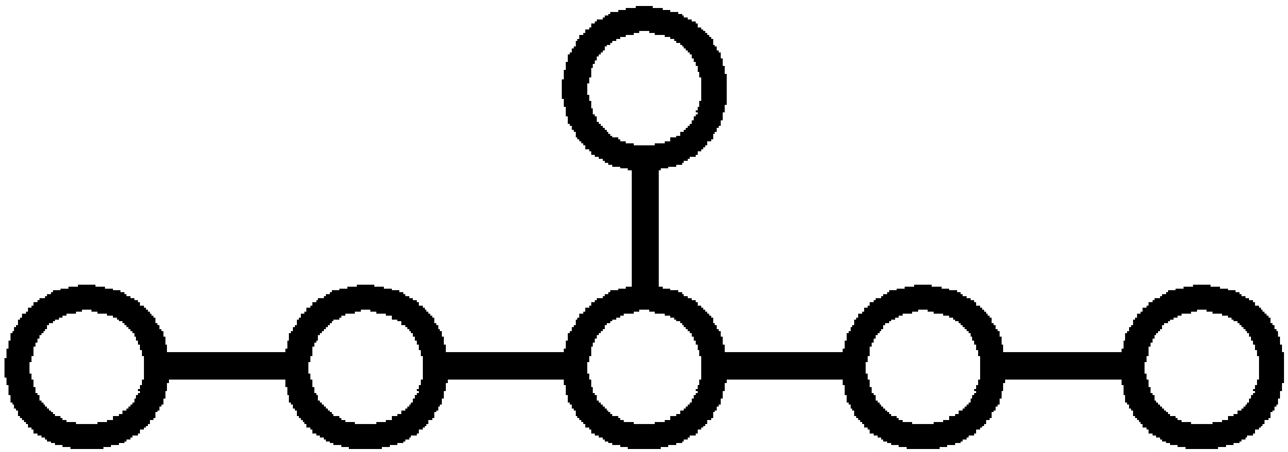
E_7



Next smaller is E_7.

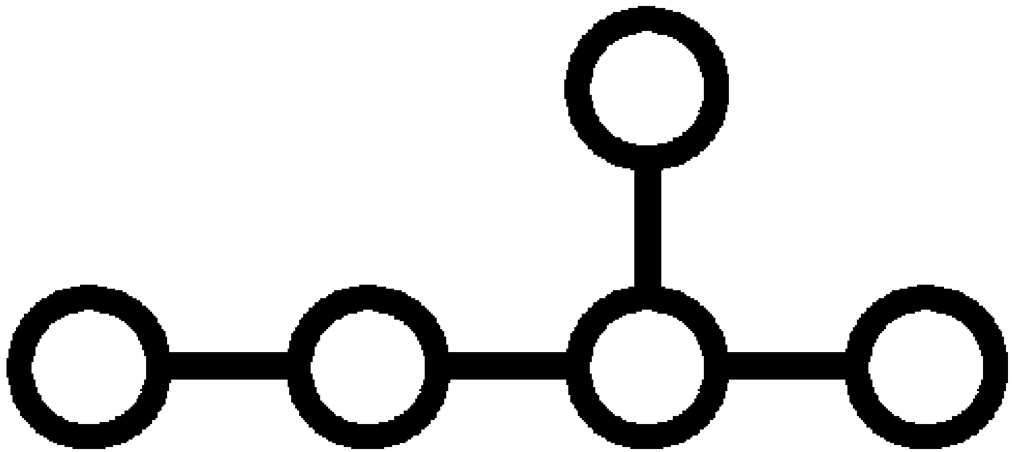
No chiral representations in $d = 4$ either.

E_6



E_6 allows for chiral representations even in $d = 4$.

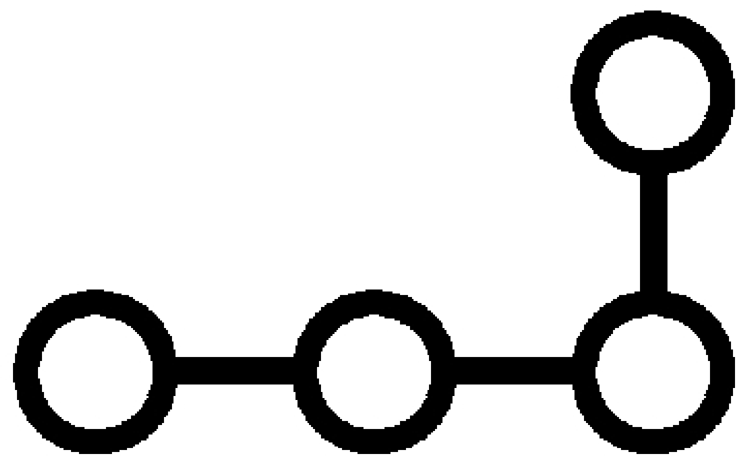
$E_5 = D_5$



E_5 is usually not called exceptional.

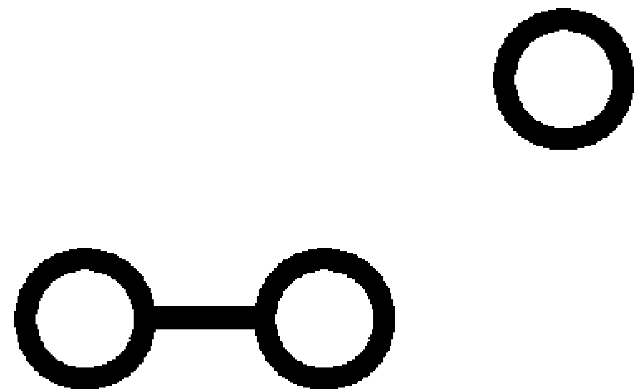
It coincides with $D_5 = SO(10)$.

$E_4 = A_4$



E_4 coincides with $A_4 = SU(5)$.

E_3



E_3 coincides with $A_2 \times A_1$ which is $SU(3) \times SU(2)$.

Candidate string models

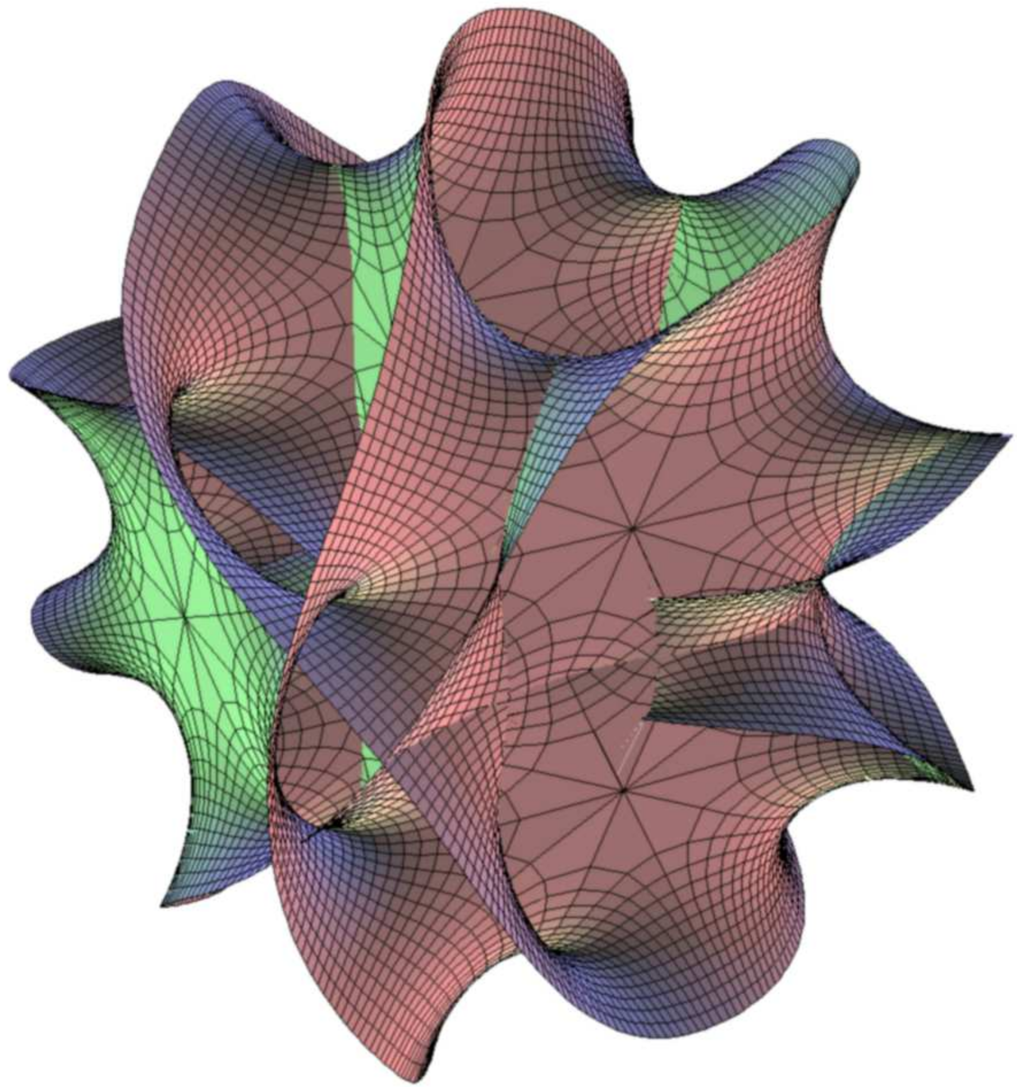
String theory “favours” E_8

- $E_8 \times E_8$ heterotic string
- E_8 enhancement as a nonperturbative effect (M- or F-theory).

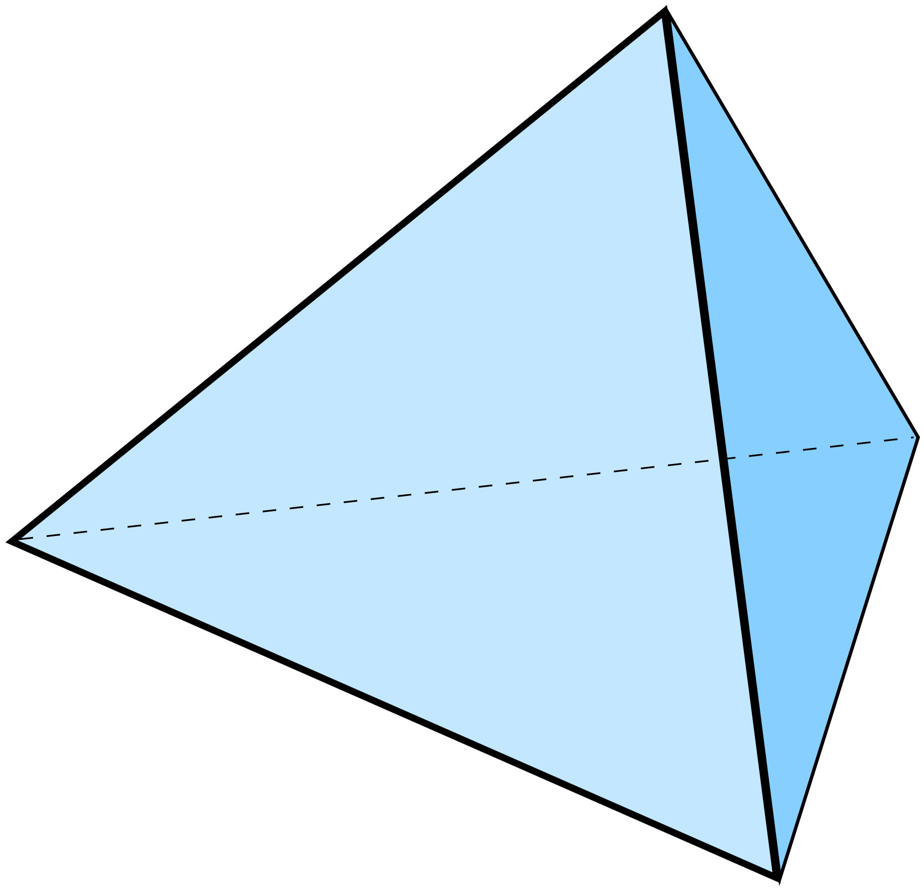
Strings live in higher dimensions:

- chiral spectrum possible even with E_8
- E_8 broken in process of compactification
- provides source for (nonabelian) discrete symmetries
- from $(E_8 \times E_8)/(SU(3) \times SU(2) \times U(1))$ and/or remnants of the higher dimensional Lorentz group $SO(6)$

Calabi Yau Manifold



Orbifold



Geography

Many properties of the models depend on the geography of extra dimensions, such as

- the location of quarks and leptons,
- the relative location of Higgs bosons,

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- the relative location of Higgs bosons,

but there is also a “localization” of gauge fields

- $E_8 \times E_8$ in the bulk
- smaller gauge groups on various branes

Observed 4-dimensional gauge group is common subroup of the various localized gauge groups!

Localization

Quarks, Leptons and Higgs fields can be localized:

- in the Bulk ($d = 10$ untwisted sector)
- on 3-Branes ($d = 4$ twisted sector fixed points)
- on 5-Branes ($d = 6$ twisted sector fixed tori)

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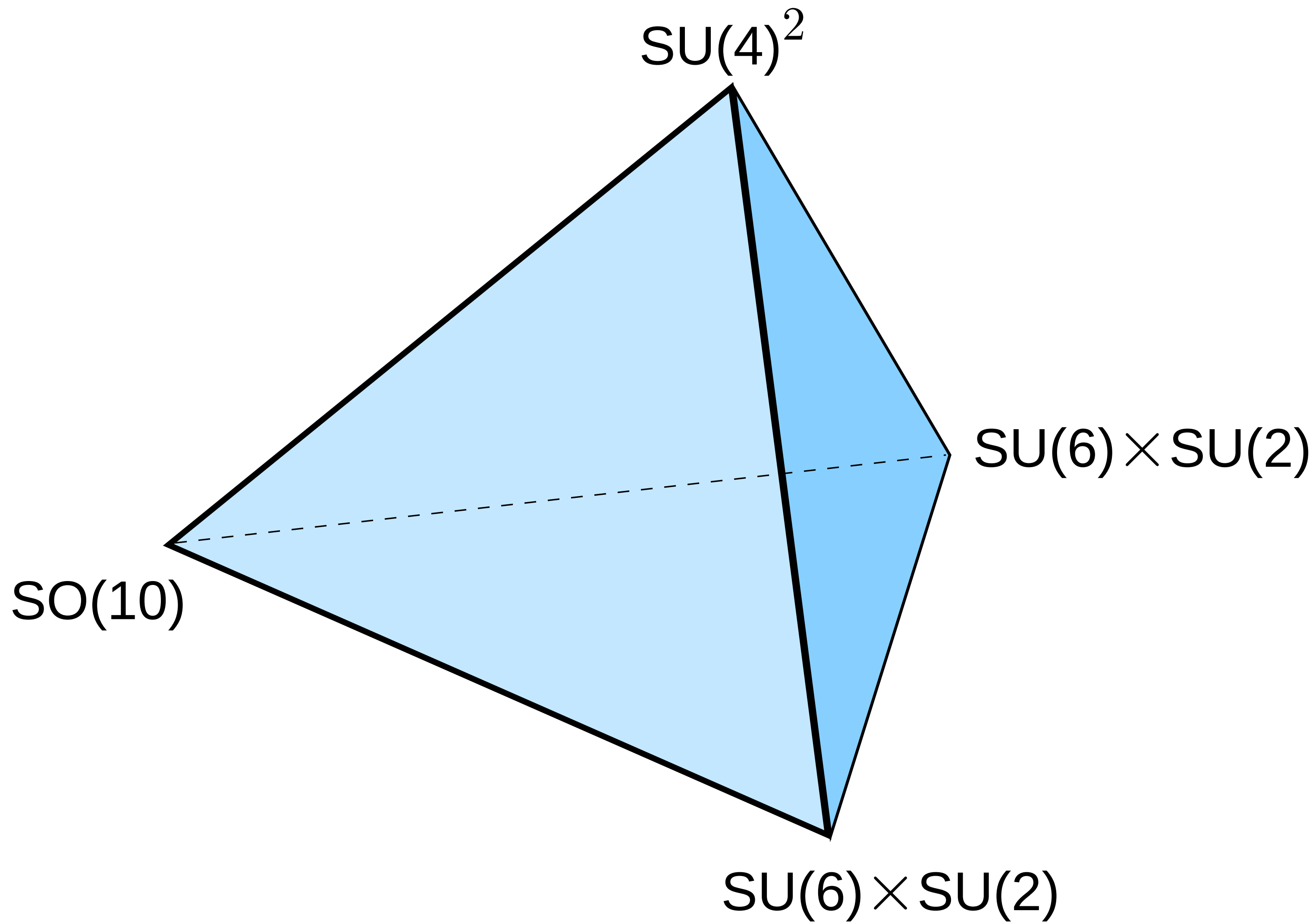
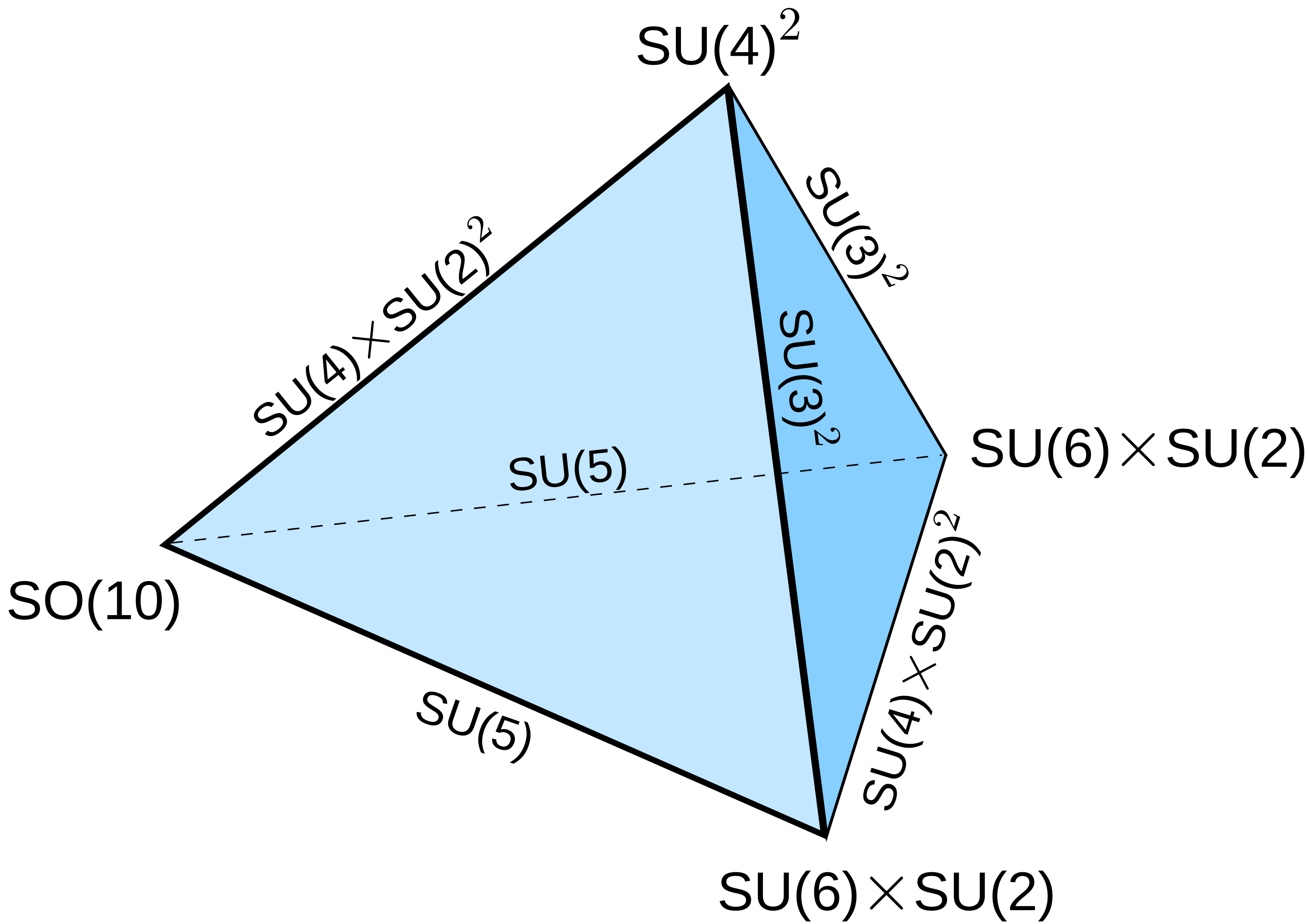
Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Standard Model Gauge Group



The Extended MiniLandscape

- construct explicit models for $Z_6 II$

  (Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007-2009)
- local $SO(10)$ grand unification (by construction)
- gauge- and (partial) Yukawa unification
- models with R-parity + solution to the μ-problem

  (Lebedev et al., 2007)
- explicit construction based on $Z_6 II$, $Z_2 \times Z_2$ and $Z_2 \times Z_4$

  (Blaszczyk, Groot-Nibbelink, Ratz, Ruehle, Trapletti, Vaudrevange, 2010; Mayorga-Pena, HPN, Oehlmann, 2012)

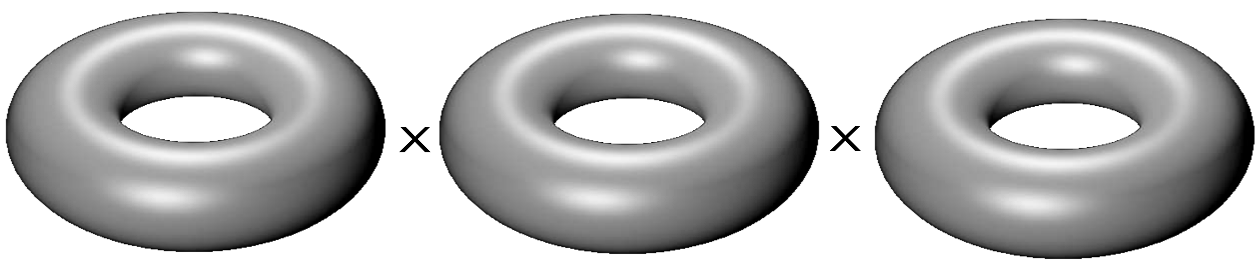
What do we learn from these explicit constructions?

Location of fields in extra dimensions will be important.

Structure of Sectors of $Z_2 \times Z_4$

The underlying $Z_2 \times Z_4$ orbifold has the following sectors:

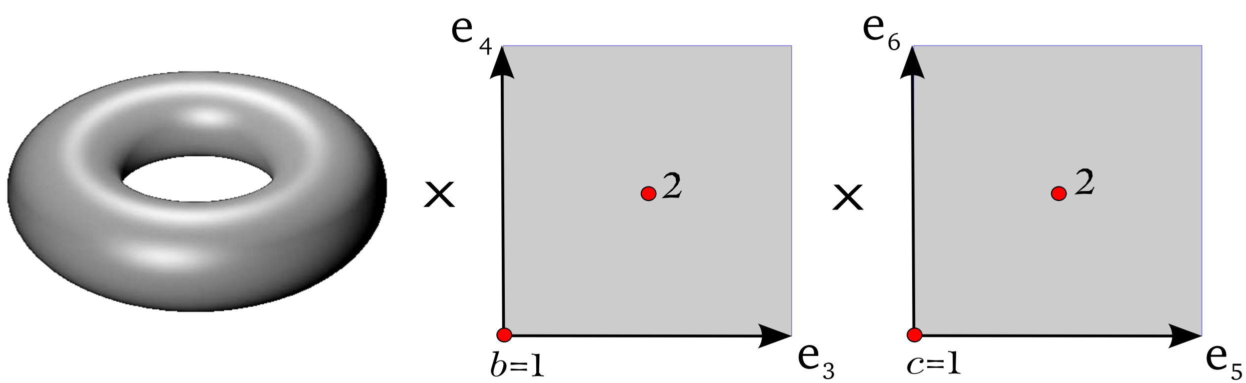
- the untwisted sector



Fields live in the bulk $d = 10$ with remnant $N = 4$ Susy

Twisted sectors

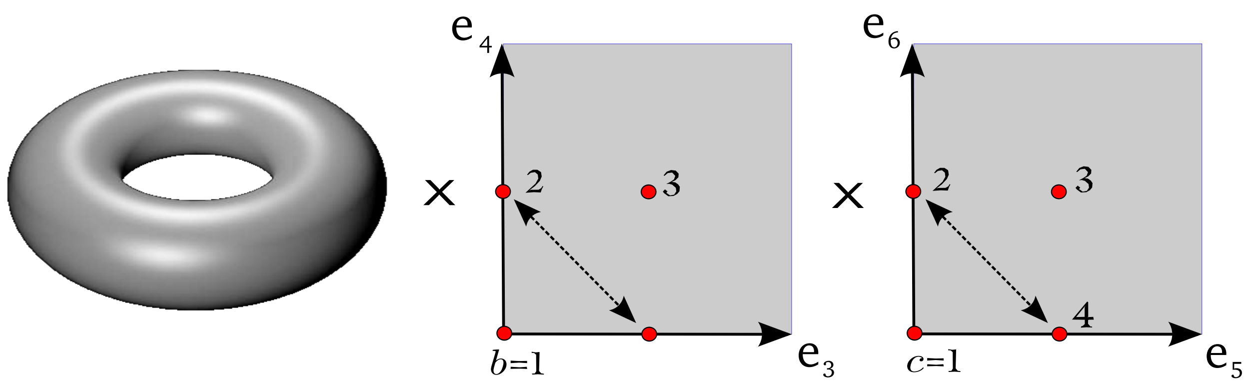
Twisted sectors correspond to the $Z_2(\theta)$ and $Z_4(\omega)$ twists



The ω sector has 2 x 2 = 4 fixed tori, corresponding to

- “5-branes” confined to $d = 6$ space time ($N = 2$ Susy).

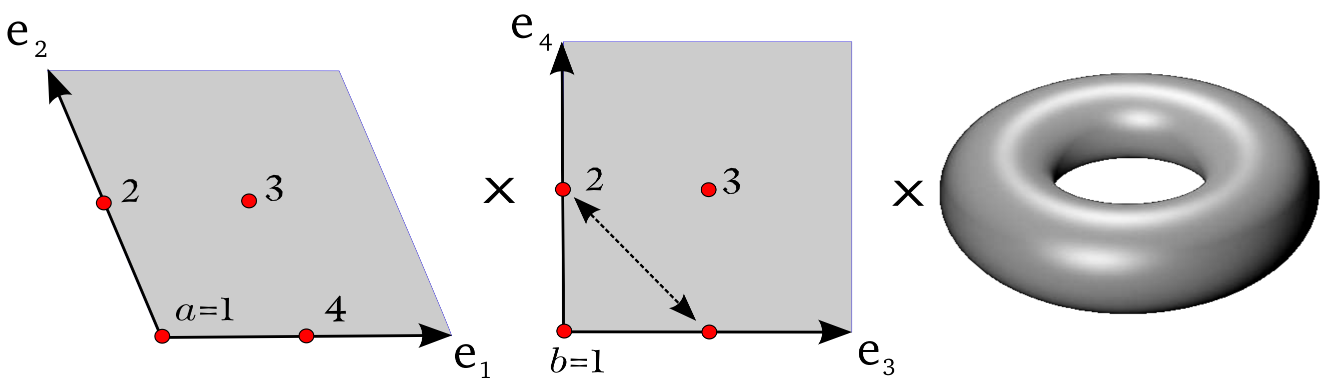
ω^2 twisted sector



The ω^2 twisted sector contains fixed tori correponding to

- "5-branes" confined to 6 space-time dimension (with remnants of $N = 2$ Susy).

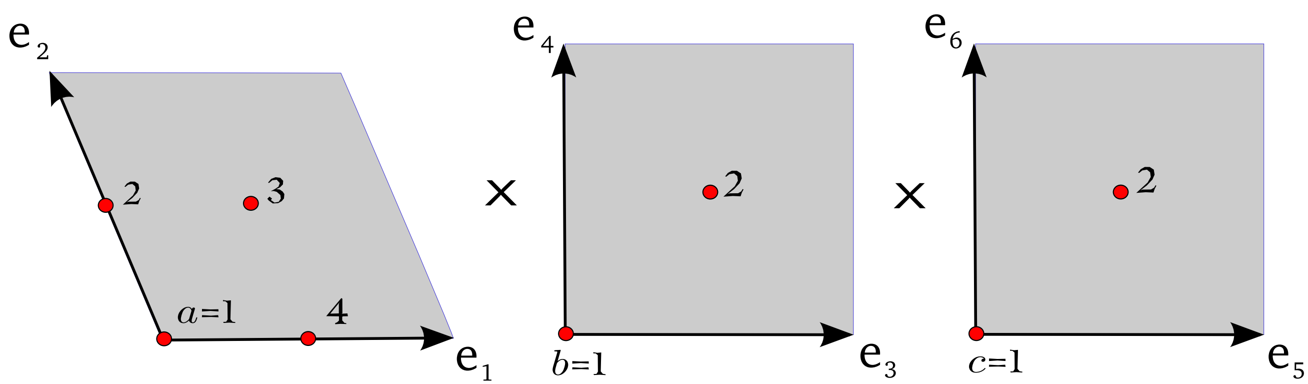
θ twisted sector



The θ twisted sector contains 4 x 3 fixed tori as well:

- "5-branes" confined to 6 space-time dimension (with remnants of $N = 2$ Susy).

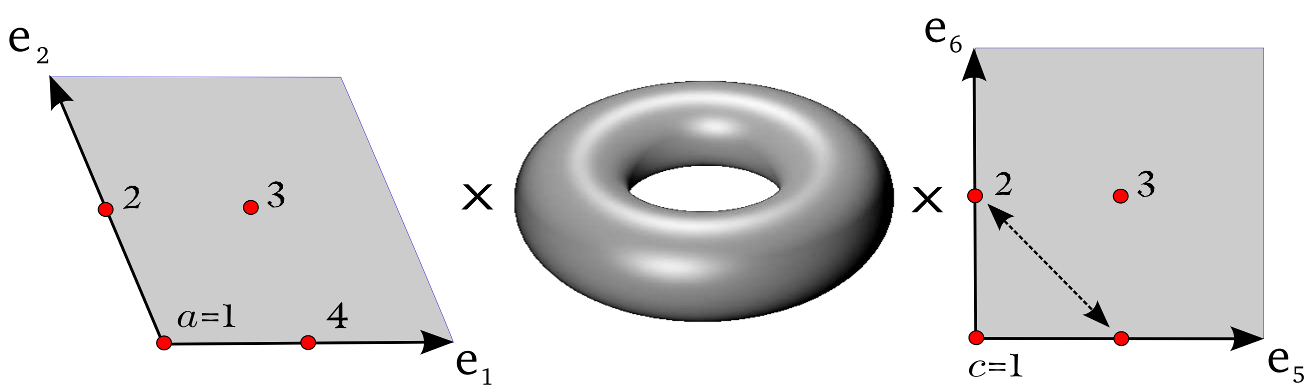
$\theta\omega$ twisted sector



The $\theta\omega$ twisted sector contains 4 x 2 x 2 fixed points:

- “3-branes” confined to 4 space-time dimension (sector with remnants of $N = 1$ Susy).

$\theta\omega^2$ twisted sector



The $\theta\omega^2$ twisted sector contains 4 x 3 fixed tori:

- “5-branes” confined to 6 space-time dimension (with remnants of $N = 2$ Susy).

Where do we find quarks, leptons and Higgs bosons in the models of the MiniLandscape?

A Benchmark Model

At the orbifold point the gauge group is

$$SU(3) \times SU(2) \times U(1)^9 \times SU(4) \times SU(2)$$

- one $U(1)$ is anomalous
- there are singlets and vectorlike exotics
- decoupling of exotics and breakdown of gauge group has been verified
- remaining gauge group

$$SU(3) \times SU(2) \times U(1)_Y \times SU(4)_{\text{hidden}}$$

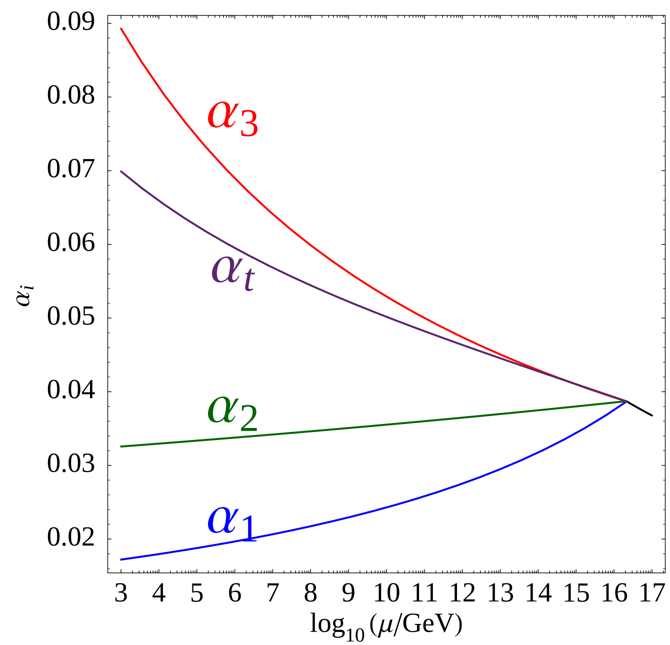
- for discussion of neutrinos and R-parity we keep also the $U(1)_{B-L}$ charges

Spectrum

#	irrep	label		#	irrep	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/6,1/3)}$	q_i		3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-1/3)}$	$\bar{u}_i$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1,1)}$	$\bar{e}_i$		8	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(0,*)}$	m_i
$3+1$	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,-1/3)}$	$\bar{d}_i$		1	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,1/3)}$	d_i
$3+1$	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,-1)}$	ℓ_i		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,1)}$	$\bar{\ell}_i$
1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(-1/2,0)}$	h_d		1	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/2,0)}$	h_u
6	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,2/3)}$	$\bar{\delta}_i$		6	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/3,-2/3)}$	δ_i
14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/2,*)}$	s_i^+		14	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/2,*)}$	s_i^-
16	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,1)}$	$\bar{n}_i$		13	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,-1)}$	n_i
5	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,1)}$	$\bar{\eta}_i$		5	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,-1)}$	η_i
10	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{(0,0)}$	h_i		2	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{2})_{(0,0)}$	y_i
6	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(0,*)}$	f_i		6	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(0,*)}$	$\bar{f}_i$
2	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1/2,-1)}$	f_i^-		2	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_{(1/2,1)}$	$\bar{f}_i^+$
4	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,\pm 2)}$	χ_i		32	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,0)}$	s_i^0
2	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/6,2/3)}$	$\bar{v}_i$		2	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/6,-2/3)}$	v_i

Unification

- Higgs doublets are in untwisted sector (bulk)
- heavy top quark in untwisted sector (bulk)
- $\mu-$term protected by a discrete symmetry



- Minkowski vacuum before Susy breakdown (no AdS)
- solution to μ-problem
- natural incorporation of gauge-Yukawa unification

Lesson 1: The Higgs system

The benchmark model illustrates some of the general properties of the “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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- μ protected by an R-symmetry

(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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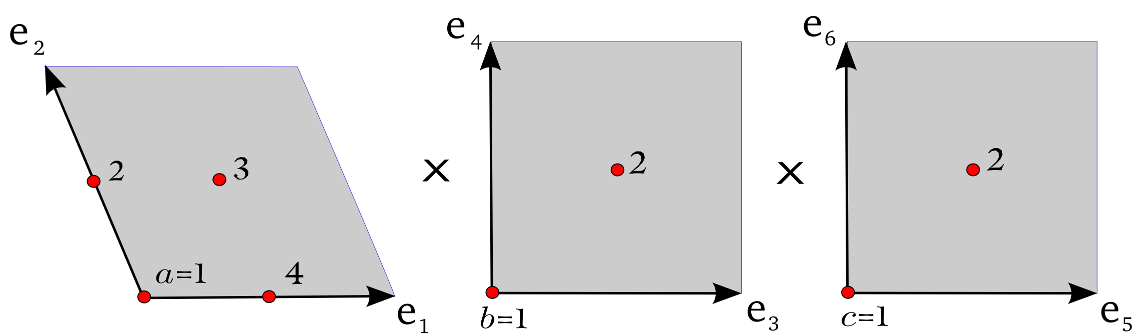
The top quark is a bulk field as well:

- 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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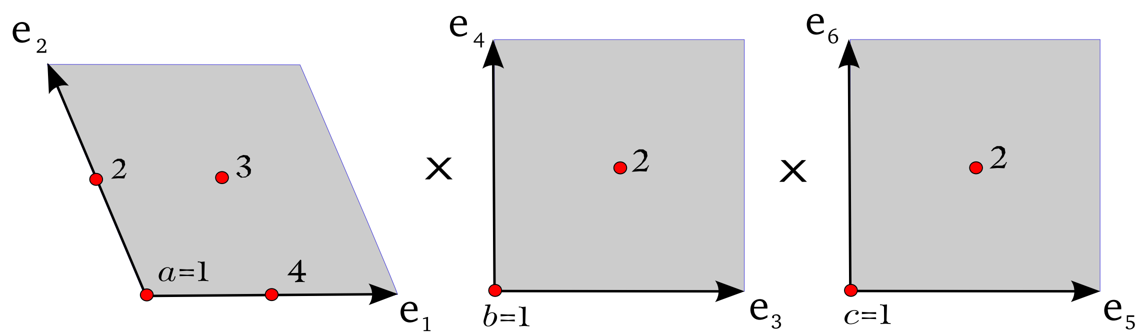
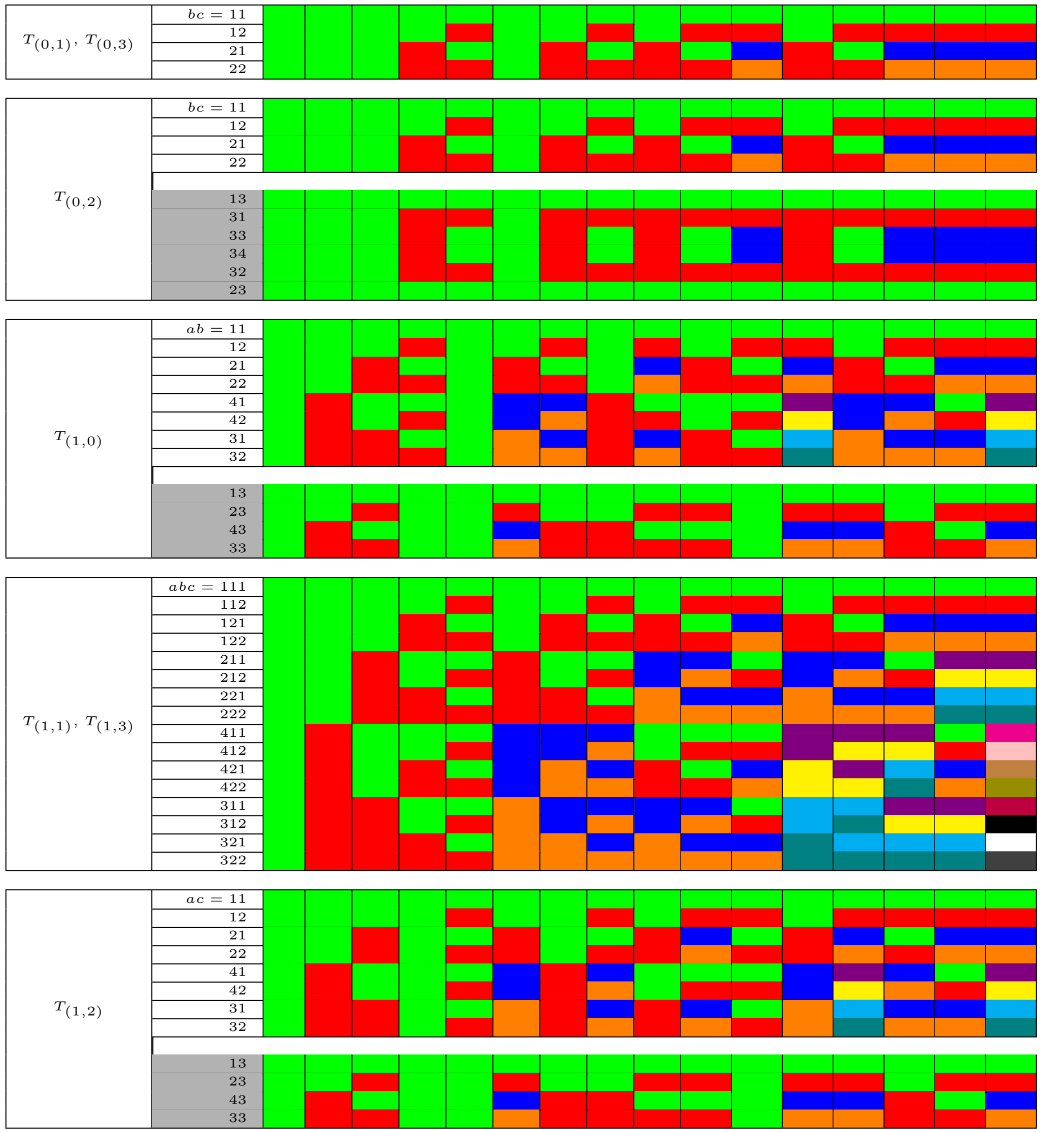


- they exhibit a D_4 family symmetry (absence of FCNC)
- no trilinear Yukawa couplings
  (suppressed masses compared to top quark)
- mass pattern is generated via a Frogatt-Nielsen mechanism (dictated by the pattern of Wilson lines)

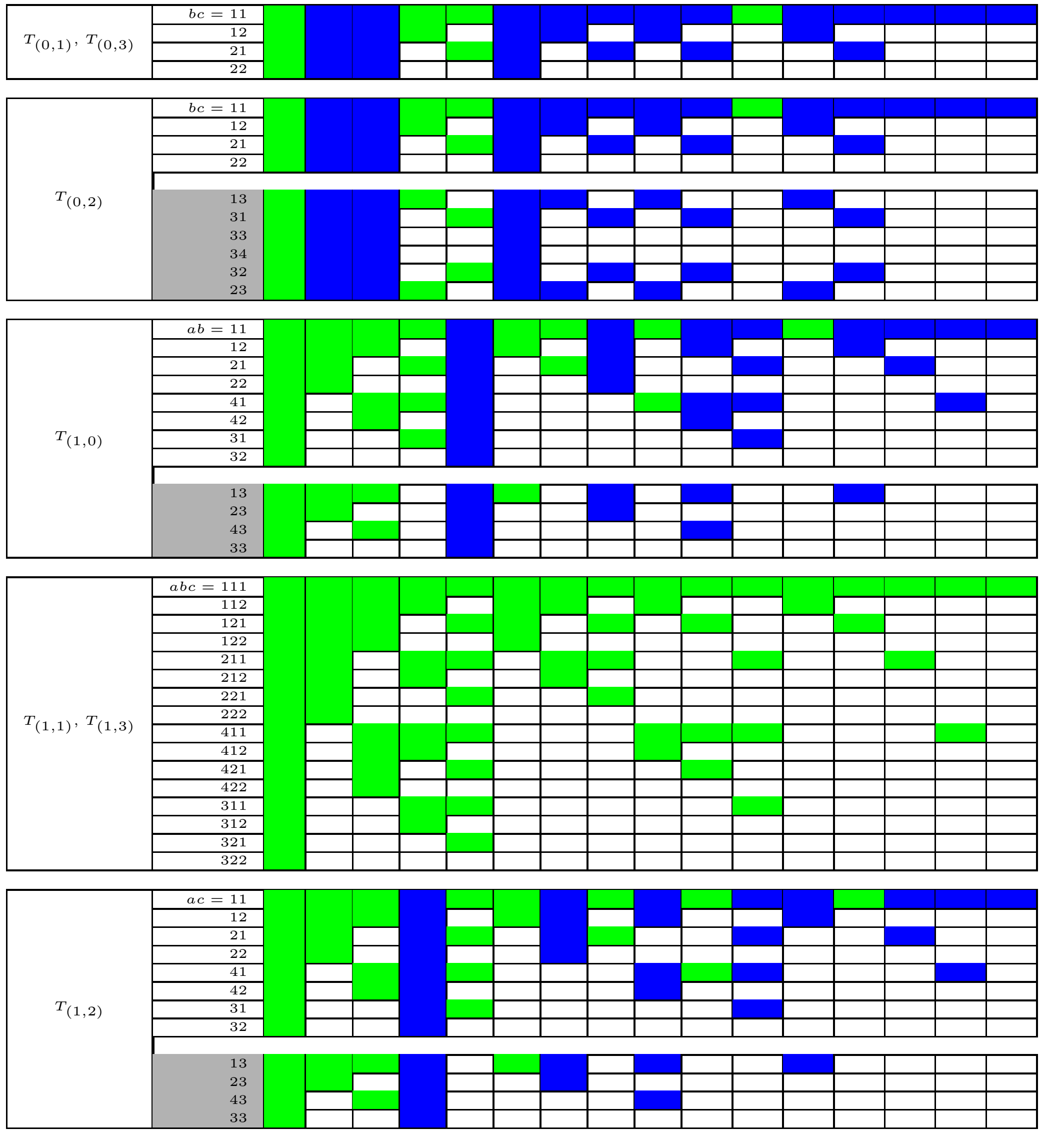
Wilson lines

Config.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
W_1		✓				✓	✓	✓				✓	✓	✓		✓
W_2			✓			✓			✓	✓		✓	✓		✓	✓
W_3				✓			✓		✓		✓	✓		✓	✓	✓
W_4					✓			✓		✓	✓		✓	✓	✓	✓

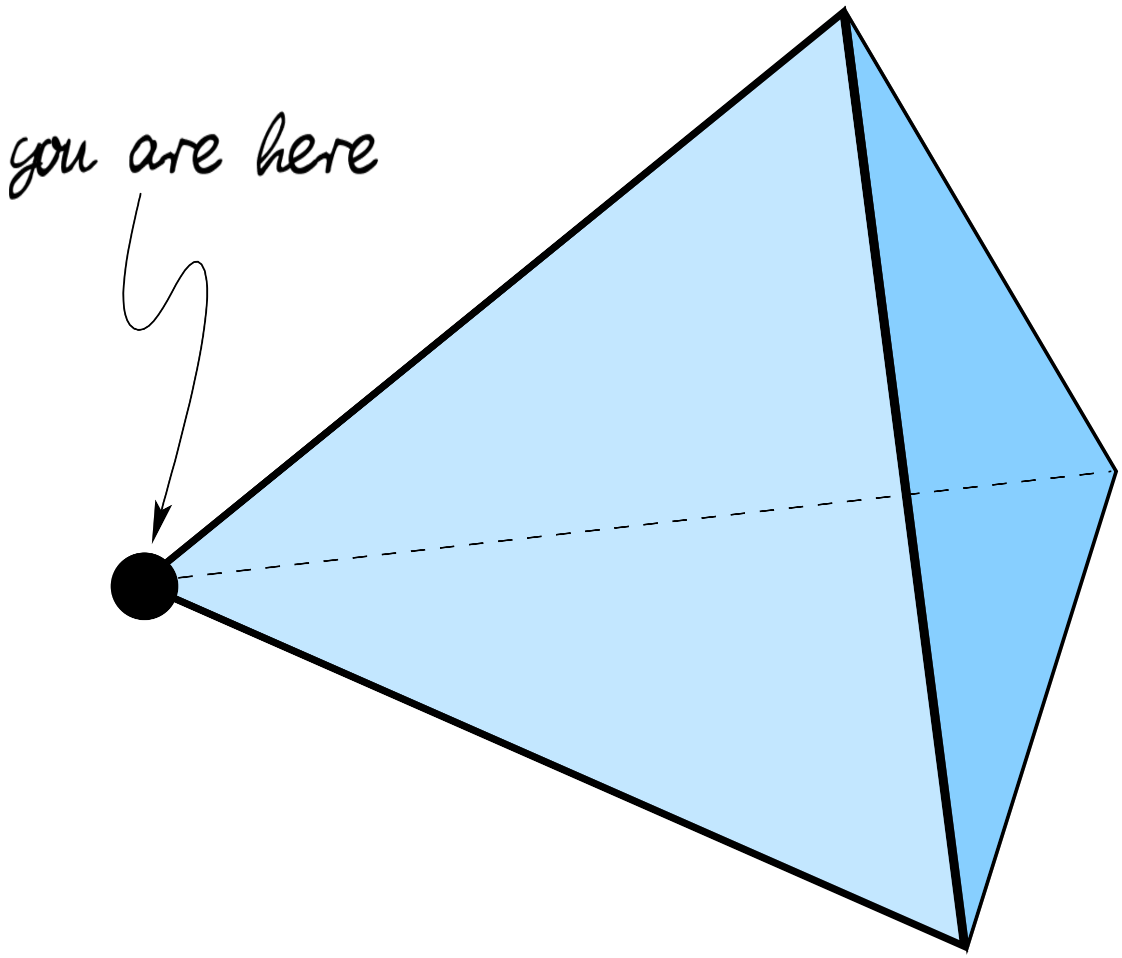


Wilson lines

config.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
W_1		✓				✓	✓	✓				✓	✓	✓		✓
W_2			✓			✓			✓	✓		✓	✓		✓	✓
W_3				✓			✓		✓		✓	✓		✓	✓	✓
W_4					✓			✓		✓	✓		✓	✓	✓	✓



Where do we live?



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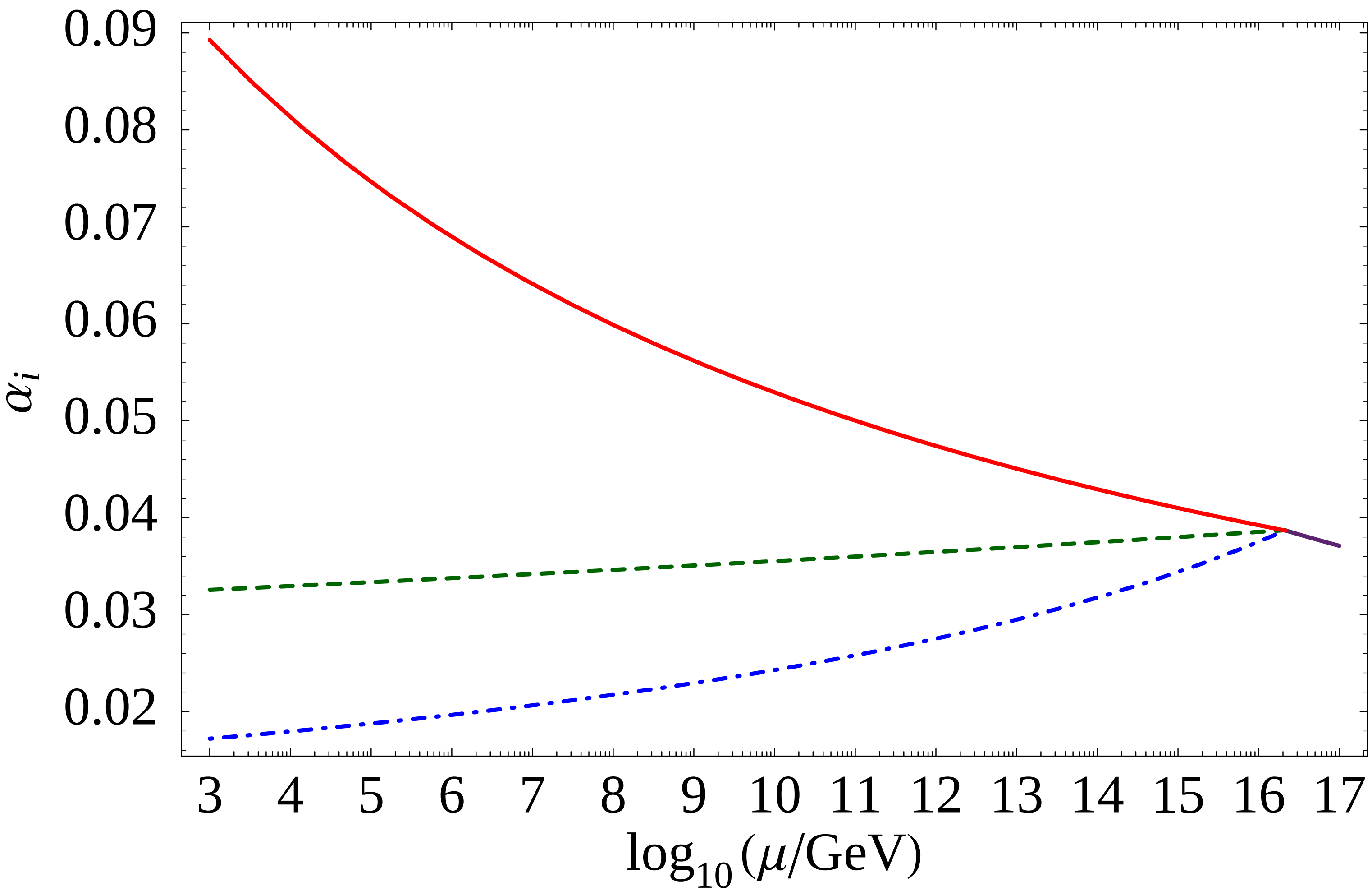
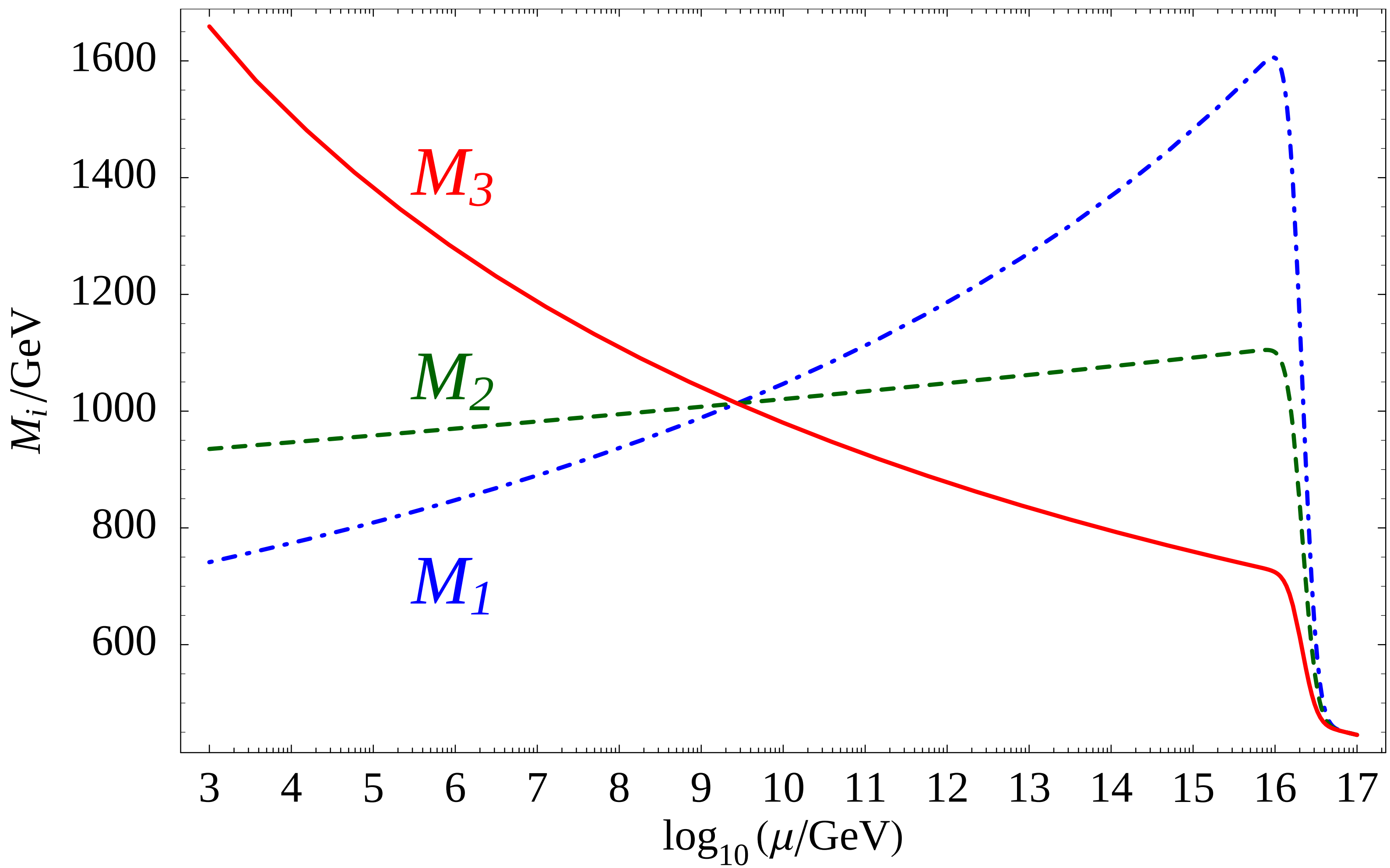
Various sectors enjoy extended Susy
and therefore a stronger protection (via loops $\sim 1/(4\pi)^2$)

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

Evolution of couplings

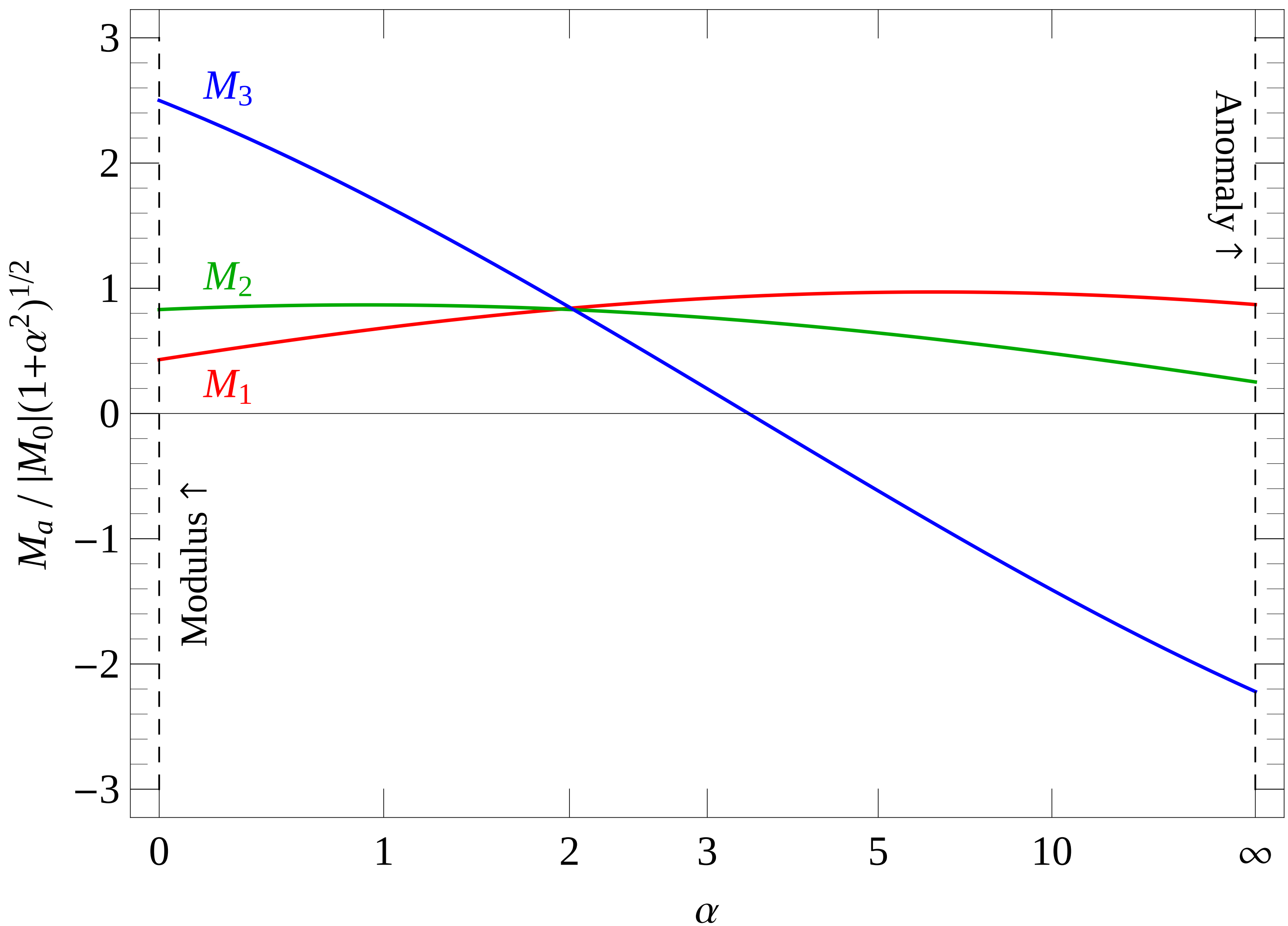


The Mirage Scale



(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

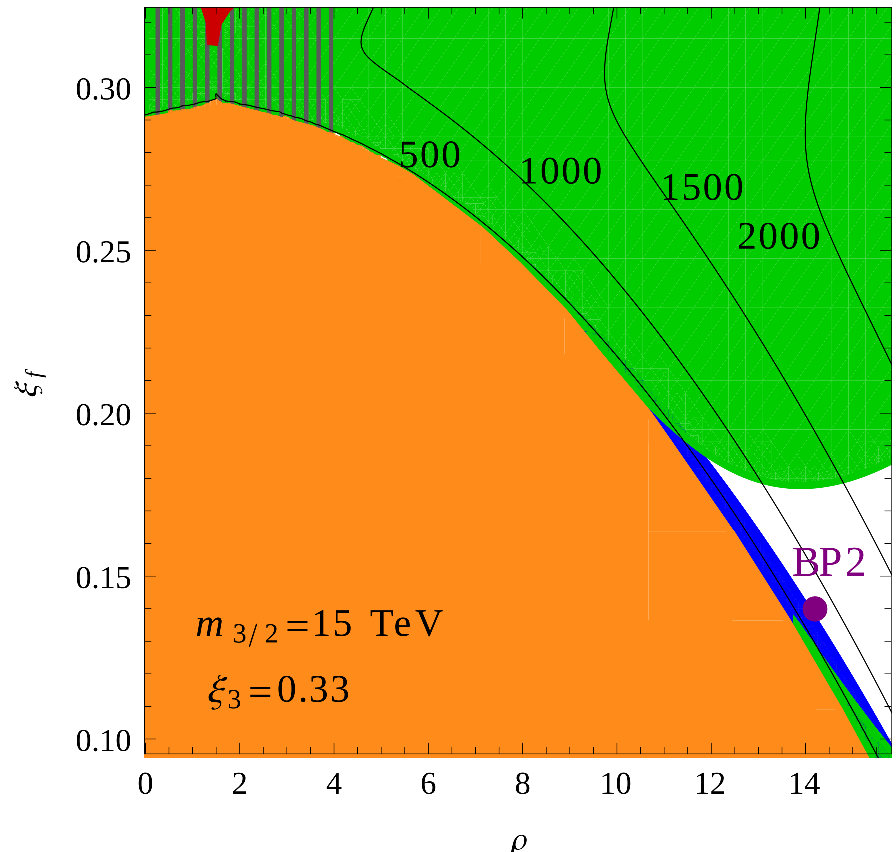
- normal squarks and sleptons in multi-TeV range
- top squarks $(\tilde{t}_L, \tilde{b}_L)$ and $\tilde{t}_R$ in TeV-range (suppressed by $\log(M_{\rm Planck}/m_{3/2}) \sim 4\pi^2$)
- A-parameters in TeV range
- gaugino masses in TeV range
- mirage pattern for gaugino masses (compressed spectrum)
- heavy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

Lessons from the MiniLandscape

Realistic MSSM-like models can be embedded in string theory. These models share some common properties that are crucial for their success:

- Higgs fields live in untwisted sector (not localized) (this allows a solution of the μ-problem with an R-symmetry and provides gauge-Higgs unification)
- top quark lives in untwisted sector as well (trilinear Yukawa coupling and gauge top unification)
- the two light families live on fixed points (a discrete D_4 avoids potential flavour problems)
- a specific pattern of soft susy breaking terms (mirage mediation and remnants of extended Susy)

Model with 3 TeV gluino

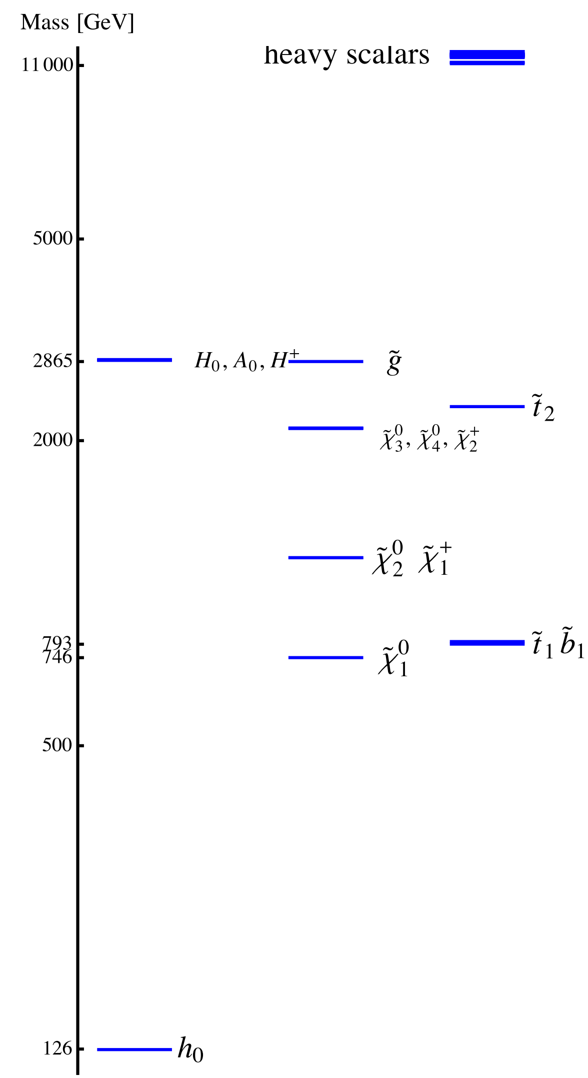


Parameter scan for a gluino mass of 3 TeV.

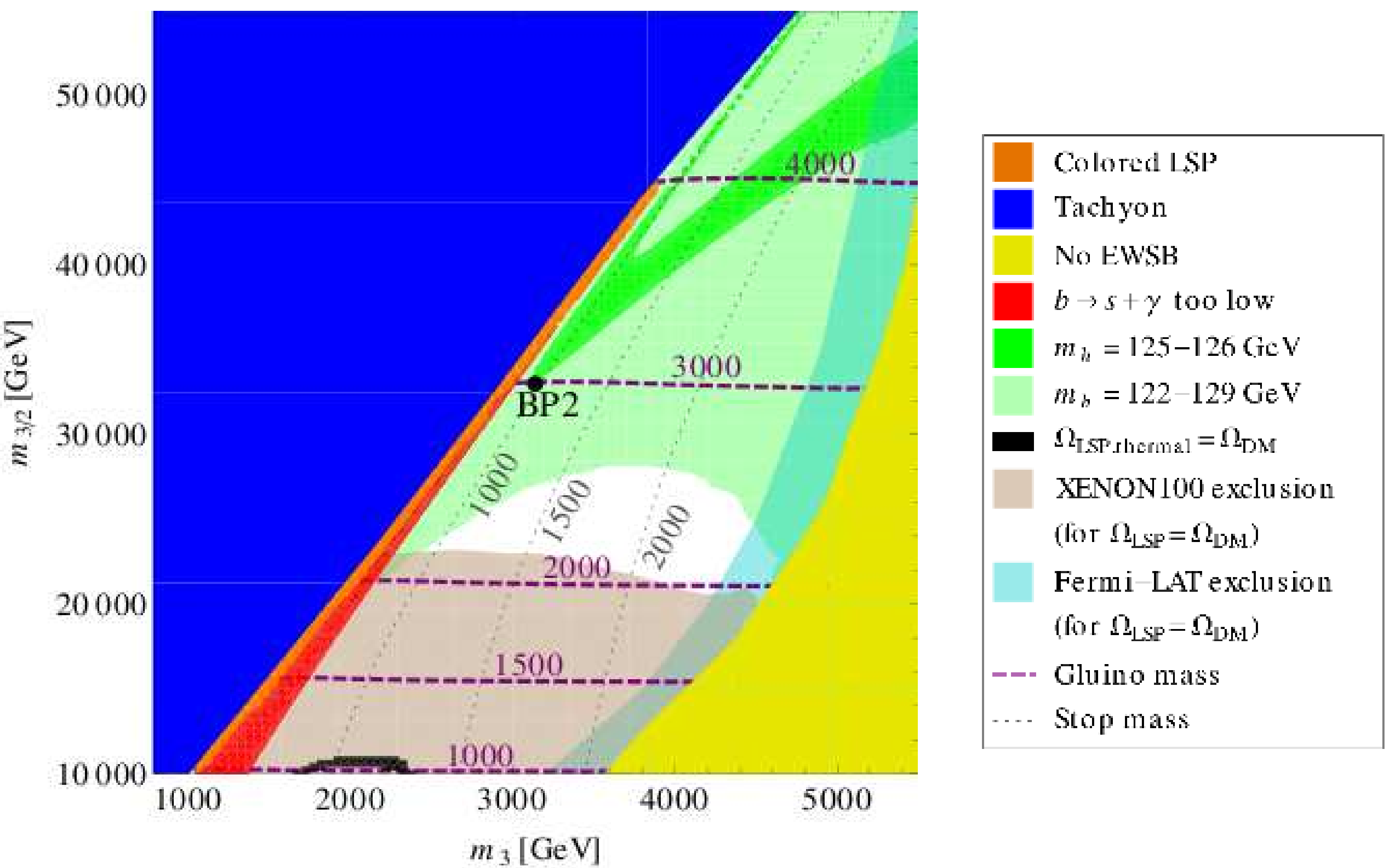
The coloured regions are excluded while the hatched region indicates the current reach of the LHC.

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

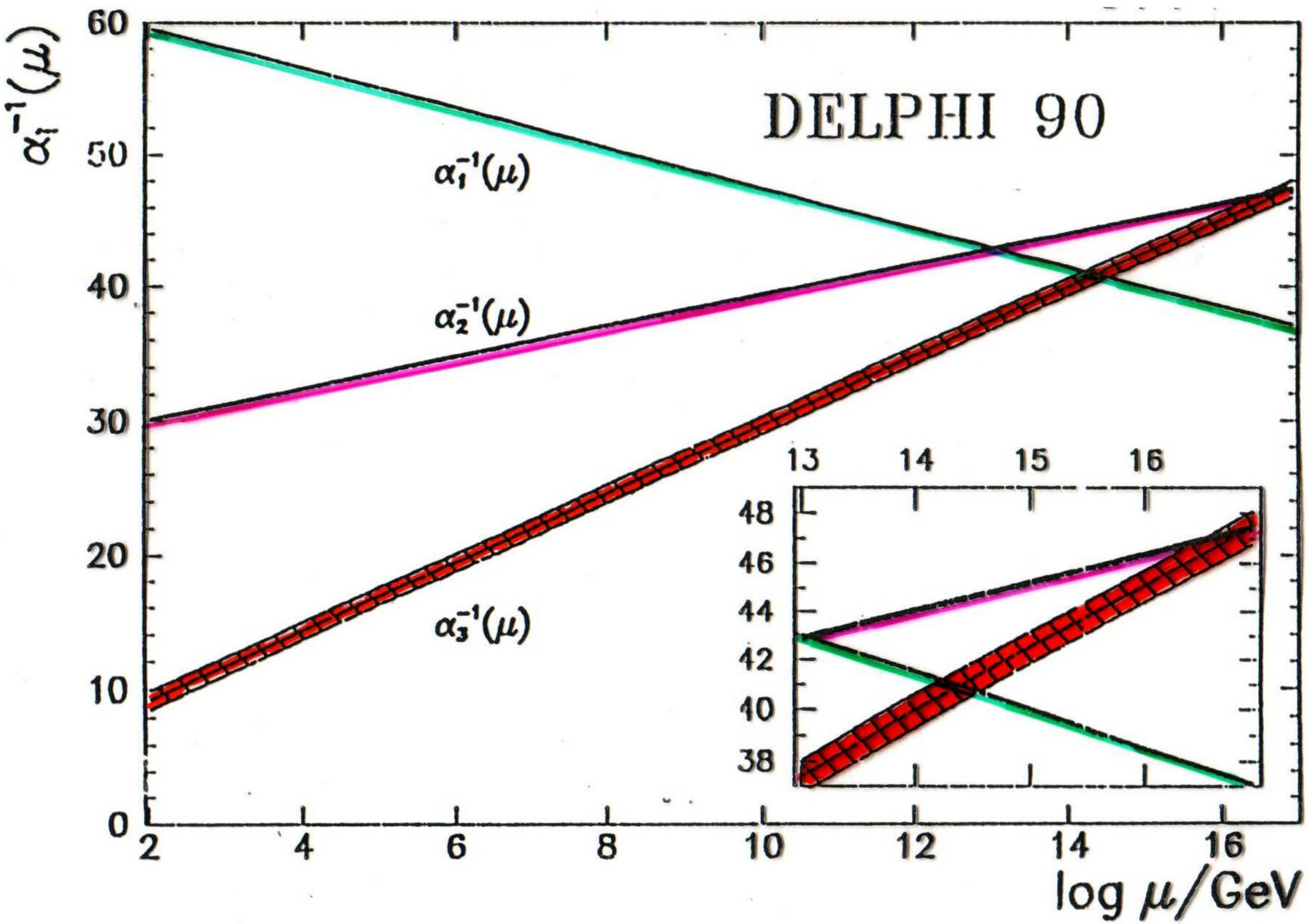
We want to take these two arguments as serious as possible and reanalyze the MSSM within the previously described scheme. We make two assumptions:

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

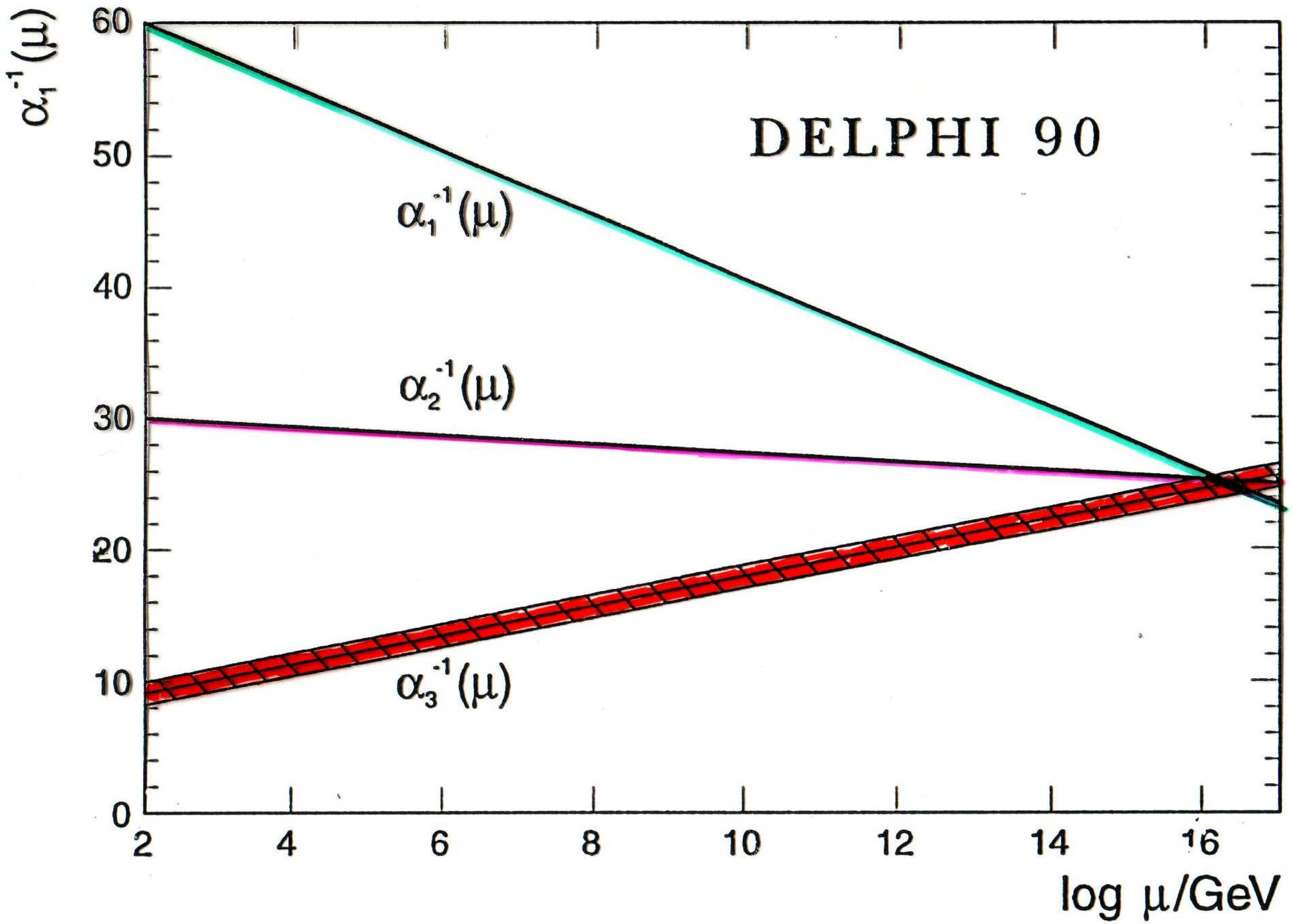
What are the consequences for the spectrum?

(Krippendorf, Nilles, Ratz, Winkler, 2013)

Standard Model



MSSM



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

Precision gauge unification

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

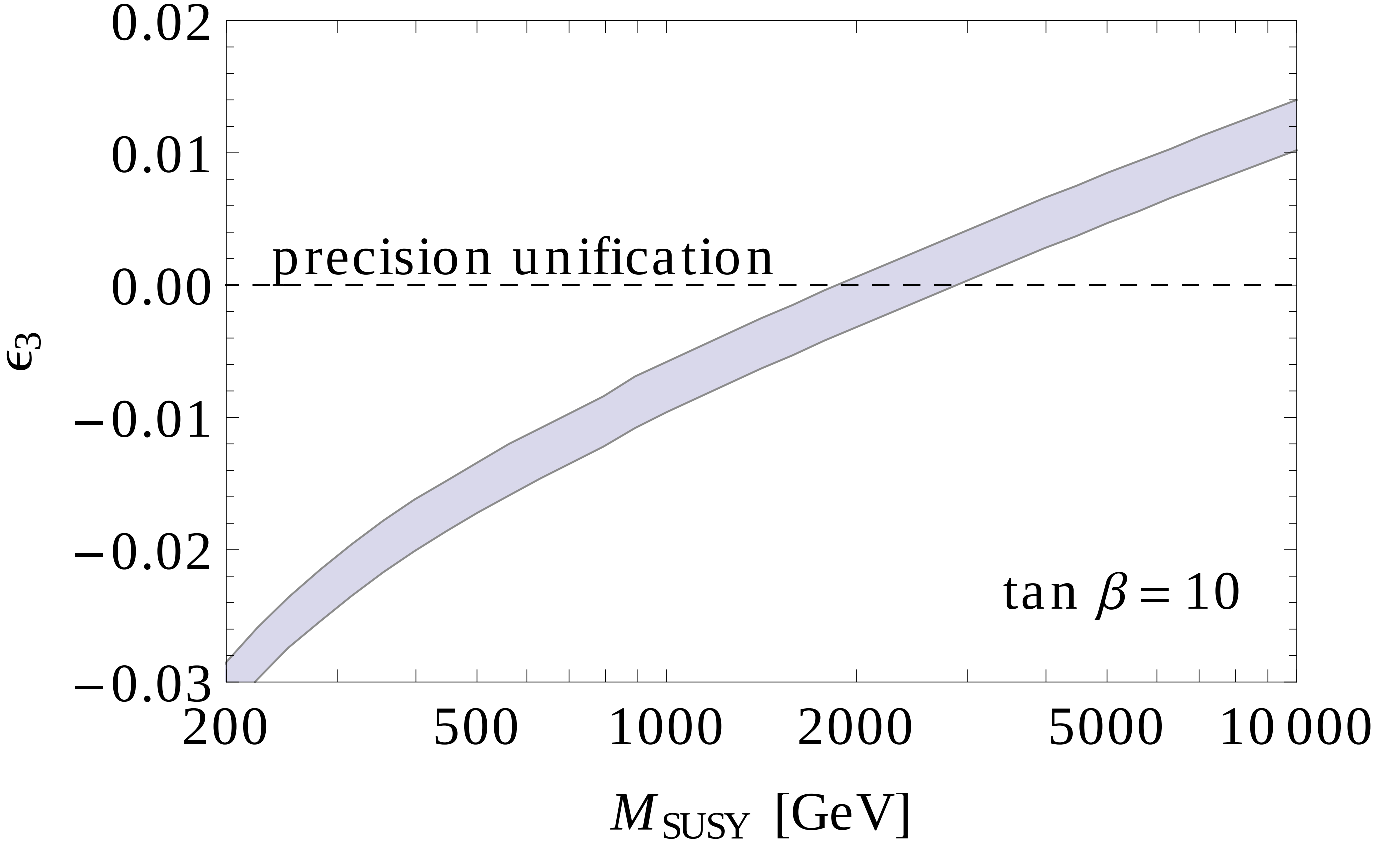
Low scale thresholds:

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

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

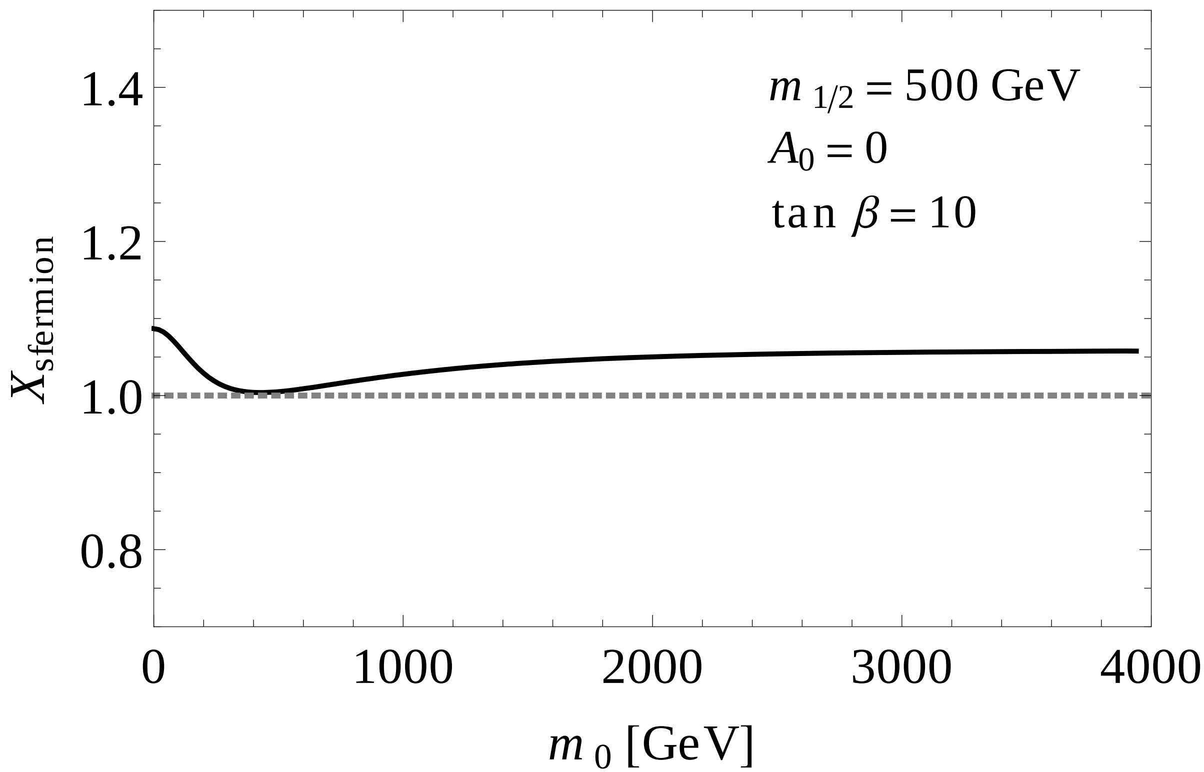
If all supersymmetric partners have the same mass M, then $M_{SUSY} = M$.
For non-universal masses we have an effective scale:

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

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:

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

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:

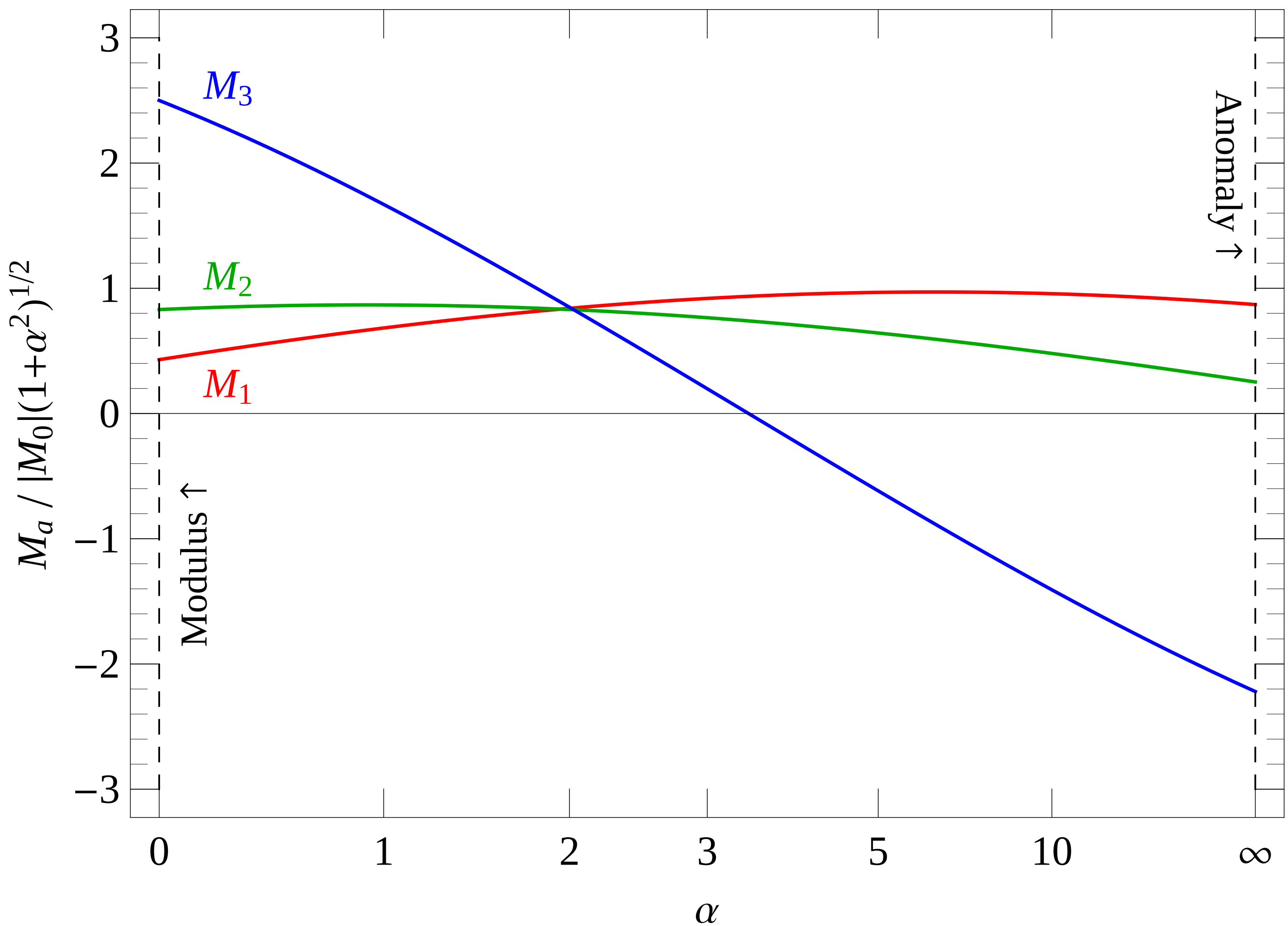
$$M_i \;=\; \frac{m_{3/2}}{16\,\pi^2}\,\left(\varrho + b_i^{\text{MSSM}}\,g^2\right)$$

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}:

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

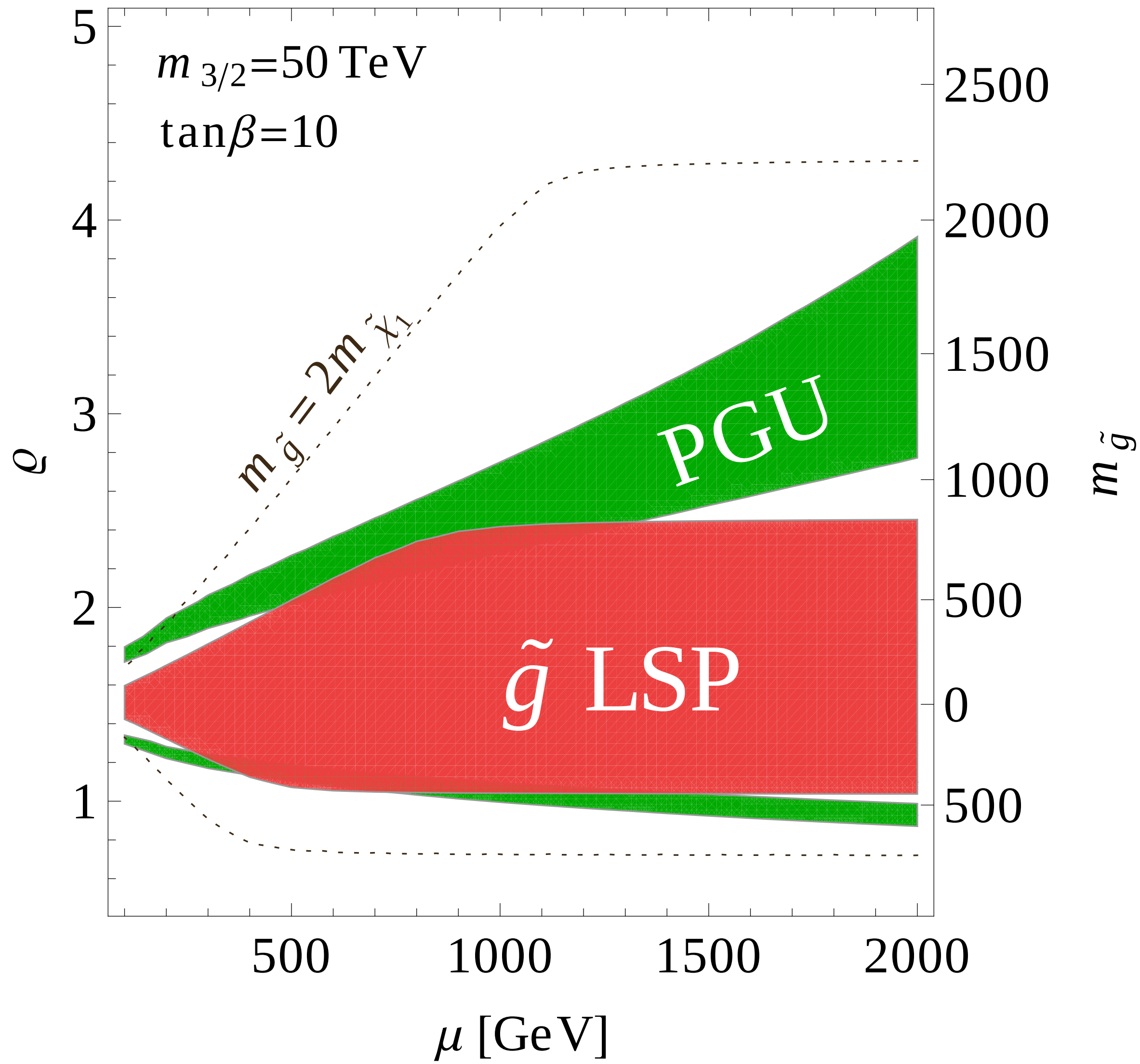
An increase of the gluino reduces M_{SUSY} and vice versa.

A highly compressed gaugino spectrum reduces M_{SUSY}

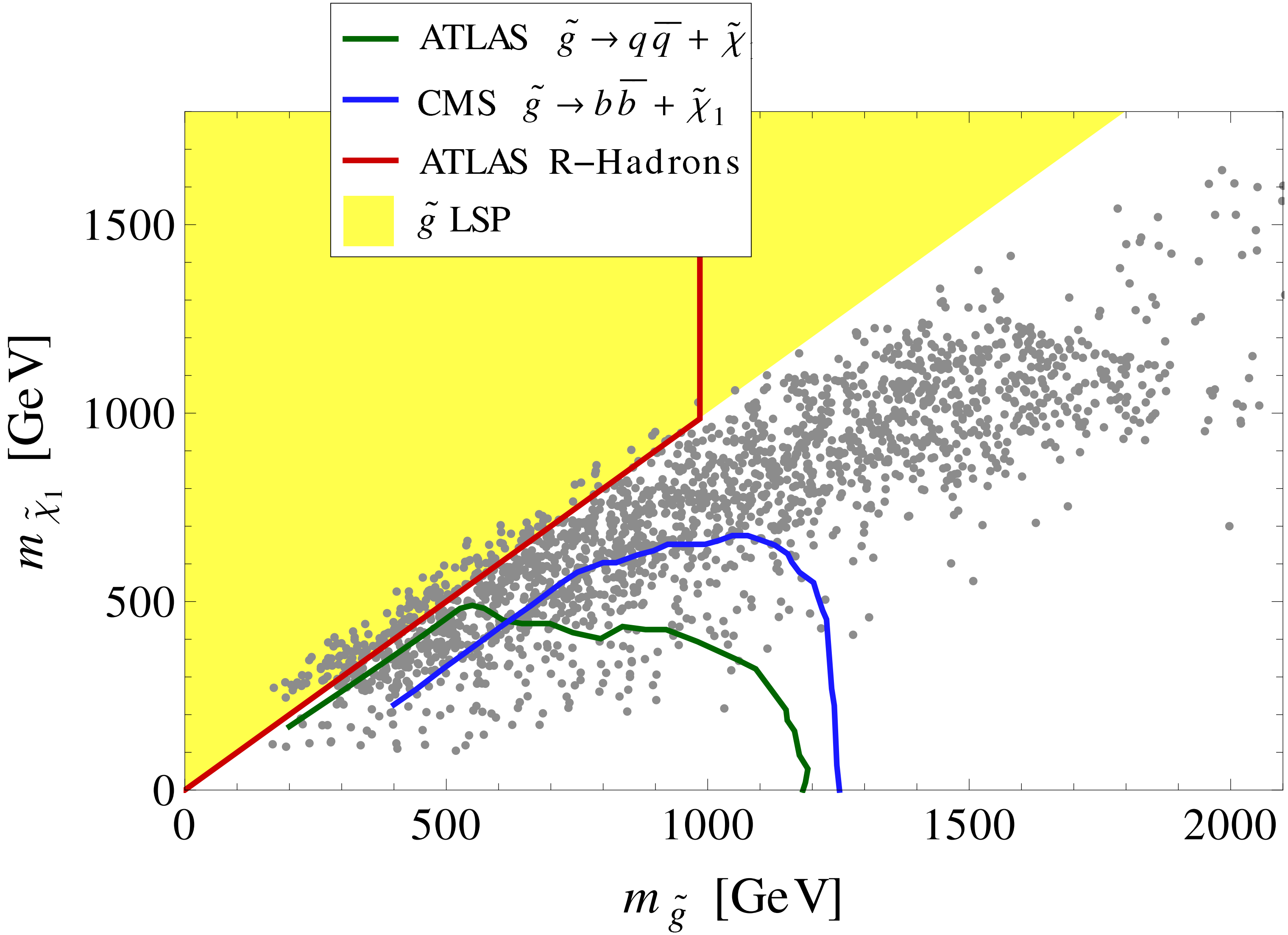
$$M_1 : M_2 : M_3 = (\varrho + 3.3) : 2(\varrho + 0.5) : 6(\varrho - 1.5)$$

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

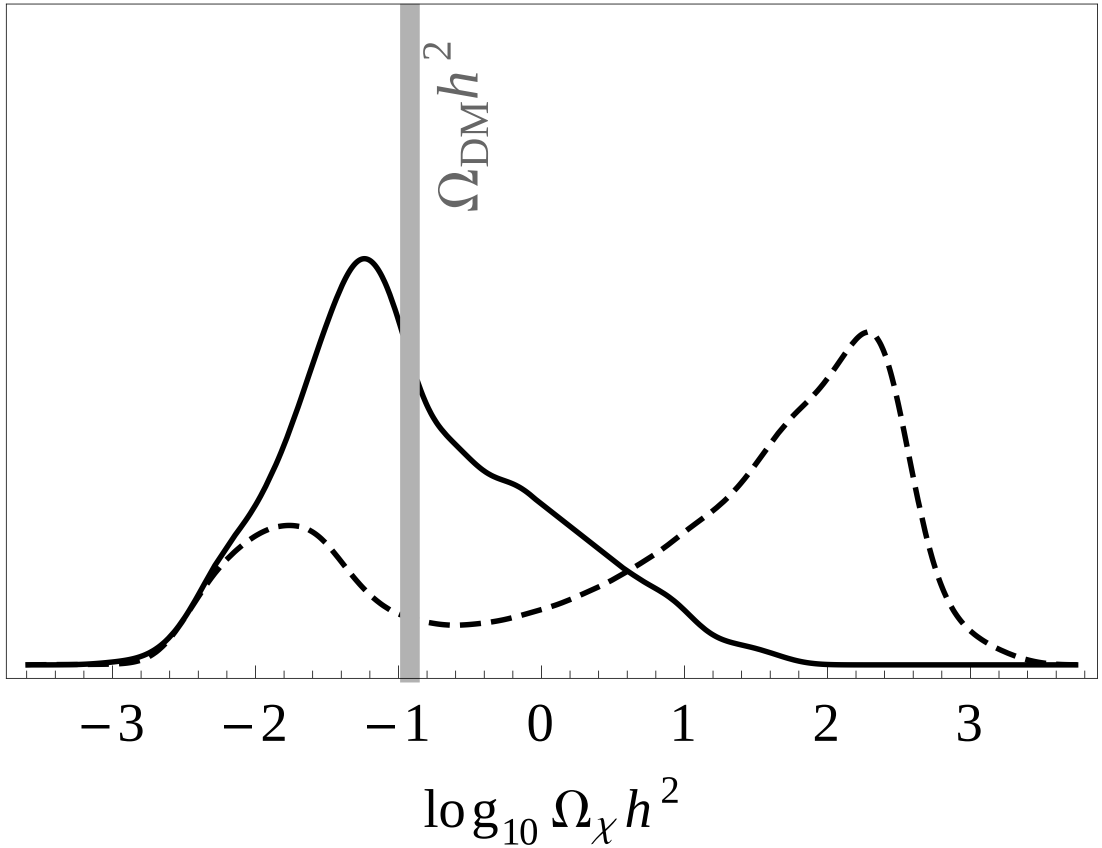
ϱ versus μ



LHC Limits are weak

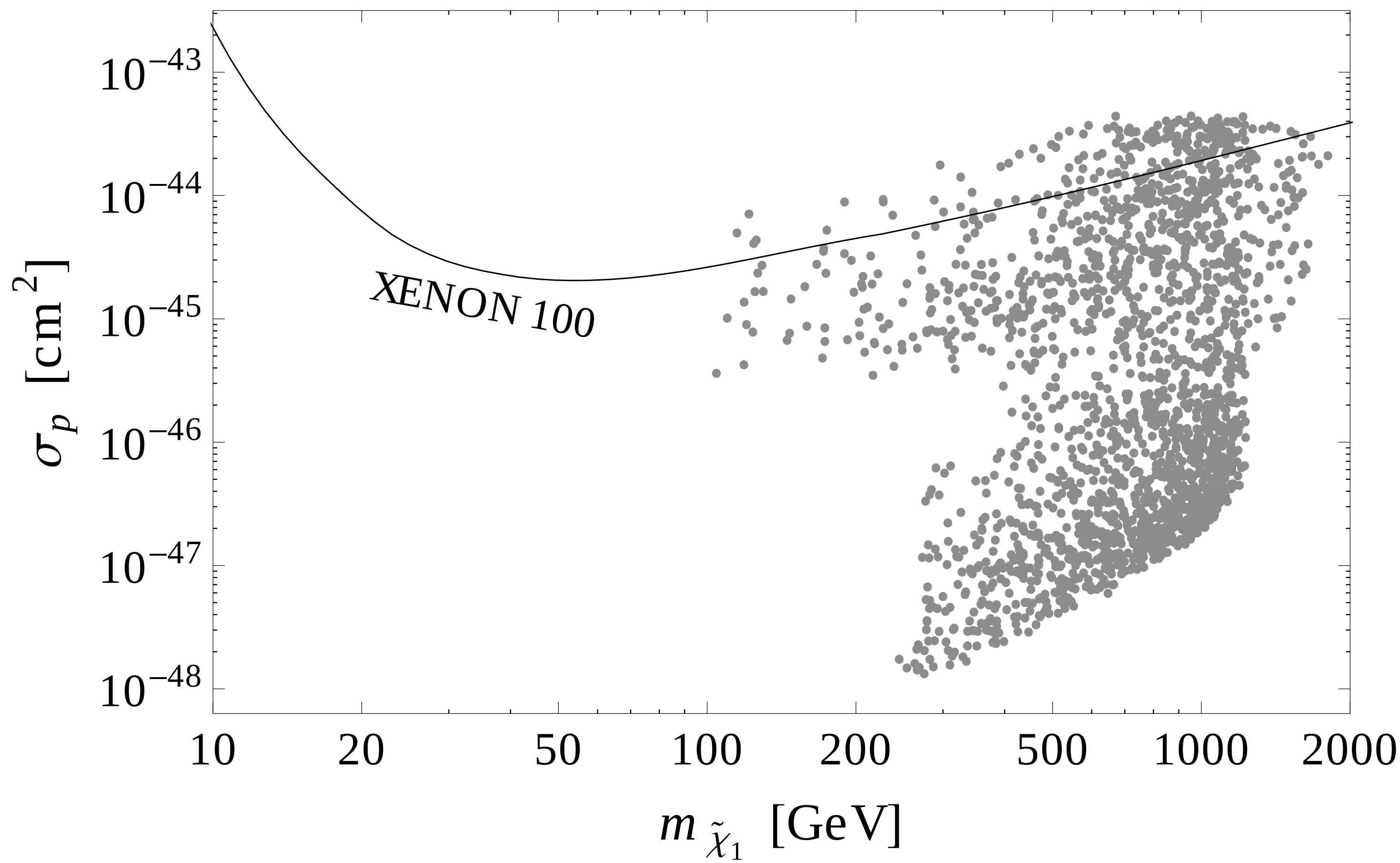


Relic Density



Distribution of thermal neutralino relic density for the benchmark sample with (solid) and without (dashed) assuming 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