Heterotic Supersymmetry: Remnants of $D = 10$ and $N = 4$

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Messages from the heterotic string

Localization properties of quarks, leptons and Higgses

- Higgs bosons and top-quark in the “bulk” lead to a solution to the μ problem and large top-quark Yukawa coupling
- first 2 families localized (exhibiting family symmetries)
- Mirage scheme for SUSY breakdown

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- first 2 families localized (exhibiting family symmetries)
- Mirage scheme for SUSY breakdown

These are remnants of N=4 SUSY from higher dimensions. We discuss two specific schemes

- NATURAL SUSY (Krippendorf, Nilles, Ratz, Winkler, 2012)
- TELE-SUSY (with axions)

(Chatzistavrakidis, Erfani, Nilles, Zavala, 2012)

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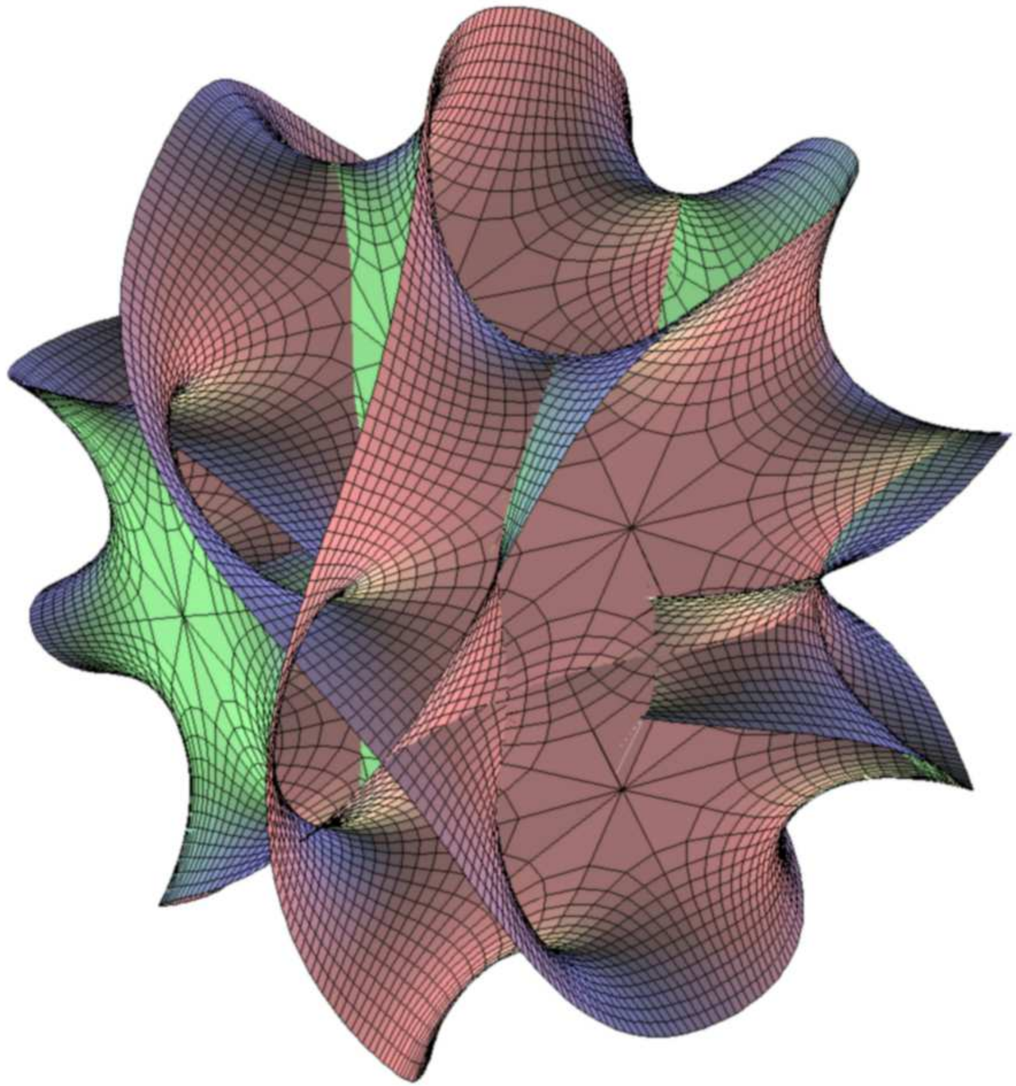
- the location of quarks and leptons,
- the relative location of Higgs bosons,

but there is also a “localization” of gauge fields

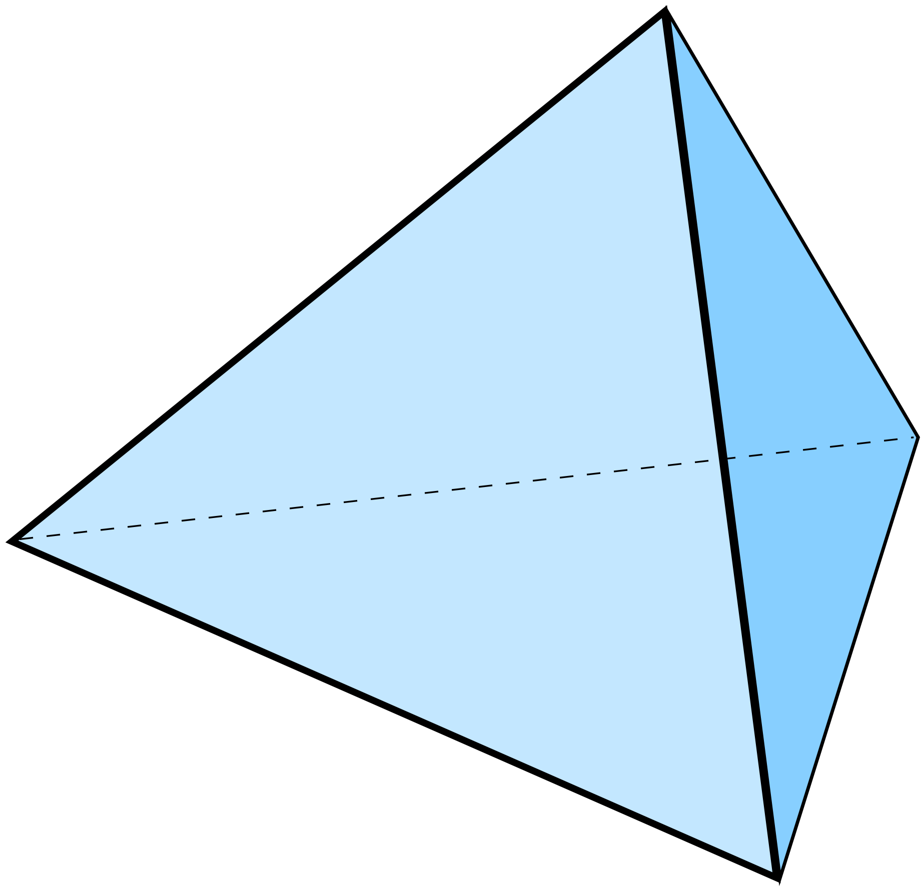
- $E_8 \times E_8$ in the bulk
- smaller gauge groups on various branes

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

Calabi Yau Manifold



Orbifold



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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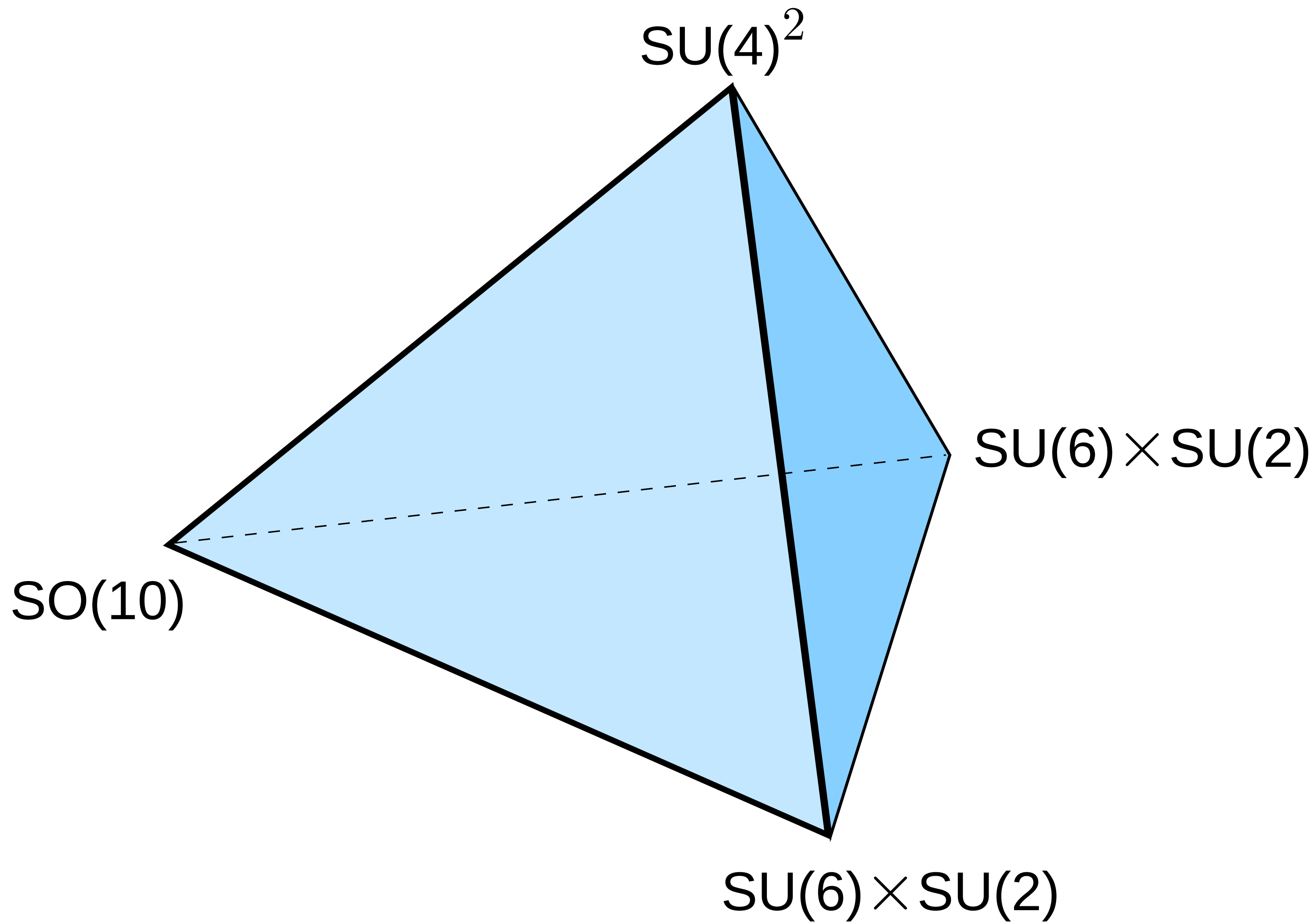
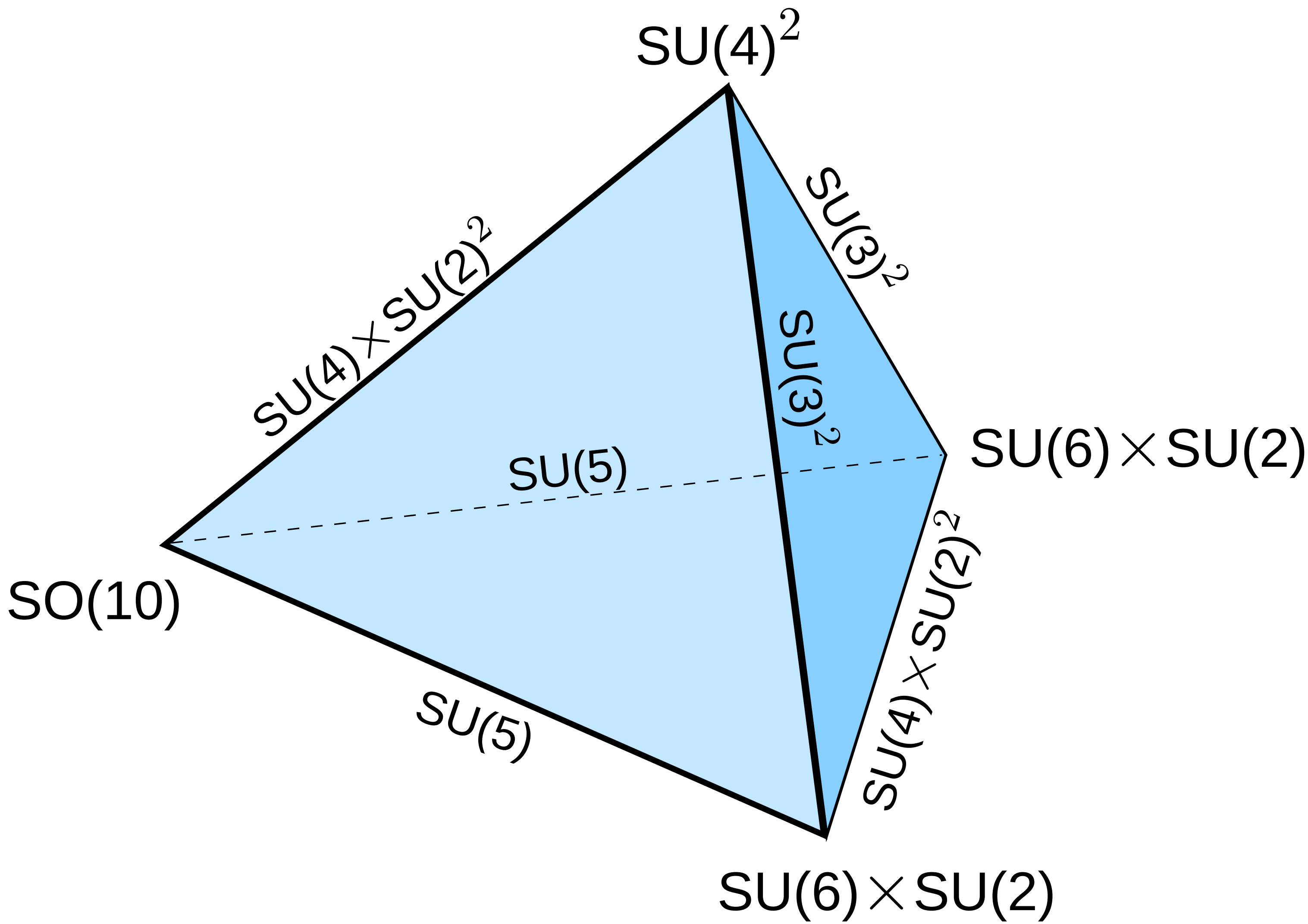
Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Standard Model Gauge Group



The MiniLandscape

- many models with the exact spectrum of the MSSM (absence of chiral exotics)

  (Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007-2009)
- family symmetries for the first two families
- gauge- and (partial) Yukawa unification

  (Raby, Wingerter, 2007)
- large top quark Yukawa coupling
- models with R-parity + solution to the μ-problem

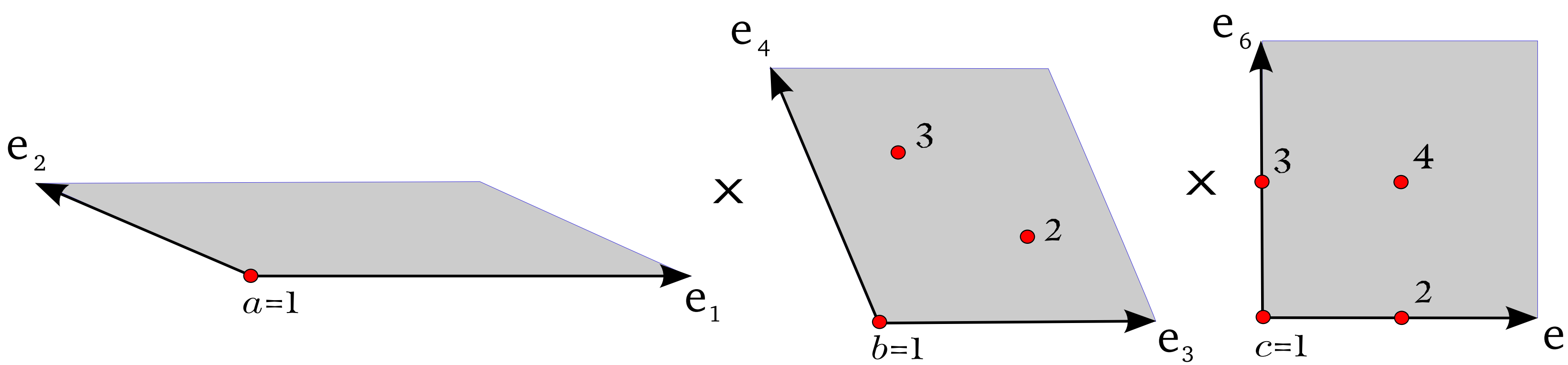
  (Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007)
- gaugino condensation and mirage mediation

  (Löwen, HPN, 2008)

Sectors

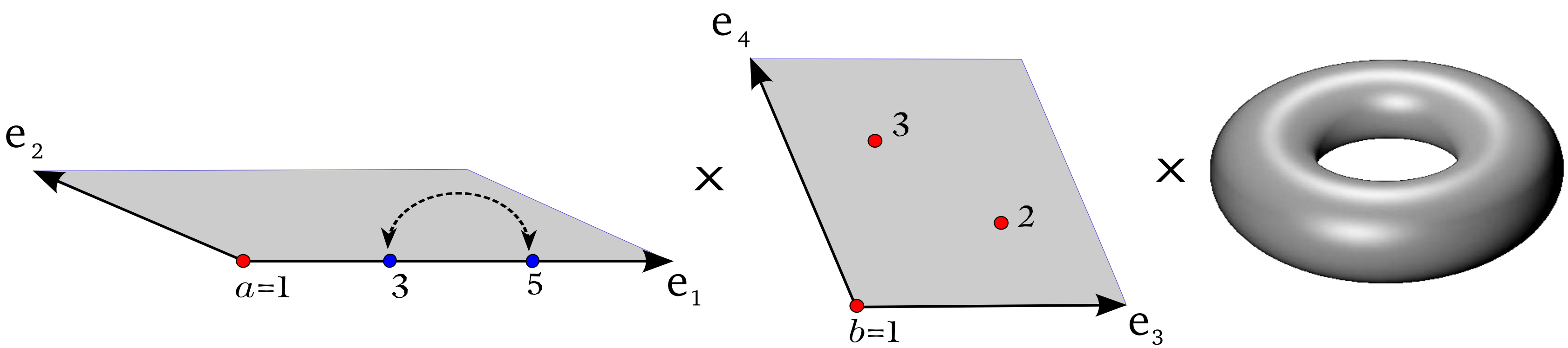
The underlying $Z_6 II$ orbifold has the following sectors:

- the untwisted sector (bulk $D = 10$, $N = 4$ Susy)
- three twisted sectors corresponding to θ, θ^2 and θ^3



The θ sector has 4 x 3 = 12 fixed points, corresponding to "3-branes" confined to D=4 space-time ($N = 1$ Susy).

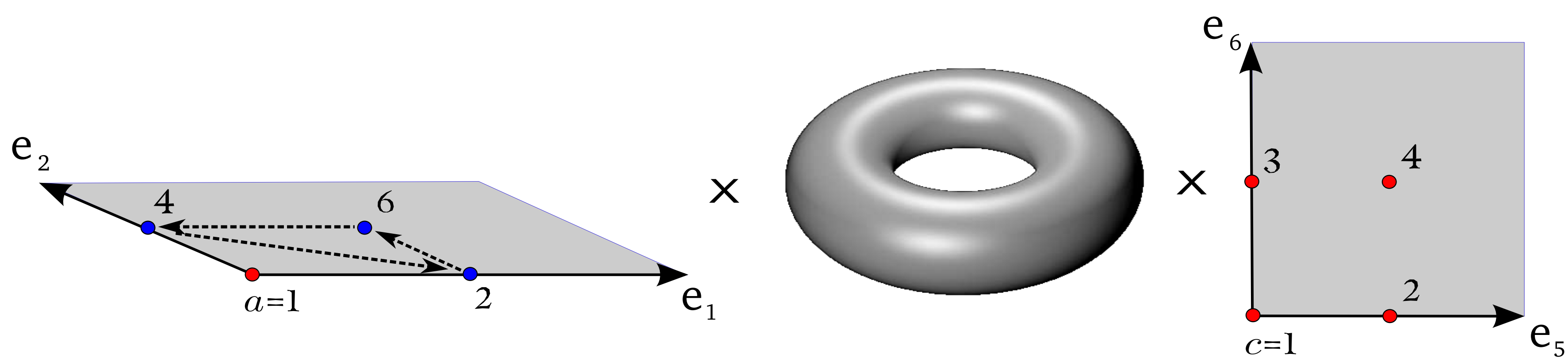
θ^2 twisted sector



The θ^2 sector contains 2 x 3 fixed tori corresponding to

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

θ^3 twisted sector



The θ^3 sector contains 2 x 4 fixed tori:

- "5-branes" confined to 6 space-time dimensions (sector with $N = 2$ 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

The location of Higgs bosons

Typically there could be multitude of Higgs doublets (and triplets) in the spectrum

- triplets heavy or projected out
- exactly two Higgs doublet multiplets should remain light
- all other heavy

This is the so-called μ problem

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This is the so-called μ problem

The MiniLandscape identifies exactly one Higgs pair protected by a discrete symmetry.

Higgs bosons live in untwisted sector (delocalized Higgs as in torus compactification: remnants of $N = 4$ susy)

Location of top quark

Given the fact that the Higgs multiplets live in the untwisted sector we now explore how to obtain a large top quark Yukawa coupling

- need maximum "overlap" with the Higgs multiplet
- results of the MiniLandscape teach us that this requires the top quark to live in the untwisted sector as well

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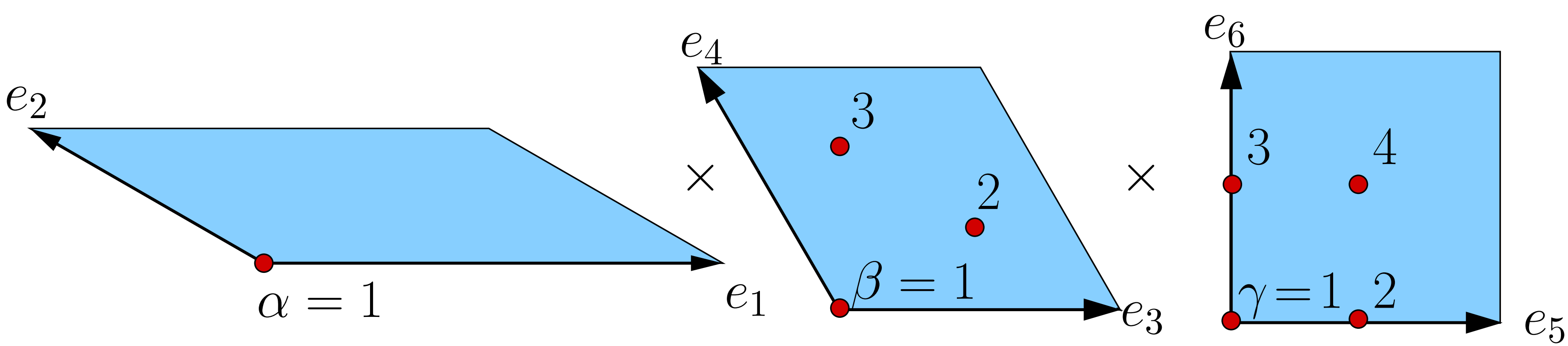
Top quark in untwisted sector. The third family is usually distributed over various sectors (it is not in a complete localized SO(10) representation).

Side remark:
3 "complete" families impossible within $Z_6 II$ orbifold

First and second family

The first and second families are in complete localized 16-dimensional representation of SO(10) (at points of “enhanced” gauge symmetry)

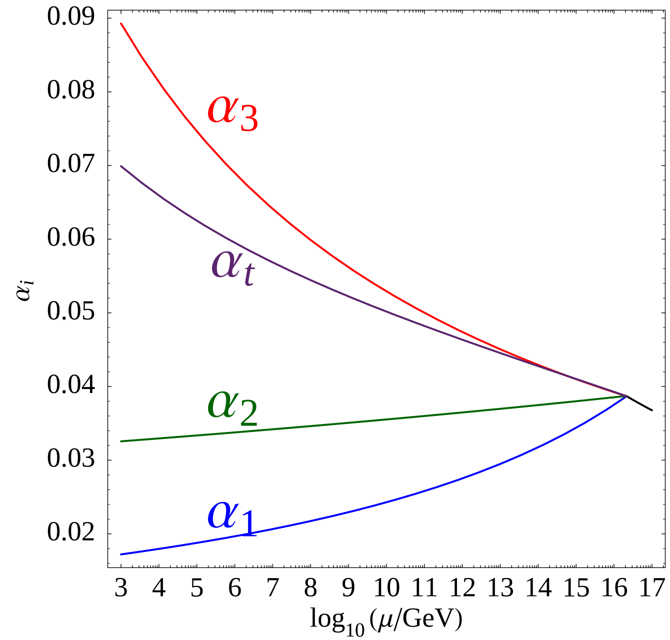


They live in the θ twisted sector and are localized at the fixed points $\alpha = 1$, $\beta = 1$ $\gamma = 1, 3$

exhibiting a D_4 family symmetry.

Unification

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



- Minkowski vacuum before Susy breakdown (no AdS)
- solution to μ-problem (Casas, Munoz, 1993)
- first two families localized (smaller Yukawa couplings) exhibiting a discrete family symmetry

Emergent localization properties

The benchmark model illustrates some of the general properties of the MiniLandscape

- exactly two Higgs multiplets (no triplets)
- the top quark lives in the untwisted sector (as well as the Higgs multiplets)
- only one trilinear Yukawa coupling (all others suppressed)

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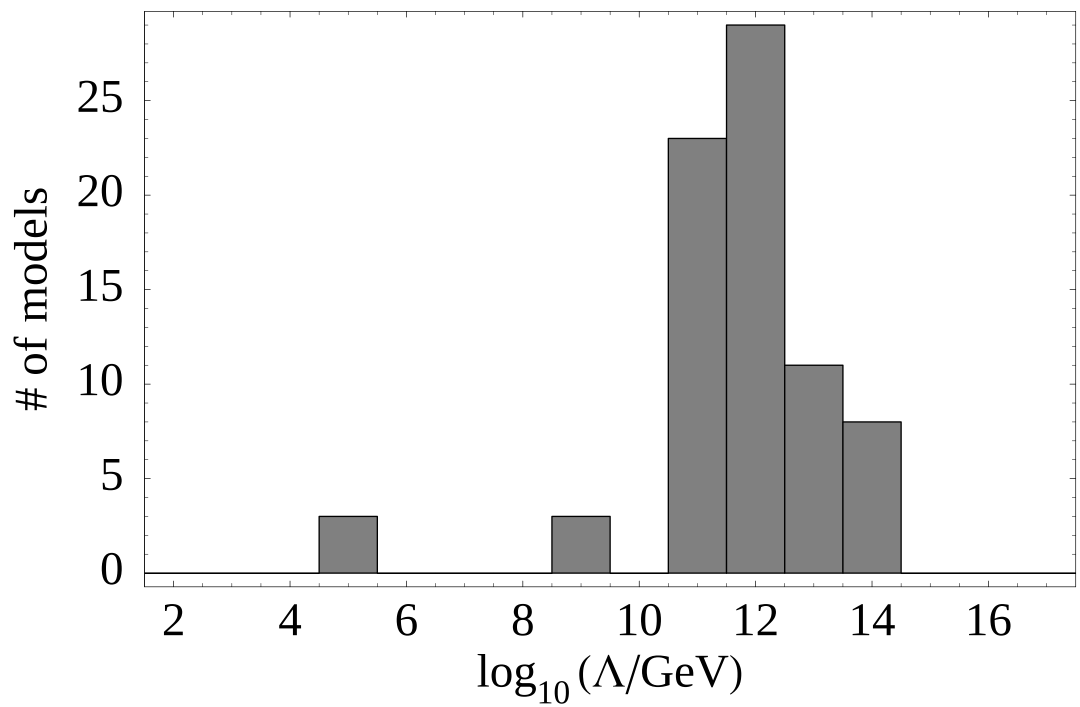
- the top quark lives in the untwisted sector (as well as the Higgs multiplets)
- only one trilinear Yukawa coupling (all others suppressed)

The fact that the top-quark has this unique property among all the quarks and leptons has important consequences for the phenomenological predictions including supersymmetry breakdown.

(Krippendorf, HPN, Ratz, Winkler, 2012)

Heterotic string: gaugino condensation



Gravitino mass $m_{3/2} = \Lambda^3 / M_{\text{Planck}}^2$ and $\Lambda \sim \exp(-\tau)$

(Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2006)

Heterotic string

Fixing U- and T- moduli in a supersymmetric way

(Kappl, Petersen, Raby, Ratz, Vaudrevange, 2010; Anderson, Gray, Lukas, Ovrut, 2011)

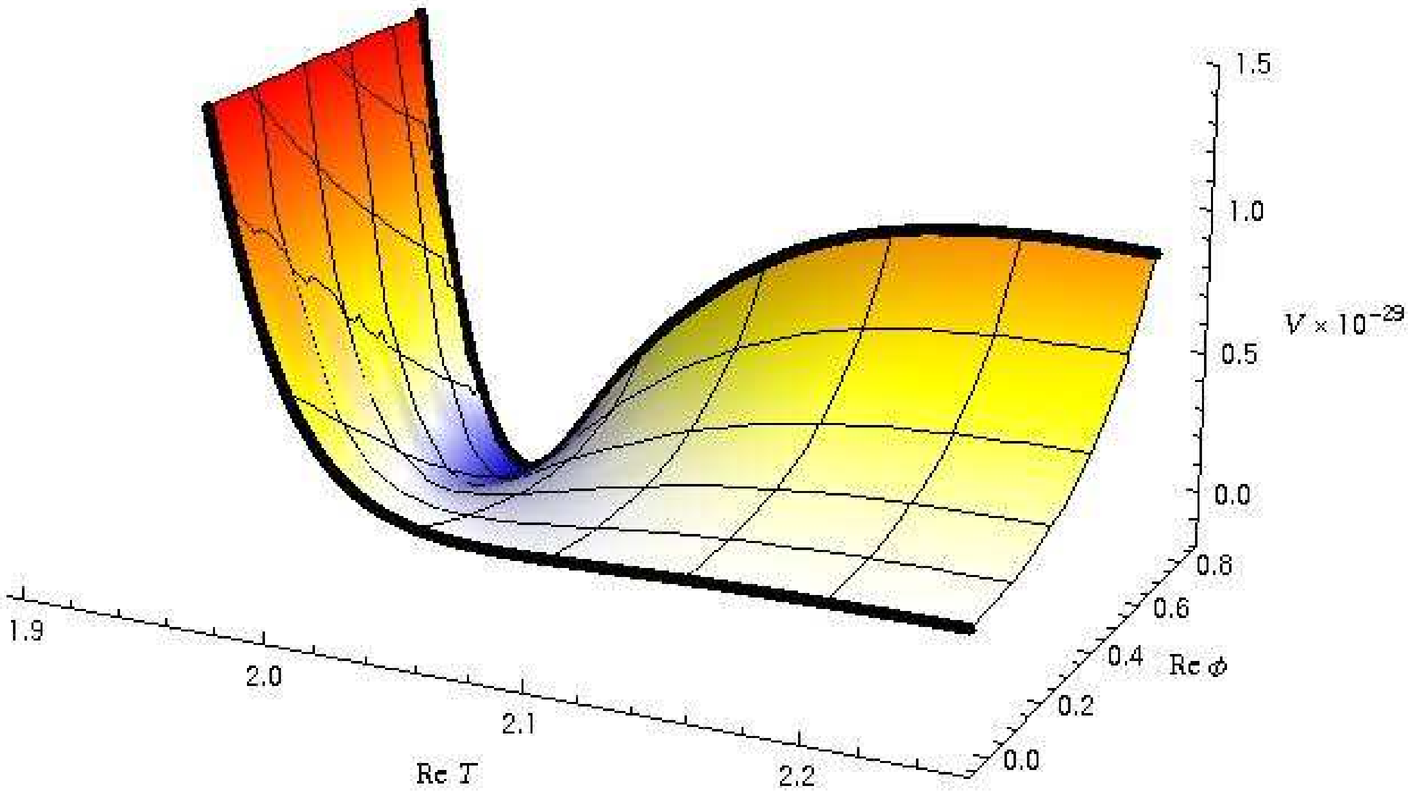
- we remain with a run-away dilaton

But we need to adjust the vacuum energy

- matter field in untwisted sector
- “downlifting” mechanism can fix τ as well (no need for nonperturbative corrections to the Kähler potential)

(Löwen, HPN, 2008)

Downlift



(Löwen, HPN, 2008)

Mirage scheme

Fixing U- and T- moduli in a supersymmetric way

(Kappl et al., 2010; Anderson et al., 2011)

- we remain with a run-away dilaton

But we need to adjust the vacuum energy

- matter field in untwisted sector
- “downlifting” mechanism can fix τ as well (no need for nonperturbative corrections to the Kähler potential)
- a so-called mirage scheme with suppression factor $\log(m_{3/2}/M_{\mathrm{Planck}})$

(Löwen, HPN, 2008)

Susy breakdown via down-lifting

In string theory we have (from flux and gaugino condensate)

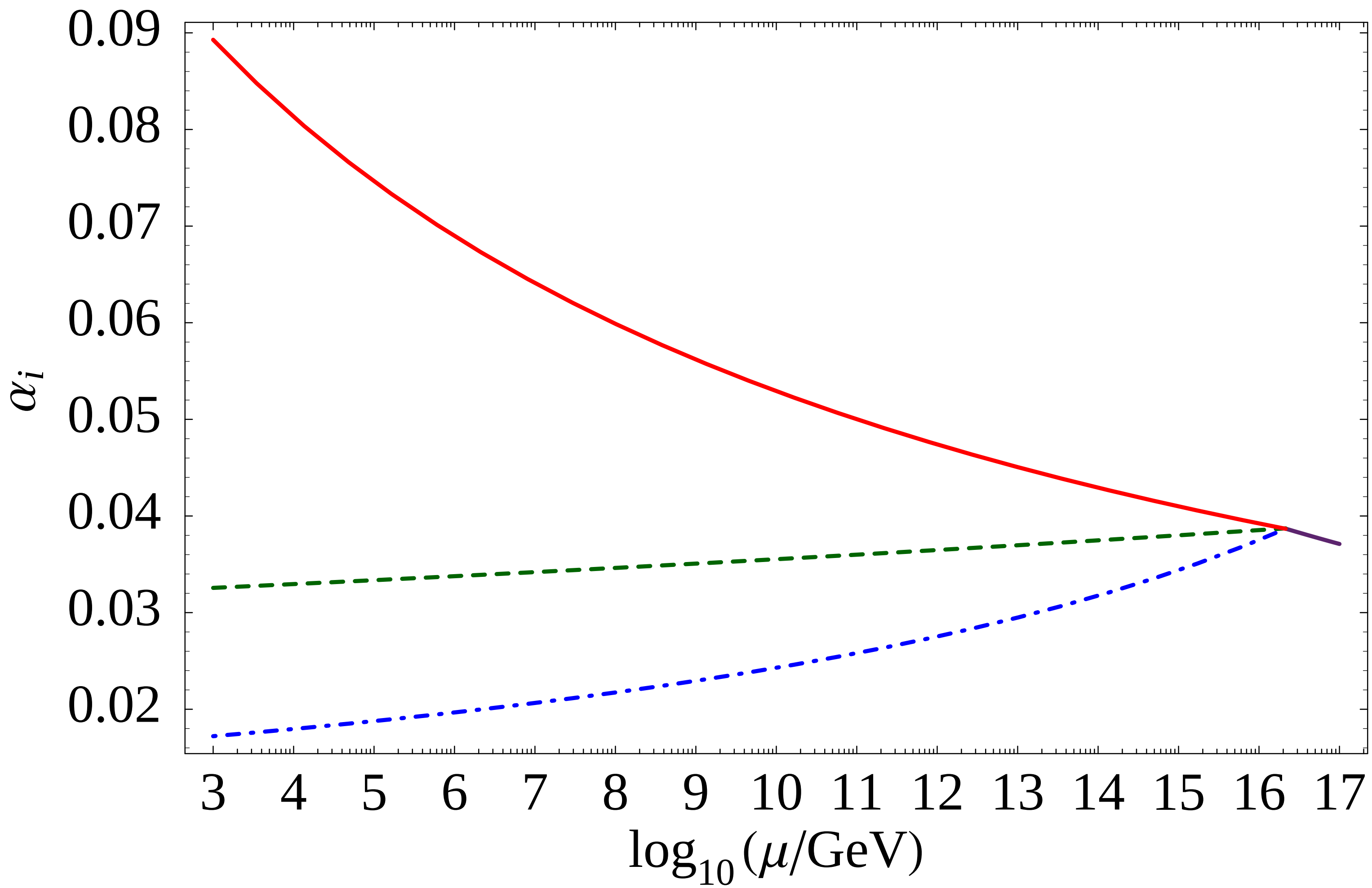
$$W = \text{flux} - \exp(-X)$$

- modulus mediation suppressed (from down-lifting) $X \sim \log(M_{\text{Planck}}/m_{3/2}) \sim 4\pi^2$
- radiative corrections become relevant (β function)
- Mixed mediation scheme: Mirage Mediation (MMAM) with mirage pattern for gaugino masses: $m_{1/2} \sim m_{3/2}/4\pi^2$ (Choi, Falkowski, Nilles, Olechowski, 2005)

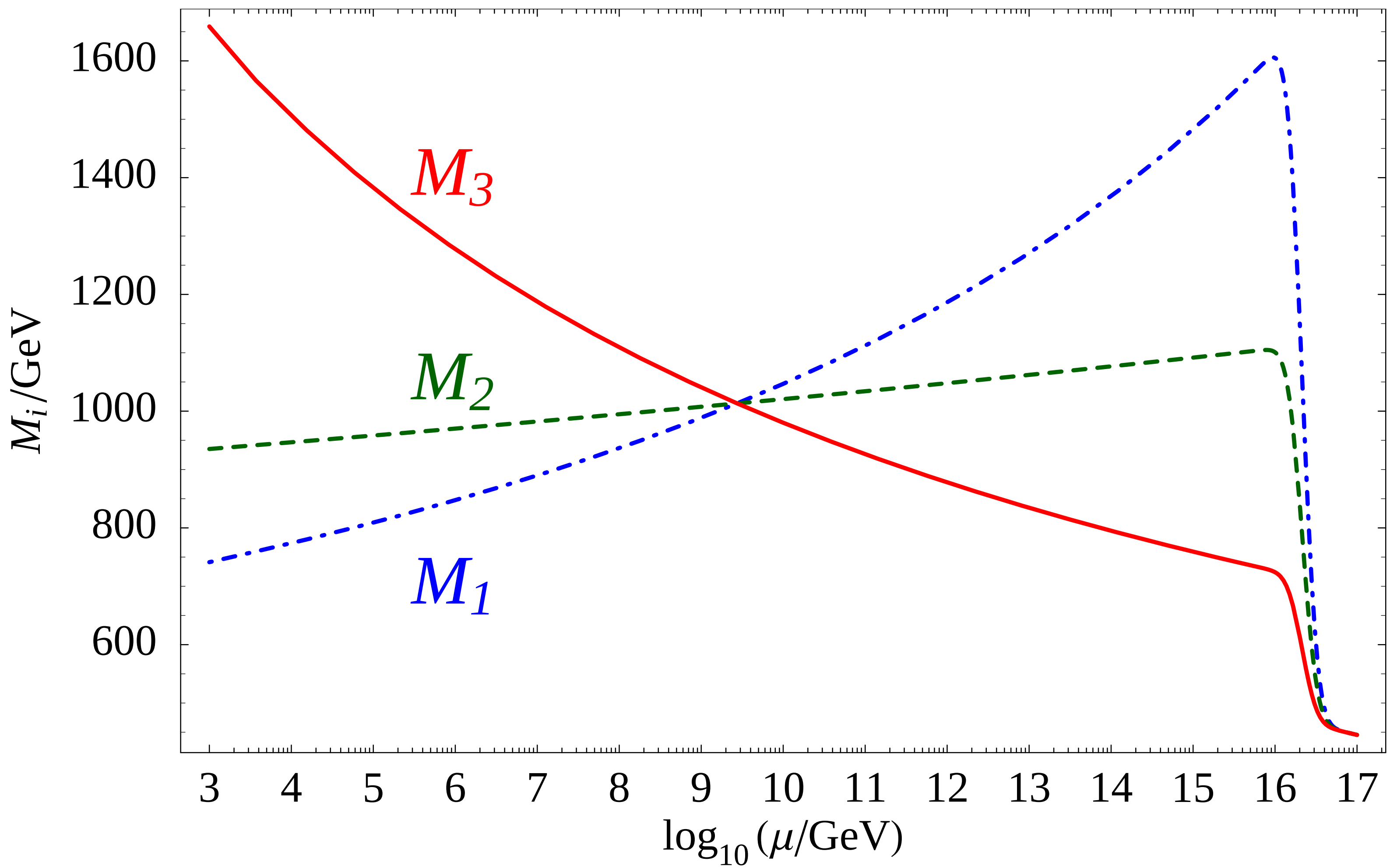
first encountered in the framework of Type IIB theory

(Kachru, Kallosh, Linde, Trivedi, 2003)

Evolution of couplings



The Mirage Scale



(Lebedev, HPN, Ratz, 2005)

Reading the Gaugino Code

Mixed boundary conditions at the GUT scale
characterized by the parameter α:
the ratio of modulus to anomaly mediation.

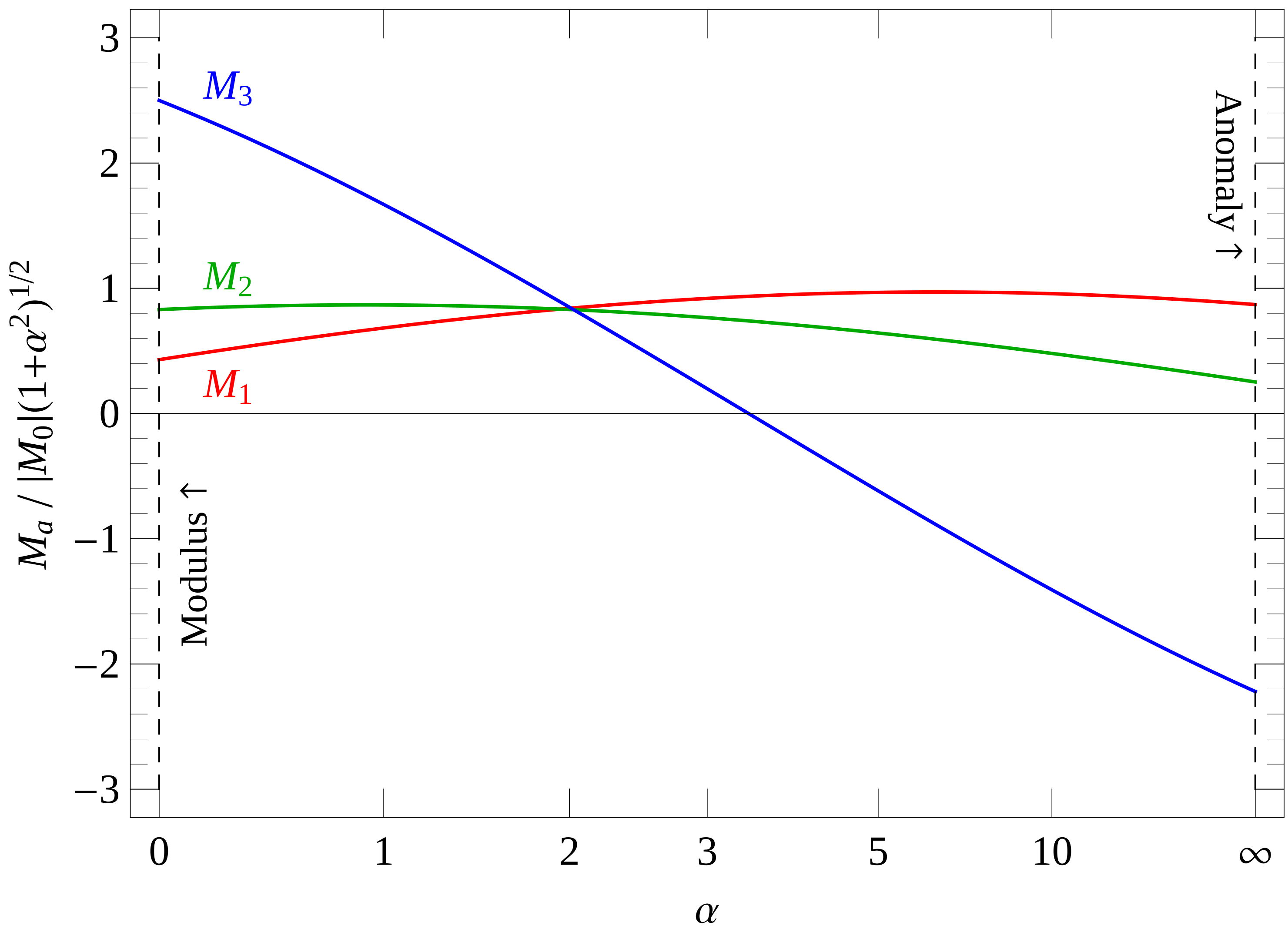
- $M_1 : M_2 : M_3 \simeq \; 1 : 2 : 6$ for $\alpha \simeq 0$
- $M_1 : M_2 : M_3 \simeq \; 1 : 1.3 : 2.5$ for $\alpha \simeq 1$
- $M_1 : M_2 : M_3 \simeq \; 1 : 1 : 1$ for $\alpha \simeq 2$
- $M_1 : M_2 : M_3 \simeq \; 3.3 : 1 : 9$ for $\alpha \simeq \infty$

The mirage scheme leads to

- LSP χ_1^0 predominantly Bino
- a “compact” (compressed) gaugino mass pattern.

(Choi, HPN, 2007; Löwen, HPN, 2009)

Gaugino Masses



Soft terms

So we have mirage suppression (compared to $m_{3/2}$) of

- gaugino masses (with compressed spectrum)
- A-parameters in the (few) TeV range.

Scalar masses are less protected

- heavy squarks and sleptons: $m_0 < O(30)$TeV

(Lebedev, Nilles, Ratz, 2006; Löwen, Nilles, 2008)

But, the top quark plays a special role

- as a result of gauge-Yukawa-unification

  $g_{\text{top}} \sim g_{\text{gauge}} \sim g_{\text{string}}$

  that explains the large value of the top-quark mass

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 twisted sectors (branes)

This 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

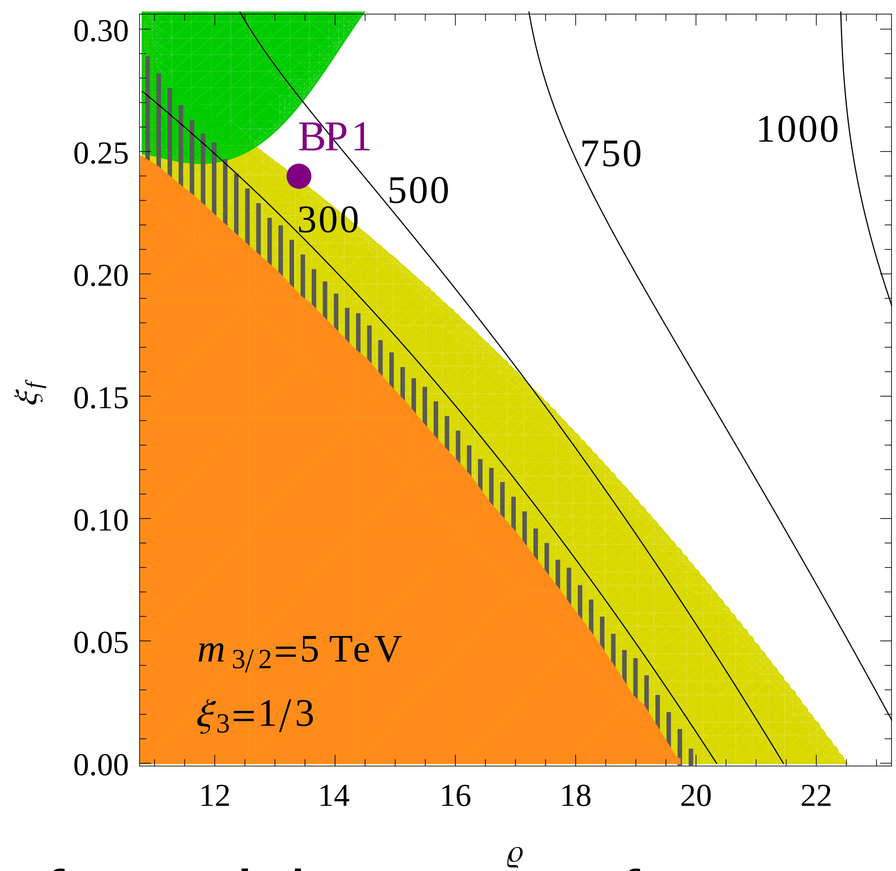
- normal squarks and sleptons in Multi-TeV range
- top squarks $(\tilde{t}_L, \tilde{b}_L)$ and $\tilde{t}_R$ in TeV-range (suppressed by $\log(M_{\rm Planck}/m_{3/2}) \sim 4\pi^2$)
- A-parameters in TeV range
- gaugino masses in TeV range
- mirage pattern for gaugino masses (compressed spectrum)
- heavy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

A Closer Look

A more detailed picture requires the analysis of specific models. Issues that have to be clarified:

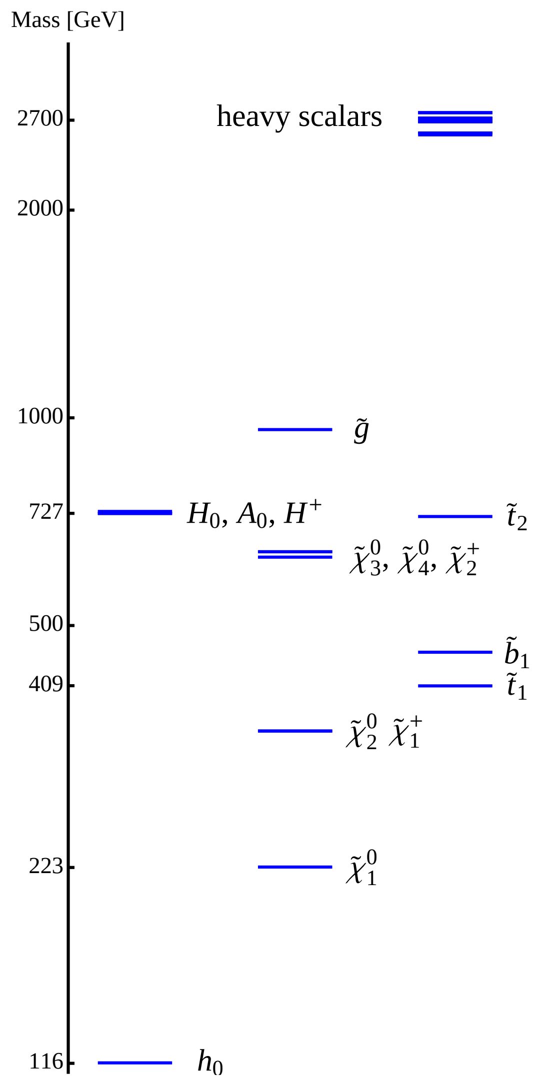
- the appearance of tachyons,
  - partially inherited from anomaly mediation
  - two loop effects in the presence of heavy scalars
- the hierarchy between gauginos and sfermions.
- Can we satisfy all phenomenological constraints?
  - mass of Higgs, correct electroweak symmetry breakdown etc.
  - nature and abundance of WIMP-LSP.
- What is the LHC reach to test this scheme?

Benchmark model with a TeV gluino



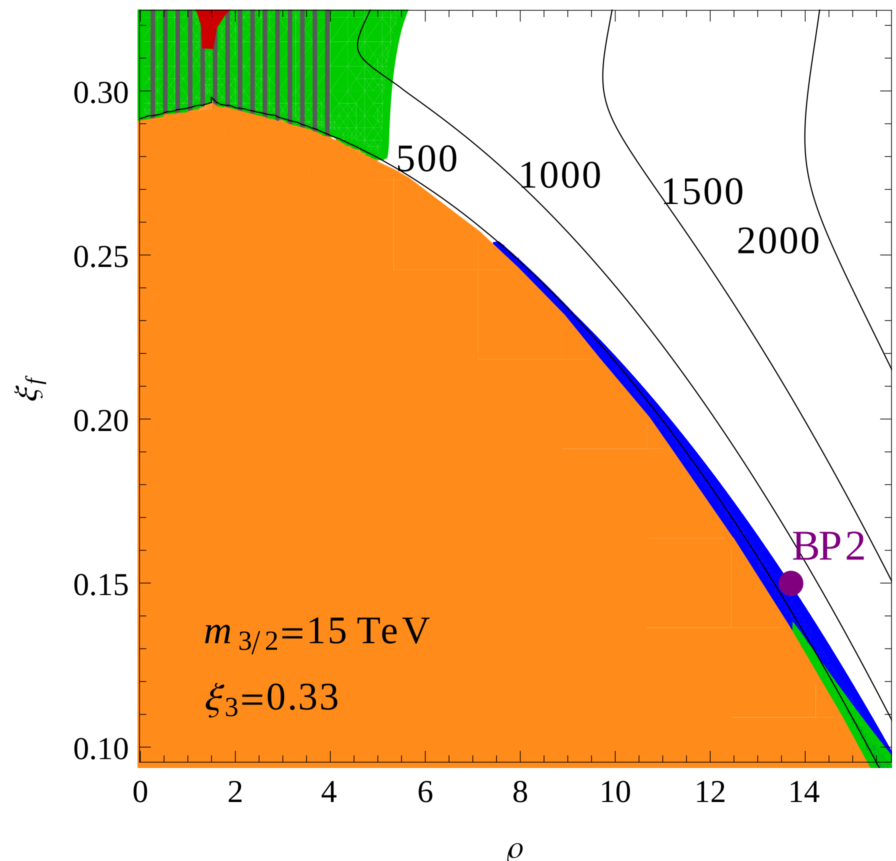
Parameter scan for a gluino mass of 1 TeV. The coloured regions are excluded while the hatched region indicates the current reach of the LHC. The contours indicate the mass of the lightest stop.

Spectrum 1



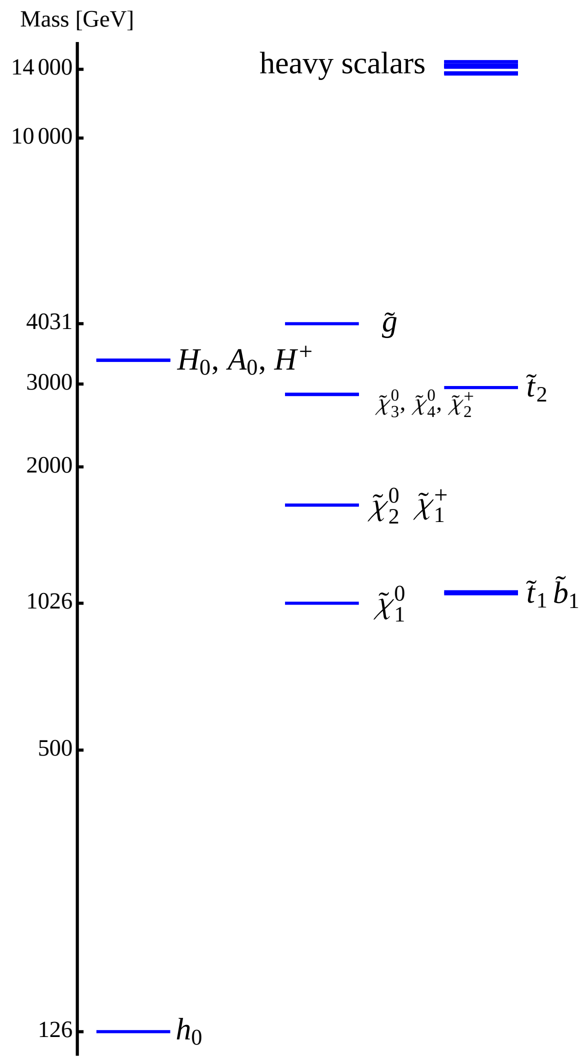
Mass [GeV]
2700
2000
1000
727
500
409
223
116
heavy scalars
$\tilde{g}$
H_0, A_0, H^+
$\tilde{t}_2$
$\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^+$
$\tilde{b}_1$
$\tilde{t}_1$
$\tilde{\chi}_2^0\ \tilde{\chi}_1^+$
$\tilde{\chi}_1^0$
h_0

Model with 4 TeV gluino



Parameter scan for a gluino mass of 4 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 4 TeV gluino



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, however, seems to be limited
- the heterotic string yields “Natural SUSY”. There is a reduced fine-tuning because of
  - the mirage pattern for gauginos,
  - and light stop masses
- and this is a severe challenge for LHC searches.

Comparison to other schemes

Mirage pattern for gaugino masses seems to be common for type II, G2MSSM and heterotic models

- type IIB
  - all sfermions unprotected
  - A-parameters in few TeV-range
- G2MSSM
  - all sfermions unprotected
  - A-parameters in multi TeV-range (e.g. $O(50)$TeV)

but there are no explicit models to test a connection between Yukawa pattern and soft breaking terms.

The overall scale

There is no (reliable) prediction for the gravitino mass

- except for fine-tuning arguments
- “no lose” criterion (SSC with 20+20 TeV)
- does LHC satisfy this criterion?

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Betting in the early 80’s

- I bet that supersymmetry will be discovered before SSC gets into operation
- I bet that supersymmetry will have been forgotten before SSC gets into operation

Conclusions (so far)

Localization of quarks, leptons and Higgs bosons

- realistic models require Higgs multiplets and top multiplets in untwisted sector (connected to μ problem)
- this implies Gauge-Yukawa unification (trilinear top quark Yukawa coupling)
- other fields tend to be localized at fixed points (tori) and exhibit discrete family symmetries

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Remnants of $N = 4$ SUSY (from $D = 10$)

- mirage mediation
- mass spectrum of “Natural Susy”

Nightmare Scenario

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Reading the LHC Higss mass discovery:
a Higgs mass of 125 GeV is

- rather high for the MSSM
- rather low for the SM (vanishing of Higgs self coupling in renormalization group evolution at $10^{10} - 10^{12}$ GeV)

(Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia, 2012)

Alternatives to SUSY

Other well motivated physics BeyondSM is axions.
We might consider three “useful” axions

- solution to strong CP problem
- shift symmetry for natural inflation
- candidates for quintessence

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The QCD-axion can provide cold dark matter:

- so it takes away the WIMP argument for cold dark matter in weak scale supersymmetry
- Do axions need supersymmetry? Not necessarily.

Axions and strings

Axions might be abundant in string theory.
Generically one gets

- axion scales f_a of order of the string scale,
- masses through various nonperturbative effects.
- Does string theory need Susy?
  Most probably: but where?

Axions and strings

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  Most probably: but where?

Dark Matter requires one axion scale to be as low as $f_a \sim 10^{12}$ GeV

- would expect Susy breakdown below or at f_a
- Could the Susy breakdown scale coincide with the scale $f_a \sim 10^{12}$ GeV of the QCD axion?

The Higgs mass at LHC

Higgs mass of 125 GeV rather high for MSSM

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Higgs mass rather low for the Standard Model

- new physics required at intermediate scale $10^{10} - 10^{12}$ GeV where Higgs self coupling runs to zero

  (Hebecker, Knochel, Weigand; Ibanez, Marchesano, Regalado, Valenzuela, 2012)
- and this is realized if the Higgs bosons are in the untwisted sector (shift symmetry of Kaehler potential, continuous Wilson lines, Gauge Higgs unification)
- remnants of N=4 SUSY lead to remote supersymmetry at the axion scale (Tele-Supersymmetry).

Susy at f_a

We obtain consistent Dark Matter scenario

- but we need fine tuning for weak scale
- in addition to fine tuning for the quintessential axion
- might use “landscape” arguments

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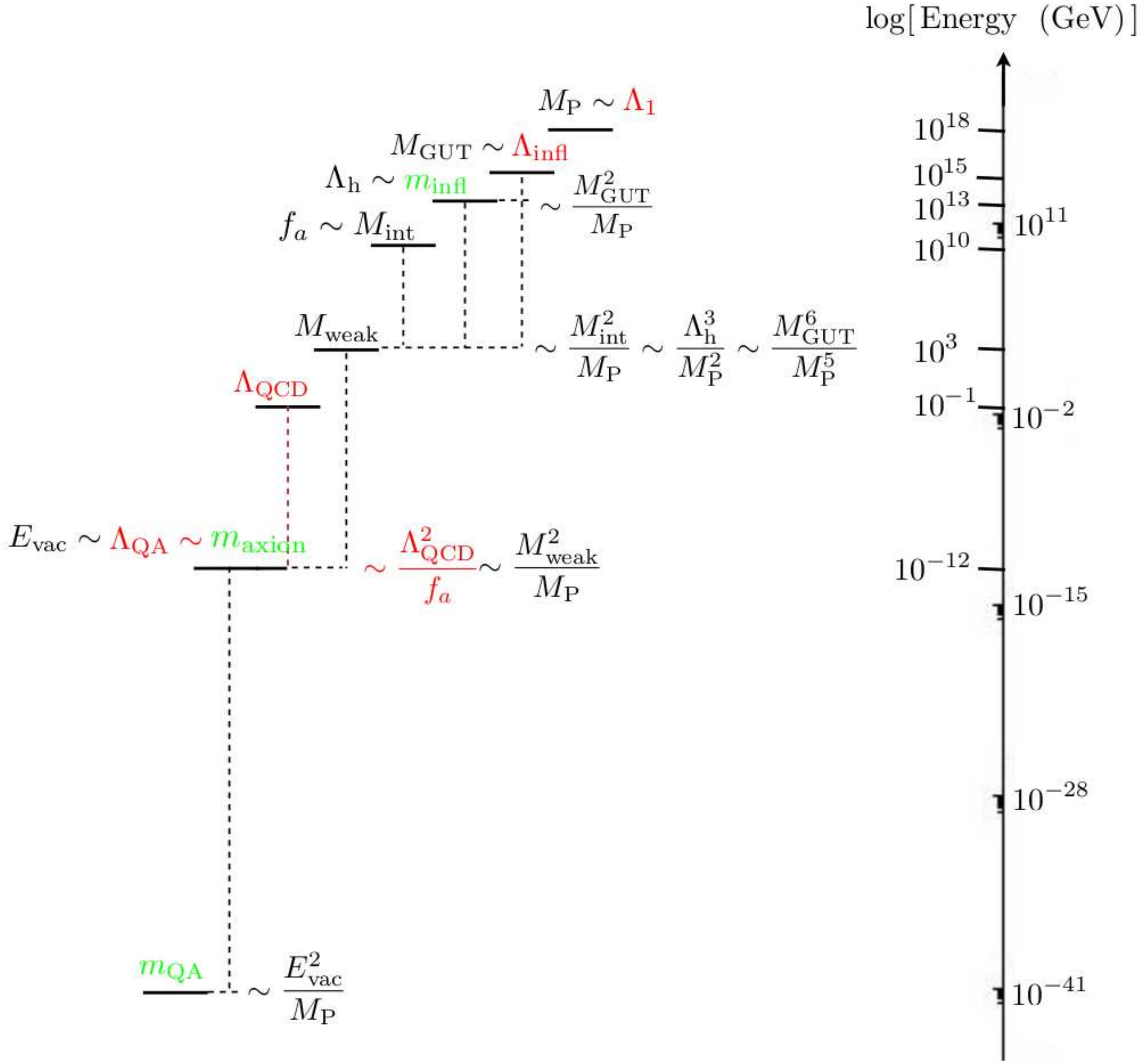
Various relations between the fundamental mass scales

- μ at the weak scale (tree level μ small compared to f_a)
- axionic see-saw (including $E_{vacuum} \sim M^2_{\rm weak}/M_{\rm Planck}$) that unifies the “useful” axions in one scheme

Axionic See-Saw



(Chatzistavrakidis, Erfani, Nilles, Zavala, 2012)

Conclusions

Overall scale of Susy breakdown still not determined

- there are hints from $m_{\mathrm{Higgs}} \sim 125$ GeV
- this is rather high for the MSSM
- and rather low for standard model (need completion at intermediate scale of order of axion scale)

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So one might speculate that Susy is broken at axion scale

- 3 useful axions (with axionic see saw)
- good candidate for cold dark matter

Remote Supersymmetry (TELE-SUSY)