The ZIP Code of Quarks, Leptons and Higgs Bosons

Hans Peter Nilles

Physikalisches Institut

Universität Bonn

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)
- REMOTE 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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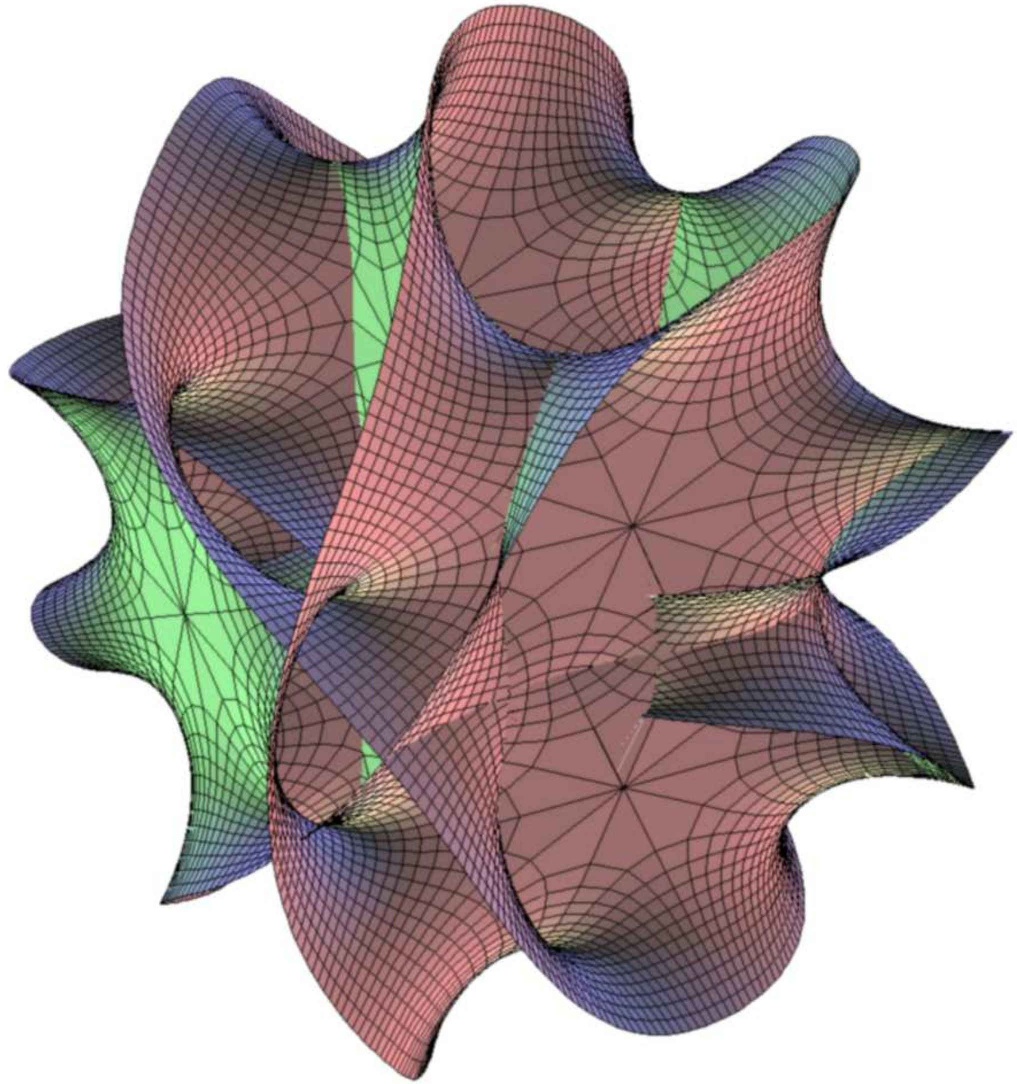
but there is also a “localization” of gauge fields

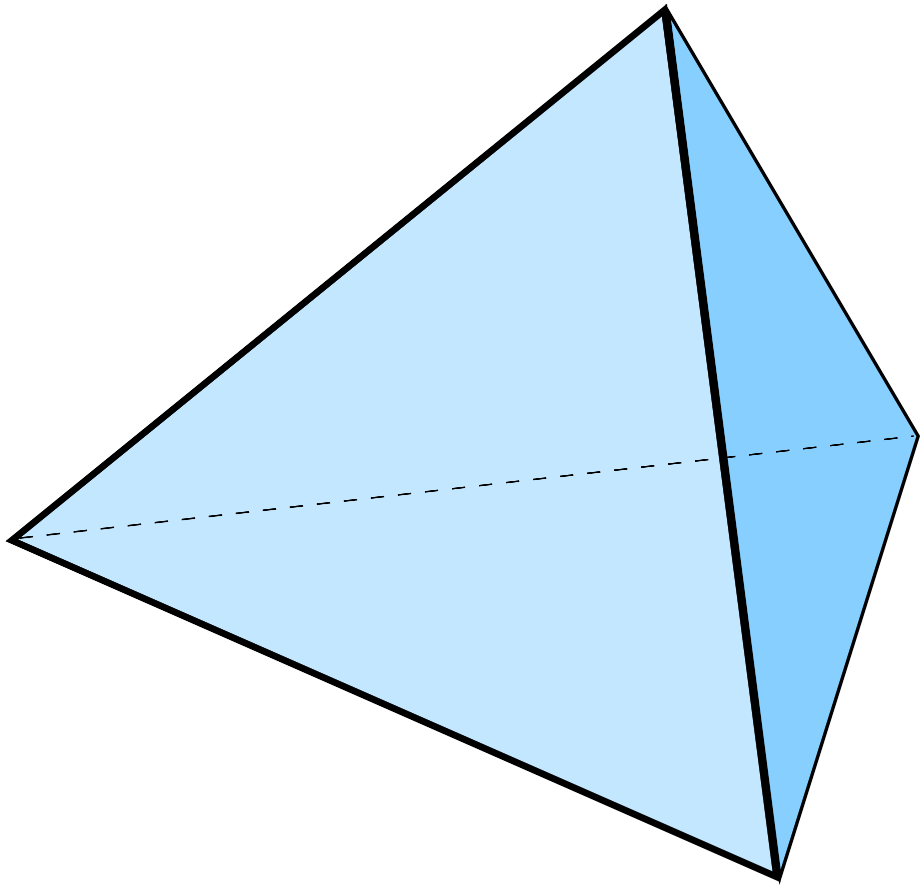
- $E_8 \times E_8$ in the bulk
- smaller gauge groups on various branes

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

Calabi Yau Manifold



Orbifold



(Dixon, Harvey, Vafa, Witten, 1985)

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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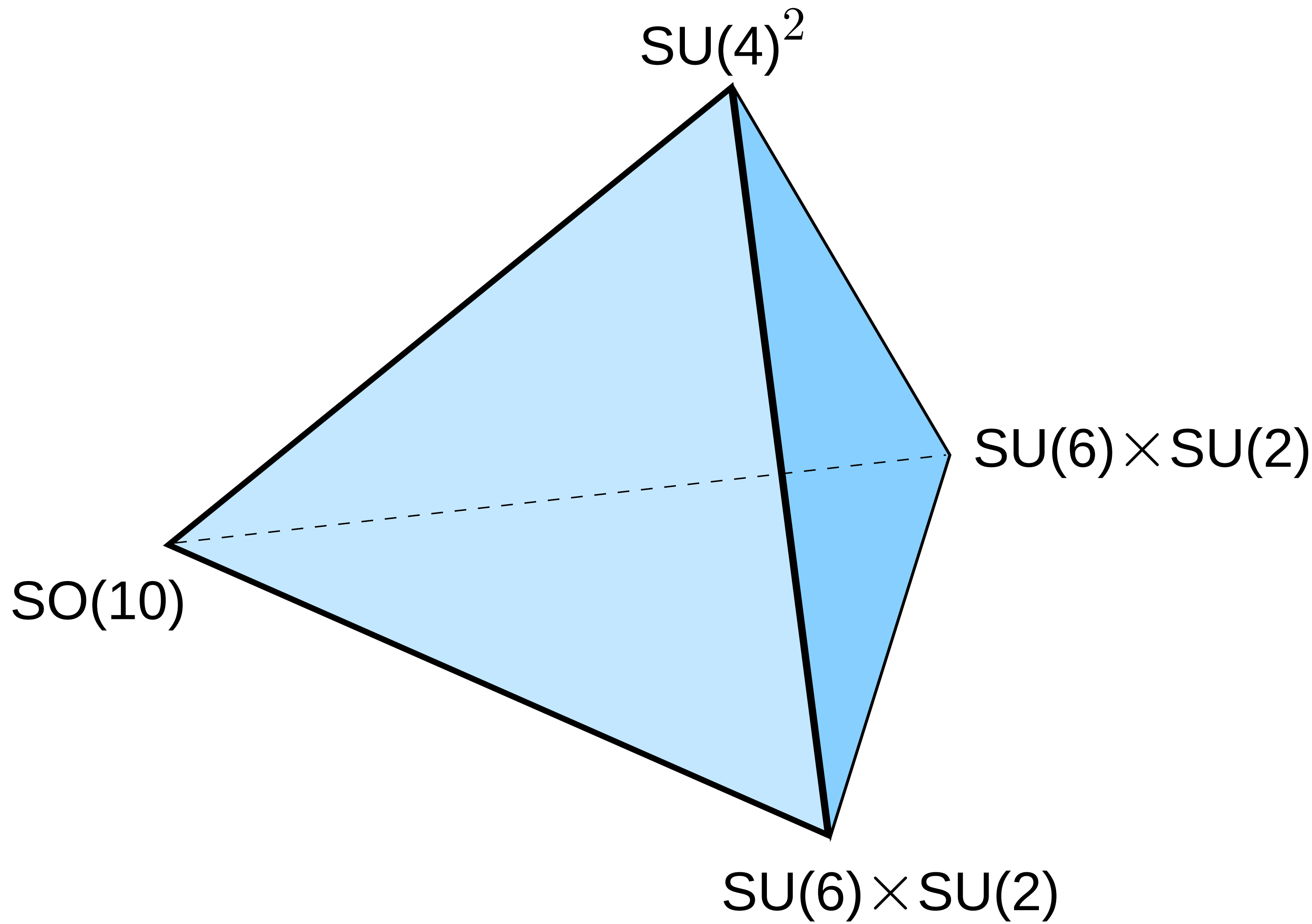
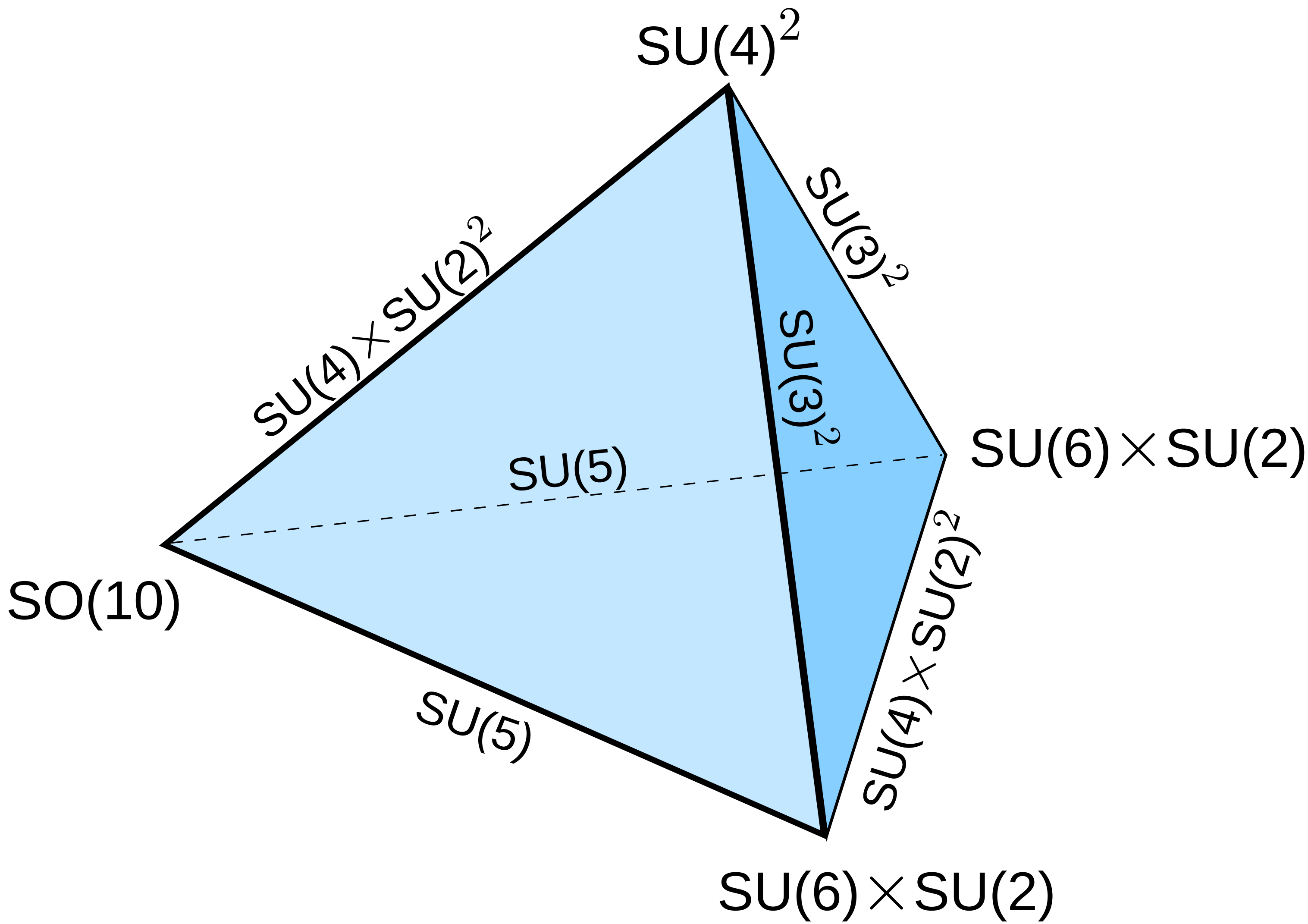
Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Standard Model Gauge Group



The MiniLandscape

- a few hundred models with the exact spectrum of the MSSM

  (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)

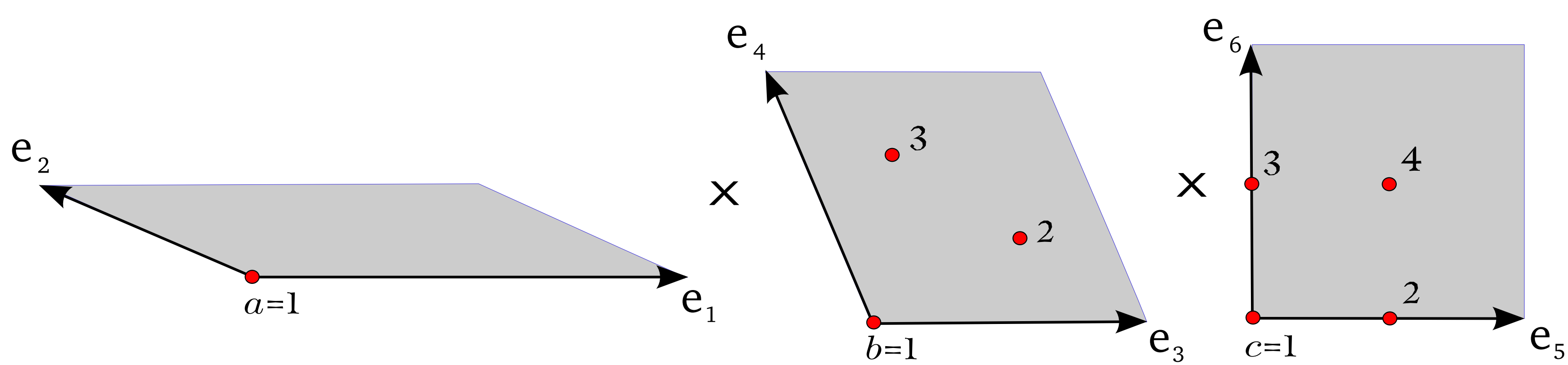
- gaugino condensation and mirage mediation

  (Löwen, HPN, 2008)

Sectors

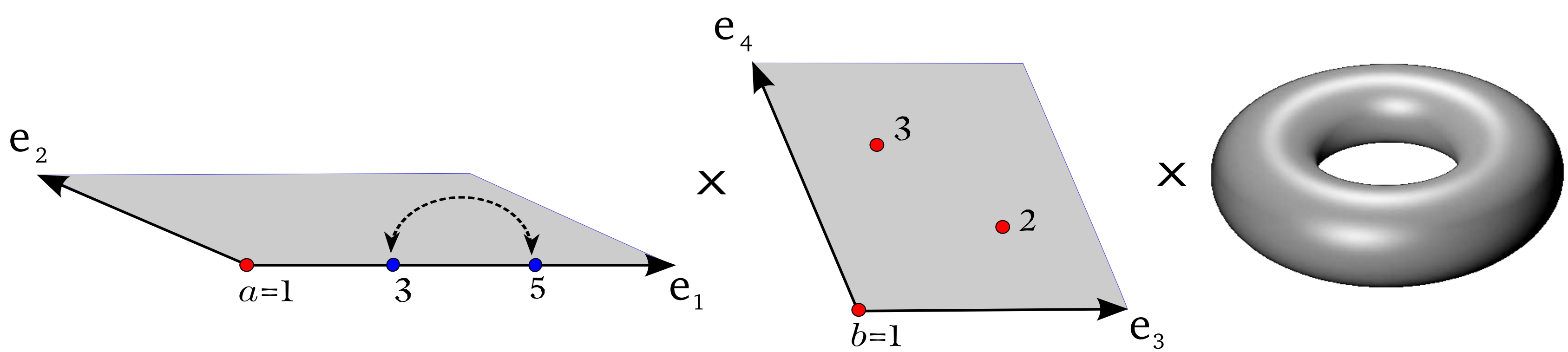
The underlying $Z_6 II$ orbifold has the following sectors:

- the untwisted sector (bulk $D = 10$)
- 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" that are confined to D=4 space-time.

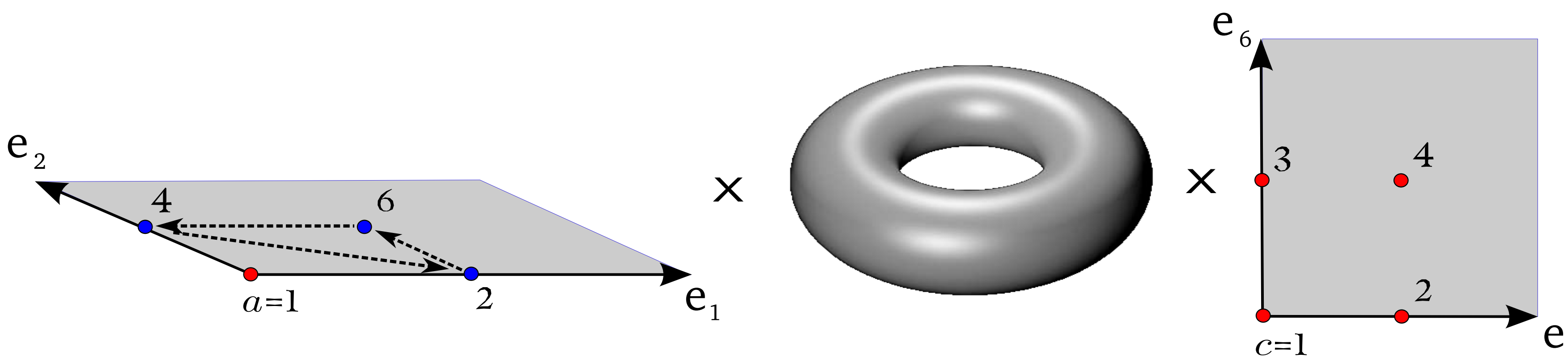
θ^2 twisted sector



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

- “5-branes” confined to 6 space-time dimensions

θ^3 twisted sector



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

- “5-branes” confined to 6 space-time dimensions

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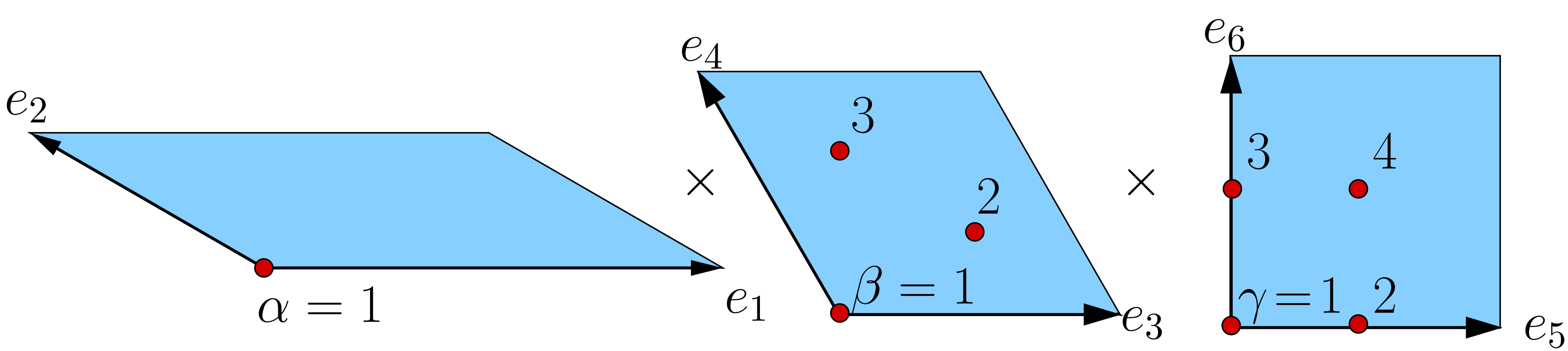
Top quark in untwisted sector. The third family is usually distributed over various sectors (it is not in a complete localized SO(10) representation).

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)

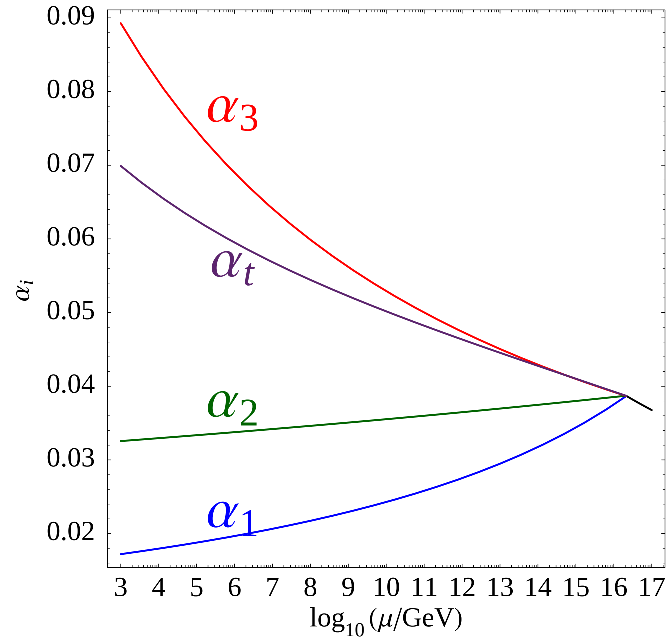


They live in the θ twisted sector and are localized at the fixed points $\alpha = 1$, $\beta = 1$ $\gamma = 1, 3$

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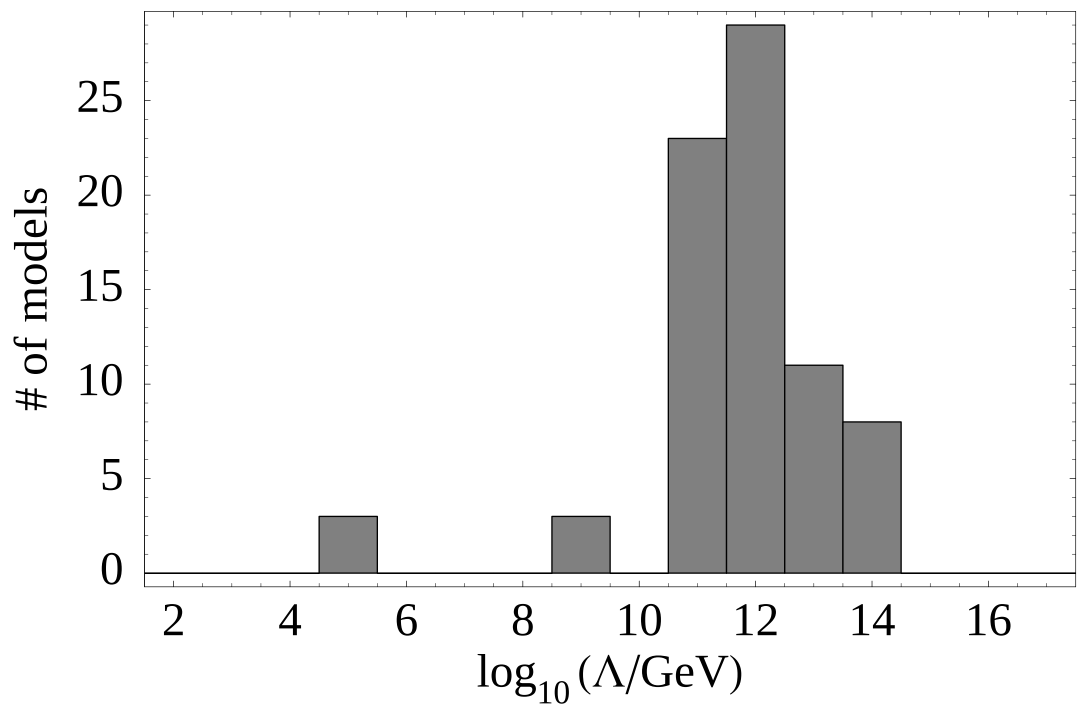
The fact that the top-quark has this unique property among all the quarks and leptons has important consequences for the phenomenological predictions including supersymmetry breakdown.

(Krippendorf, HPN, Ratz, Winkler, 2012)

Heterotic string: gaugino condensation



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

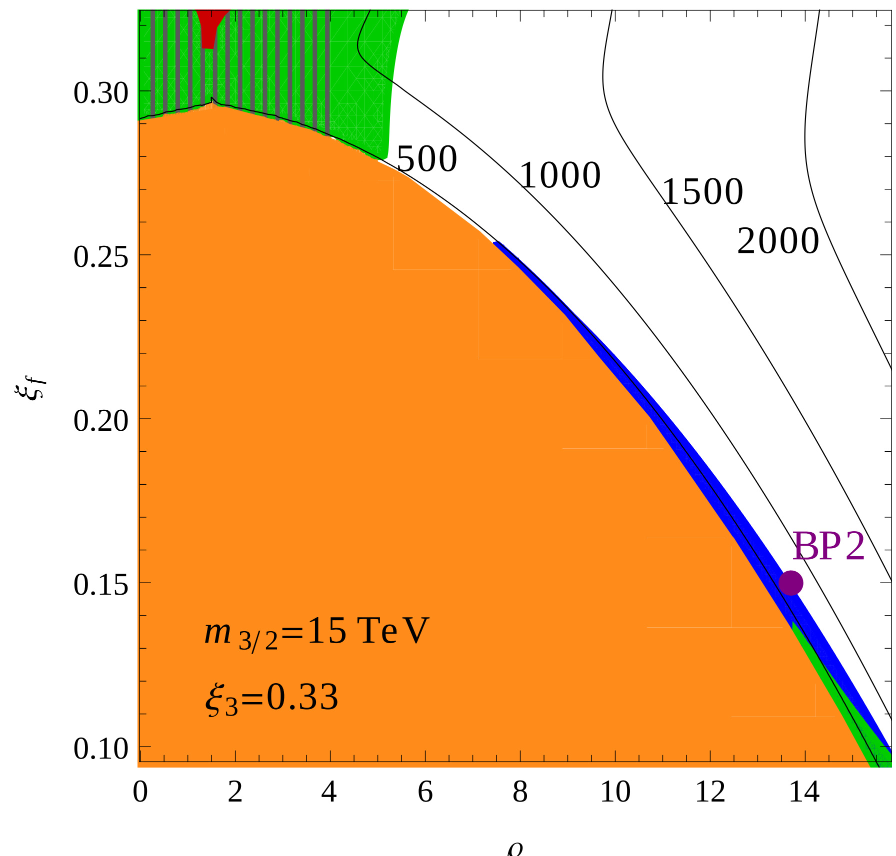
(Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2006)

Pattern of Natural SUSY

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

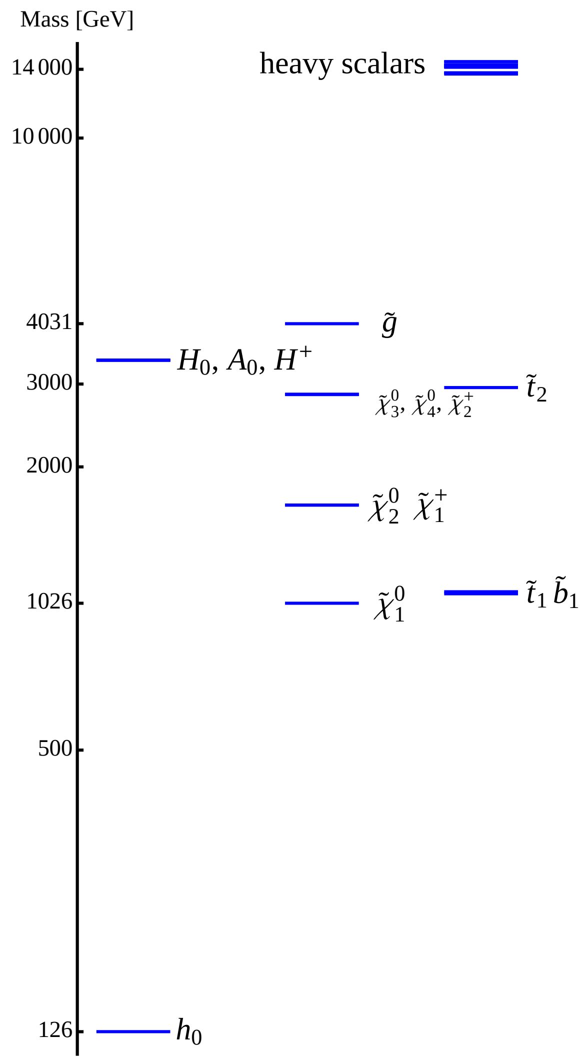
- normal squarks and sleptons in Multi-TeV range
- top squarks $(\tilde{t}_L, \tilde{b}_L)$ and $\tilde{t}_R$ in TeV-range (suppressed by $\log(M_{\rm Planck}/m_{3/2}) \sim 4\pi^2$)
- A-parameters in TeV range
- gaugino masses in TeV range
- mirage pattern for gaugino masses (compressed spectrum)
- heavy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

Model with 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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Reading the LHC Higss mass hints:
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?

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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 from higher dimensions lead to "Remote Supersymmetry" at the axion scale.

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

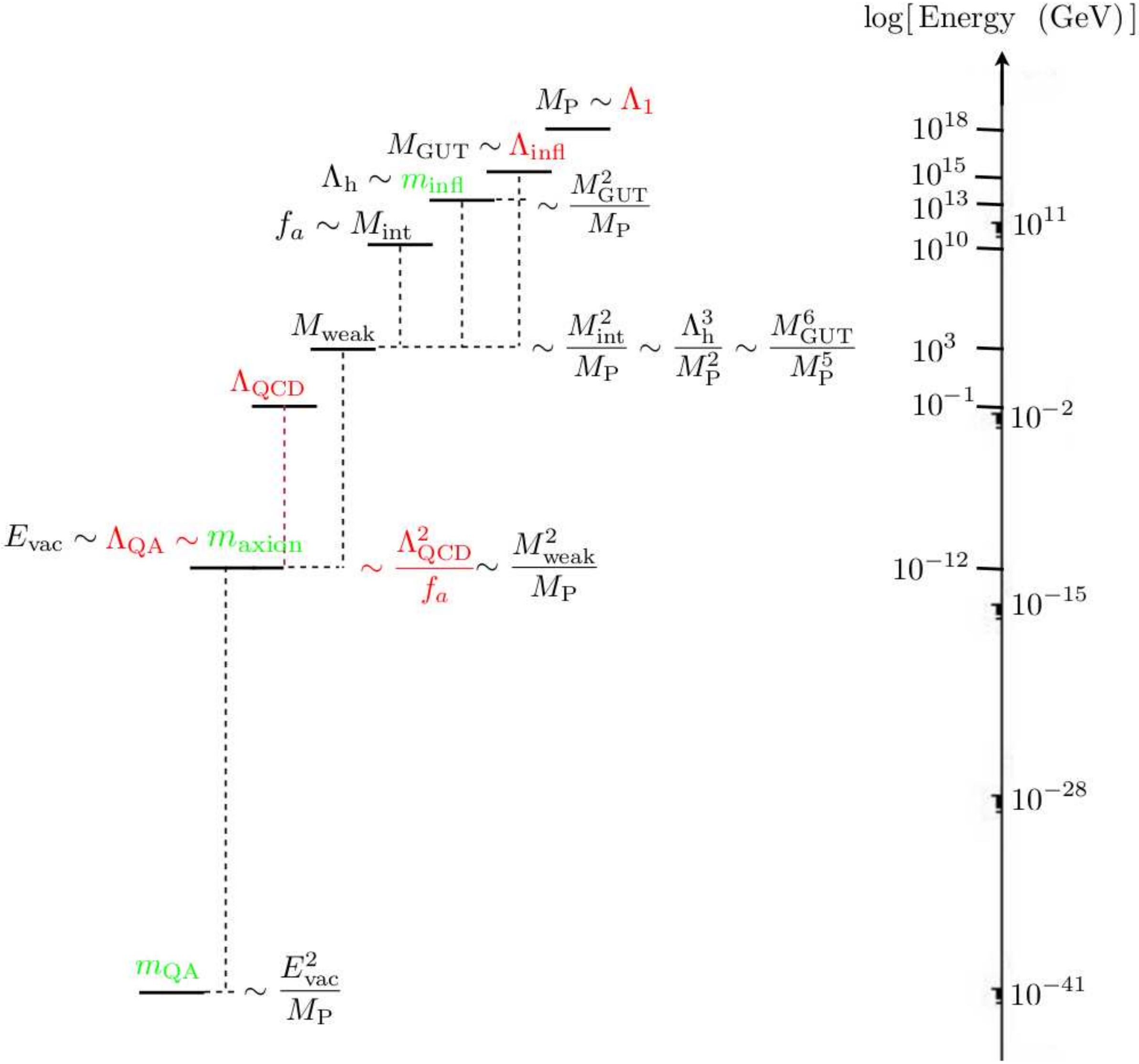
- μ at the weak scale (tree level μ small compared to f_a)

(Kim, Nilles, 1984)

- axionic see-saw (including $E_{vacuum} \sim M^2_{\rm weak}/M_{\rm Planck}$) that unifies the “useful” axions in one scheme

(Kim, Nilles, 2002)

Axionic See-Saw



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Conclusions

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 “torus compactification”)

- mirage mediation
- mass spectrum of “Natural Susy”

Conclusions

Overall scale of Susy breakdown still not determined

- there are hints from $m_{\mathrm{Higgs}} \sim 125$ GeV
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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 as remnant of N=4 Susy (a result of the “delocalized Higgs” in the untwisted sector).