The Geography of the (heterotic) MSSM-Landscape

Hans Peter Nilles

Physikalisches Institut

Universität Bonn

String Theory shows us where to go

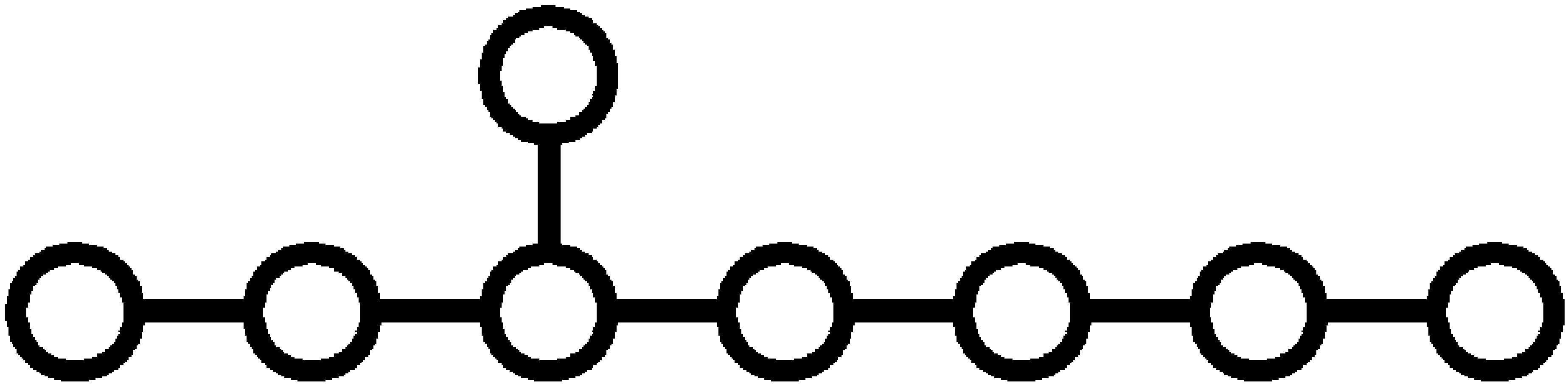
Strings and the (MS)SM

- 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

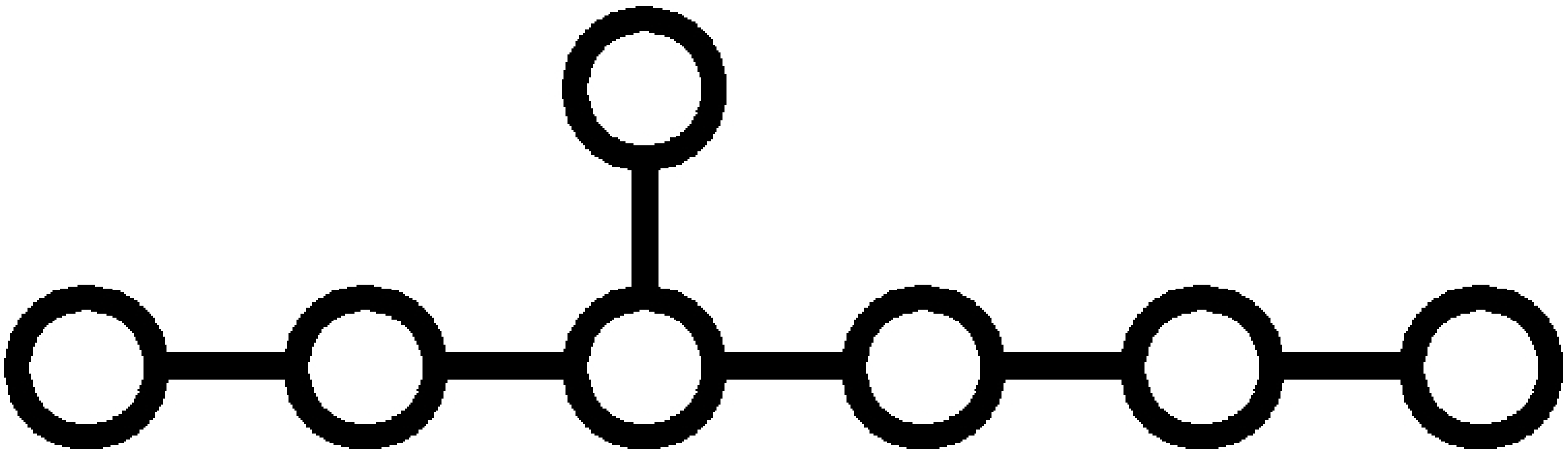
Maximal Group E_8



E_8 is the maximal group.

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

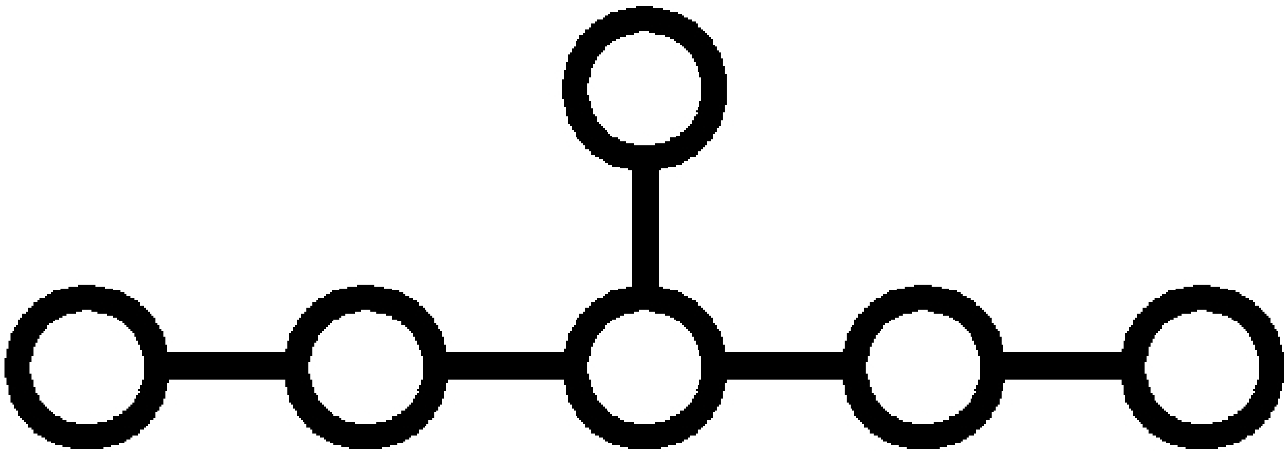
E_7



Next smaller is E_7.

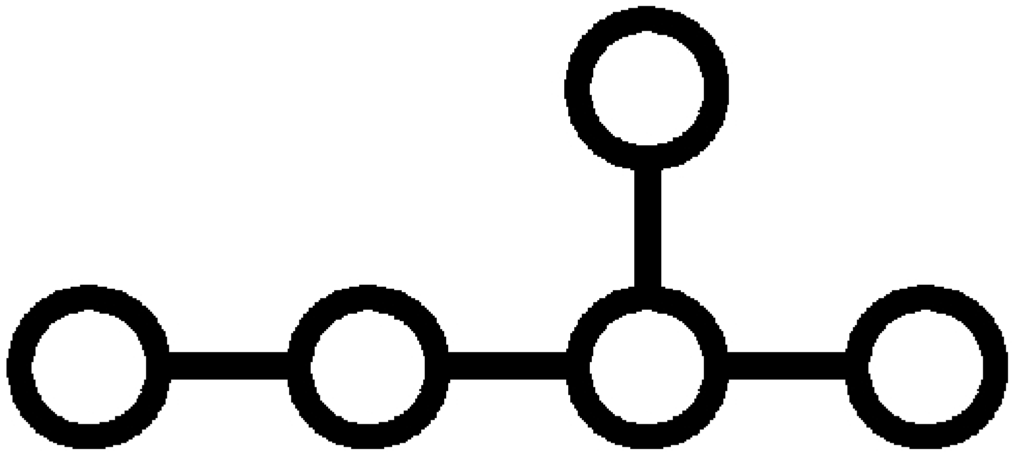
No chiral representations in $d = 4$ either.

E_6



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

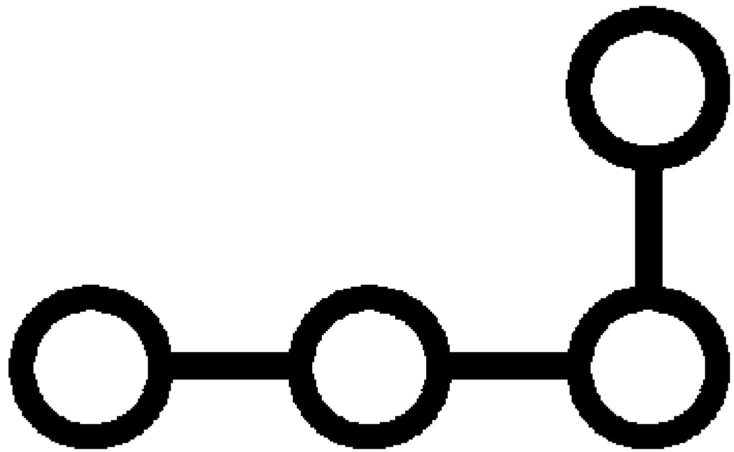
$E_5 = D_5$



E_5 is usually not called exceptional.

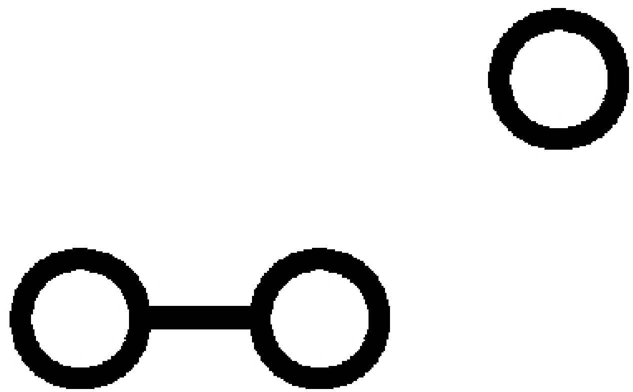
It coincides with $D_5 = SO(10)$.

$E_4 = A_4$



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

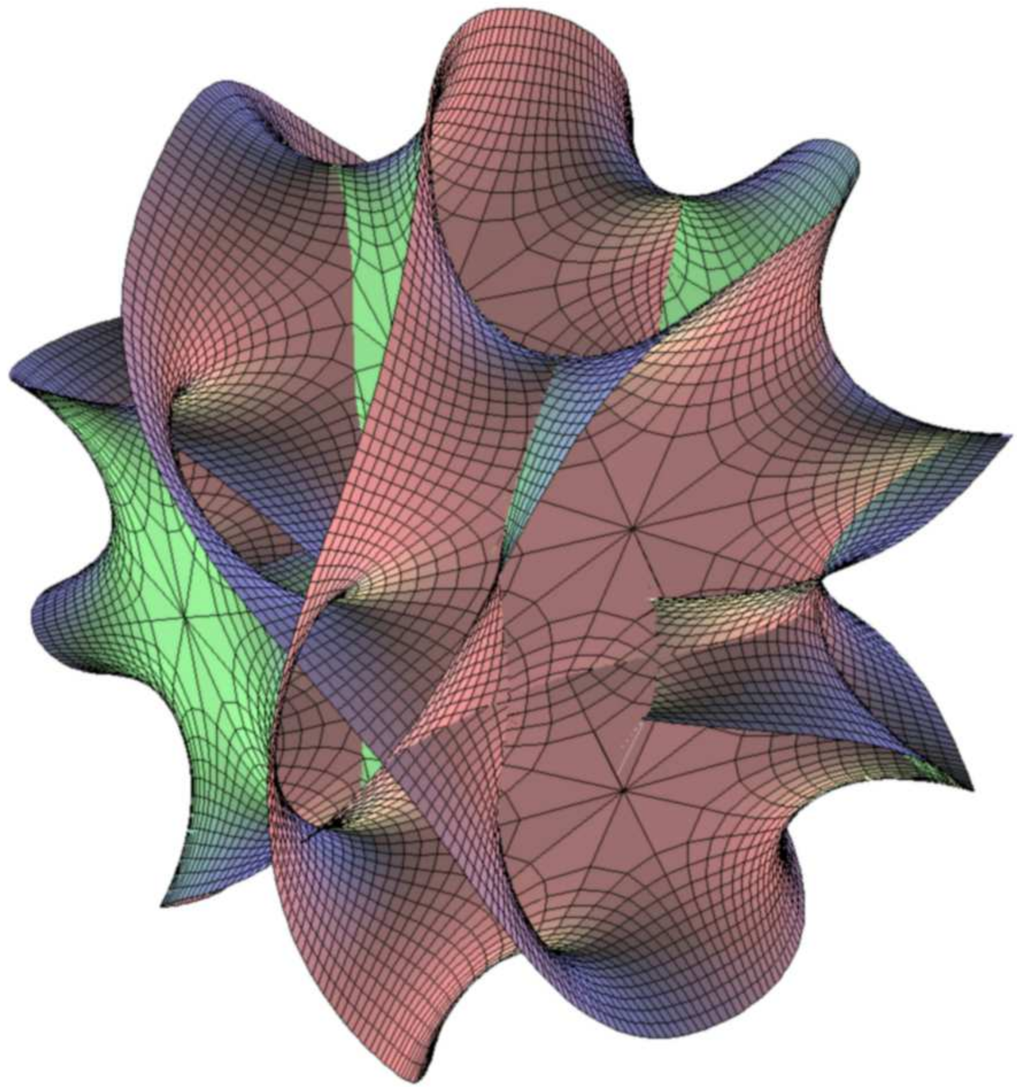
String theory "favours" E_8

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

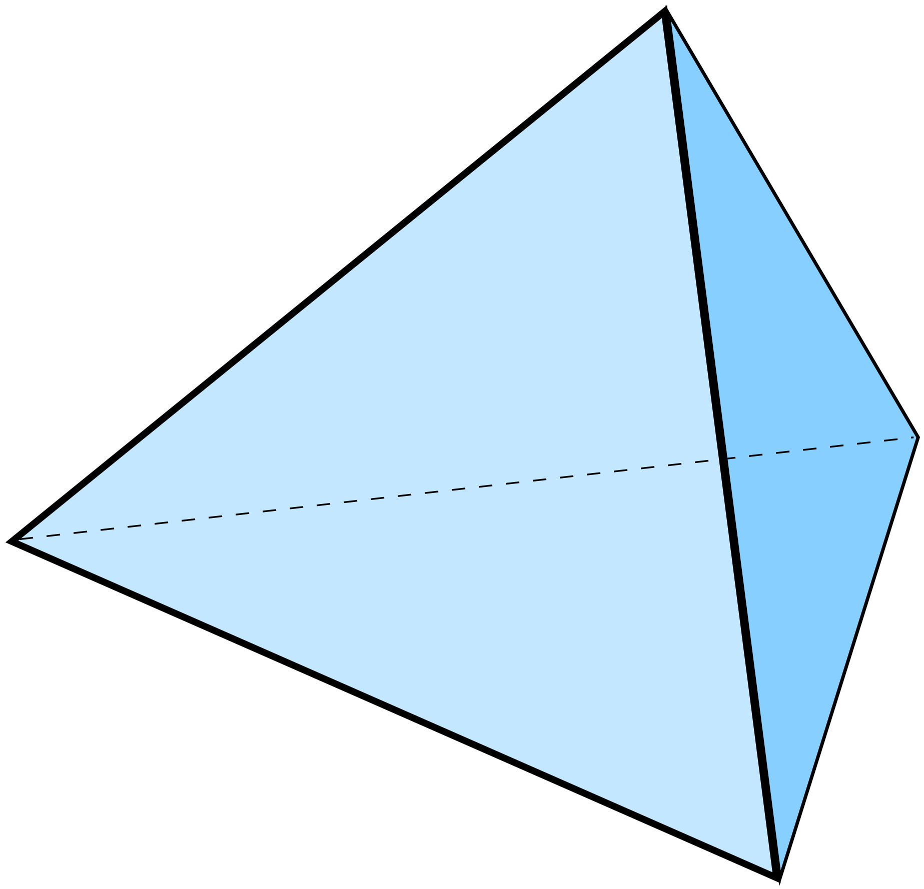
Strings live in higher dimensions:

- 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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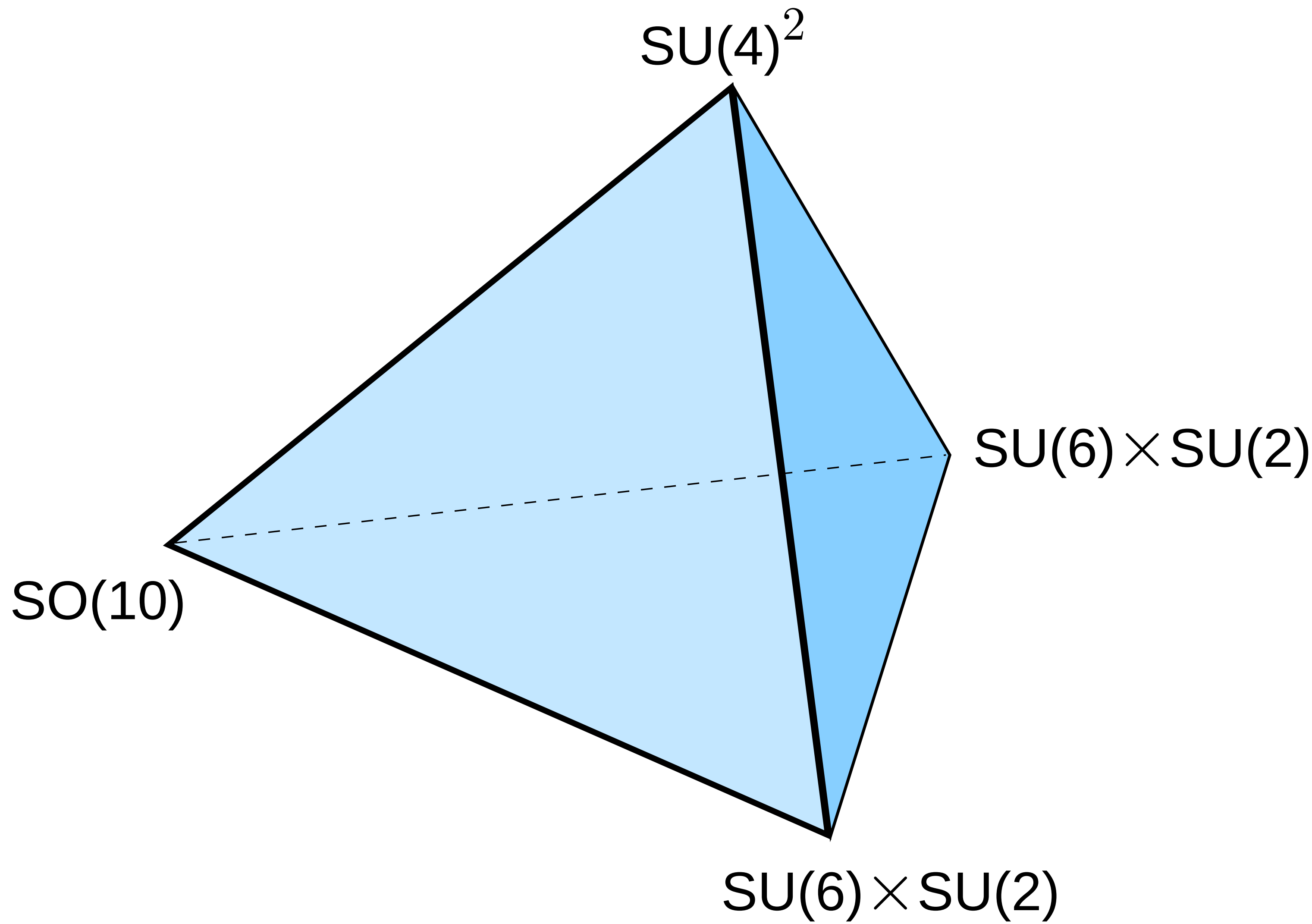
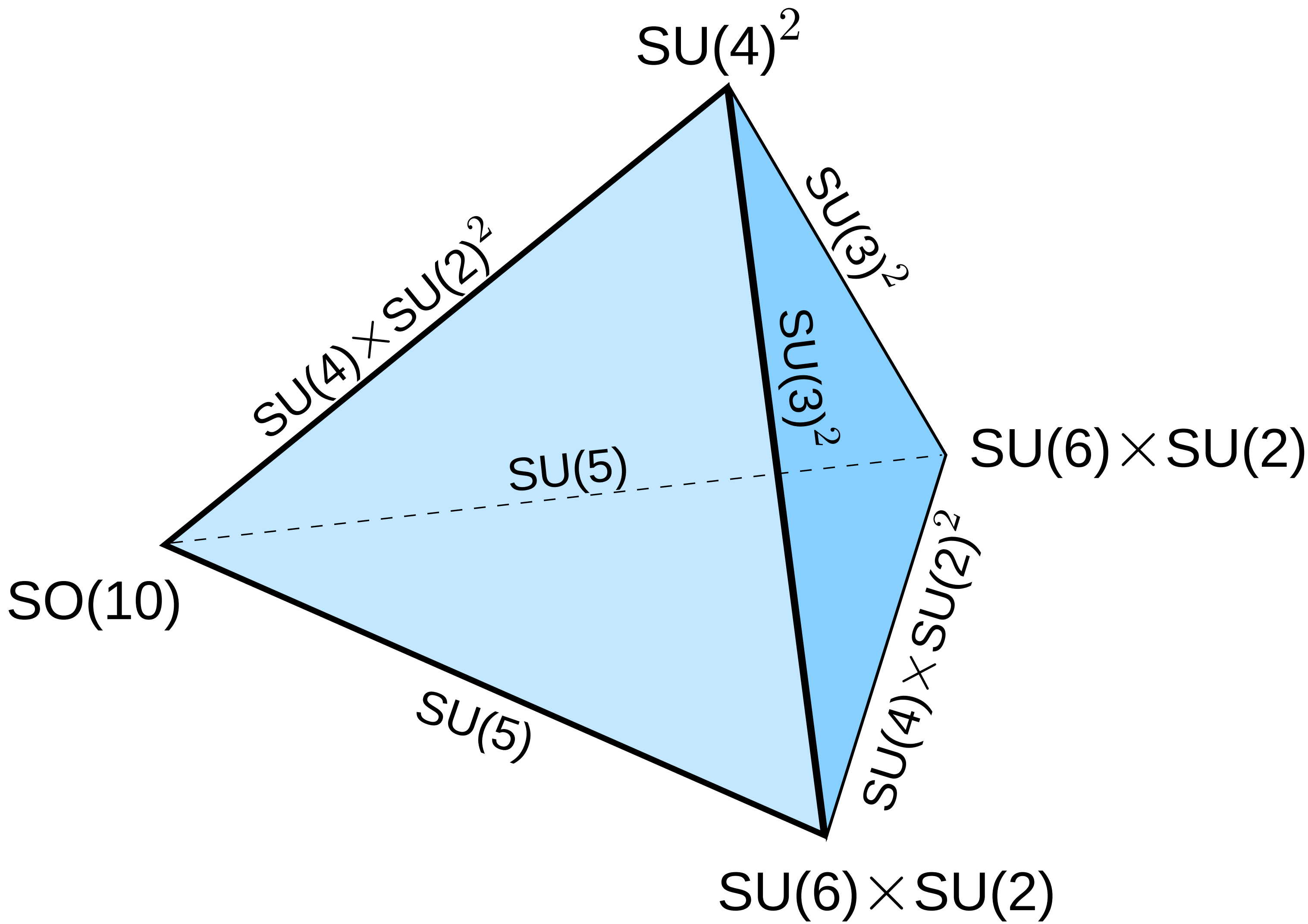
Localized gauge symmetries



(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)

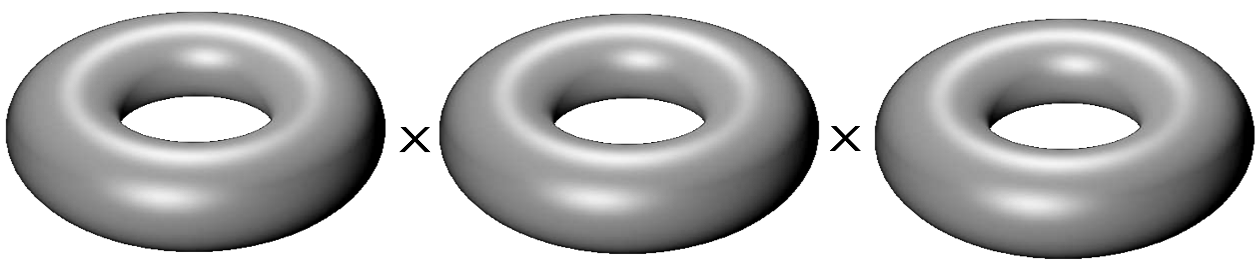
What do we learn from these explicit constructions?

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:

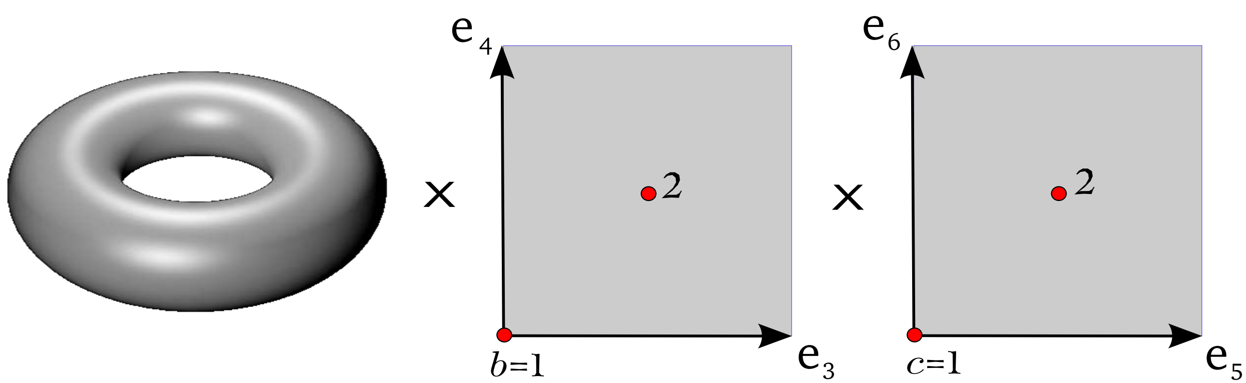
- the untwisted sector



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

Twisted sectors

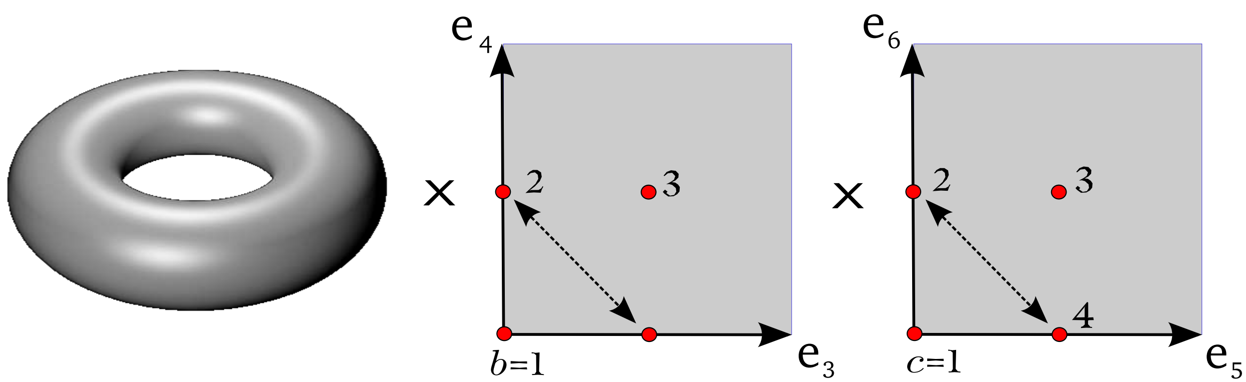
Twisted sectors correspond to the $Z_2(\theta)$ and $Z_4(\omega)$ twists



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

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

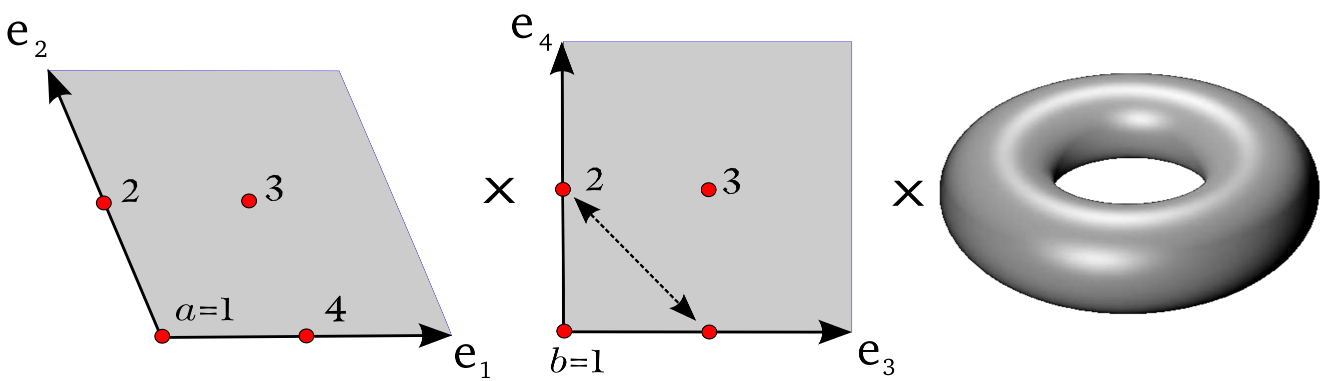
ω^2 twisted sector



The ω^2 twisted sector contains fixed tori correponding to

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

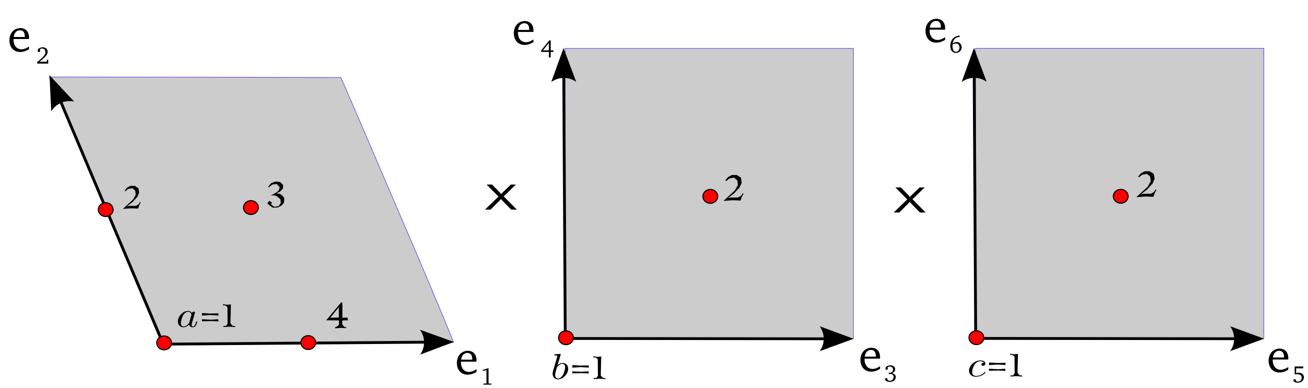
θ twisted sector



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).

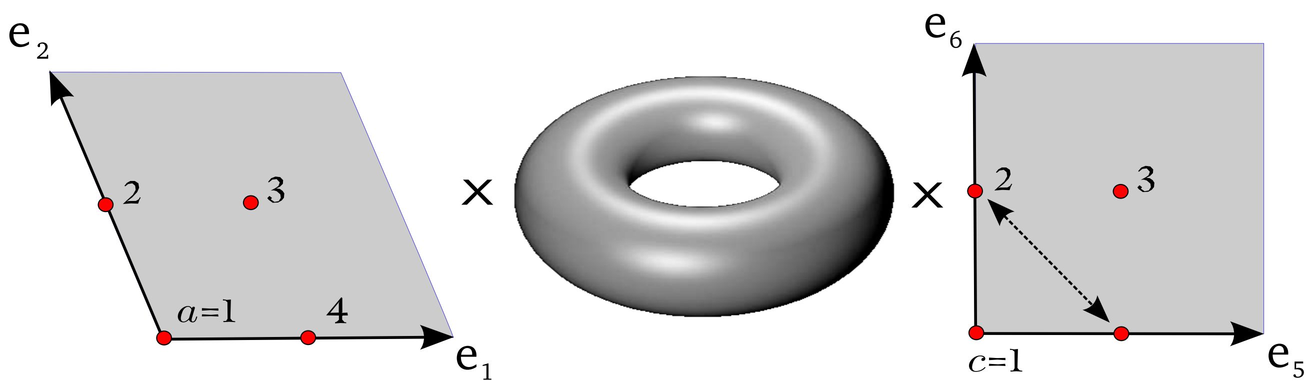
$\theta\omega$ twisted sector



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

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

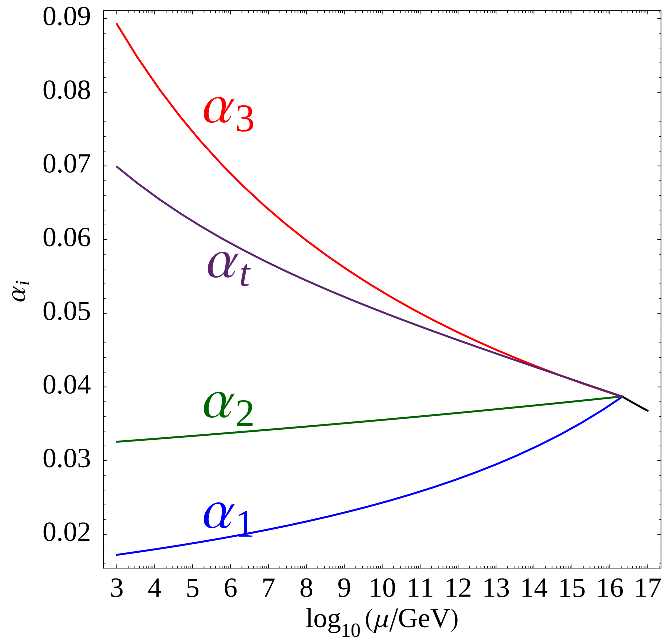
- for discussion of neutrinos and R-parity we keep also the $U(1)_{B-L}$ charges

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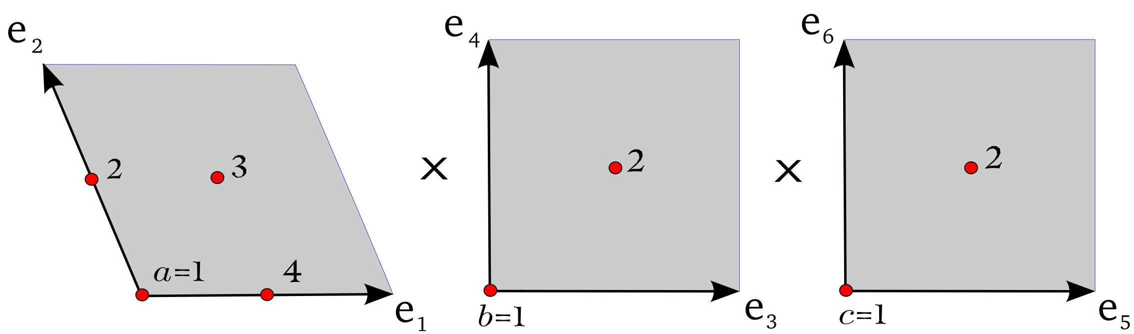
The top quark is a bulk field as well:

- 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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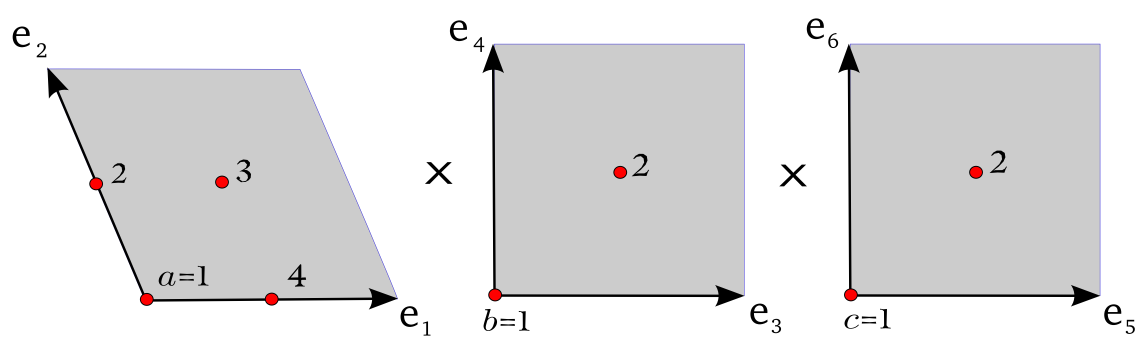
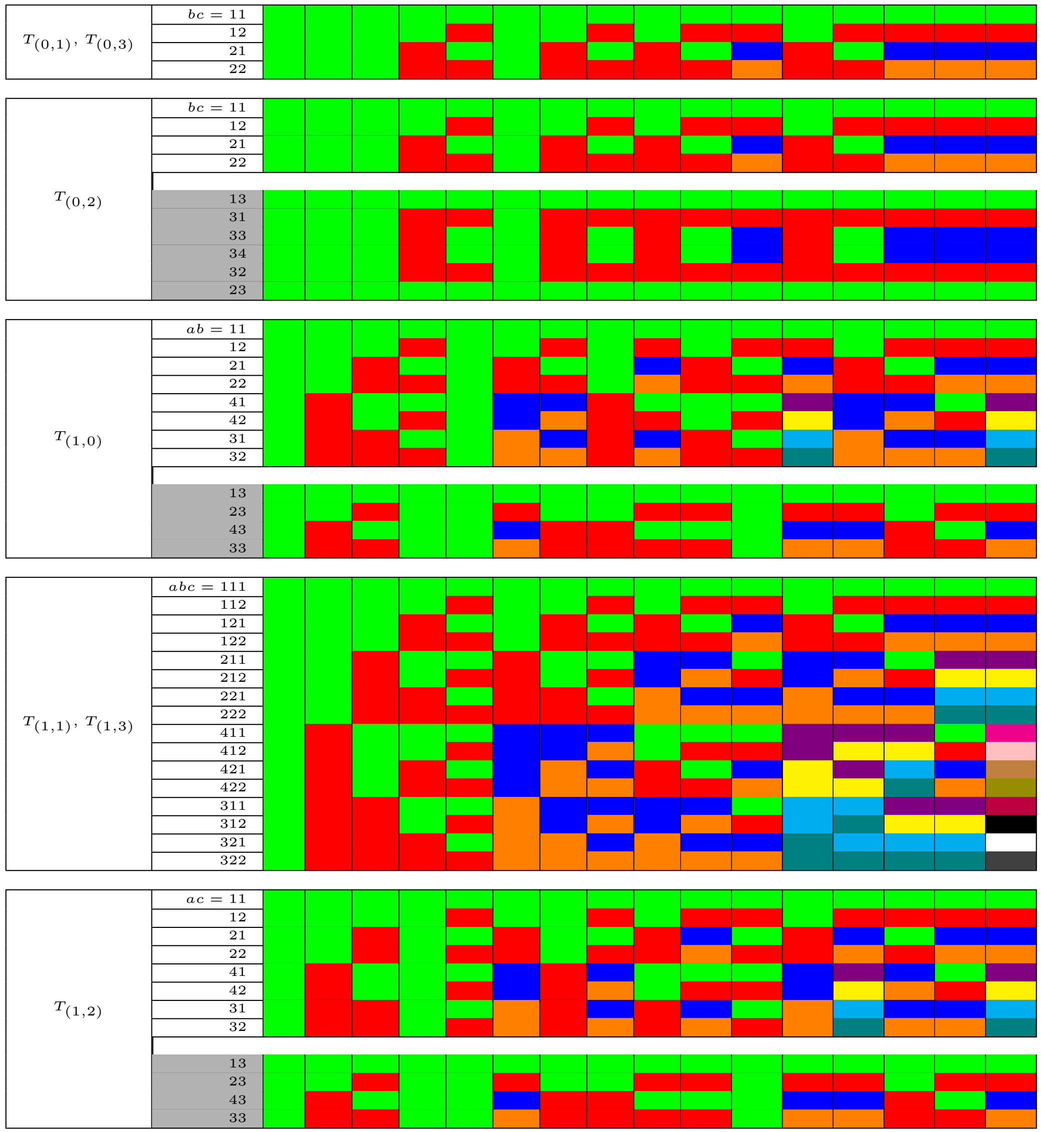


- they exhibit a D_4 family symmetry (absence of FCNC)
- no trilinear Yukawa couplings
  (suppressed masses compared to top quark)
- mass pattern is generated via a Frogatt-Nielsen mechanism (dictated by the pattern of Wilson lines)

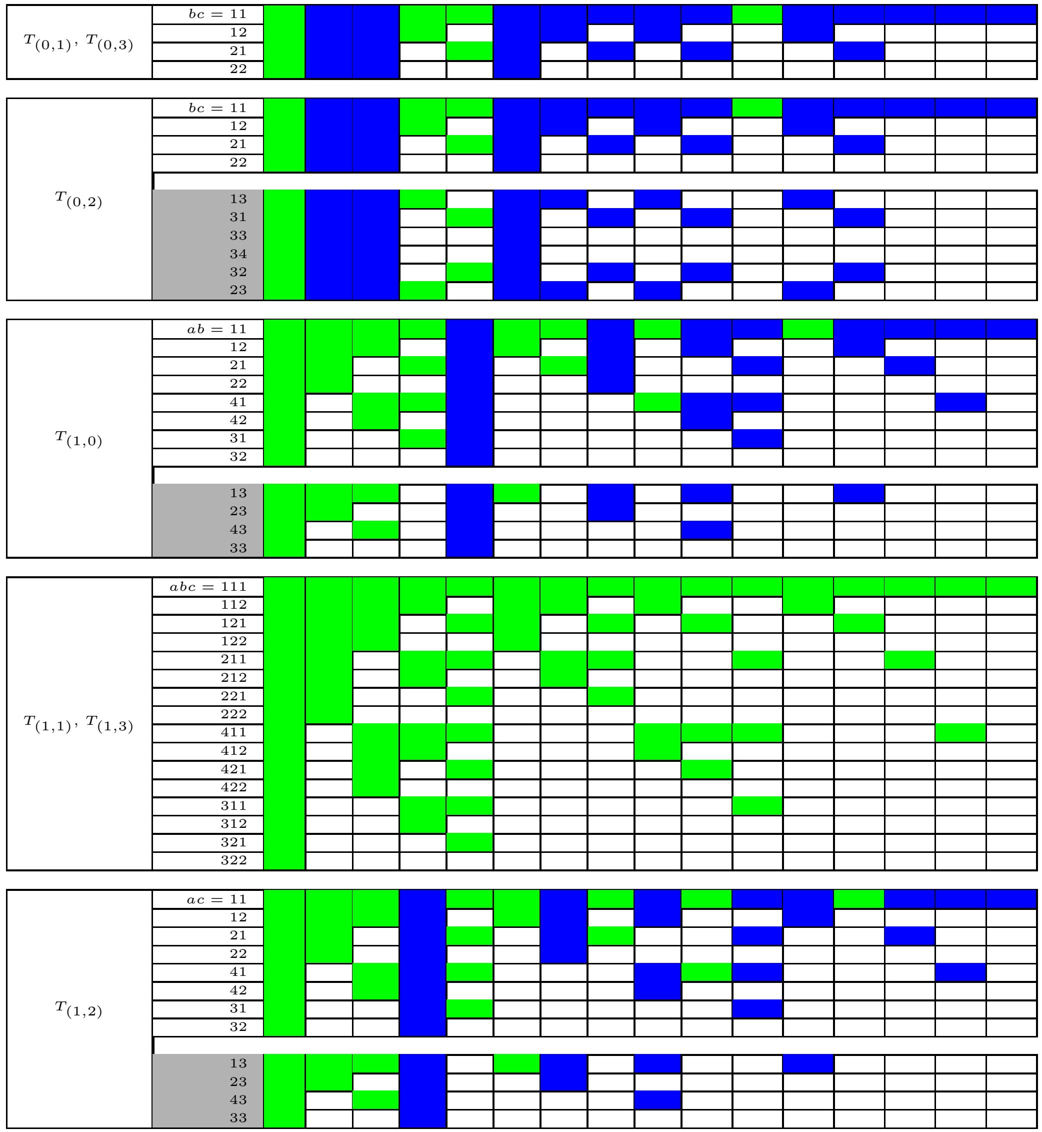
Wilson lines

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					✓			✓		✓	✓		✓	✓	✓	✓

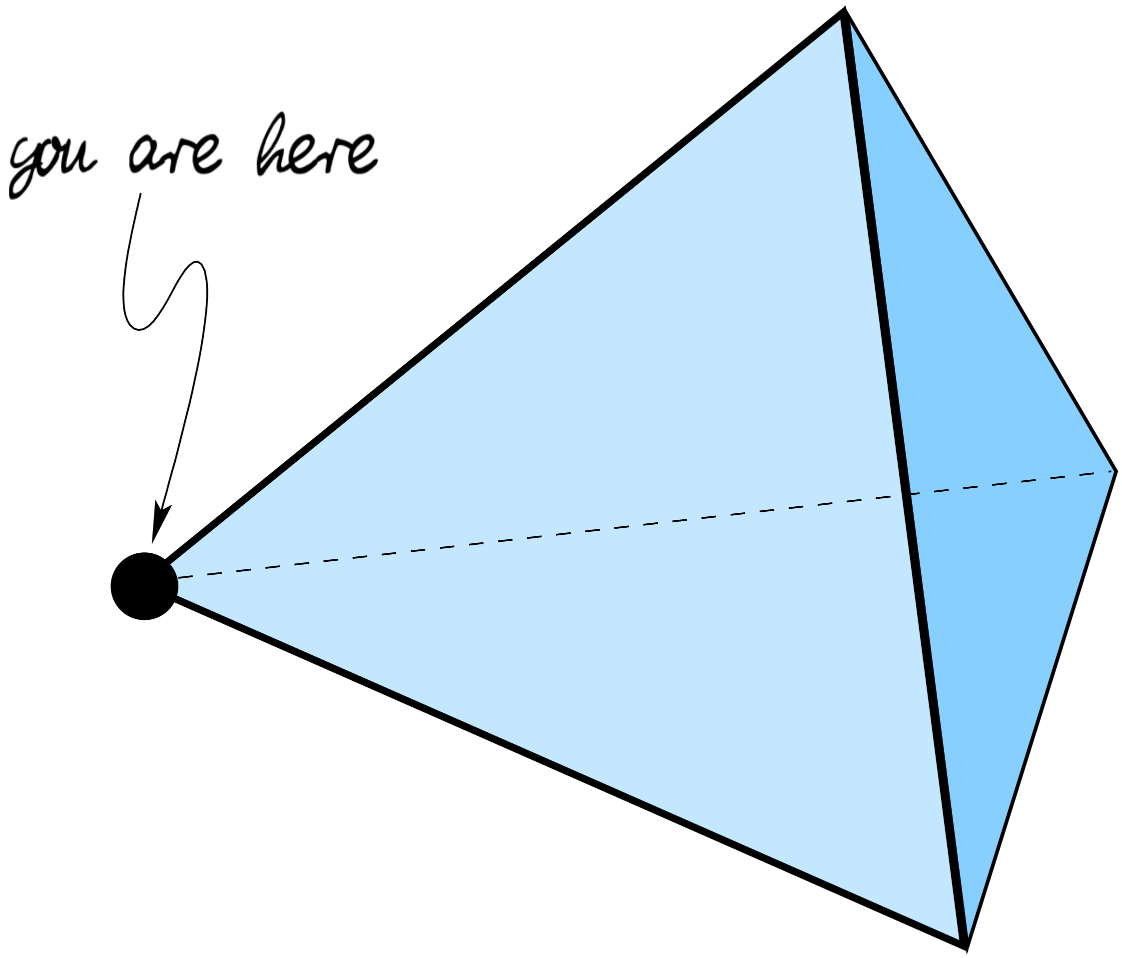


Wilson lines

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”:

- scalar masses of order of the gravitino mass $m_{3/2}$
- gaugino masses and A-parameters suppressed by $\log(M_{\rm Planck}/m_{3/2}) \sim 4\pi^2$
- 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: $N = 2$
- fixed points $N = 1$

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

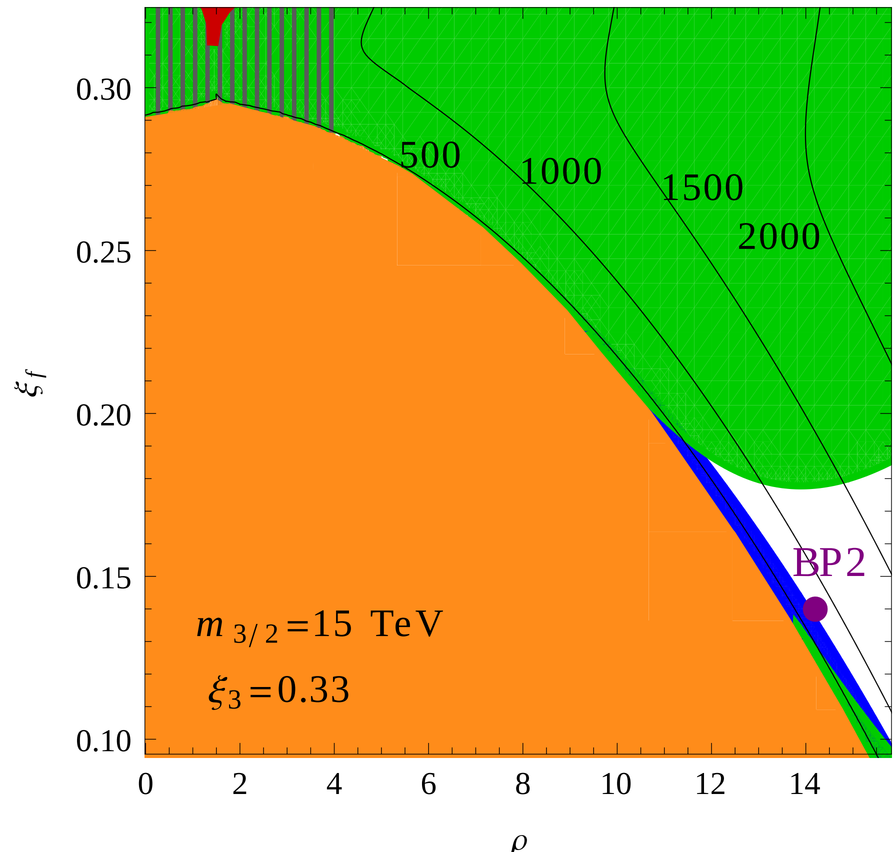
- normal squarks and sleptons in multi-TeV range
- top squarks $(\tilde{t}_L, \tilde{b}_L)$ and $\tilde{t}_R$ in TeV-range (suppressed by $\log(M_{\text{Planck}}/m_{3/2}) \sim 4\pi^2$)
- A-parameters in TeV range
- gaugino masses in TeV range
- mirage pattern for gaugino masses (compressed spectrum)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

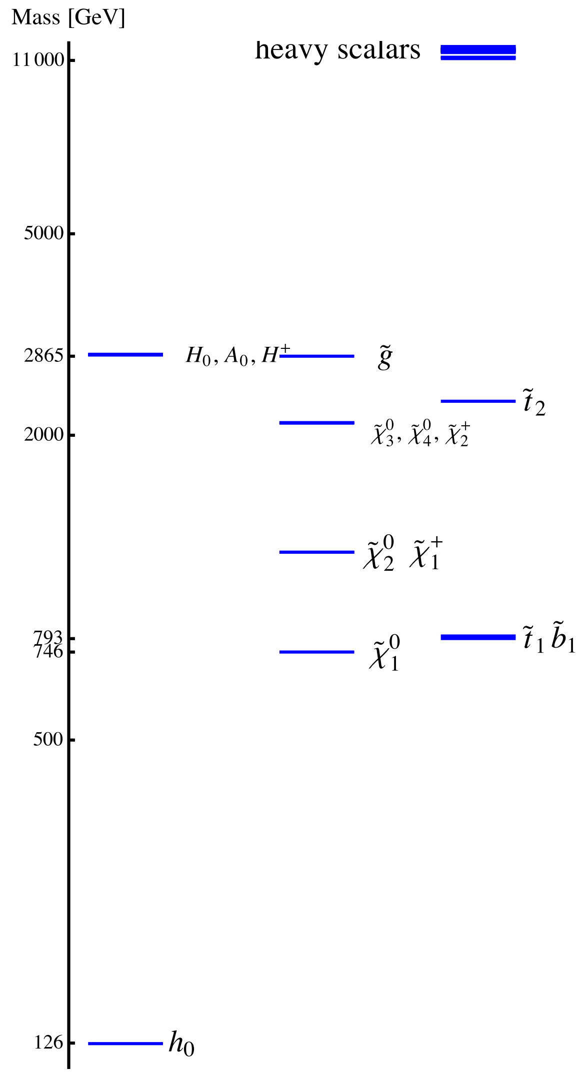
- Higgs fields live in untwisted sector (not localized)
  (this allows a solution of the μ-problem with an R-symmetry and provides gauge-Higgs unification)
- top quark lives in untwisted sector as well
  (trilinear Yukawa coupling and gauge top unification)
- the two light families live on fixed points
  (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 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: $m_{3/2} \log(M_{\text{Planck}}/m_{3/2})$
- 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.