Strings and Unification

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bctp Bethe Center for Theoretical Physics

Questions

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Recent progress:

- explicit model building towards the MSSM
  - Heterotic brane world
  - local grand unification
- moduli stabilization and Susy breakdown
  - gaugino condensation and uplifting
  - mirage mediation

The road to the Standard Model

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But there might be more:

- supersymmetry (SM extended to MSSM)
- neutrino masses and mixings

as a hint for a large mass scale around 10^{16} GeV

Indirect evidence

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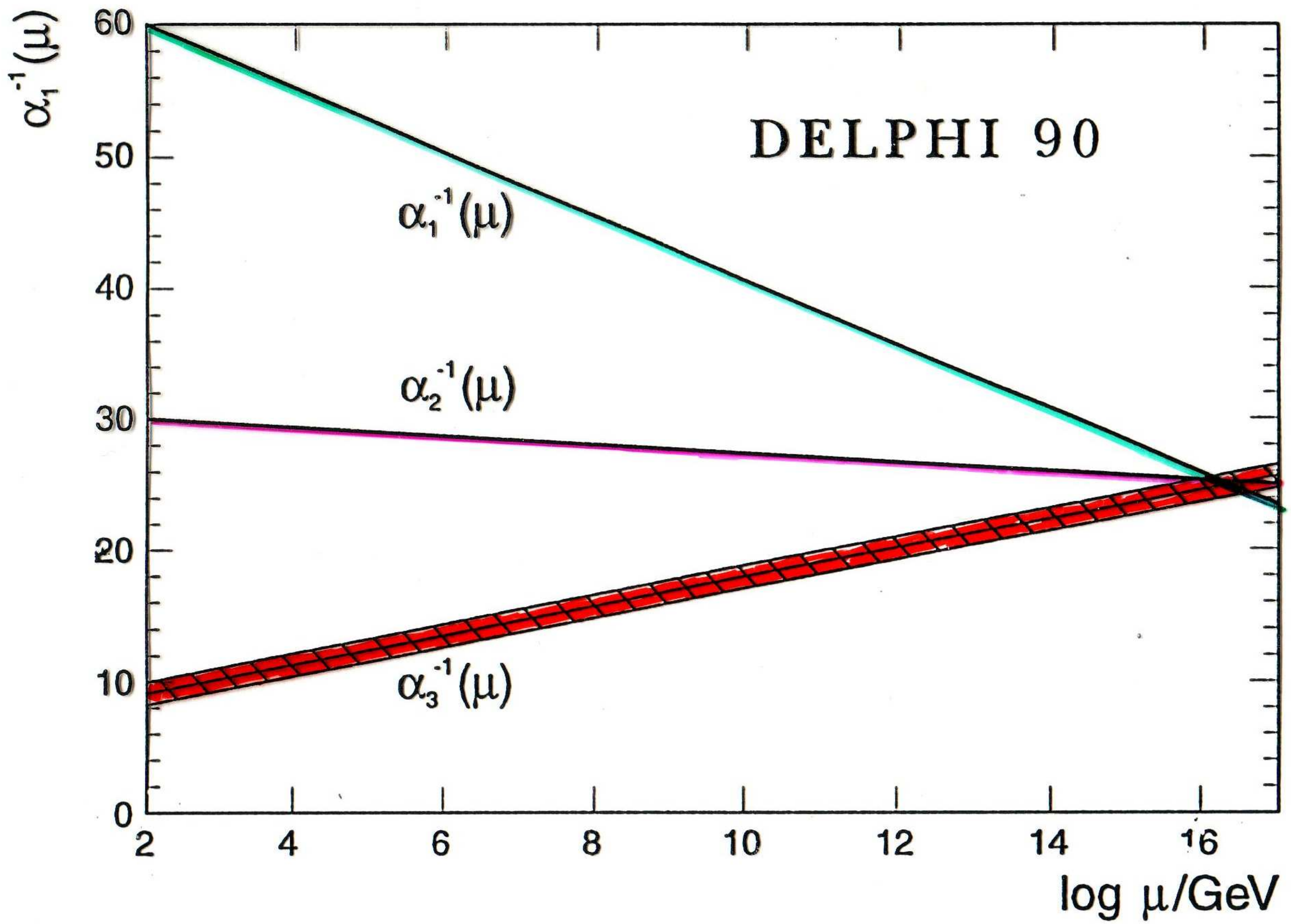
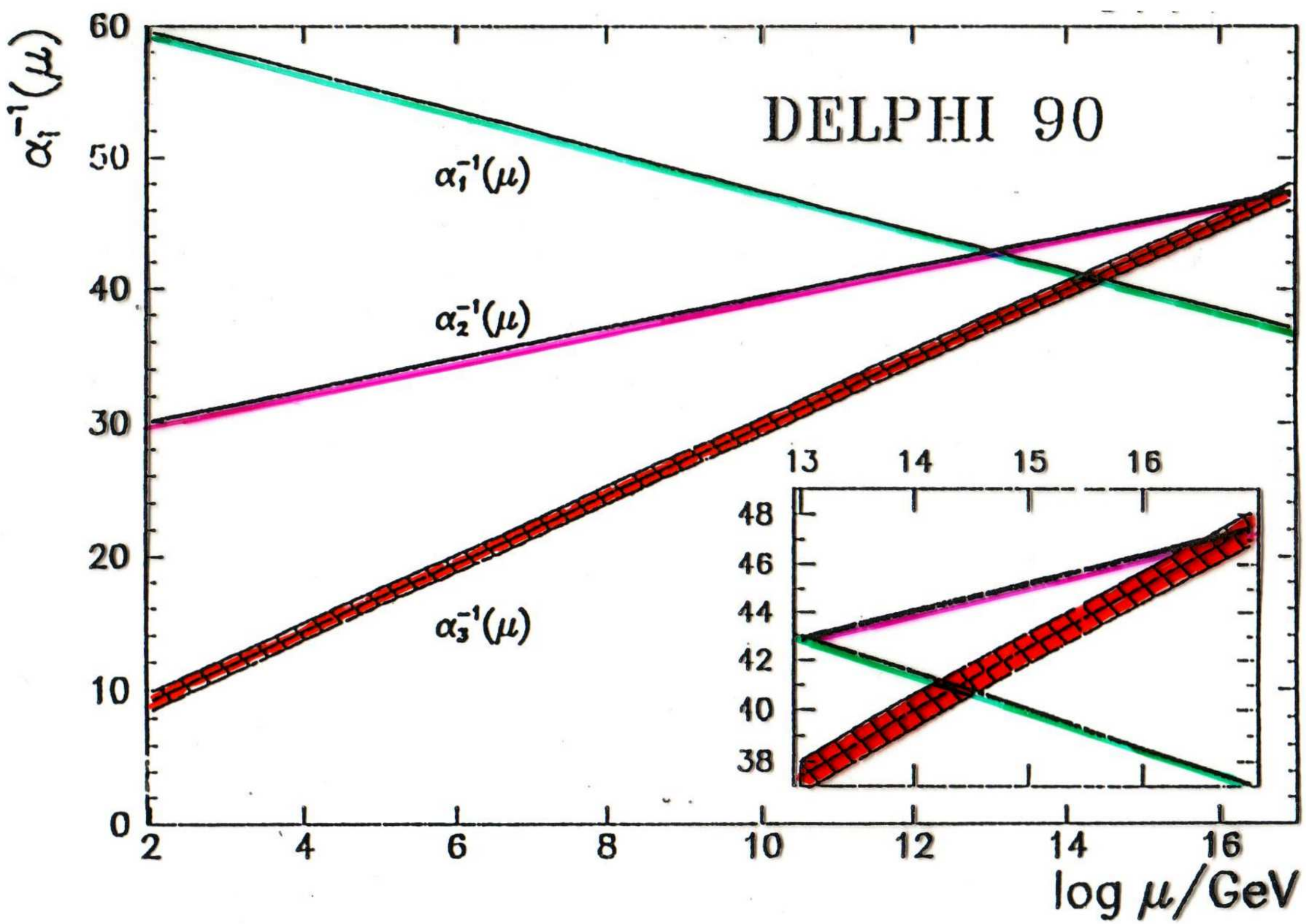
- Evolution of couplings constants of the standard model towards higher energies.

MSSM (supersymmetric)



Standard Model



Grand Unification

This leads to SUSY-GUTs with nice things like

- unified multiplets (e.g. spinors of SO(10))
- gauge coupling unification
- Yukawa unification
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But there remain a few difficulties:

- breakdown of GUT group (large representations)
- doublet-triplet splitting problem (incomplete multiplets)
- proton stability (need for R-parity)

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has changed our view of the world,
but there are also some problematic aspects of the grand unified picture.

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Can we avoid these problems in a more complete theory?

String theory candidates

In ten space-time dimensions.....

- Type I SO(32)
- Type II orientifolds (F-theory)
- Heterotic SO(32)
- Heterotic $E_8 \times E_8$
- Intersecting Branes $U(N)^M$

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- extra spatial dimensions
- large unified gauge groups
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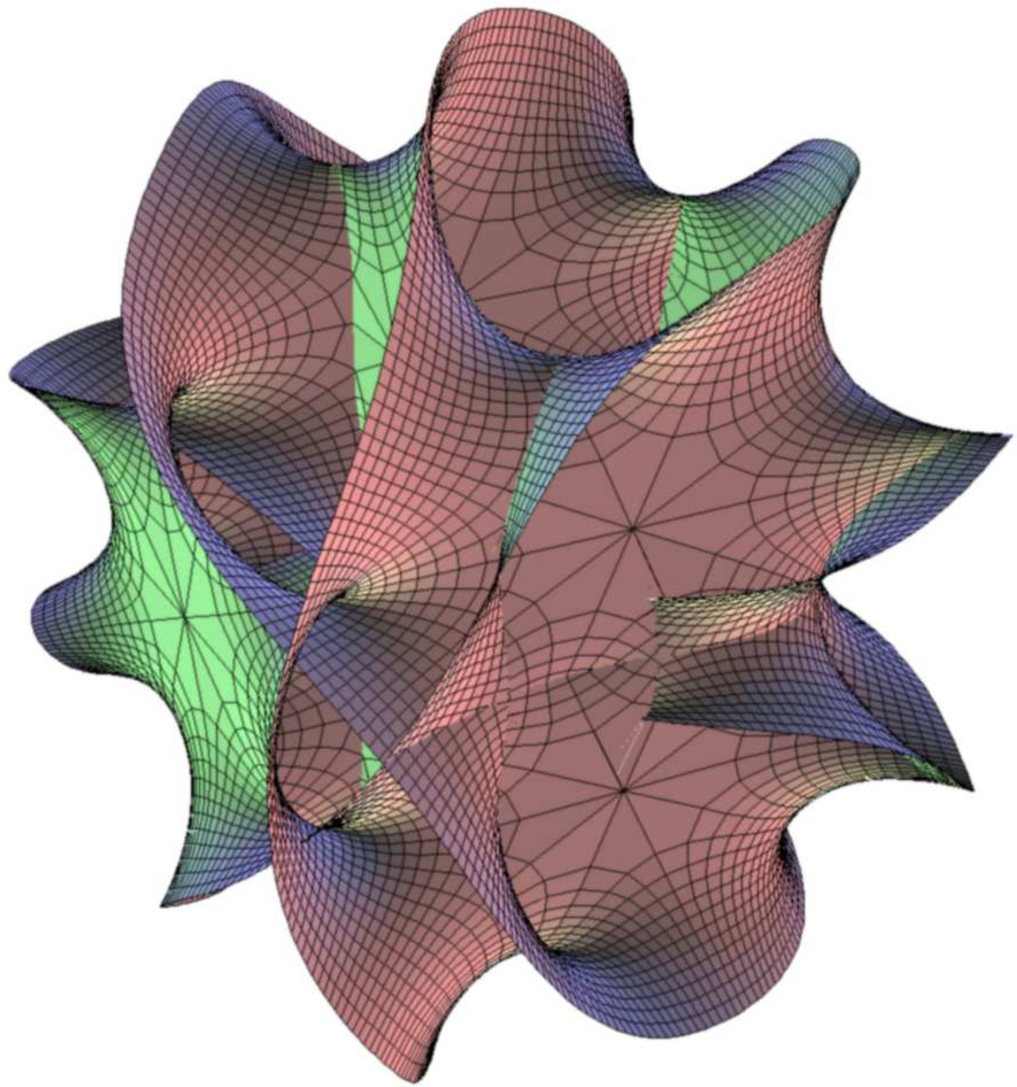
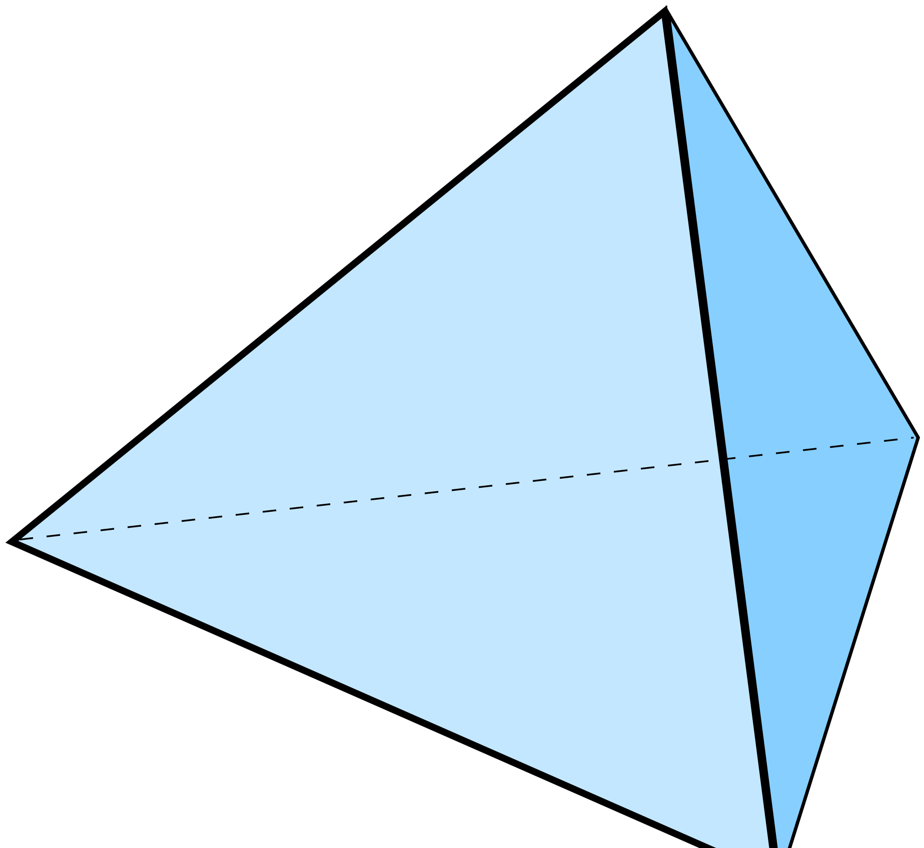
These are the building blocks for a unified theory of all the fundamental interactions.
But do they fit together, and if yes how?

We need to understand the mechanism of compactification of the extra spatial dimensions

Calabi Yau Manifold



Orbifold



Orbifolds

Orbifold compactifications combine the

- success of Calabi-Yau compactification
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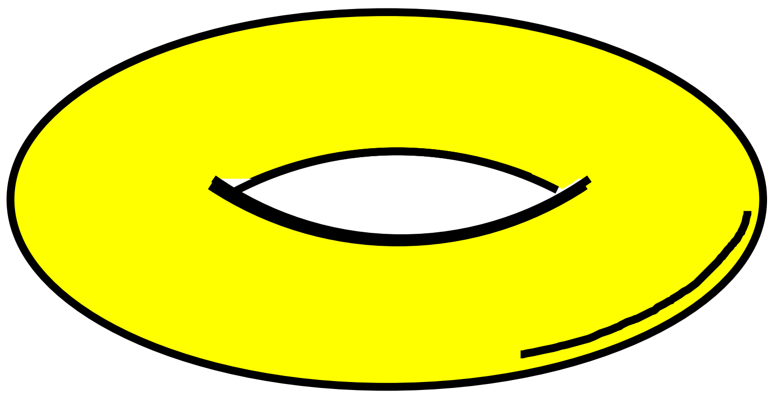
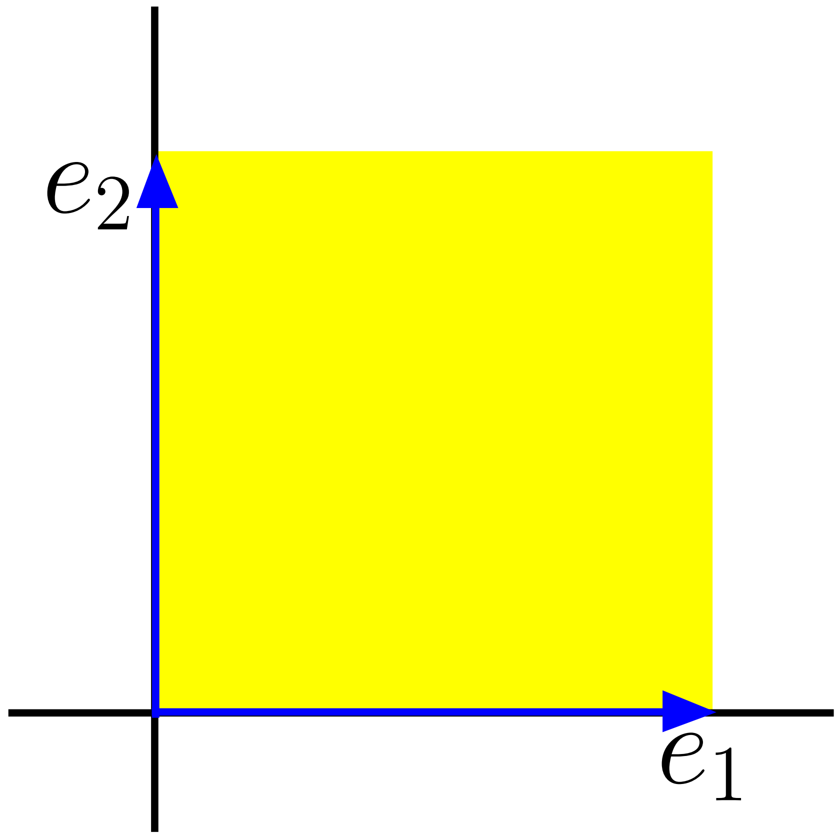
In case of the heterotic string fields can propagate

- 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)

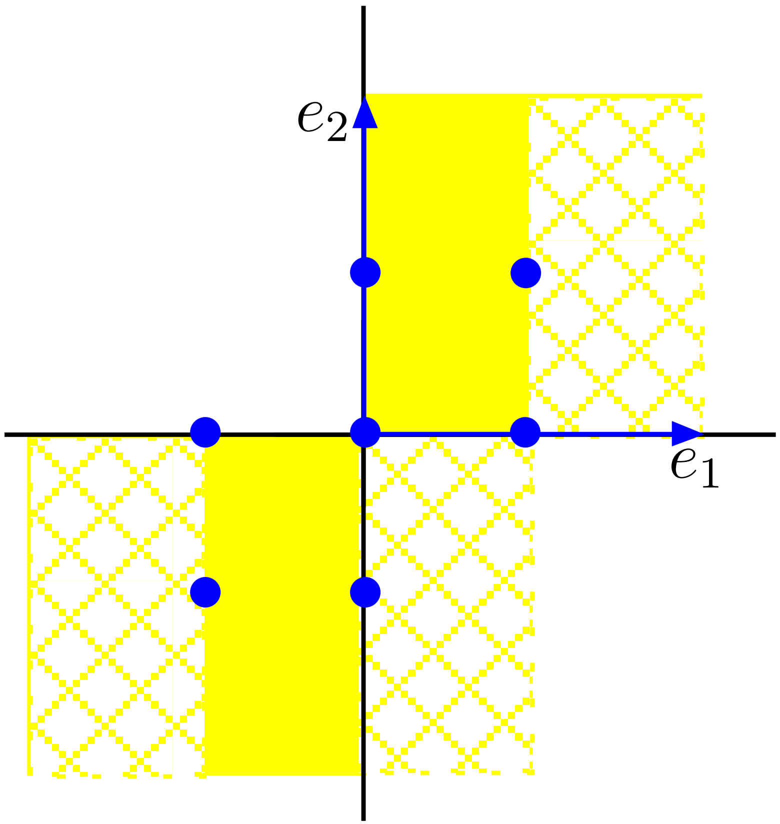
Example: Torus T_2



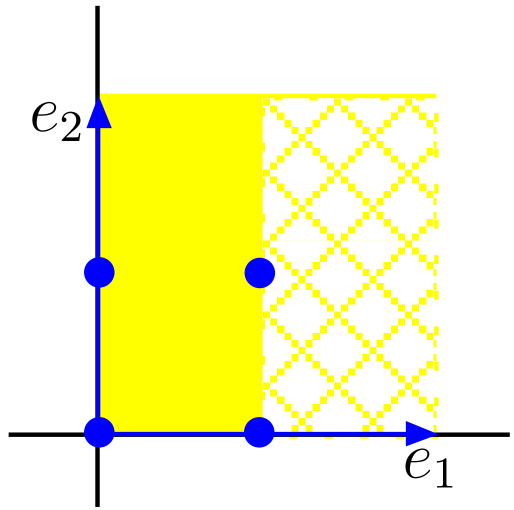
Torus T_2



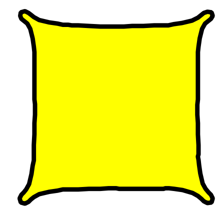
Orbifolding



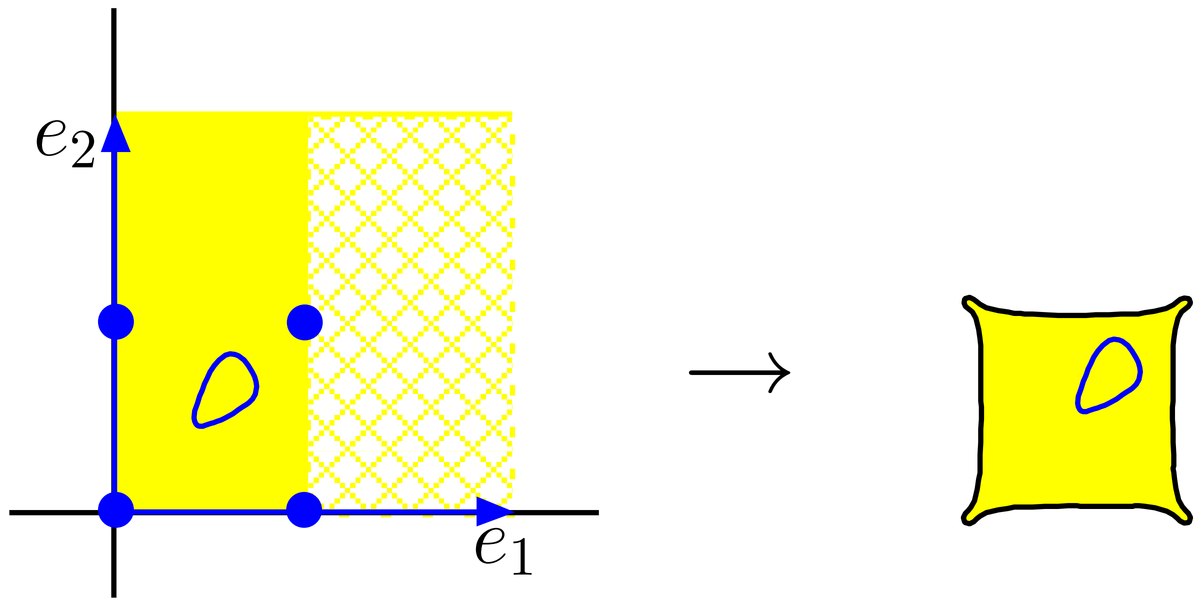
Ravioli



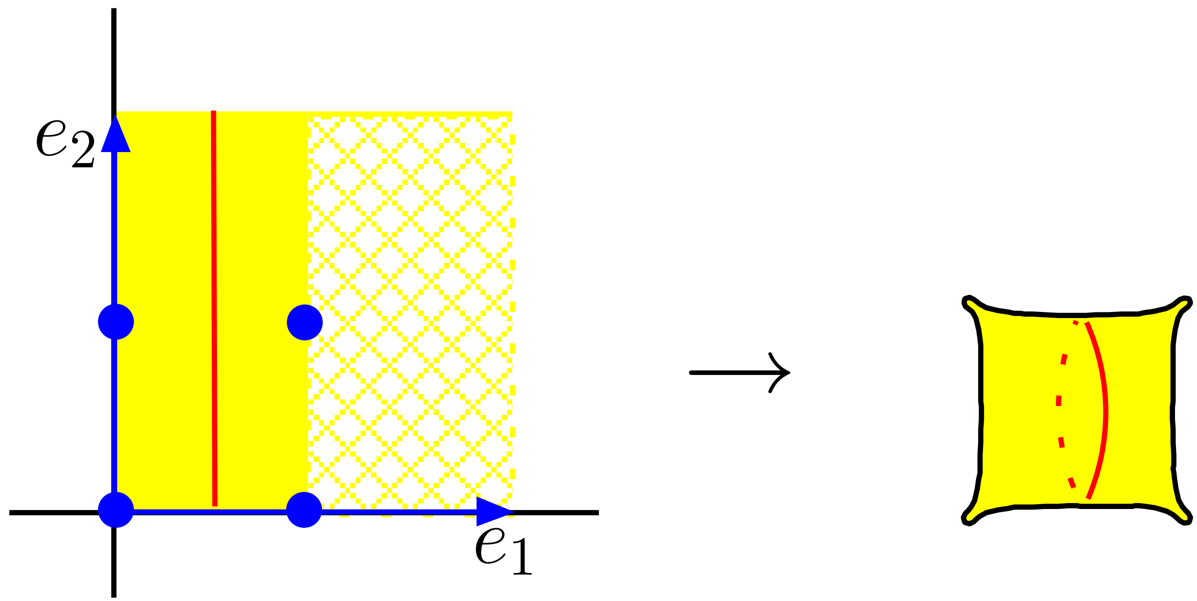
$\longrightarrow$



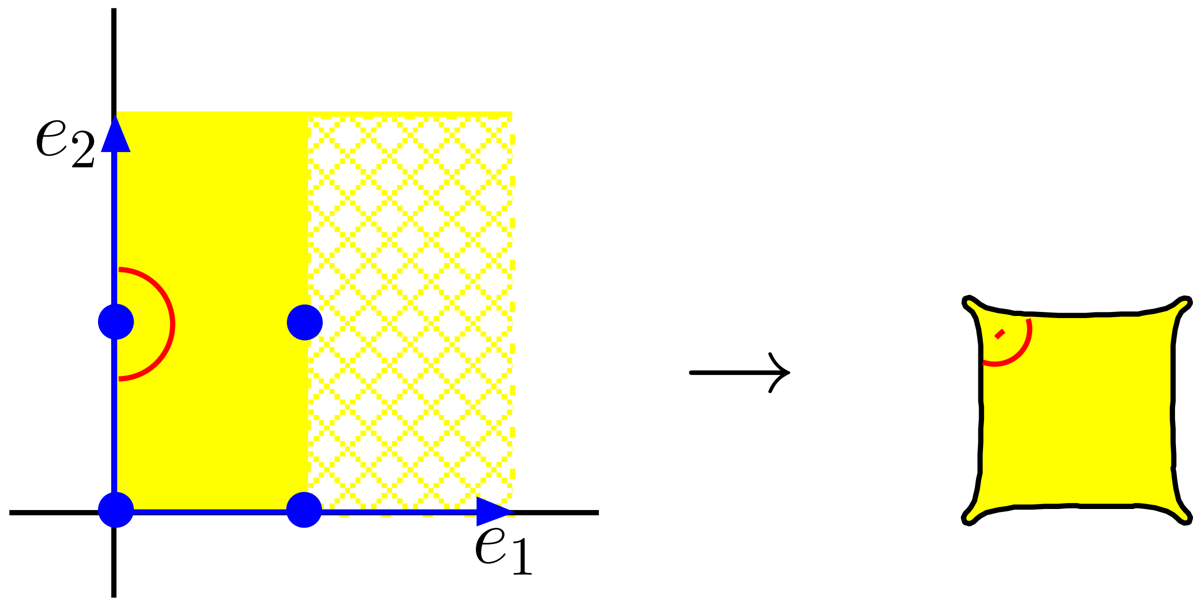
Bulk Modes



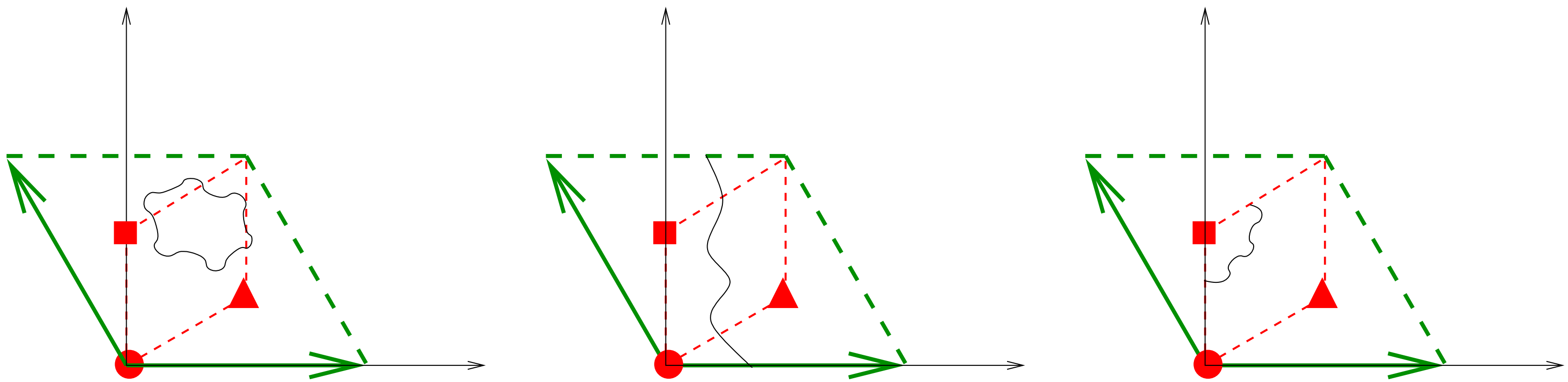
Winding Modes



Brane Modes



$\mathbb{Z}_3$ Example



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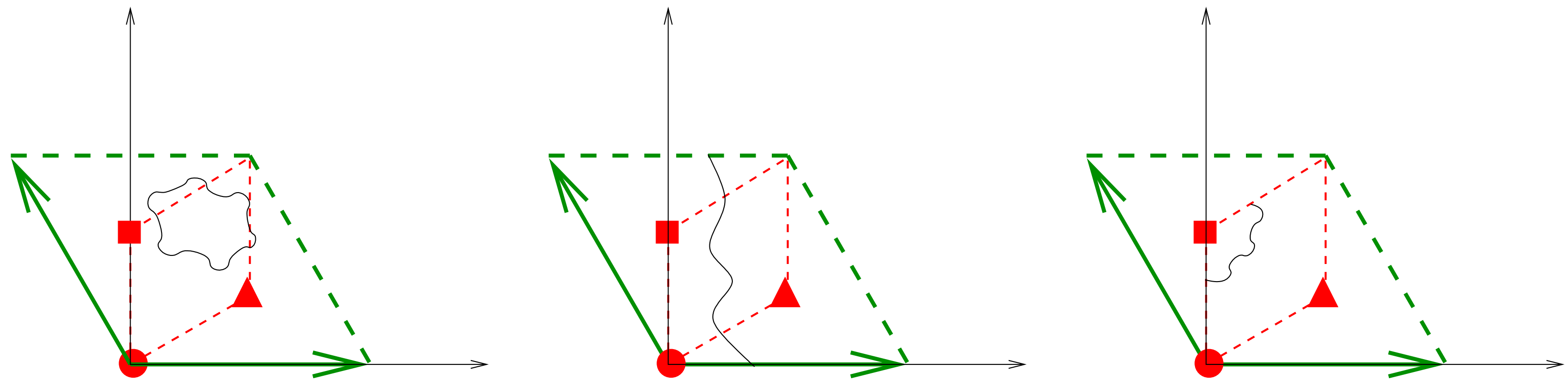

- Action of the space group on coordinates

$$X^i \to (\theta^k X)^i + n_\alpha e^i_\alpha, \quad k = 0, 1, 2, \quad i, \alpha = 1, \ldots, 6$$

- Embed twist in gauge degrees of freedom

$$X^I \to (\Theta^k X)^I \quad I = 1, \ldots, 16$$

Classification of $\mathbb{Z}_3$ Orbifold

Very few inequivalent models

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Case	Shift V	Gauge Group	Gen.
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3	$\left(\frac{1}{3}, \frac{1}{3}, 0^6\right) \left(\frac{2}{3}, 0^7\right)$	$\mathsf{E}_7 \times \mathsf{U}(1) \times \mathsf{SO}(14)' \times \mathsf{U}(1)'$	0
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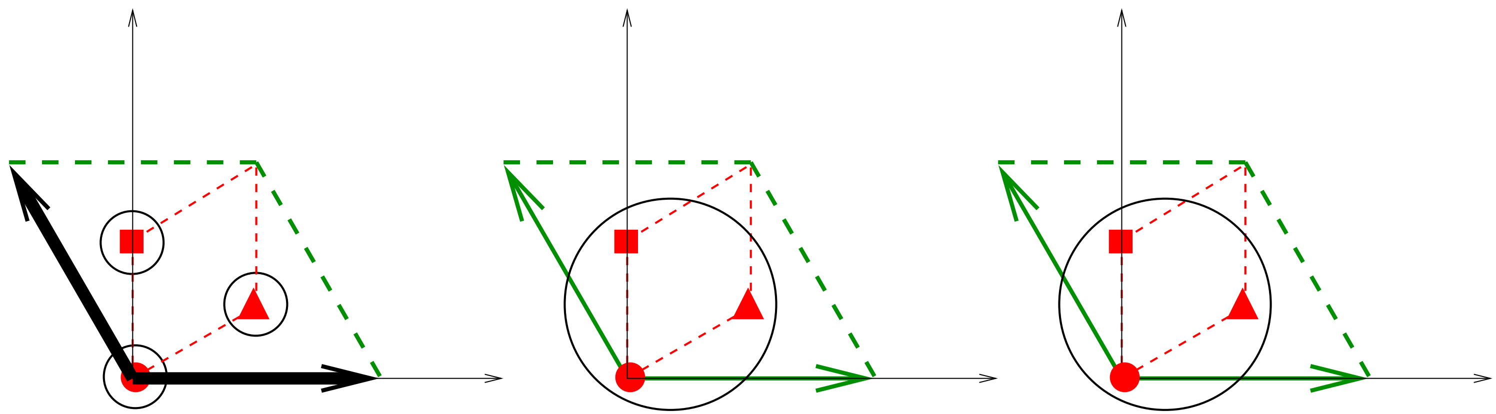
We need to lift this degeneracy ...

Orbifolds with Wilson lines



Torus shifts embedded in gauge group as well

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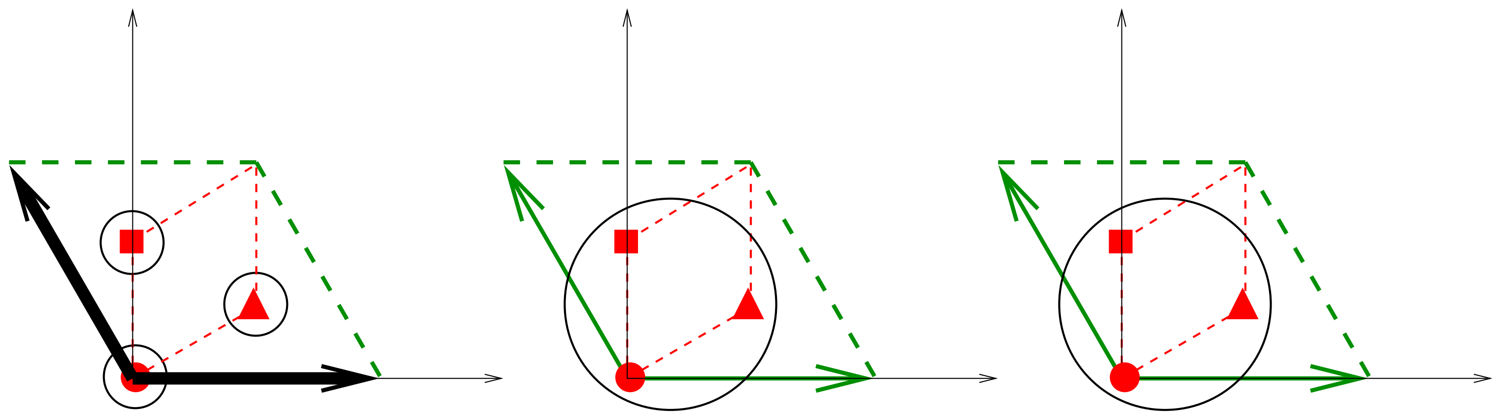

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- further gauge symmetry breakdown
- number of generations reduced

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Can we incorporate this into a string theory description?

Five golden rules

- Family as spinor of SO(10)
  (resulting essentially from exceptional groups)
- Incomplete multiplets
- $N = 1$ superymmetry in $d = 4$
- Repetition of families from geometry
- Discrete symmetries of stringy origin (HPN, 2004)

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We need more general constructions to identify remnants of $SO(10)$ in string theory .....

Candidates

In ten space-time dimensions.....

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Remnants of $SO(10)$ symmetry

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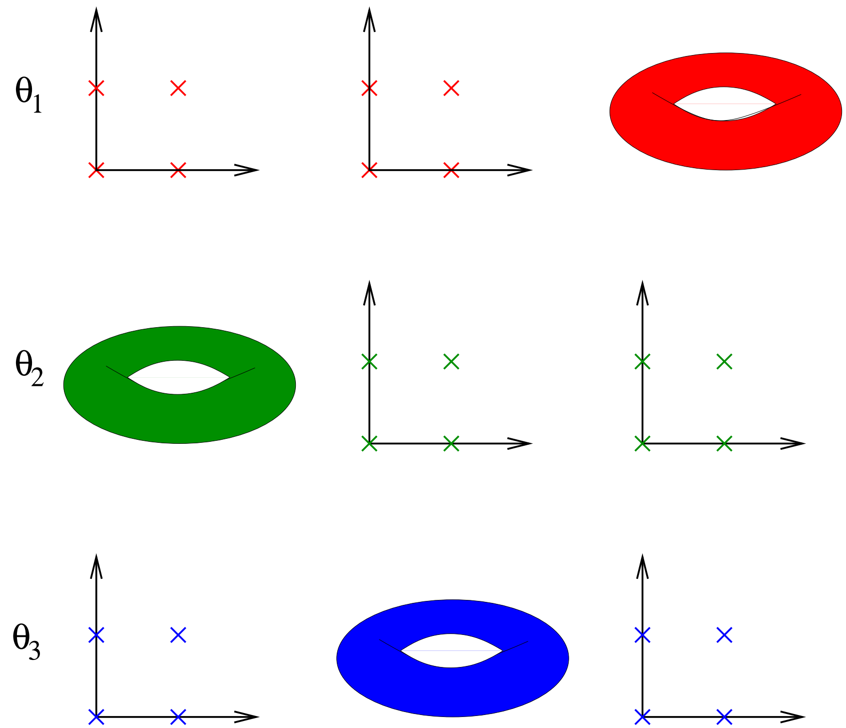
From this point of view, the Z_{2N} or $Z_N \times Z_M$ orbifolds do look more promising

$\mathbb{Z}_2 \times \mathbb{Z}_2$ Orbifold Example



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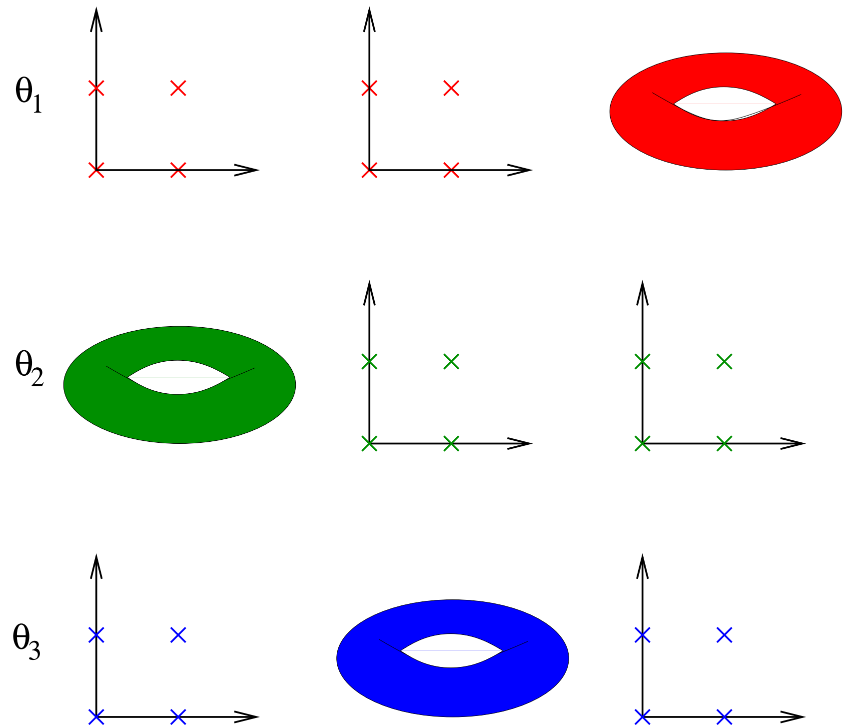
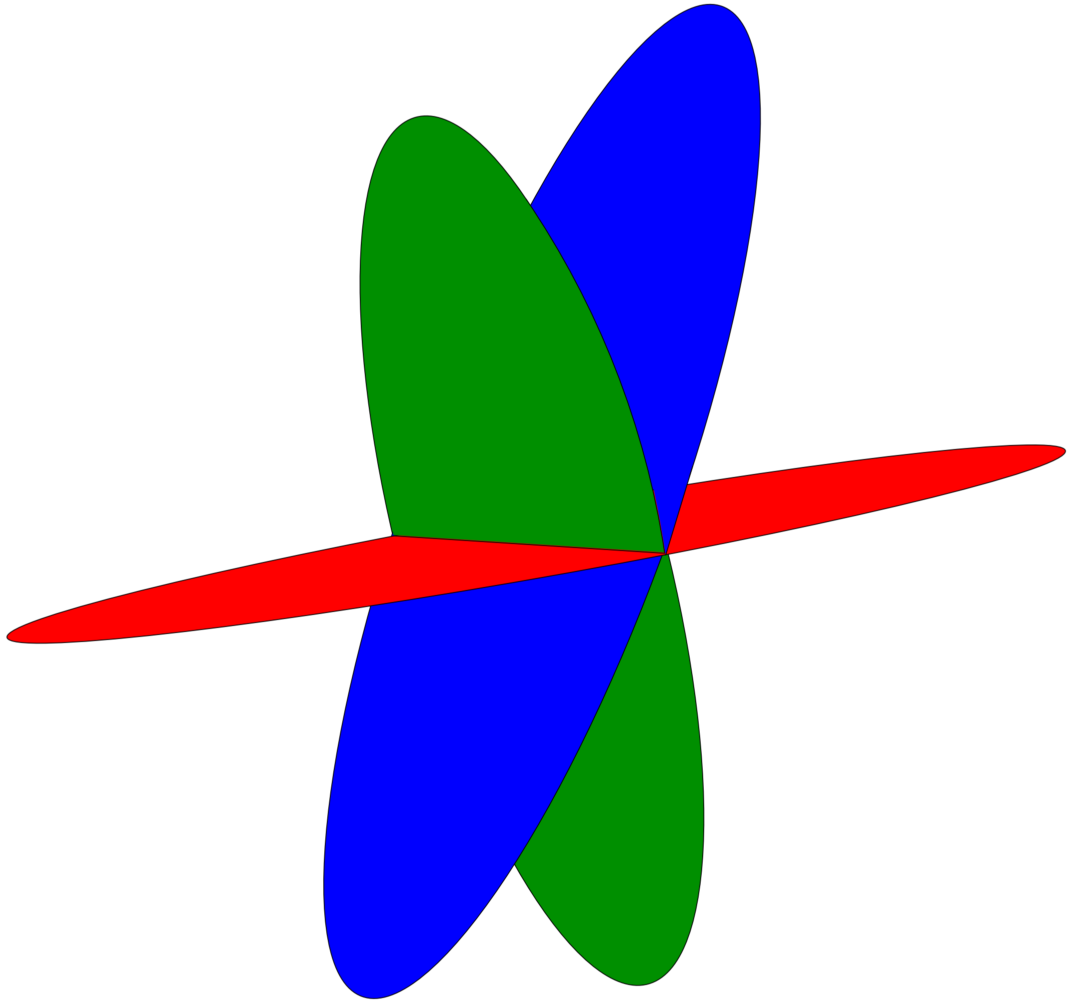


3 twisted sectors (with 16 fixed tori in each) lead to a geometrical picture of ....

Intersecting Branes



$\mathbb{Z}_2 \times \mathbb{Z}_2$ classification

Case	Shifts	Gauge Group	Gen.
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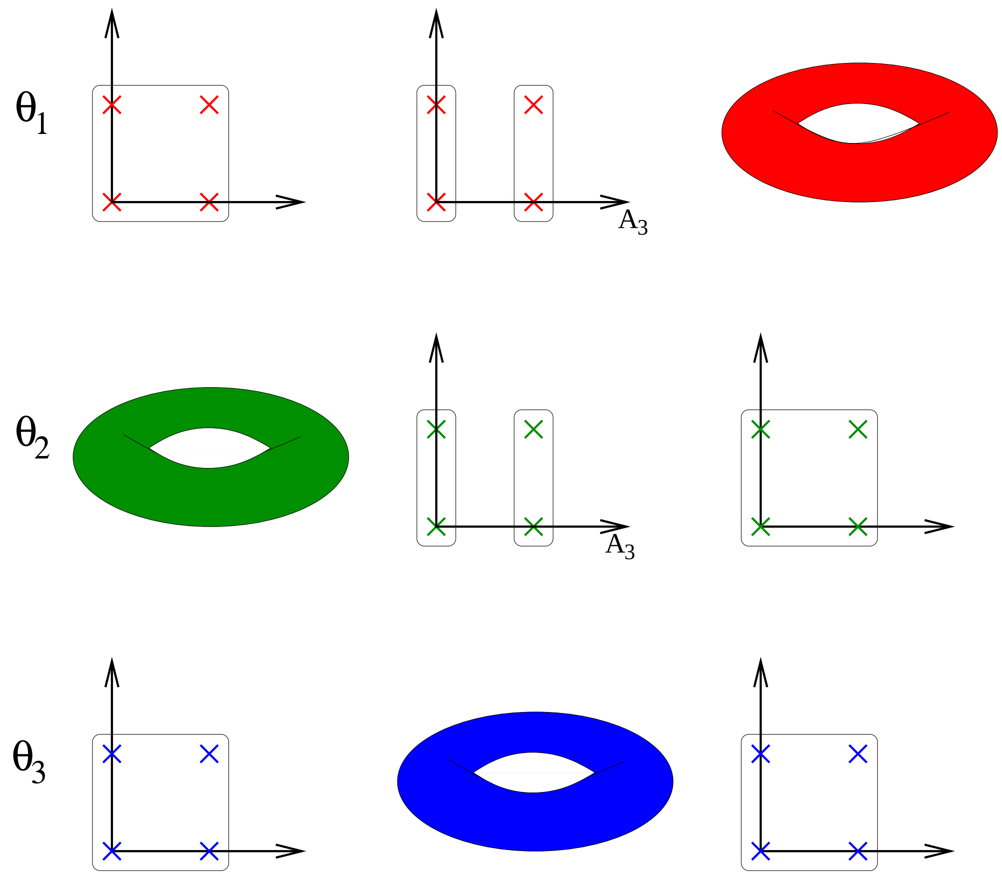
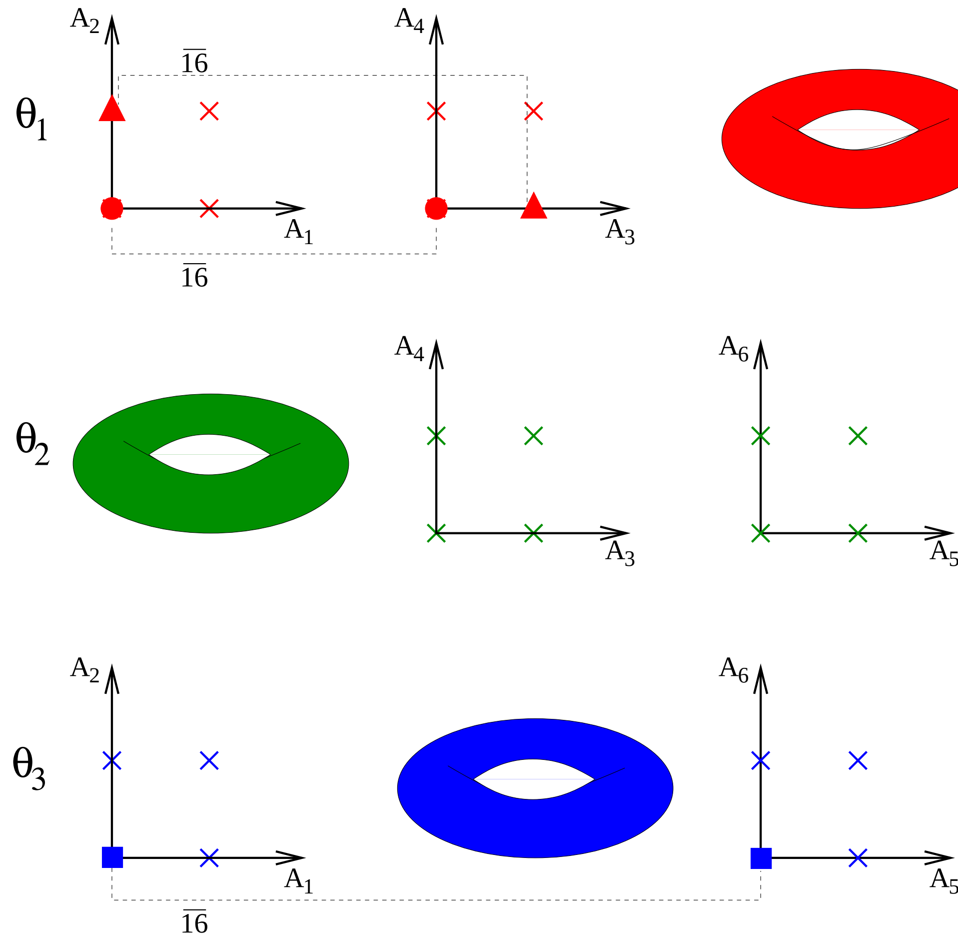
2	$\left(\frac{1}{2}, -\frac{1}{2}, 0^6\right)\ \left(0^8\right)$ $\left(0, \frac{1}{2}, -\frac{1}{2}, 0^4, 1\right)\ \left(1, 0^7\right)$	$\mathsf{E}_6 \times \mathsf{U}(1)^2 \times \mathsf{SO}(16)'$	16
3	$\left({\frac{1}{2}}^2, 0^6\right)\ \left(0^8\right)$ $\left(\frac{5}{4}, {\frac{1}{4}}^7\right)\ \left(\frac{1}{2}, \frac{1}{2}, 0^6\right)$	$\mathsf{SU}(8) \times \mathsf{U}(1) \times \mathsf{E}_7' \times \mathsf{SU}(2)'$	16
4	$\left({\frac{1}{2}}^2, 0^5, 1\right)\ \left(1, 0^7\right)$ $\left(0, \frac{1}{2}, -\frac{1}{2}, 0^5\right)\ \left(-\frac{1}{2}, {\frac{1}{2}}^3, 1, 0^3\right)$	$\mathsf{E}_6 \times \mathsf{U}(1)^2 \times \mathsf{SO}(8)'^2$	0
5	$\left(\frac{1}{2}, -\frac{1}{2}, -1, 0^5\right)\ \left(1, 0^7\right)$ $\left(\frac{5}{4}, {\frac{1}{4}}^7\right)\ \left(\frac{1}{2}, \frac{1}{2}, 0^6\right)$	$\mathsf{SU}(8) \times \mathsf{U}(1) \times \mathsf{SO}(12)' \times \mathsf{SU}(2)'^2$	0

$\mathbb{Z}_2 \times \mathbb{Z}_2$ with Wilson lines



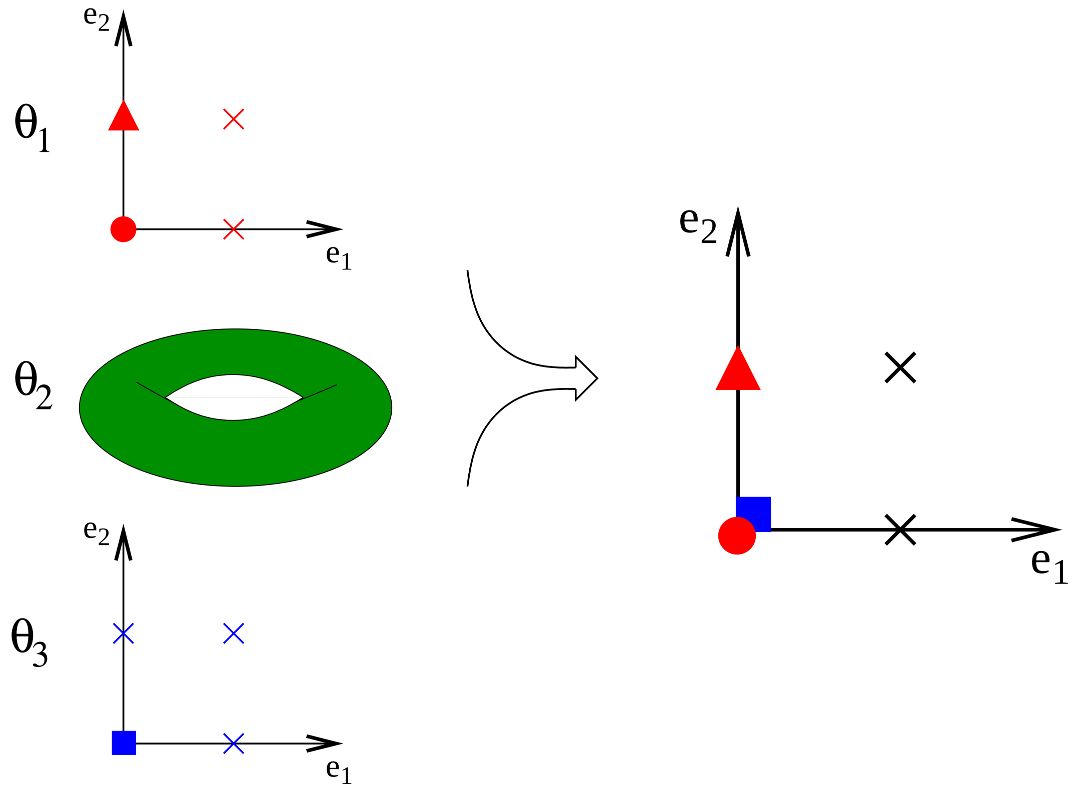
Again, Wilson lines can lift the degeneracy....

Three family $SO(10)$ toy model



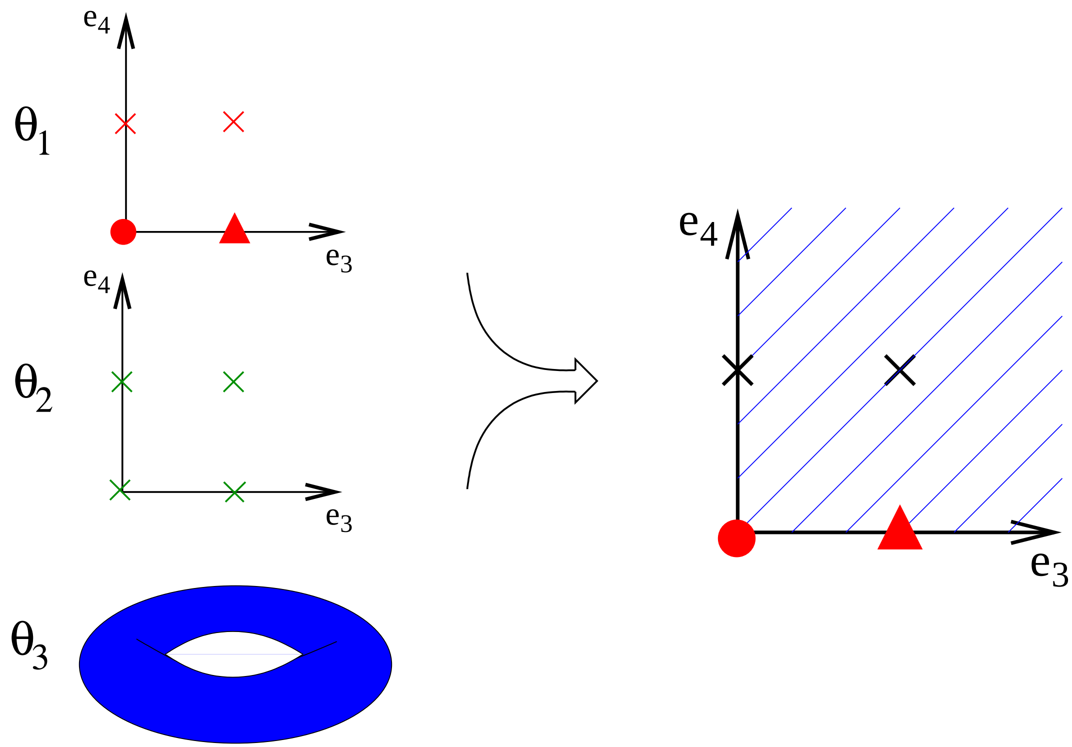
Localization of families at various fixed tori

Zoom on first torus ...



Interpretation as 6-dim. model with 3 families on branes

second torus ...



... 2 families on branes, one in (6d) bulk ...

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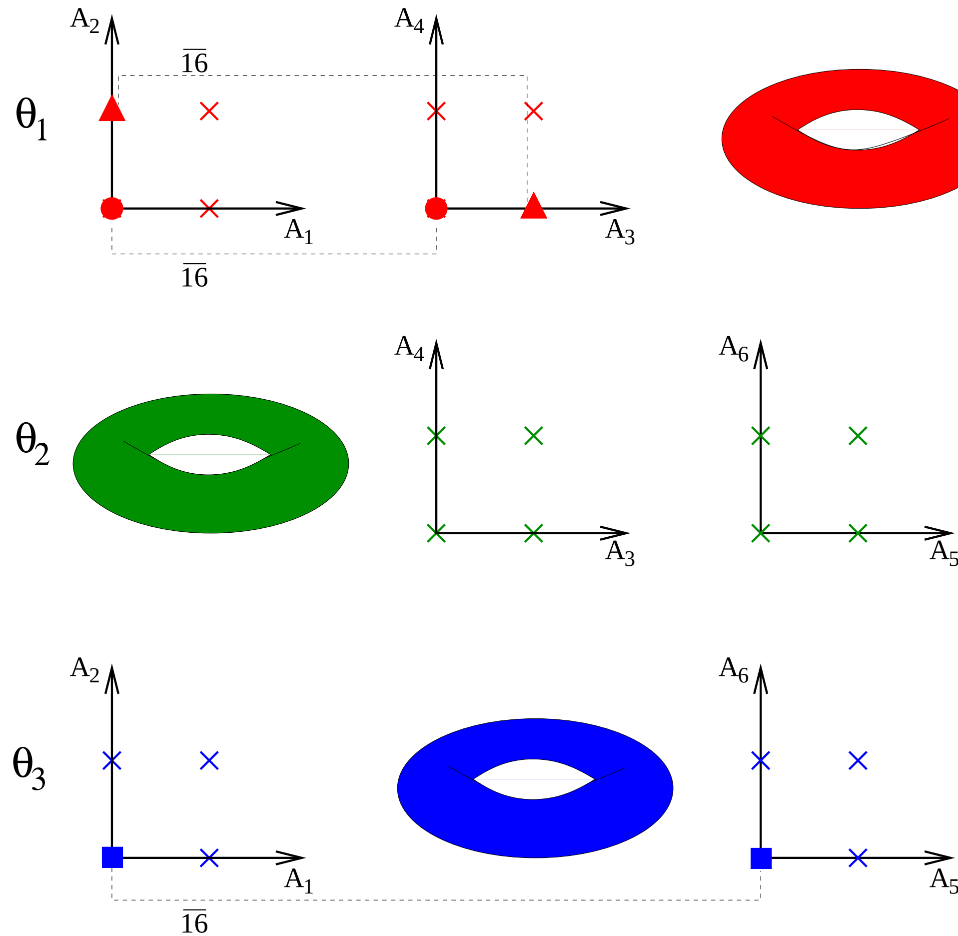

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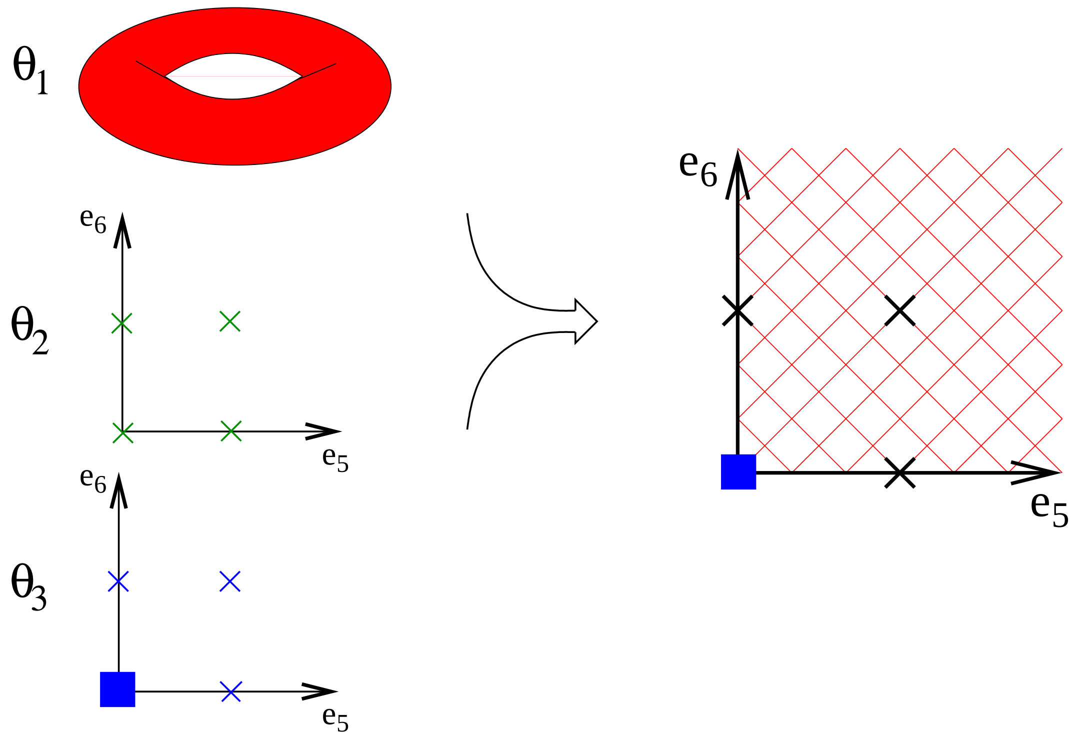

... 1 family on brane, two in (6d) bulk.

Geography

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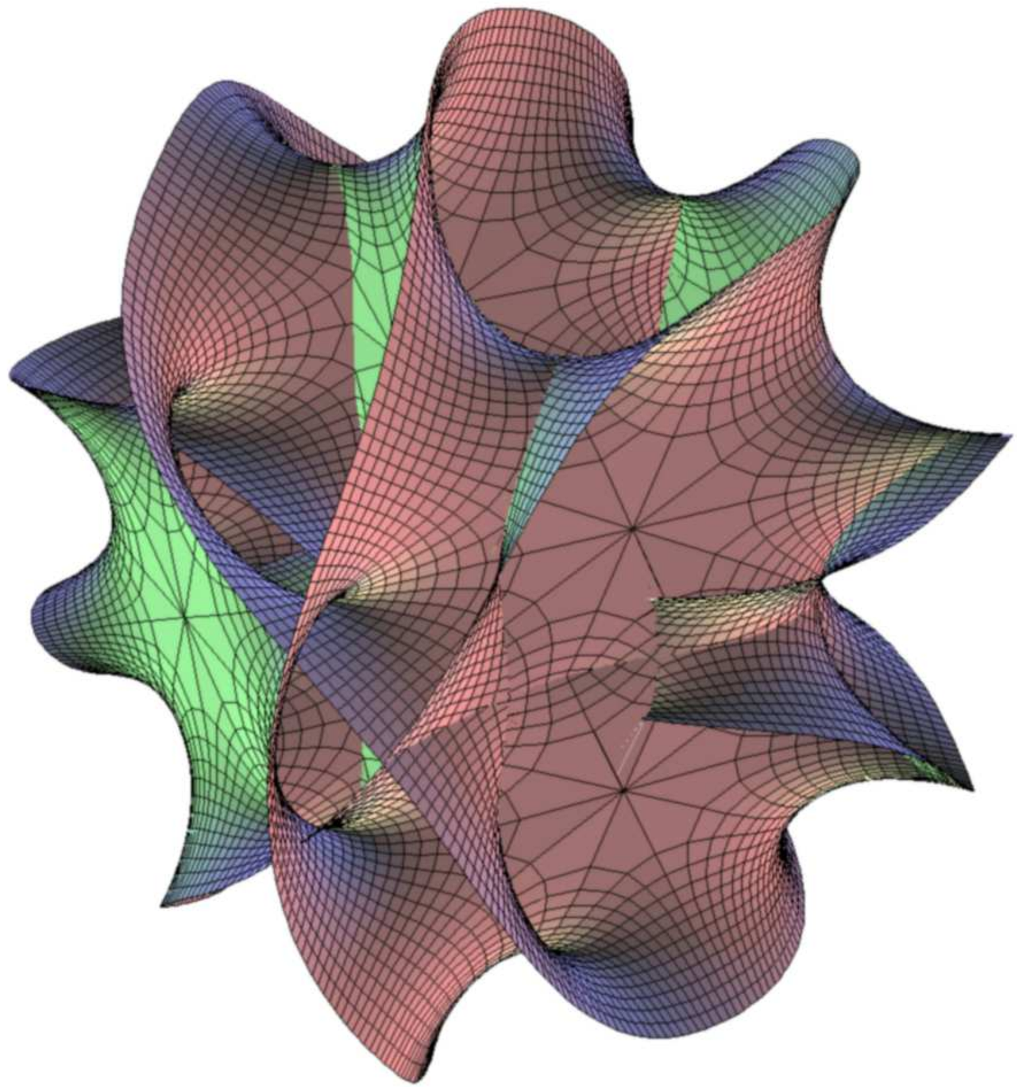
but there is also a “localization” of gauge fields

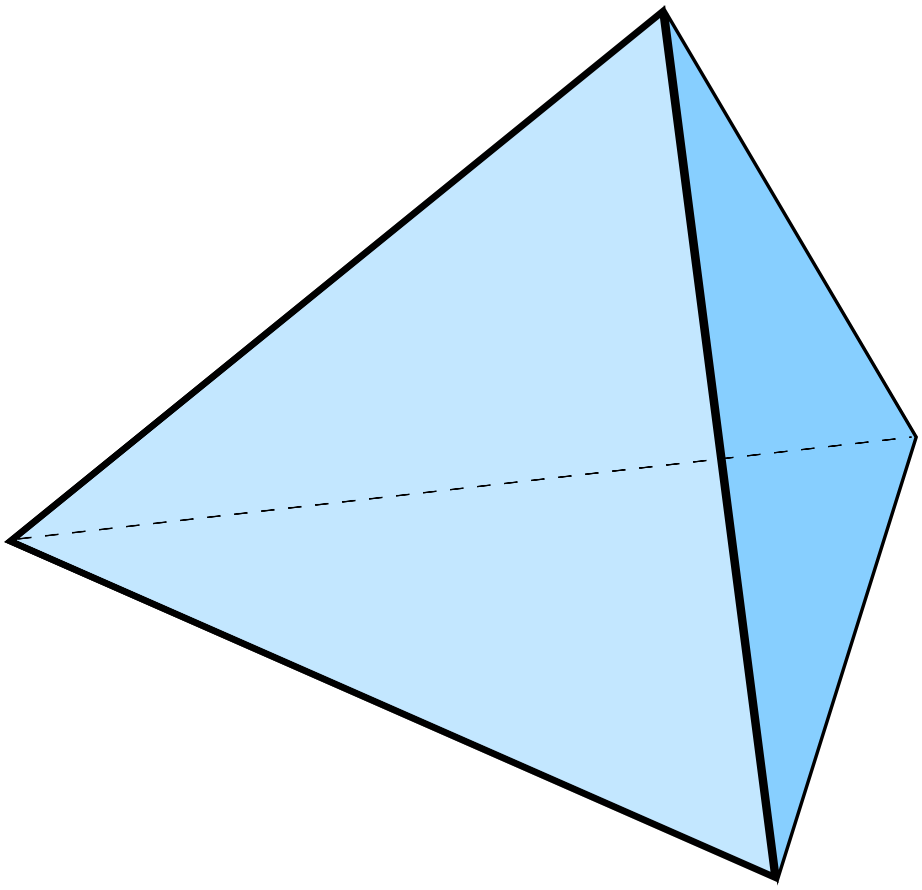
- $E_8 \times E_8$ in the bulk
- smaller gauge groups on various branes

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

Calabi Yau Manifold



Orbifold



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Localization

Quarks, Leptons and Higgs fields can be localized:

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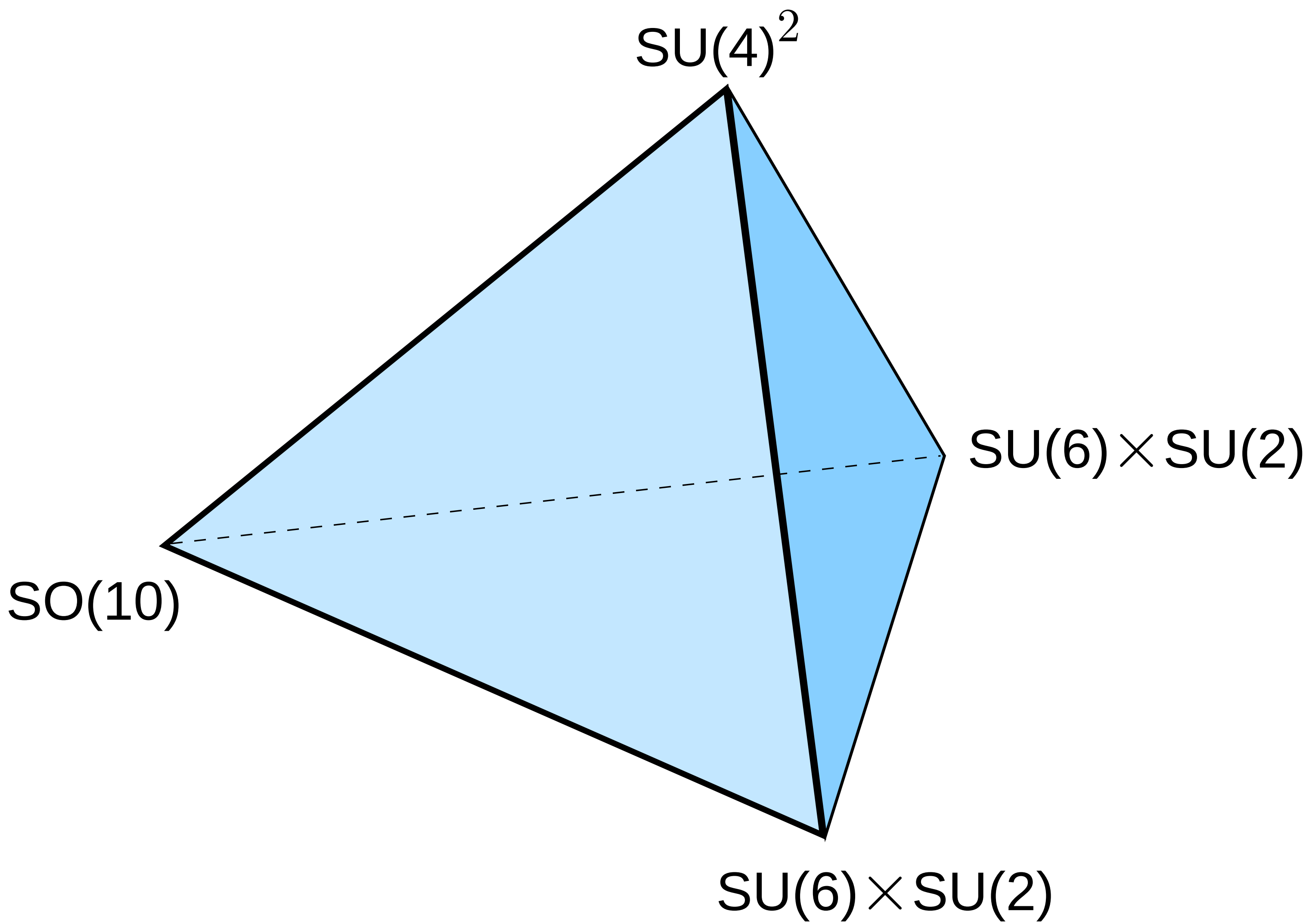
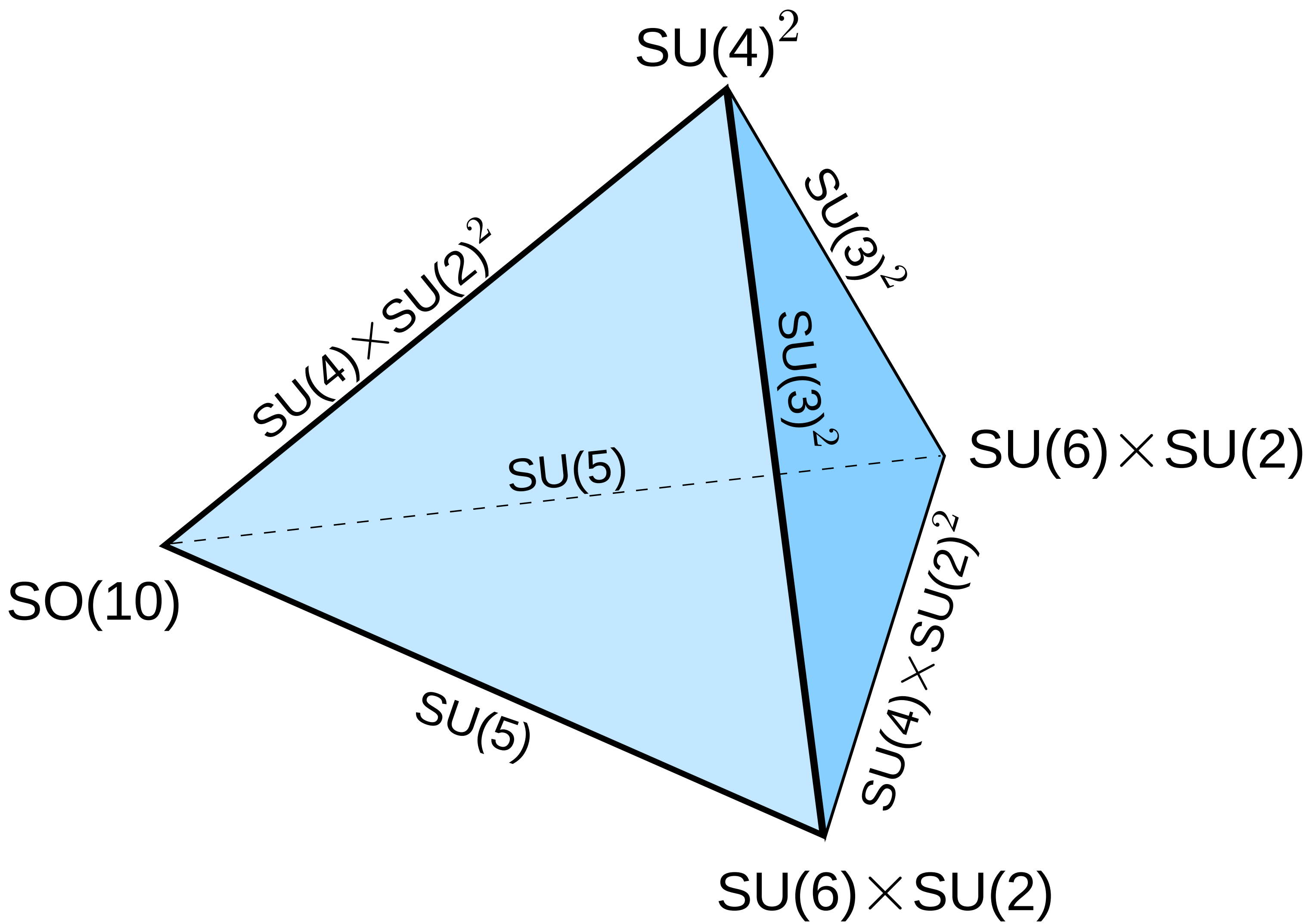
Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Standard Model Gauge Group



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Local Grand Unification

In fact string theory gives us a variant of GUTs

- complete multiplets for fermion families
- split multiplets for gauge- and Higgs-bosons
- partial Yukawa unification

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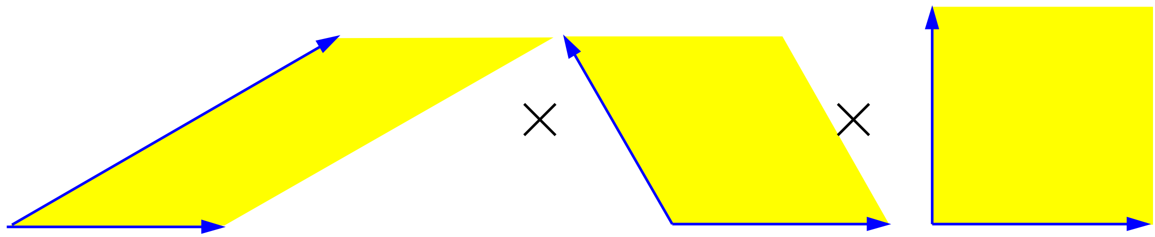
Key properties of the theory depend on the geography of the fields in extra dimensions.

This geometrical set-up called local GUTs, can be realized in the framework of the “heterotic braneworld”.

(Förste, HPN, Vaudrevange, Wingerter, 2004; Buchmüller, Hamaguchi, Lebedev, Ratz, 2004)

The “fertile patch”: Z_6 II orbifold



(Kobayashi, Raby, Zhang, 2004; Buchmüller, Hamaguchi, Lebedev, Ratz, 2004)

- provides fixed points and fixed tori
- allows $SO(10)$ gauge group
- allows for localized 16-plets for 2 families
- $SO(10)$ broken via Wilson lines
- nontrivial hidden sector gauge group

Selection Strategy

criterion	$V^{\mathrm{SO}(10),1}$	$V^{\mathrm{SO}(10),2}$
② models with 2 Wilson lines	$22,000$	$7,800$
③ SM gauge group $\subset$ SO(10)	3563	1163
④ 3 net families	1170	492
⑤ gauge coupling unification	528	234
⑥ no chiral exotics	128	90

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

Decoupling of exotics

requires extensive technical work:

- analysis of Yukawa couplings $S^n E \bar{E}$
- vevs of S break additional $U(1)$ symmetries
- our analysis includes $n \leq 6$

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Requirement of D-flatness

- vevs of S should not break supersymmetry
- anomalous U(1) and Fayet-Iliopoulos terms
- checking D-flatness with method of gauge invariant monomials

MSSM candidates

criterion	$V^{\mathrm{SO}(10),1}$	$V^{\mathrm{SO}(10),2}$
SM gauge group $\subset$ SO(10)	3563	1163
3 net $(\mathbf{3},\mathbf{2})$	1170	492
non–anomalous $\mathrm{U}(1)_Y \subset \mathrm{SU}(5)$	528	234
3 generations $+$ vector-like	128	90
exotics decouple	106	85
D-flat solutions	105	85

(Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007)

The road to the MSSM

This scenario leads to

- 200 models with the exact spectrum of the MSSM (absence of chiral exotics)
- local grand unification (by construction)
- gauge- and (partial) Yukawa unification

  (Raby, Wingerter, 2007)
- examples of neutrino see-saw mechanism

  (Buchmüller, Hamguchi, Lebedev, Ramos-Sanchez, Ratz, 2007)
- 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)

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

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

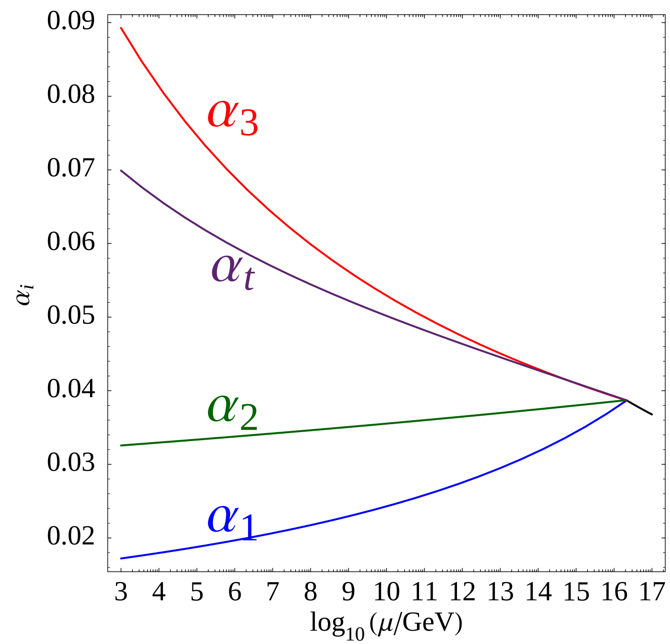
- for discussion of neutrinos and R-parity we keep also the $U(1)_{B-L}$ charges

Spectrum

#	irrep	label		#	irrep	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/6,1/3)}$	q_i		3	$(\bar{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-1/3)}$	$\bar{u}_i$
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
$3+1$	$(\bar{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,-1/3)}$	$\bar{d}_i$		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	$(\bar{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/3,2/3)}$	$\bar{\delta}_i$		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	$(\mathbf{1},\mathbf{1};\bar{\mathbf{4}},\mathbf{1})_{(0,*)}$	$\bar{f}_i$
2	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1/2,-1)}$	f_i^-		2	$(\mathbf{1},\mathbf{1};\bar{\mathbf{4}},\mathbf{1})_{(1/2,1)}$	$\bar{f}_i^+$
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	$(\bar{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-1/6,2/3)}$	$\bar{v}_i$		2	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{(1/6,-2/3)}$	v_i

Unification

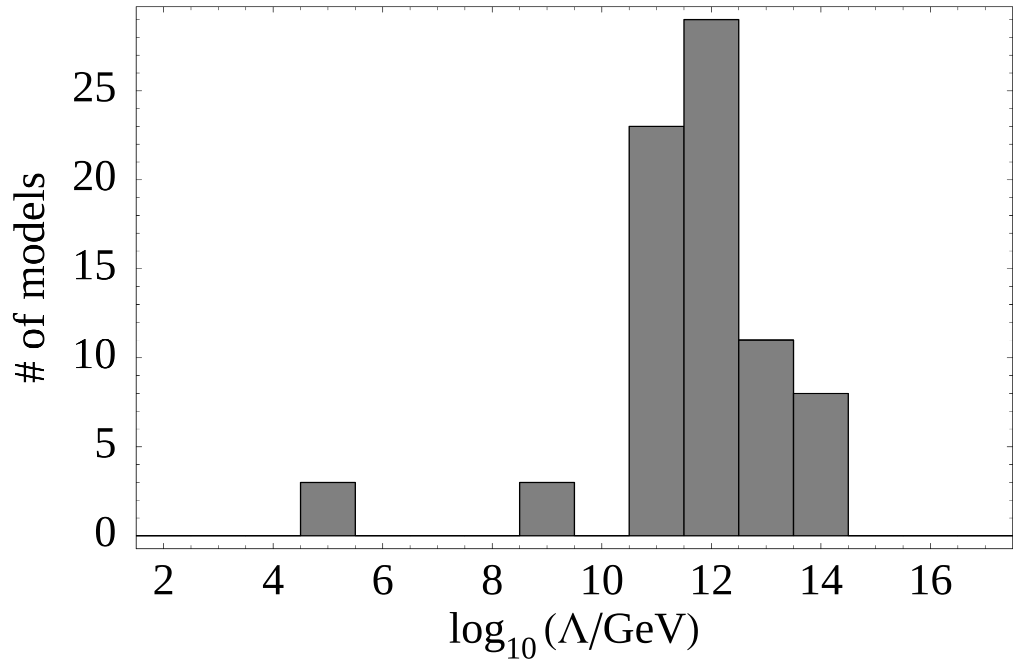
- Higgs doublets are in untwisted (U3) sector
- heavy top quark
- $\mu-$term protected by a discrete symmetry



- threshold corrections (“on third torus”) allow unification at correct scale around 10^{16} GeV
- natural incorporation of gauge-Yukawa unification

(Faraggi, 1991; Hosteins, Kappl, Ratz, Schmidt-Hoberg, 2009)

Hidden Sector Susy Breakdown



Gravitino mass $m_{3/2} = \Lambda^3/M^2_{\mathrm{Planck}}$ is in the TeV range for the hidden sector gauge group $SU(4)$

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

See-saw neutrino masses

The see-saw mechanism requires

- right handed neutrinos ($Y = 0$ and $B - L = \pm 1$),
- heavy Majorana neutrino masses M_{Majorana},
- Dirac neutrino masses M_{Dirac}.

The benchmark model has 49 right handed neutrinos:

- the left handed neutrino mass is $m_\nu \sim M^2_{\mathrm{Dirac}}/M_{\mathrm{eff}}$
- with $M_{\mathrm{eff}} < M_{\mathrm{Majorana}}$ and depends on the number of right handed neutrinos.

(Buchmüller, Hamguchi, Lebedev, Ramos-Sanchez, Ratz, 2007;

Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007)

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R-parity

- R-parity allows the distinction between Higgs bosons and sleptons
- $SO(10)$ contains R-parity as a discrete subgroup of $U(1)_{B-L}$.
- in conventional "field theory GUTs" one needs large representations to break $U(1)_{B-L}$ (≥ 126 dimensional)
- in heterotic string models one has more candidates for R-parity (and generalizations thereof)
- one just needs singlets with an even $B-L$ charge that break $U(1)_{B-L}$ down to R-parity

(Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007)

Discrete Symmetries

There are numerous discrete symmetries:

- from geometry
- and stringy selection rules,
- both of abelian and nonabelian nature

(Kobayashi, HPN, Plöger, Raby, Ratz, 2006)

The importance of these discrete symmetries cannot be underestimated. After all, besides the gauge symmetries this is what we get in string theory.

At low energies the discrete symmetries might appear as accidental continuous global $U(1)$ symmetries.

Symmetries

String theory gives us

- gauge symmetries
- discrete global symmetries from geometry and stringy selection rules (Kobayashi, HPN, Plöger, Raby, Ratz, 2006)
- accidental global $U(1)$ symmetries in the low energy effective action

  (Choi, Kim, Kim, 2006; Choi, HPN, Ramos-Sanchez, Vaudrevange, 2008)

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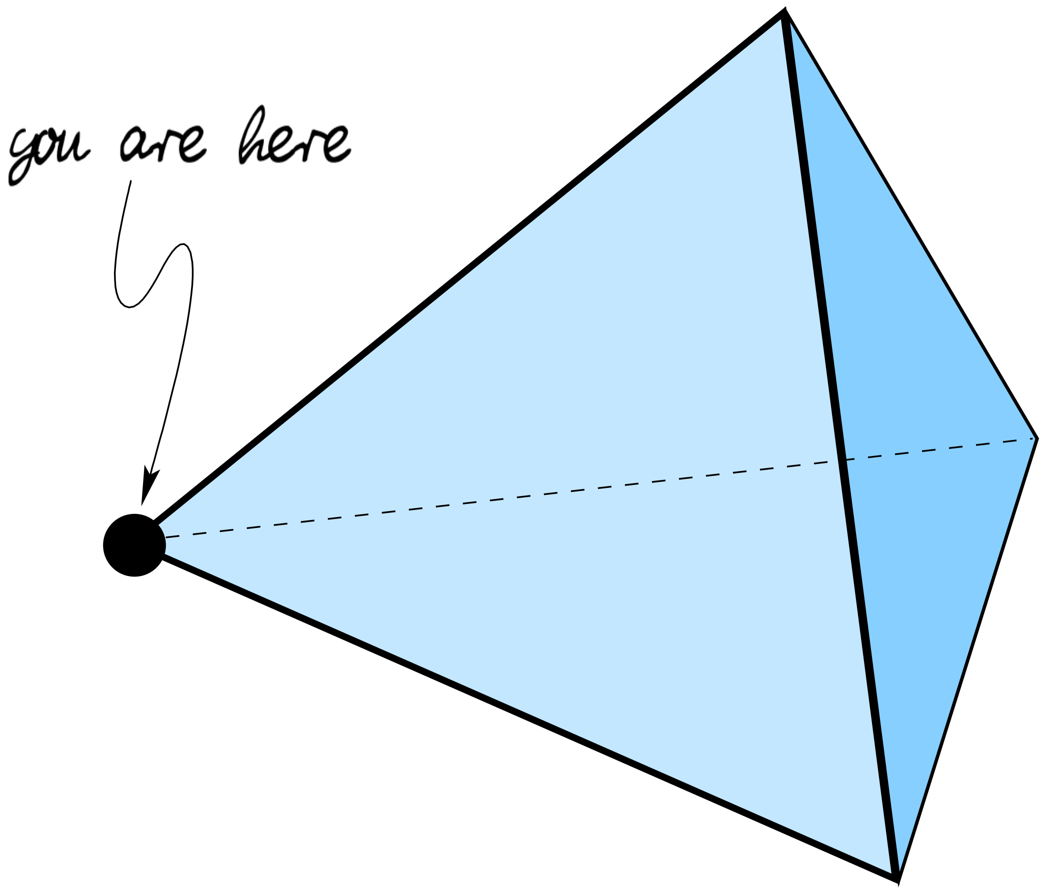
We might live close to a fixed point with enhanced symmetries that explain small parameters in the low energy effective theory.

Location matters



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We might live close to a fixed point with enhanced symmetries that explain small parameters in the low energy effective theory.

These symmetries can be trusted as we are working within a consistent theory of gravity.

Accidental Symmetries

Applications of discrete and accidental global symmetries:

- (nonabelian) family symmetries (and FCNC)

  (Ko, Kobayashi, Park, Raby, 2007)

- Yukawa textures (via Frogatt-Nielsen mechanism)
- a solution to the μ-problem

  (Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007)

- creation of hierarchies

  (Kappl, HPN, Ramos-Sanchez, Ratz, Schmidt-Hoberg, Vaudrevange, 2008)

- proton stability via “Proton Hexality”

  (Dreiner, Luhn, Thormeier, 2005; Förste, HPN, Ramos-Sanchez, Vaudrevange, 2009)

- approximate global $U(1)$ for a QCD accion

  (Choi, Kim, Kim, 2006; Choi, HPN, Ramos-Sanchez, Vaudrevange, 2008)

The μ problem

In general we have to worry about

- doublet-triplet splitting
- mass term for additional doublets
- the appearance of “naturally” light doublets

In the benchmark model we have

- only 2 doublets
- which are neutral under all selection rules
- if $M(s_i)$ allowed in superpotential
- then $M(s_i)H_uH_d$ is allowed as well

The μ problem II

We have verified that (up to order 6 in the singlets)

- $F_i = 0$ implies automatically
- $M(s_i) = 0$ for all allowed terms $M(s_i)$ in the superpotential W

Therefore

- $W = 0$ in the supersymmetric (Minkowski) vacuum
- as well as $\mu = \partial^2 W / \partial H_u \partial H_d = 0$, while all the vectorlike exotics decouple
- with broken supersymmetry $\mu \sim m_{3/2} \sim < W >$

This solves the μ-problem (Casas, Munoz, 1993)

The creation of the hierarchy

Is there an explanation for a vanishing μ?

- string miracle?
- underlying symmetry?

Consider a superpotential

$$W = \sum c_{n_1\cdots n_M} \phi_1^{n_1} \cdots \phi_M^{n_M} .$$

with an exact R-symmetry

$$W \to e^{2\mathrm{i}\,\alpha}\, W , \quad \phi_j \to \phi_j' = e^{\mathrm{i}\, r_j\, \alpha}\, \phi_j$$

where each monomial in W has total R-charge 2.

...hierarchy continued...

Consider a field configuration $\langle \phi_i \rangle$ with

$$F_i = \frac{\partial W}{\partial \phi_i} = 0 \quad \text{at } \phi_j = \langle \phi_j \rangle \; \forall \; i, j \; .$$

Under an infinitesimal $U(1)_R$ transformation, the superpotential transforms nontrivially

$$W(\phi_j) \rightarrow W(\phi_j') = W(\phi_j) + \sum_i \frac{\partial W}{\partial \phi_i} \Delta \phi_i \; .$$

This proves that, if the $F = 0$ equations are satisfied, W vanishes at the minimum (as a consequence of a continuous R-symmetry)

Continuous R-symmetry

Thus for a continous R-symmetry we would have

- a supersymmetric ground state with $W = 0$ and $\mathrm{U}(1)_R$ spontaneously broken
- a problematic R-Goldstone-Boson

However, the above R-symmetry appears as an accidental continous symmetry resulting from an exact discrete symmetry of (high) order N

- Goldstone-Boson massive and harmless
- a nontrivial VEV of W of higher order in ϕ

(Kappl, HPN, Ramos-Sanchez, Ratz, Schmidt-Hoberg, Vaudrevange, 2008)

Hierarchy

Such accidental symmetries lead to

- creation of a small constant in the superpotential
- explanation of a small μ term

(Kappl, HPN, Ramos-Sanchez, Ratz, Schmidt-Hoberg, Vaudrevange, 2008)

Even with a moderate hierarchy like $\phi/M_P \sim 10^{-2}$ one can generate small values for μ and $< W >$ and thus a hierarchically small TeV-scale for the gravitino mass

$$m_{3/2} \sim W_{\rm eff} = c + A\,{\rm e}^{-a\,S}$$

in the framework of a modulus or mirage mediation scheme of supersymmetry breakdown.

(Löwen, HPN,2008)

The Higgs-mechanism in string theory...

...can be achieved via continuous Wilson lines. The aim is:

- electroweak symmetry breakdown
- breakdown of Trinification or Pati-Salam group to the Standard Model gauge group
- rank reduction

Continuous Wilson lines require specific embeddings of twist in the gauge group

(Ibanez, HPN, Quevedo, 1987)

- difficult to implement in the Z_3 case
- more promising for Z_2 twists

An example

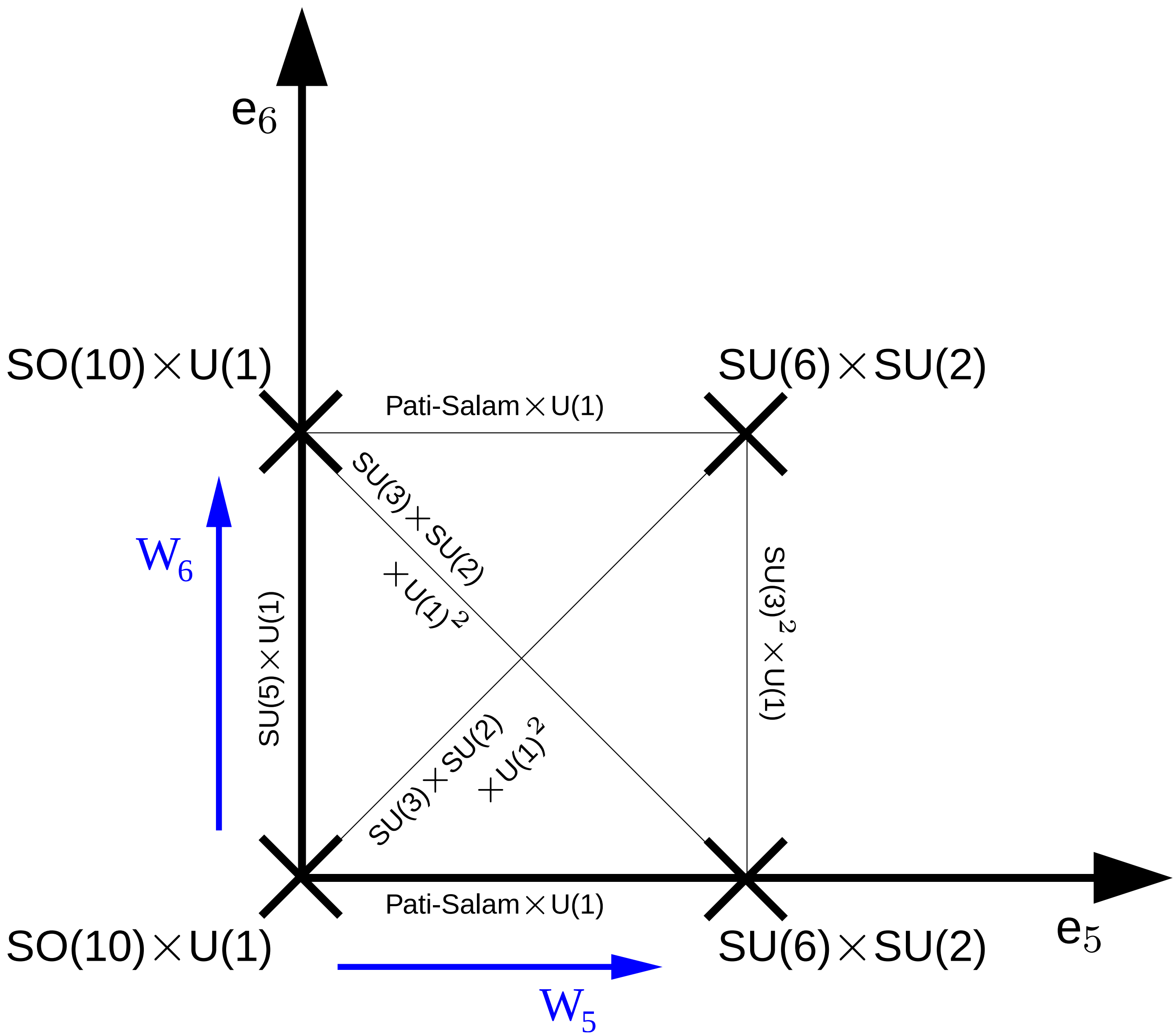
We consider a model that has E_6 gauge group in the bulk of a “6d orbifold”. The breakdown pattern is

- $E_6 \rightarrow SO(10)$ via a Z_2 twist
- $SO(10) \rightarrow SU(4) \times SU(2) \times SU(2) \times U(1)$ via a discrete (quantized) Wilson line
- $SU(4) \times SU(2) \times SU(2) \rightarrow SU(3) \times SU(2) \times U(1)$ via a continuous Wilson line (Förste, HPN, Wingerter, 2005)

Such 6d models can be embedded in 10d string theory orbifolds. Models with consistent electroweak symmetry breakdown have been constructed.

(Förste, HPN, Wingerter, 2006)

Pati-Salam breakdown



Accions

Absence of continuous global U(1) symmetries in string theory leads to a question towards the

- axion as a solution to the strong CP-problem

A gauge anomalous $U(1)$ symmetry might help, but there we expect

- a too large axion decay constant of order of string scale

Again additional accidental gobal U(1) symmetries arising as a consequence of discrete symmetries might help,

(Choi, Kim, Kim, 2007; Choi, HPN, Ramos-Sanchez, Vaudrevange, 2009)

but we need to control the accion scale F_a.

Multi-Axion Systems

Consider a system with two $U(1)$ symmetries: $U(1)_P \times U(1)_Q$ and suppose that they are broken spontaneously.

$$F_{a_1} \;=\; -\, v_1 \, \frac{q_P^1 \, q_Q^2 - q_Q^1 \, q_P^2}{q_f^2} \,, \qquad\qquad F_{a_2} \;=\; v_2 \, \frac{q_P^1 \, q_Q^2 - q_Q^1 \, q_P^2}{q_f^1} \,.$$

The relevant accion decay constant will then be

$$F_a = \left(\left(\frac{1}{F_{a_1}} \right)^2 + \left(\frac{1}{F_{a_2}} \right)^2 \right)^{-1/2} \;=\; \frac{v_1 \, v_2 \, (q_P^1 \, q_Q^2 - q_Q^1 \, q_P^2)}{\sqrt{(q_f^1 \, v_1)^2 + (q_f^2 \, v_2)^2}} \,.$$

and it is dominated by the smallest VEV!

The Accion Program

- find a model with an accidental (colour)-anomalous $U(1)^*$
- identify a vacuum configuration where the VEVs driven by the Fayet-Iliopoulos term do not break $U(1)^*$
- search for a vacuum configuration where $U(1)^*$ is broken by a VEV in the axion window (some other gauge $U(1)$'s might be broken here as well)
- check that higher order non-renormalizable terms that break $U(1)^*$ explicitely are sufficiently suppressed to avoid a too “large” axion mass.

(Choi, HPN, Ramos-Sanchez, Vaudrevange, 2009)

can be accomodated in the Heterotic Brane World.

Proton stability

In the standard model Baryon number $U(1)_B$ is not a good symmetry

- Baryon and lepton number are anomalous
- cannot be gauged in a consistent way
- unstable proton

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Baryon number violation is needed for baryogenesis.

- Grand unification addresses these questions
- proton decay via dimension-6 operators
- GUT scale has to be sufficiently high

GUTs need SUSY

Grand unification most natural in the framework of SUSY

- evolution of gauge couplings
- GUT scale is pushed to higher value

GUTs need SUSY

Grand unification most natural in the framework of SUSY

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But there is a problem

- dimension-4 and -5 operators
- more symmetries needed
- matter parity (or R-parity)
- baryon triality, proton hexality

(Ibanez, Ross, 1991; Dreiner, Luhn, Thormeier, 2005)

The fate of global symmetries

Global symmetries are very useful for

- absence of FCNC (solve flavour problem)
- Yukawa textures à la Frogatt-Nielsen
- solutions to the μ problem
- axions and the strong CP-problem
- proton stability

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- absence of FCNC (solve flavour problem)
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- proton stability

But they might be destroyed by gravitational effects:

- we need a UV-completion of the theory
- with a consistent incorporation of gravity

String theory as UV-completion

What do we get from string theory?

- supersymmetry
- extra spatial dimensions
- (large unified) gauge groups
- consistent theory of gravity
- many discrete symmetries
- no global continuous symmetries

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- supersymmetry
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- consistent theory of gravity
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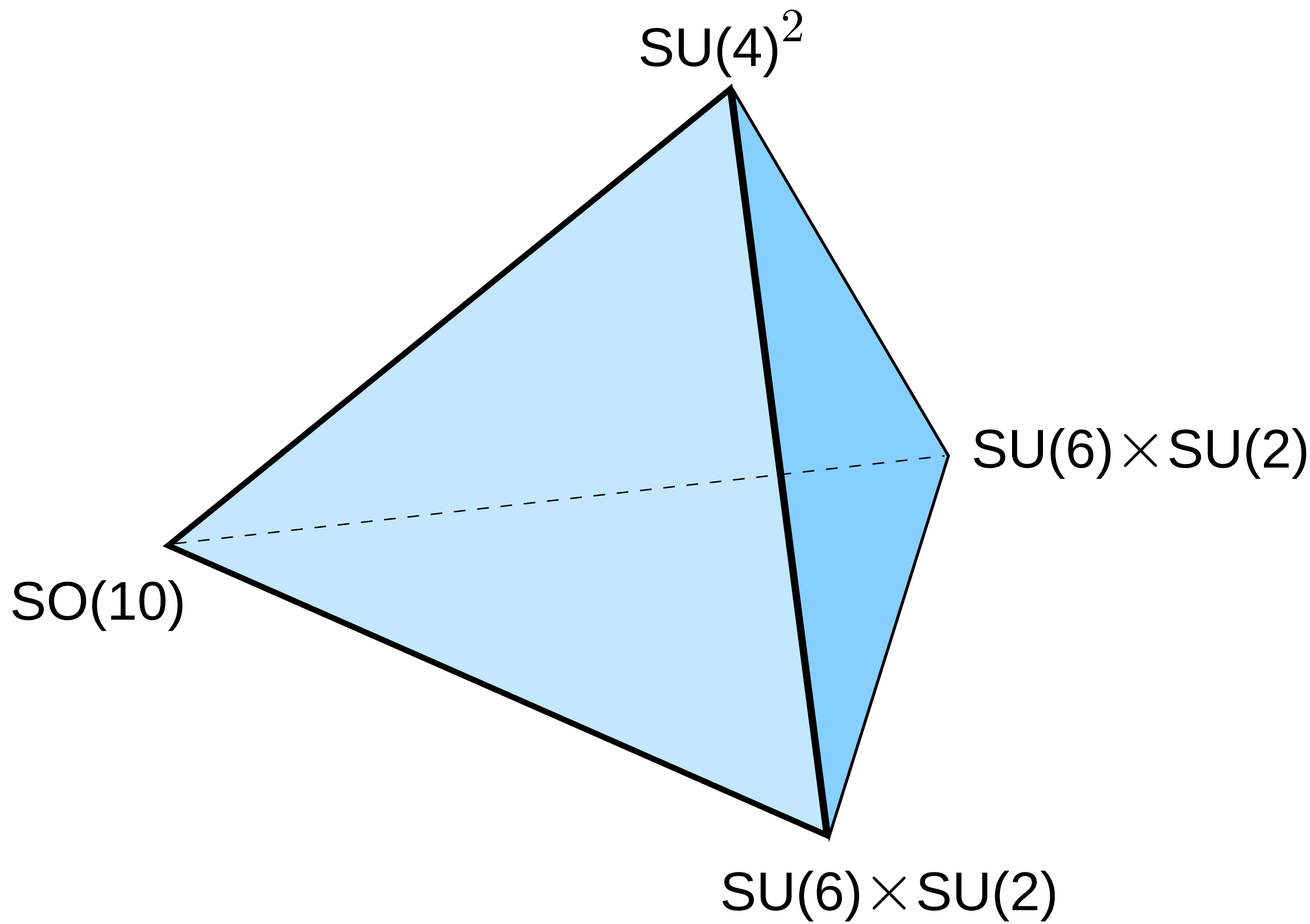
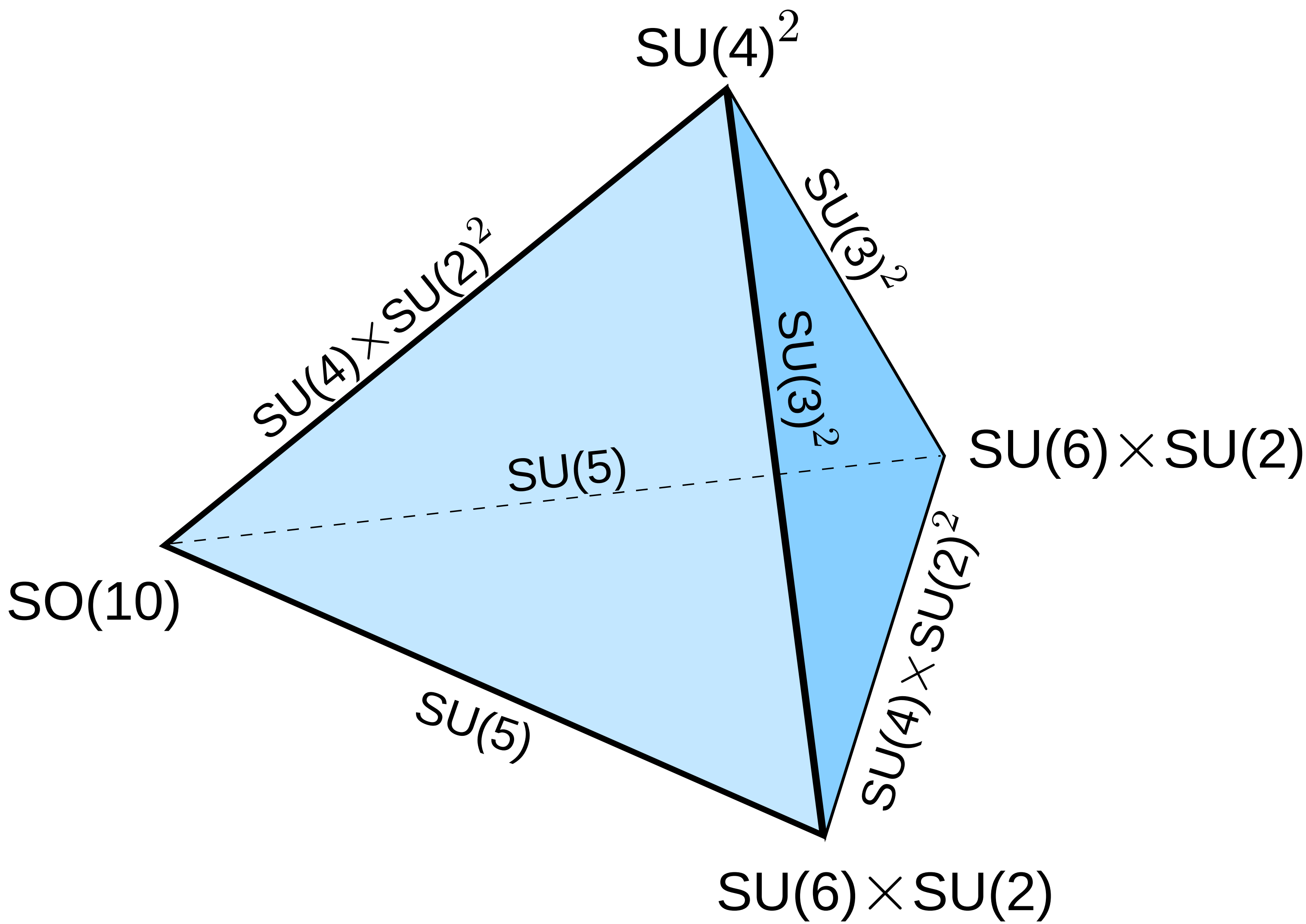
String theory serves as a UV-completion with a consistent incorporation of gravity,
and thus provides exact global symmetries.

Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Standard Model Gauge Group



MSSM

The minimal particle content of the susy extension of the standard model includes chiral superfields

- Q, $\bar{U}$, $\bar{D}$ for quarks and partners
- L, $\bar{E}$ for leptons and partners
- H_d, H_u Higgs supermultiplets

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with superpotential

$$W = QH_d\bar{D} + QH_u\bar{U} + LH_d\bar{E} + \mu H_u H_d.$$

Also allowed (but problematic) are dimension-4 operators

$$\bar{U}\bar{D}\bar{D} + QL\bar{D} + LL\bar{E}.$$

The question of proton stability

These dimension-4 operators could be forbidden by some symmetry

- like matter parity (or R-parity)
- stable LSP for dark matter

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- like matter parity (or R-parity)
- stable LSP for dark matter

But there are in addition dimension-5 operators that might mediate too fast proton decay

$$QQQL + \bar{U}\bar{U}\bar{D}\bar{E}$$

and we might need alternative symmetries like
baryon triality or proton hexality.

(Ibanez, Ross, 1991; Dreiner, Luhn, Thormeier, 2005)

Proton Hexality

	Q	$\bar{U}$	$\bar{D}$	L	$\bar{E}$	H_u	H_d	$\bar{\nu}$
$6\,Y$	1	-4	2	-3	6	3	-3	0
$\mathbb{Z}_2^{\text{matter}}$	1	1	1	1	1	0	0	1
B_3	0	-1	1	-1	2	1	-1	0
P_6	0	1	-1	-2	1	-1	1	3

Proton hexality is exactly what we need:

- dangerous dimension 4 and 5 operators forbidden
- neutrino Majorana masses allowed (LLH_uH_u)

GUTs and Hexality

Combination of GUTs and proton hexality is perfect

But GUTs and Hexality are incompatible

(Luhn, Thormeier, 2007)

Excluded are basically all GUTs

- $SU(4) \times SU(2) \times SU(2)$
- $SU(5)$ even when flipped
- $SO(10)$

Example:
the 10-dimensional representation of SU(5) includes $\bar{U}$, Q and $\bar{E}$ and they cannot all have the same charge under hexality.

Bottom up approach

Are there ways out? We could try to enhance the gauge group and get P_6 from an additional $U(1)_X$ as e.g.

- $SU(4) \times SU(2)_L \times SU(2)_R \times U(1)_X$
- broken to $SU(3) \times SU(2)_L \times U(1) \times Z_{12}$
- where Z_{12} acts a P_6 on the standard model sector

But this is not really a grand unified theory. Closer to GUTs might be

- $SO(10) \times U(1)_X$ broken to
- $SU(4) \times SU(2)_L \times SU(2)_R \times P_6$
- with $(4, 2, 1)_1$ and $(\bar{4}, 1, 2)_{-1}$

Split multiplets

In fact we could consider

$$SO(12) \to SO(10) \times U(1)_X \to SU(3) \times SU(2)_L \times U(1) \times P_6$$

This would mean that P_6 is a subgroup of $SO(12)$
(in the same way as matter parity is a subgroup of $SO(10)$)

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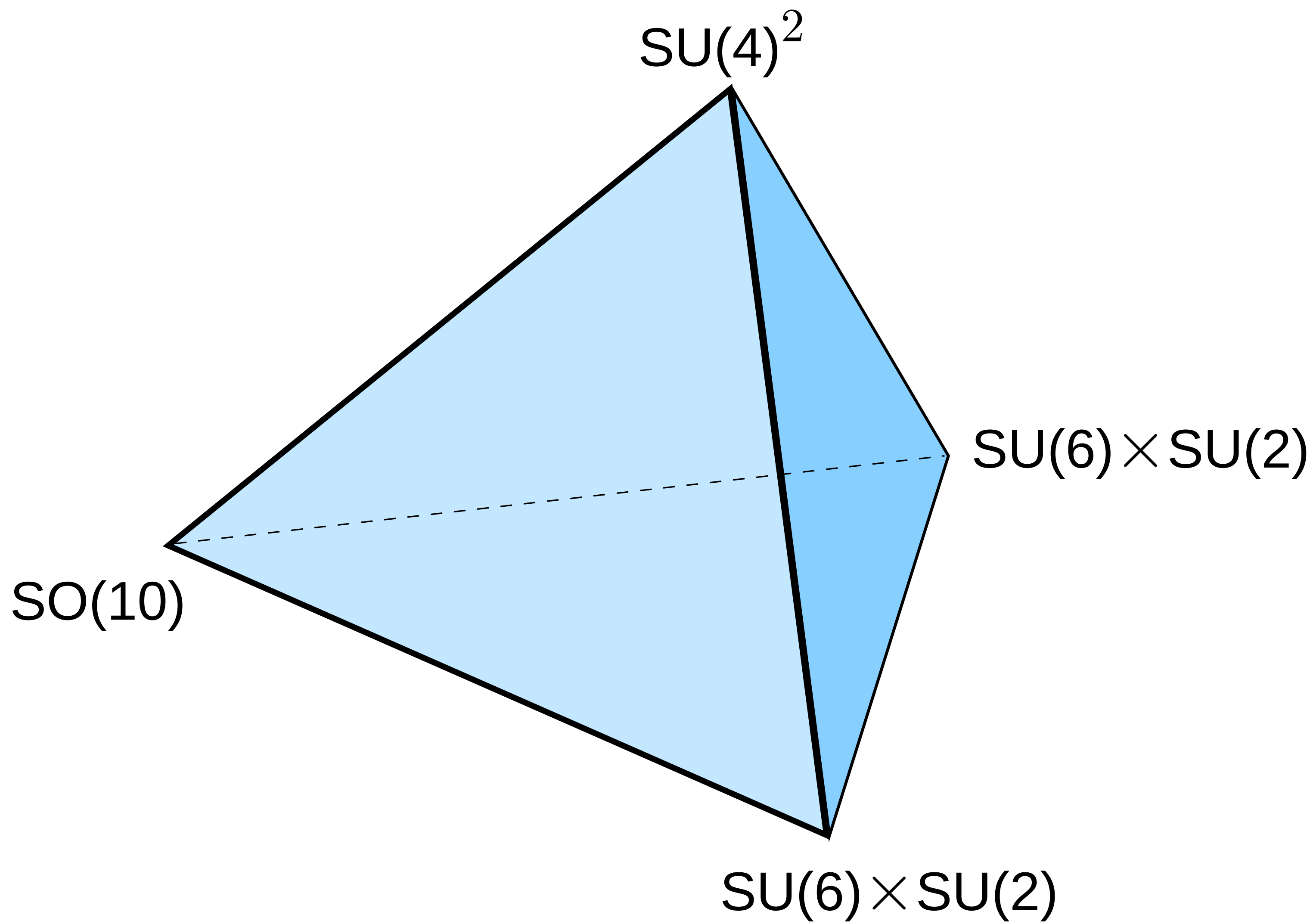
Consequences:

- we need representations of (ridiculously) high dimensionality to break $SO(12)$ (analogue of 126 of $SO(10)$ for matter parity)
- appearance of split multiplets

This is exactly what we get in the framework of local grand unification in the braneworld picture.

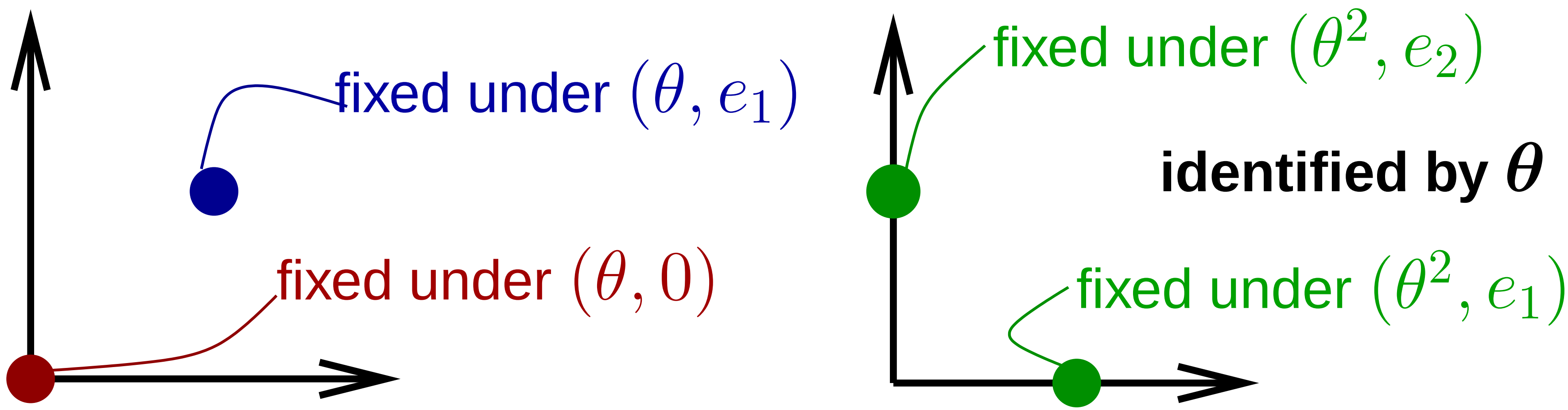
Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

A T_2/Z_4 toy example

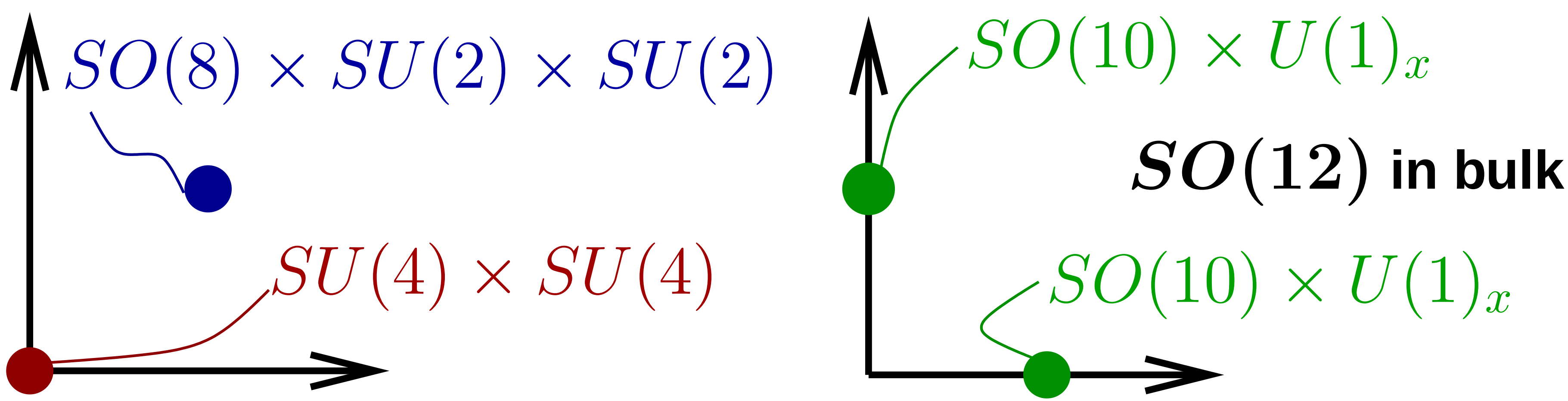
Consider the T_2/Z_4 orbifold, where we have two different types of fixed points



under rotation of $\theta = \pi/2$ and shift of the lattice vectors.

A T_2/Z_4 toy example

For a suitable embedding of twist and shift in the gauge group $SO(12)$ we have the following
local gauge group structure



This allows split representations compatible with P_6 and does not require huge representations for the breakdown of $SO(12)$.

The top-down picture

Can we incorporate this in globally consistent string models? The above example of P_6 from $SO(12)$

- has been realized in a $T_6/(Z_4 \times Z_4)$ orbifold
- with vectorlike exotics

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Models of the Mini-Landscape T_6/Z_6

- would have SU(6) instead of SO(12)
- are not too well suited
- but proton hexality could come from an accidental $U(1)$ symmetry

Lessons

Hexality can appear in the framework of the heterotic braneworld as

- a subgroup of a nonanomalous gauge symmetry
- a subgroup of a anomalous gauge symmetry
- accidental global symmetry

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Note that we have consistent string models with exact global symmetries.

So we do not have to discuss things like “anomaly free discrete symmetries”, that might be useful in a bottom-up approach.

Outlook

String theory might provide us with a consistent UV-completion of the MSSM including

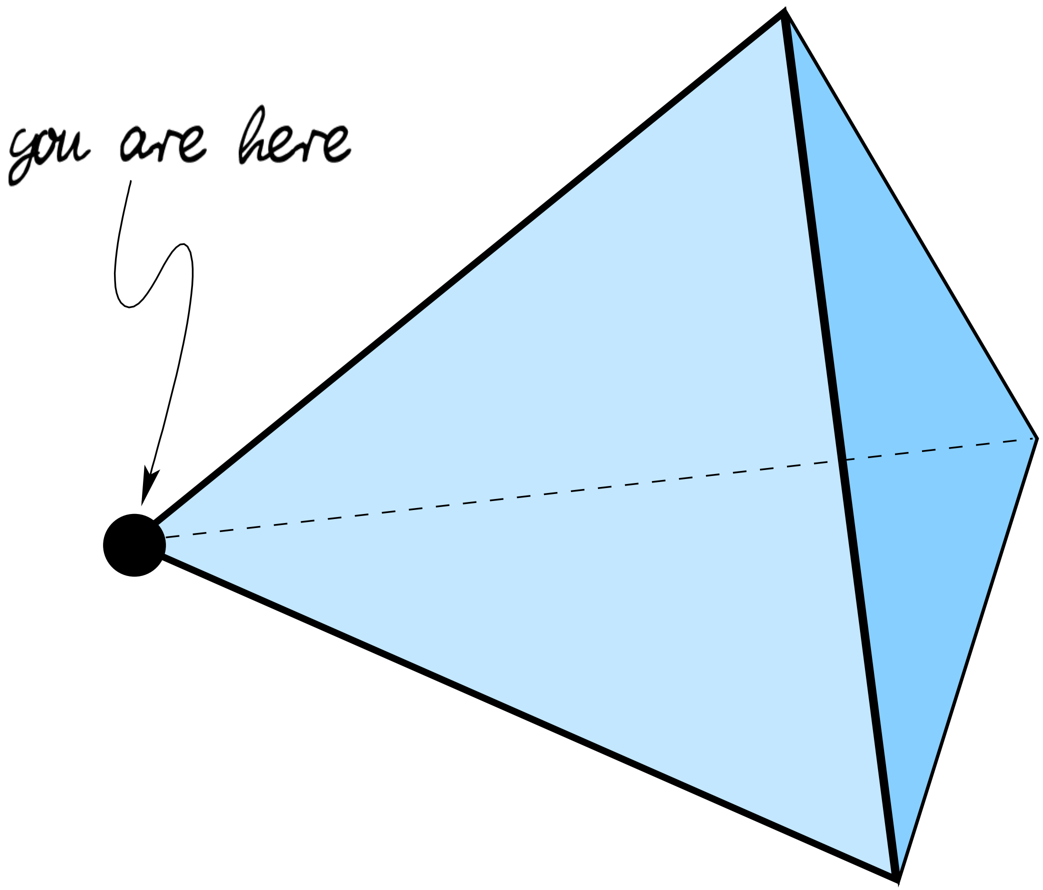
- Local Grand Unification and
- discrete (accidental) symmetries.

Geography of extra dimensions plays a crucial role:

Local Grand Unification is the right way to proceed.

We seem to live at a special place in the extra dimensions!

Where do we live?



Comparison to TypeII braneworld

- strategy based on geometrical intuition is successful
- properties of models can trace back the geometry of extra dimensions
- heterotic versus Type II braneworld
  - bulk gauge group
  - complete chiral multiplets
  - chiral exotics
  - R-parity (B-L and seesaw mechanism)
- localization of fields at various “corners” of Calabi-Yau manifold
- remnants of Grand Unification indicate that we live in a special place of the compactified extra dimensions!

Conclusion

String theory provides us with new ideas for particle physics model building, leading to concepts such as

- MSSM via Local Grand Unification
- Accidental symmetries (of discrete origin)

Geography of extra dimensions plays a crucial role:

- localization of fields on branes,
- sequestered sectors and mirage mediation

We seem to live at a special place in the extra dimensions!

The LHC might clarify the case for (local) grand unification.