Heterotic Brane world:
the Geography of Extra Dimensions

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Outline

- MSSM and Grand Unification
- Heterotic string compactifications
- Gauge group geography in extra dimensions
- Local Grand Unification
- A fertile patch of the landscape
- Hidden sector susy breakdown
- The Benchmark model
- Comparison to type II braneworld
- Outlook

Bottom-up input

Experimental findings suggest the existence of two new scales of physics beyond the standard model

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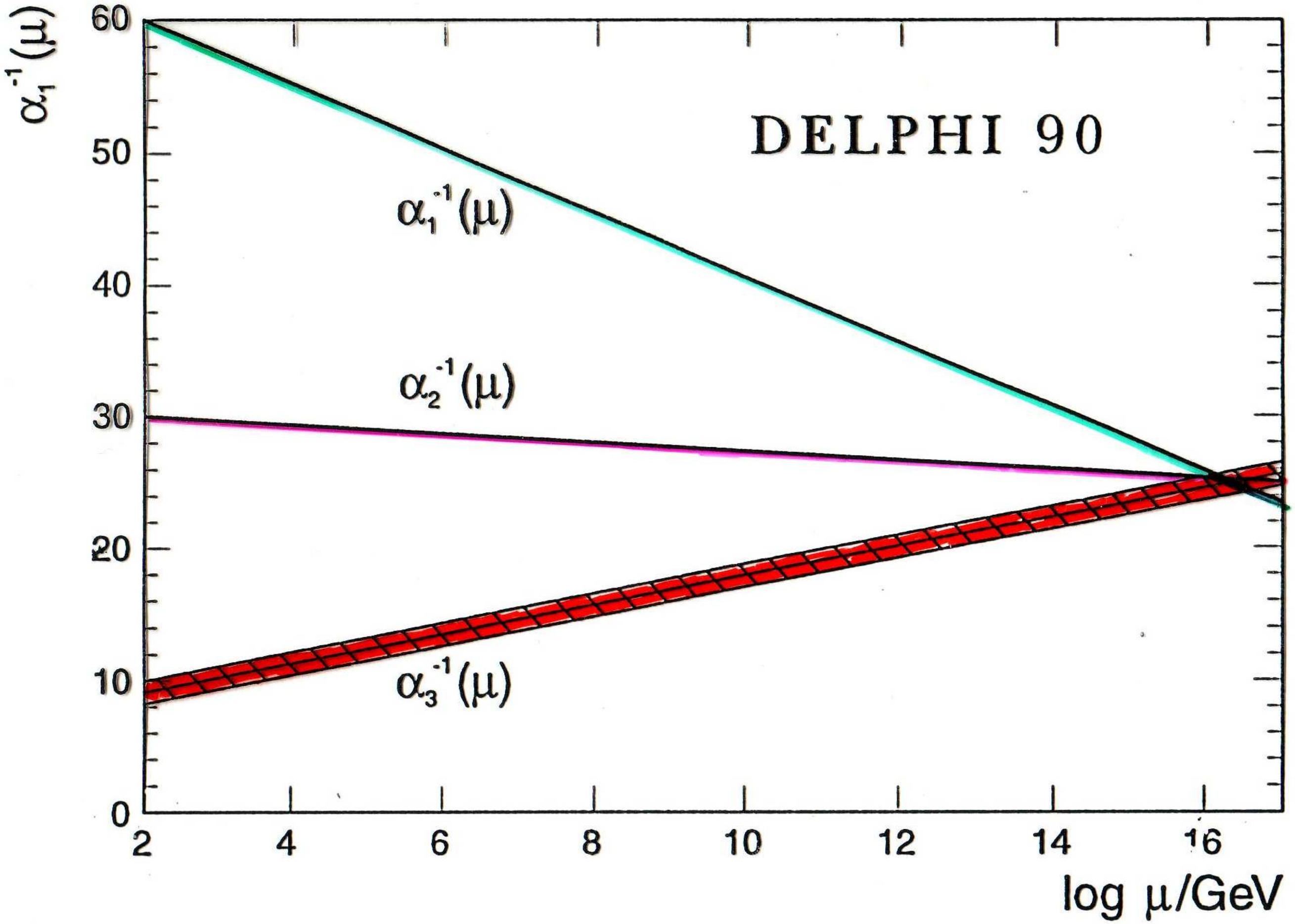
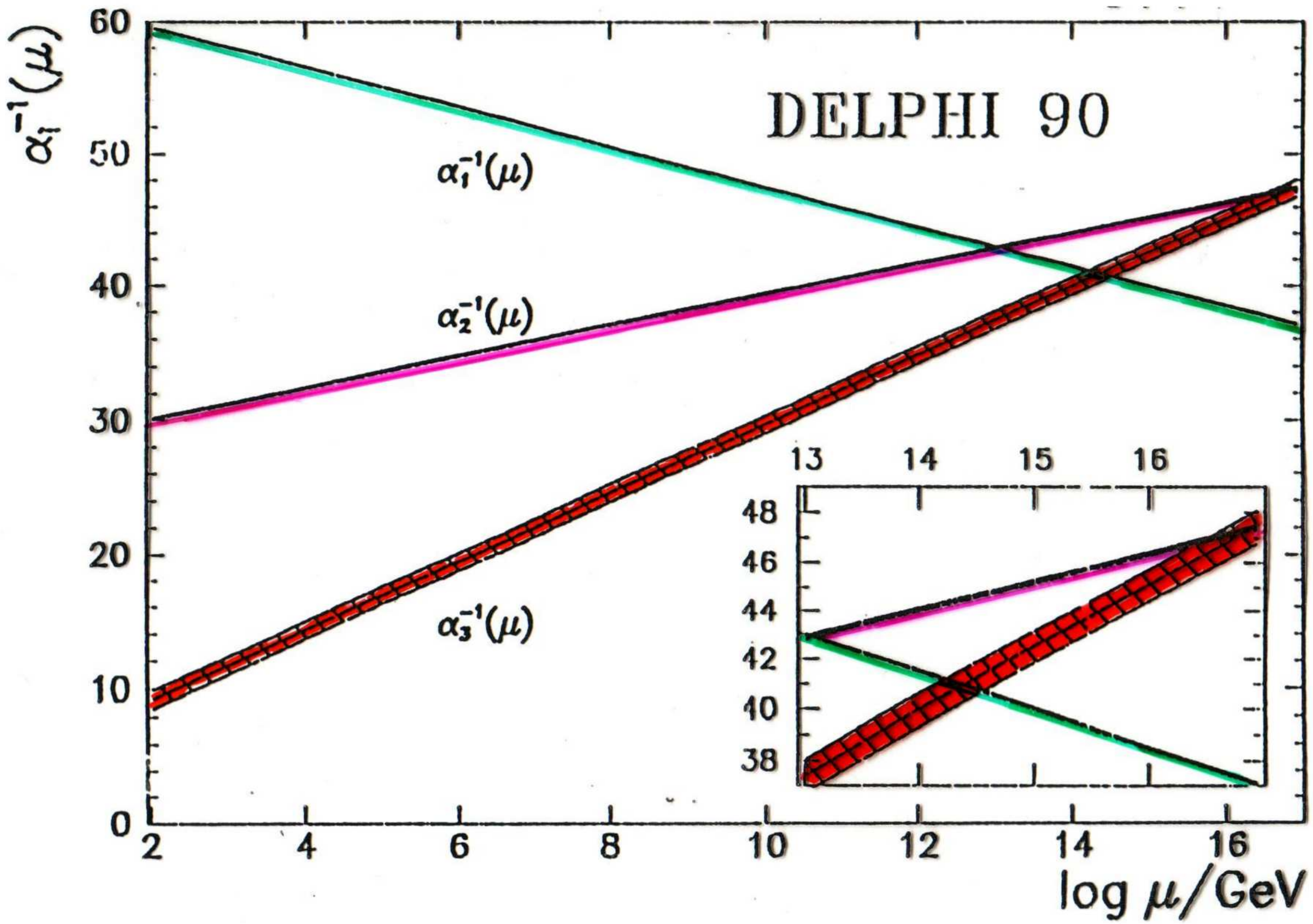
- Evolution of couplings constants of the standard model towards higher energies.

MSSM (supersymmetric)



Standard Model



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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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....or in eleven

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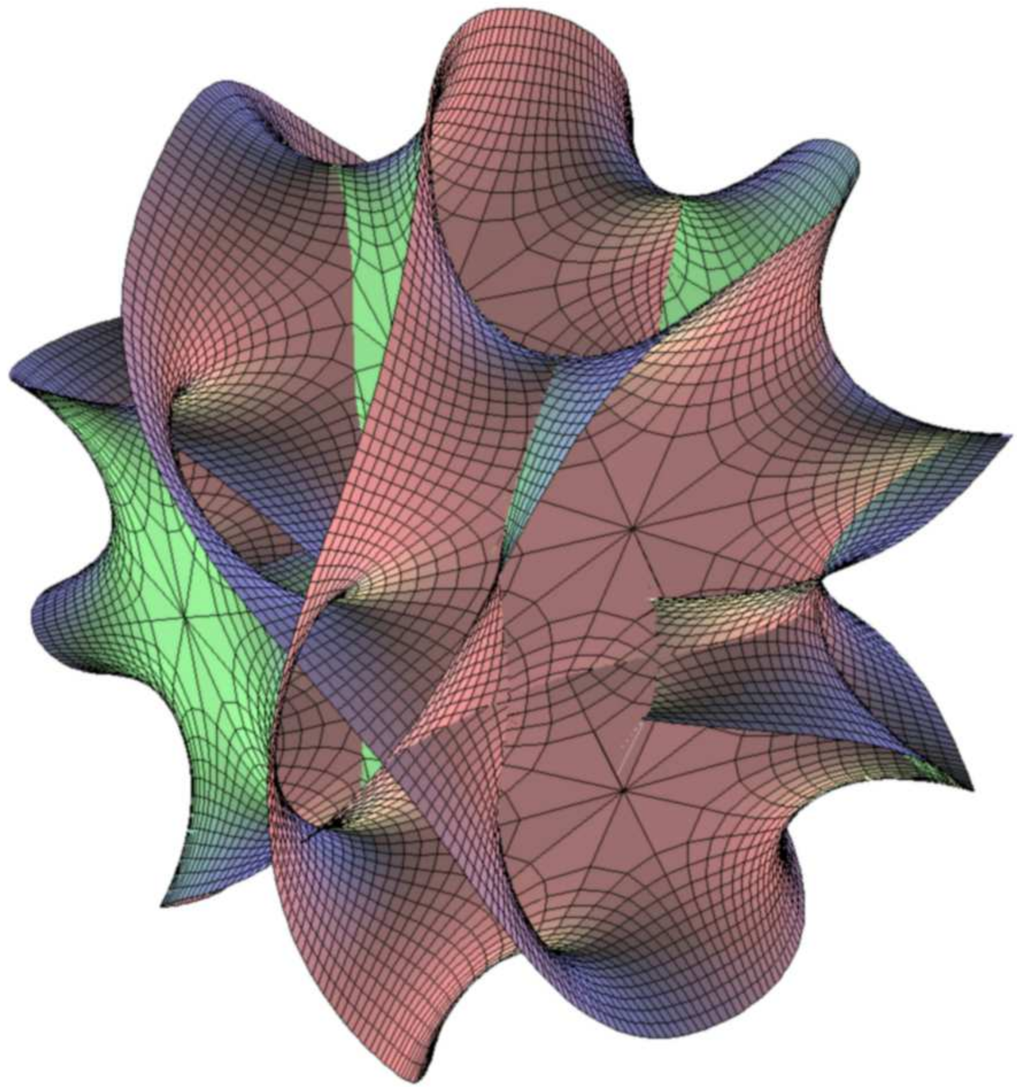
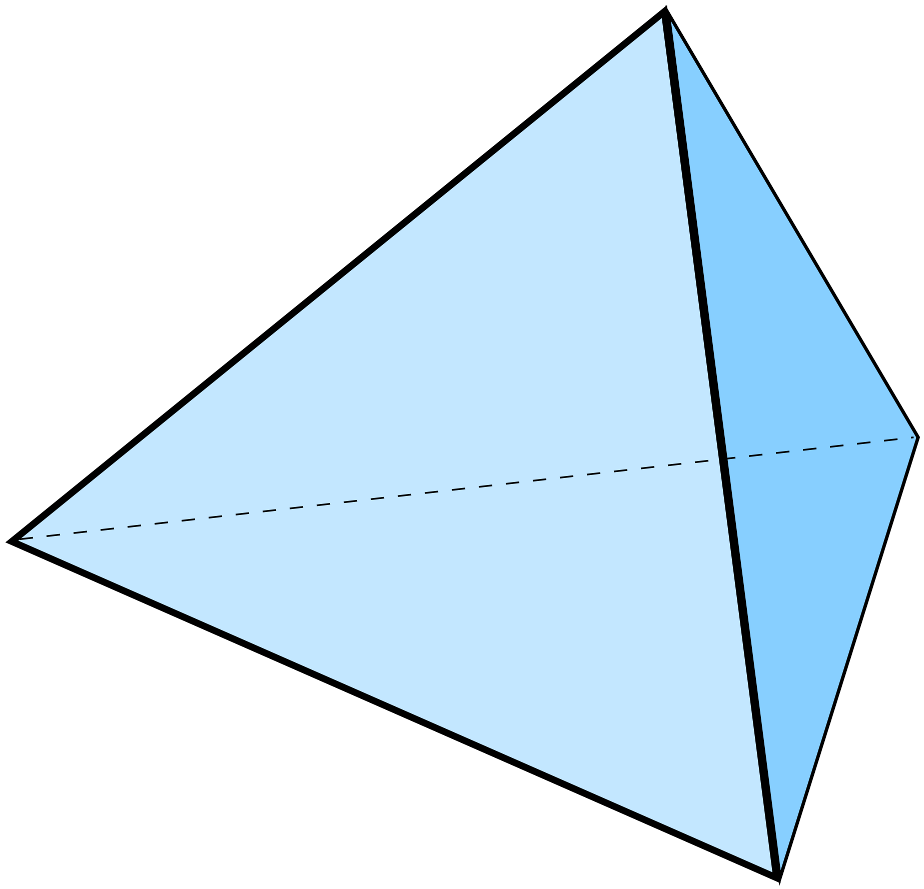
These are the building blocks for a unified theory of all the fundamental interactions.
But do they fit together, and if yes how?

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

Calabi Yau Manifold



Orbifold



Orbifolds

Orbifold compactifications combine the

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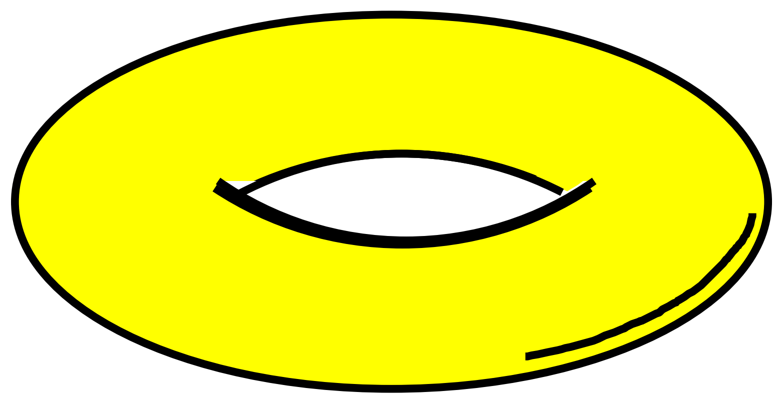
In case of the heterotic string fields can propagate

- 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)

Torus T_2



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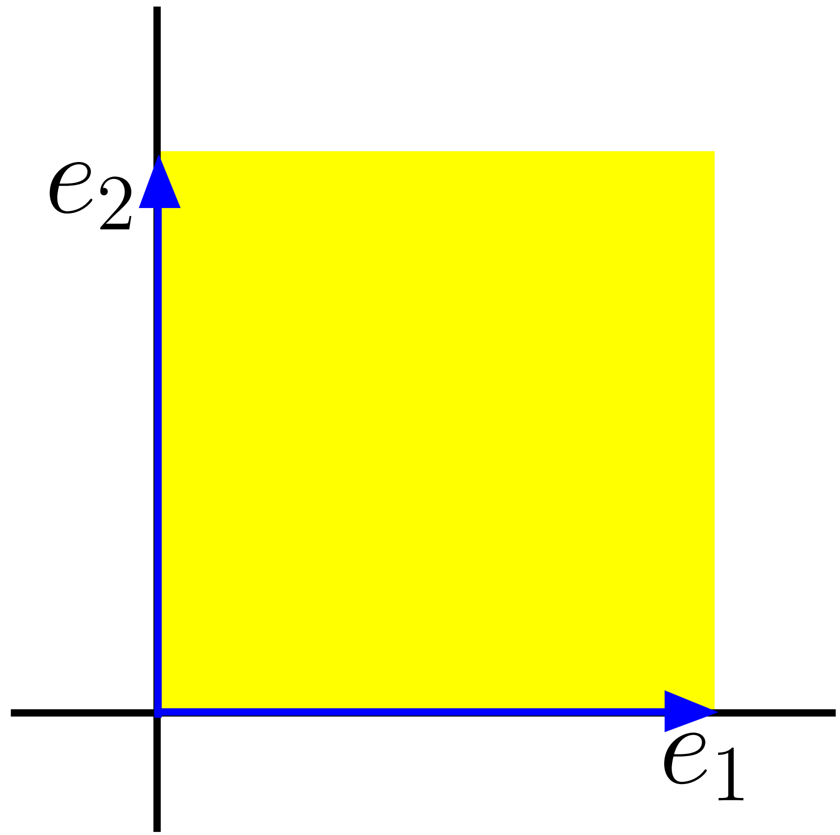
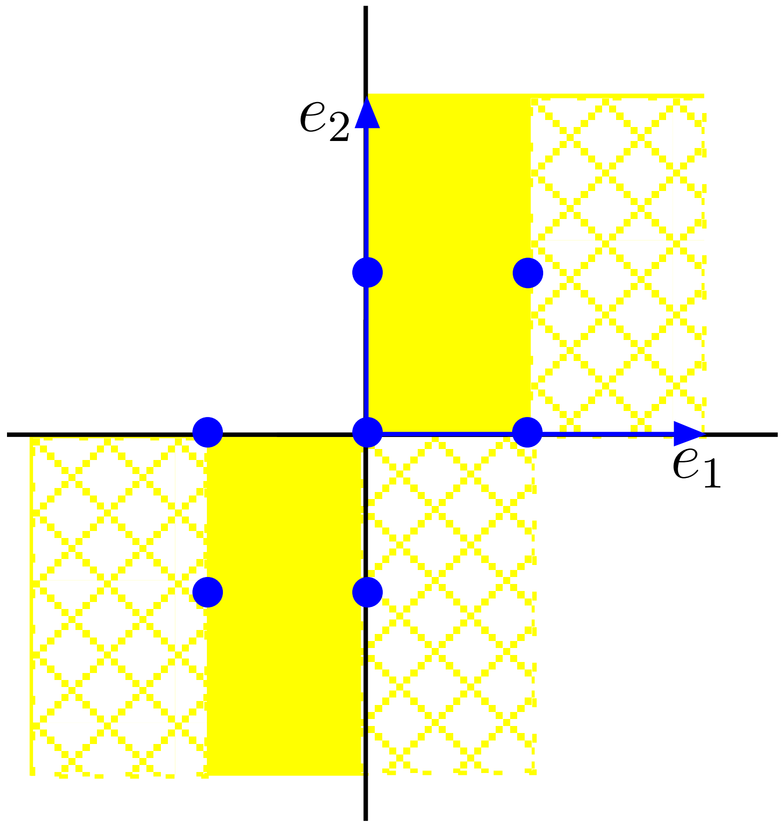
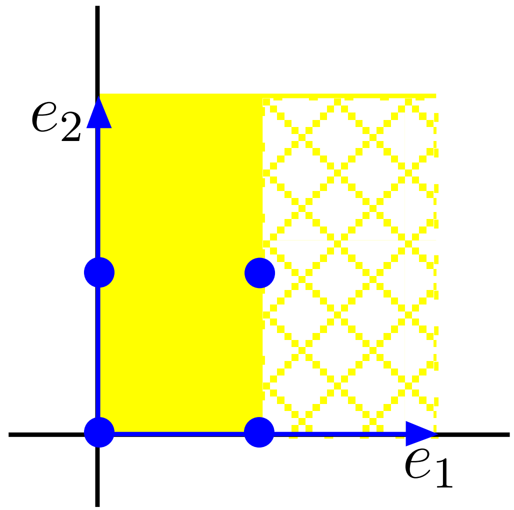


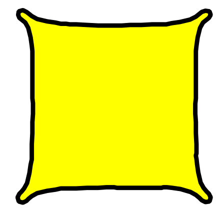
Orbifolding



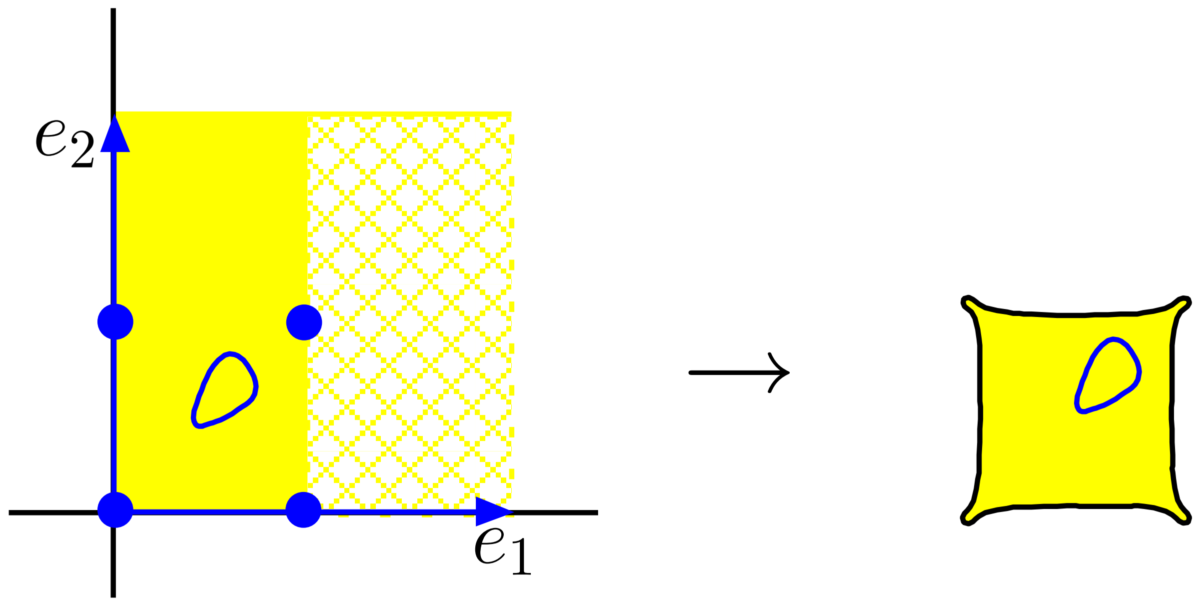
Ravioli



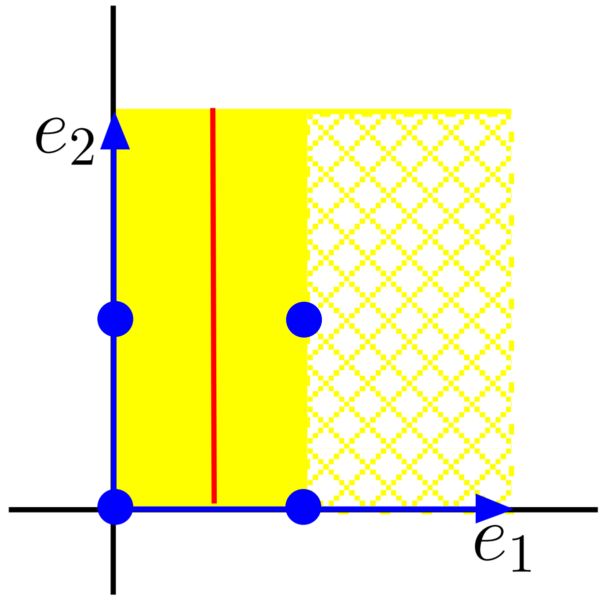
$\longrightarrow$



Bulk Modes



Winding Modes



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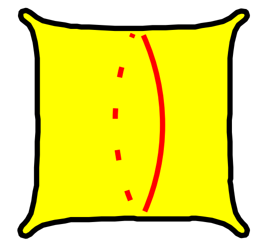
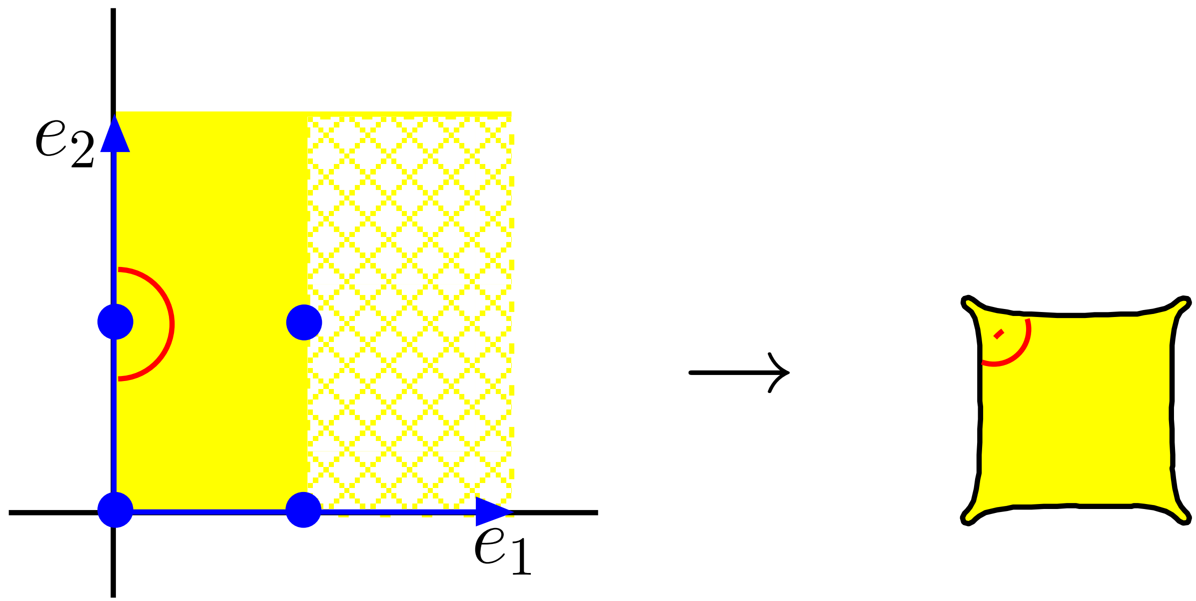
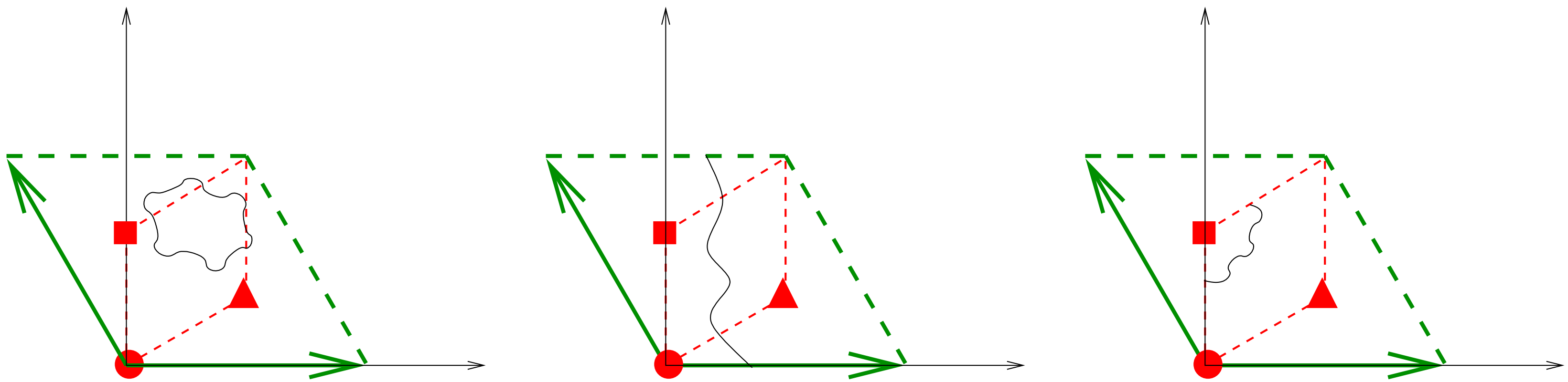


Brane Modes



$\mathbb{Z}_3$ Example



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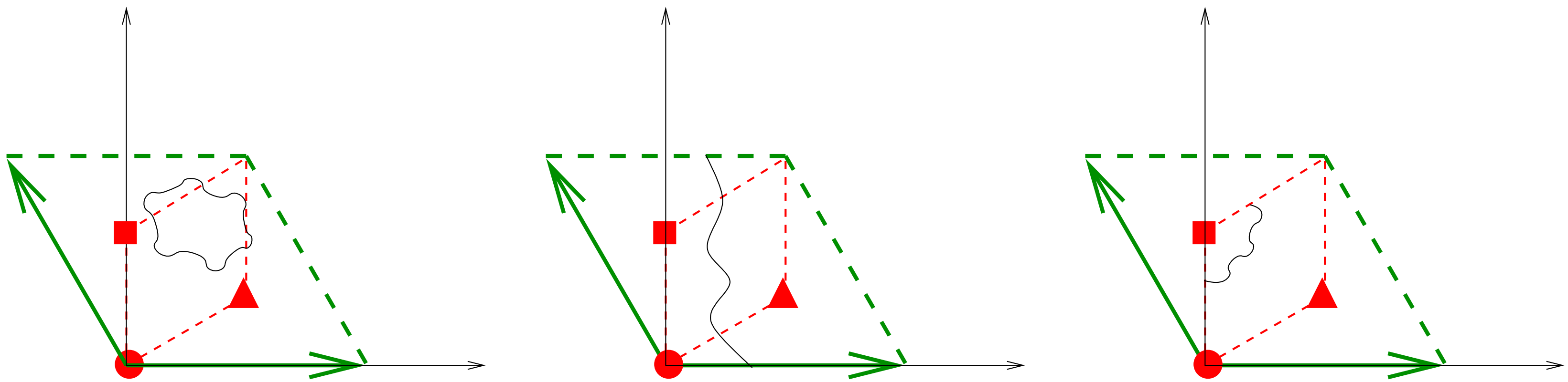

- Action of the space group on coordinates

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

- 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.
1	$\left(\frac{1}{3},\frac{1}{3},\frac{2}{3},0^5\right)\left(0^8\right)$	$\mathrm{E}_6\times\mathrm{SU}(3)\times\mathrm{E}_8'$	36
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3	$\left(\frac{1}{3},\frac{1}{3},0^6\right)\left(\frac{2}{3},0^7\right)$	$\mathrm{E}_7\times\mathrm{U}(1)\times\mathrm{SO}(14)'\times\mathrm{U}(1)'$	0
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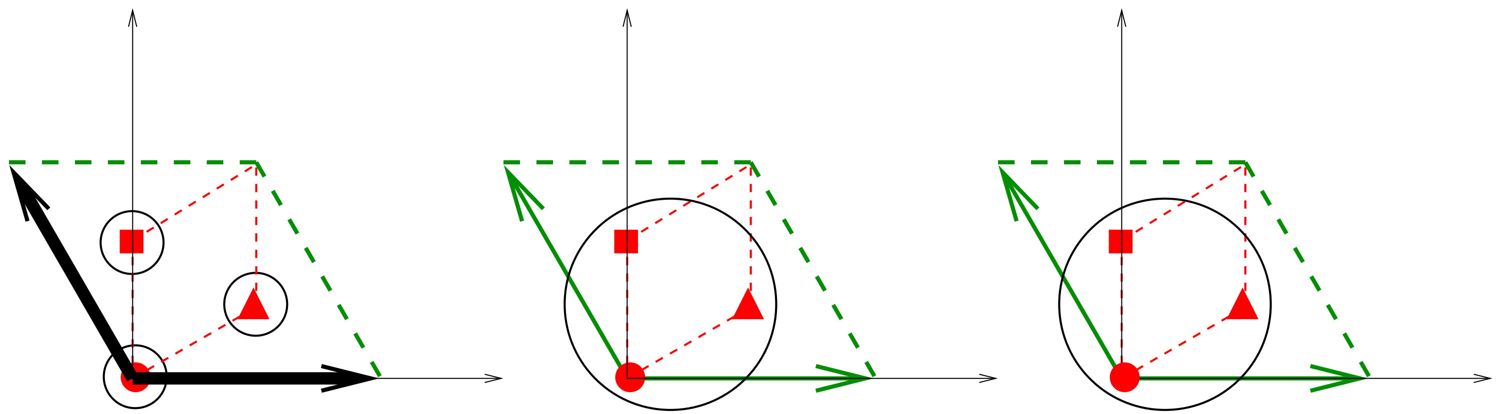
We need to lift this degeneracy ...

$\mathbb{Z}_3$ Orbifold with Wilson lines



Torus shifts embedded in gauge group as well

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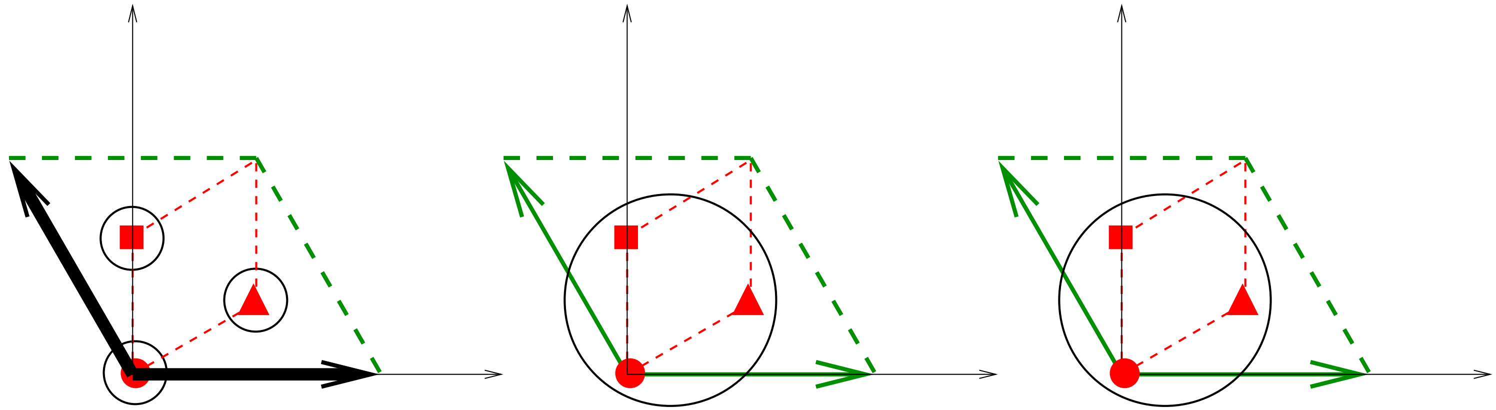

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- further gauge symmetry breakdown
- number of generations reduced

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Can we incorporate this into a string theory description?

Five golden rules

- Family as spinor of SO(10)
- 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

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Remnants of $SO(10)$ symmetry

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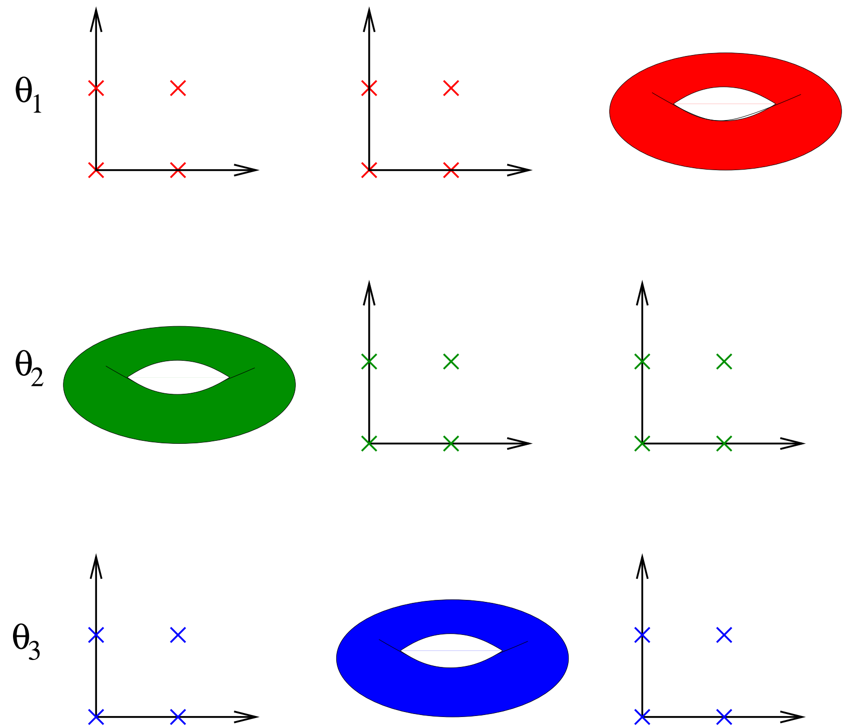
From this point of view, the Z_{2N} or $Z_N \times Z_M$ orbifolds do look more promising

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



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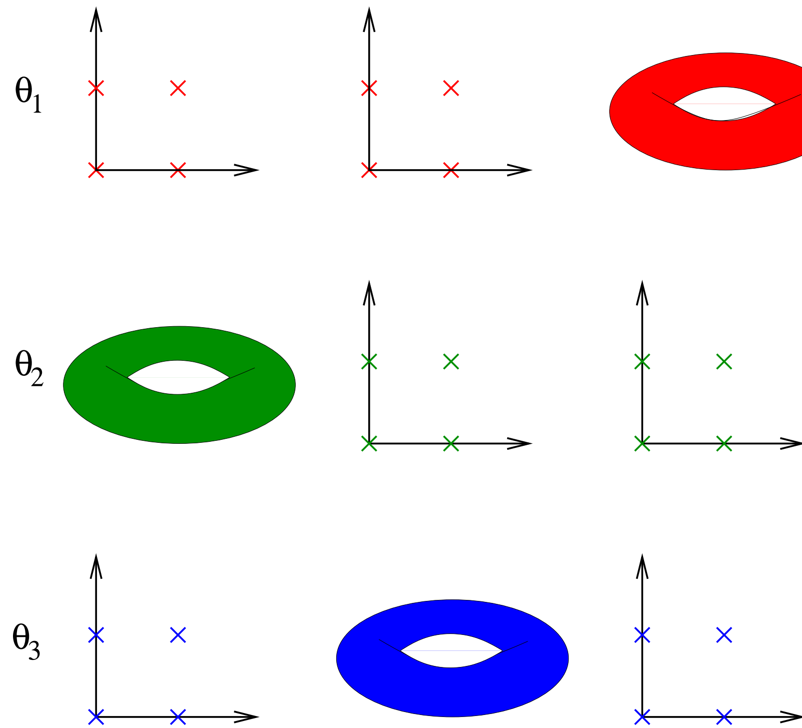
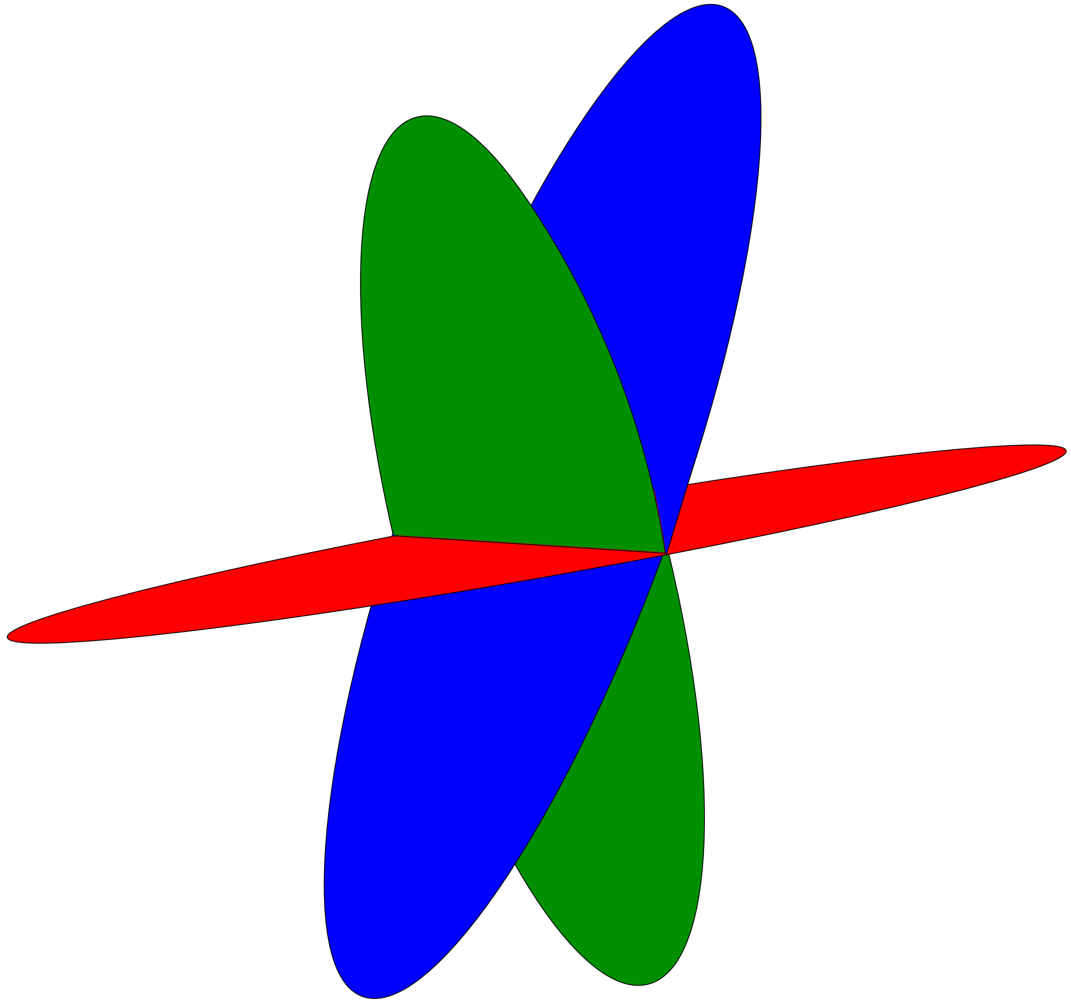


3 twisted sectors (with 16 fixed tori in each) lead to a geometrical picture of ....

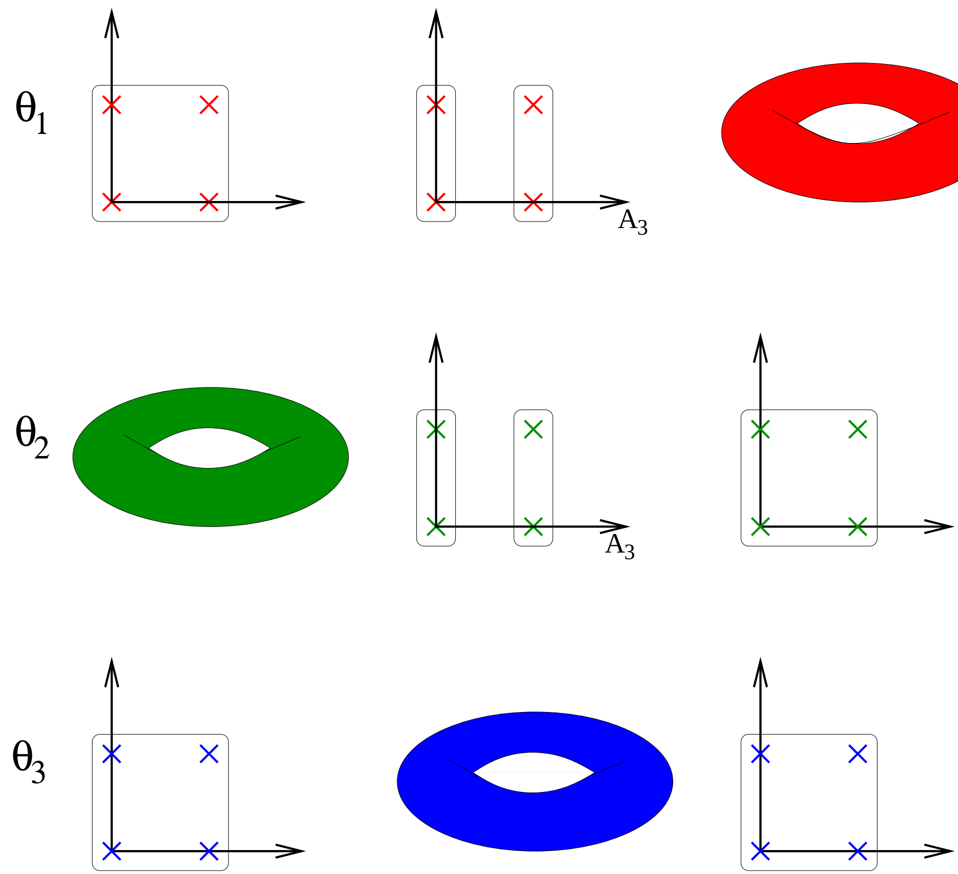
Intersecting Branes



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

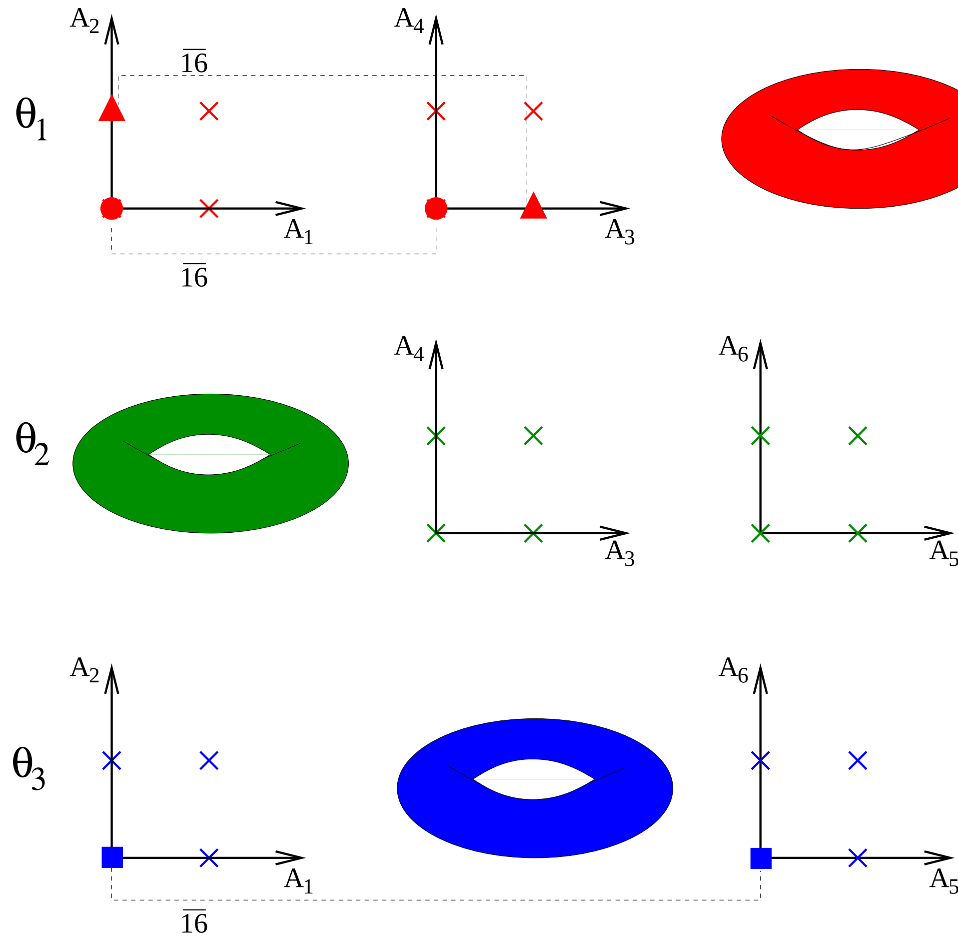
Case	Shifts	Gauge Group	Gen.
1	$\left(\frac{1}{2}, -\frac{1}{2}, 0^6\right)\ \left(0^8\right)$ $\left(0, \frac{1}{2}, -\frac{1}{2}, 0^5\right)\ \left(0^8\right)$	$\mathsf{E}_6 \times \mathsf{U}(1)^2 \times \mathsf{E}_8'$	48
2	$\left(\frac{1}{2}, -\frac{1}{2}, 0^6\right)\ \left(0^8\right)$ $\left(0, \frac{1}{2}, -\frac{1}{2}, 0^4, 1\right)\ \left(1, 0^7\right)$	$\mathsf{E}_6 \times \mathsf{U}(1)^2 \times \mathsf{SO}(16)'$	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



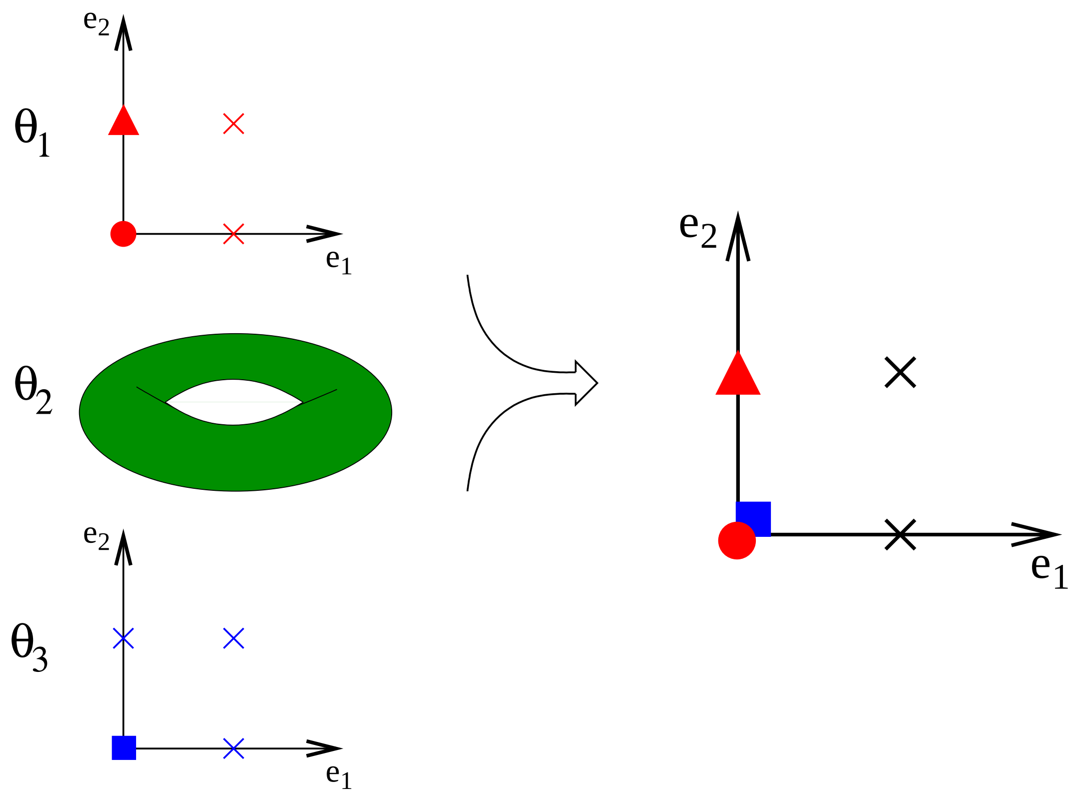
Again, Wilson lines can lift the degeneracy....

Three family $SO(10)$ toy model



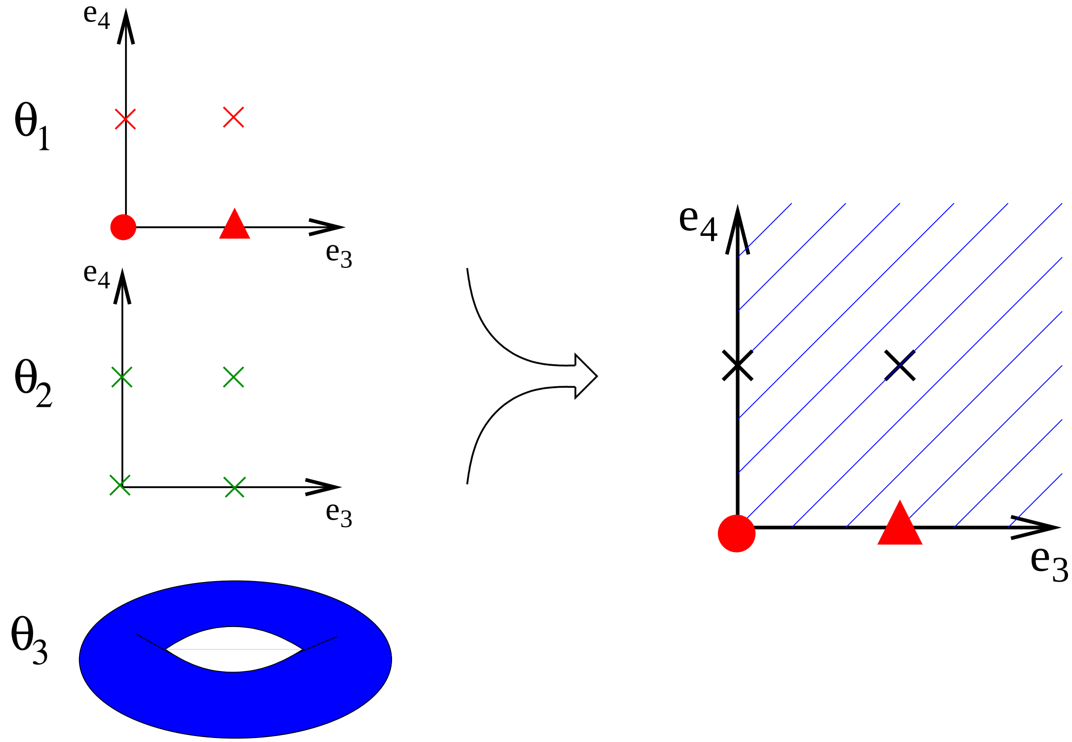
Localization of families at various fixed tori

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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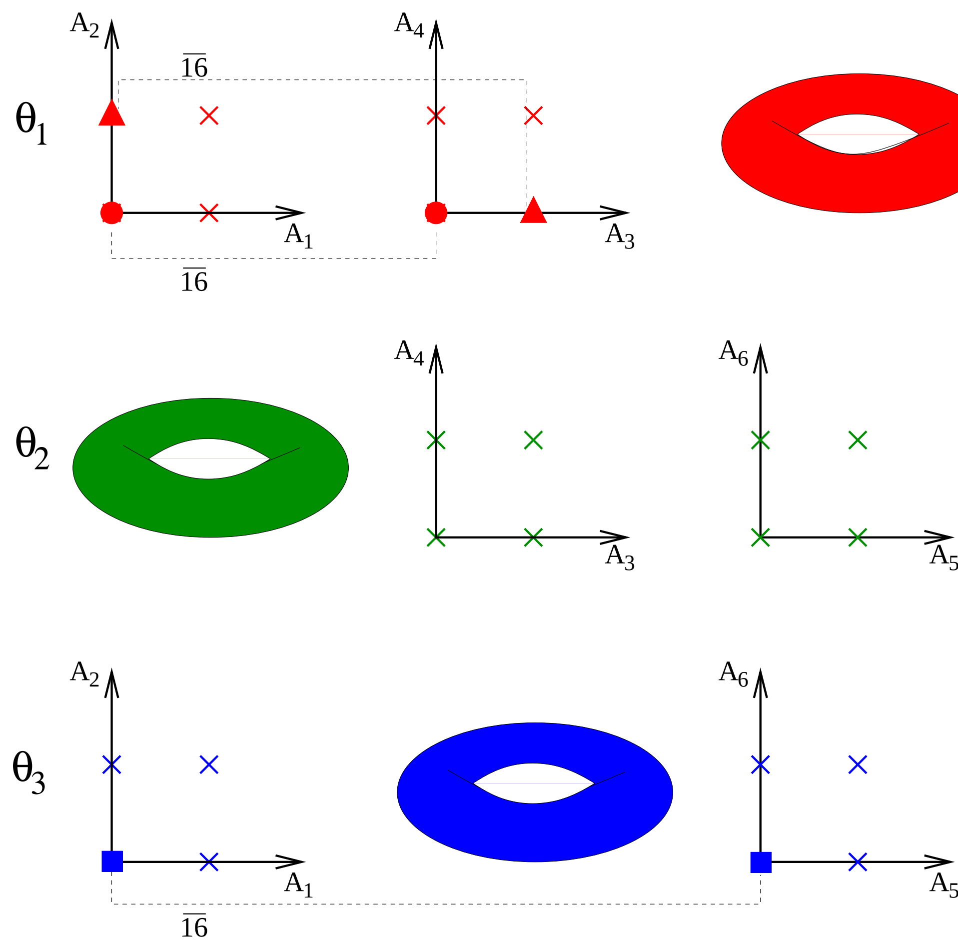

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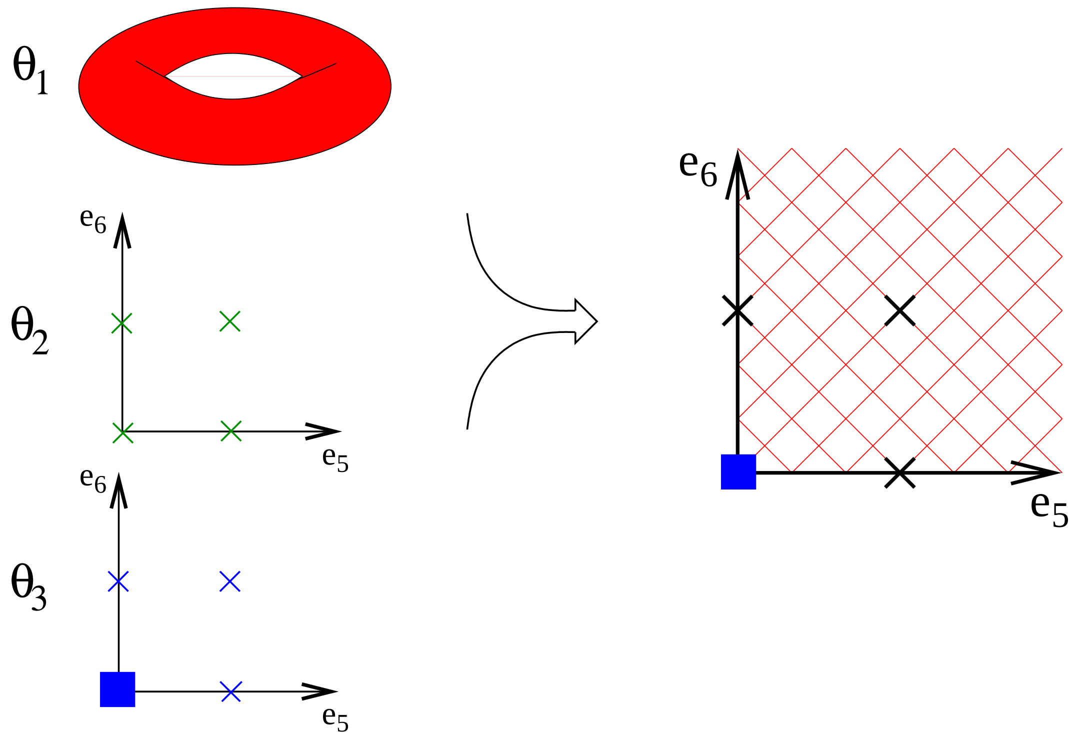

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Geography

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

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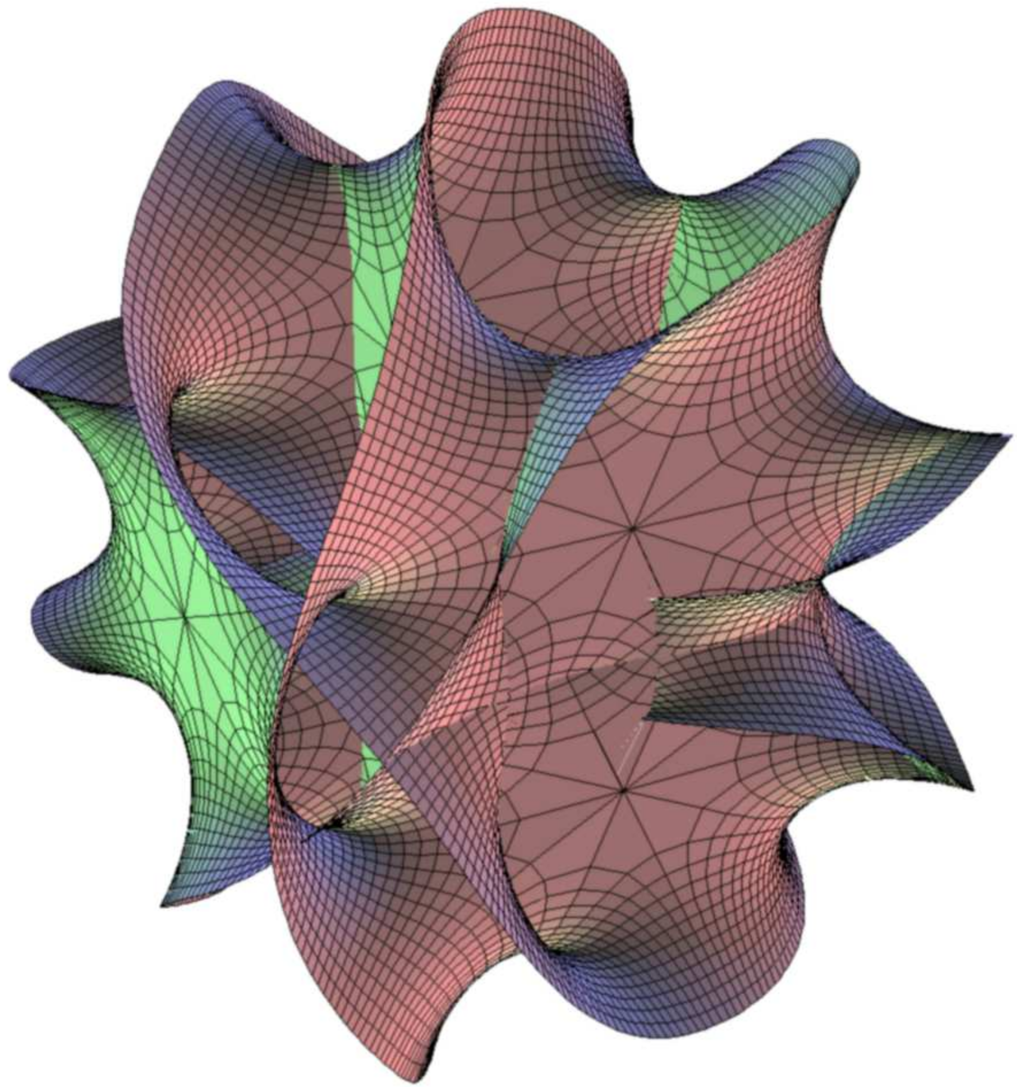
but there is also a “localization” of gauge fields

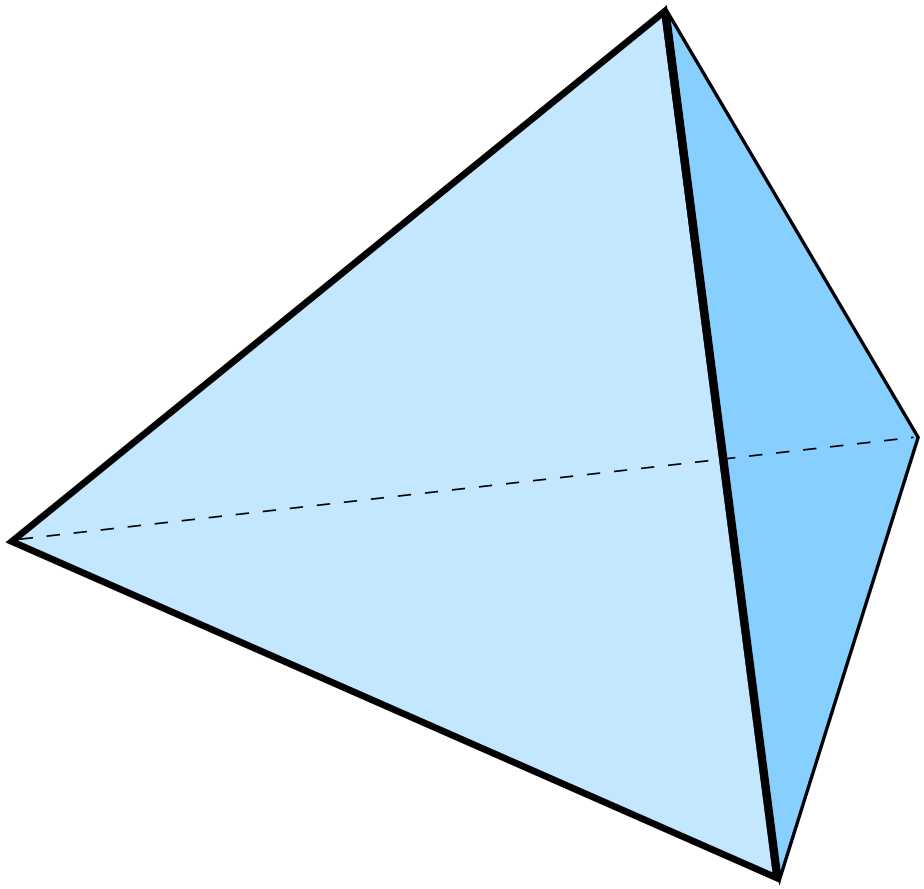
- $E_8 \times E_8$ in the bulk
- smaller gauge groups on various branes

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

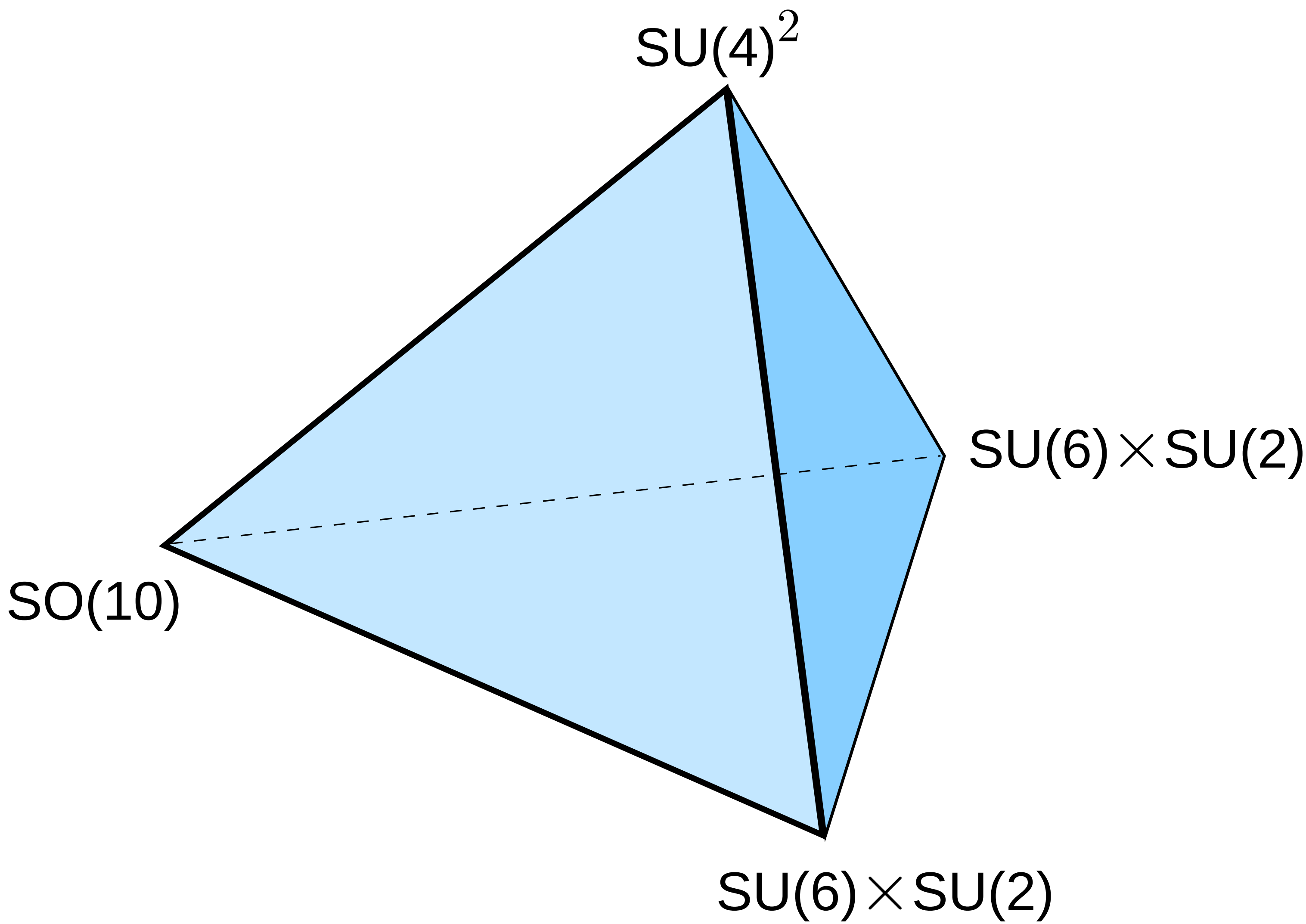
Calabi Yau Manifold



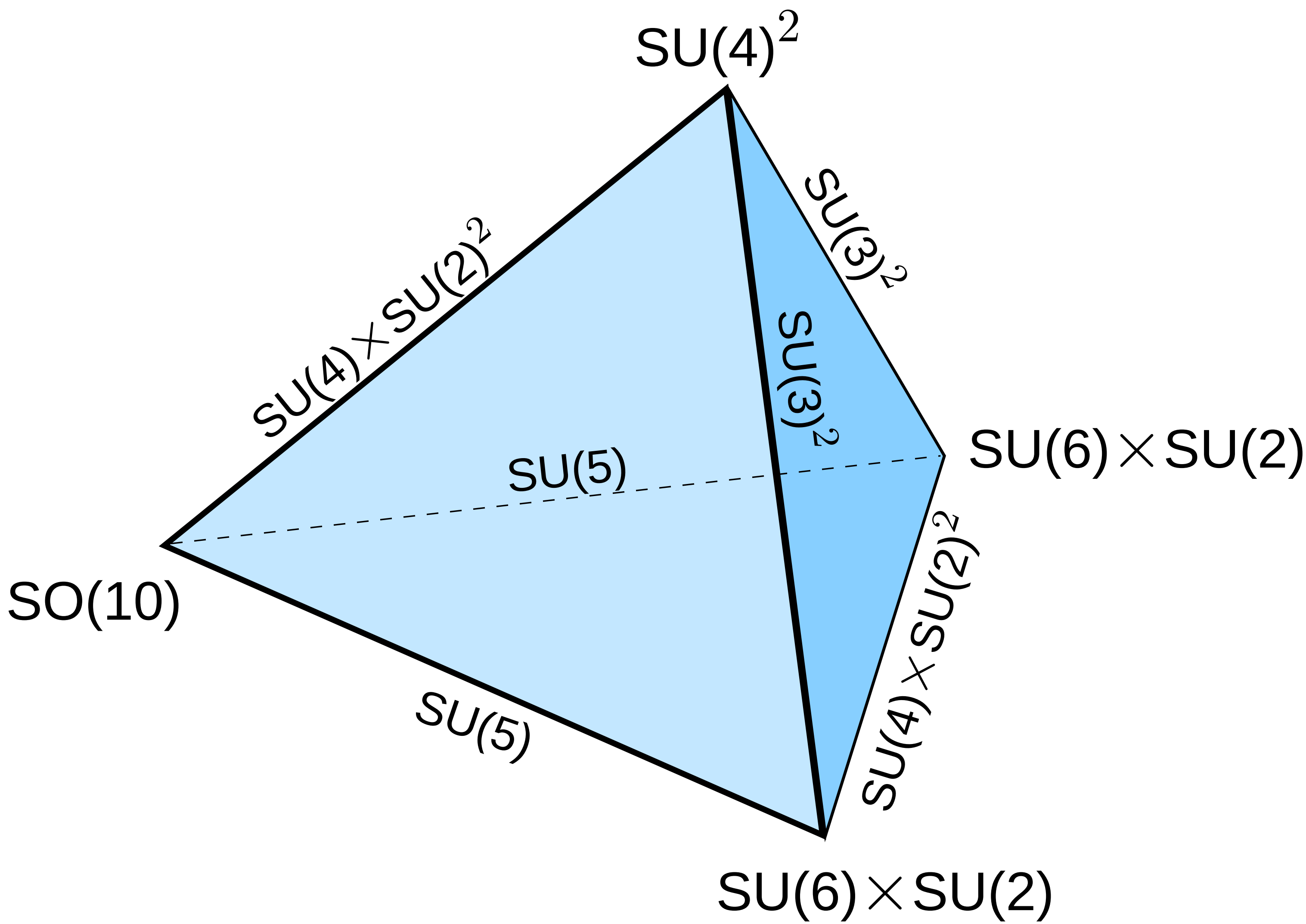
Orbifold



Localized gauge symmetries



Standard Model Gauge Group



Model building

We can easily find

- models with gauge group $SU(3) \times SU(2) \times U(1)$
- 3 families of quarks and leptons
- doublet-triplet splitting
- $N = 1$ supersymmetry

(Förste, HPN, Vaudrevange, Wingerter, 2004)

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But explicit model building is tedious:

- removal of exotic states
- R parity
- “correct” hypercharge

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Key properties of the models depend on geometry:

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- number of families
- local gauge groups on branes
- electroweak symmetry breakdown

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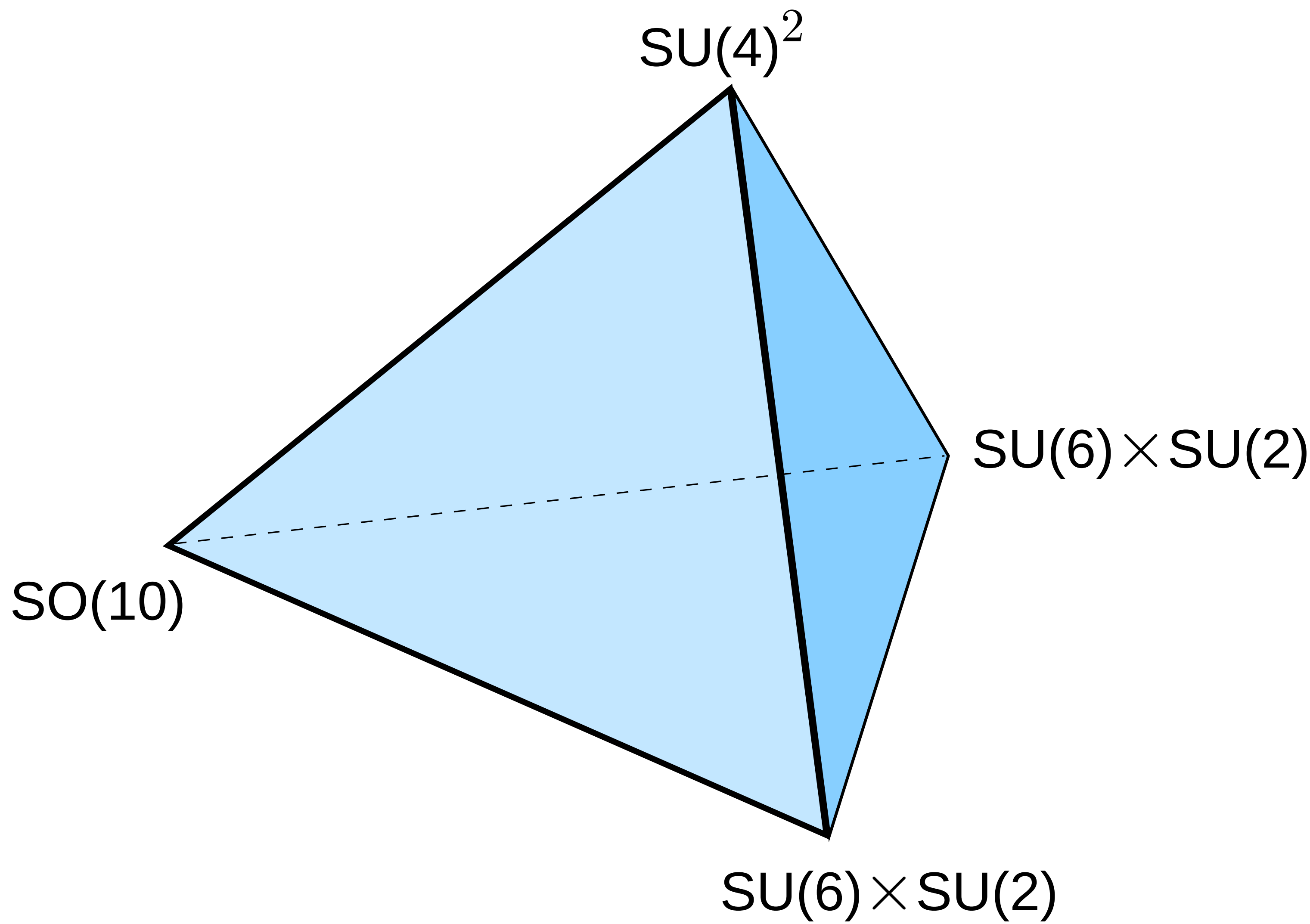
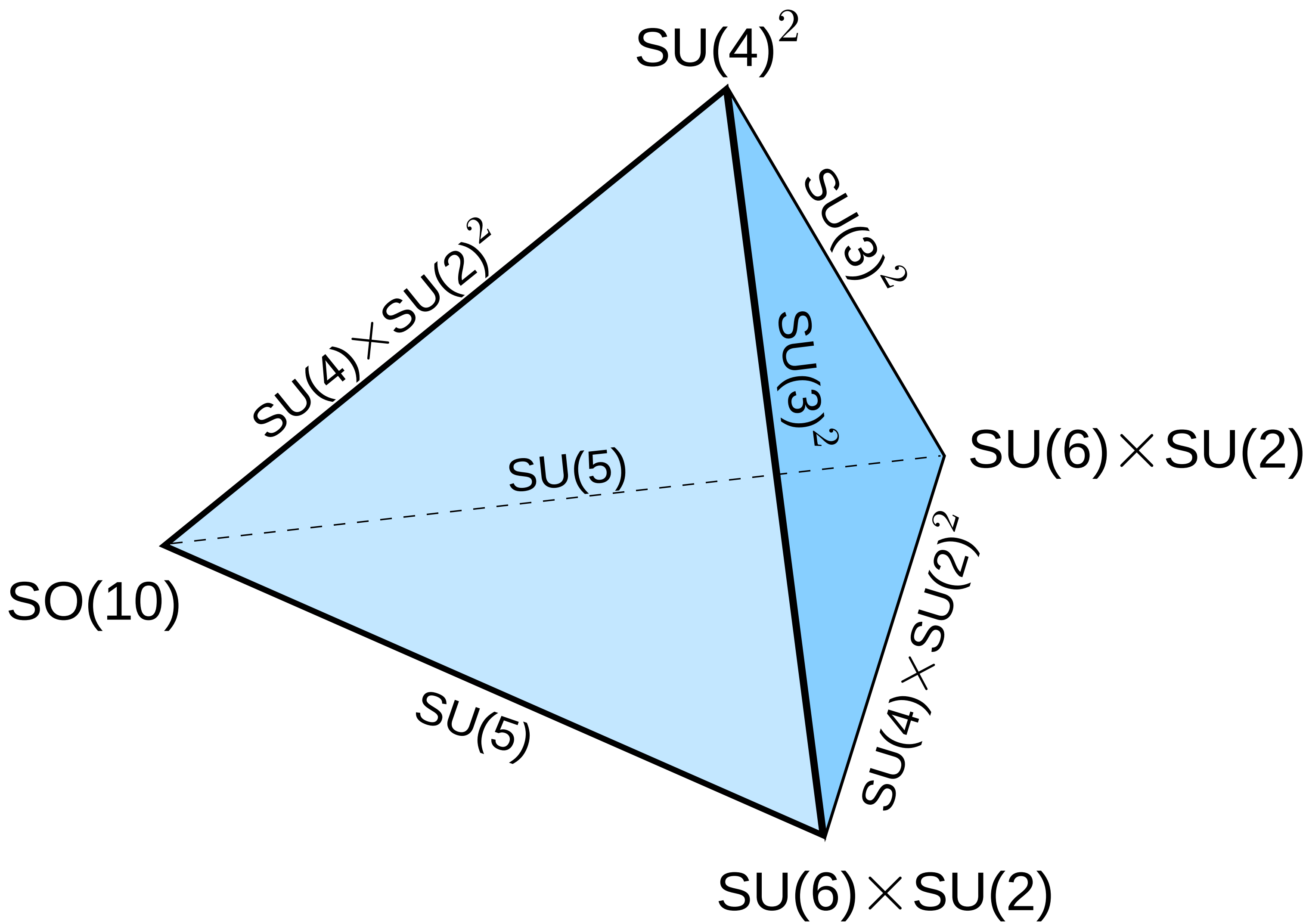
We need to exploit these geometric properties......

Localized gauge symmetries



Standard Model Gauge Group



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".

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

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There could still be remnants of $SO(10)$ symmetry

- 16 of SO(10) at some branes
- correct hypercharge normalization
- R-parity
- family symmetries

that are very useful for realistic model building ...

Proton decay

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There are lots of opportunities,

but there is a strong model dependence

Unification

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- no Yukawa unification for first and second family required

Yukawa textures and family symmetries

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Yukawa textures and family symmetries

- Yukawa couplings depend on location of Higgs and matter fields
- family symmetries arise if different fields live on the same brane
- Exponential suppression if fields at distant branes
- family symmetries might also arise if there is a symmetry between various fixed point locations
- GUT relations could be partially present, depending on the nature of the brane (e.g. SO(10) brane)

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Work in progress:

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- $Z_2 \times Z_3$ standard model

  (Buchmüller, Hamaguchi, Lebedev, Ratz, 2005)

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

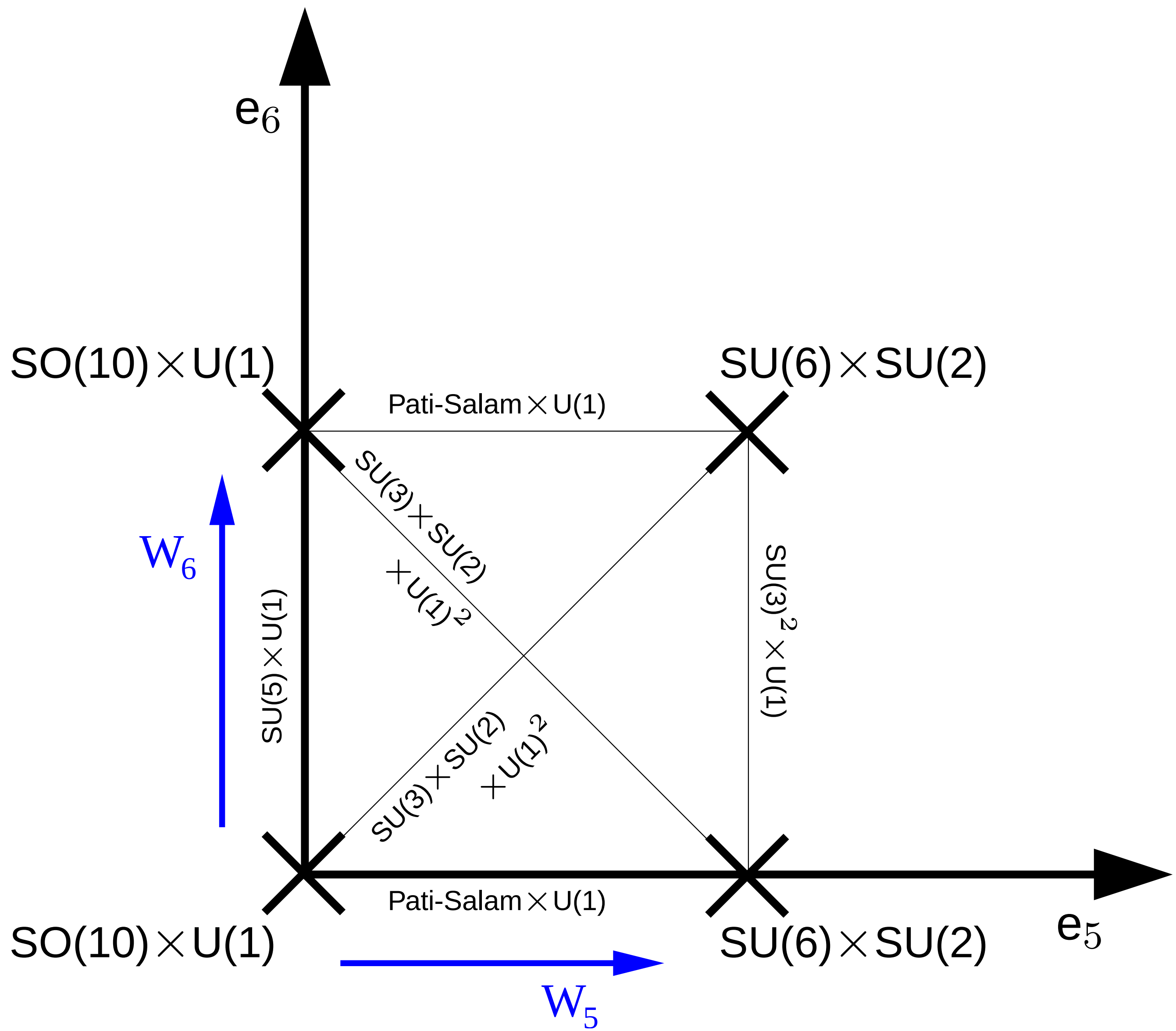
We consider a model that has E_6 gauge group in the bulk of a "6d orbifold". The breakdown pattern is

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

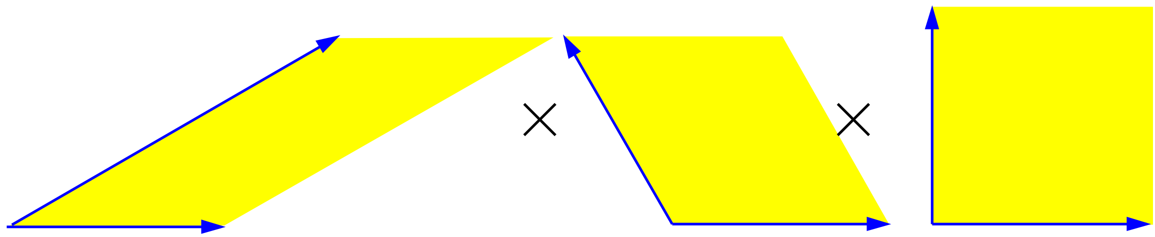
Such 6d models can be embedded in 10d string theory orbifolds. Models with consistent electroweak symmetry breakdown have been constructed.

(Förste, HPN, Wingerter, 2006)

Pati-Salam breakdown



A "fertile patch": Z_6 II orbifold



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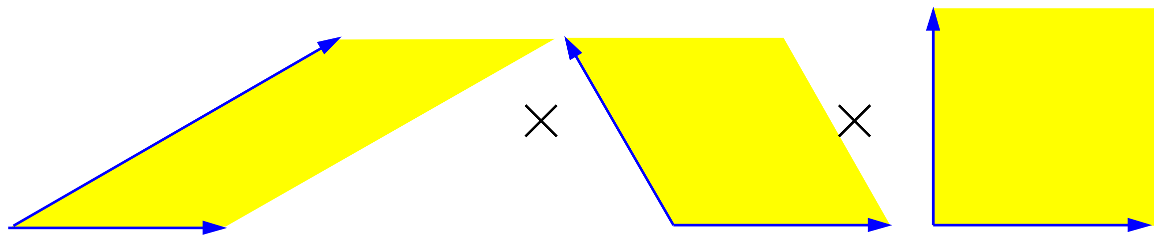

(Kobayashi, Raby, Zhang, 2004; Buchmüller, Hamaguchi, Lebedev, Ratz, 2004)

- provides fixed points and fixed tori
- allows for 61 different shifts out of which 2 lead to $SO(10)$ gauge group
- allows for localized 16-plets for 2 families
- $SO(10)$ broken via Wilson lines
- nontrivial hidden sector gauge group

Selection Strategy

criterion	$V^{\mathrm{SO}(10),1}$	$V^{\mathrm{SO}(10),2}$
models with 2 Wilson lines	$22,000$	$7,800$
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

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

Decoupling of exotics

requires extensive technical work:

- analysis of Yukawa couplings $S^n E\bar{E}$
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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

The benchmark 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)

- hidden sector gaugino condensation

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

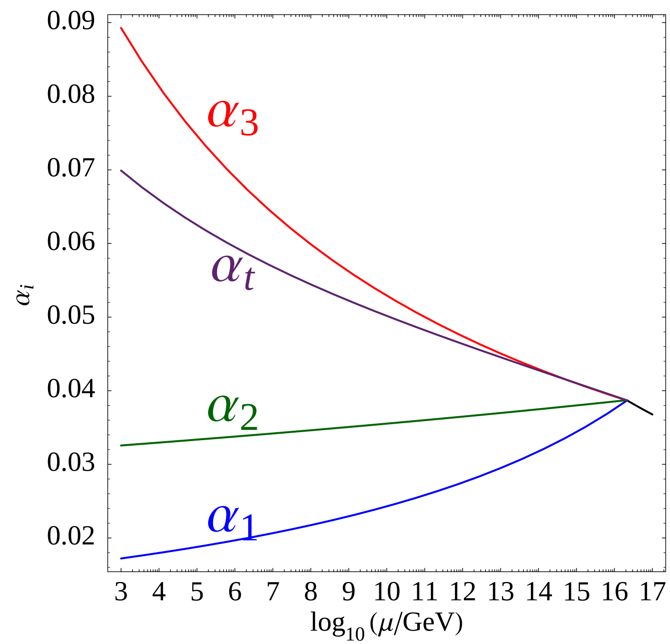
Spectrum

#	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

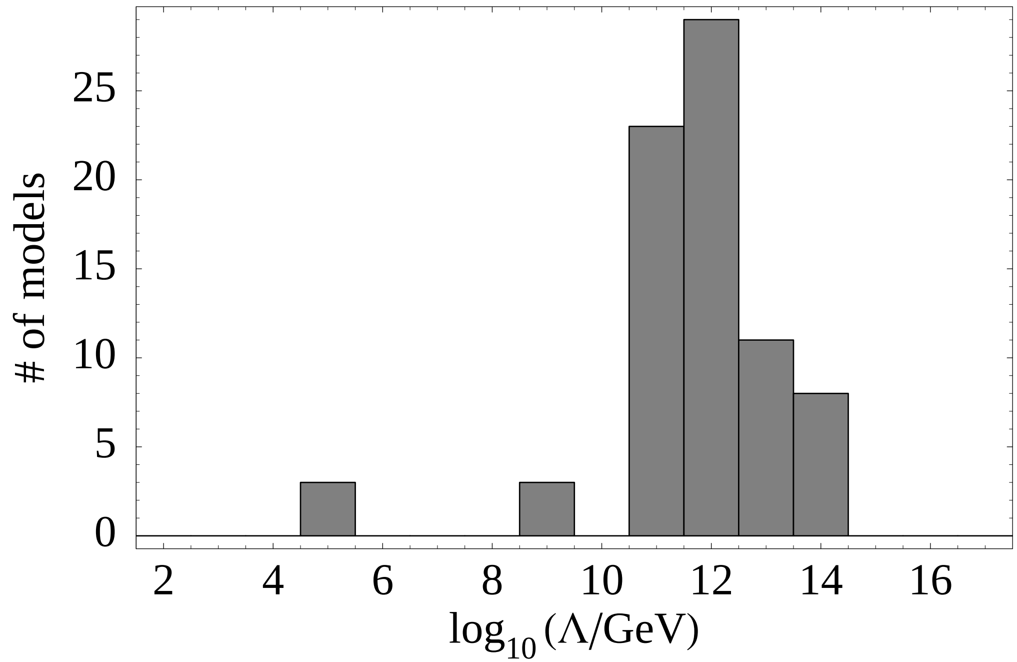
- Higgs doublets are in untwisted (U3) sector

- trilinear coupling to the top-quark allowed



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

Hidden Sector Susy Breakdown



Gravitino mass $m_{3/2} = \Lambda^3/M^2_{\text{Planck}}$ 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;

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

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

Possible applications:

- (nonabelian) family symmetries
- Yukawa textures
- approximate global $U(1)$ for a QCD axion

(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)

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

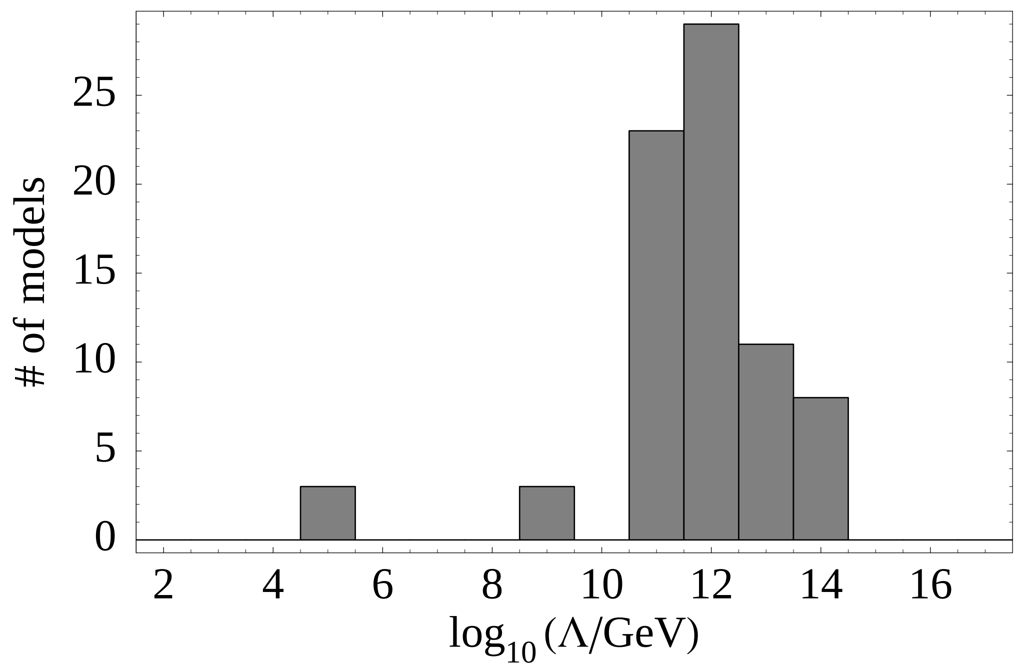
- Local Grand Unification
- realistic MSSM candidates

Geography of extra dimensions plays a crucial role:

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

LHC might help us to verify some of these ideas!

Gaugino Condensation

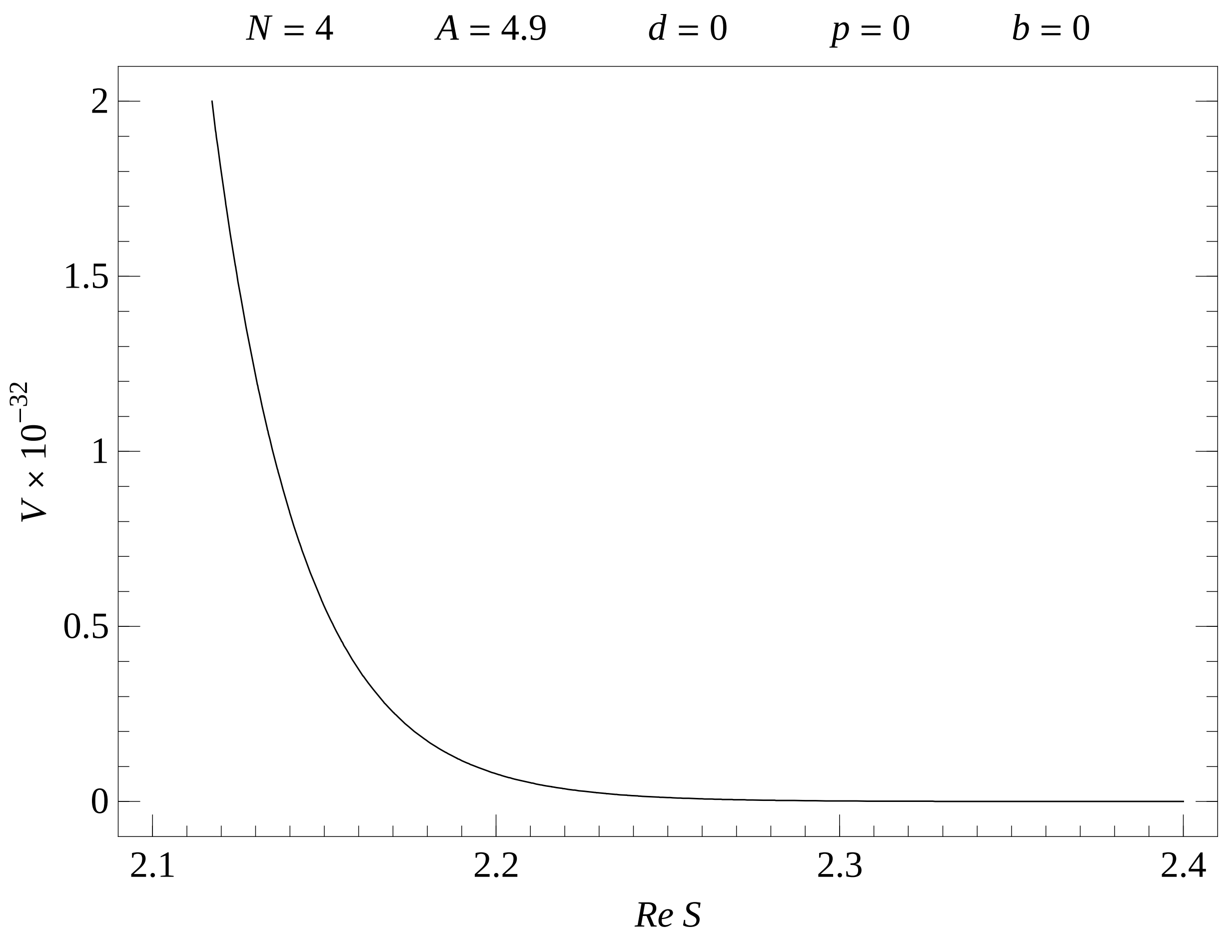


Gravitino mass $m_{3/2} = \Lambda^3/M^2_{\text{Planck}}$ and $\Lambda \sim \exp(-S)$

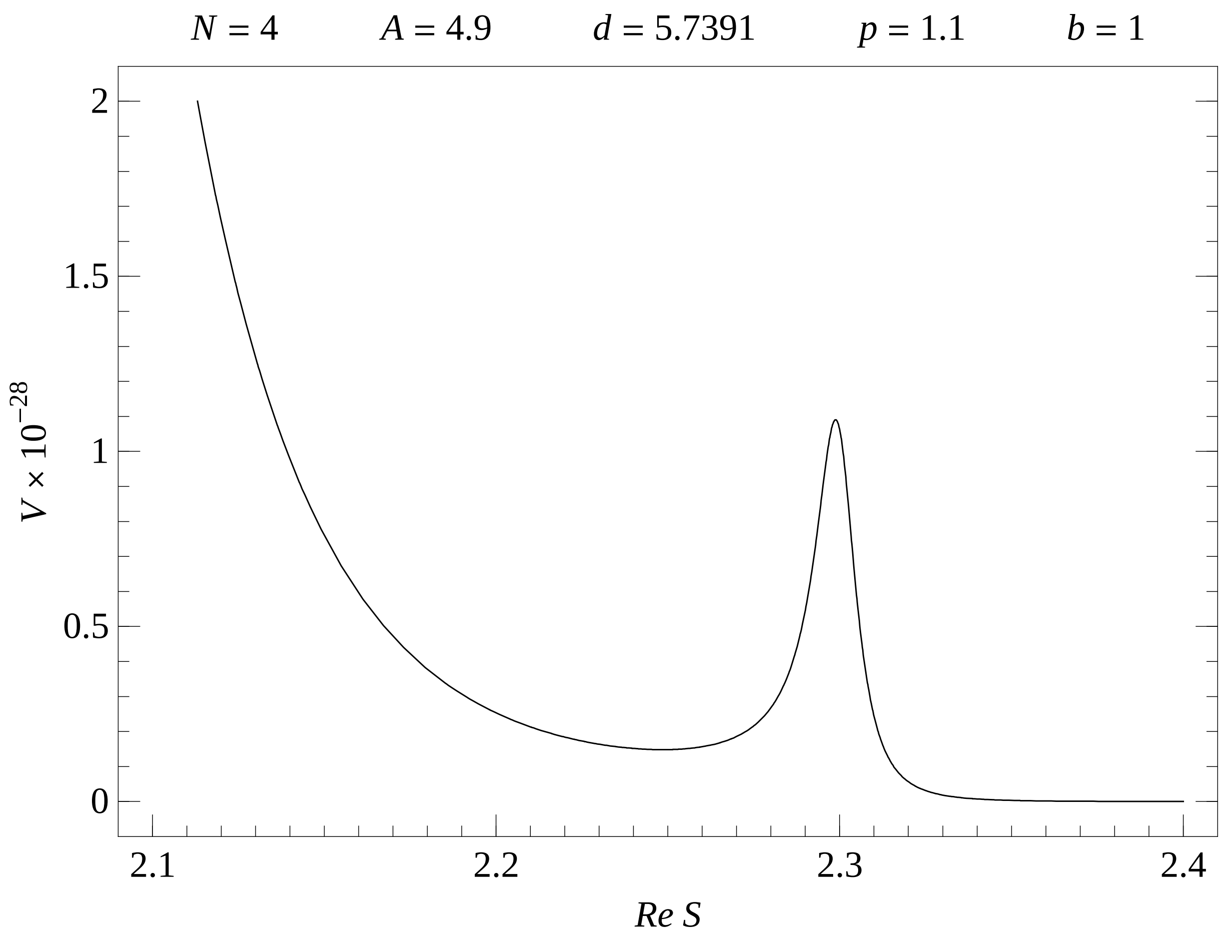
We need to fix the dilaton!

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

Run-away potential



Corrections to Kähler potential



(Casas, 1996; Barreiro, de Carlos, Copeland, 1998)

Dilaton Domination?

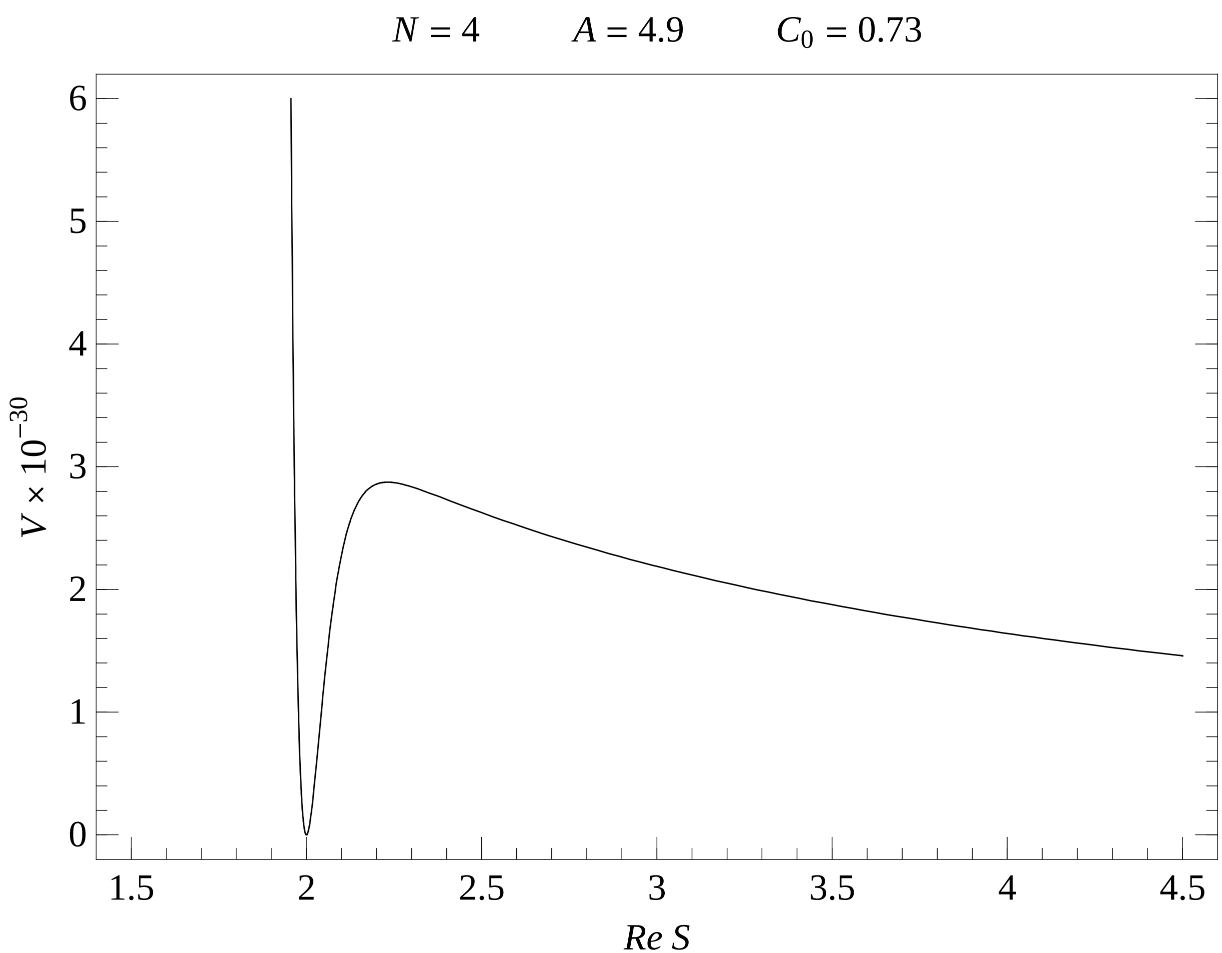
This is known as the dilaton domination scenario,

- but there are problems to remove the vacuum energy.

One needs a “downlifting” mechanism:

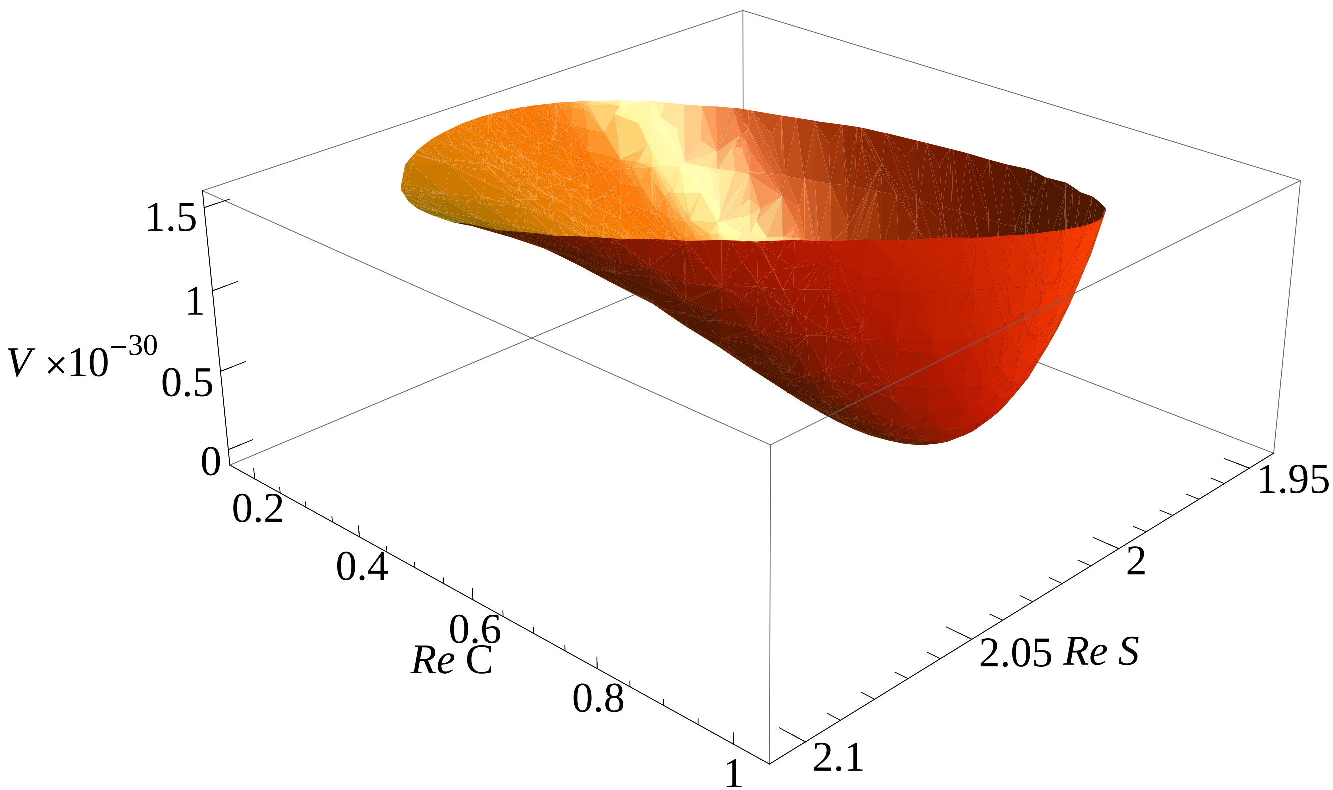
- the analogue to the F-term “uplifting” in the type IIB case (Gomez-Reino, Scrucca, 2006; Lebedev, HPN, Ratz, 2006)
- “downlifting” mechanism fixes S as well (no need for nonperturbative corrections to the Kähler potential) (Löwen, HPN,2008)
- mirage mediation for gaugino masses

Sequestered sector “uplifting”



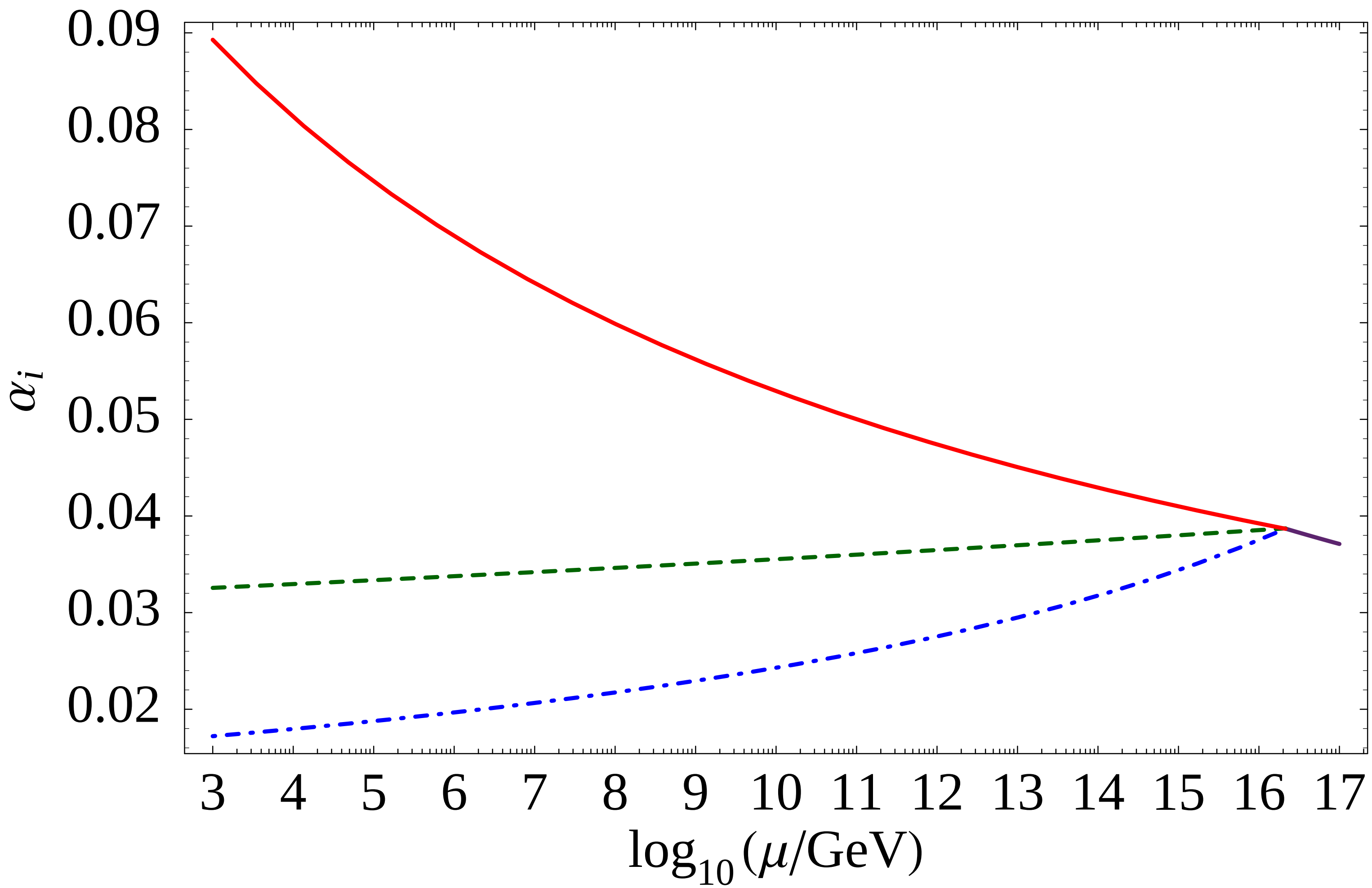
(Lebedev, HPN, Ratz, 2006; Löwen, HPN, 2008)

Metastable "Minkowski" vacuum

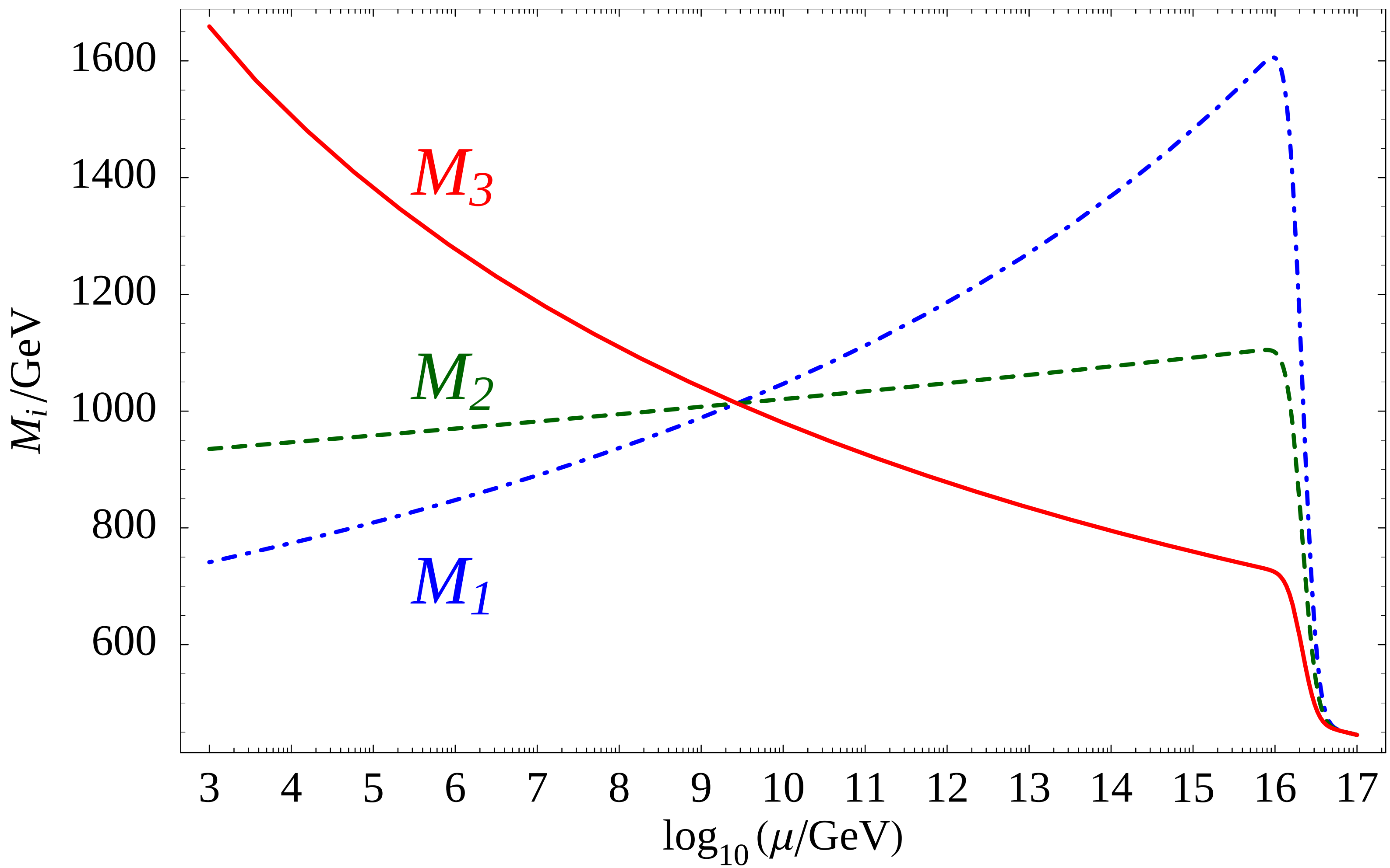


(Löwen, HPN, 2008)

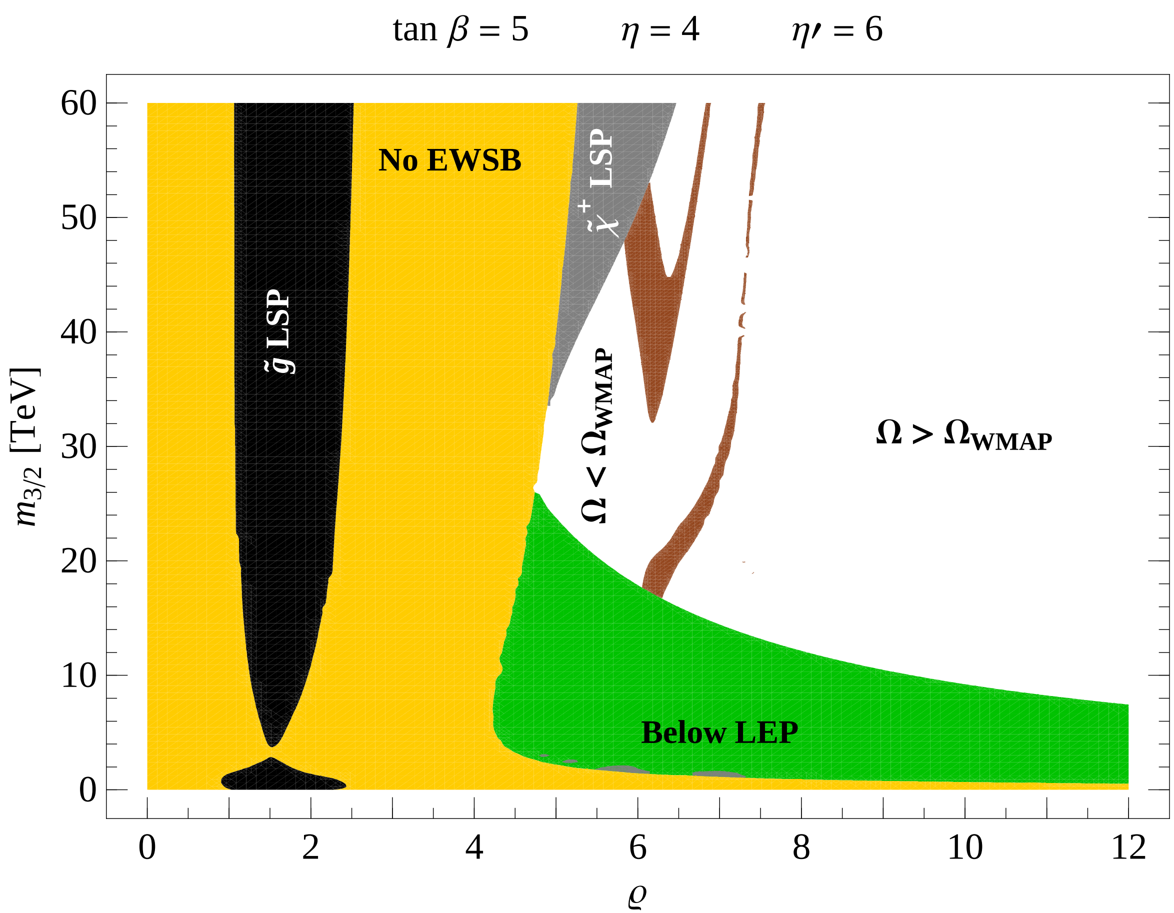
Evolution of couplings



The Mirage Scale



Constraints on the mixing parameter



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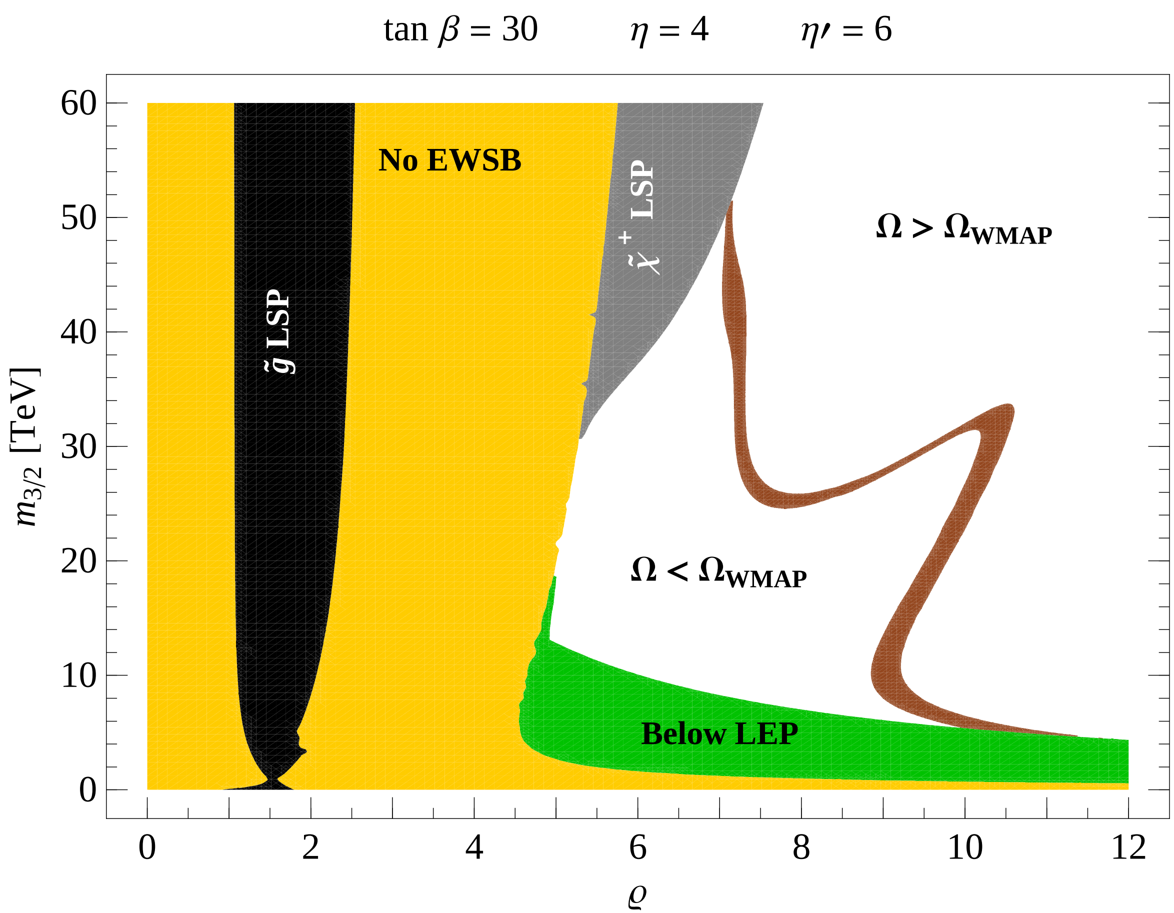

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