String Phenomenology

Hans Peter Nilles

Physikalisches Institut

Universität Bonn

universität bonn

bctp Bethe Center for Theoretical Physics

Strategy

String models as a top-down approach to particle physics

- how to proceed in view of a huge “landscape”?
- we need some guidelines from theory and phenomenology

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String models as a top-down approach to particle physics

- how to proceed in view of a huge “landscape”?
- we need some guidelines from theory and phenomenology

This requires the construction of explicit models

- look for promising models
- identify similarities
- isolate special properties

We need some guidelines for model construction

5 Golden Rules (2004)

- Spinors of SO(10) (for families)
- Incomplete multiplets (for Higgs)
- Repetition of families (from extra dimensions)
- $N = 1$ supersymmetry
- Importance of discrete symmetries

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These rules have bottom-up and top-down motivation

- grand unification (evolution of couplings)
- quark and lepton (neutrino) masses
- proton stability (R-Parity)

Rule 1 and 5

- Spinors if SO(10) might be important even in absence of GUT gauge group
- one can incorporate top-Yukawa coupling and neutrino see-saw mechanism
- discrete symmetries with many applications

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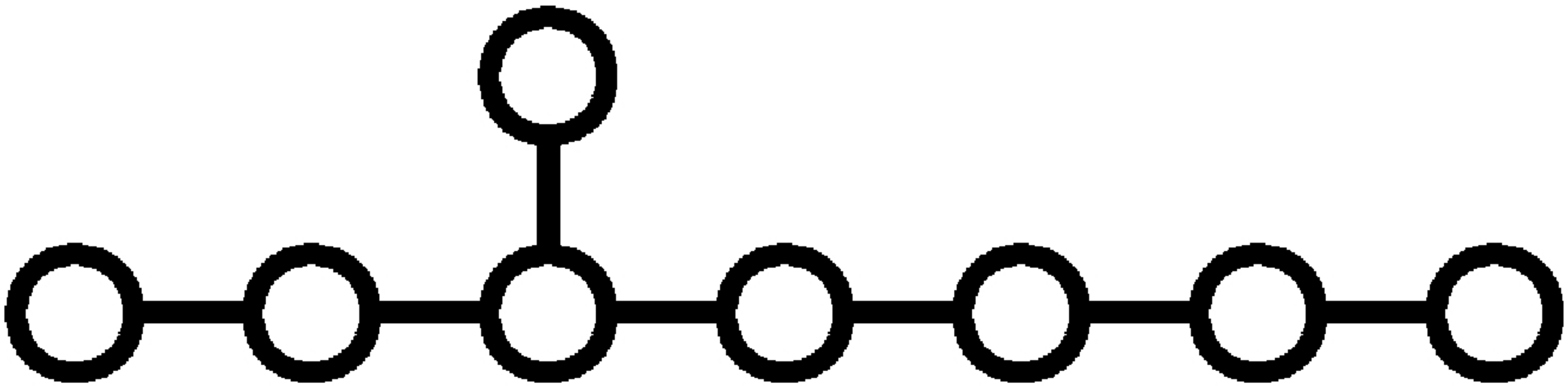
From the mathematical structure we would prefer exceptional groups

- There is a maximal group: E_8,
- but E_8 and E_7 do not allow chiral fermions in $d = 4$.
- How does this fit with our usual picture of unification based on SU(5) or SO(10)?

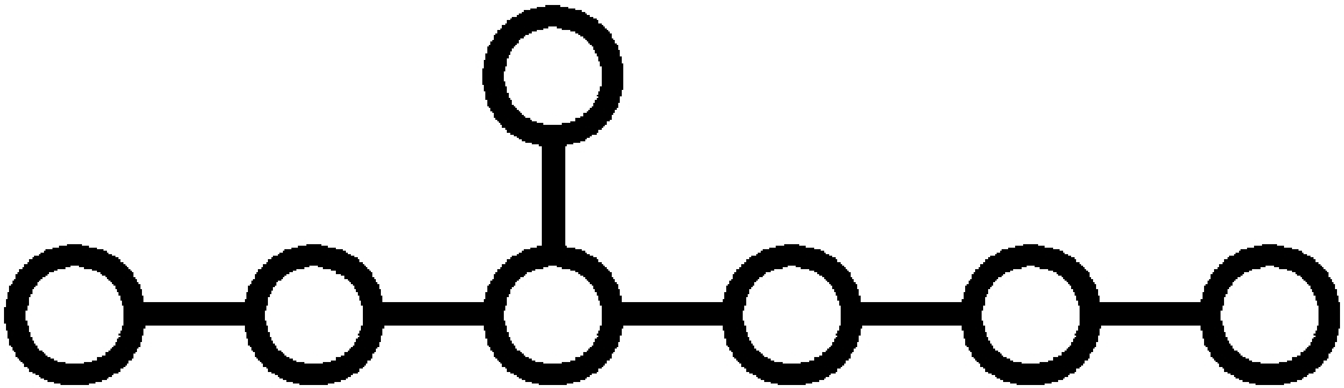
Maximal Group



E_8 is the maximal group.

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

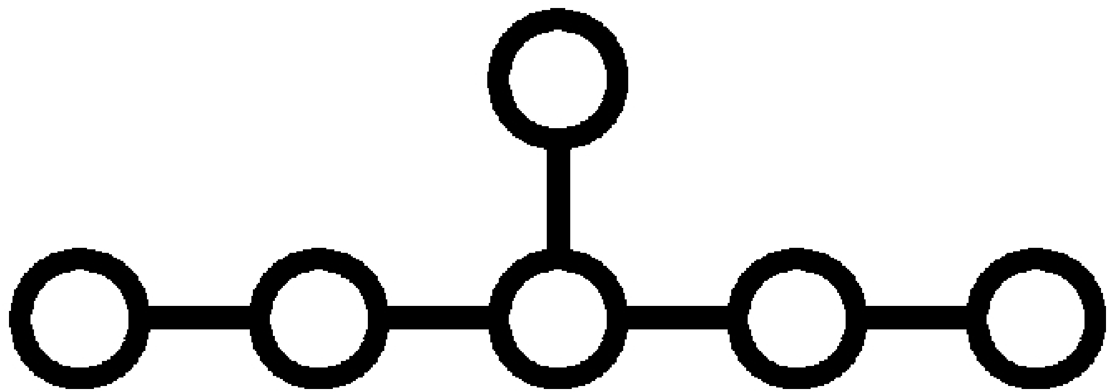
E_7



Next smaller is E_7.

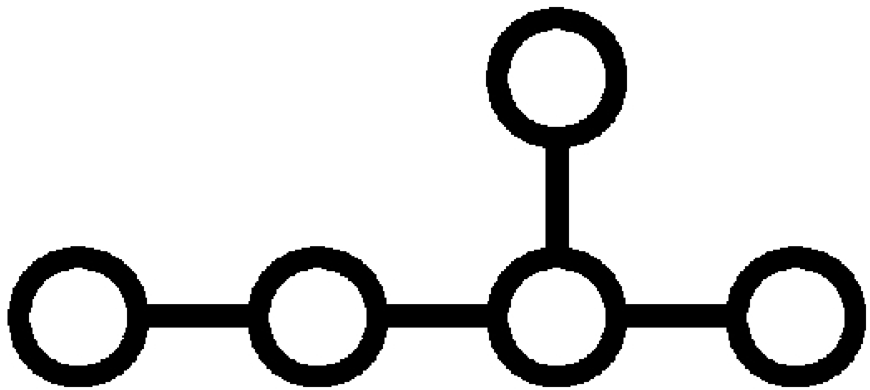
No chiral representations in $d = 4$ either

E_6



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

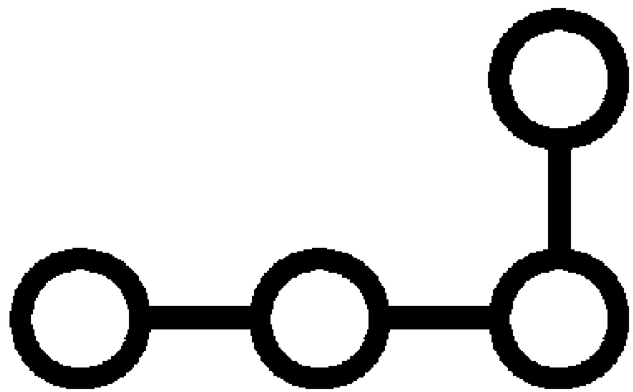
$E_5 = D_5$



E_5 is usually not called exceptional.

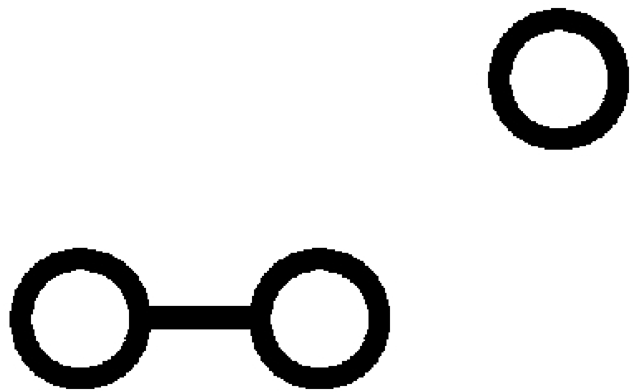
It coincides with $D_5 = SO(10)$.

$E_4 = A_4$



E_4 coincides with $A_4 = SU(5)$

E_3



E_3 coincides with $A_2 \times A_1$ which is $SU(3) \times SU(2)$.

Exceptional groups in string theory

String theory favours E_8

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

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Strings live in higher dimensions:

- chiral spectrum possible even with E_8
- E_8 broken in process of compactification
- provides source for more discrete symmetries
- from $E_8/SO(10)$ and $SO(6)$ of the higher dimensional Lorentz group

The use of additional symmetries

Symmetries are very useful for

- absence of FCNC (solve flavour problem)
- Yukawa textures à la Frogatt-Nielsen
- solutions to the μ problem
- creation of hierarchies
- proton stability

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Continuous global symmetries might be destroyed by gravitational effects. We have to rely on

- gauge symmetries
- discrete symmetries

(Banks, Seiberg, 2010)

Heterotic Braneworld

The heterotic braneworld is based on

- orbifold compactification of the heterotic string
- with calculability from conformal field theory

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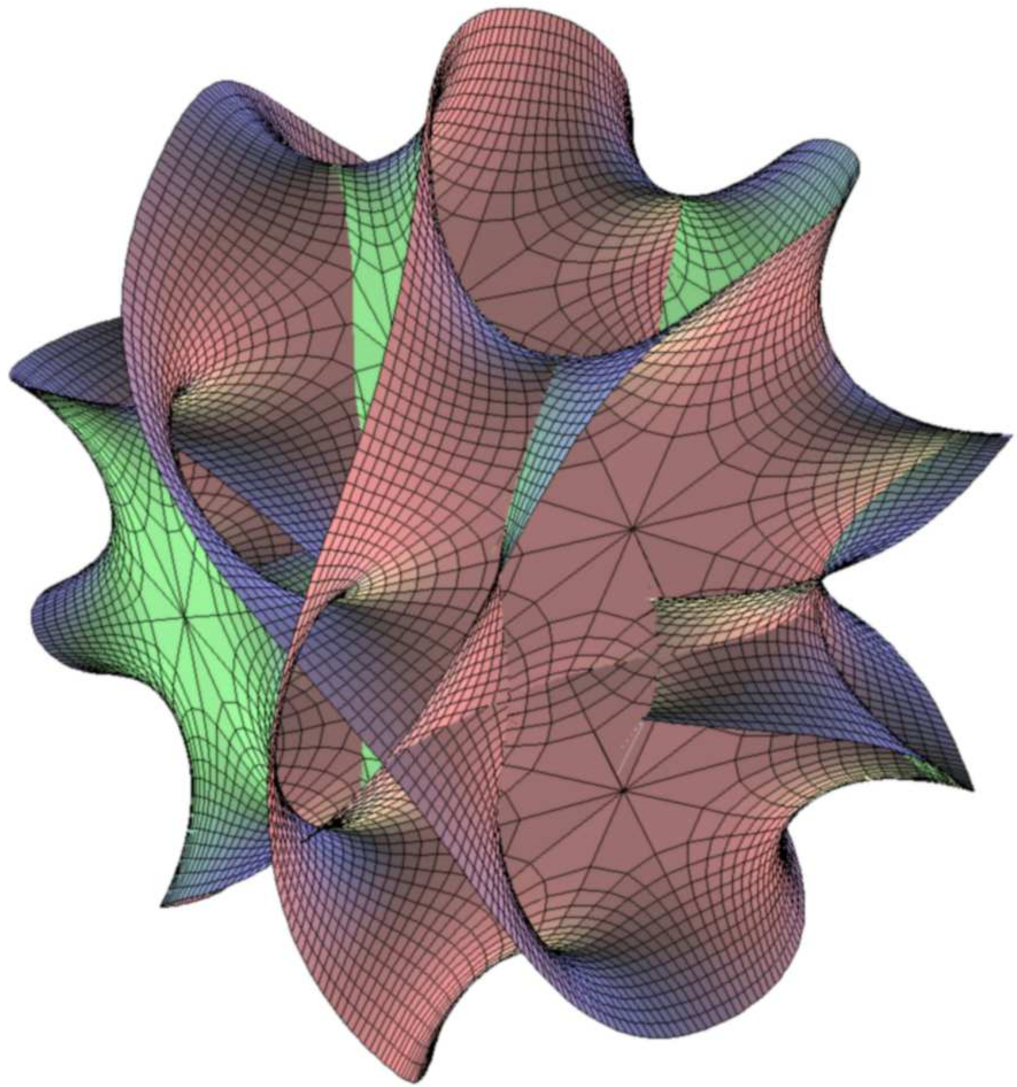
Fields can propagate

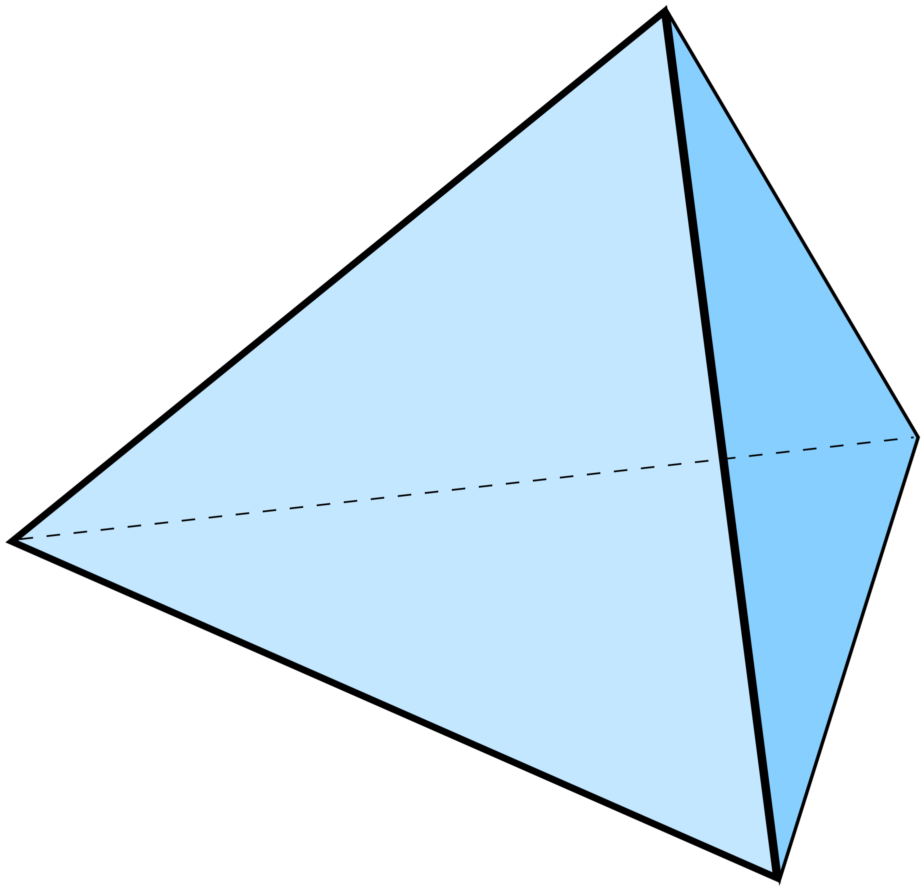
- in the Bulk ($d = 10$ untwisted sector)
- on 3-Branes ($d = 4$ twisted sector fixed points)
- on 5-Branes ($d = 6$ twisted sector fixed tori)

This localization is an important property of the set-up and should be taken seriously (it is not just an approximation to obtain calculability)

Calabi Yau Manifold



Orbifold



Local Grand Unification

String theory gives us a variant of GUTs

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

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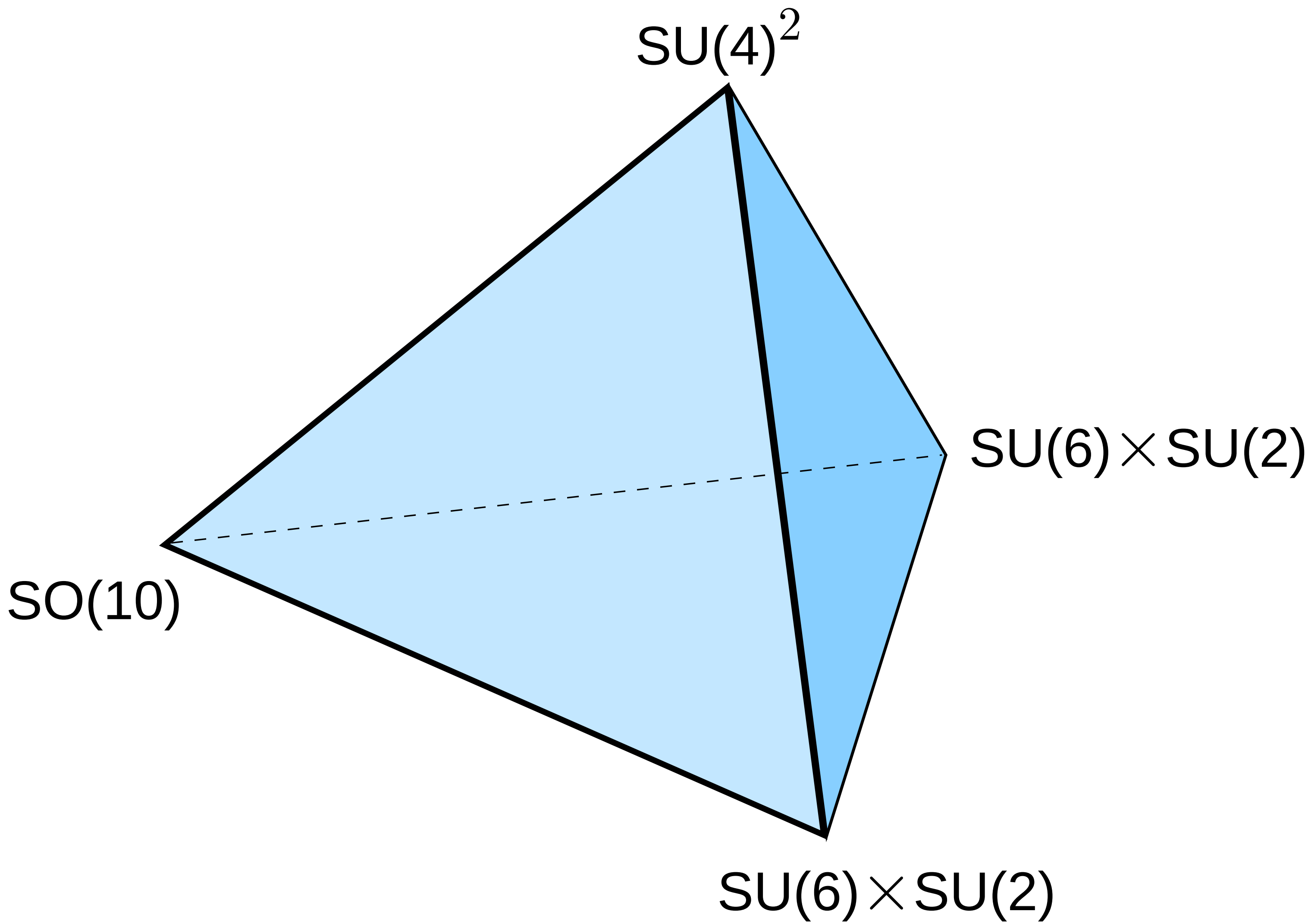
Key properties of the theory depend on the geography of the fields in extra dimensions.

This geometrical set-up is called local grand unification.

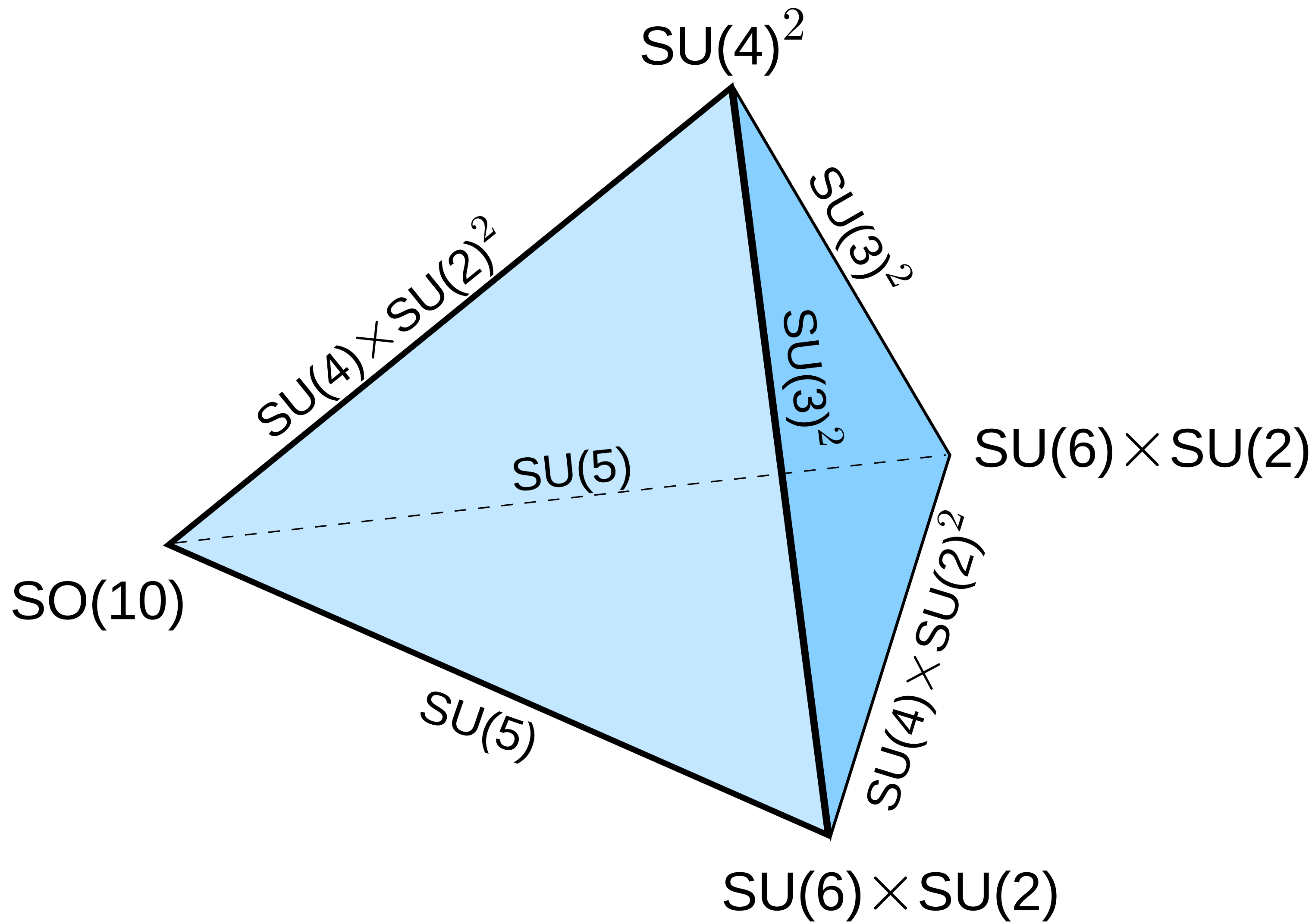
The localization of matter as well as the local structure of the gauge group determines the properties of the theory.

Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

Standard Model Gauge Group



Symmetries

In the heterotic braneworld we find

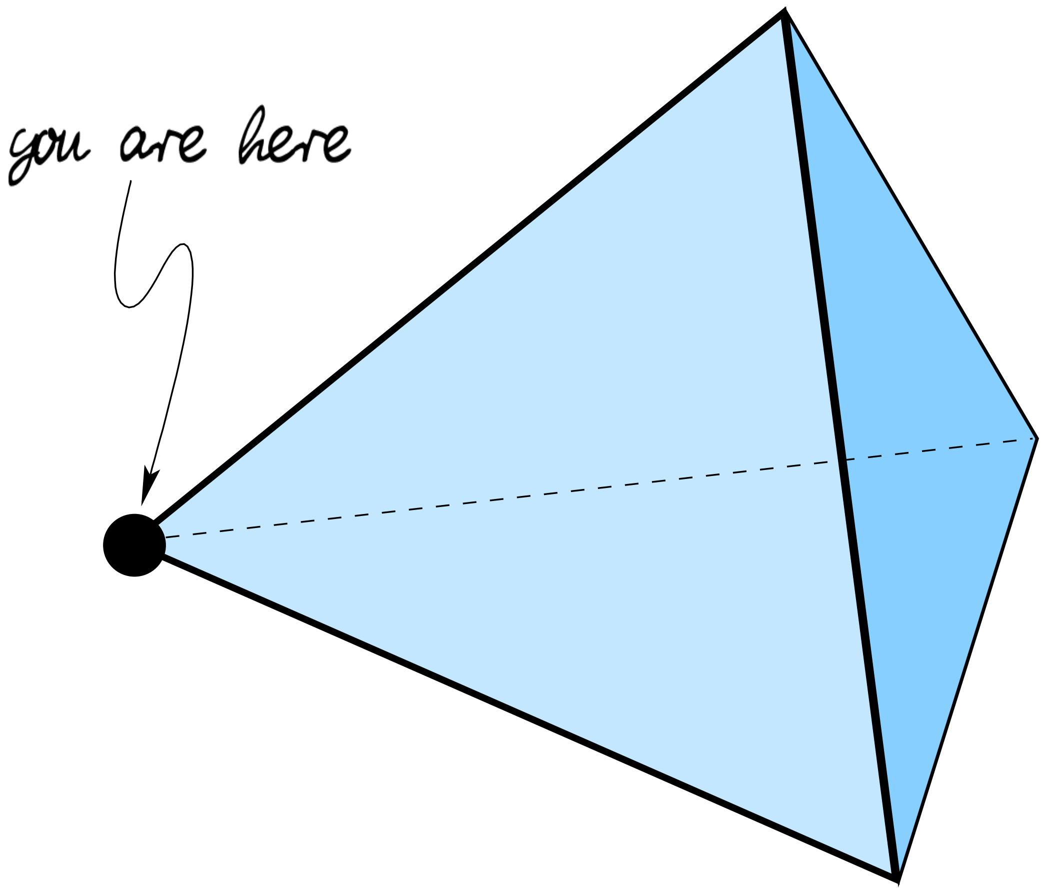
- gauge symmetries (no continuous global symmetries)
- discrete symmetries from geometry and stringy selection rules (Kobayashi, HPN, Plöger, Raby, Ratz, 2006)

The orbifold point is a special point in the moduli space of the compact extra dimensions with enhanced symmetries.

These symmetries might be slightly broken. This will introduce small parameters that lead to a creation of hierarchies.

We might live close to the orbifold point.

Location matters



Symmetries in heterotic braneworld

Applications of discrete 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” or Z_4^R

  (Förste et al. 2010; Lee et al. 2011)

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

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

F-theory

F-theory with enhanced exceptional gauge symmetry is the way to incorporate rule 1 in Type II theories. It allows

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Phenomenological constructions are based on the concept of local models, e.g. at the local E_8 point. (Heckman, Vafa, 2010)

- a single gauge group like E_8
- containing other symmetries like R-parity as well
- there might not be a global completion!

Local E_8 point does not possess all the ingredients for realistic model building.

(Marsano, Schafer-Namecki, Saulina, 2011; Lüdeling, HPN, Stephan, 2011)

Clarification

Do not confuse

"Local Grand Unification" with "Local Model Building".

- Local Grand Unification appears in consistent (global) string models where the gauge symmetries are enhanced at special points in extra-dimensional space.
- Local Model Building is an attempt to construct models without the incorporation of gravity (these models are potentially inconsistent).

Do not trust the predictions of "Local Models" unless they are confirmed by a global completion!

Rule 6: Global Models

Sometimes it is said that globally consistent models are only relevant for questions like moduli stabilization......

- this needs not be correct (as experience shows)
- the really reliable (discrete) symmetries can only be understood within a global approach (e.g. R-parity)

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Phenomenological analyses of local models typically

- rely on continuous global U(1)s
- that might be broken in the full theory
- what are the remaining symmetries?

We need to answer this question before any predictions can be made!

Rule 7: Berechenbarkeit

Nowadays we need calculability that goes beyond the effective supergravity field theory approach, e.g. exact conformal field theory

- flat orbifolds, free fermionic constructions
- tensoring CFTs (Gepner models)

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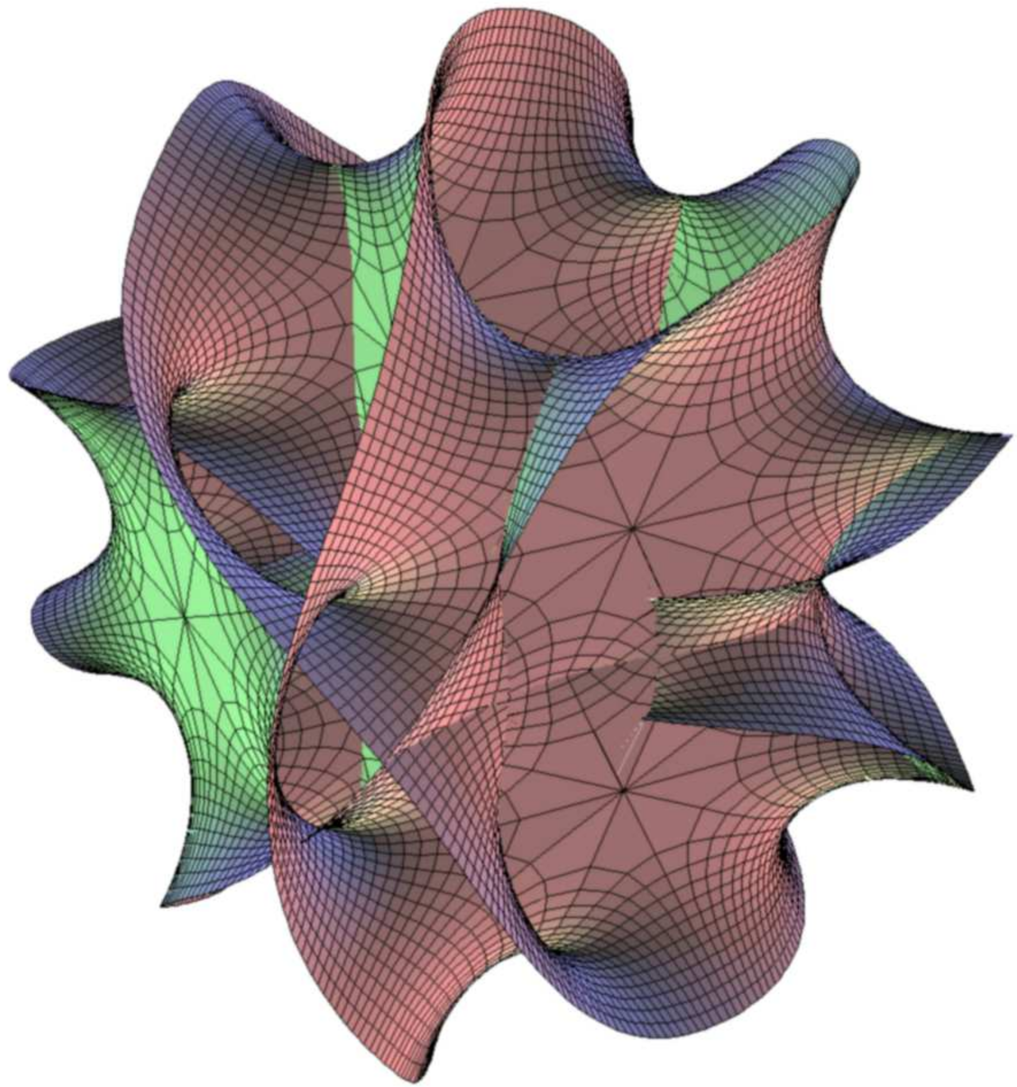
- flat orbifolds, free fermionic constructions
- tensoring CFTs (Gepner models)

We have to analyze points of enhanced symmetries and enhanced particle spectra

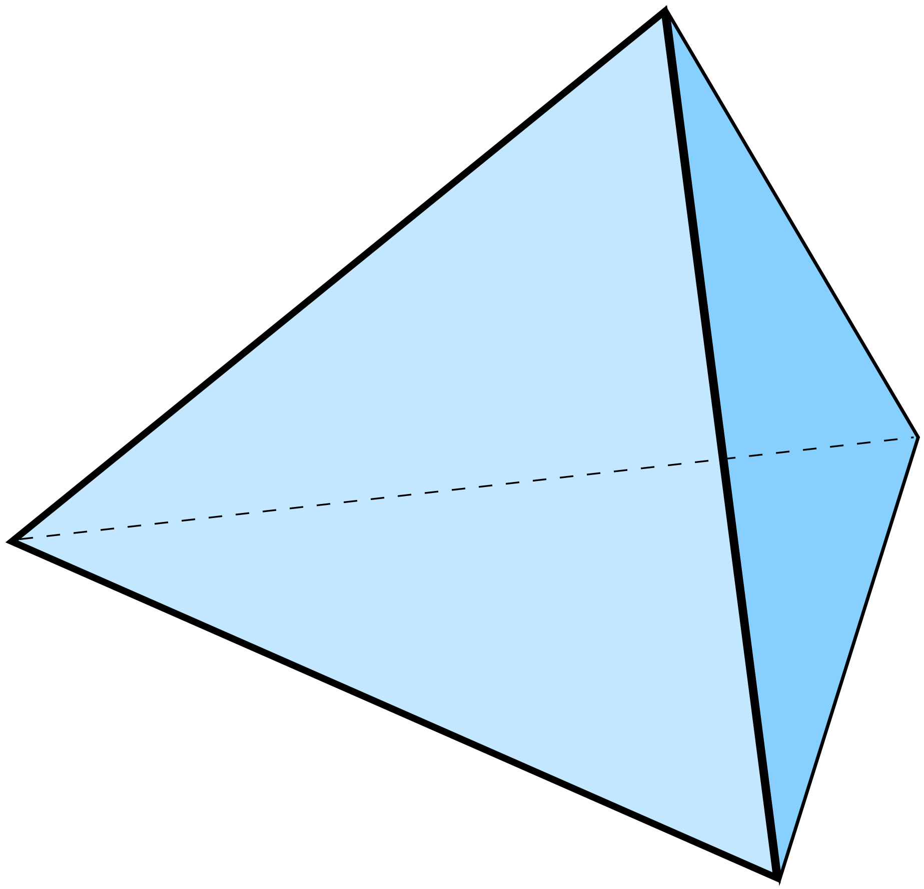
- slightly broken symmetries (Frogatt-Nielsen)
- small parameters to create hierarchies

Hopefully nature is close to points of enhanced calculability.

Calabi Yau Manifold



Orbifold



The fate of smooth compactification

Models on smooth manifolds describe generic points in moduli space

- limited calculability in practice (not full CFT)
- do not see locally enhanced symmetries and spectra
- but location of fields is of physical relevance

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As a result, phenomenological analyses of these models often rely on continuous gobal symmetries

- an approximation is needed for “calculability”
- heterotic Calabi-Yau compactification should be related e.g. to a point with exact CFT

For F-theory it seems to be a real challenge to find a flat (CFT) approximation.

Improve calculability

Have to connect smooth compactification to e.g. flat orbifolds (Groot Nibbelink et al.; Blaszczyk et al.; 2009-2011)

- resolution of singularities within toric geometry
- is a good approximation in large volume limit

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But there are still some points that have to be clarified

- relation of number of massless states in orbifold and blow-up
- “missing” Yukawa couplings in large volume limit

Local anomalies might play an important role in the attempt to transfer calculability from orbifolds to smooth manifolds.

(Blaszczyk, Cabo Bizet, HPN, Ruehle, 2011)

The Anomaly Polynomial

The Green-Schwarz anomaly polynomial is a useful tool to study the relation between various schemes. The 12-form

$$I_{12}(F_i, R) = I_4 \times I_8$$

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The Anomaly Polynomial

The Green-Schwarz anomaly polynomial is a useful tool to study the relation between various schemes. The 12-form

$$I_{12}(F_i, R) = I_4 \times I_8$$

contains crucial information on the properties of the model:

- can be computed independently in the different set-ups
- controls the coupling of “axions” to matter fields
- reveals broken and unbroken (discrete) symmetries.

Relate models of reduced calculability to those where explicit calculations can be done.

(Blaszczyk, Cabo Bizet, HPN, Ruehle, 2011)

Golden Rules (2012)

- Spinors of SO(10) (for families)
- Incomplete multiplets (for Higgs)
- Repetition of families (from extra dimensions)
- $N = 1$ supersymmetry
- Importance of discrete symmetries
- globally consistent models
- Berechenbarkeit
- study GS-anomaly polynomial

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Let us hope that nature sits at a point of enhanced symmetry and calculability.

The MiniLandscape

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

  (Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007-2009)

- local grand unification (by construction)
- gauge- and (partial) Yukawa unification

  (Raby, Wingerter, 2007)

- examples of neutrino see-saw mechanism

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

- models with R-parity + solution to the μ-problem

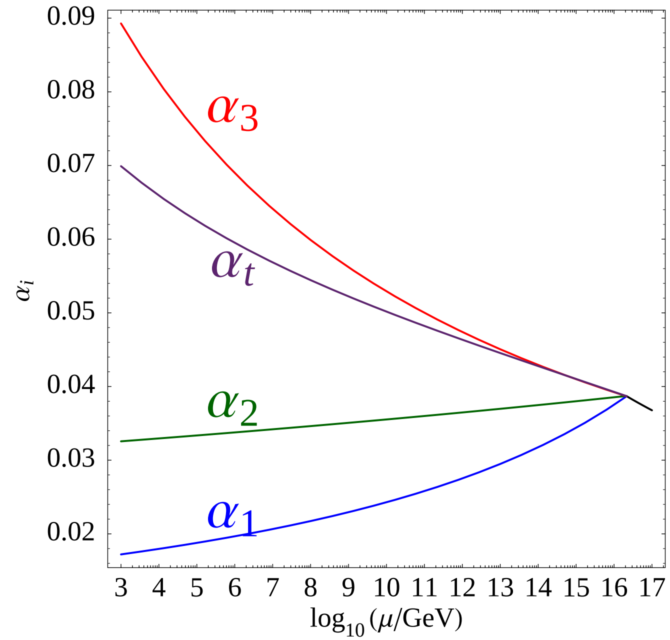
  (Lebedev, HPN, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007)

- gaugino condensation and mirage mediation

  (Löwen, HPN, 2008)

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)
- natural incorporation of gauge-Yukawa unification

Emergent localization properties

The benchmark model illustrates some of the general properties of the Heterotic Brane World

- 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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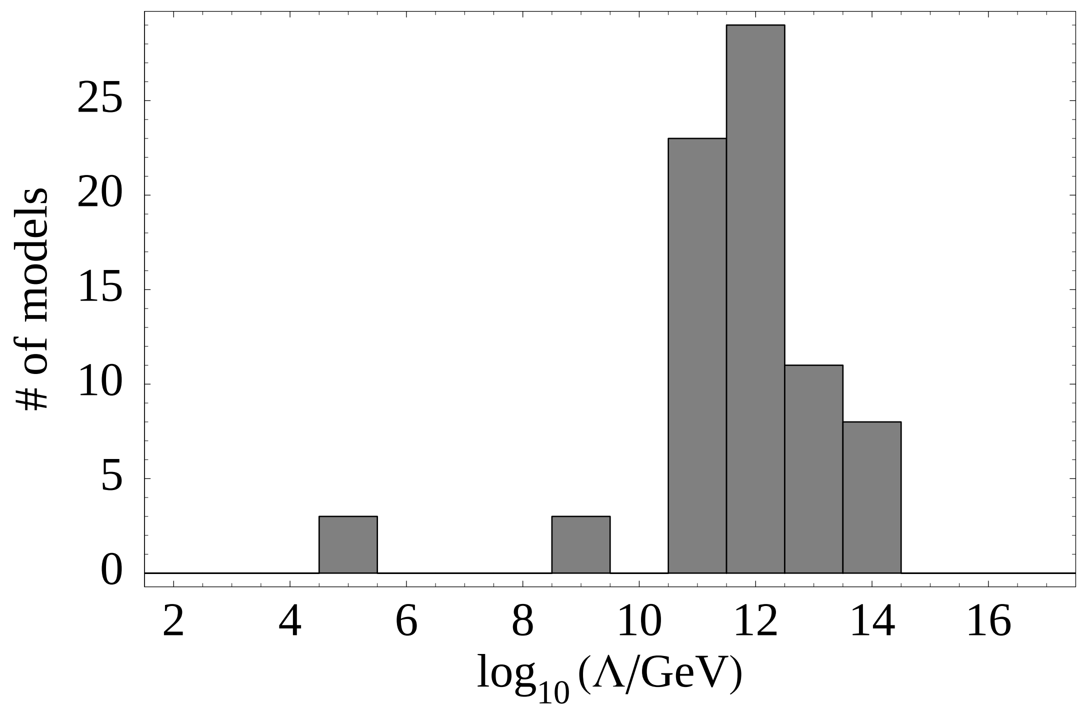
- only one trilinear Yukawa coupling (all others suppressed)

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

(Krippendorf, HPN, Ratz, Winkler, 2012)

Heterotic string: gaugino condensation



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

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

Heterotic string

Fixing U- and T- moduli in a supersymmetric way

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

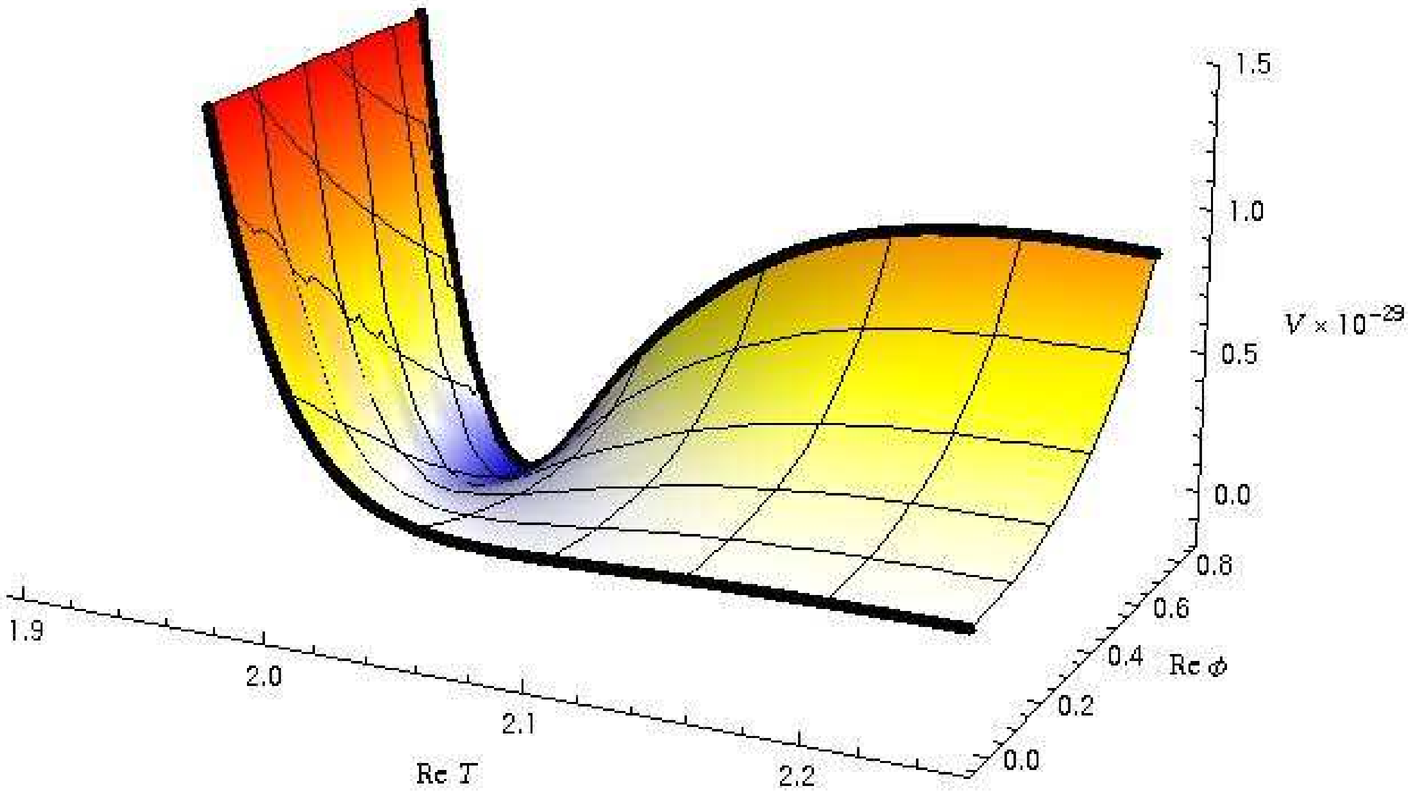
- we remain with a run-away dilaton

But we need to adjust the vacuum energy

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

(Löwen, HPN, 2008)

Downlift



(Löwen, HPN, 2008)

Mirage scheme

Fixing U- and T- moduli in a supersymmetric way

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

- we remain with a run-away dilaton

But we need to adjust the vacuum energy

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

(Löwen, HPN, 2008)

Soft terms

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

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

Scalar masses are less protected

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

But, the top quark plays a special role

- as a result of gauge-Yukawa-unification

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

  that explains the large value of the top-quark mass

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

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) (GaugeTopUnification and GaugeHiggsUnification)
- all other multiplets live twisted sectors (branes)

This can be understood as a remnant of

- extended supersymmetry in higher dimensions
- $N = 4$ supersymmetry from $N = 1$ in $D = 10$ via torus compactification
- Higgs und stops remain in the TeV-range

(Krippendorf, Nilles, Ratz, Winkler, 2012)

The overall pattern

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

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

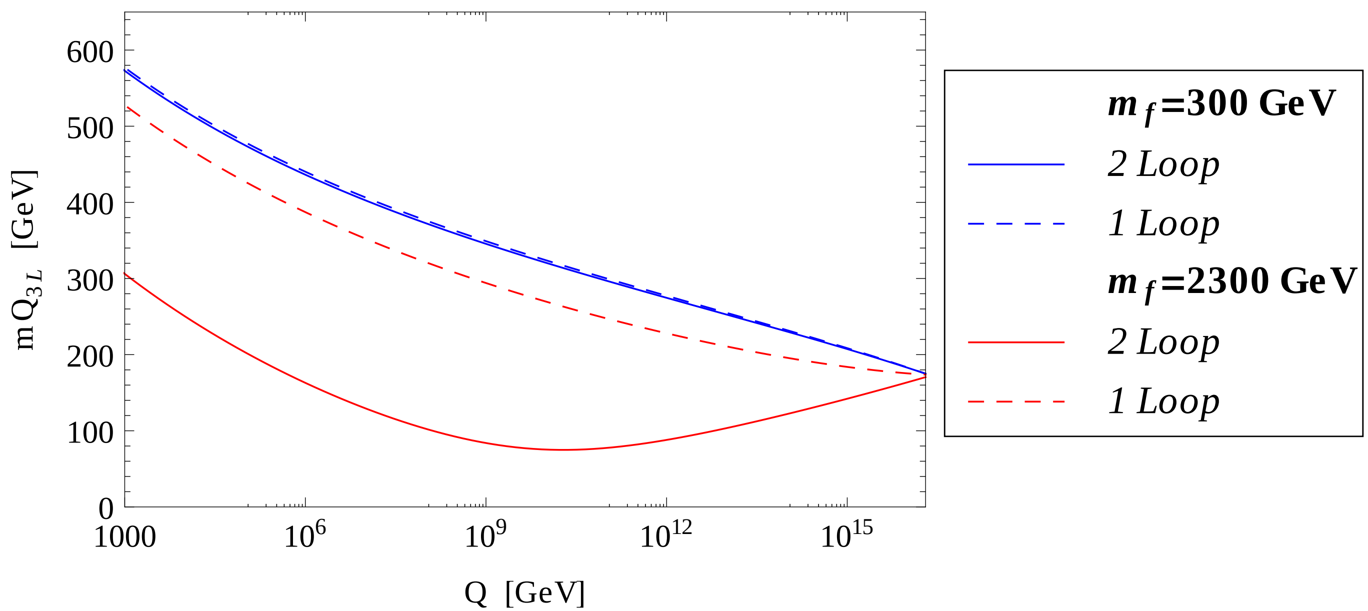
A Closer Look

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

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

Tachyons

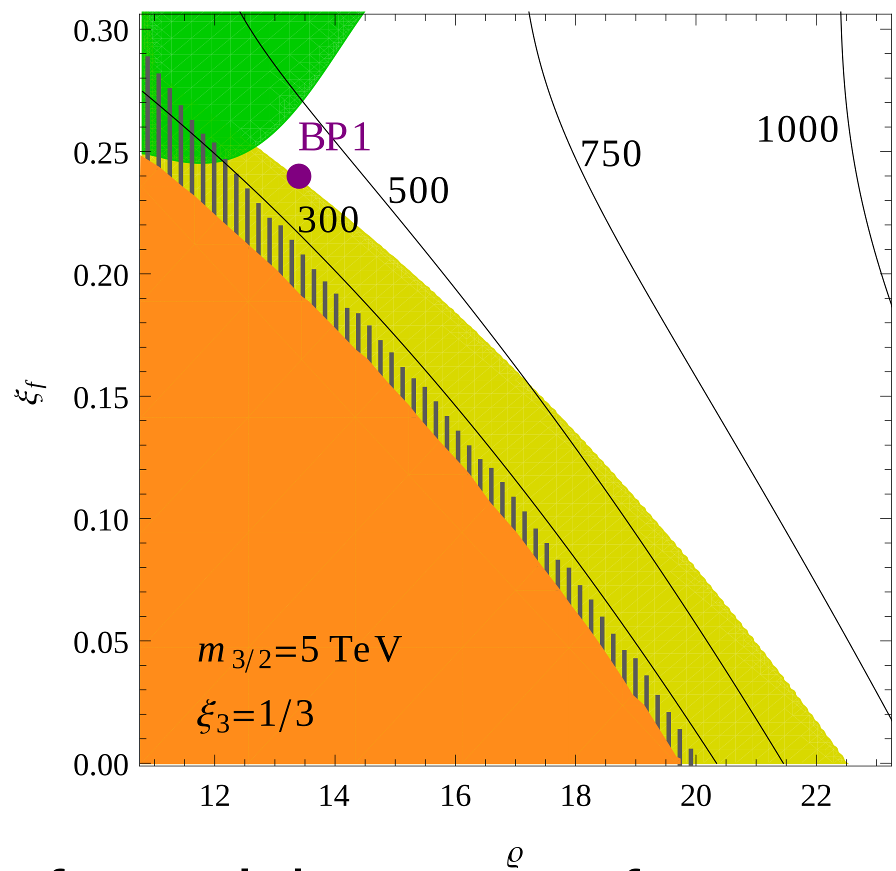
Light stops are close to the tachyonic boundary and two-loop effects might become important (a generic problem of models with heavy sfermions)



Are intermediate scale tachyons cosmologically acceptable?

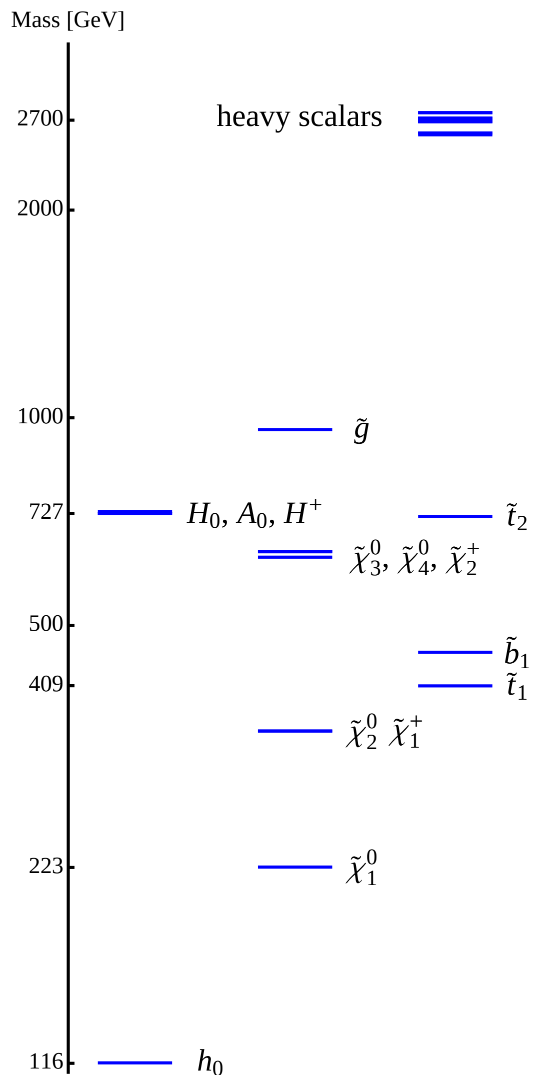
(Ellis, Giedt, Lebedev, Olive, Srednicki; 2008)

Benchmark model with a TeV gluino



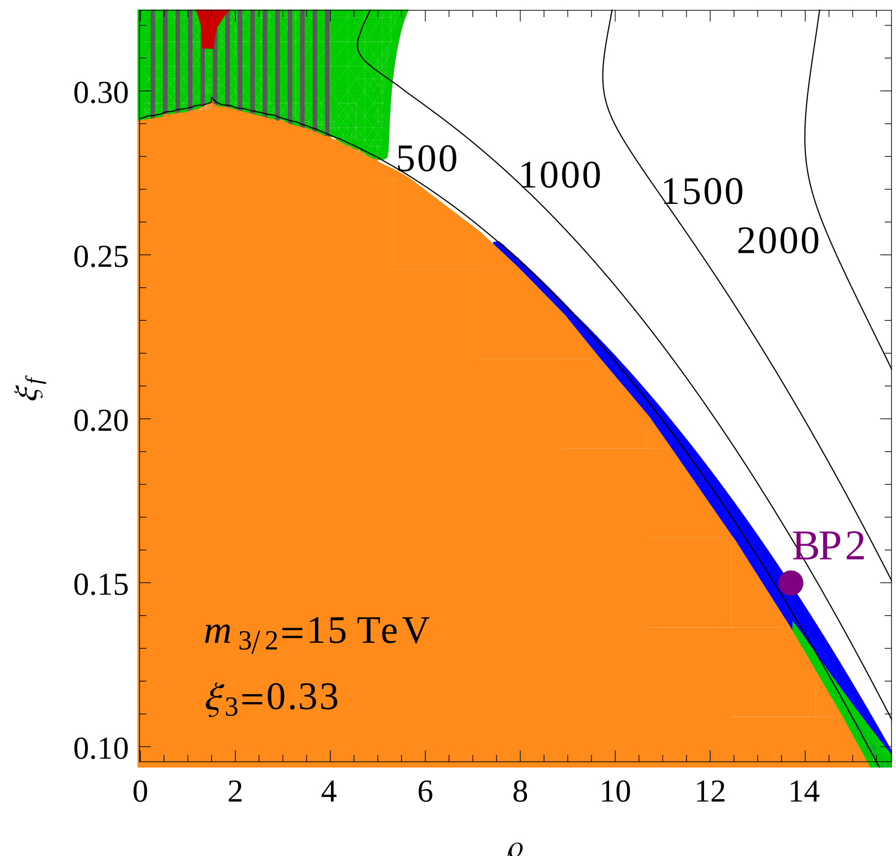
Parameter scan for a gluino mass of 1 TeV. The coloured regions are excluded while the hatched region indicates the current reach of the LHC. The contours indicate the mass of the lightest stop.

Spectrum 1



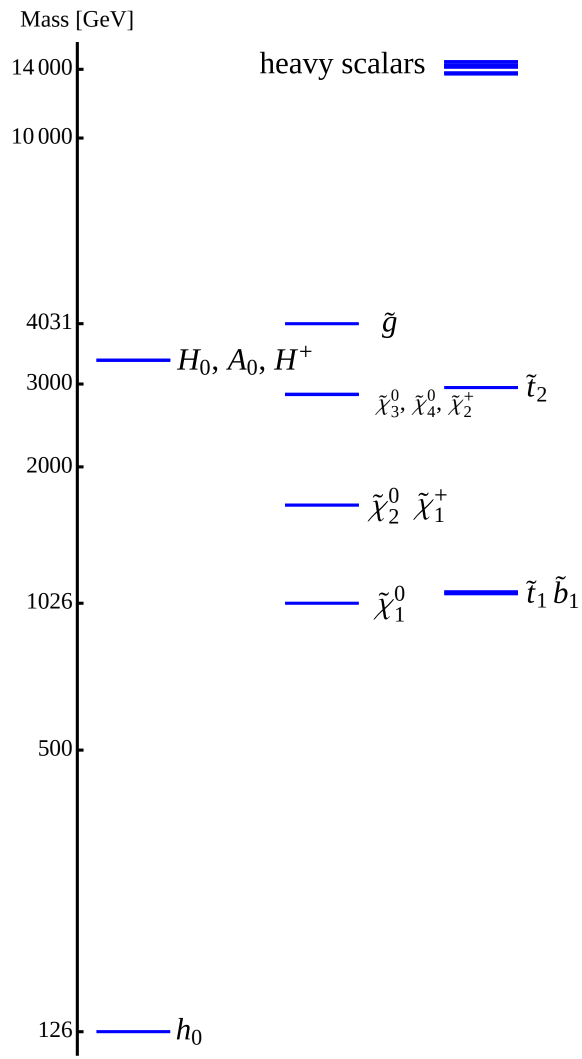
Mass [GeV]
2700
2000
1000
727
500
409
223
116
heavy scalars
$\tilde{g}$
H_0, A_0, H^+
$\tilde{t}_2$
$\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_2^+$
$\tilde{b}_1$
$\tilde{t}_1$
$\tilde{\chi}_2^0\ \tilde{\chi}_1^+$
$\tilde{\chi}_1^0$
h_0

Model with 4 TeV gluino



Parameter scan for a gluino mass of 4 TeV. The coloured regions are excluded while the hatched region indicates the current reach of the LHC. The contours indicate the mass of the lightest stop.

Spectrum of model with a 4 TeV gluino



Messages

- large gravitino mass (multi TeV-range)
- heavy moduli: $m_{3/2} \log(M_{\text{Planck}}/m_{3/2})$
- 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.

Comparison to other schemes

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

- type IIB (Kachru, Kallosh, Linde, Trivedi, 2003)
  - all sfermions unprotected
  - A-parameters in few TeV-range
- G2MSSM (Acharya, Bobkov, Kane, Kumar, Vaman, 2006)
  - all sfermions unprotected (even up to $O(100)$TeV
  - A-parameters in multi TeV-range as well

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

The mass of the lightest Higgs

The mass of the lightest Higgs should be

- somewhere between 115 GeV and 127 GeV
- depends on the value of $\tan\beta$
- usually requires some fine tuning

This fine tuning is

- severe in type IIB and G2MSSM,
- rather mild in the heterotic picture
  (as a result of the mirage spectrum of gauginos and the suppression of soft terms for Higgs- and top-multiplets).

Lessons from heterotic string theory

- scalar masses are less protected
  - heavy squarks and sleptons in the multi-TeV range
- But, the top quark plays a special role
  - a large value of the top-quark Yukawa coupling requires a special location of top and Higgs in extra dimensions of string theory

    (Lebedev, Nilles, Raby, Ramos-Sanchez, Ratz, Vaudrevange, Wingerter, 2007)
  - this is a result of gauge-Yukawa-unification

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

    that explains the large value of the top-quark mass
- stops and Higgs bosons remain in TeV range

(Krippendorf, Nilles, Ratz, Winkler, 2012)

The overall scale

There is no (reliable) prediction for the gravitino mass

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

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Betting in the early 80’s

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

Conclusions

Assume realistic top-quark Yukawa coupling

- this implies Gauge-Yukawa unification (trilinear top quark Yukawa coupling)
- realistic models require Higgs multiplets and top multiplets in untwisted sector (GaugeHiggsUnification)
- other fields tend to be localized at fixed points (tori)

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- this implies Gauge-Yukawa unification (trilinear top quark Yukawa coupling)
- realistic models require Higgs multiplets and top multiplets in untwisted sector (GaugeHiggsUnification)
- other fields tend to be localized at fixed points (tori)

Remnants of N=4 SUSY

- mirage mediation
- special properties of untwisted sector
- untwisted SUSY partners rather light while others heavy