From Strings to the MSSM

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Questions

- What can we learn from strings for particle physics?
- Can we incorporate particle physics models within the framework of string theory?

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Recent progress:

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

The road to the Standard Model

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- gauge group $SU(3) \times SU(2) \times U(1)$
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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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- Neutrino-oscillations and “See-Saw Mechanism”

  $m_\nu \sim M_W^2/M_{\mathrm{GUT}}$

  $m_\nu \sim 10^{-3}\mathrm{eV}$ for $M_W \sim 100\mathrm{GeV}$,

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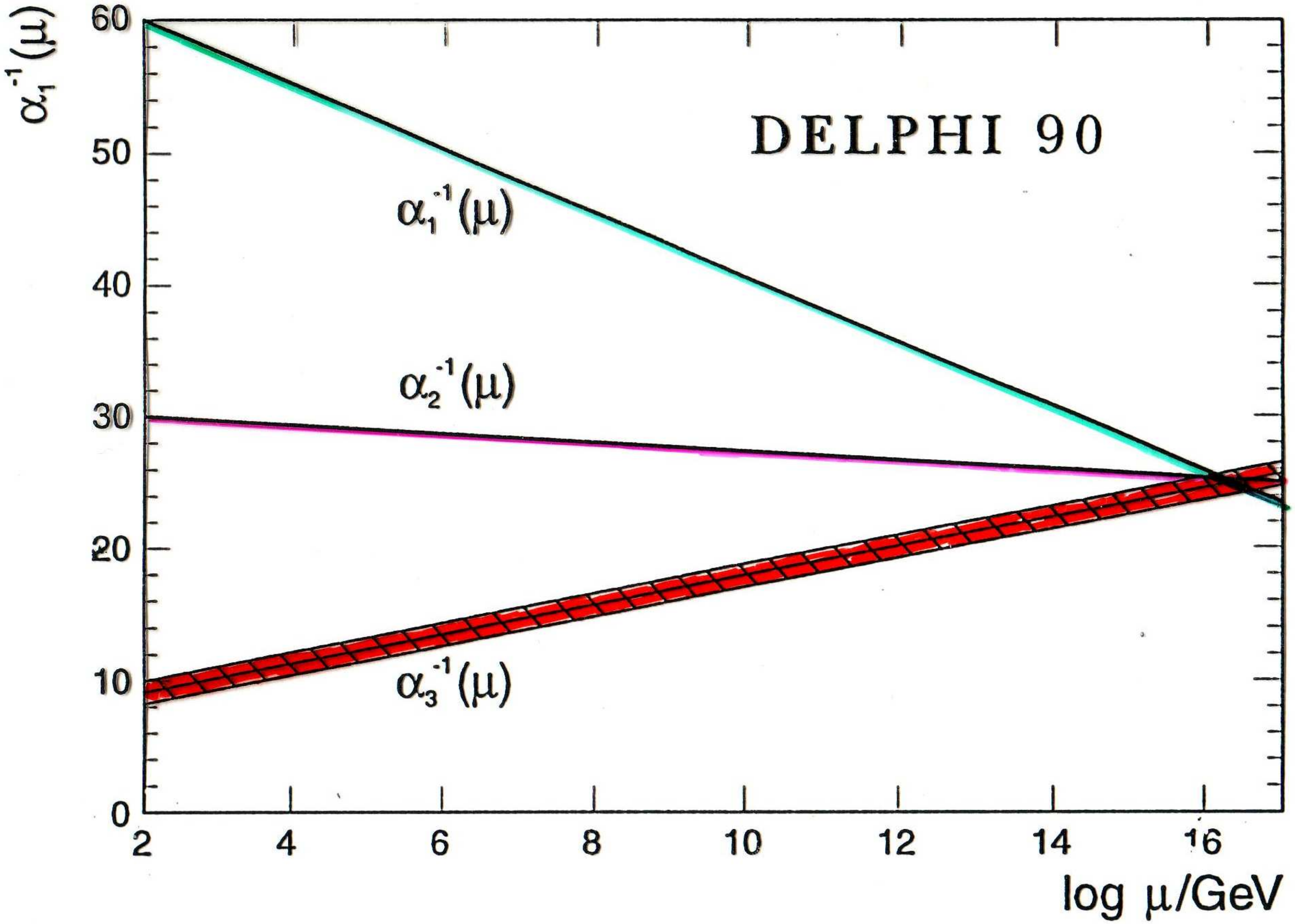
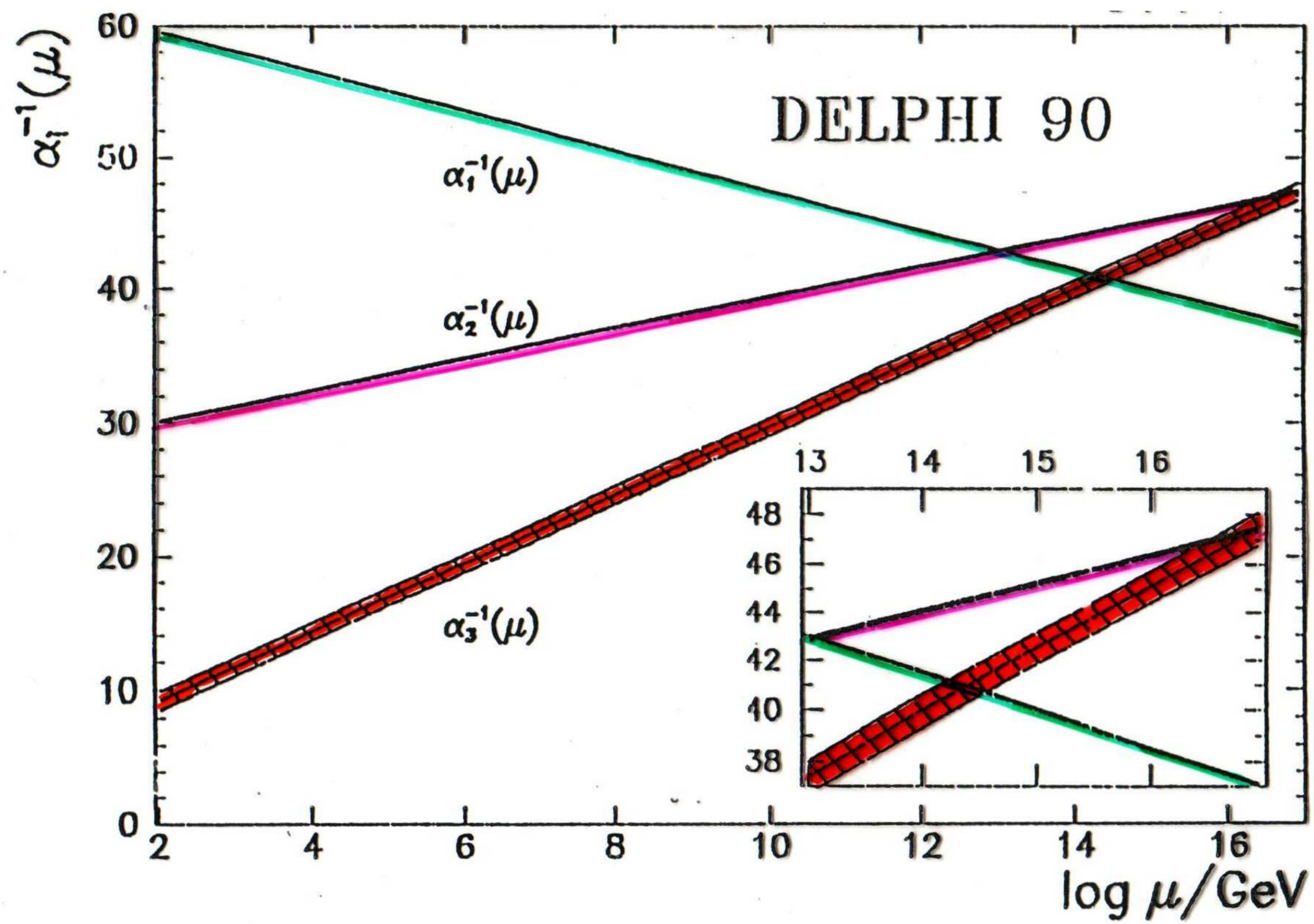
- Evolution of couplings constants of the standard model towards higher energies.

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)

String Theory

What do we get from string theory?

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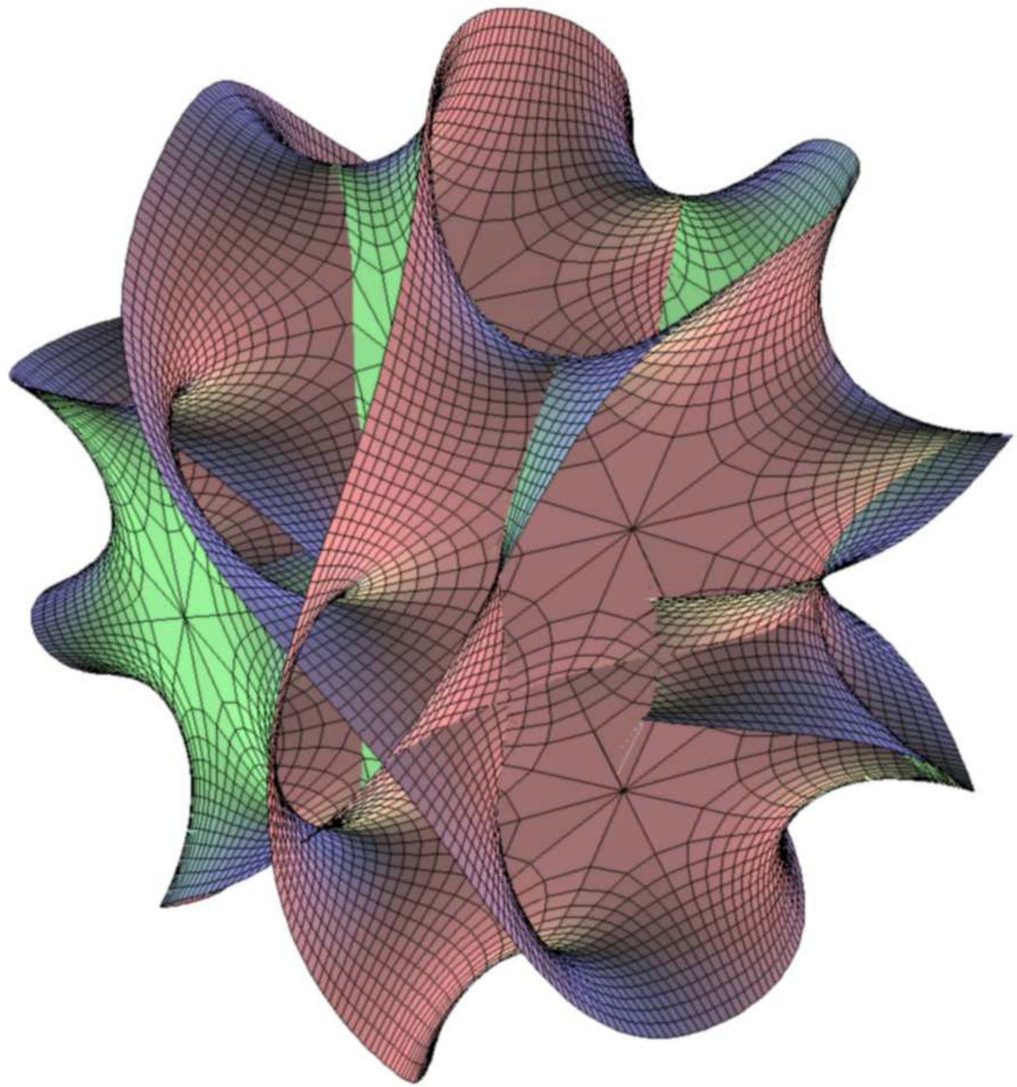
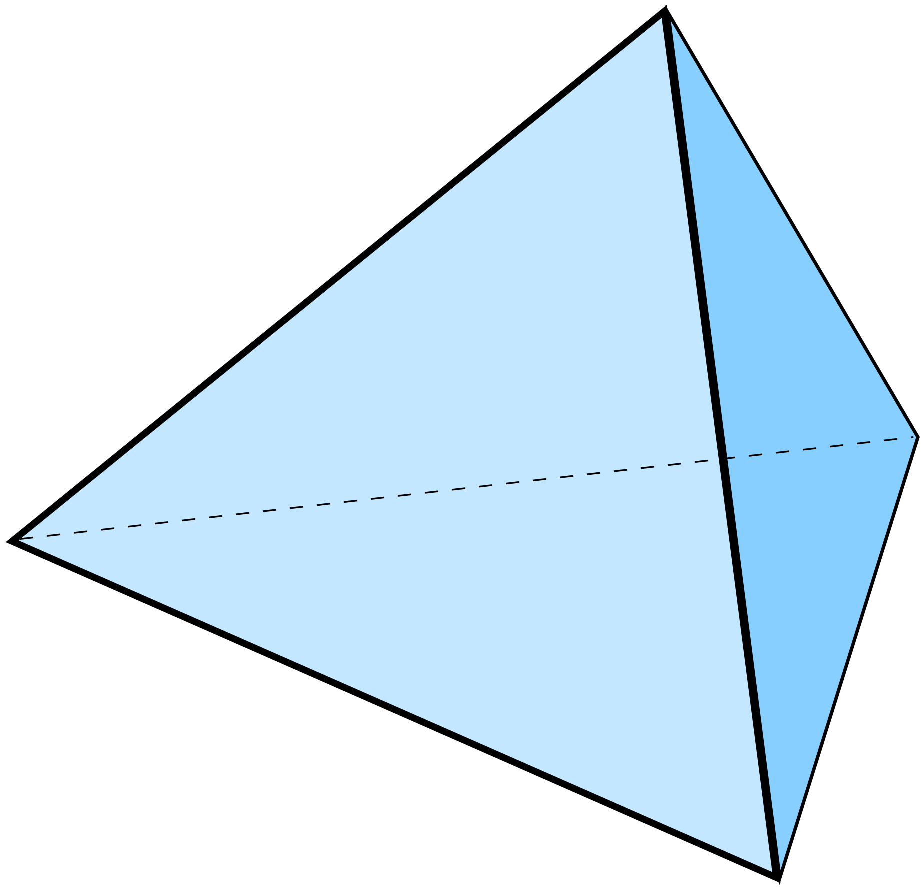
These are the building blocks for a unified theory of all the fundamental interactions.
But do they fit together, and if yes how?

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

Calabi Yau Manifold



Orbifold



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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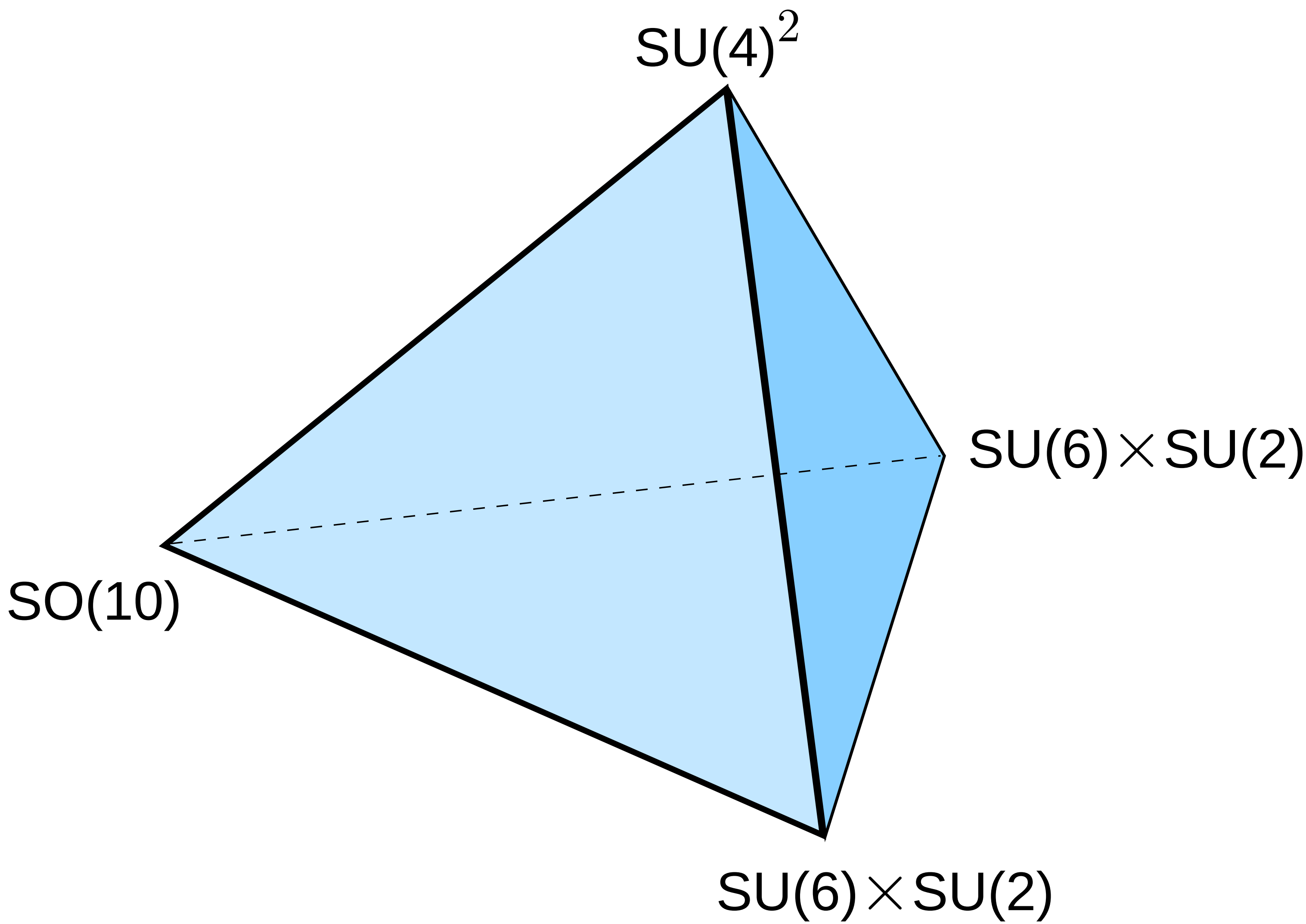
but there is also a “localization” of gauge fields

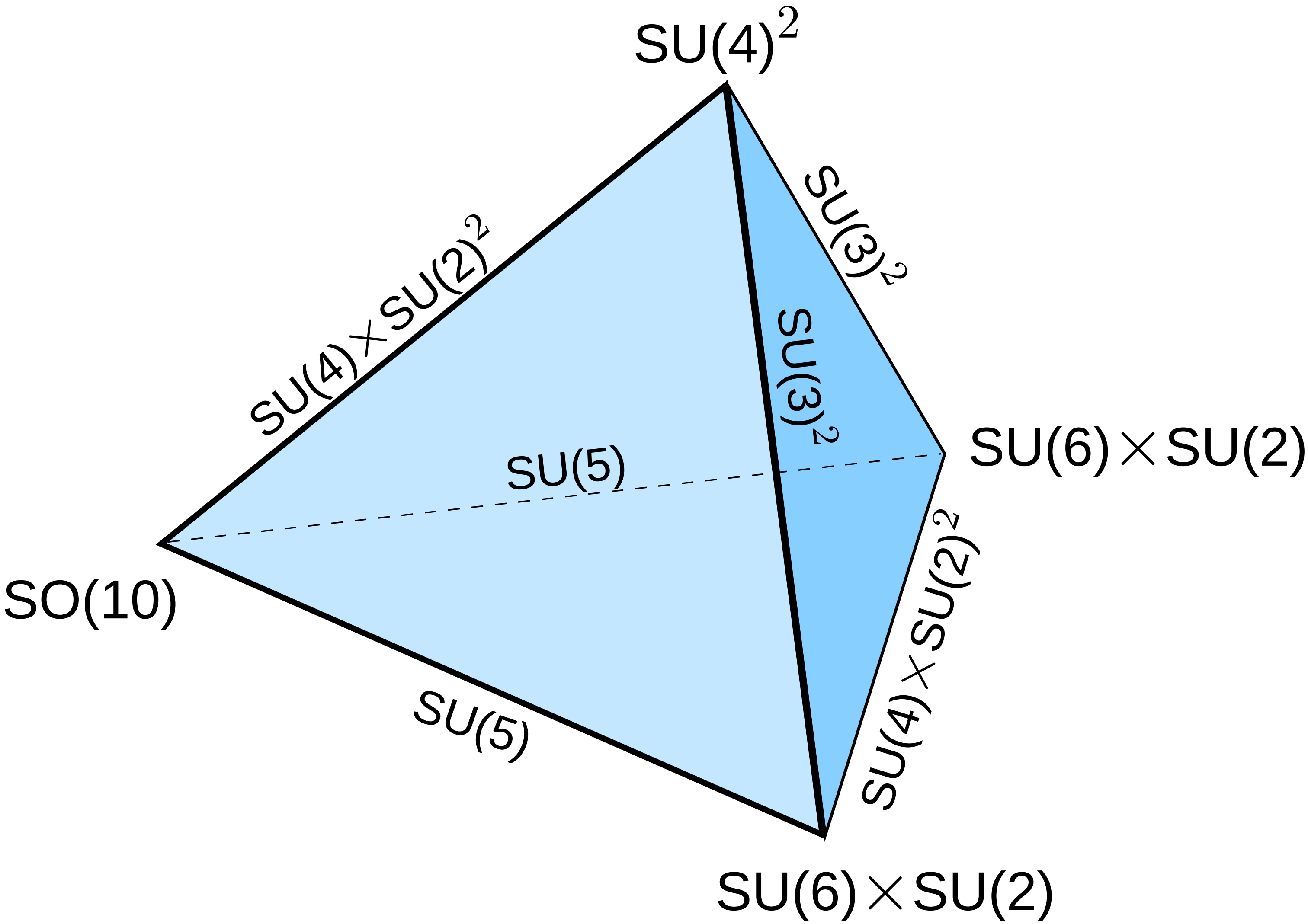
- $E_8 \times E_8$ in the bulk
- smaller gauge groups on various branes

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

Localized gauge symmetries



Standard Model Gauge Group



Local Grand Unification

In fact string theory gives us a variant of GUTs

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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)

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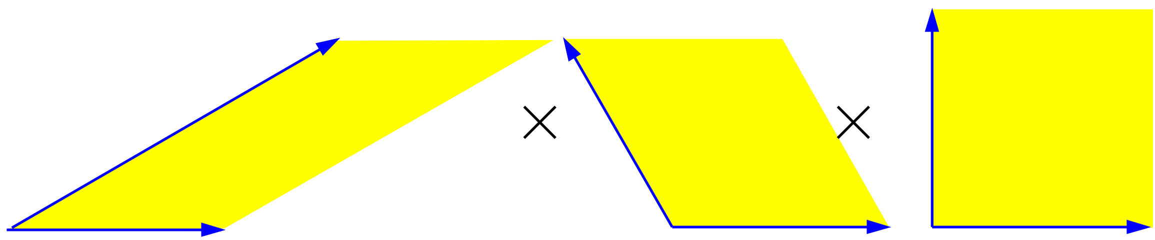
Still there could be remnants of $SO(10)$ symmetry

- 16 of SO(10) at some branes
- correct hypercharge normalization
- R-parity
- distinction between different families

that are very useful for realistic model building ...

Benchmark Scenario: 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)

The road to the MSSM

The benchmark scenario leads to

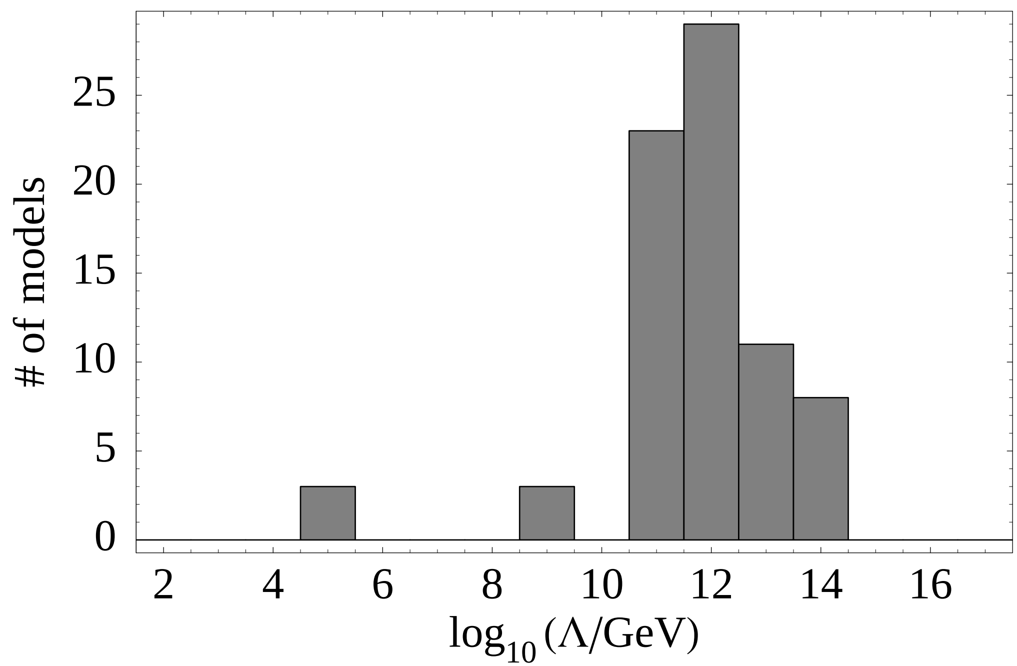
- 200 models with the exact spectrum of the MSSM (absence of chiral exotics)
- local grand unification (by construction)
- gauge- and (partial) Yukawa unification

  (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

Hidden Sector Susy Breakdown



$m_{3/2} = \Lambda^3/M^2_{\text{Planck}}$ (with $\Lambda = \mu \exp(-1/g^2_{\text{hidden}}(\mu))$)
from hidden sector gaugino condensation

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

Basic Questions

- origin of the small scale?
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Recent progress in

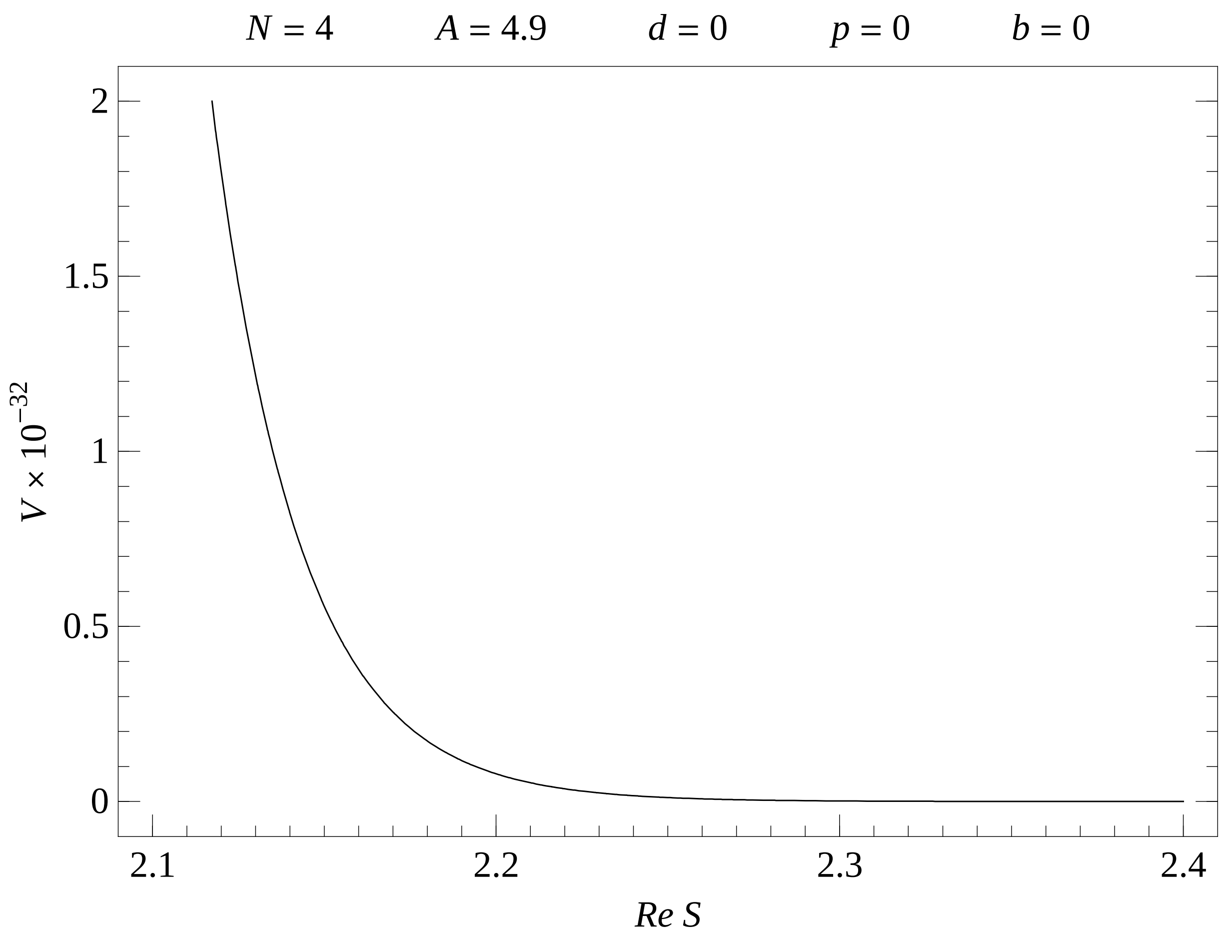
- moduli stabilization via fluxes in warped compactifications of Type IIB string theory

  (Dasgupta, Rajesh, Sethi, 1999; Giddings, Kachru, Polchinski, 2001)

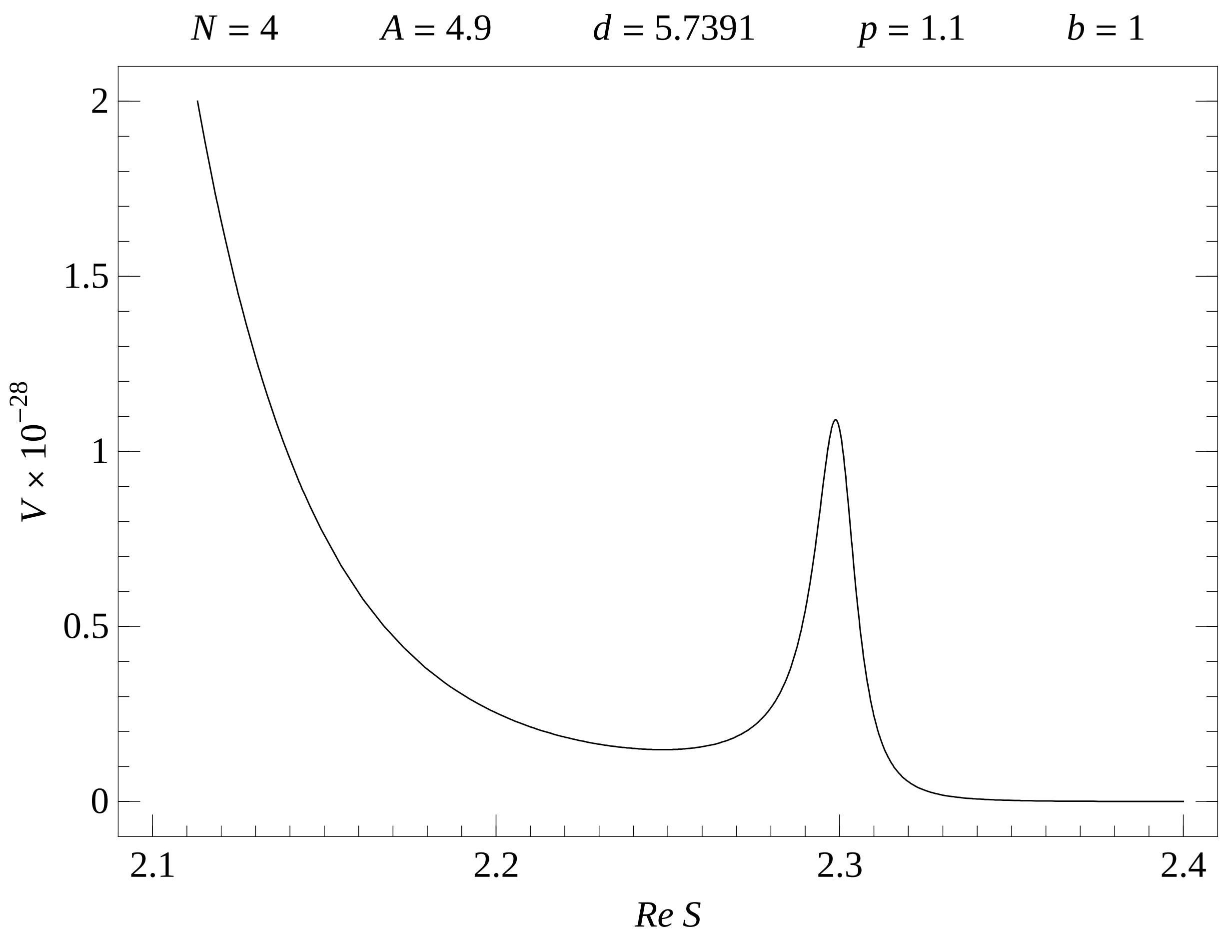
- generalized flux compactifications of heterotic string theory

  (Becker, Becker, Dasgupta, Prokushkin, 2003; Gurrieri, Lukas, Micu, 2004)

Run-away potential

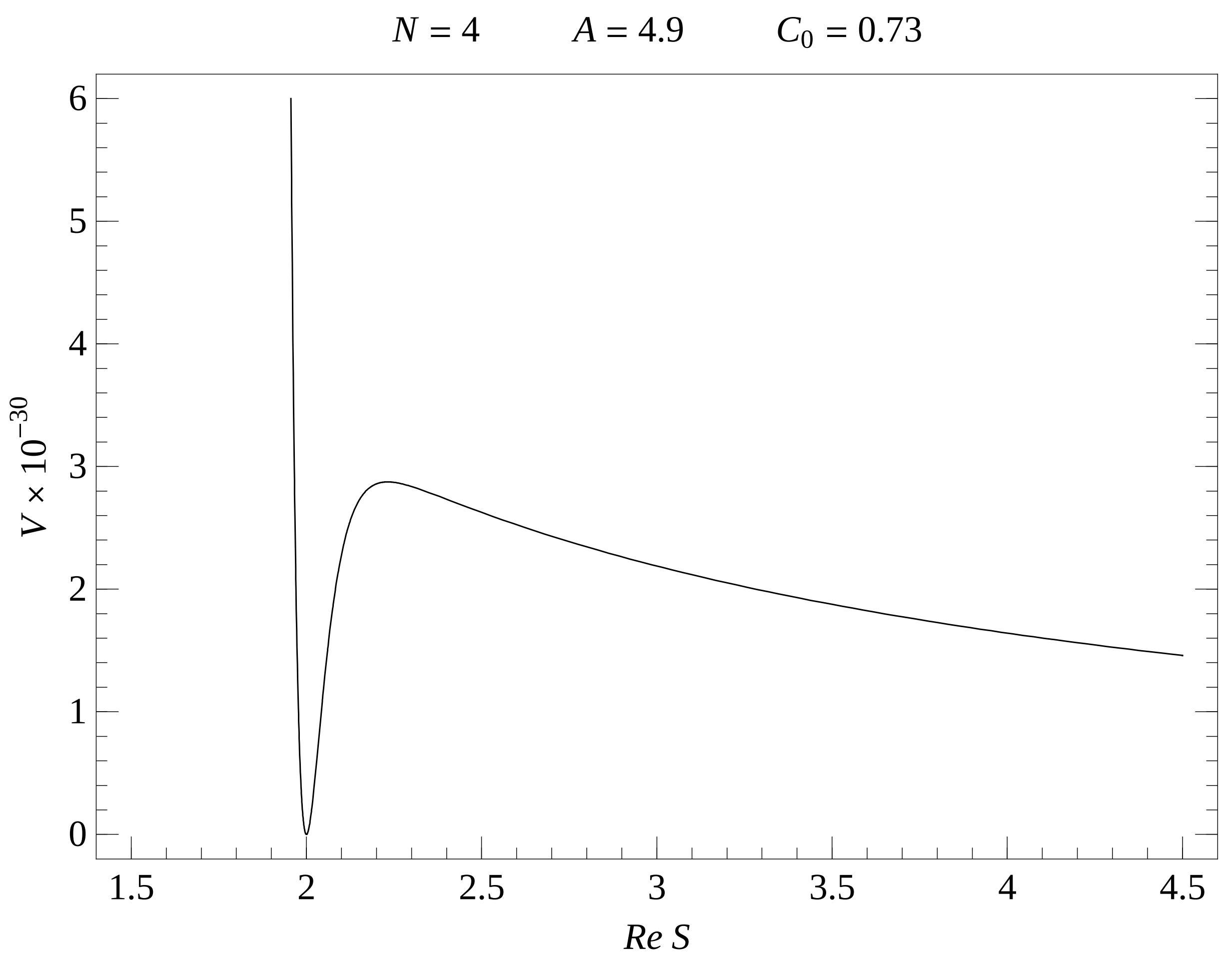


Corrections to Kähler potential



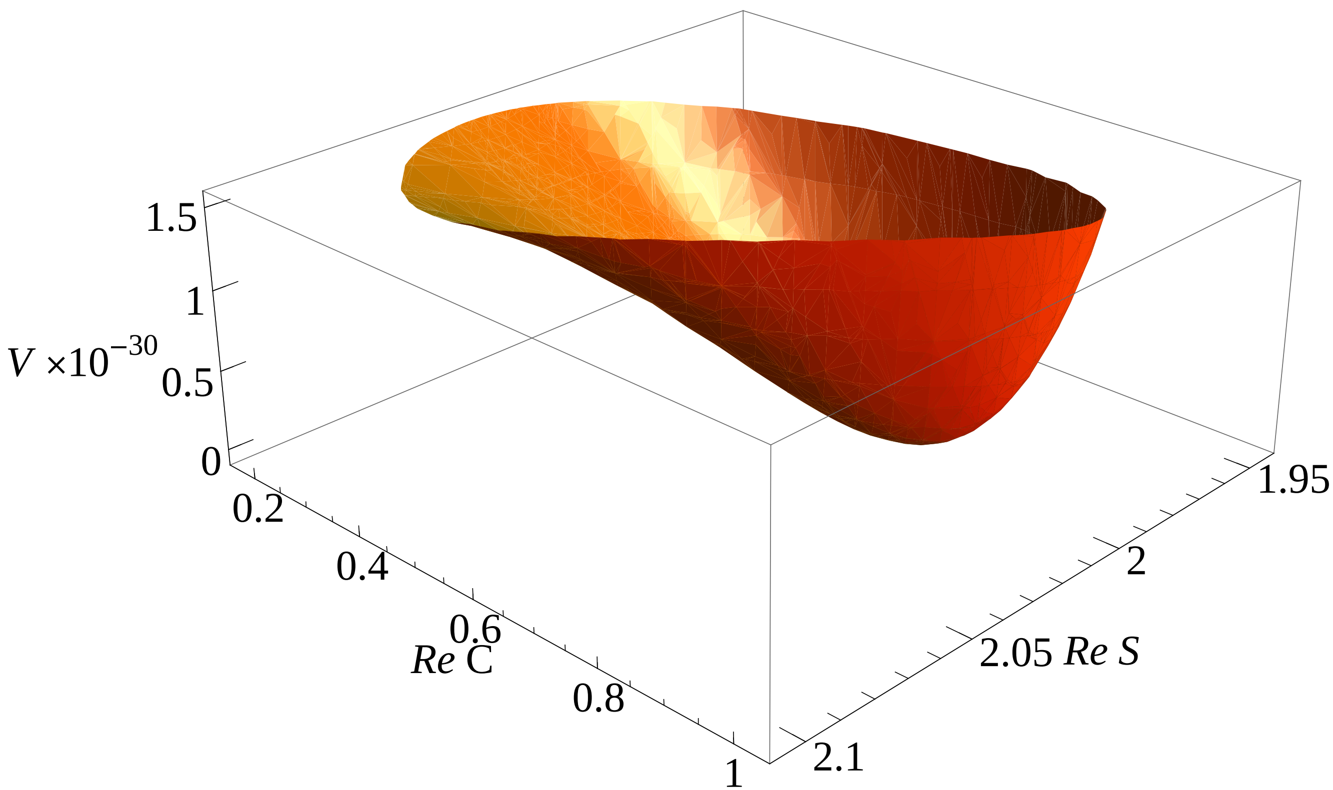
(Barreiro, de Carlos, Copeland, 1998)

Sequestered sector “uplifting”



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

Metastable “Minkowski” vacuum



(Löwen, HPN, 2008)

Fluxes and gaugino condensation

Is there a general pattern of the soft mass terms?

We have (from "flux" and gaugino condensate)

$$W = \text{something} - \exp(-X)$$

where "something" is small and X is moderately large.

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$$W = \text{something} - \exp(-X)$$

where "something" is small and X is moderately large.

In fact in this simple scheme

$$X \sim \log(M_{\text{Planck}}/m_{3/2})$$

providing a "little" hierarchy.

(Choi, Falkowski, HPN, Olechowski, Pokorski, 2004)

Mixed Modulus Anomaly Mediation

The universal contribution from "Modulus Mediation" is therefore suppressed by the factor

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Thus contributions from radiative corrections such as "Anomaly Mediation" become competitive, leading to a Mixed Modulus-Anomaly-Mediation scheme.

For reasons that will be explained later we call this scheme

MIRAGE MEDIATION

(Loaiza, Martin, HPN, Ratz, 2005)

The little hierarchy

$$m_X \sim \langle X \rangle m_{3/2} \sim \langle X \rangle^2 m_{\rm soft}$$

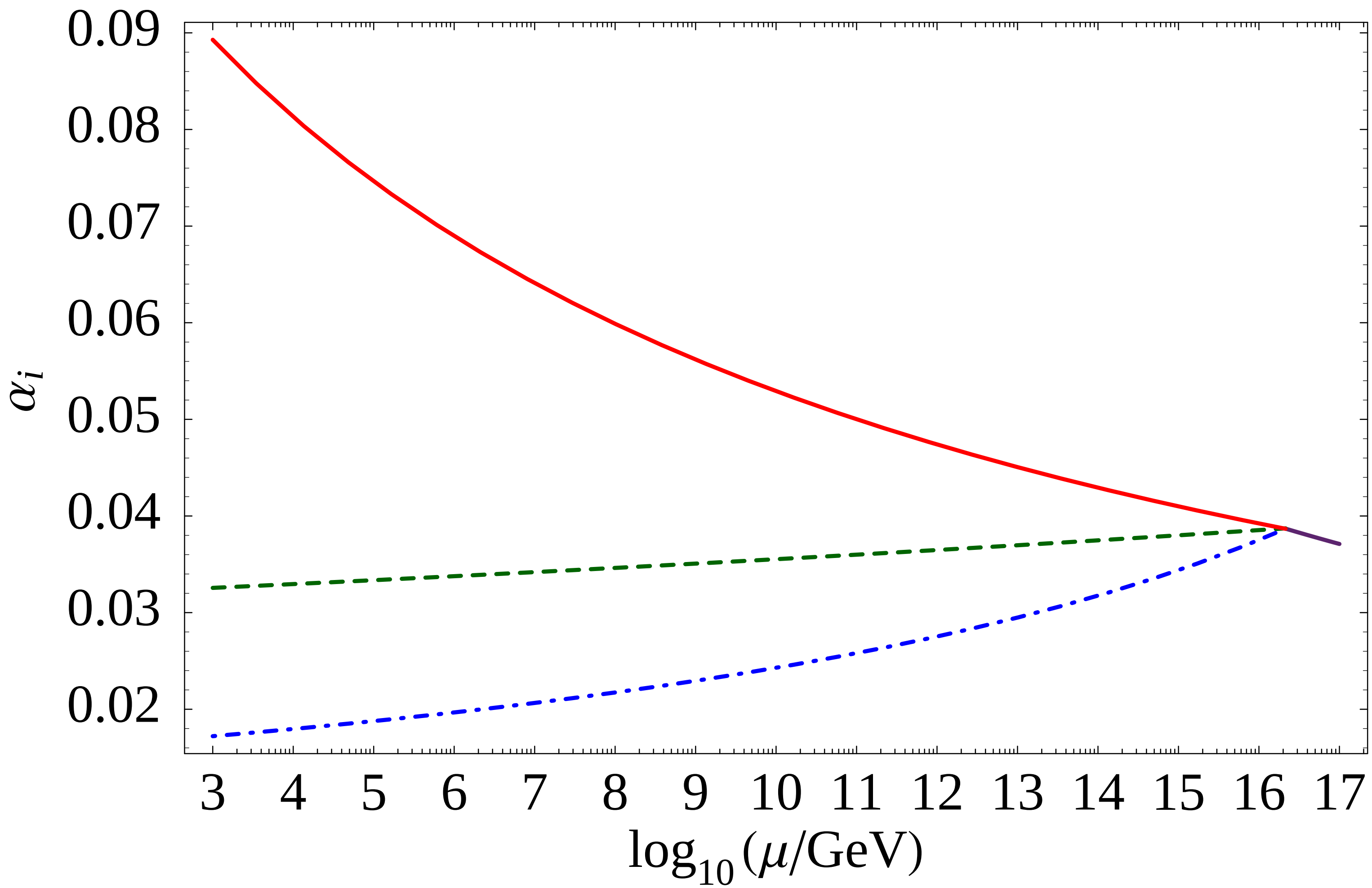
is a generic signal of such a scheme

- moduli and gravitino are heavy
- gaugino mass spectrum is compressed

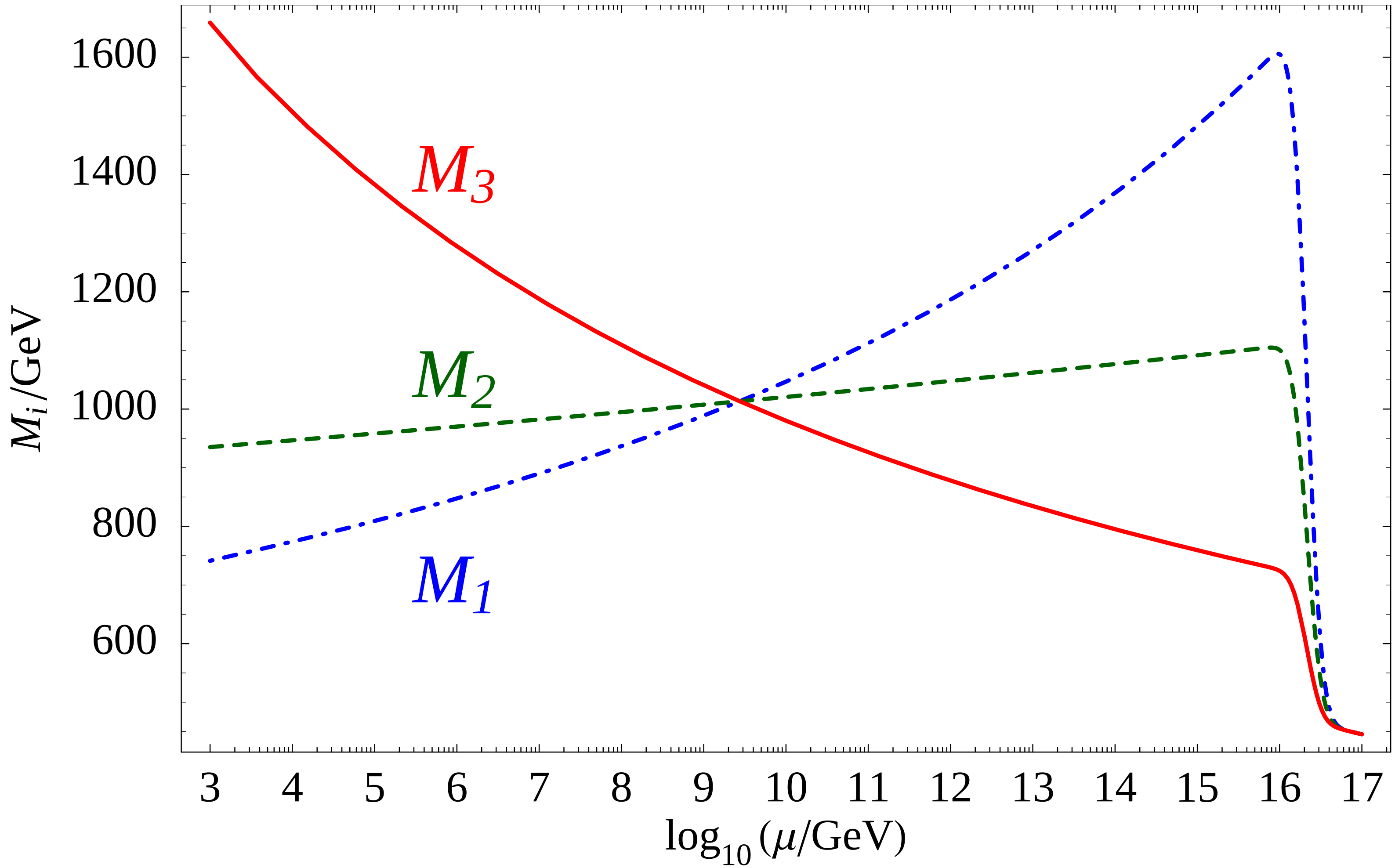
- mirage unification of gaugino masses

(Choi, Falkowski, HPN, Olechowski, 2005; Endo, Yamaguchi, Yoshioka, 2005; Choi, Jeong, Okumura, 2005)

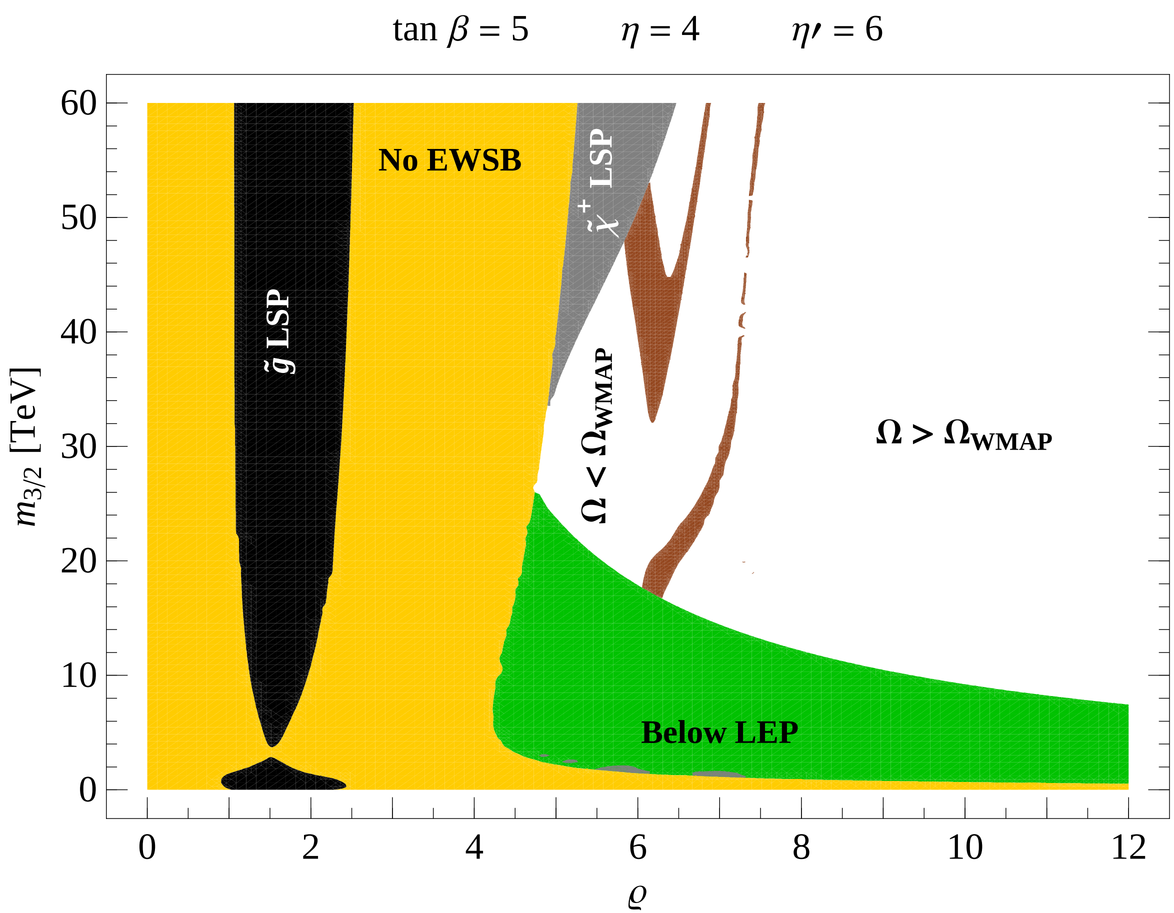
Evolution of couplings



The Mirage Scale



Constraints on the mixing parameter



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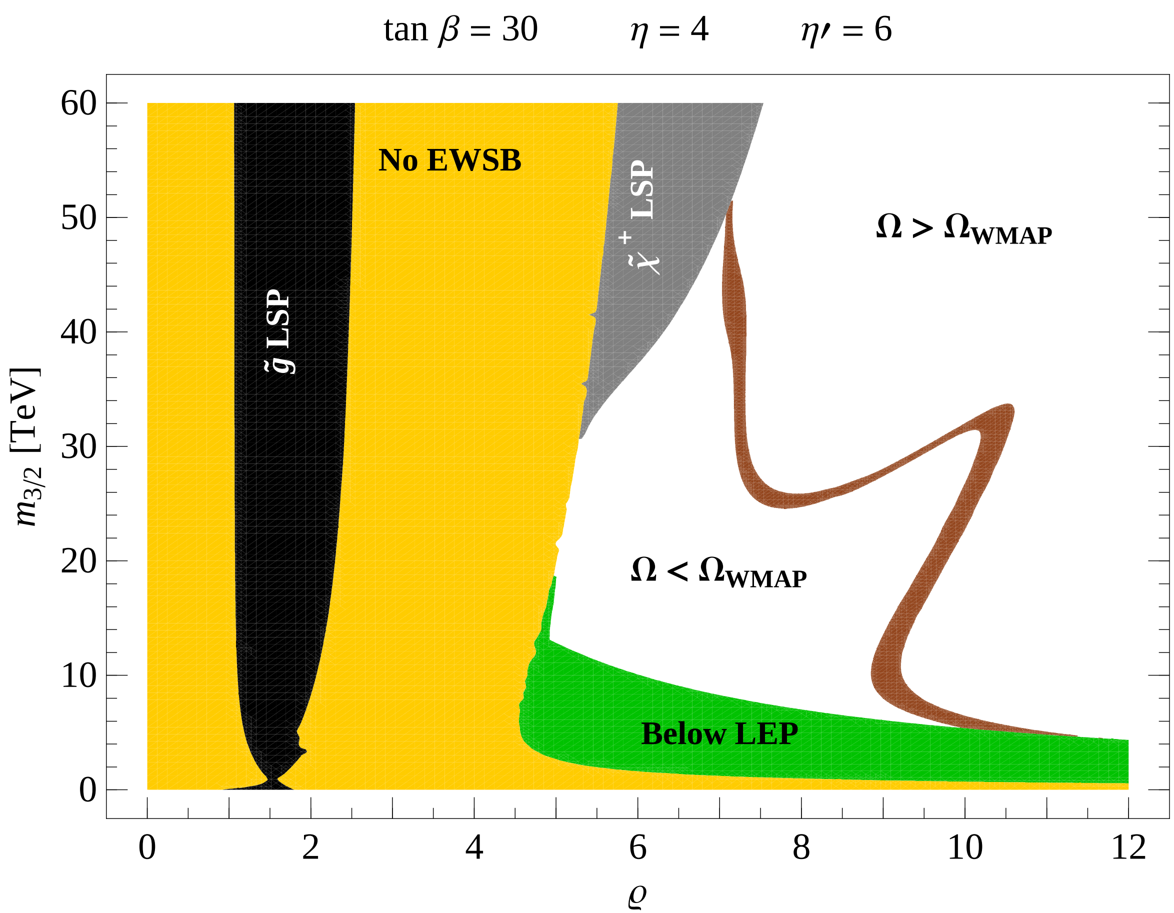

(Löwen, HPN, 2008)

Some important messages

Please keep in mind:

- the uplifting mechanism plays an important role for the pattern of the soft susy breaking terms
- predictions for gaugino masses are more robust than those for sfermion masses
- dilaton/modulus mediation suppressed in many cases
- mirage pattern for gaugino masses rather generic

The Gaugino Code

How can we test these ideas at the LHC?

Look for pattern of gaugino masses

Let us assume the

- low energy particle content of the MSSM
- measured values of gauge coupling constants

$$g_1^2 : g_2^2 : g_3^2 \simeq \ 1 : 2 : 6$$

The evolution of gauge couplings would then lead to unification at a GUT-scale around 10^{16} GeV

The Gaugino Code

Observe that

- evolution of gaugino masses is tied to evolution of gauge couplings
- for MSSM M_a/g_a^2 does not run (at one loop)

This implies

- robust prediction for gaugino masses
- gaugino mass relations are the key to reveal the underlying scheme

3 CHARACTERISTIC MASS PATTERNS

(Choi, HPN, 2007)

mSUGRA Pattern

Universal gaugino mass at the GUT scale

- mSUGRA pattern:

$$M_1 : M_2 : M_3 \simeq \ 1 : 2 : 6 \simeq \ g_1^2 : g_2^2 : g_3^2$$

as realized in popular schemes such as
gravity-, modulus- or dilaton-mediation

This leads to

- LSP χ_1^0 predominantly Bino
- $M_{\rm gluino}/m_{\chi_1^0} \simeq 6$

as a characteristic signature of these schemes.

Anomaly Pattern

Gaugino masses below the GUT scale determined by the β functions

- anomaly pattern:

$$M_1 : M_2 : M_3 \simeq \; 3.3 : 1 : 9$$

at the TeV scale as the signal of anomaly mediation.

For the gauginos, this implies

- LSP χ_1^0 predominantly Wino
- $M_{\rm gluino}/m_{\chi_1^0} \simeq 9$

Pure anomaly mediation inconsistent, as sfermion masses are problematic in this scheme (tachyonic sleptons).

Mirage Pattern

Mixed boundary conditions at the GUT scale
characterized by the parameter ρ
(the ratio of modulus to anomaly mediation).

- $M_1 : M_2 : M_3 \simeq\ 1 : 1.3 : 2.5$ for $\rho \simeq 5$
- $M_1 : M_2 : M_3 \simeq\ 1 : 1 : 1$ for $\rho \simeq 2$

The mirage scheme leads to

- LSP χ_1^0 predominantly Bino
- $M_{\rm gluino}/m_{\chi_1^0} < 6$
- a "compressed" gaugino mass pattern.

Conclusion

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

- Local Grand Unification
- Mirage Mediation

Geography of extra dimensions plays a crucial role:

- localization of fields on branes,
- presence of sequestered sectors

LHC might help us to verify some of these ideas!