From the Standard Model to String Theory

Hans Peter Nilles

Physikalisches Institut

Universität Bonn

universität bonn

bctp Bethe Center for Theoretical Physics

Questions

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

Questions

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

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

What do we want?

- gauge group $SU(3) \times SU(2) \times U(1)$
- 3 families of quarks and leptons
- scalar Higgs doublet

The road to the Standard Model

What do we want?

- gauge group $SU(3) \times SU(2) \times U(1)$
- 3 families of quarks and leptons
- scalar Higgs doublet

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

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

$M_{\mathrm{GUT}} \sim 10^{16}\mathrm{GeV}$ and $M_{\mathrm{SUSY}} \sim 10^{3}\mathrm{GeV}$:

Indirect evidence

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

$M_{\rm GUT} \sim 10^{16}{\rm GeV}$ and $M_{\rm SUSY} \sim 10^{3}{\rm GeV}$:

- Neutrino-oscillations and “See-Saw Mechanism”

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

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

Indirect evidence

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

$M_{\rm GUT} \sim 10^{16}{\rm GeV}$ and $M_{\rm SUSY} \sim 10^{3}{\rm GeV}$:

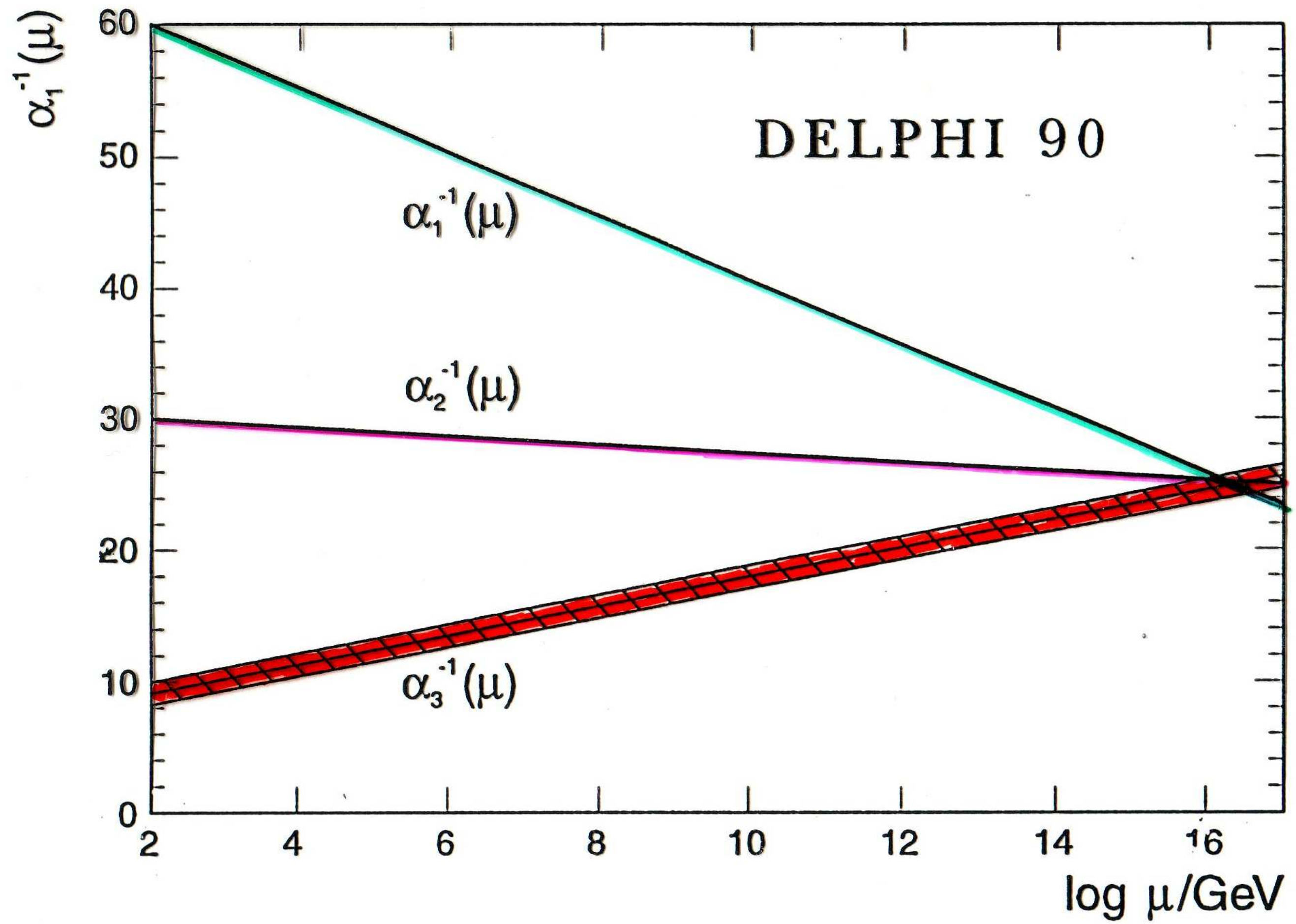
- Neutrino-oscillations and “See-Saw Mechanism”

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

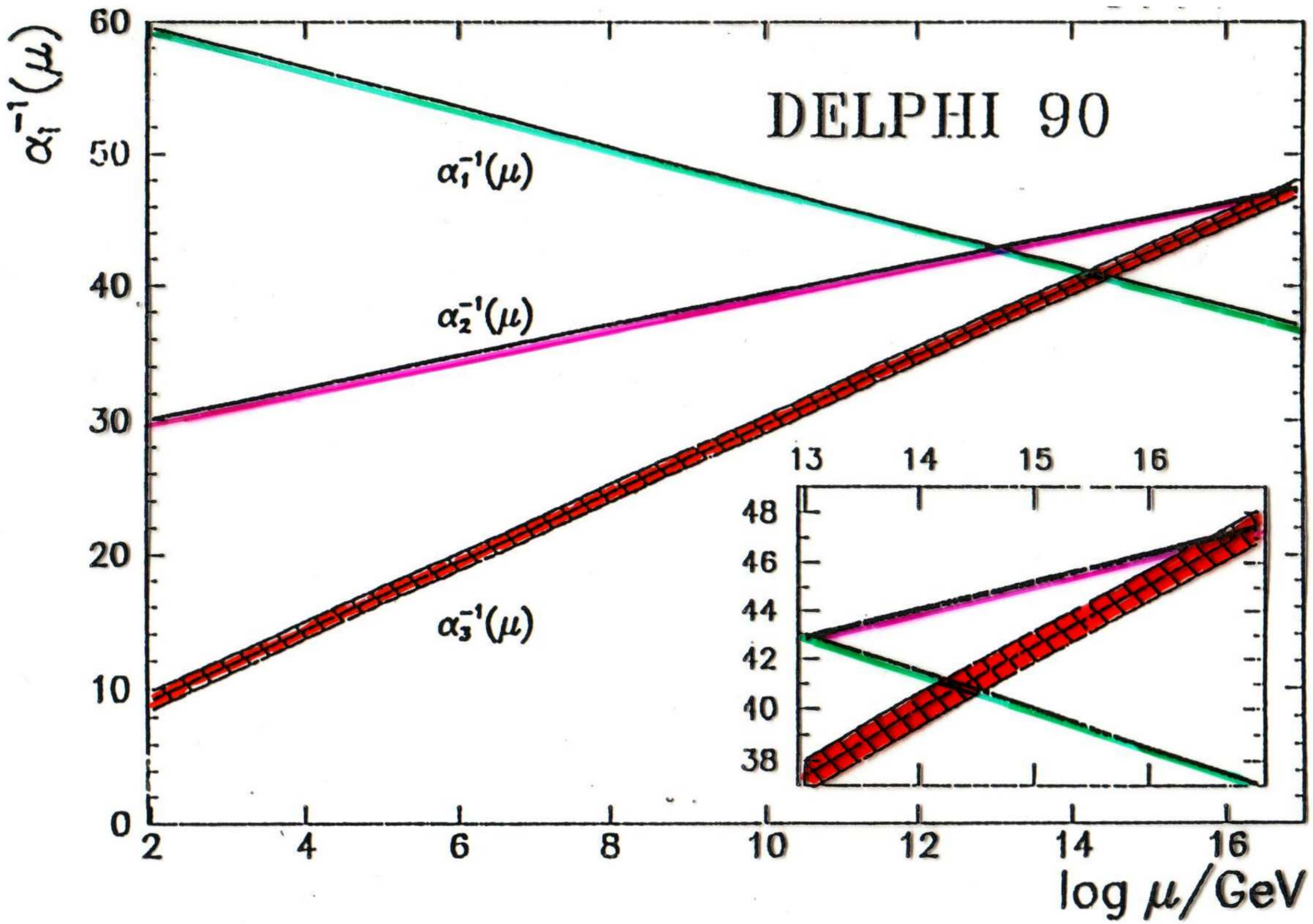
  $m_\nu \sim 10^{-3}{\rm eV}$ for $M_W \sim 100{\rm GeV}$,

- Evolution of coupling 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
- neutrino see-saw mechanism

Grand Unification

This leads to SUSY-GUTs with nice things like

- unified multiplets (e.g. spinors of SO(10))
- gauge coupling unification
- Yukawa unification
- neutrino see-saw mechanism

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
- large unified gauge groups
- consistent theory of gravity

String Theory

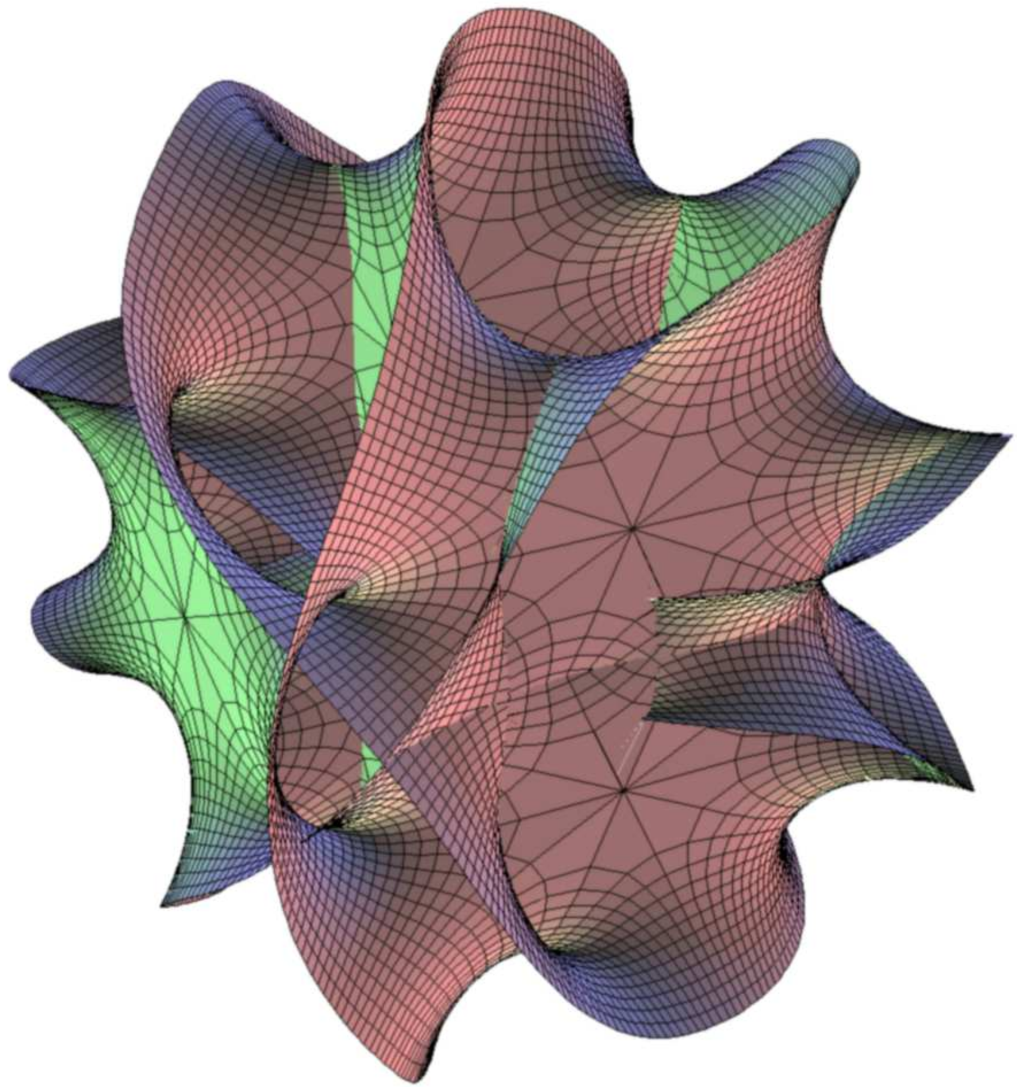
What do we get from string theory?

- supersymmetry
- extra spatial dimensions
- large unified gauge groups
- consistent theory of gravity

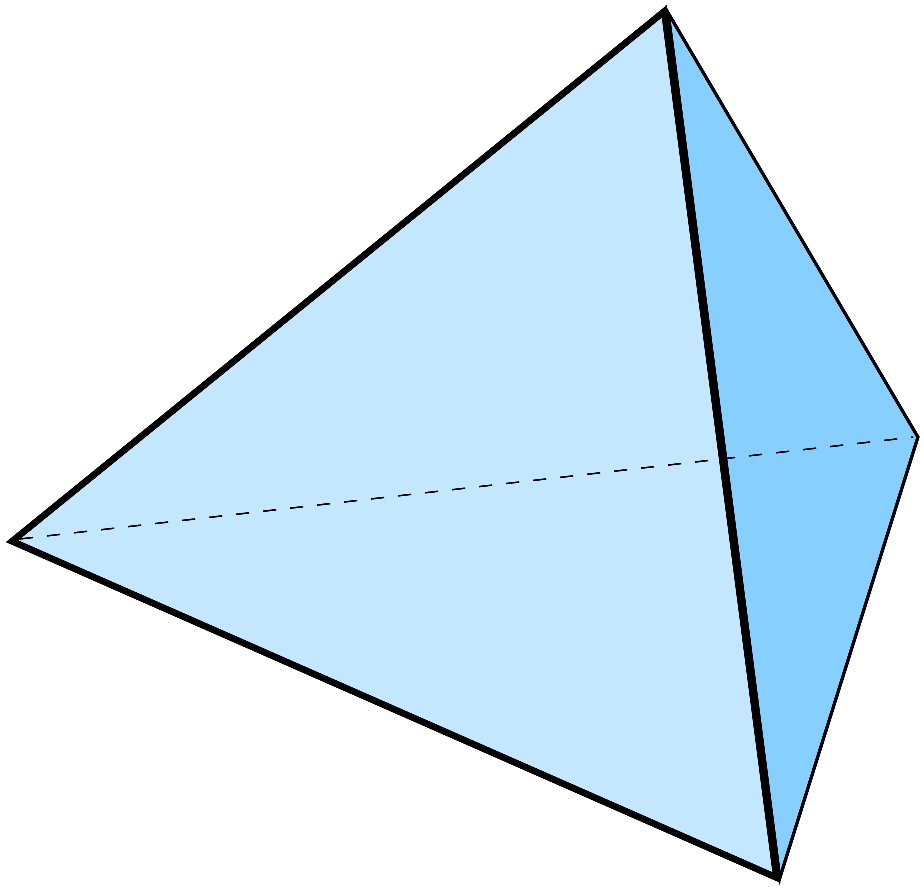
These are the building blocks for a unified theory of all the fundamental interactions.
But do they fit together, and if yes how?

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

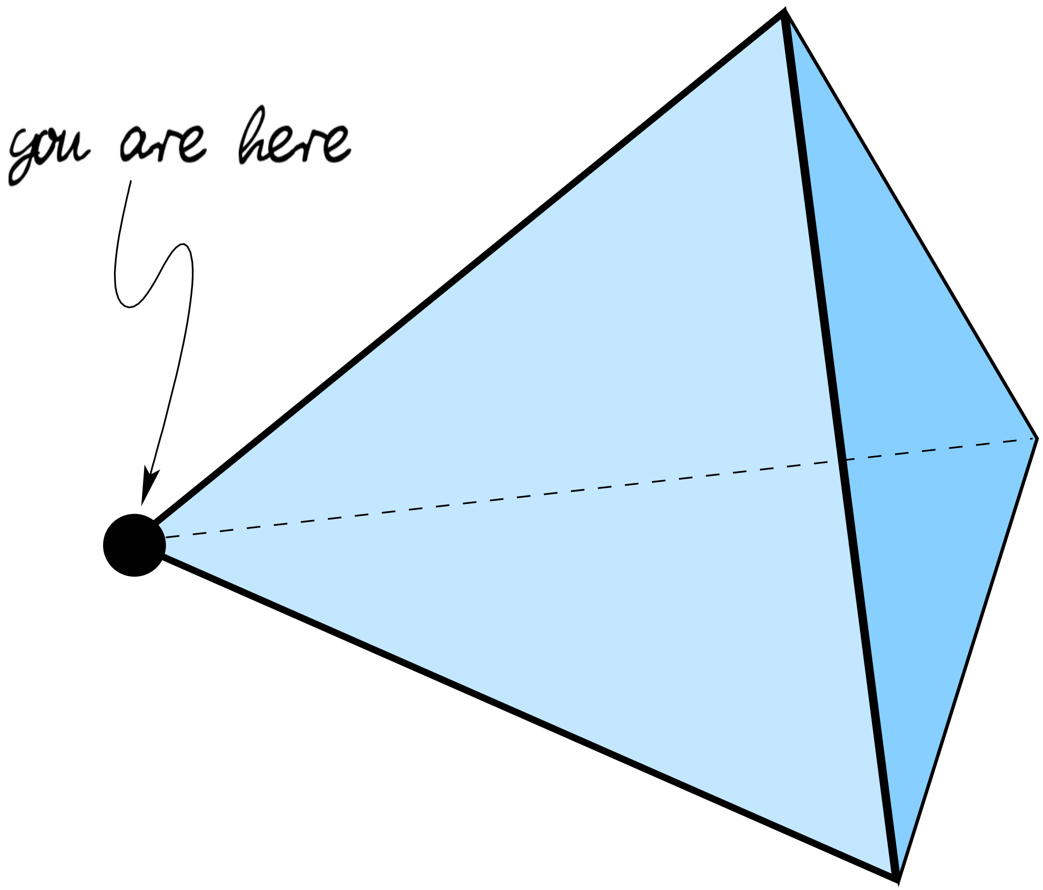
Calabi Yau Manifold



Orbifold



Where do we live?



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)

Localization

Quarks, Leptons and Higgs fields can be localized:

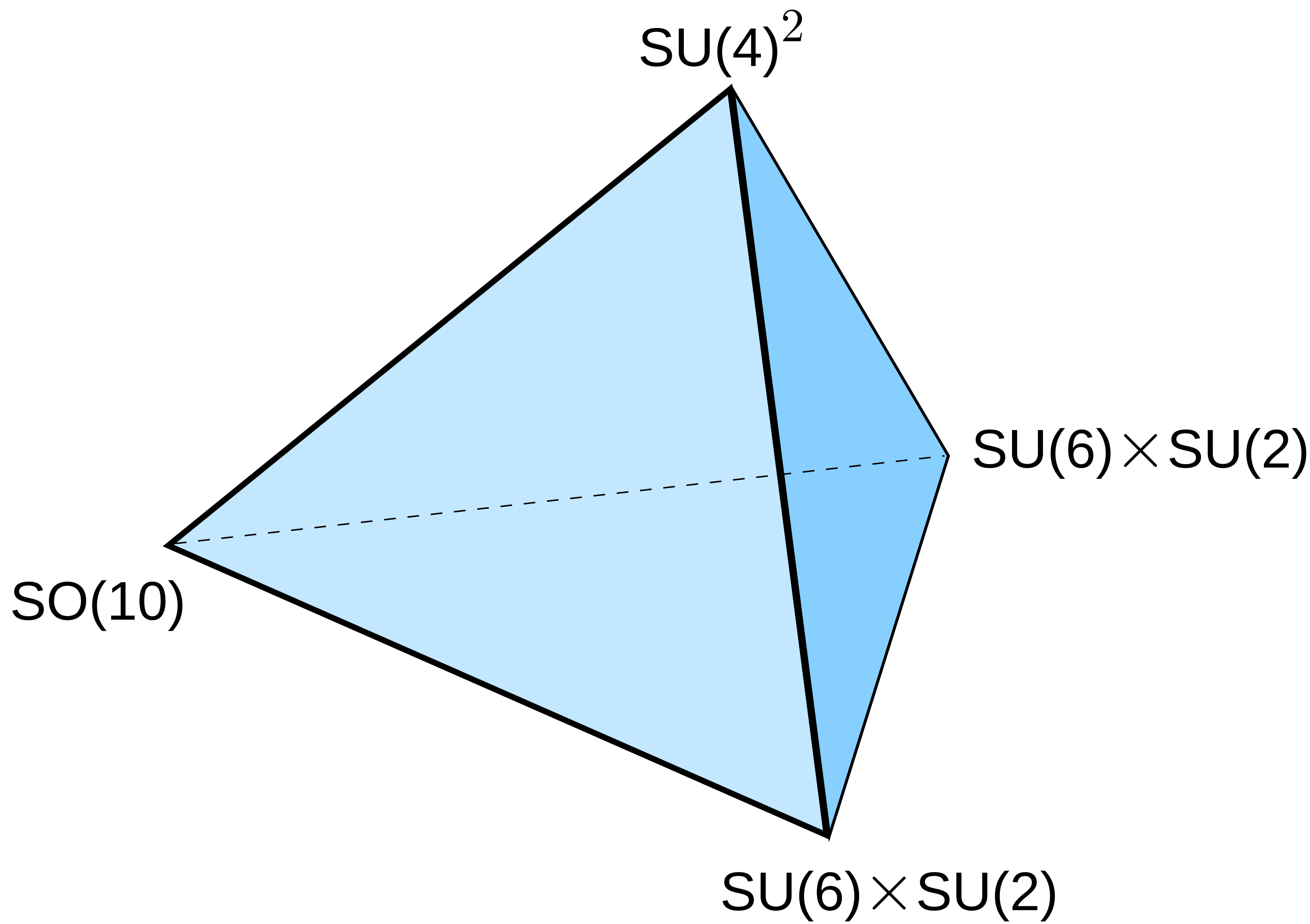
- in the Bulk ($d = 10$ untwisted sector)
- on 3-Branes ($d = 4$ twisted sector fixed points)
- on 5-Branes ($d = 6$ twisted sector fixed tori)

but there is also a “localization” of gauge fields

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

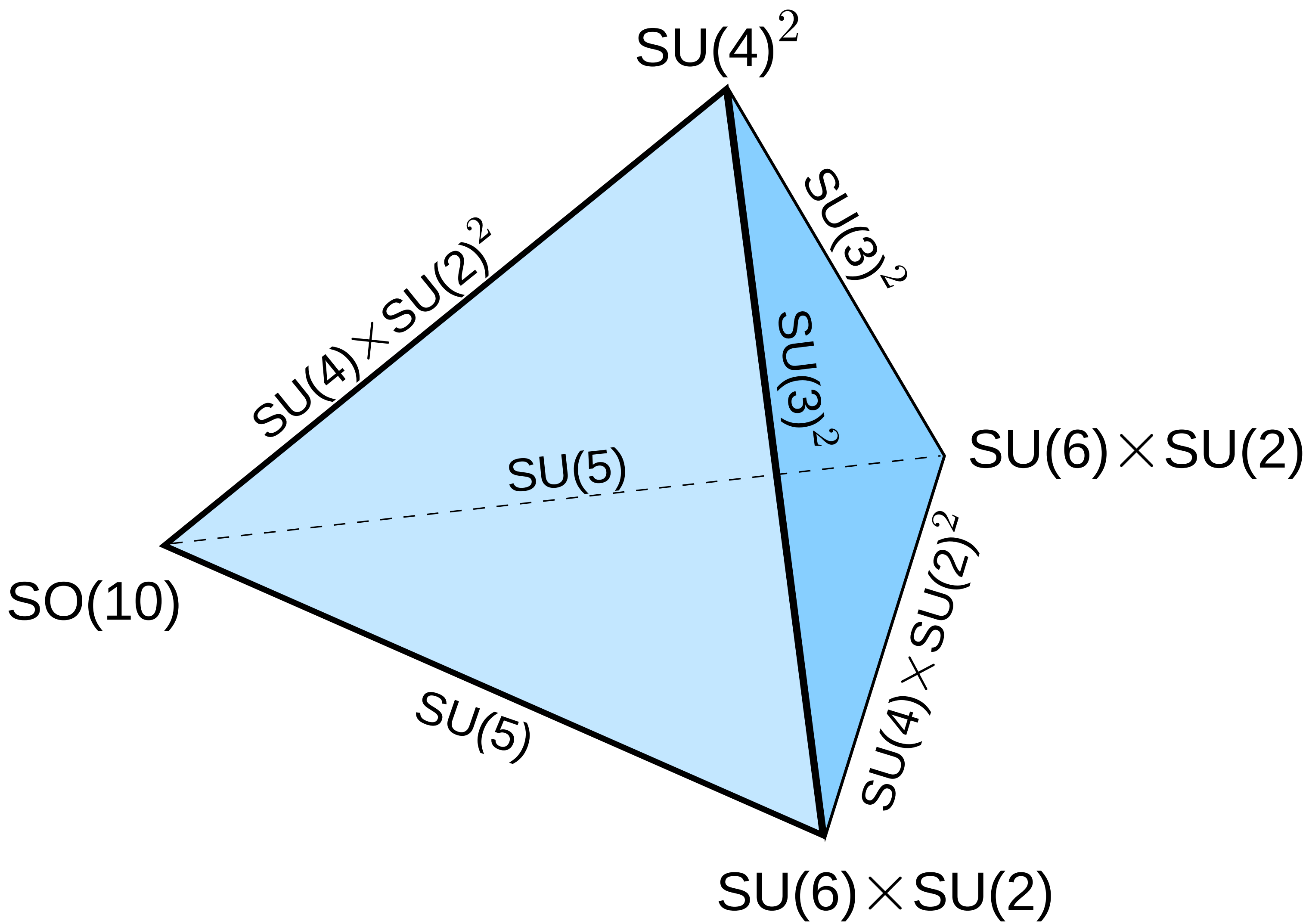
Observed 4-dimensional gauge group is common subroup of the various localized gauge groups!

Localized gauge symmetries



(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

Local Grand Unification

In fact string theory gives us a variant of GUTs

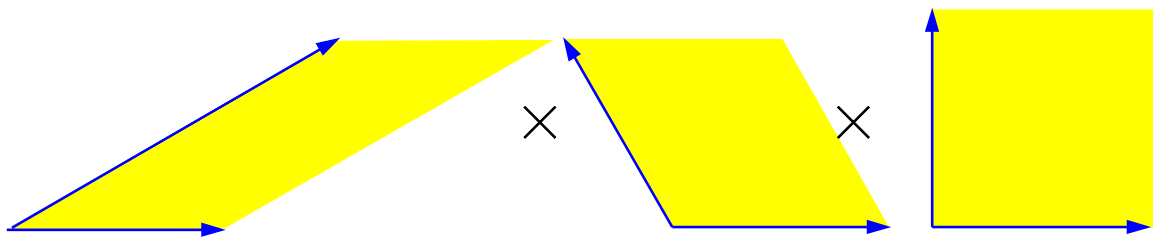
- complete multiplets for fermion families
- split multiplets for gauge- and Higgs-bosons
- partial Yukawa unification

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)

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 matter-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

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

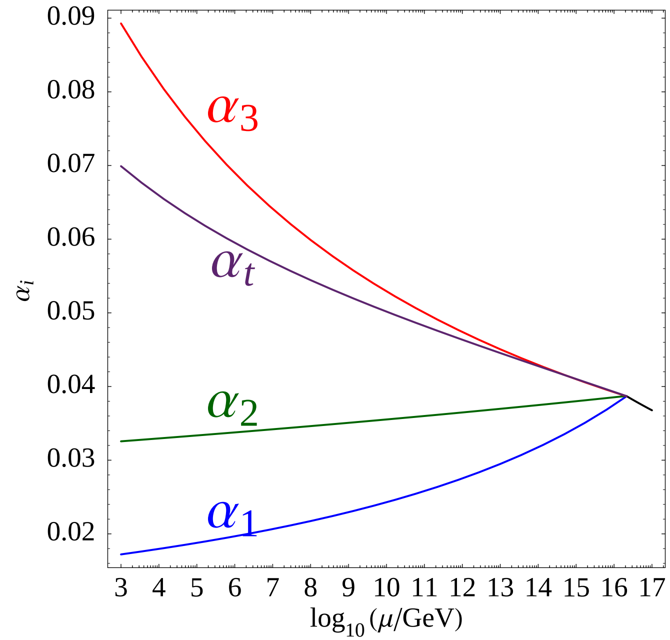
- for discussion of neutrinos and R-parity we keep also the $U(1)_{B-L}$ charges

Spectrum

#	irrep	label		#	irrep	label
3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{(1/6,1/3)}$	q_i		3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{(-2/3,-1/3)}$	$\bar{u}_i$
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
- 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)

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)

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

Matter-Parity

- matter-parity allows the distinction between Higgs bosons and sleptons
- $SO(10)$ contains matter-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 matter-parity (and generalizations thereof)
- one just needs singlets with an even $B - L$ charge that break $U(1)_{B-L}$ down to matter-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.

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)

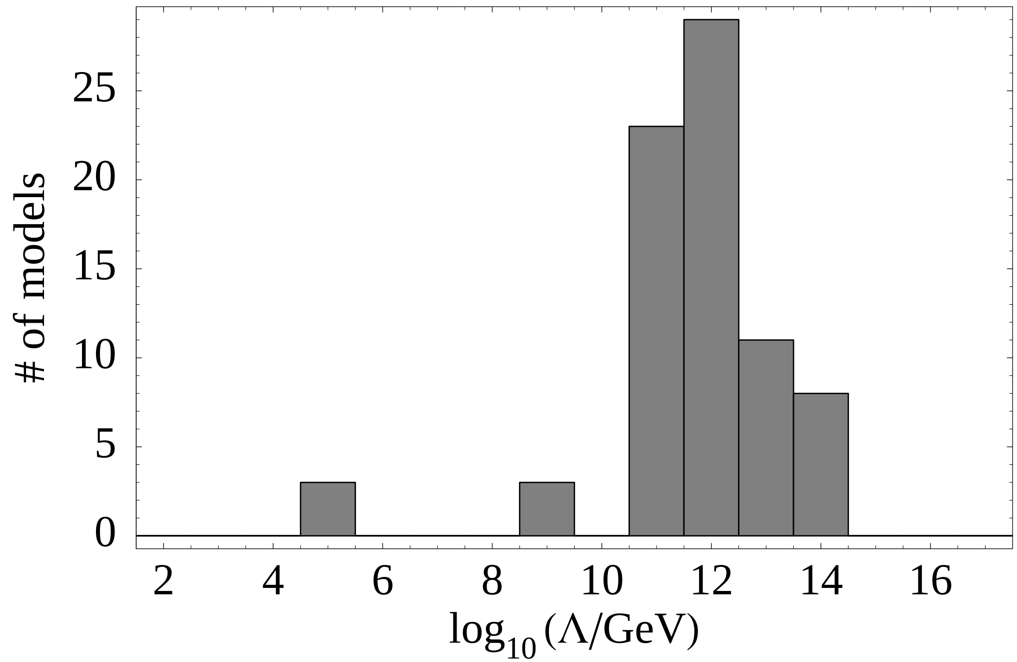
- proton stability via “Proton Hexality”

  (Dreiner, Luhn, Thormeier, 2005; Förste, HPN, Ramos-Sanchez, Vaudrevange, 2010)

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

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

Gaugino Condensation

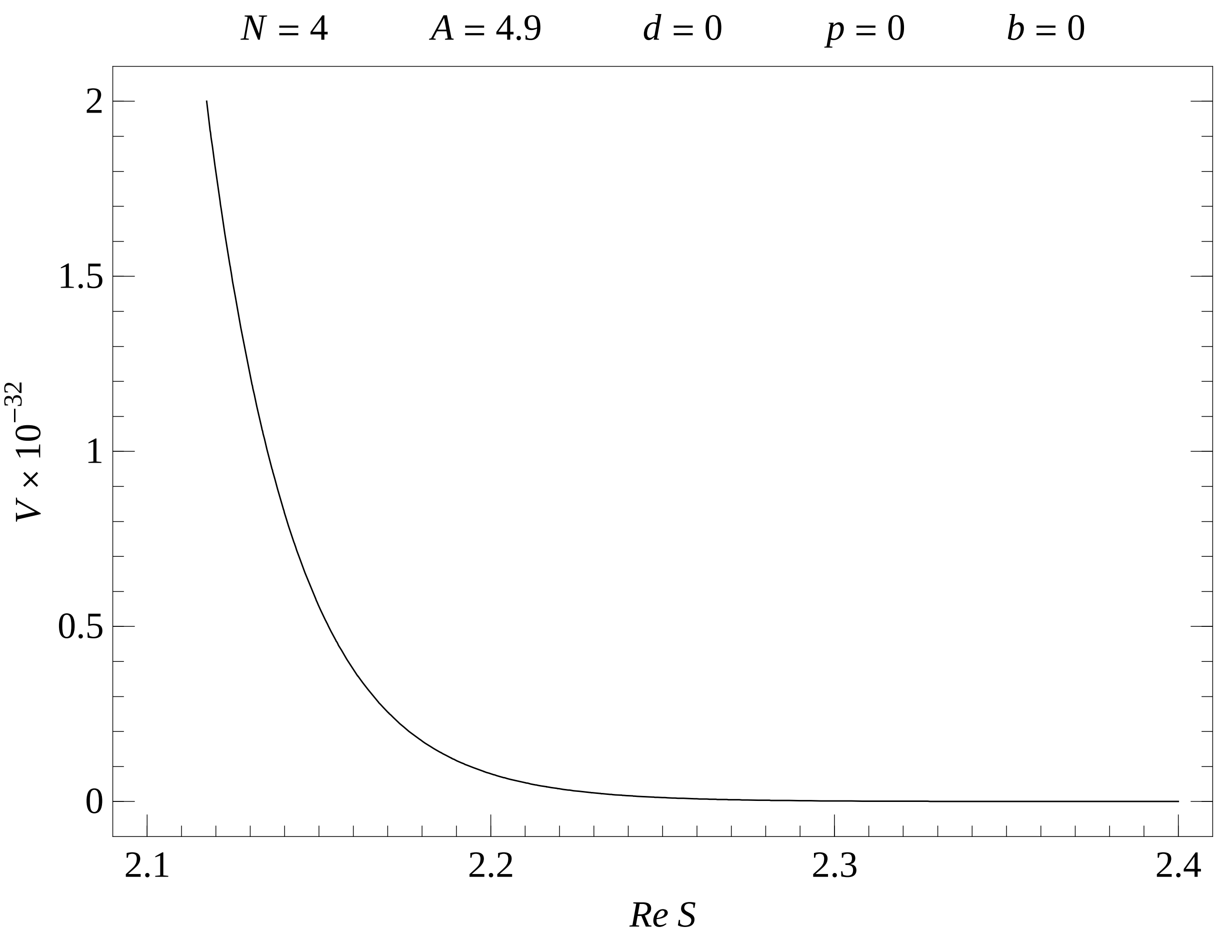


Gravitino mass $m_{3/2} = \Lambda^3 / M_{\mathrm{Planck}}^2$ and $\Lambda \sim \exp(-S)$

We need to fix the dilaton!

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

Run-away potential



Basic Questions

- origin of the small scale?
- stabilization of moduli?

Basic Questions

- origin of the small scale?
- stabilization of moduli?

Recent progress in

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

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

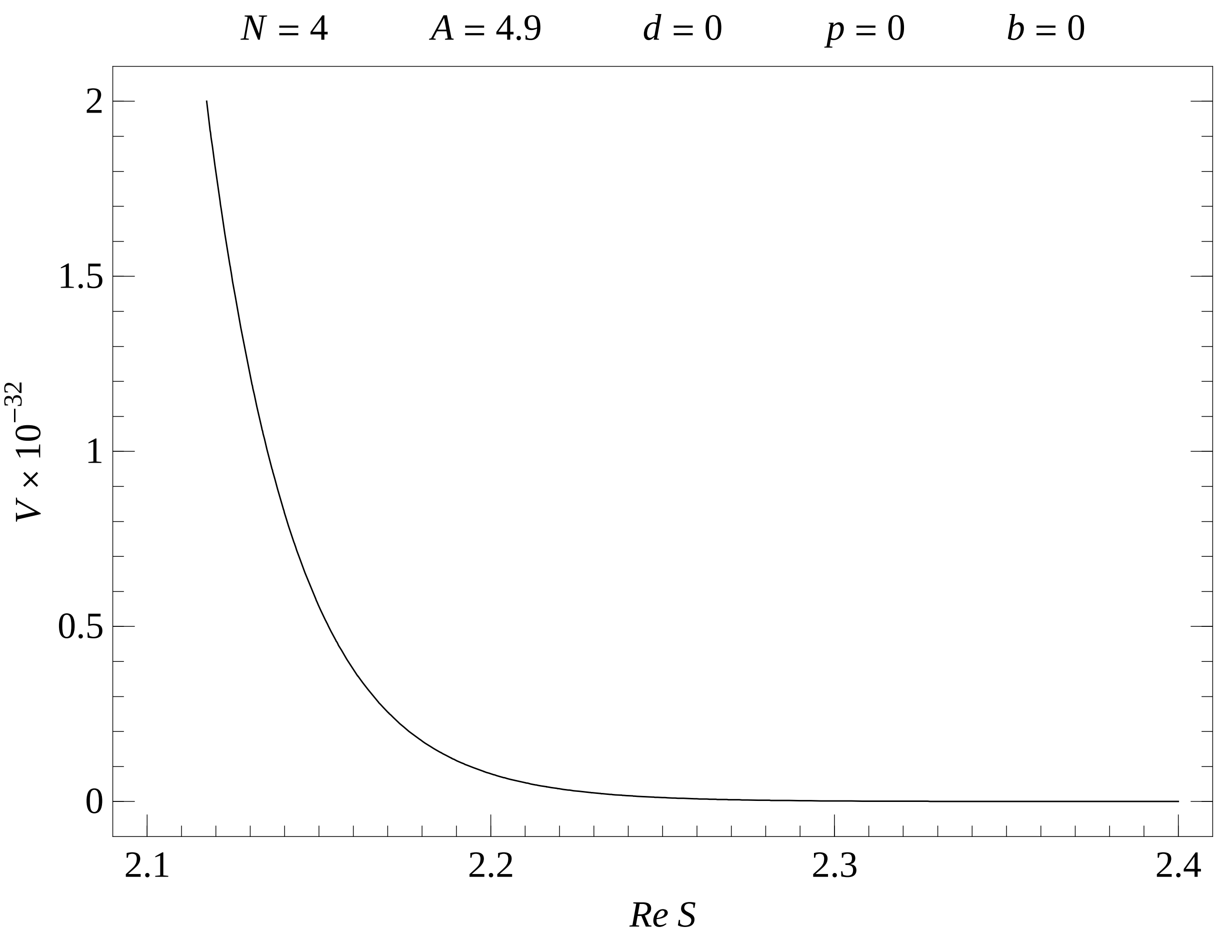
- generalized flux compactifications of heterotic string theory

  (Gurrieri, Lukas, Micu, 2004; Parameswaran, Ramos-Sanchez, Zavala, 2010)

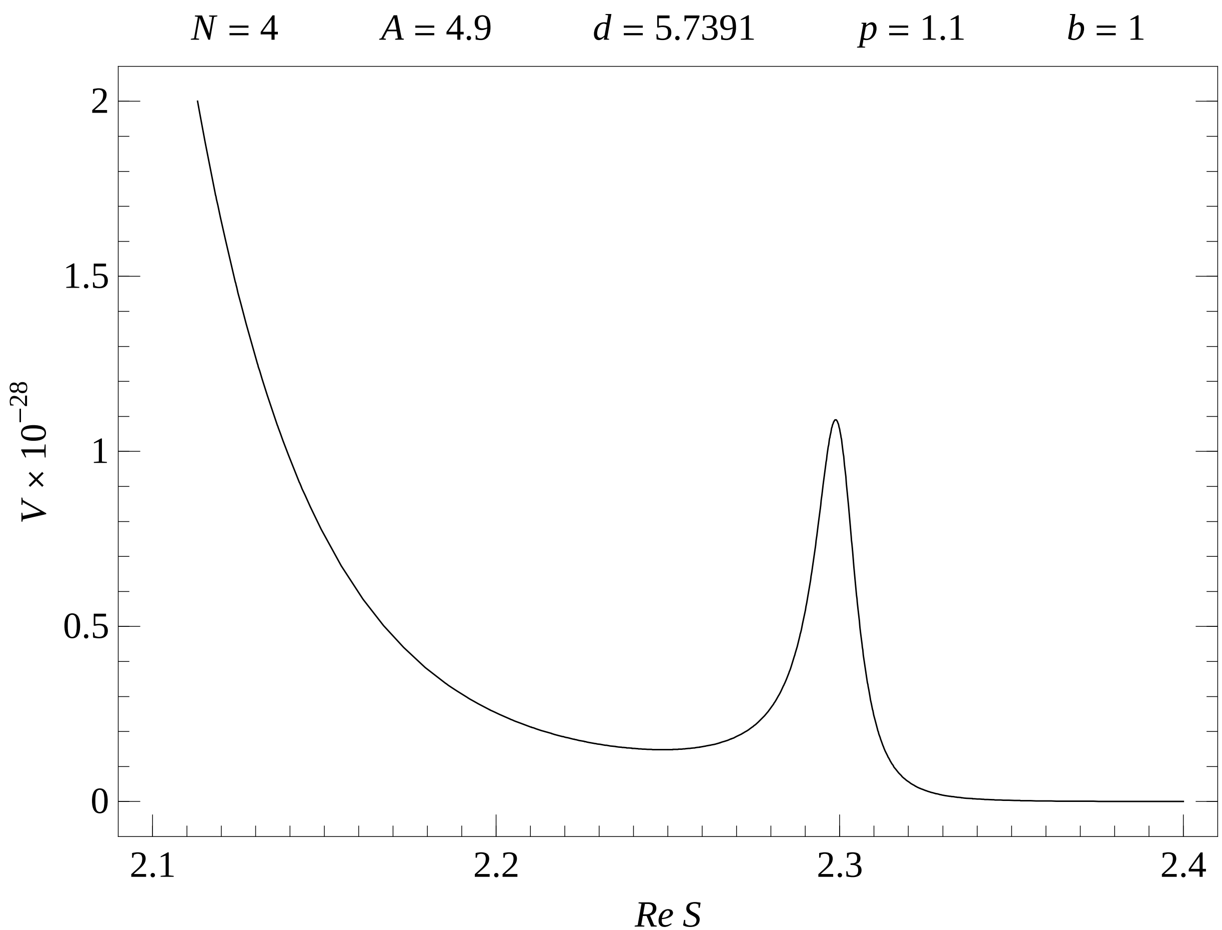
- combined with gaugino condensates and “uplifting”

  (Kachru, Kallosh, Linde, Trivedi, 2003; Löwen, HPN, 2008)

Run-away potential

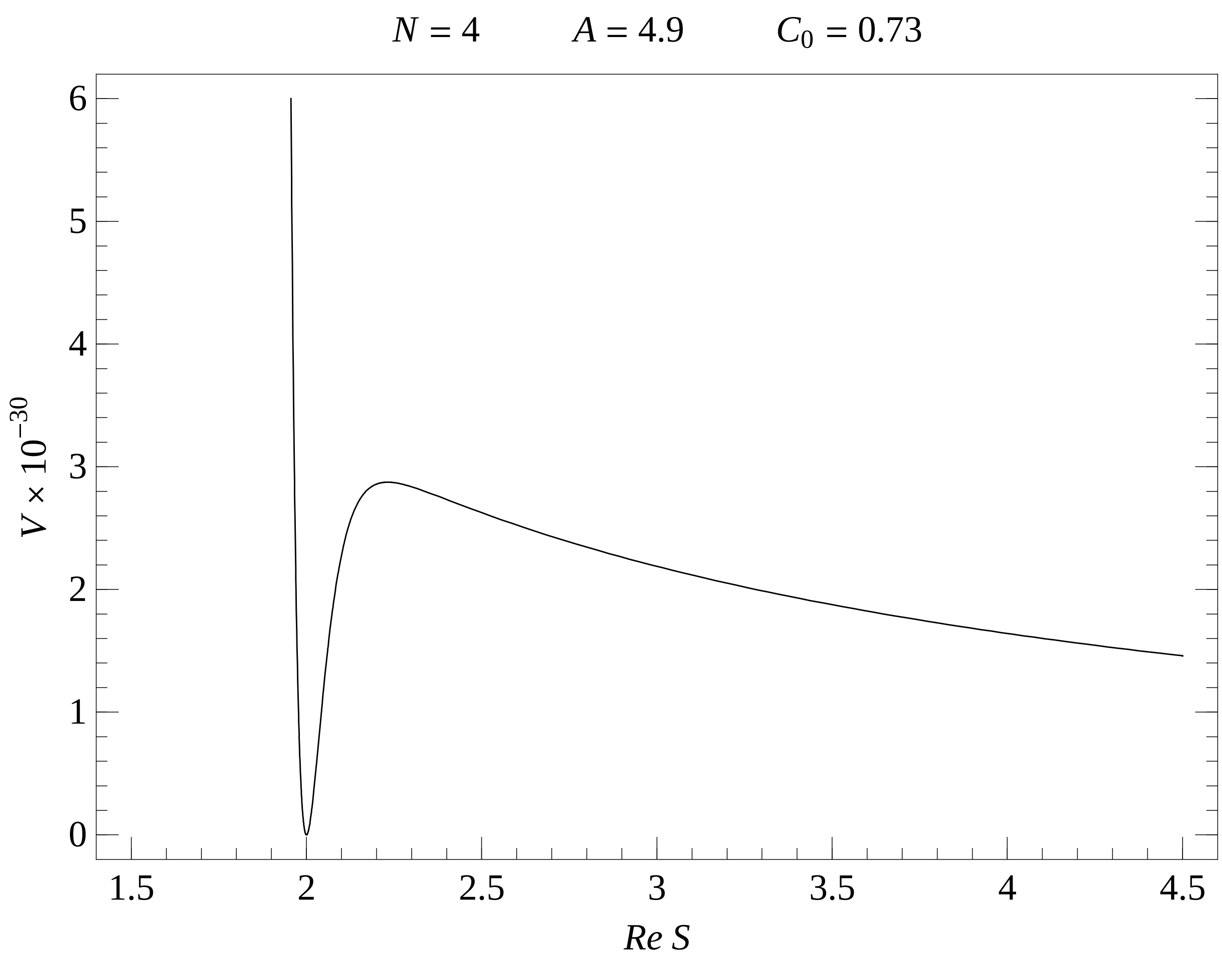


Corrections to Kähler potential



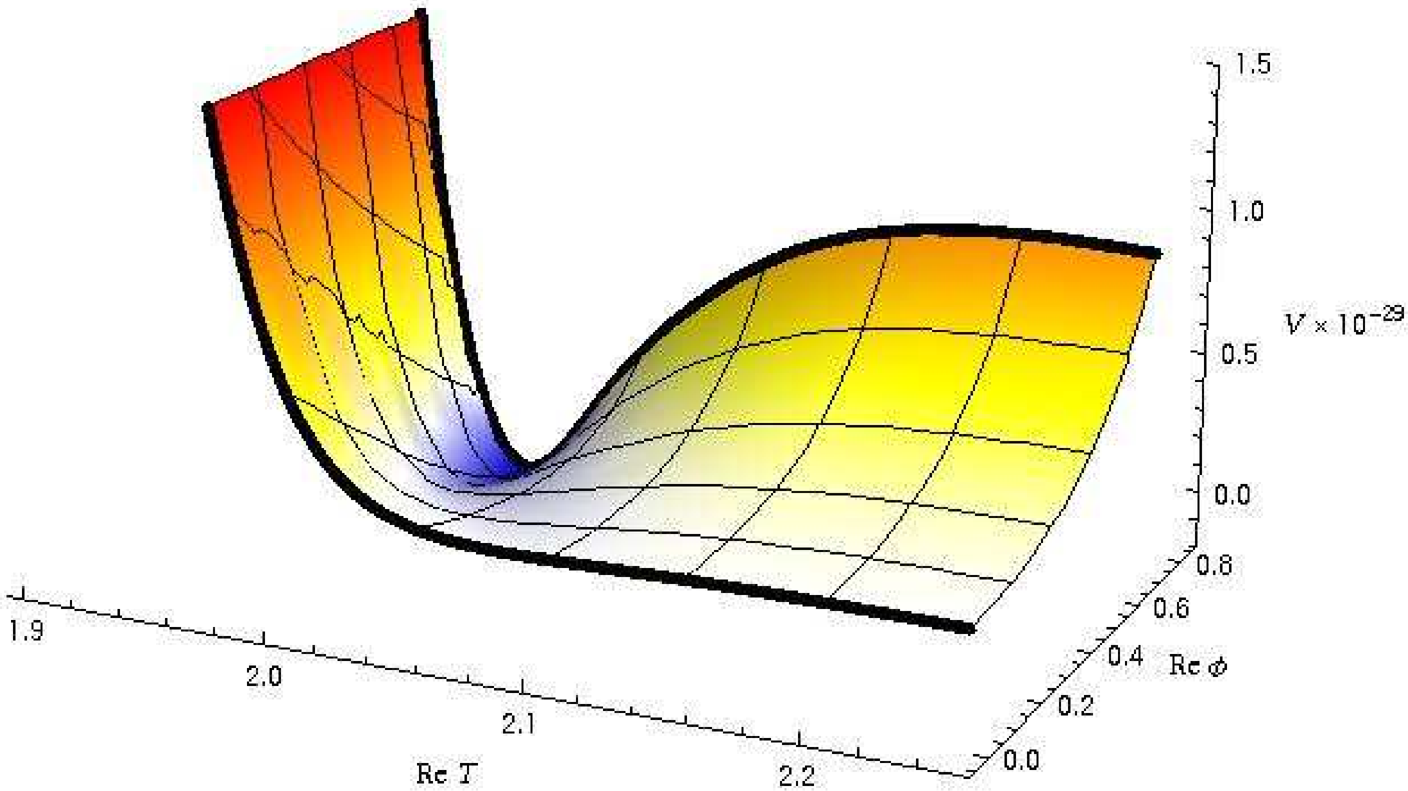
(Barreiro, de Carlos, Copeland, 1998)

Sequestered sector "uplifting"



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

Downlift



(Löwen, HPN, 2008)

Fluxes and gaugino condensation

Is there a general pattern of the soft mass terms?

We always have (from flux and gaugino condensate)

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

where “something” is small and X is moderately large.

Fluxes and gaugino condensation

Is there a general pattern of the soft mass terms?

We always have (from flux and gaugino condensate)

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

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 Mediation Schemes

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

$$X \sim \log(M_{\rm Planck}/m_{3/2}) \sim 4\pi^2.$$

Mixed Mediation Schemes

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

$$X \sim \log(M_{\text{Planck}}/m_{3/2}) \sim 4\pi^2.$$

Thus the contribution due to radiative corrections becomes competitive, leading to mixed mediation schemes.

The simplest case for radiative corrections leads to anomaly mediation competing now with the suppressed contribution of modulus mediation.

For reasons that will be explained later we call this scheme

MIRAGE MEDIATION

(Loaiza, Martin, HPN, Ratz, 2005)

The little hierarchy

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

is a generic signal of such a scheme

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

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

- such a situation occurs if SUSY breaking is e.g. "sequestered" on a warped throat

(Kachru, McAllister, Sundrum, 2007)

Mirage Unification

Mirage Mediation provides a

- characteristic pattern of soft breaking terms.

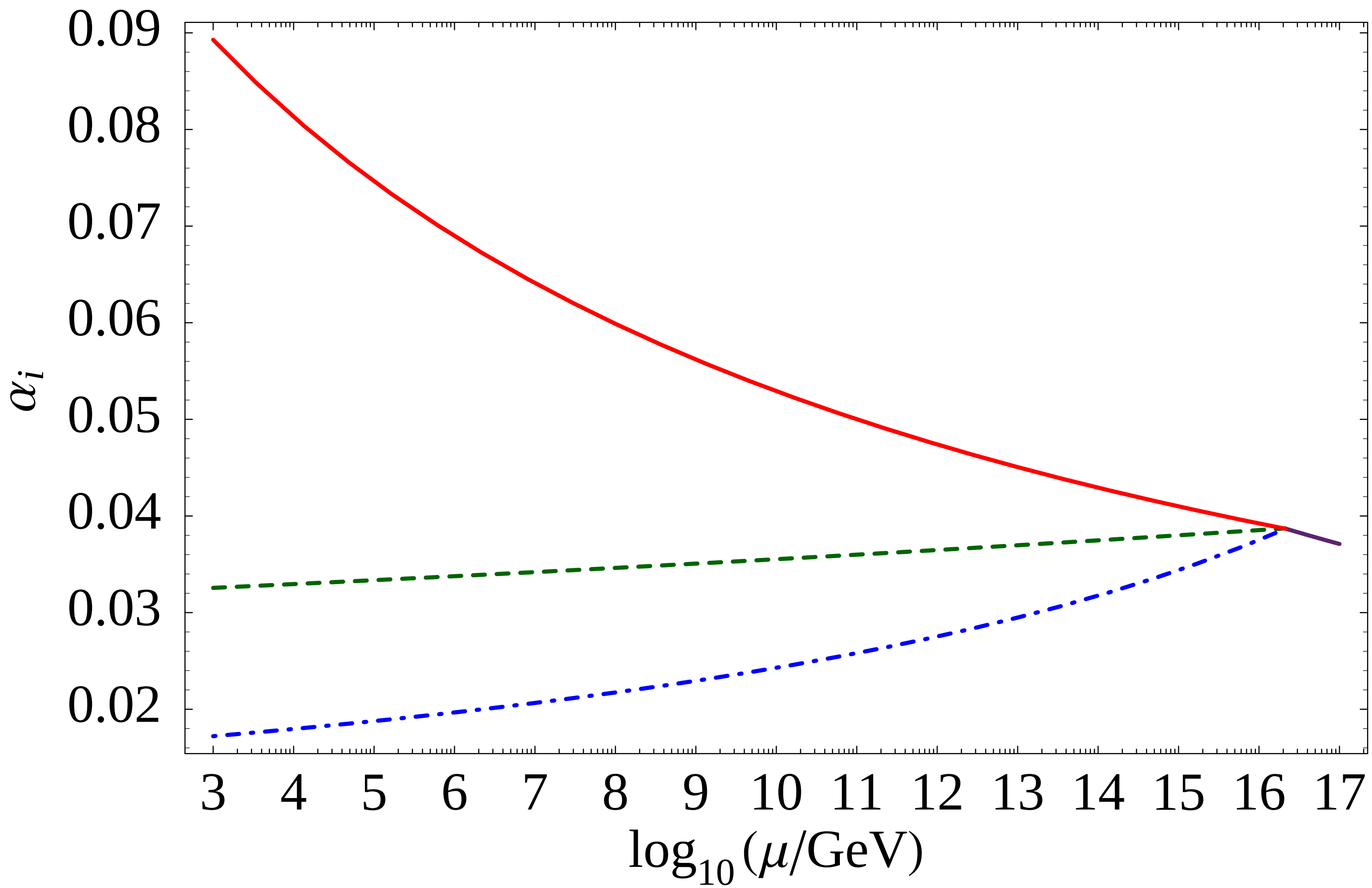
To see this, let us consider the gaugino masses

$$M_{1/2} = M_{\rm modulus} + M_{\rm anomaly}$$

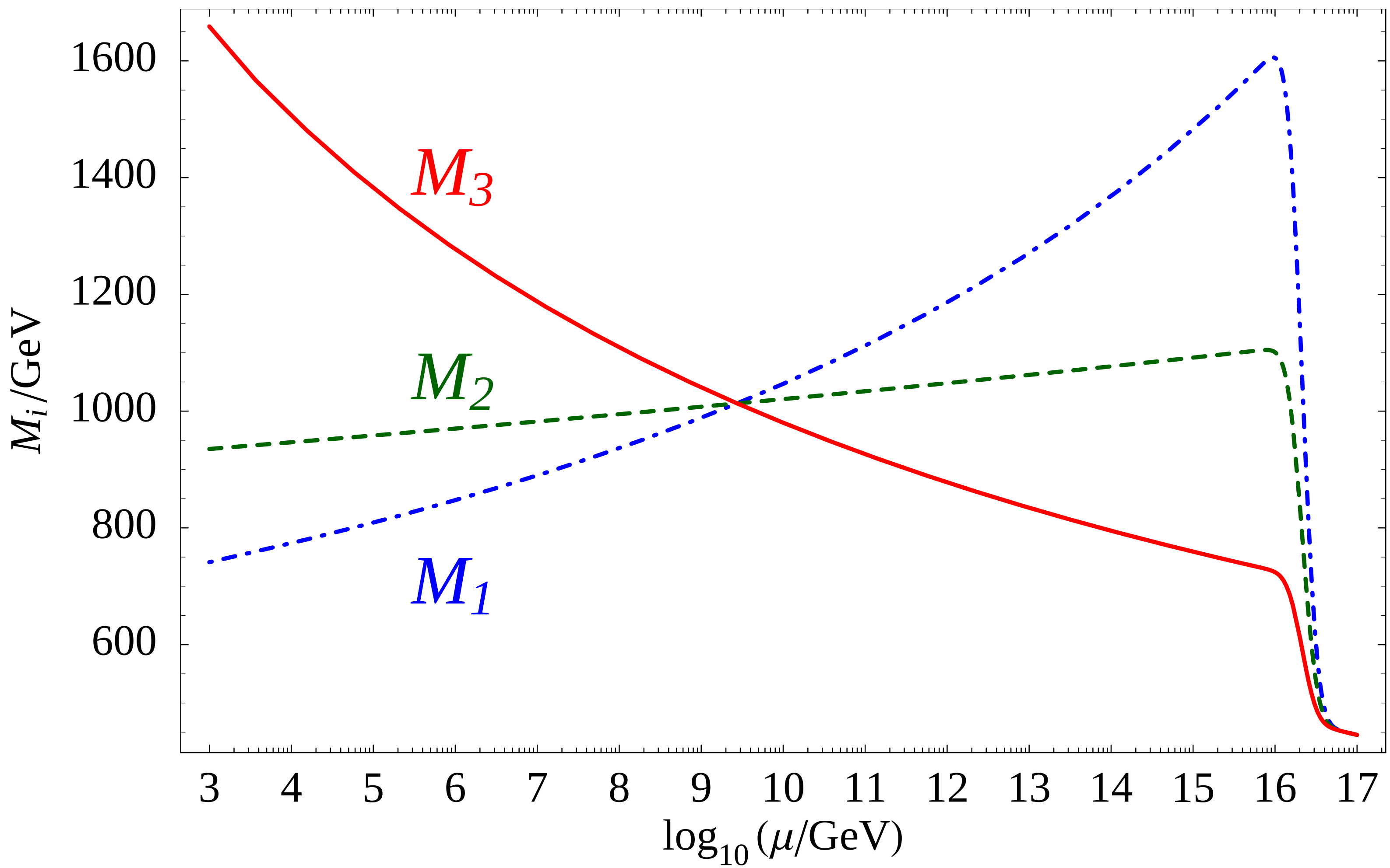
as a sum of two contributions of comparable size.

- $M_{\rm anomaly}$ is proportional to the β function,
  i.e. negative for the gluino, positive for the bino
- thus $M_{\rm anomaly}$ is non-universal below the GUT scale

Evolution of couplings



The Mirage Scale



(Lebedev, HPN, Ratz, 2005)

The Mirage Scale (II)

The gaugino masses coincide

- above the GUT scale
- at the mirage scale $\mu_{\text{mirage}} = M_{\text{GUT}} \exp(-8\pi^2/\rho)$

where ρ denotes the “ratio” of the contribution of modulus vs. anomaly mediation. We write the gaugino masses as

$$M_a = M_s(\rho + b_a g_a^2) = \frac{m_{3/2}}{16\pi^2}(\rho + b_a g_a^2)$$

and $\rho \to 0$ corresponds to pure anomaly mediation.

The Mirage Scale (III)

The gaugino masses coincide

- above the GUT scale
- at the mirage scale $\mu_{\text{mirage}} = M_{\text{GUT}} \exp(-8\pi^2/\rho)$

There is a different notation used in the literature using a parameter α where

- the mirage scale is $\mu_{\text{mirage}} = M_{\text{GUT}} \left(\frac{m_{3/2}}{M_{\text{Planck}}} \right)^{\alpha/2}$
- $\alpha \to 0$ corresponds to pure gravity mediation
- and $\alpha \log \left(\frac{m_{3/2}}{M_{\text{Planck}}} \right) \sim 1/\rho$

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 string signatures

We might consider the following schemes:

- Type II string theory
- Heterotic string theory
- M-theory on manifolds with G_2 holonomy
- F-theory

The string signatures

We might consider the following schemes:

- Type II string theory
- Heterotic string theory
- M-theory on manifolds with G_2 holonomy
- F-theory

Questions:

- are there distinct signatures for the various schemes?
- can they be identified with LHC data?

(Choi, HPN, 2007)

What to expect from the LHC

At the LHC we scatter

- protons on protons, i.e.
- quarks on quarks and/or
- gluons on gluons

Thus LHC will be a machine to produce strongly interacting particles. If TeV-scale susy is the physics beyond the standard model we might expect LHC to become a

GLUINO FACTORY

with cascade decays down to the LSP neutralino.

The Gaugino Code

First step to 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

Formulae for gaugino masses

$$\left(\frac{M_a}{g_a^2}\right)_{\text{TeV}} = \tilde{M}_a^{(0)} + \tilde{M}_a^{(1)}|_{\text{loop}} + \tilde{M}_a^{(1)}|_{\text{gauge}} + \tilde{M}_a^{(1)}|_{\text{string}}$$

$$\tilde{M}_a^{(0)} = \frac{1}{2} F^I \partial_I f_a^{(0)}$$

$$\tilde{M}_a^{(1)}|_{\text{loop}} = \frac{1}{16\pi^2} b_a \frac{F^C}{C} - \frac{1}{8\pi^2} \sum_m C_a^m F^I \partial_I \ln(e^{-K_0/3} Z_m)$$

$$\tilde{M}_a^{(1)}|_{\text{string}} = \frac{1}{8\pi^2} F^I \partial_I \Omega_a$$

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)

SUGRA Pattern

Universal gaugino mass at the GUT scale

- SUGRA 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- and gaugino-mediation

This leads to

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

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
- $G = M_{\rm gluino}/m_{\chi_1^0} \simeq 9$

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 anomaly to modulus 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
- $G = M_{\rm gluino}/m_{\chi_1^0} < 6$
- a “compact” gaugino mass pattern.

The Mirage Scale (III)

The gaugino masses coincide

- above the GUT scale
- at the mirage scale $\mu_{\text{mirage}} = M_{\text{GUT}} \exp(-8\pi^2/\rho)$

There is a different notation used in the literature using a parameter α where

- the mirage scale is $\mu_{\text{mirage}} = M_{\text{GUT}} \left(\frac{m_{3/2}}{M_{\text{Planck}}} \right)^{\alpha/2}$
- $\alpha \to 0$ corresponds to pure gravity mediation
- and $\alpha \log \left(\frac{m_{3/2}}{M_{\text{Planck}}} \right) \sim 1/\rho$

The Gaugino Code

Mixed boundary conditions at the GUT scale
characterized by the parameter α:
the ratio of modulus to anomaly mediation.

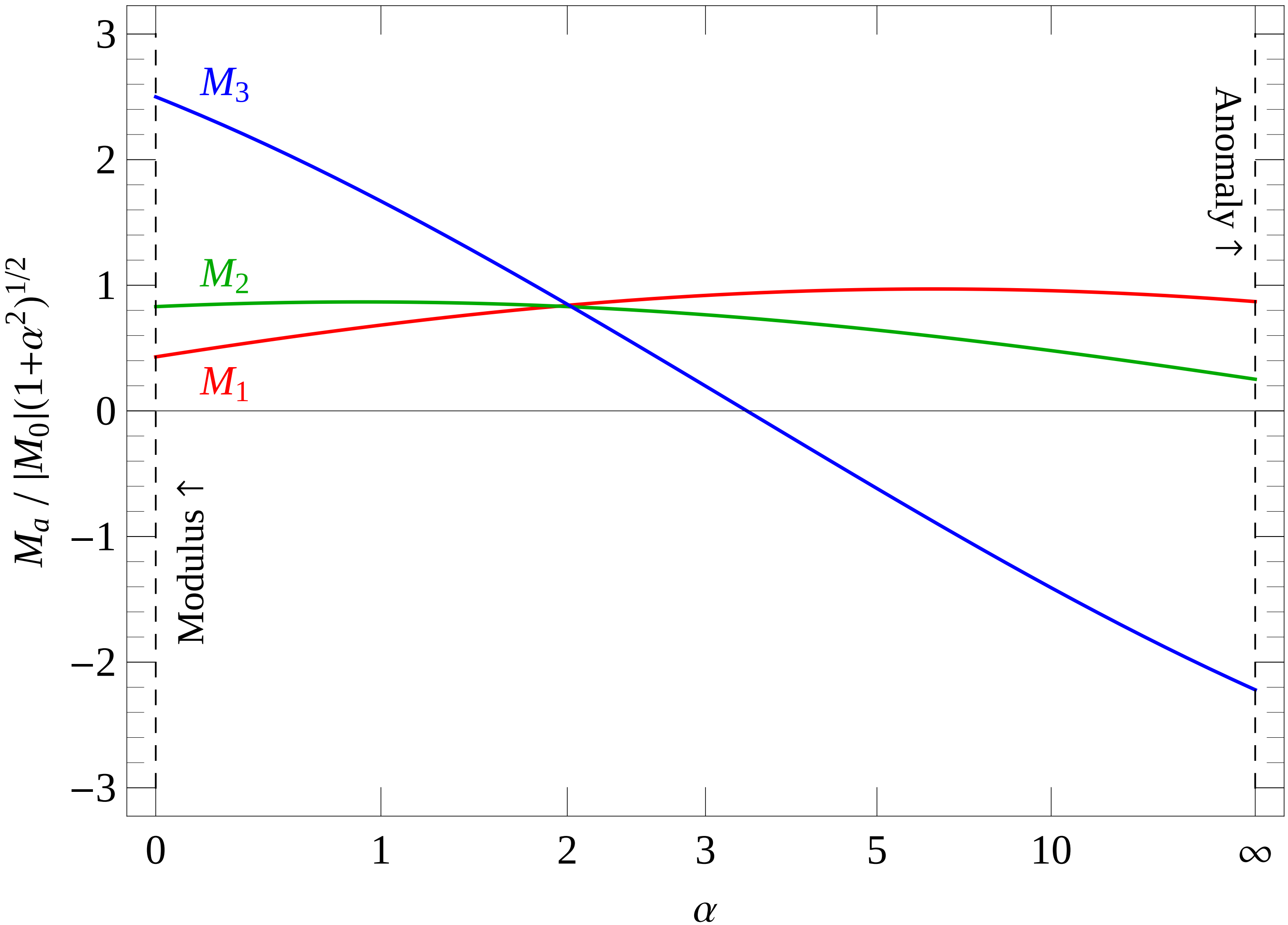
- $M_1 : M_2 : M_3 \simeq\ 1 : 2 : 6$ for $\alpha \simeq 0$
- $M_1 : M_2 : M_3 \simeq\ 1 : 1.3 : 2.5$ for $\alpha \simeq 1$
- $M_1 : M_2 : M_3 \simeq\ 1 : 1 : 1$ for $\alpha \simeq 2$
- $M_1 : M_2 : M_3 \simeq\ 3.3 : 1 : 9$ for $\alpha \simeq \infty$

The mirage scheme leads to

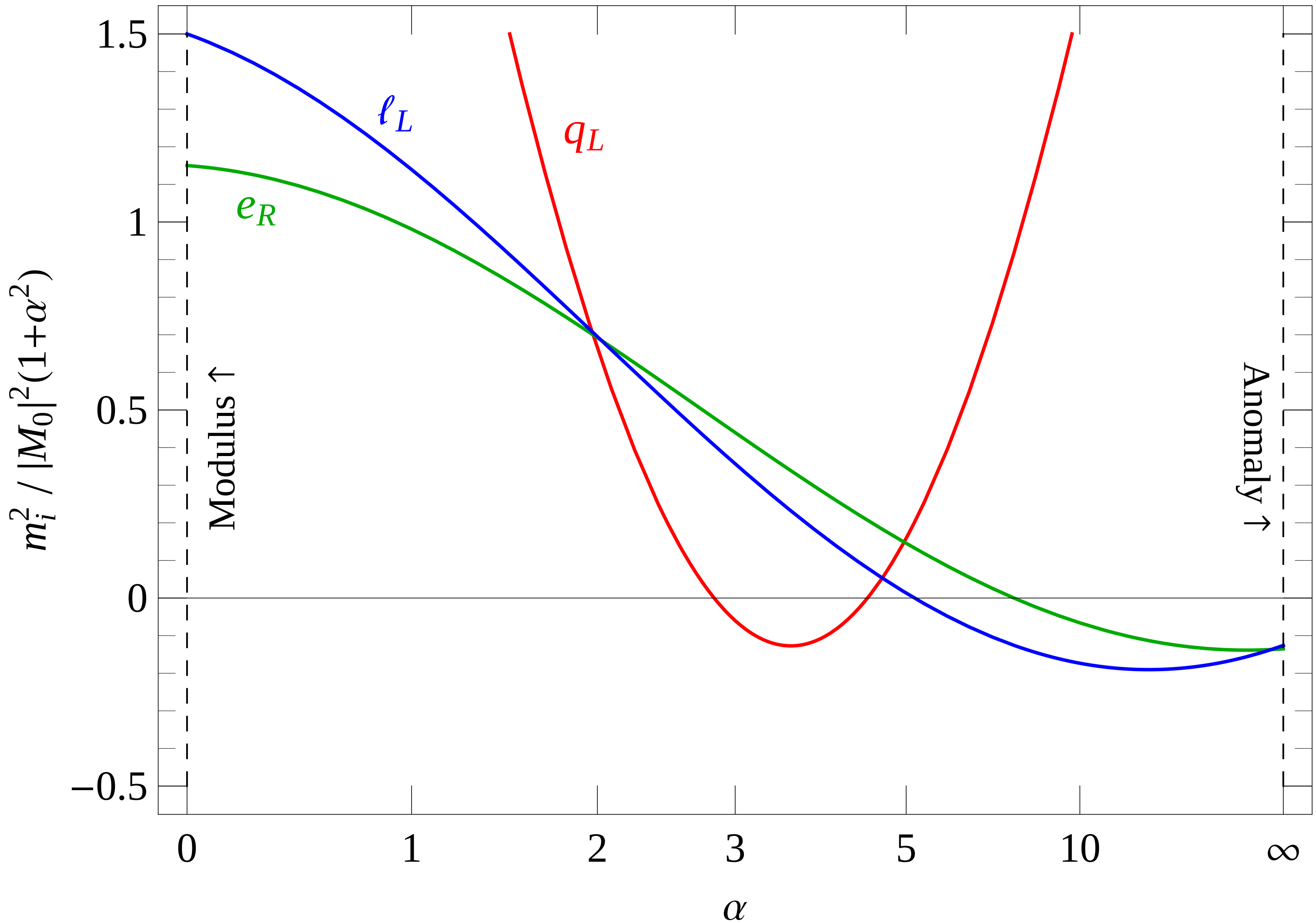
- LSP χ_1^0 predominantly Bino
- a “compact” gaugino mass pattern.

(Choi, HPN, 2007; Löwen, HPN, 2009)

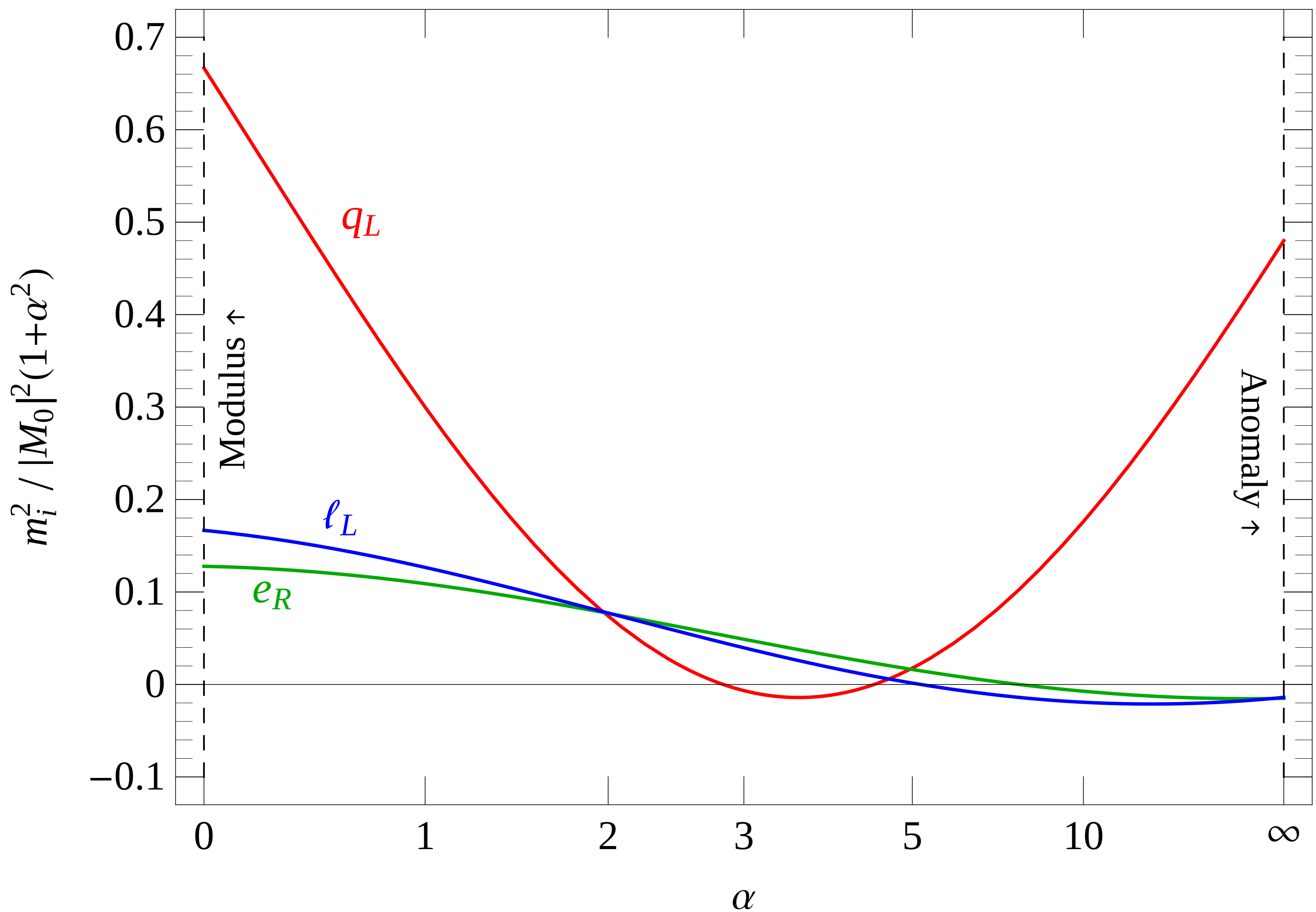
Gaugino Masses



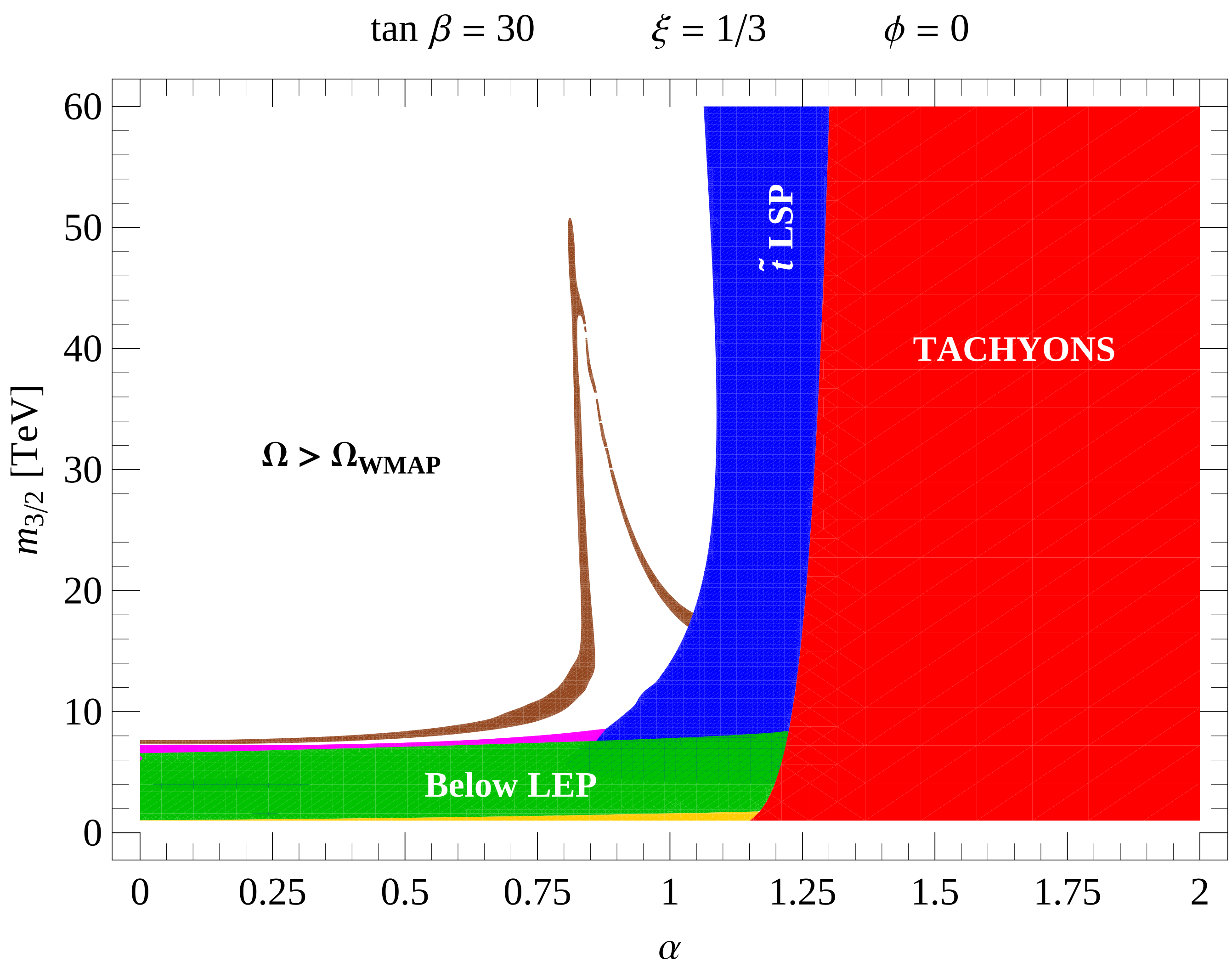
Scalar Masses



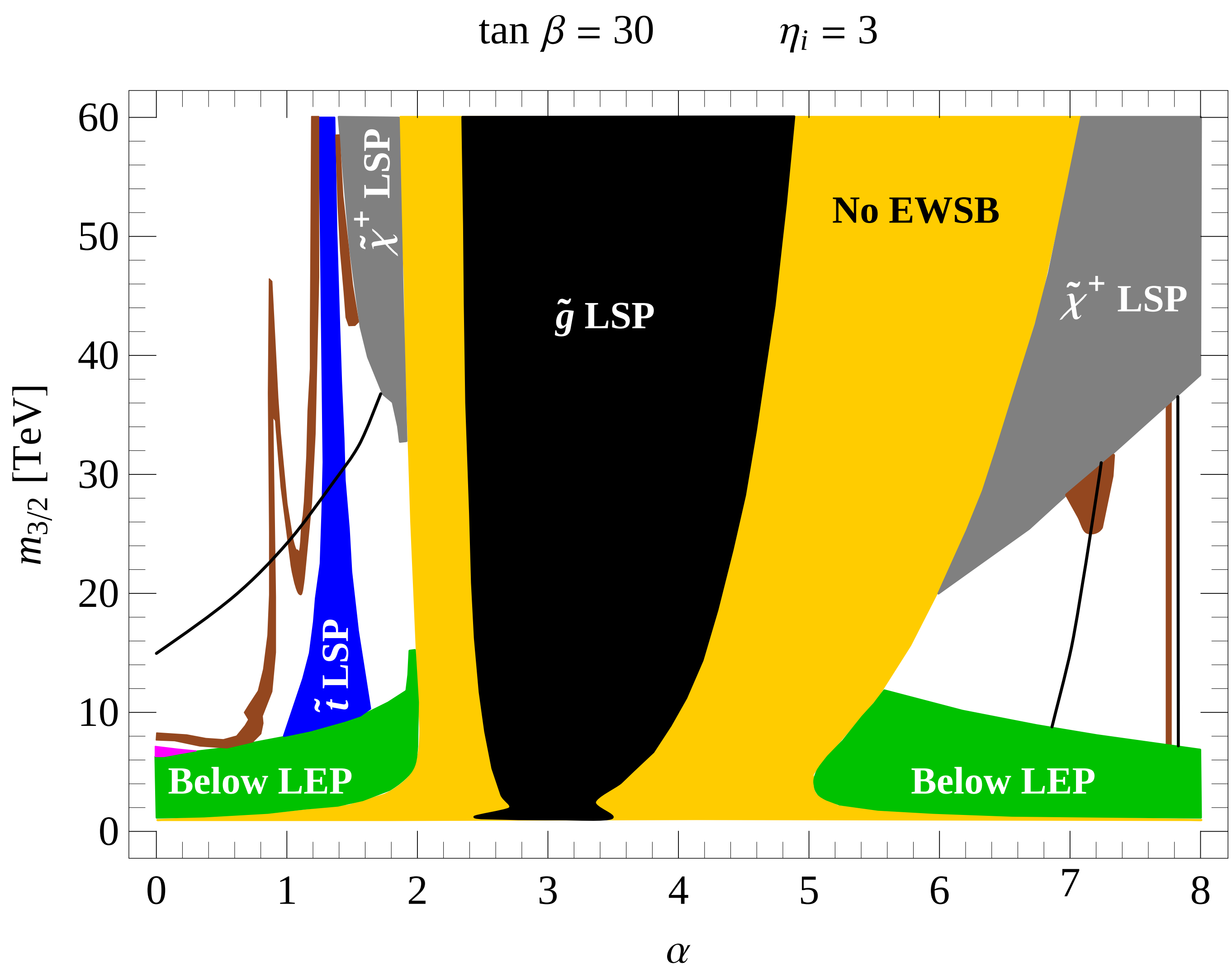
Scalar Masses



Constraints on α



Constraints on α (modified mirage)



Various string schemes

- Type IIB with matter on D7 branes:
  mirage mediation (Choi, Falkowski, HPN, Olechowski, 2005)
- Type IIB with matter on D3 branes:
  anomaly mediation? (Choi, Falkowski, HPN, Olechowski, 2005)
- Heterotic string with dilaton domination:
  mirage mediation (Löwen, HPN, 2008)
- Heterotic string with modulus domination:
  string thresholds might spoil anomaly pattern
  (Derendinger, Ibanez, HPN, 1986)
- M theory on "G_2 manifold":
  Kähler corrections might spoil mirage pattern
  (Acharya, Bobkov, Kane, Kumar, Shao, 2007)

Keep in mind

In the calculation of the soft masses we get the most robust predictions for gaugino masses

- Modulus Mediation: (fWW with $f = f(\mathrm{Moduli})$)

If this is supressed we might have loop contributions, e.g.

- Anomaly Mediation as simplest example

Keep in mind

In the calculation of the soft masses we get the most robust predictions for gaugino masses

- Modulus Mediation: (fWW with $f = f(\mathrm{Moduli})$)

If this is supressed we might have loop contributions, e.g.

- Anomaly Mediation as simplest example

How much can it be suppressed?

$$\log(m_{3/2}/M_{\mathrm{Planck}})$$

So we might expect

a mixture of tree level and loop contributions.

Conclusion

Gaugino masses can serve as a promising tool for an early test for supersymmetry at the LHC

- Rather robust predictions
- 3 basic and simple patterns (Sugra, anomaly, mirage)
- Mirage pattern rather generic

With some luck we might find such a simple scheme at the LHC and measure the ratio $G = M_{\rm gluino}/m_{\chi_1^0}$!

Let us hope for a bright future of SUSY at the LHC.

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.

Where do we live?