The Geography of Unification

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Questions

- 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
  - accidental symmetries (of discrete origin)
- 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
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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

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

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

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

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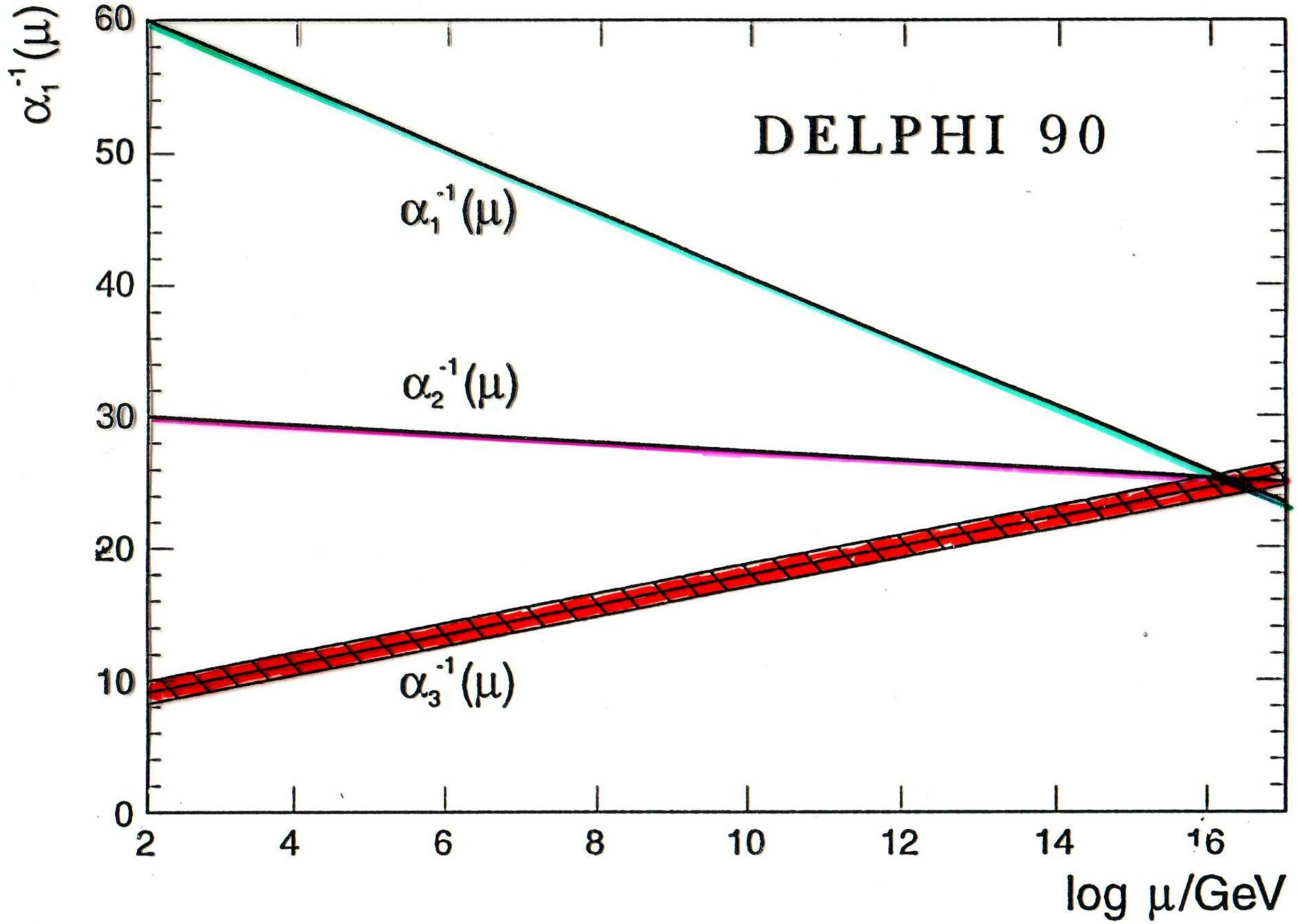
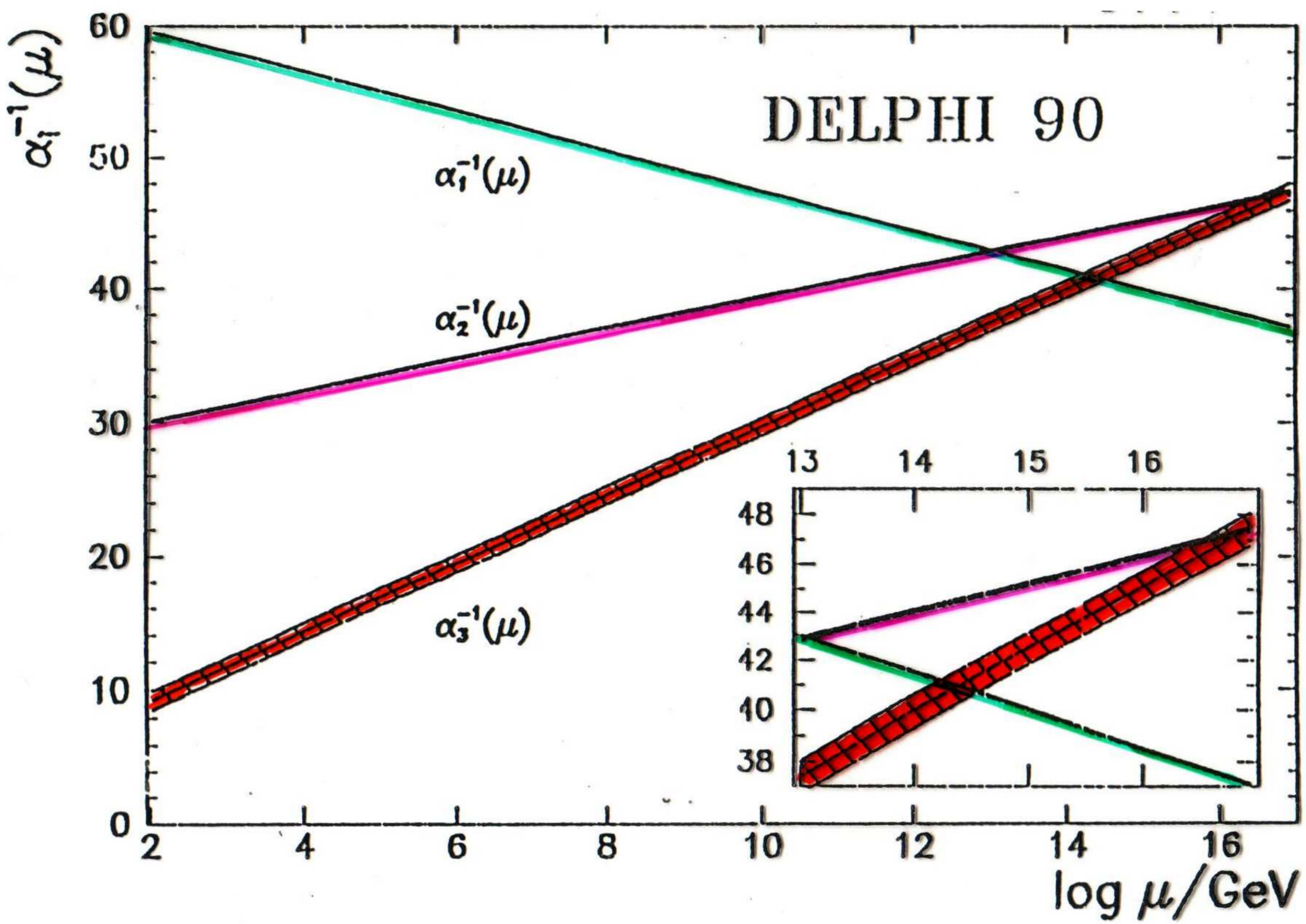
- Evolution of couplings constants of the standard model towards higher energies.

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
- neutrino see-saw mechanism

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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
- large unified gauge groups
- consistent theory of gravity

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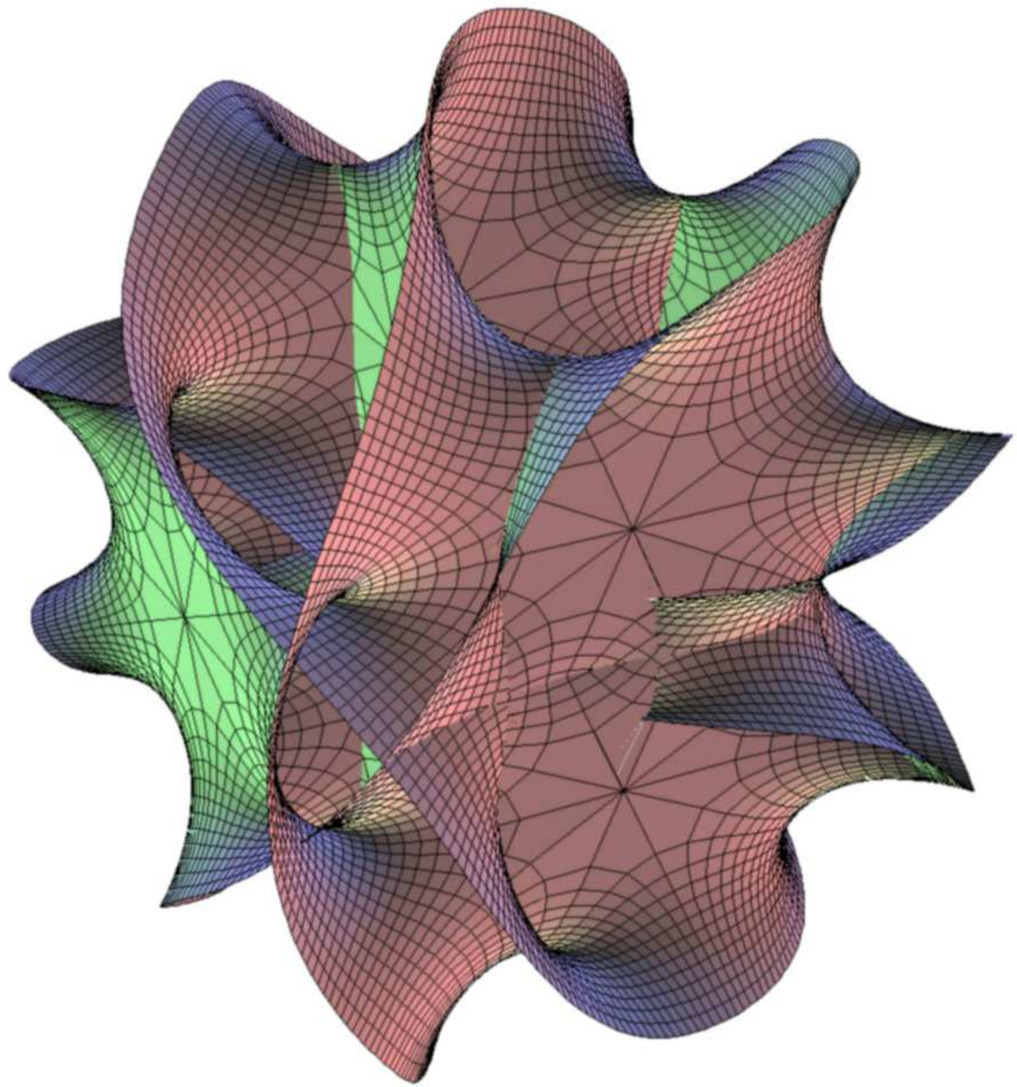
- large unified gauge groups
- consistent theory of gravity

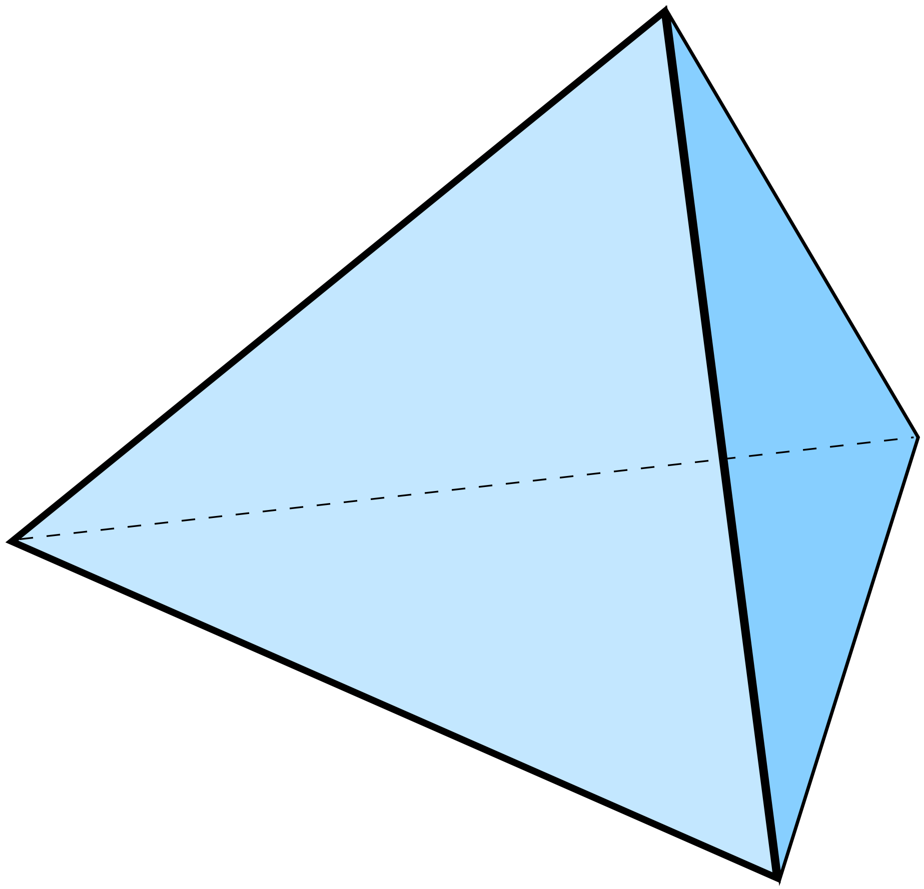
These are the building blocks for a unified theory of all the fundamental interactions.
But do they fit together, and if yes how?

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

Calabi Yau Manifold



Orbifold



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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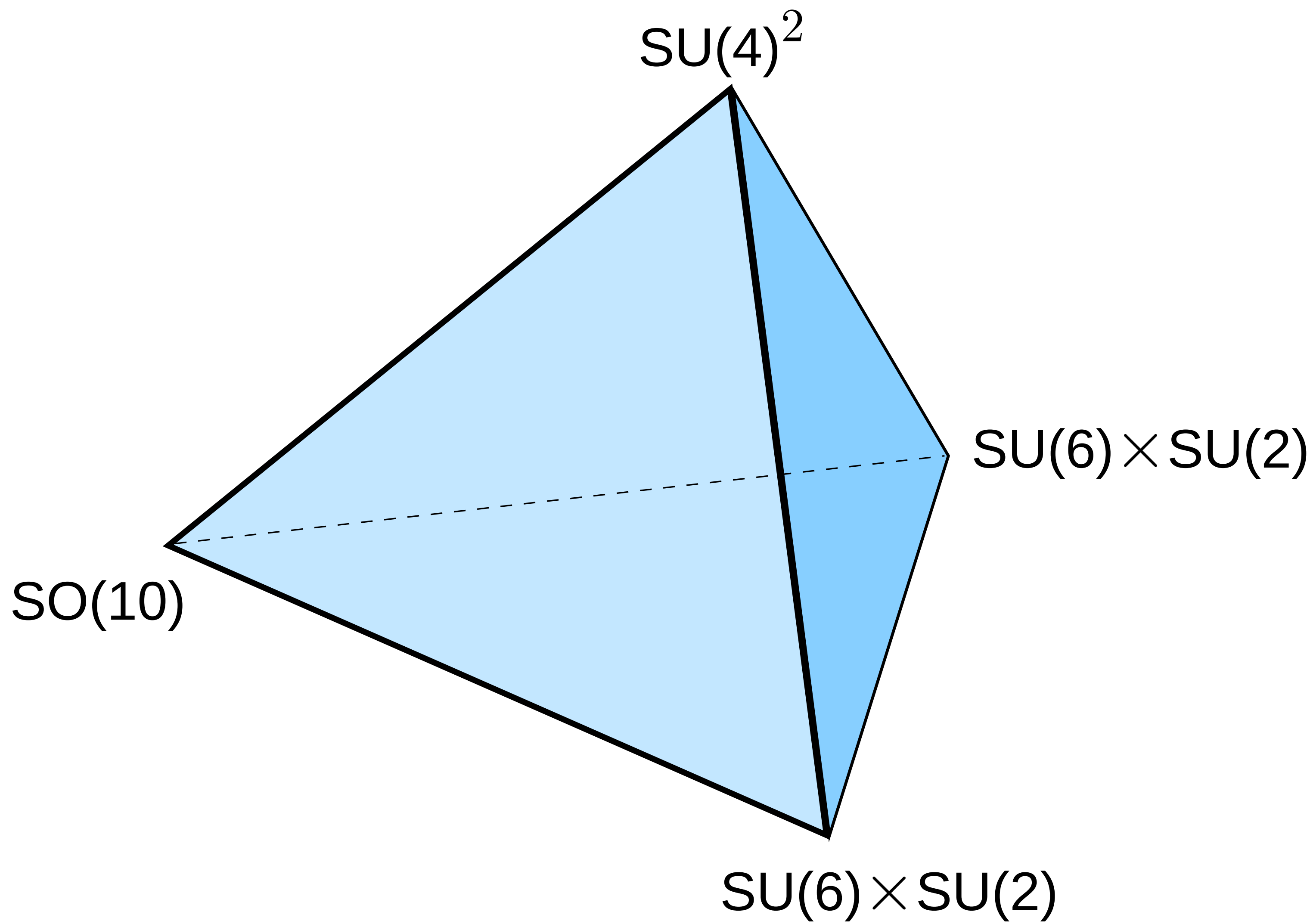
but there is also a “localization” of gauge fields

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

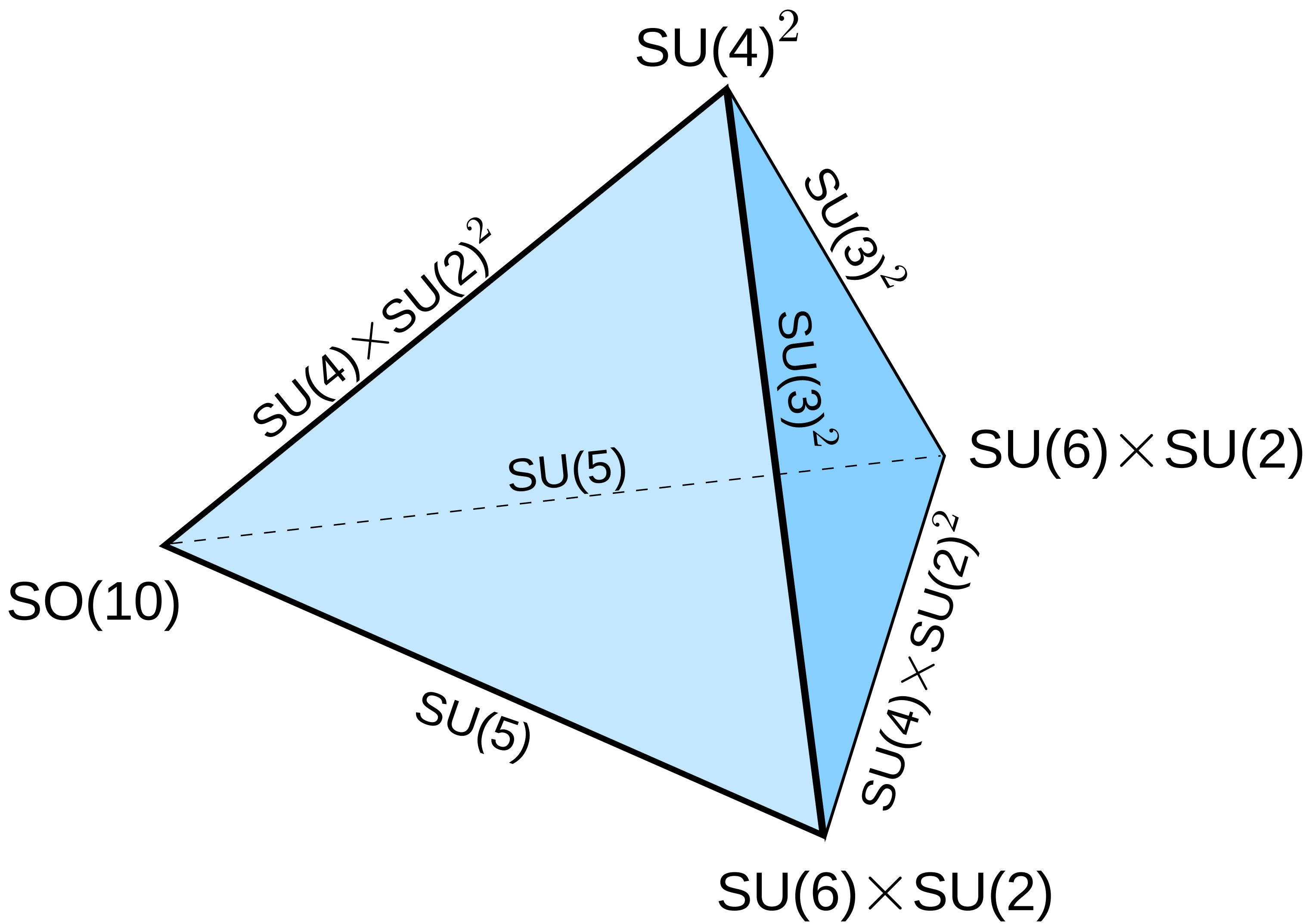
Observed 4-dimensional gauge group is common subroup of the various localized gauge groups!

Localized gauge symmetries



(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

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- split multiplets for gauge- and Higgs-bosons
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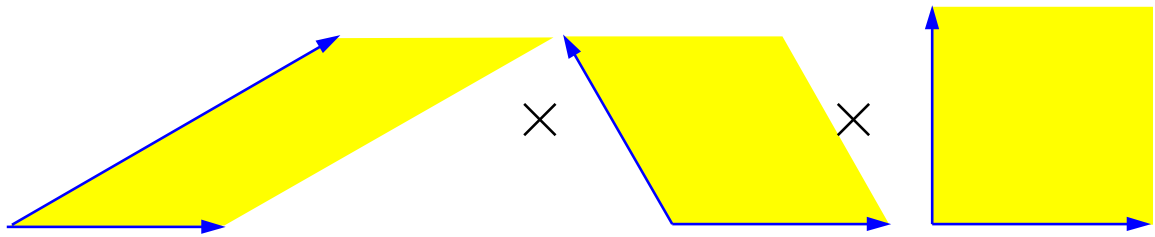
Key properties of the theory depend on the geography of the fields in extra dimensions.

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; Kim, Kim, Kyae, 2007)

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, 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)

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

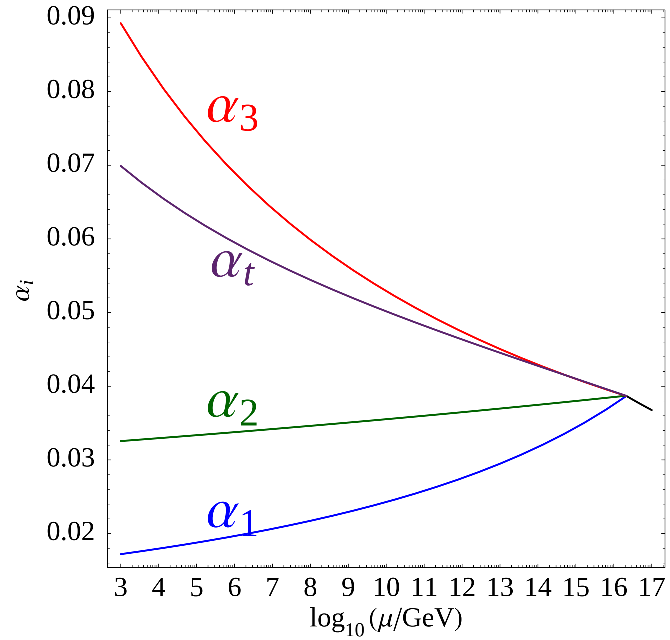
Spectrum

#	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

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

(Buchmüller, Hamaguchi, 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 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)

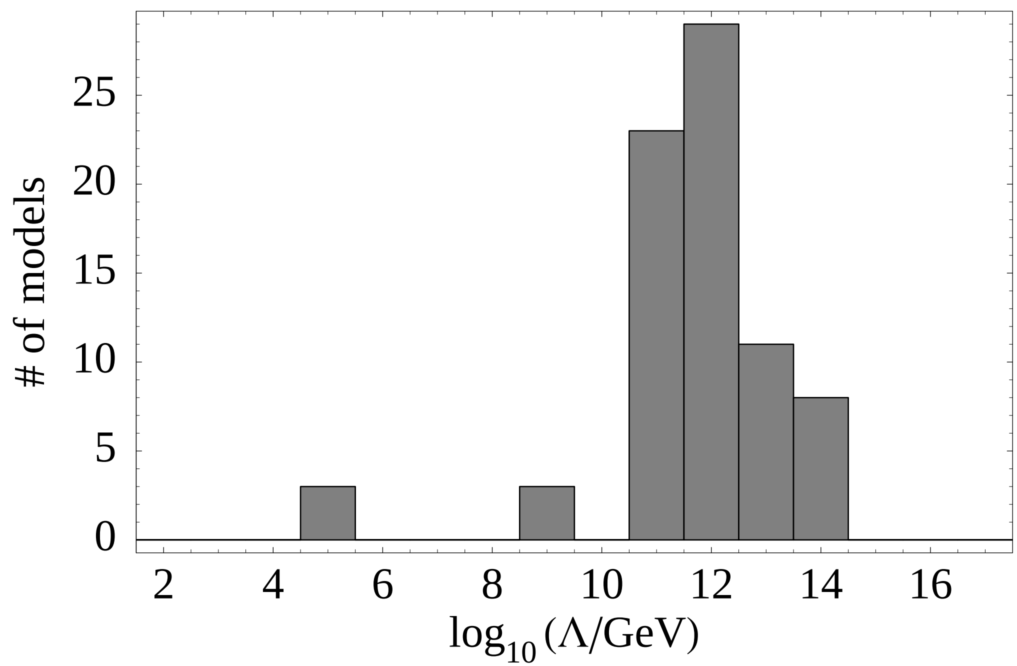
- proton stability via “Proton Hexality”

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

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

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

Gaugino Condensation



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

We need to fix the dilaton!

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

Dilaton (Modulus) Domination

This leads to a “gravity mediation” scenario,

- but we still have to adjust the vacuum energy.

Here we need a “downlifting” mechanism:

- “downlifting” mechanism can fix S as well (no need for nonperturbative corrections to the Kähler potential)

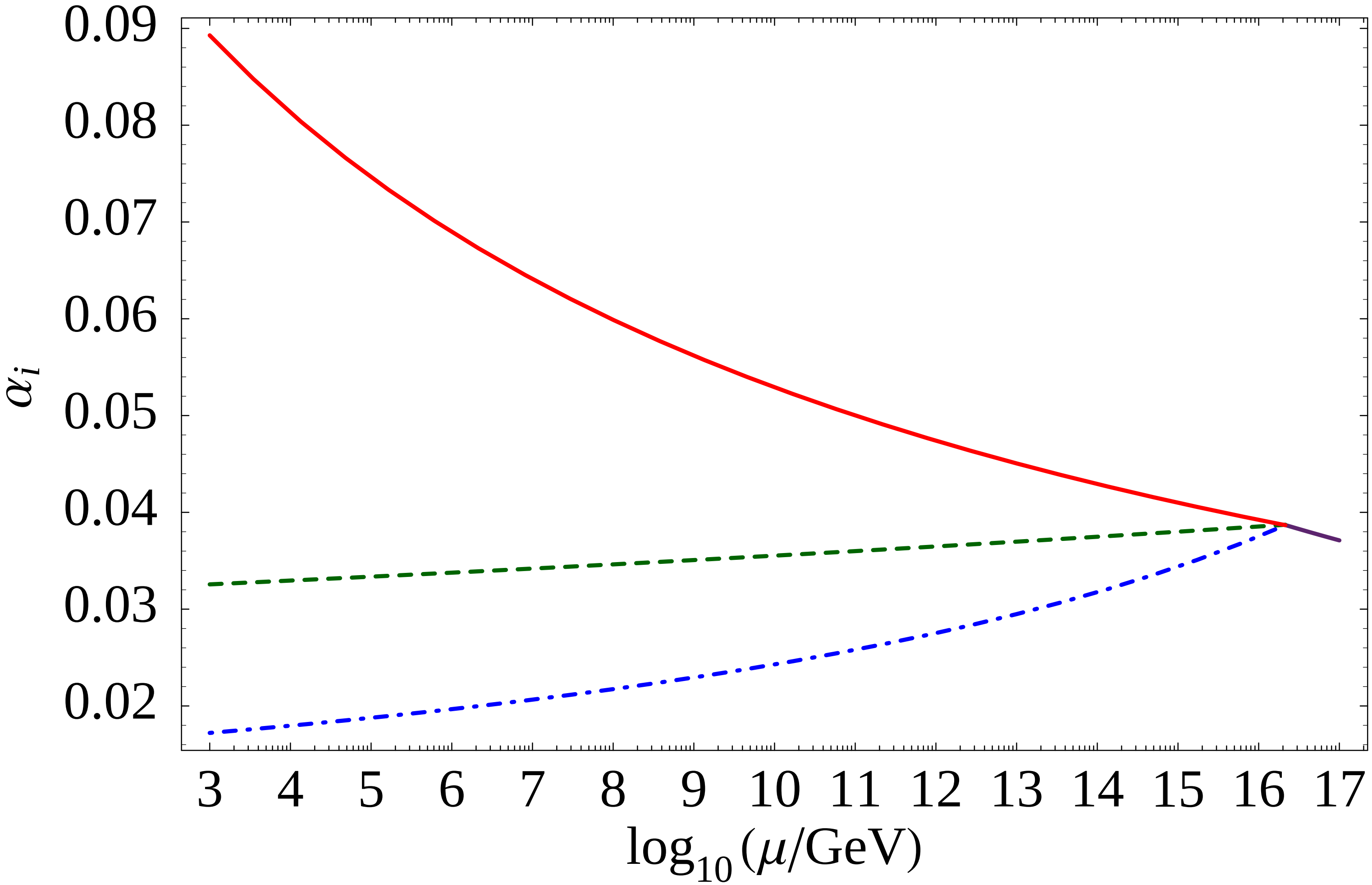
  (Löwen, HPN, 2008)

- gives a suppression factor $\log(m_{3/2}/M_{\rm Planck})$

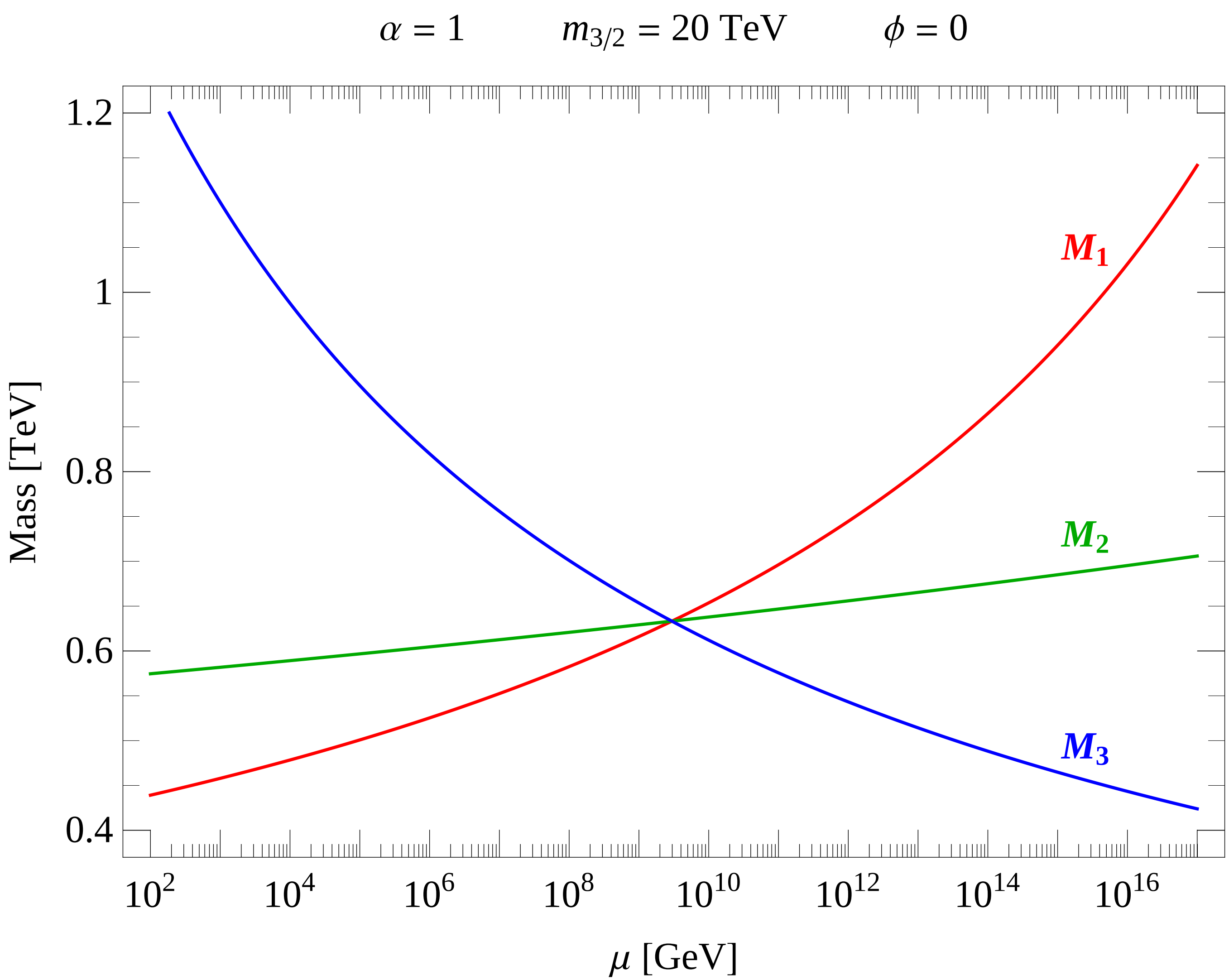
  (Choi, Falkowski, HPN, Olechowski, 2005)

- mirage mediation for gaugino masses

Evolution of couplings



Mirage Scale



Can we test this at 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

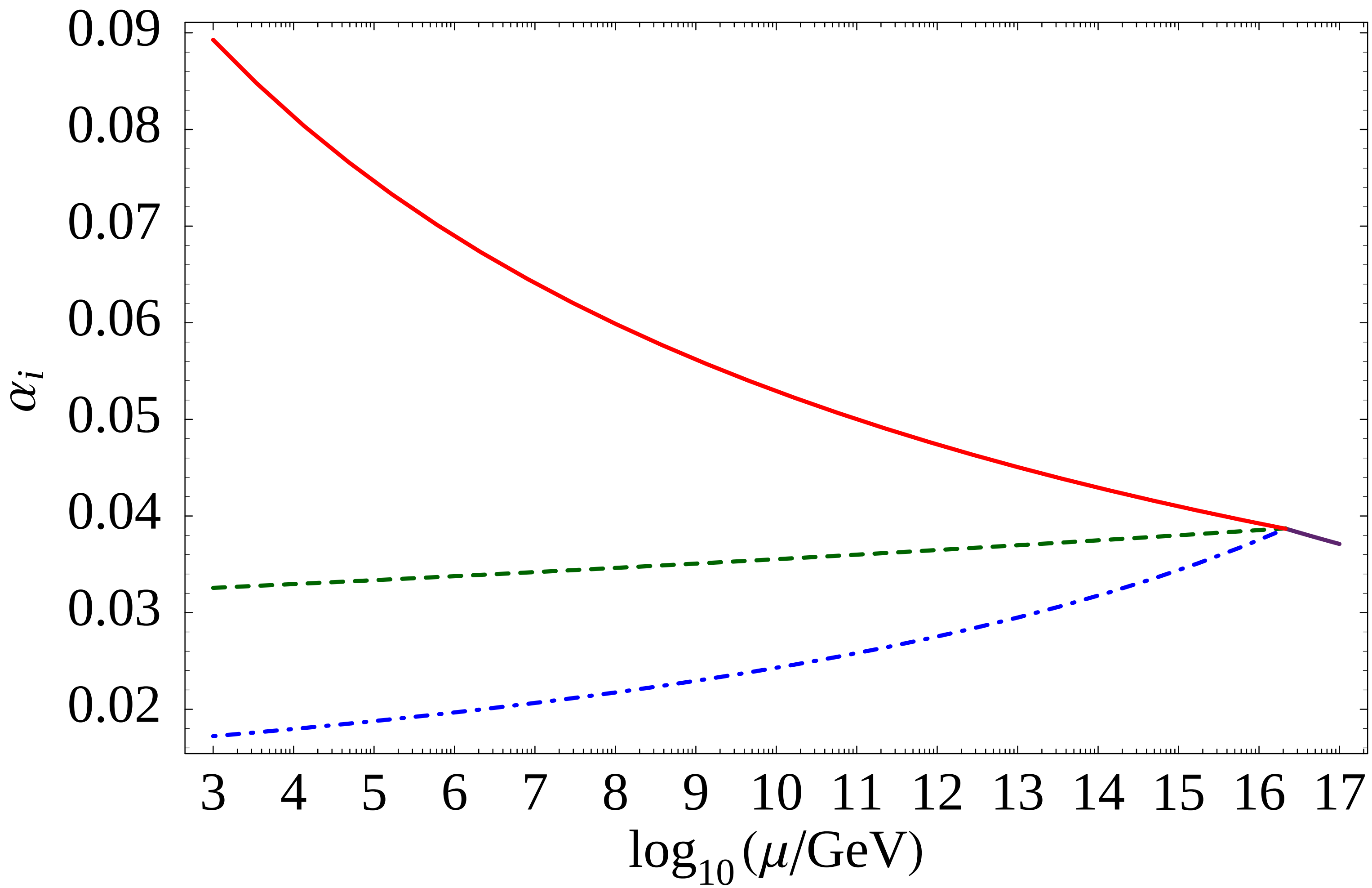
Let us assume the

- 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

Evolution of couplings



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

FEW CHARACTERISTIC MASS PATTERNS

(Choi, HPN, 2007)

Mirage Mediation

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

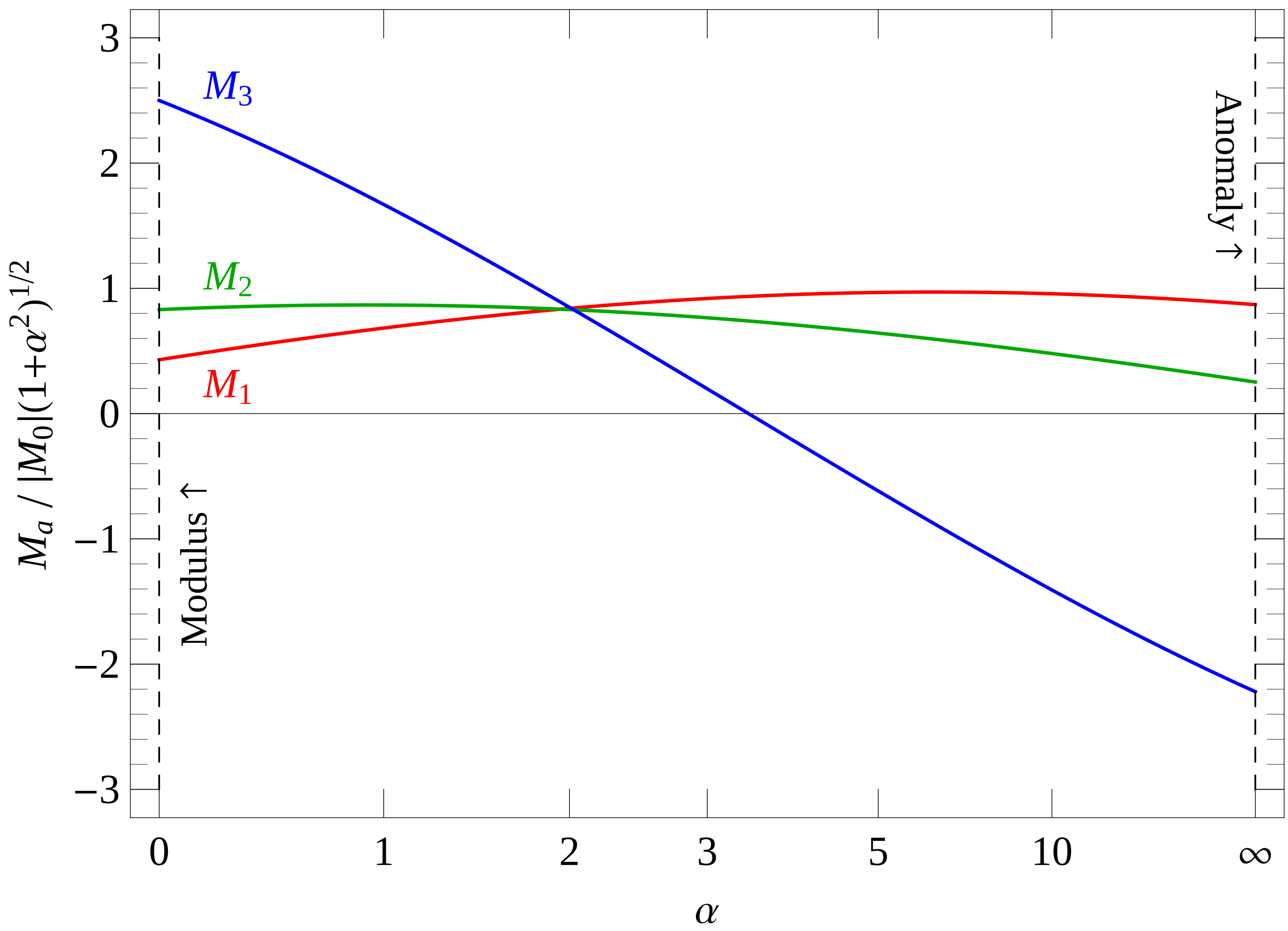
- $M_1 : M_2 : M_3 \simeq\ 1 : 2 : 6$ for $\alpha \simeq 0$
- $M_1 : M_2 : M_3 \simeq\ 1 : 1.3 : 2.5$ for $\alpha \simeq 1$
- $M_1 : M_2 : M_3 \simeq\ 1 : 1 : 1$ for $\alpha \simeq 2$
- $M_1 : M_2 : M_3 \simeq\ 3.3 : 1 : 9$ for $\alpha \simeq \infty$

The mirage scheme leads to

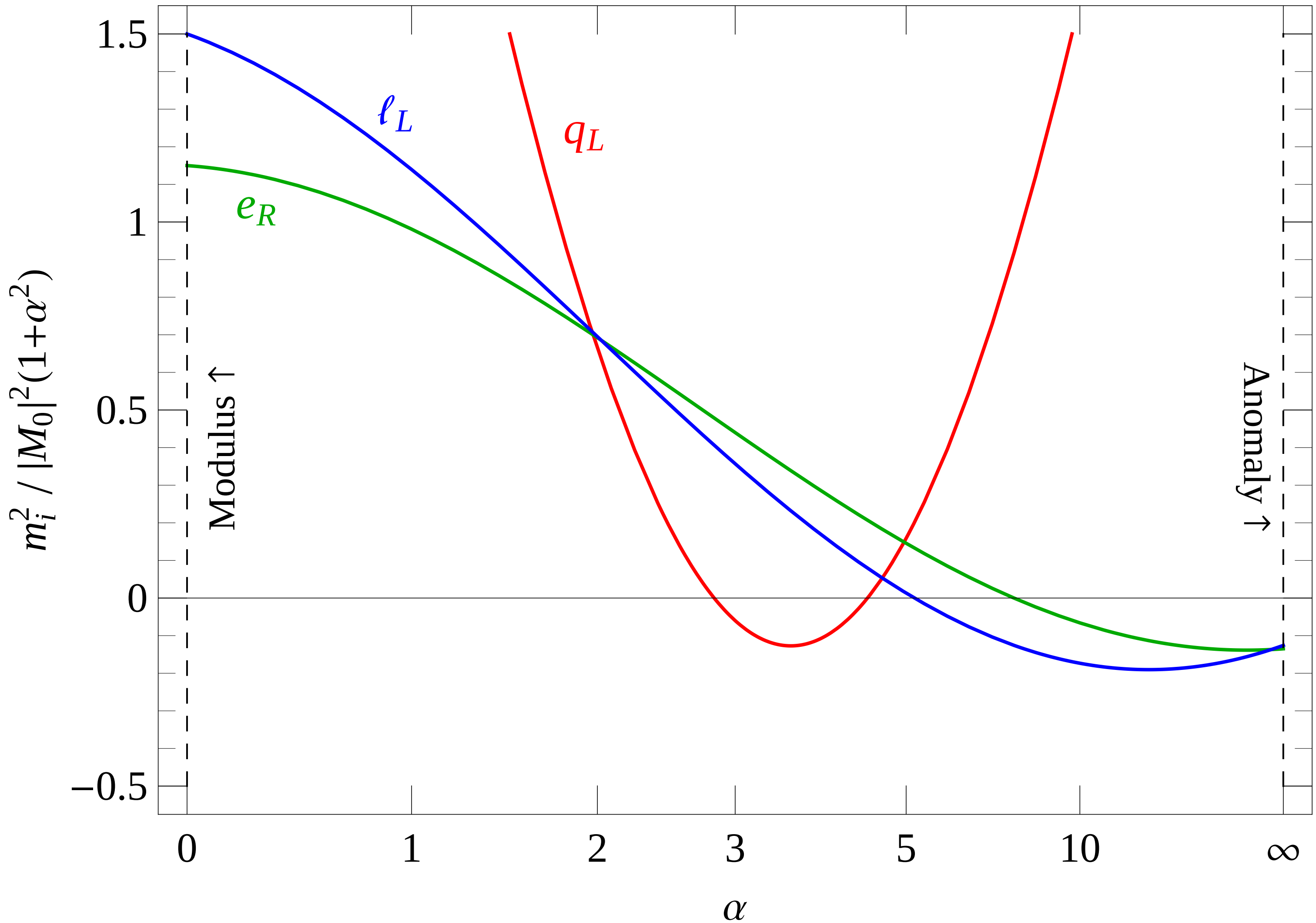
- LSP χ_1^0 predominantly Bino
- a "compact" gaugino mass pattern.

(Choi, HPN, 2007; Löwen, HPN, 2009)

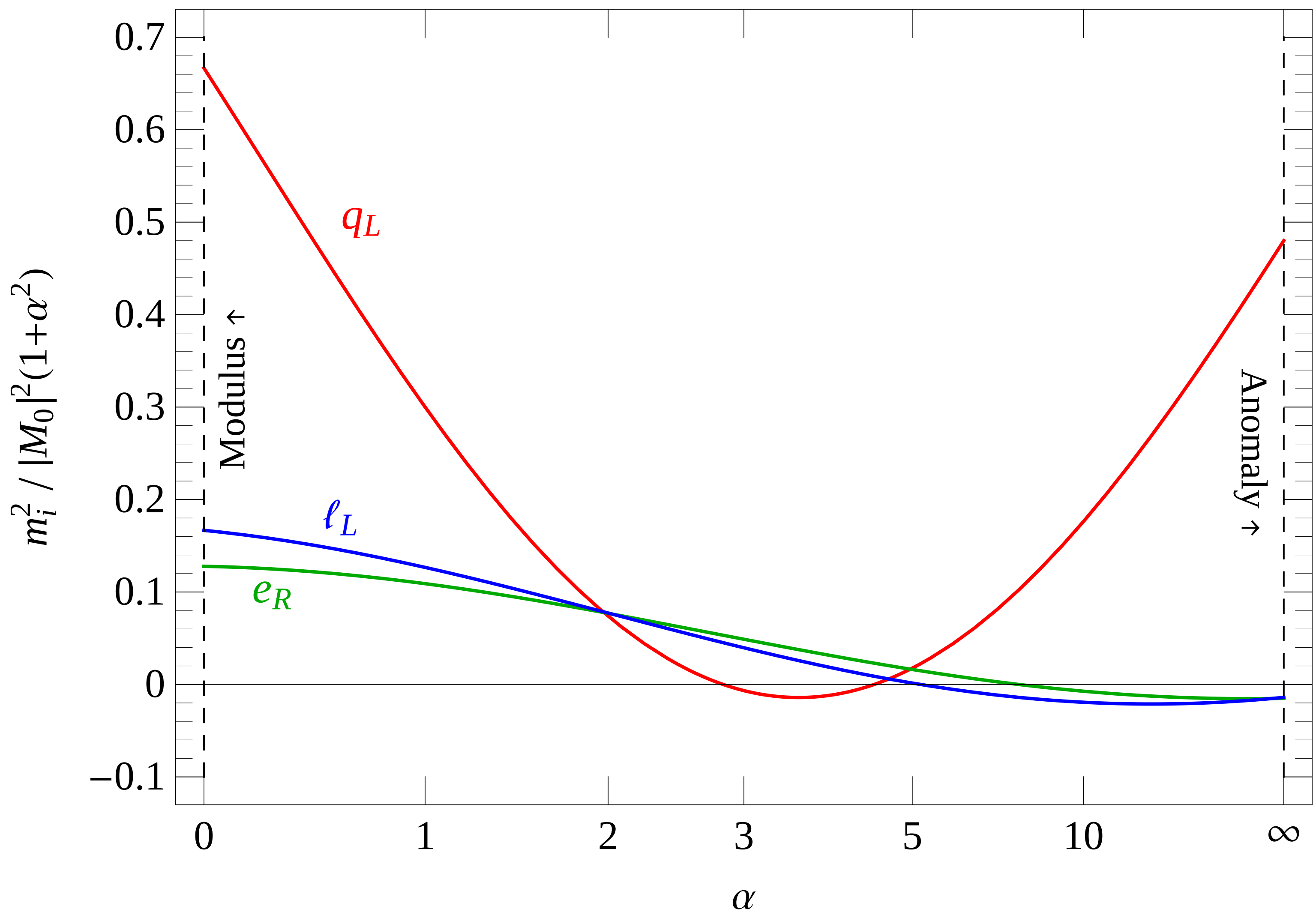
Gaugino Masses



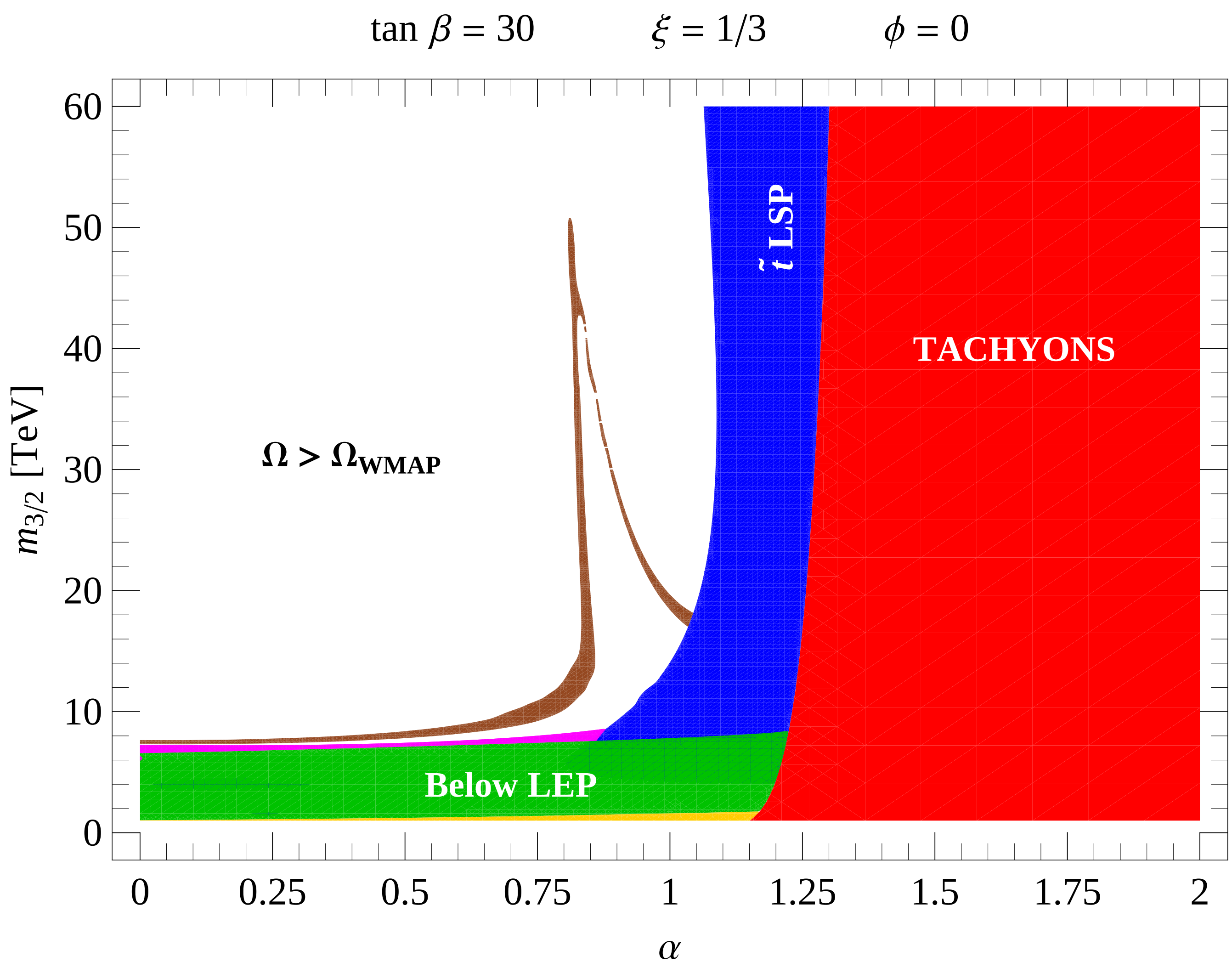
Scalar Masses



Scalar Masses



Constraints on α



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.