Heterotic String yields Natural Susy

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The Heterotic String Pattern

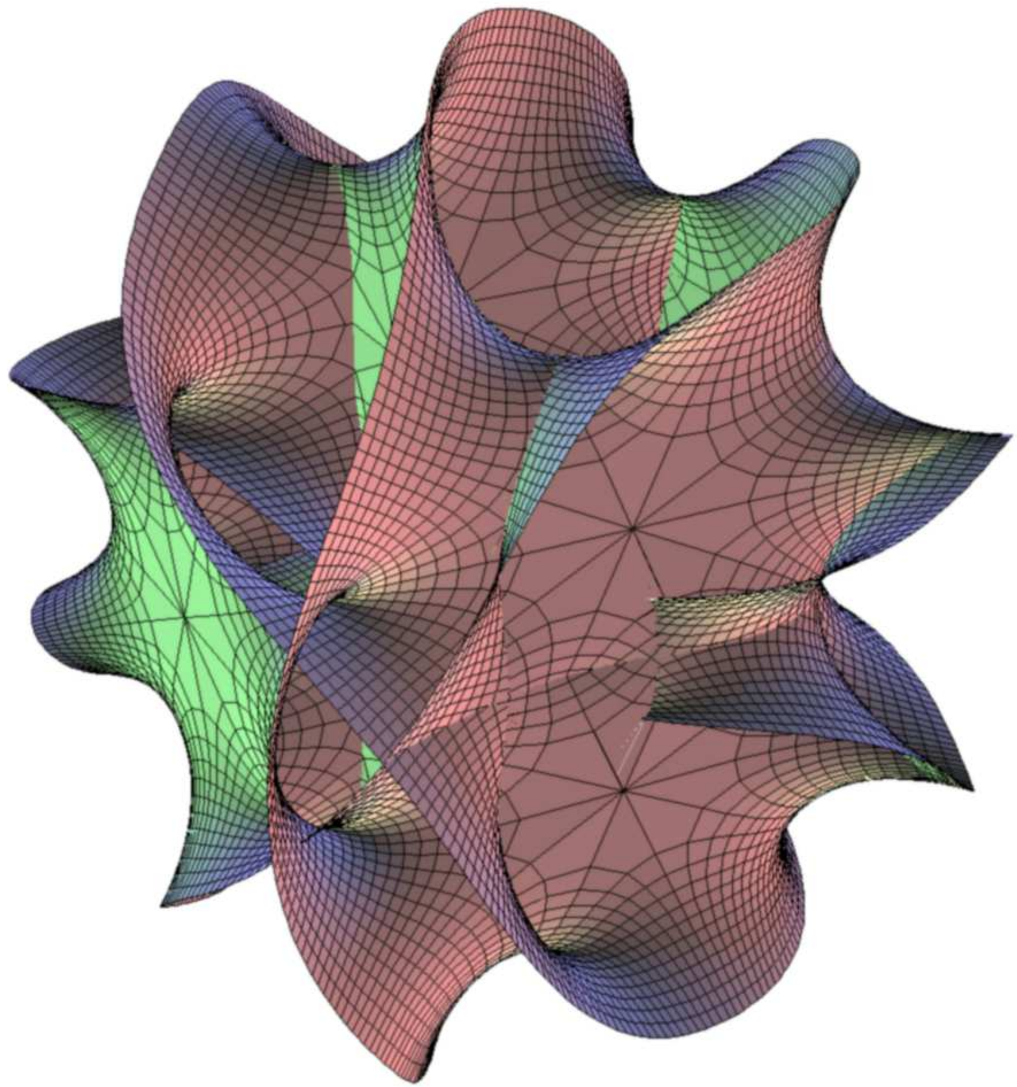
A specific pattern for the soft masses with a large gravitino mass in the multi-TeV range ($< O(30)$TeV)

(Krippendorf, Nilles, Ratz, Winkler, 2012)

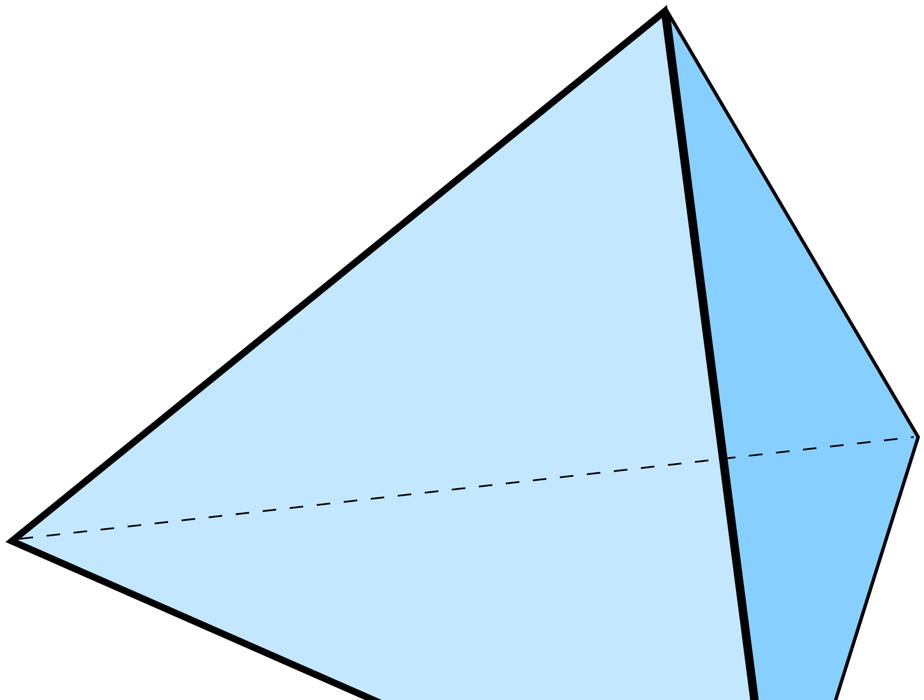
- normal squarks and sleptons in multi-TeV range
- top squarks $(\tilde{t}_L, \tilde{b}_L)$ and $\tilde{t}_R$ in TeV range (suppressed by $\log(M_{\text{Planck}}/m_{3/2}) \sim 4\pi^2$)
- A-parameters in TeV range
- gaugino masses in TeV range
- mirage pattern for gaugino masses (compressed spectrum)

“Natural Susy” emerging from the heterotic string.

Calabi Yau Manifold



Orbifold



Geography

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

- the location of quarks and leptons,
- the relative location of Higgs bosons,

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- the location of quarks and leptons,
- the relative location of Higgs bosons,

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!

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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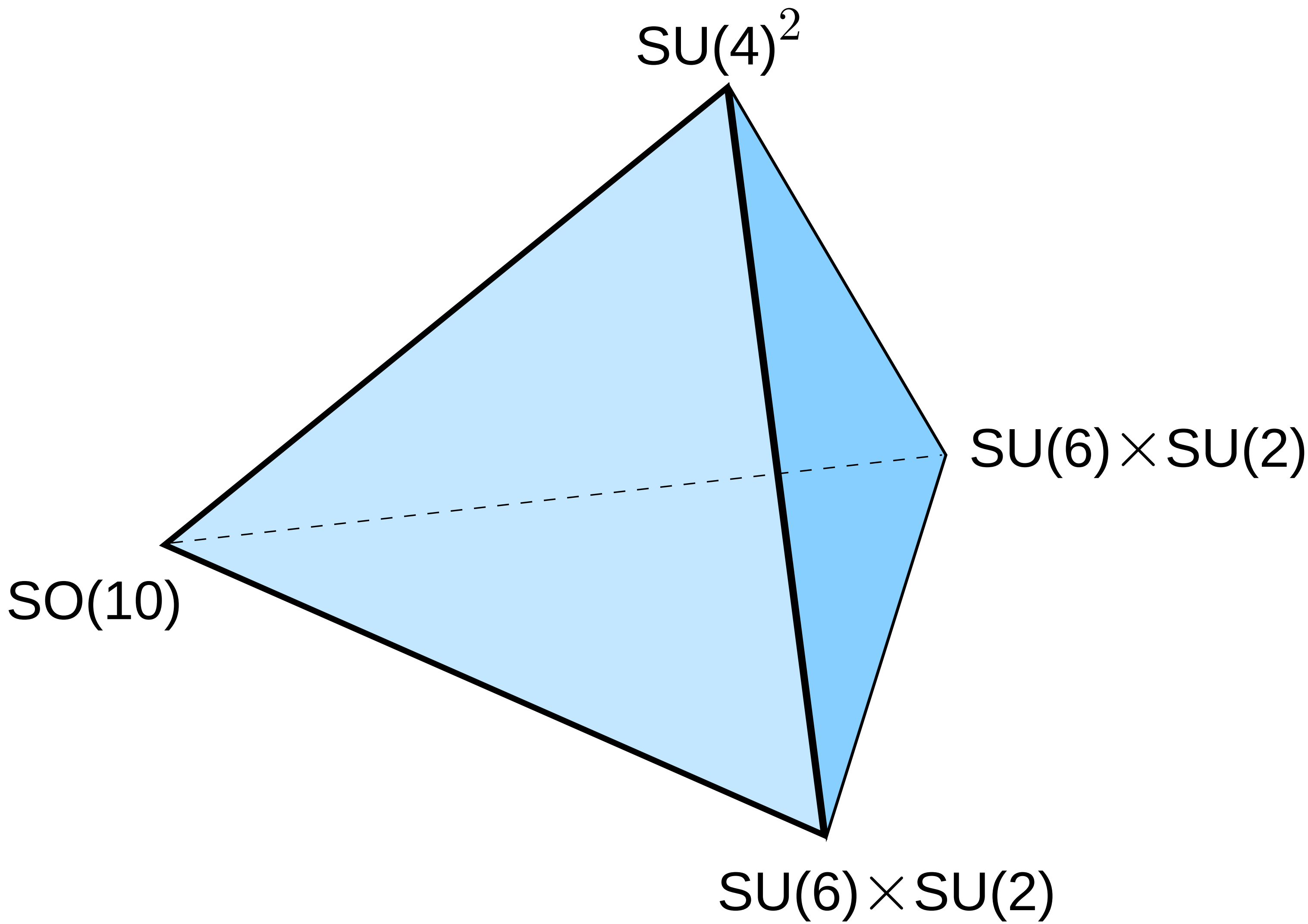
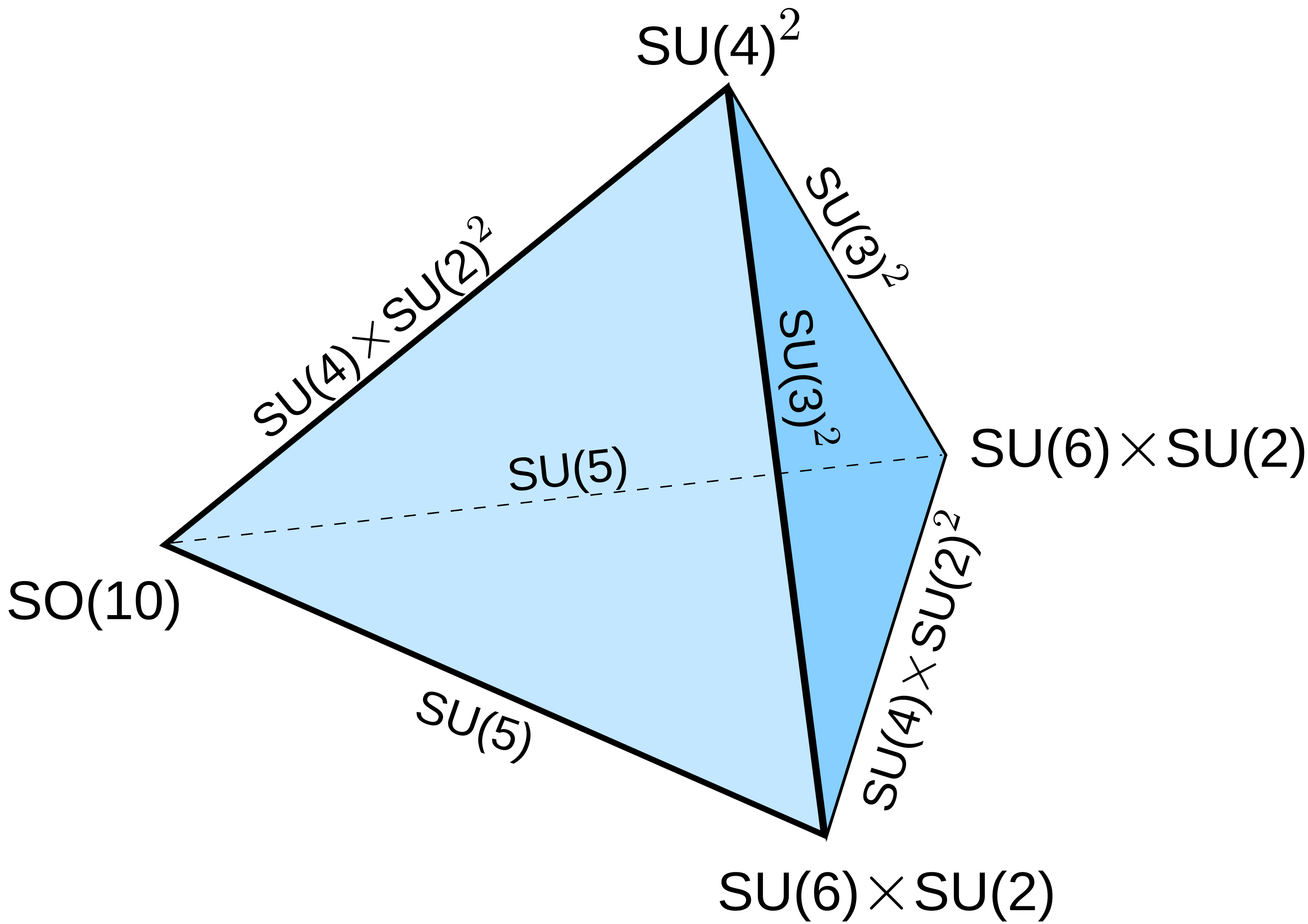
Localized gauge symmetries



(Förste, HPN, Vaudrevange, Wingerter, 2004)

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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- 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 grand unification, can be realized in the framework of the

"heterotic braneworld".

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

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, Hamguchi, 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

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

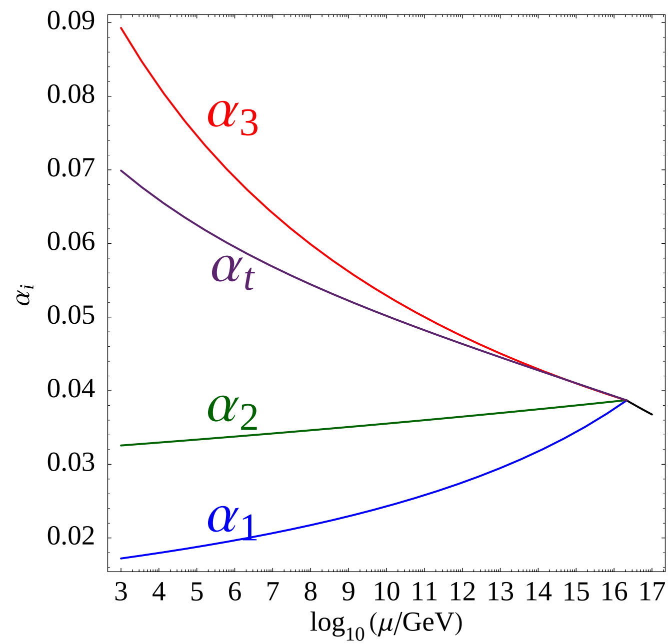
- for discussion of neutrinos and R-parity we keep also the $U(1)_{B-L}$ charges

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 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 MiniLandscape

- 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)

Emergent localization properties

The benchmark model illustrates some of the general properties of the MiniLandscape

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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)

Susy breakdown via uplifting

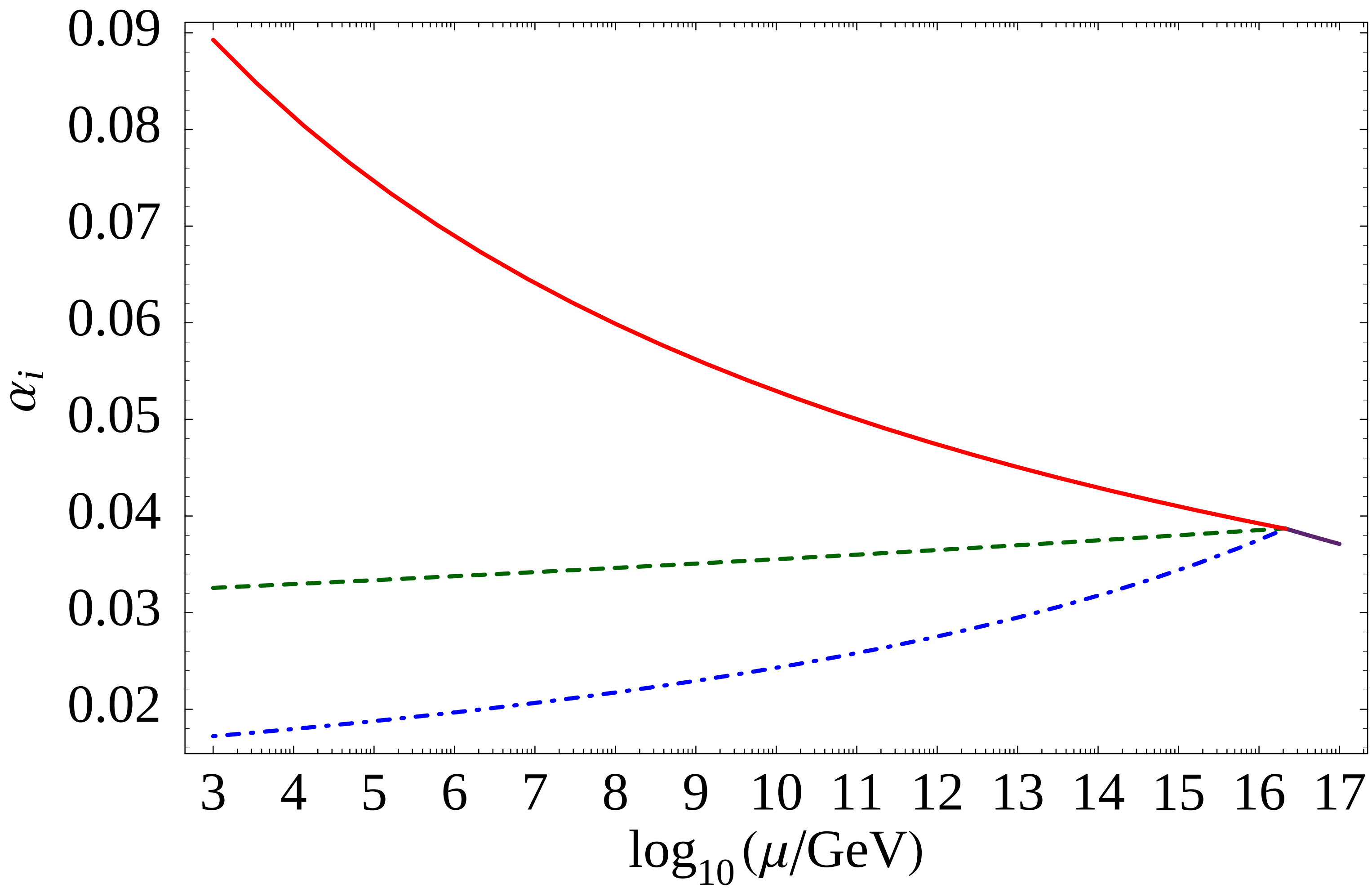
In string theory we have (from flux and gaugino condensate)

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

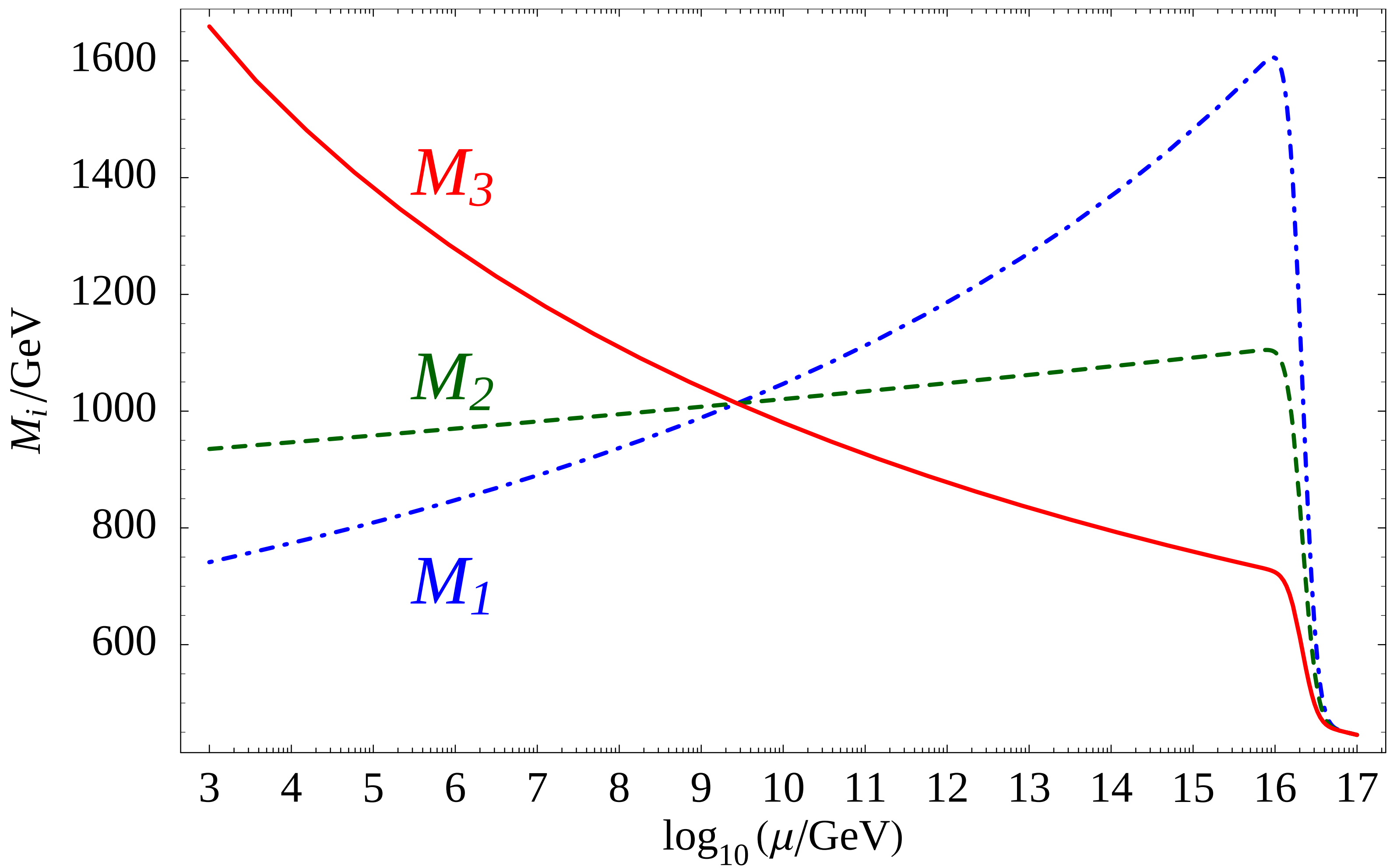
- modulus mediation suppressed (from uplifting)
  $X \sim \log(M_{\text{Planck}}/m_{3/2}) \sim 4\pi^2$
- radiative corrections become relevant (proportional to the β function, i.e. negative for the gluino, positive for the bino)
- Mixed mediation scheme: Mirage Mediation (MMAM)
- Mirage pattern for gaugino masses:
  $m_{1/2} \sim m_{3/2}/4\pi^2$

(Choi, Falkowski, Nilles, Olechowski, 2005)

Evolution of couplings



The Mirage Scale



(Lebedev, HPN, Ratz, 2005)

Reading the Gaugino Code

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

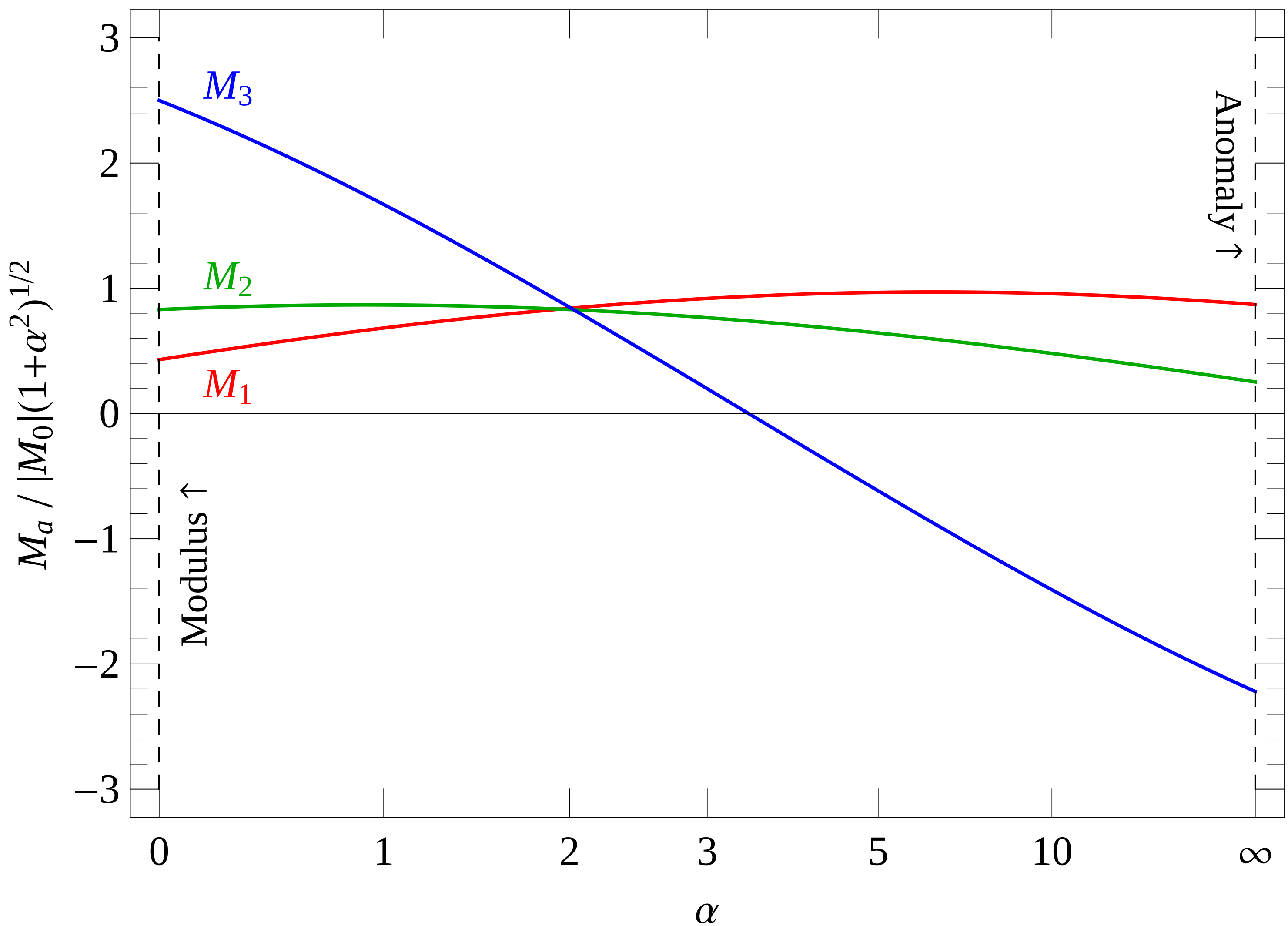
- $M_1 : M_2 : M_3 \simeq \ 1 : 2 : 6$ for $\alpha \simeq 0$
- $M_1 : M_2 : M_3 \simeq \ 1 : 1.3 : 2.5$ for $\alpha \simeq 1$
- $M_1 : M_2 : M_3 \simeq \ 1 : 1 : 1$ for $\alpha \simeq 2$
- $M_1 : M_2 : M_3 \simeq \ 3.3 : 1 : 9$ for $\alpha \simeq \infty$

The mirage scheme leads to

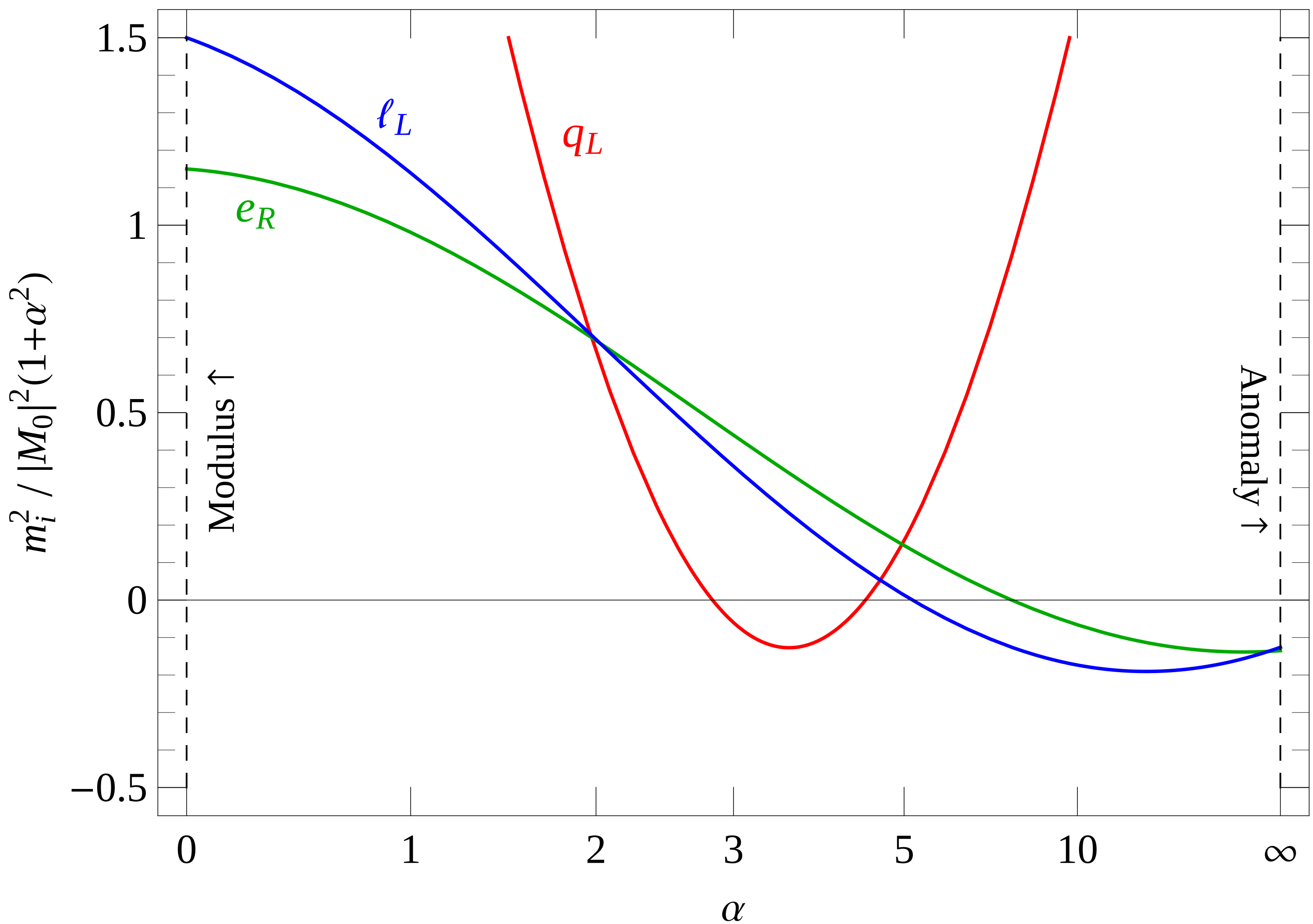
- LSP χ_1^0 predominantly Bino
- a “compact” (compressed) gaugino mass pattern.

(Choi, HPN, 2007; Löwen, HPN, 2009)

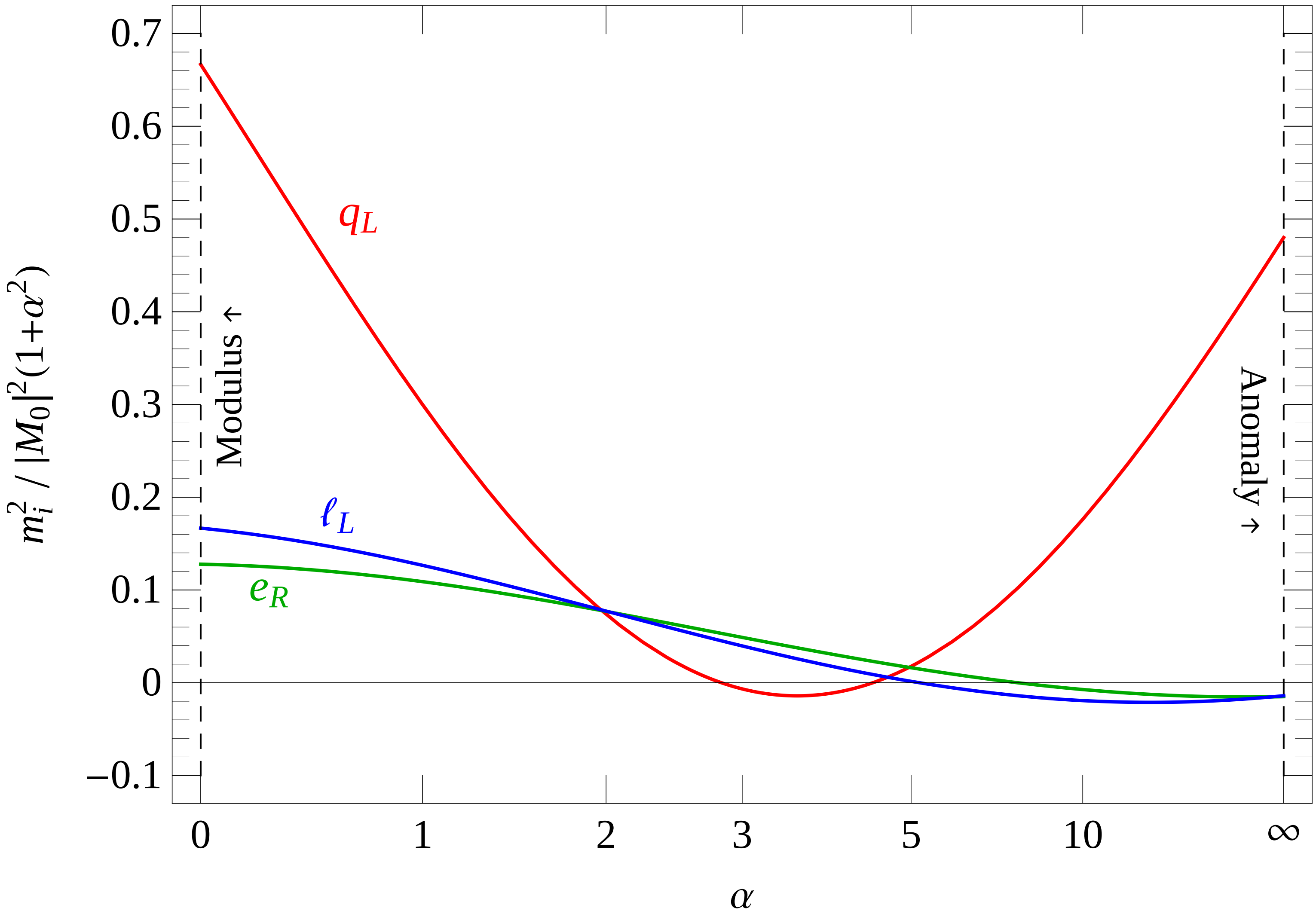
Gaugino Masses



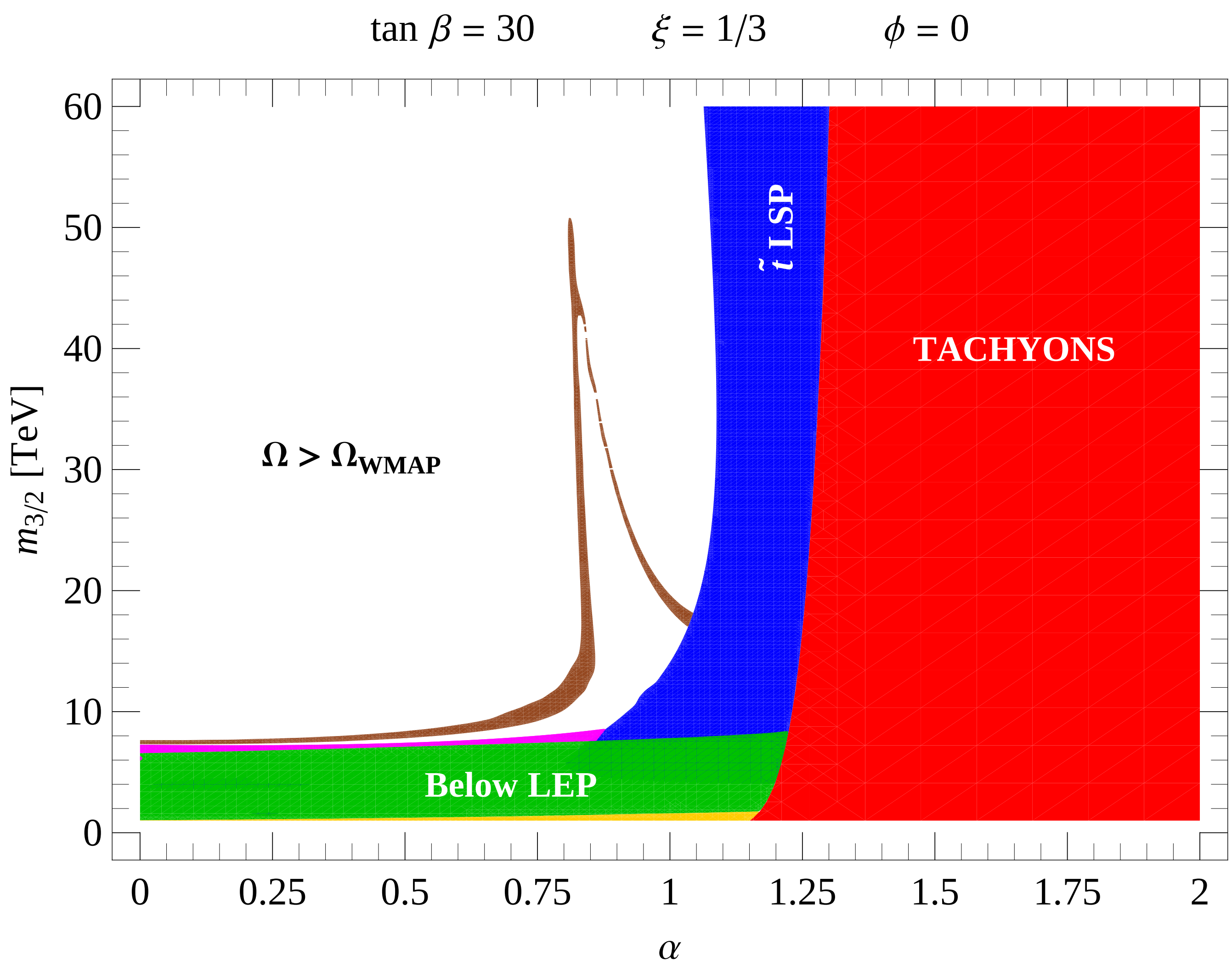
Scalar Masses



Scalar Masses



Constraints on α



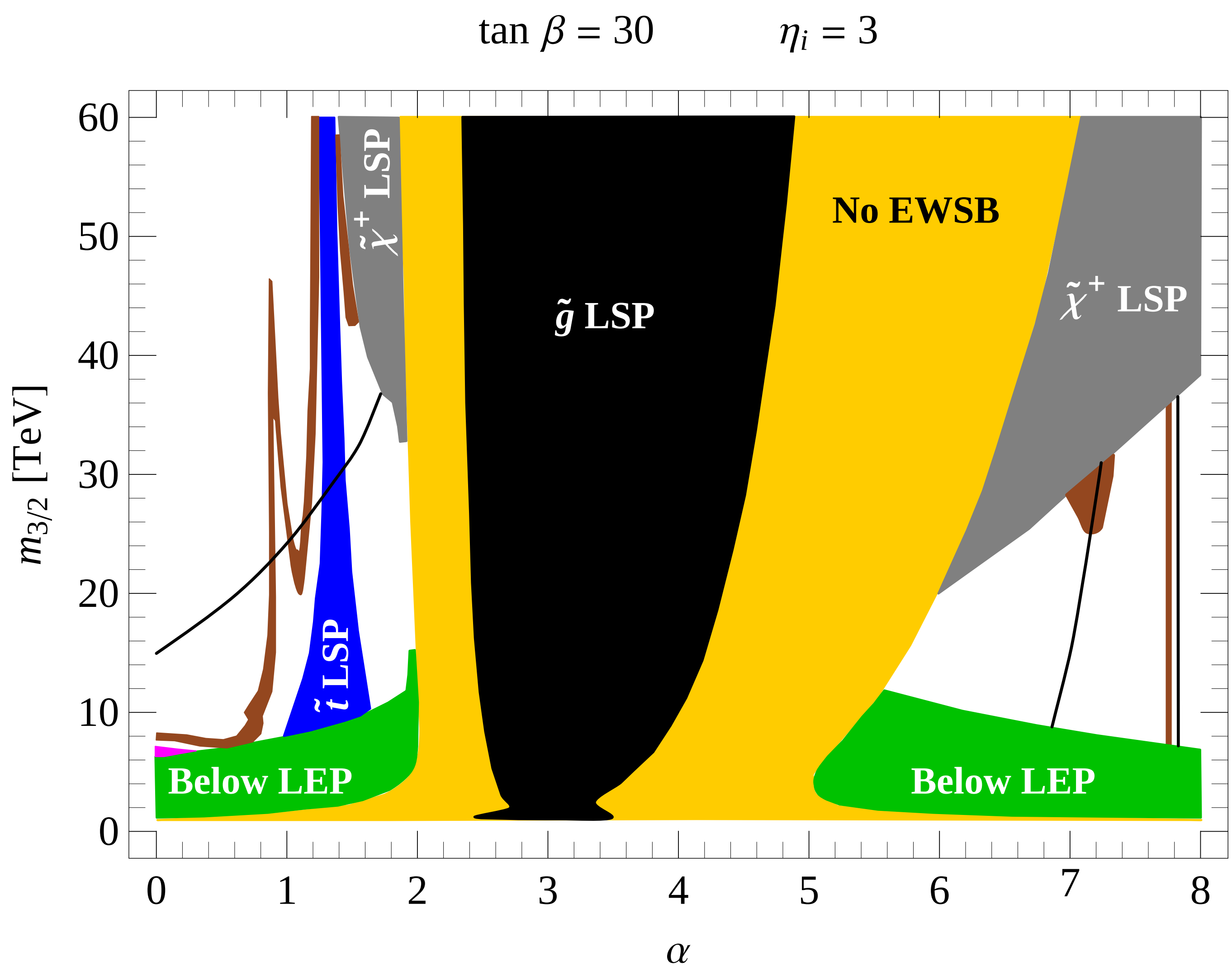
Soft scalar mass terms

- scalar masses are less protected

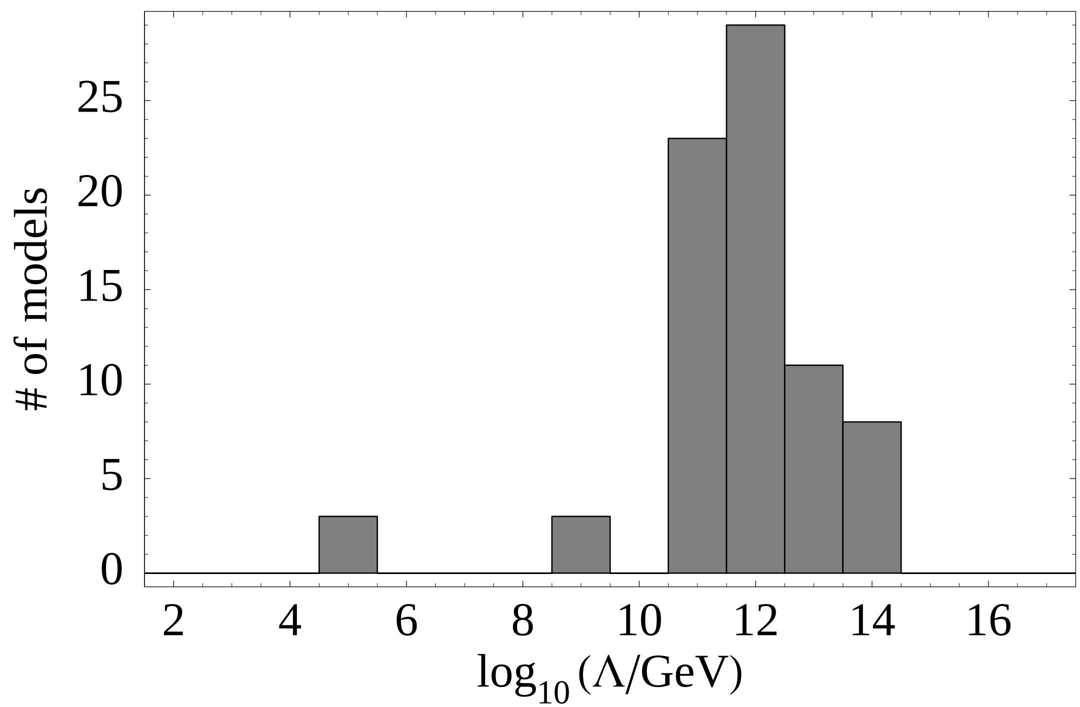
(Lebedev, Nilles, Ratz, 2006; Löwen, Nilles, 2008)

  - large contributions to sfermion masses
  - removes potential tachyons
  - Heavy squarks and sleptons: e.g. $m_0 < 30$TeV

Constraints on α



Heterotic string: gaugino condensation



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

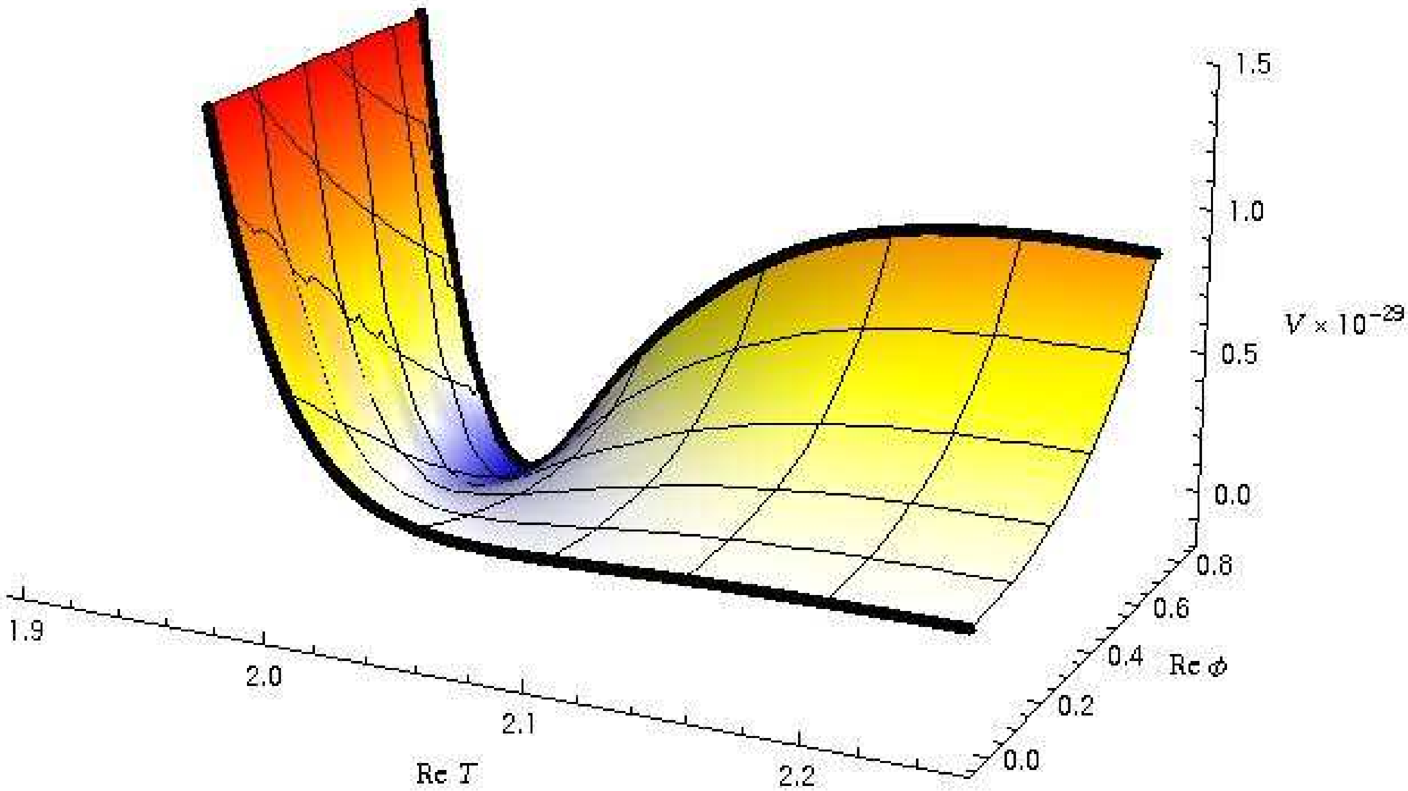
- we remain with a run-away dilaton

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

(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

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

  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)
- 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 Pattern

This provides a specific pattern for the soft masses with a large gravitino mass in the multi-TeV range (e.g. $O(30)$TeV)

- 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)

There seems to be un upper limit on the ratio of sfermion to gaugino masses

Comparison to other schemes

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

- type IIB
  - all sfermions unprotected
  - A-parameters in few TeV-range
- G2MSSM
  - all sfermions unprotected
  - A-parameters in multi TeV-range (e.g. $O(50)$TeV)

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

The mass of the lightest Higgs

The mass of the lightest Higgs should be

- somewhere between 114 GeV and 130 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 suppression of soft terms for Higgs- and top-multiplets)

Messages

- large gravitino mass (multi TeV-range)
- mirage pattern for gaugino masses rather robust
- compressed gaugino mass pattern (challenge for LHC)
- gaugino masses and A-parameter suppressed
- sfermion masses are not suppressed compared to $m_{3/2}$
- type IIB and G2MSSM have all sfermions heavy and need fine-tuning
- heterotic models reveal a reason for light Higgs and top multiplets from the location in extra dimensions
- heterotic string yields “Natural Susy”