From strings to the MSSM

Michael Ratz

Padova, 26.5.2009

Based on collaborations with:
W. Buchmüller, K. Hamaguchi, P. Hosteins, R. Kappl, T. Kobayashi, O. Lebedev, H.P. Nilles, P. Paradisi, F. Plöger, S. Raby, S. Ramos-Sánchez, R. Schieren, K. Schmidt-Hoberg, C. Simonetto, P. Vaudrevange & A. Wingerter

partial reviews:

- M.R., arXiv:0711.1582 (hep-ph)
- H.P. Nilles, S. Ramos-Sánchez, M.R., P. Vaudrevange, EPJ C 59, 2 (=arXiv:0806.3905 (hep-th))

Disclaimers and apologies

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for other attempts see talk by A. Uranga

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- I will only consider constructions with a clear geometric interpretation
- There are alternatives, satisfying the above criteria, which I will also not discuss:
  - Calabi-Yau compactifications — Bouchard, Donagi (2005); Braun, He, Ovrut, Pantev (2005)
  - $\mathbb{Z}_{12}$-I orbifold — Kim, Kyae (2006); see also talk by J.E. Kim

Why do string model building at all?

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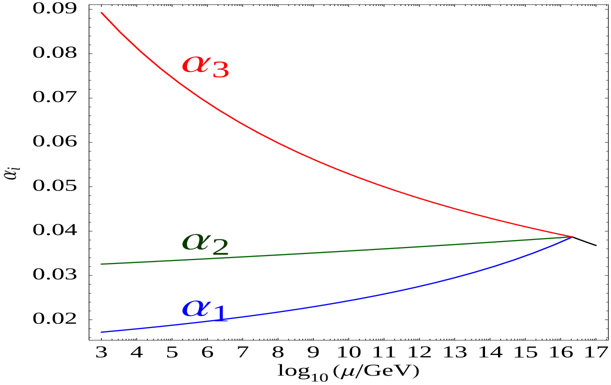
- **This talk**: merging grand unification, orbifold GUTs and strings leads to very promising models

Beautiful and ugly aspects of grand unification

☺ MSSM gauge coupling unification @ $M_{\mathrm{GUT}} \sim 10^{16}\,\mathrm{GeV}$



Beautiful and ugly aspects of grand unification

- ☺ MSSM gauge coupling unification

- ☺ One generation of observed matter fits into **16** of $\mathrm{SO}(10)$

$$\begin{array}{rcl} \mathrm{SO}(10) & \to & \mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)_{\mathrm{Y}} = G_{\mathrm{SM}} \\ \mathbf{16} & \to & (\mathbf{3},\mathbf{2})_{1/6}\oplus(\overline{\mathbf{3}},\mathbf{1})_{-2/3}\oplus(\overline{\mathbf{3}},\mathbf{1})_{1/3} \\ & & \oplus\,(\mathbf{1},\mathbf{1})_{1}\oplus(\mathbf{1},\mathbf{2})_{-1/2}\oplus(\mathbf{1},\mathbf{1})_{0} \end{array}$$

Beautiful and ugly aspects of grand unification

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☺ **16** of SO(10)

☹ However: Higgs only as doublet(s)

$$\mathbf{10} \longrightarrow \underbrace{(\mathbf{1},\mathbf{2})_{1/2} \oplus (\mathbf{1},\mathbf{2})_{-1/2}}_{\text{doublets: needed}} \oplus \underbrace{(\mathbf{3},\mathbf{1})_{-1/3} \oplus (\overline{\mathbf{3}},\mathbf{1})_{1/3}}_{\text{triplets: excluded}}$$

Beautiful and ugly aspects of grand unification

- ☺ MSSM gauge coupling unification
- ☺ **16** of $SO(10)$

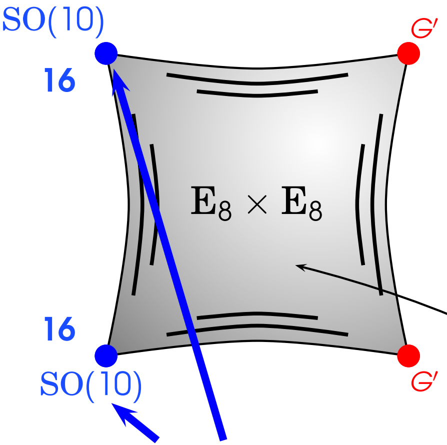
} . . . we take these hints seriously

- ☹ However: Higgs only as doublet(s)

matter in **complete** multiplets ⟷ **Why?** ⟷ Higgs in split multiplets

convincing answer:
'localized gauge groups'

Local grand unification (a specific realization)



Buchmüller, Hamaguchi, Lebedev, M.R. (2004-2006)
Lebedev, Nilles, Raby, Ramos-Sánchez, M.R., Vaudrevange, Wingerter (2006-2007)

$\xrightarrow[\text{effective theory}]{\text{`low-energy'}}$ standard model as an intersection of SO(10), G' ... in $E_8 \times E_8$

(2) SM generation(s):

localized in region with SO(10) symmetry

Higgs doublets:

live in the ‘bulk’

Higher-dimensional GUTs vs. heterotic orbifolds

top-down

→ Orbifold compactifications of the heterotic string

Dixon, Harvey, Vafa, Witten (1985-86)
Ibáñez, Nilles, Quevedo (1987)
Ibáñez, Kim, Nilles, Quevedo (1987)
Font, Ibáñez, Nilles, Quevedo (1988)
Font, Ibáñez, Quevedo, Sierra (1990)
Katsuki, Kawamura, Kobayashi, Ohtsubo, Ono, Tanioka (1990)
...

- has UV completion
- automatically consistent
- explain representations

bottom-up

→ Orbifold GUTs

Kawamura (1999-2001)
Altarelli, Feruglio (2001)
Hall, Nomura (2001)
Hebecker, March-Russell (2001)
Asaka, Buchmüller, Covi (2001)
Hall, Nomura, Okui, Smith (2001)
...

- simple geometrical interpretation
- shares many features with 4D GUTs

combine both approaches

implement field-theoretic GUTs in non-prime orbifold compactifications of the heterotic string

Kobayashi, Raby, Zhang (2004)
Förste, Nilles, Vaudrevange, Wingerter (2004)
Hebecker, Trapletti (2004)
Buchmüller, Hamaguchi, Lebedev, M.R. (2004-2006)
Faraggi, Förste, Timirgaziu (2006)
Kim, Kyae (2006)
Lebedev, Nilles, Raby, Ramos-Sánchez,
M.R., Vaudrevange, Wingerter (2006-7)
...

100 MSSMs

from

heterotic orbifolds

Orbifold compactification with local SO(10) GUT

Cartoon of heterotic orbifold compactification with local SO(10) GUT structures

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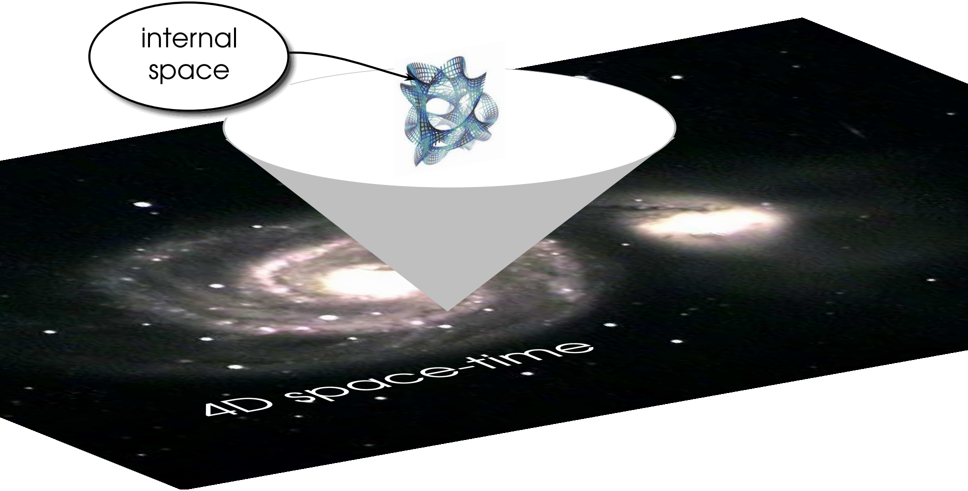

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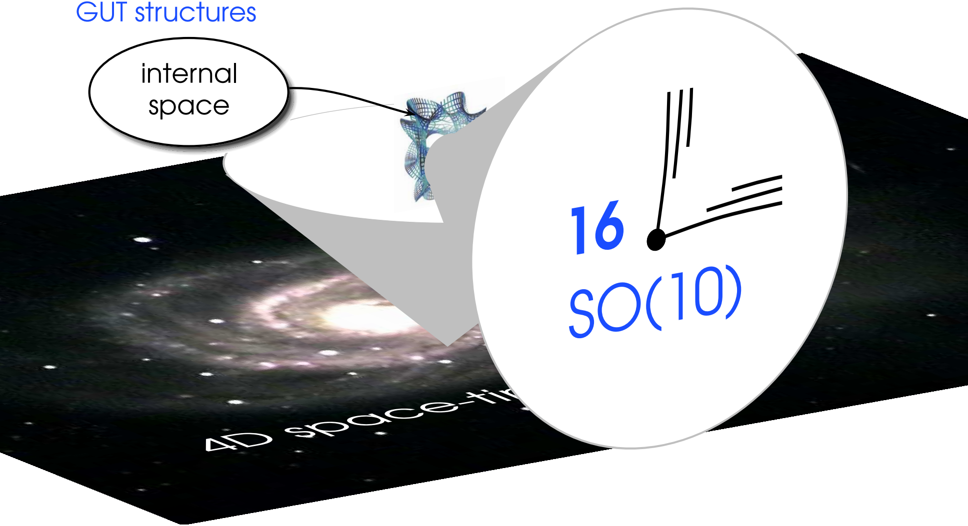
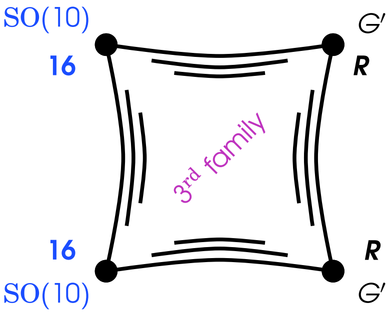


2+1 family models

Focus on models with the **features:**

- ☞ Two families come from two equivalent fixed points
- ☞ 3$^{\mathrm{rd}}$ family comes from 'somewhere else' (untwisted sector, $T_{k>1}$)



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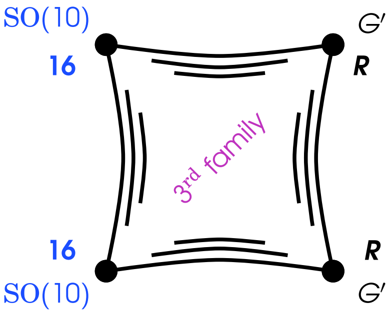

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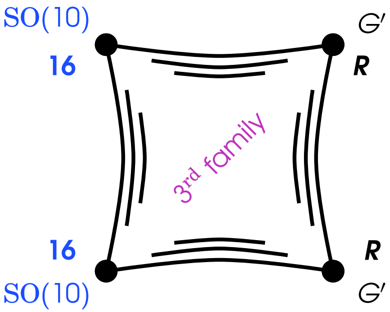

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- **This talk**: discuss MSSM models with this structure

Buchmüller, Hamaguchi, Lebedev, M.R. (2005-2006)

Lebedev, Nilles, Raby, Ramos-Sánchez, M.R., Vaudrevange, Wingerter (2006-2007)

A Mini-Landscape of MSSM models

Lebedev, Nilles, Raby, Ramos-Sañchez, M.R., Vaudrevange, Wingerter (2006)

☞ We construct 3×10^4 inequivalent models

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- Out of those 218 have the chiral MSSM spectrum with $G_{\mathrm{SM}} \subset \mathrm{SU}(5) \subset \mathrm{SO}(10)$ (such that hypercharge is in GUT normalization)

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- Discuss one model in detail

(…but please keep in mind that there are $\mathcal{O}(100)$ very similar models…)

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- **remark**: if one abandons the requirement of a $2+1$ family structure, one has a total of 10^7 models but only $\mathcal{O}(100)$ additional MSSM candidates

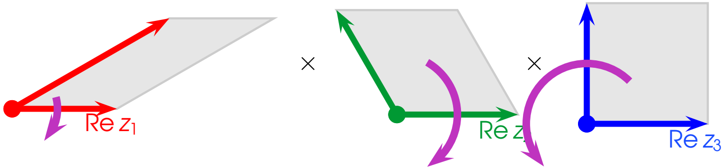
Lebedev, Nilles, Ramos-Sañchez, M.R., Vaudrevange (2008)

A heterotic ‘benchmark’ model

Model definition and spectrum

O. Lebedev, H.P. Nilles, S. Raby, S. Ramos-Sánchez, M.R., P. Vaudrevange, A. Wingerter (2007)

- Input = geometry, shift & Wilson lines



$$V = \left(\frac{1}{3}, -\frac{1}{2}, -\frac{1}{2}, 0, 0, 0, 0, 0\right)\left(\frac{1}{2}, -\frac{1}{6}, -\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, \frac{1}{2}\right)$$

$$W_2 = \left(0, -\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, \frac{1}{2}, 0, 0, 0\right)\left(4, -3, -\frac{7}{2}, -4, -3, -\frac{7}{2}, -\frac{9}{2}, \frac{7}{2}\right)$$

$$W_3 = \left(-\frac{1}{2}, -\frac{1}{2}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}, \frac{1}{6}\right)\left(\frac{1}{3}, 0, 0, \frac{2}{3}, 0, \frac{5}{3}, -2, 0\right)$$

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- ➥ Gauge group

$$G = [\overbrace{\mathrm{SU}(3)\times\mathrm{SU}(2)\times\mathrm{U}(1)_Y}^{\subset\,\mathrm{SU}(5)\,\subset\,\mathrm{SO}(10)}\times\mathrm{U}(1)_{B-L}]\times[\mathrm{SU}(4)\times\mathrm{SU}(2)']\times\mathrm{U}(1)^7$$

GUT normalization ➡ gauge coupling unification

$$t_Y = \left(0,0,0,\tfrac{1}{2},\tfrac{1}{2},-\tfrac{1}{3},-\tfrac{1}{3},-\tfrac{1}{3}\right)(0,0,0,0,0,0,0,0)$$

$$t_{B-L} = \left(0,0,0,0,0,-\tfrac{2}{3},-\tfrac{2}{3},-\tfrac{2}{3}\right)(0,0,0,0,0,2,0,0)$$

normalization not as in $\mathrm{SO}(10)$

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- Spectrum

$$\text{spectrum} = 3 \times \text{generation} + \text{vector-like w.r.t. } G_{\mathrm{SM}} \times \mathrm{U}(1)_{B-L}$$

Spectrum @ orbifold point

#	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
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10	(					
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spectrum = 3 generations + vector-like

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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	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6	[illegible]	[illegible]	[illegible]	[illegible] $_{(0,*)}$	[illegible]
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	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{(0,+2)}$	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

spectrum = 3 generations + vector-like

Spectrum @ orbifold point

#	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
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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	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2}$					η_i
10	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2}$					y_i
6	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1}$					$\bar{f}_i$
2	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(-1/2,-1)}$				$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_{(1/2,1)}$	$\bar{f}_i^+$
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
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$B-L$ allows to discriminate
- between lepton and Higgs fields
- between neutrinos and other singlets

Spectrum @ orbifold point

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

crucial:

existence of SM singlets with $q_{B-L}=\pm 2$

Decoupling of exotics vs. μ term

- Decoupling of exotics

$$X_i\,\overline{X}_j \quad \underbrace{s_{i_1}\dots s_{i_n}}_{\text{vev}\to\text{mass term}}$$

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We have checked that:

1. exotics' mass matrices have **full rank** with

$$s_i \;=\; G_{\mathrm{SM}} \times \mathrm{SU}(4) \text{ singlets with } q_{B-L} = 0 \text{ or } \pm 2$$

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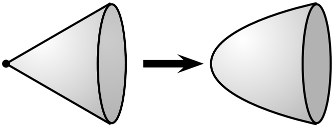
2. s_i vevs are consistent with supersymmetry

☞ Note that giving vevs to (localized) fields corresponds to blowing up the orbifold singularities

for recent work see e.g. Groot Nibbelink, Held, Ruehle, Trapletti, Vaudrevange



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Questions:

- Is there a reason why the Higgs doublets' mass is much smaller than the exotics' masses?
- Is there a reason why the Higgs mass is of the order of the weak scale?

A stringy solution to the μ problem

- The pair h_u-h_d are the only fields from U_3

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- **question:** why is $\langle \mathscr{W} \rangle$ small

Large hierarchies from approximate R symmetries

Kappl, Nilles, Ramos-Sánchez, M.R., Schmidt-Hoberg, Vaudrevange (2009)

☞ We find that R symmetries allow us to control the superpotential

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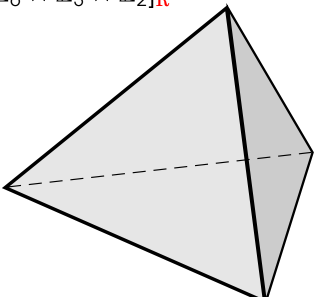
- In 'our' $\mathbb{Z}_6$-II orbifold one has exact discrete R symmetries

e.g. Araki, Kobayashi, Kubo, Ramos-Sánchez, M.R., Vaudrevange (2008)

$$G_{\mathrm{R}} = [\mathbb{Z}_6 \times \mathbb{Z}_3 \times \mathbb{Z}_2]_{\mathrm{R}}$$



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- Discrete symmetries imply approximate continuous symmetries

- In the 'vacuum' discussed so far one obtains

  $$\mu \simeq \langle \mathscr{W} \rangle \sim \langle s \rangle^9 \simeq m_{3/2}$$

Stringy solutions to the μ problem - literature

☞ There exist proposals for precisely this situation

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❶ μ from $\mathscr{W}$

Casas, Muñoz (1993)

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1. μ from $\mathscr{W}$

   Casas, Muñoz (1993)

2. μ from K

   Antoniadis, Gava, Narain, Taylor (1994)

   Brignole, Ibáñez, Muñoz (1995-1997)

$$K \supset -\log\left[\left(T_3+\overline{T_3}\right)\left(Z_3+\overline{Z_3}\right)-\left(h_u+\overline{h_d}\right)\left(\overline{h_u}+h_d\right)\right]$$

Kähler modulus

complex structure modulus

... leads effectively to the Giudice-Masiero mechanism

Giudice, Masiero (1988)

cf. talk by A. Hebecker

Stringy solutions to the μ problem - literature

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☞ **note:** there are attractive alternative (though related) explanations of a suppressed μ term

Buchmüller, Lüdeling, Schmidt (2007)
Buchmüller, Schmidt (2008)

Gauge-top unification (GTU)

- Untwisted sector (=internal components of the gauge bosons)

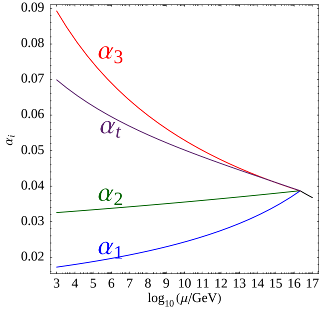
	field-theoretic description	state
U_1	$\sim A_5 + \mathrm{i}\,A_6$	$\overline{u}_1 + \ldots$
U_2	$\sim A_7 + \mathrm{i}\,A_8$	$q_1 + \ldots$
U_3	$\sim A_9 + \mathrm{i}\,A_{10}$	$h_u + \ldots$

Renormalizable coupling

$$y_t\, u_1\, q_1\, h_u$$

$$y_t \simeq g \text{ @ } M_{\mathrm{comp}}$$

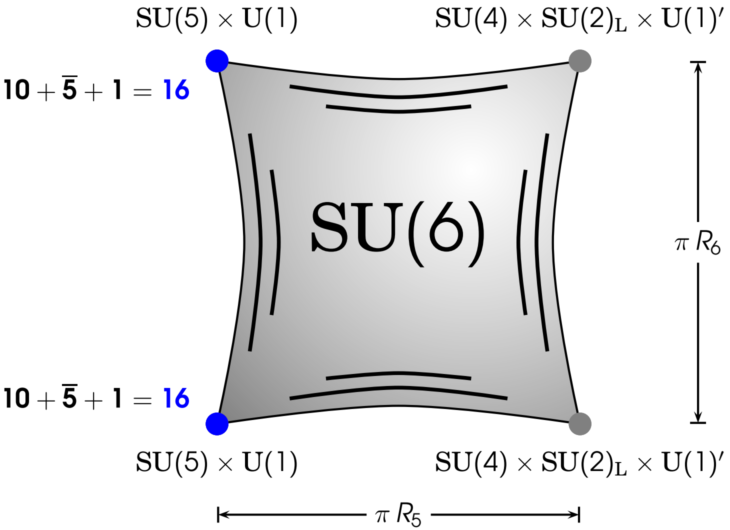
- all other Yukawa couplings are suppressed (i.e. appear at higher order in s_i)



GTU in more detail

☞ Focus on 6D orbifold GUT limit

see also Hall, Nomura (2004)
Buchmüller, Lüdeling, Schmidt (2007)



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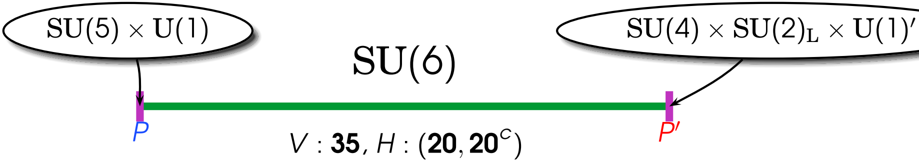
Burdman, Nomura (2003)



GTU in more detail

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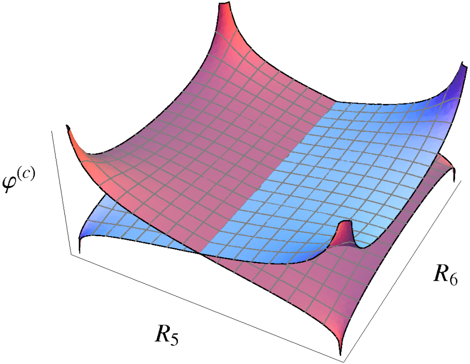
- For $R_5 \gg R_6$ this is similar to a model by Burdman & Nomura
- Because of localized Fayet-Iliopoulos terms at the fixed points the components φ and φ^c of the bulk hypermultiplet, containing q_3 and $\bar{u}_3$, attain non-trivial profiles

Lee, Nilles, Zucker (2004)



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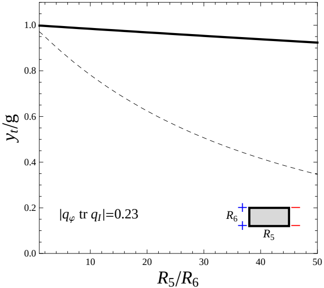
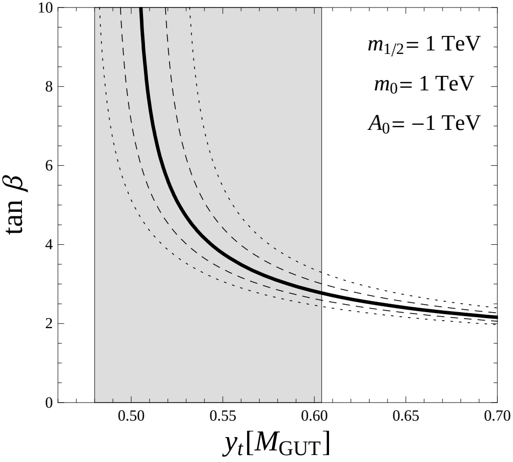
- Because of localized Fayet-Iliopoulos terms at the fixed points the components φ and φ^c of the bulk hypermultiplet, containing q_3 and $\bar{u}_3$, attain non-trivial profiles
- This leads to a suppression of y_t at the compactification scale

Hosteins, Kappl, M.R., Schmidt-Hoberg (2009)



Top-down motivation for orbifold GUTs

- y_t correlated with $\tan\beta$



Top-down motivation for orbifold GUTs

- ☞ y_t correlated with $\tan\beta$
- ☞ Reasonable values for $\tan\beta$ seem to require rather anisotropic compactifications

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Top-down motivation for orbifold GUTs

- y_t correlated with $\tan\beta$
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Hosteins, Kappl, M.R., Schmidt-Hoberg (2009)

- Highly anisotropic compactifications allow us to resolve the discrepancy between GUT and string scales

Witten (1996)

⋮

Hebecker, Trapletti (2004)

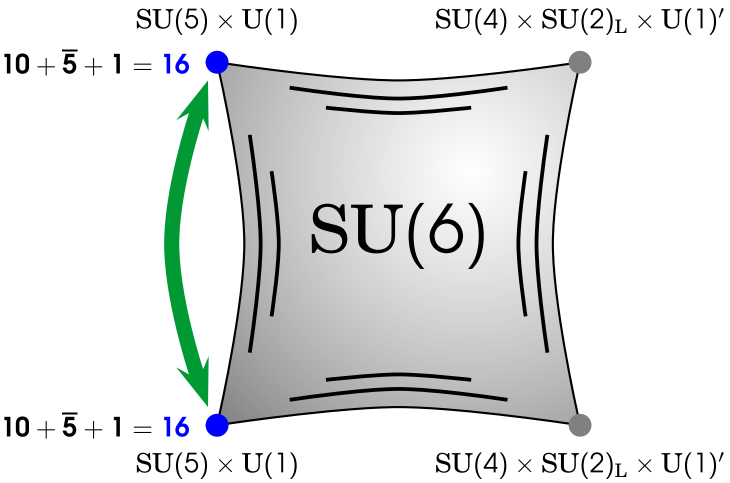
$$R_5 \simeq \frac{1}{M_{\mathrm{GUT}}} \quad \text{and} \quad R_{\geq 6} \sim \frac{1}{M_{\mathrm{string}}} \simeq \frac{1}{8.6 \cdot 10^{17}\,\mathrm{GeV}}$$

- Orbifold GUT limit appears to yield valid intermediate description

cf. talk by A. Hebecker

Comments on the structure of soft masses

☞ Two families reside on two equivalent orbifold fixed points



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- ➥ This leads to a discrete D_4 flavor symmetry under which the first two generations transform as a doublet

Kobayashi, Raby, Zhang (2004)

Kobayashi, Nilles, Plöger, Raby, M.R. (2006)

for other interesting applications of non-Abelian discrete flavor symmetries see talk by C. Hagedorn

- Note: anomalies of non-Abelian discrete symmetries cancel in string-derived models

Araki, Kobayashi, Kubo, Ramos-Sánchez, M.R., Vaudrevange (2008)

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- At this level, the structure of the soft mass terms is

$$\widetilde{m}^2 = \begin{pmatrix} a & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & b \end{pmatrix}$$

Ko, Kobayashi, Park, Raby (2007)

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- The singlet VEVs $\langle s_i \rangle$ that generate the Yukawa coupling also break D_4
- ➥ MFV-like structure of soft masses

$$\widetilde{m}^2 \sim \alpha\,\mathbb{1} + \beta\, Y^\dagger\, Y$$

MFV = Minimal Flavor Violation

Buras, Gambino, Gorbahn, Jäger, Silvestrini (2000)
D'Ambrosio, Giudice, Isidori, Strumia (2002)

Example: soft masses of squark doublets

Paradisi, M.R., Schieren, Simonetto (2008)

Colangelo, Nikolidakis, Smith (2008)

cf. talk by C. Smith

☞ Ansatz (@ M_{GUT}):

$$\widetilde{m}_Q^2 = \alpha_1 \mathbb{1} + \beta_1 Y_u^\dagger Y_u + \beta_2 Y_d^\dagger Y_d + (\beta_3 Y_d^\dagger Y_d Y_u^\dagger Y_u + \text{h.c.})$$

Example: soft masses of squark doublets

Paradisi, M.R., Schieren, Simonetto (2008)

Colangelo, Nikolidakis, Smith (2008)

cf. talk by C. Smith

- Ansatz (@ M_{GUT}):

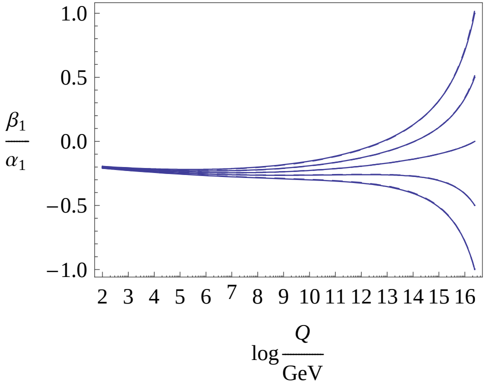
$$\widetilde{m}_Q^2 \;=\; \alpha_1\, \mathbb{1} + \beta_1\, Y_u^\dagger Y_u + \beta_2\, Y_d^\dagger Y_d + (\beta_3\, Y_d^\dagger Y_d\, Y_u^\dagger Y_u + \text{h.c.})$$

- The form of $\widetilde{m}_Q^2$ is RG invariant, only the coefficients α_i & β_i run

Example: Running of β_1

"SPS + MFV"

$$\beta_i = \beta_0 \text{ @ } M_{\mathrm{GUT}}$$
$$\alpha_i = m_0^2 \text{ @ } M_{\mathrm{GUT}}$$



SPS Point	m_0	$m_{1/2}$	A	$\tan\beta$
1a	100 GeV	250 GeV	-100 GeV	10

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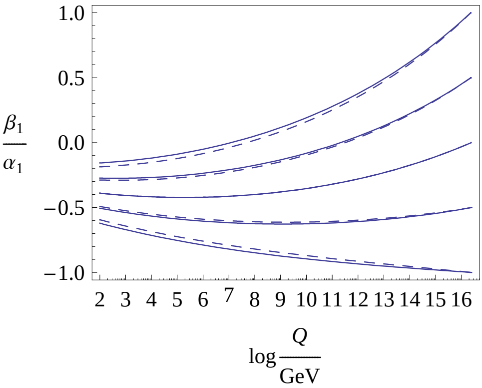

SPS Point	m_0	$m_{1/2}$	A	$\tan\beta$
2	1450 GeV	300 GeV	0	10

Example: Running of β_1

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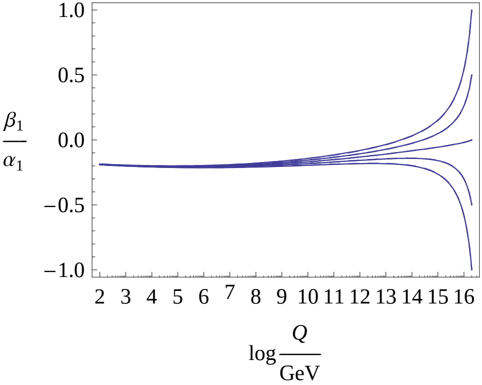


SPS Point	m_0	$m_{1/2}$	A	$\tan\beta$
3	90 GeV	400 GeV	0	10

Example: Running of β_1

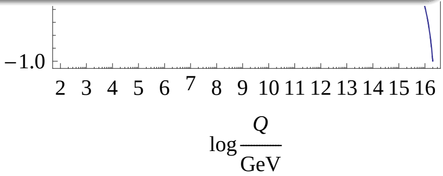
"SPS

$\beta_i =$

$\alpha_i =$

Bottom-line:

- SUSY flavor problem(s) may be avoided/ameliorated because of stringy D_4 flavor symmetry
- Deviation of $\widetilde{m}^2$ from unit matrices at M_{GUT} might not even be measurable at low energies



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Summary

Summary of search strategy

- We explore possibilities of getting the MSSM from strings

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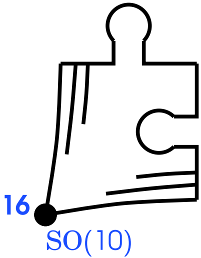


- The concept of 'local grand unification' has led us to beautiful spots

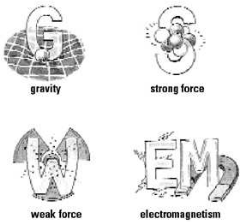
Summary of features

1. $3 \times \mathbf{16} + \text{Higgs} + \text{nothing}$

No exotics

Summary of features

1. $3 \times \mathbf{16} + \text{Higgs} + \text{nothing}$
2. $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)_Y \times G_{\mathrm{hid}}$



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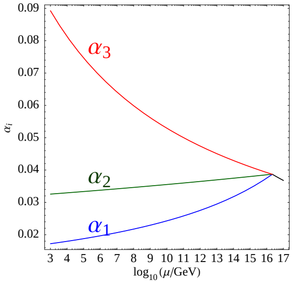

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2. $\mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)_Y \times G_{\mathrm{hid}}$
3. unification
4. R-parity
   ... but potential problems with dimension 5 proton decay

$\cancel{\bar{u}\bar{d}\bar{d}}$ $\cancel{q\bar{d}\ell}$

$\cancel{\ell\ell\bar{e}}$ $\cancel{\ell\bar{\phi}}$

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4. R-parity
5. solution to the μ-problem

   i.e. well-known solutions to the μ-problem are automatically realized in explicit models

$$\mu \sim \langle \mathscr{W} \rangle$$

$\langle \mathscr{W} \rangle \ll 1$ from approximate $\mathrm{U}(1)_R$ symmetries

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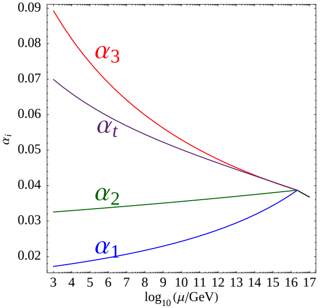
6. gauge-top unification: $y_t \lesssim g$ @ M_{GUT}, y_t/g related to geometry (anisotropy) & potentially realistic flavor structures à la Froggatt-Nielsen



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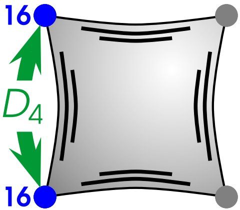
7. Non-Abelian discrete flavor symmetries relaxing/solving the supersymmetric flavor problems



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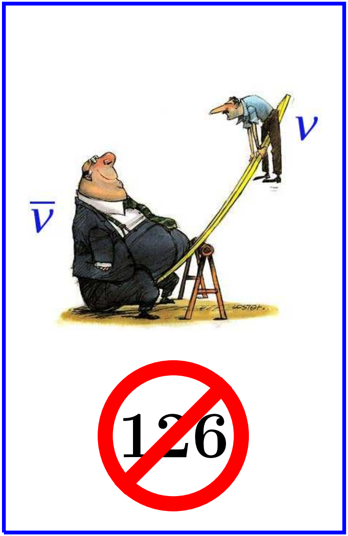

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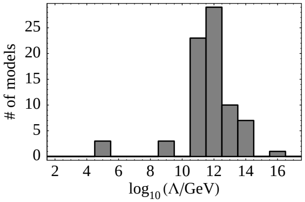

scale of hidden sector strong dynamics is consistent with TeV-scale soft masses and realistic gauge coupling

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that's what we searched for. . .

5. solution to the μ-problem
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7. Non-Abelian discrete flavor symmetries
8. see-saw
9. 'realistic' hidden sector

. . . that's what we got 'for free'

"stringy surprises"

Mille grazie

See-saw couplings

▸ Summary

☞ see-saw couplings: $W_{\mathrm{see-saw}} = Y_\nu^{ij}\, h_u\, \ell_i\, \bar{\nu}_j + M_{ij}\, \bar{\nu}_i\, \bar{\nu}_j$

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singlet

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➥ see-saw mass matrix

$$W_{\mathrm{see-saw}} \xrightarrow{h_u \to v} (\nu, \bar{\nu}) \begin{pmatrix} 0 & y_\nu\, v \\ y_\nu\, v & M \end{pmatrix} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix} \simeq \frac{y_\nu^2\, v^2}{M}\, \nu\, \nu + M\, \bar{\nu}\, \bar{\nu}$$

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... suspiciously close to observed values

$$\sqrt{\Delta m^2_{\mathrm{atm}}} \simeq 0.04\,\mathrm{eV} \quad \& \quad \sqrt{\Delta m^2_{\mathrm{sol}}} \simeq 0.008\,\mathrm{eV}$$

Heterotic see-saw

▸ Summary

W. Buchmüller, K. Hamaguchi, O. Lebedev, M.R. (2006)
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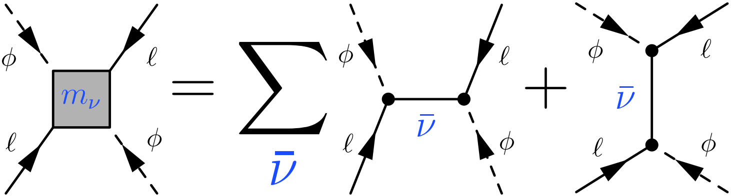

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- ➥ $\mathcal{O}(100)$ contributions to the (effective) neutrino mass operator
- ➥ effective suppression of the see-saw scale

$$m_\nu \sim \frac{v^2}{M_*} \qquad M_* \sim \frac{M_{\mathrm{GUT}}}{10\ldots100}$$

… seems consistent with observation

$$\left(\sqrt{\Delta m^2_{\mathrm{atm}}} \simeq 0.04\,\mathrm{eV}\ \&\ \sqrt{\Delta m^2_{\mathrm{sol}}} \simeq 0.008\,\mathrm{eV}\right)$$

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See-saw is a **generic feature** in heterotic MSSM vacua

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Main conclusion:

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- Note: in $\mathbb{Z}_3$ orbifolds one arrives at a different conclusion

cf. Giedt, Kane, Langacker, Nelson (2005)

Why is $\langle \mathscr{W} \rangle$ small?

Summary

Kappl, Nilles, Ramos-Sánchez, M.R., Schmidt-Hoberg, Vaudrevange (2008)

Two ingredients:

1. One can show:

$\mathscr{W}$ has $\mathrm{U}(1)_R$ symmetry $\curvearrowright$ $\dfrac{\partial \mathscr{W}}{\partial \phi_i} = 0 \curvearrowright \mathscr{W} = 0$

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2. Orbifolds have high-power discrete R symmetries
   $\curvearrowright$ approximate R symmetries
   $\curvearrowright$ $\langle \mathscr{W} \rangle \sim \langle \phi \rangle^N$ with N large

$\langle \mathscr{W} \rangle = 0$ because of $\mathrm{U}(1)_R$ (I)

Kappl, Nilles, Ramos-Sánchez, M.R., Schmidt-Hoberg, Vaudrevange (2008)

aim: show that

$\mathscr{W}$ has $\mathrm{U}(1)_R$ symmetry $\curvearrowright$ $\dfrac{\partial \mathscr{W}}{\partial \phi_i} = 0 \curvearrowright \mathscr{W} = 0$

Consider a superpotential

$$\mathscr{W} = \sum c_{n_1 \cdots n_M} \phi_1^{n_1} \cdots \phi_M^{n_M}$$

with an exact *R*-symmetry

$$\mathscr{W} \to \mathrm{e}^{2\mathrm{i}\,\alpha}\,\mathscr{W}\,, \quad \phi_j \to \phi_j' = \mathrm{e}^{\mathrm{i}\,r_j\,\alpha}\,\phi_j$$

where each monomial in $\mathscr{W}$ has total R-charge 2.

$\langle\mathscr{W}\rangle = 0$ because of $\mathrm{U}(1)_R$ (II)

Kappl, Nilles, Ramos-Sánchez, M.R., Schmidt-Hoberg, Vaudrevange (2008)

Consider a field configuration $\langle\phi_i\rangle$ with

$$F_i = \frac{\partial \mathscr{W}}{\partial \phi_i} = 0 \quad \text{at } \phi_j = \langle\phi_j\rangle$$

Under an infinitesimal $\mathrm{U}(1)_R$ transformation, the superpotential transforms nontrivially

$$\mathscr{W}(\phi_j) \to \mathscr{W}(\phi_j') = \mathscr{W}(\phi_j) + \sum_i \frac{\partial \mathscr{W}}{\partial \phi_i} \Delta\phi_i$$

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This is only possible if $\langle \mathscr{W} \rangle = 0$!

bottom-line:

$\mathscr{W}$ has $\mathrm{U}(1)_R$ symmetry $\curvearrowright$ $\frac{\partial \mathscr{W}}{\partial \phi_i} = 0$ $\curvearrowright$ $\mathscr{W} = 0$

Comments

1. Relation to Nelson-Seiberg theorem

Nelson & Seiberg (1994)

$$\left\{\begin{array}{c}\text{setting without}\\ \text{supersymmetric}\\ \text{ground state}\end{array}\right\} \xrightarrow{\text{requires}} \mathrm{U}(1)_R \text{ symmetry}$$

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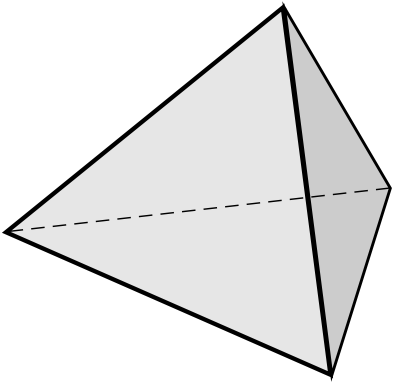
However, the above $\mathrm{U}(1)_R$-symmetry appears as an accidental continous symmetry resulting from an exact discrete symmetry of (high) order N; hence
- Goldstone-Boson massive and harmless
- a nontrivial VEV of $\mathscr{W}$ of higher order in ϕ

Origin of high-power discrete R-symmetries



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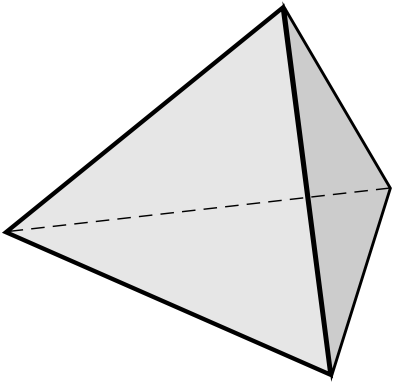

- Orbifold breaks $\mathrm{SO}(6) \simeq \mathrm{SU}(4)$ Lorentz symmetry of compact space to discrete subgroup
- Specifically, in 'our' $\mathbb{Z}_6$-II orbifold one has

$$G_R \;=\; [\mathbb{Z}_6 \times \mathbb{Z}_3 \times \mathbb{Z}_2]_R$$

e.g. Araki, Kobayashi, Kubo, Ramos-Sánchez, M.R., Vaudrevange (2008)

Application: moduli stabilization

There exist various possibilities to fix the gauge coupling/stabilize the dilaton:

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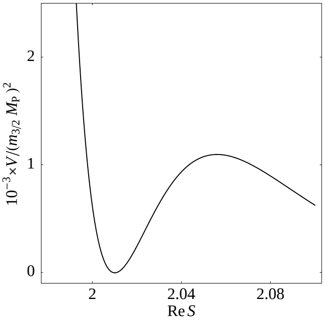
- Race-track

  Krasnikov (1987)

use several gaugino condensates



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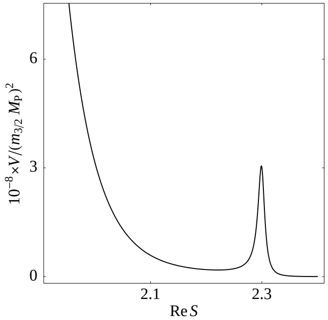
- Race-track
- Kähler stabilization

Casas (1996)

Binétruy, Gaillard & Wu (1996)

...

non-perturbative corrections to the Kähler potential



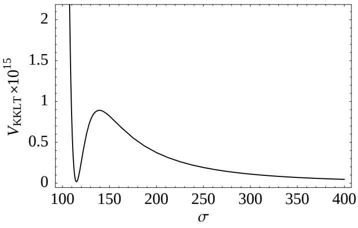
Application: moduli stabilization

There exist various possibilities to fix the gauge coupling/stabilize the dilaton:

- Race-track
- Kähler stabilization
- Flux compactification

e.g. Kachru, Kallosh, Linde & Trivedi (2003)

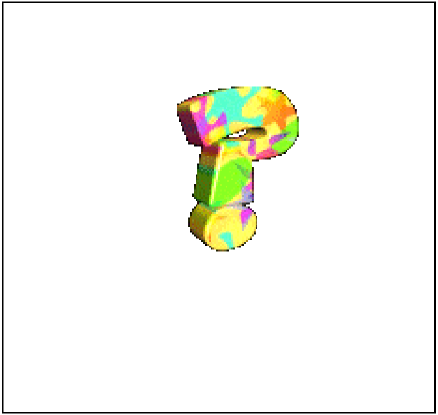
e.g. KKLT proposal



Application: moduli stabilization

There exist various possibilities to fix the gauge coupling/stabilize the dilaton:

- Race-track
- Kähler stabilization
- Flux compactification
- etc. . . .



Constant + exponential scheme

☞ KKLT type proposal

$$\mathscr{W}_{\text{eff}} = c + A\,\mathrm{e}^{-a\,S}$$

constant

non-perturbative

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- Our proposal: small expectation of the perturbative superpotential due to approximate $\mathrm{U}(1)_R$ symmetry

$$\mathscr{W}_{\mathrm{eff}} = \langle \mathscr{W}_{\mathrm{pert}} \rangle + A\,\mathrm{e}^{-a\,S}$$

$\langle \mathscr{W}_{\mathrm{pert}} \rangle \sim \langle \phi \rangle^N$

"gaugino condensate"

Embedding into the MiniLandscape

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  - fixes the gauge coupling / dilaton
- **question**: is the dilaton fixed at realistic values?

Hidden sector strong dynamics

Summary back

- Relation between $m_{3/2} \ll M_\mathrm{P}$ and the scale of hidden sector strong dynamics

$$G = G_\mathrm{SM} \times G_4$$

$$\underbrace{m_{3/2}}_{\text{gravitino mass}} \simeq \frac{\overbrace{\Lambda^3}^{\text{scale of hidden sector strong dynamics}}}{M_\mathrm{P}^2}$$

Hidden sector strong dynamics

Summary back

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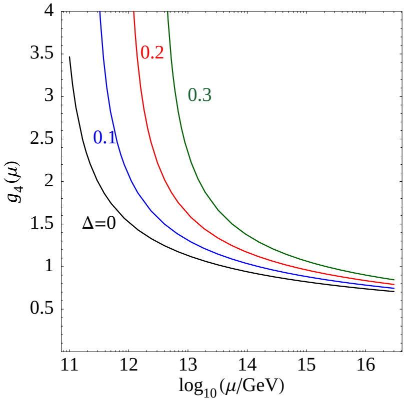
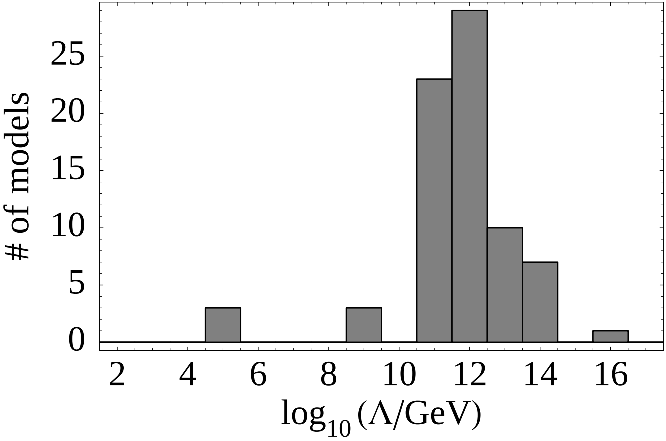
- We *estimate* the scale of hidden sector strong dynamics (i.e. calculate the β-function)



Properties of the hidden sector

- Distribution of the (naive) scale of hidden sector strong dynamics



2 Wilson line case

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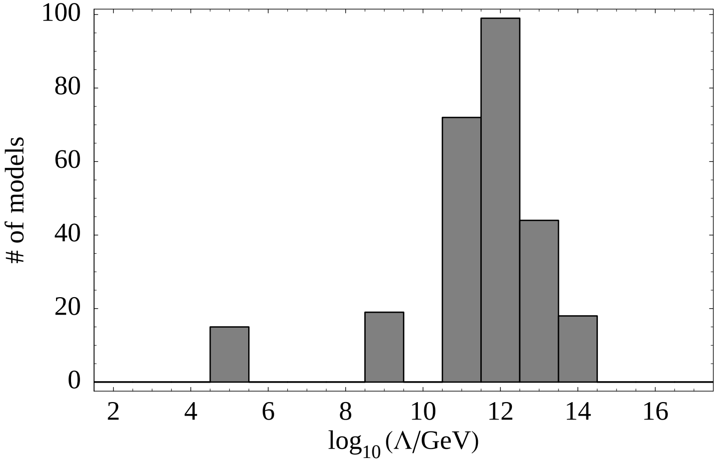

2+3 Wilson line case (heavy top)

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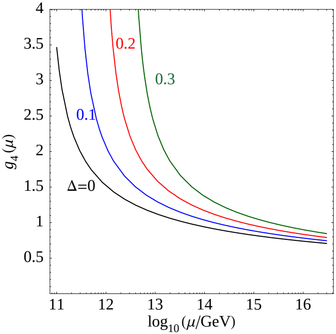

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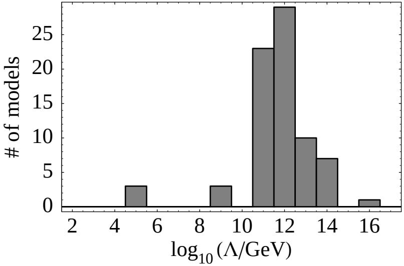

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bottom-line:

statistical preference for intermediate scale of condensation / a realistic gauge coupling

Yukawa structure

☞ Yukawa couplings in the configuration discussed so far up to s^6

$$Y_u = \begin{pmatrix} s^5 & s^5 & s^5 \\ s^5 & s^5 & s^6 \\ s^6 & s^6 & \mathcal{O}(g) \end{pmatrix}, \quad Y_d = \begin{pmatrix} 0 & 0 & s^5 \\ 0 & s^5 & 0 \\ 0 & 0 & s^6 \end{pmatrix}, \quad Y_e = \begin{pmatrix} s^6 & s^6 & 0 \\ 0 & s^5 & s^6 \\ s^5 & 0 & 0 \end{pmatrix}$$

each s entry represents a monomial of singlets with the indicated order

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➥ Effective Yukawa couplings are vacuum/moduli dependent

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- Effective Yukawa couplings $\sim s^n$ vanish @ orbifold point

$$\left\{ \begin{array}{c} \text{hierarchical} \\ \text{Yukawa} \\ \text{couplings} \\ \text{in Nature} \end{array} \right\} \longleftrightarrow \left\{ \begin{array}{c} \text{do we live} \\ \text{close to an} \\ \text{orbifold point} \\ ??? \end{array} \right\}$$

Summary