From strings to the MSSM

Michael Ratz

Padova, 26.5.2009

Based on collaborations with:

partial reviews:
Disclaimers and apologies

☞ Aim of this talk: discuss progress in getting the MSSM from string theory
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☞ This is **not** going to be a complete survey of all attempts

for other attempts see talk by A. Uranga
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I will focus on models with the **exact MSSM spectrum** and built-in **gauge coupling unification**
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There are alternatives, satisfying the above criteria, which I will also not discuss:

- Calabi-Yau compactifications
- $\mathbb{Z}_{12}$-I orbifold

Bouchard, Donagi (2005)
Braun, He, Ovrut, Pantev (2005)

Kim, Kyae (2006)
see also talk by J.E. Kim
Why do string model building at all?

☞ Wish list:

1. find a model that is **consistent with observation**
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3. try to find answers to **open questions** within this model
   - MSSM $\mu$ problem
   - strong CP problem
   - . . .
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☞ **Main problem:**
first step highly non-trivial
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☞ **This talk**: merging grand unification, orbifold GUTs and strings leads to very promising models
MSSM gauge coupling unification @ $M_{\text{GUT}} \sim 10^{16}$ GeV
MSSM gauge coupling unification

One generation of observed matter fits into 16 of SO(10)

\[
\begin{align*}
\text{SO}(10) & \rightarrow \text{SU}(3) \times \text{SU}(2) \times U(1)_Y = G_{\text{SM}} \\
16 & \rightarrow (3,2)_{1/6} \oplus (\bar{3},1)_{-2/3} \oplus (\bar{3},1)_{1/3} \\
& \quad \oplus (1,1)_1 \oplus (1,2)_{-1/2} \oplus (1,1)_0
\end{align*}
\]
MSSM gauge coupling unification

16 of \( \text{SO}(10) \)

However: Higgs only as doublet(s)

\[
10 \rightarrow (1,2)_{1/2} \oplus (1,2)_{-1/2} \oplus (3,1)_{-1/3} \oplus (\overline{3},1)_{1/3}
\]

doublets: needed

triplets: excluded
Beautiful and ugly aspects of grand unification

- MSSM gauge coupling unification
- **16** of \(SO(10)\)
- However: Higgs only as doublet(s)

> ... we take these hints seriously

**convincing answer:**

'localized gauge groups'
Local grand unification (a specific realization)

SO(10) \rightarrow \text{E}_8 \times \text{E}_8


(2) SM generation(s):
localized in region with SO(10) symmetry

Higgs doublets:
live in the 'bulk'

standard model
as an intersection of SO(10), G'...
in E_8 \times E_8

'low-energy' effective theory
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)

**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

- Faraggi, Förste, Timirgazi (2006)
- Kim, Kyae (2006)

...
100 MSSMs from heterotic orbifolds
Orbifold compactification with local SO(10) GUT

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

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4D space-time

internal space
Orbifold compactification with local $SO(10)$ GUT

Cartoon of heterotic orbifold compactification with local $SO(10)$ GUT structures.
2+1 family models

Focus on models with the features:

☞ Two families come from two equivalent fixed points

☞ 3rd family comes from ‘somewhere else’ (untwisted sector, $T_k>1$)
2+1 family models

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☞ Note: this structure has been obtained in the context of string-derived Pati-Salam models

2+1 family models

Focus on models with the features:

- Two families come from two equivalent fixed points
- 3rd family comes from ‘somewhere else’ (untwisted sector, \( T_k > 1 \))

Note: this structure has been obtained in the context of string-derived Pati-Salam models

This talk: discuss MSSM models with this structure

We construct $3 \times 10^4$ inequivalent models
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Out of those 218 have the chiral MSSM spectrum with $G_{\text{SM}} \subset SU(5) \subset SO(10)$ (such that hypercharge is in GUT normalization).
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The models have vector-like exotics which can, however, get large masses.
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**Strategy for the remainder of the talk:**

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.
A heterotic
‘benchmark’ model
Input = geometry, shift & Wilson lines

\[ V = \begin{pmatrix} \frac{1}{3}, & -\frac{1}{2}, & -\frac{1}{2}, & 0, & 0, & 0, & 0, & 0 \end{pmatrix} \begin{pmatrix} \frac{1}{2}, & -\frac{1}{6}, & -\frac{1}{2}, & -\frac{1}{2}, & -\frac{1}{2}, & -\frac{1}{2}, & -\frac{1}{2}, & -\frac{1}{2} \end{pmatrix} \]

\[ W_2 = \begin{pmatrix} 0, & -\frac{1}{2}, & -\frac{1}{2}, & -\frac{1}{2}, & 0, & 0, & 0, & 0 \end{pmatrix} \begin{pmatrix} 4, & -3, & -\frac{7}{2}, & -4, & -3, & -\frac{7}{2}, & -\frac{9}{2}, & -\frac{7}{2} \end{pmatrix} \]

\[ W_3 = \begin{pmatrix} -\frac{1}{2}, & -\frac{1}{2}, & -\frac{1}{6}, & -\frac{1}{6}, & -\frac{1}{6}, & -\frac{1}{6}, & -\frac{1}{6}, & -\frac{1}{6} \end{pmatrix} \begin{pmatrix} \frac{1}{3}, & 0, & 0, & \frac{2}{3}, & 0, & \frac{5}{3}, & -2, & 0 \end{pmatrix} \]
Model definition and spectrum

Input = geometry, shift & Wilson lines

Gauge group

\[ G = \left[ SU(3) \times SU(2) \times U(1)_Y \times U(1)_{B-L} \right] \times \left[ SU(4) \times SU(2)' \right] \times U(1)^7 \]

GUT normalization ➡ gauge coupling unification

\[ t_Y = \left( 0, 0, 0, \frac{1}{2}, \frac{1}{2}, -\frac{1}{3}, -\frac{1}{3}, -\frac{1}{3} \right) (0, 0, 0, 0, 0, 0, 0, 0) \]

\[ t_{B-L} = \left( 0, 0, 0, 0, 0, -\frac{2}{3}, -\frac{2}{3}, -\frac{2}{3} \right) (0, 0, 0, 0, 2, 0, 0, 0) \]

normalization not as in SO(10)
Model definition and spectrum

Input = geometry, shift & Wilson lines

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\[ G = \left[ SU(3) \times SU(2) \times U(1)_Y \times U(1)_{B-L} \right] \times \left[ SU(4) \times SU(2)' \right] \times U(1)^7 \]

Spectrum

spectrum = 3 \times \text{generation} + \text{vector-like w.r.t. } G_{SM} \times U(1)_{B-L}
### Spectrum @ orbifold point

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<tr>
<td>3</td>
<td>(3, 2; 1, 1)</td>
<td>$q_i$</td>
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<tr>
<td>3 + 1</td>
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<td>4</td>
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**Spectrum = 3 generations + vector-like**
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**spectrum = 3 generations + vector-like**
A benchmark model

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</tr>
<tr>
<td>3 + 1</td>
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<td>$h_d$</td>
<td>1</td>
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<td>6</td>
<td>$\left( 3, 1; 1, 1 \right)_{(-1/3,-2/3)}$</td>
<td>$\delta_i$</td>
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<tr>
<td>14</td>
<td>$\left( 1, 1; 1, 1 \right)_{(1/2,*)}$</td>
<td>$s_i^+$</td>
<td>14</td>
<td>$\left( 1, 1; 1, 1 \right)_{(-1/2,*)}$</td>
<td>$s_i^-$</td>
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<tr>
<td>16</td>
<td>$\left( 1, 1; 1, 1 \right)_{(0,1)}$</td>
<td>$\bar{n}_i$</td>
<td>13</td>
<td>$\left( 1, 1; 1, 1 \right)_{(0,-1)}$</td>
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<tr>
<td>5</td>
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<td>6</td>
<td>$\left( 1, 1; 1, 1 \right)_{(0,1)}$</td>
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<tr>
<td>4</td>
<td>$\left( 1, 1; 1, 1 \right)_{(0,2)}$</td>
<td>$\chi_i$</td>
<td>32</td>
<td>$\left( 1, 1; 1, 1 \right)_{(0,0)}$</td>
<td>$s_i^0$</td>
</tr>
<tr>
<td>2</td>
<td>$\left( 3, 1; 1, 1 \right)_{(-1/6,2/3)}$</td>
<td>$\bar{\nu}_i$</td>
<td>2</td>
<td>$\left( 3, 1; 1, 1 \right)_{(1/6,-2/3)}$</td>
<td>$v_i$</td>
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</table>

Spectrum = 3 generations + vector-like
### Spectrum @ orbifold point

<table>
<thead>
<tr>
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<tr>
<td>3</td>
<td>$(3, 2; 1, 1)_{(1/6,1/3)}$</td>
<td>$q_i$</td>
<td>3</td>
<td>$\bar{3}, 1; 1, 1)_{(-2/3,-1/3)}$</td>
<td>$\bar{u}_i$</td>
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<tr>
<td>3</td>
<td>$(1, 1; 1, 1)_{(1,1)}$</td>
<td>$\bar{e}_i$</td>
<td>8</td>
<td>$(1, 2; 1, 1)_{(0,*)}$</td>
<td>$m_i$</td>
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<tr>
<td>$3 + 1$</td>
<td>$(\bar{3}, 1; 1, 1)_{(1/3,-1/3)}$</td>
<td>$\bar{d}_i$</td>
<td>1</td>
<td>$(3, 1; 1, 1)_{(-1/3,1/3)}$</td>
<td>$d_i$</td>
</tr>
<tr>
<td>$3 + 1$</td>
<td>$(1, 2; 1, 1)_{(-1/2,-1)}$</td>
<td>$\ell_i$</td>
<td>1</td>
<td>$(1, 2; 1, 1)_{(1/2,1)}$</td>
<td>$\bar{\ell}_i$</td>
</tr>
<tr>
<td>1</td>
<td>$(1, 2; 1, 1)_{(-1/2,0)}$</td>
<td>$h_\alpha$</td>
<td>1</td>
<td>$(1, 2; 1, 1)_{(1/2,0)}$</td>
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<td>$6$</td>
<td>$(\bar{3}, 1; 1, 1)_{(1/3,2/3)}$</td>
<td>$\bar{\delta}_i$</td>
<td>6</td>
<td>$(3, 1; 1, 1)_{(-1/3,-2/3)}$</td>
<td>$\delta_i$</td>
</tr>
<tr>
<td>$14$</td>
<td>$(1, 1; 1, 1)_{(1/2,*)}$</td>
<td>$s^+_i$</td>
<td>14</td>
<td>$(1, 1; 1, 1)_{(-1/2,*)}$</td>
<td>$s^-_i$</td>
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<tr>
<td>16</td>
<td>$(1, 1; 1, 1)_{(0,1)}$</td>
<td>$\bar{n}_i$</td>
<td>13</td>
<td>$(1, 1; 1, 1)_{(0,-1)}$</td>
<td>$n_i$</td>
</tr>
<tr>
<td>$5$</td>
<td>$(1, 1; 2, 1)_{1}$</td>
<td>$\chi_i$</td>
<td>$32$</td>
<td>$(1, 1; 1, 1)_{(0,0)}$</td>
<td>$s^0_i$</td>
</tr>
<tr>
<td>$10$</td>
<td>$(1, 1; 2, 1)_{1}$</td>
<td>$\bar{\chi}_i$</td>
<td>2</td>
<td>$(3, 1; 1, 1)_{(1/6,-2/3)}$</td>
<td>$\nu_i$</td>
</tr>
<tr>
<td>$6$</td>
<td>$(1, 1; 4, 1)_{(-1/2,-1)}$</td>
<td>$\bar{t}_i$</td>
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<td>$(1, 1; 4, 1)_{(1/2,1)}$</td>
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<td>$(1, 1; 4, 1)_{(0,±2)}$</td>
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<td>$s^0_i$</td>
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<tr>
<td>$2$</td>
<td>$(3, 1; 1, 1)_{(-1/6,2/3)}$</td>
<td>$\bar{\nu}_i$</td>
<td>2</td>
<td>$(3, 1; 1, 1)_{(1/6,-2/3)}$</td>
<td>$\nu_i$</td>
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</tbody>
</table>

**B–L** allows to discriminate
- between lepton and Higgs fields
- between neutrinos and other singlets
### Model Definition and Spectrum

#### Spectrum @ Orbifold Point

<table>
<thead>
<tr>
<th>#</th>
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<tr>
<td>3</td>
<td>(3, 2; 1, 1)_{(1/6, 1/3)}</td>
<td>q_i</td>
<td>3</td>
<td>(3, 1; 1, 1)_{(−2/3, −1/3)}</td>
<td>u_i</td>
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<tr>
<td>3</td>
<td>(1, 1; 1, 1)_{(1, 1)}</td>
<td>e_i</td>
<td>8</td>
<td>(1, 2; 1, 1)_{(0, *)}</td>
<td>m_i</td>
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<td>3 + 1</td>
<td>(3, 1; 1, 1)_{(1/3, −1/3)}</td>
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<td>(3, 1; 1, 1)_{(−1/3, 1/3)}</td>
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<td></td>
<td>δ_i</td>
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<tr>
<td>14</td>
<td>(1, 1; 1, 1)_{(1/2, *)}</td>
<td></td>
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<td></td>
<td>s_i</td>
</tr>
<tr>
<td>16</td>
<td>(1, 1; 1, 1)_{(0, 1)}</td>
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<td>n_i</td>
</tr>
<tr>
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</tr>
<tr>
<td>6</td>
<td>(1, 1; 4, 1)_{(0, *)}</td>
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<td>Γ_i</td>
</tr>
<tr>
<td>2</td>
<td>(1, 1; 4, 1)_{(−1/2, −1)}</td>
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<td></td>
<td></td>
<td>Γ_i</td>
</tr>
<tr>
<td>4</td>
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<td>s_i</td>
</tr>
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<td>v_i</td>
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</table>

**Crucial:**

Existence of SM singlets with $q_{B-L} = ±2$
Decoupling of exotics vs. $\mu$ term

Decoupling of exotics

\[ X_i \overline{X}_j \underbrace{S_{i_1} \ldots S_{i_n}} \quad \text{vev} \rightarrow \text{mass term} \]
Decoupling of exotics vs. $\mu$ term

Decoupling of exotics

\[ X_i \bar{X}_j \underbrace{s_i \ldots s_{i_n}} \]

vev $\rightarrow$ mass term

We have checked that:

1. exotics’ mass matrices have full rank with

\[ s_i = G_{\text{SM}} \times SU(4) \text{ singlets with } q_{B-L} = 0 \text{ or } \pm 2 \]
Decoupling of exotics vs. $\mu$ term

Decoupling of exotics

$$X_i \overline{X}_j \left\{ s_{i_1} \ldots s_{i_n} \right\}$$

vev $\rightarrow$ mass term

We have checked that:

1. **Exotics’ mass matrices** have full rank with

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

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
Decoupling of exotics vs. $\mu$ term

Decoupling of exotics

\[ X_i \bar{X}_j \quad s_{i_1} \ldots s_{i_n} \quad \text{vev} \rightarrow \text{mass term} \]

We have checked that:

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

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

2. **$s_i$ vevs** are consistent with **supersymmetry**

   ➜ Have obtained an MSSM vacuum with $R$-parity
Decoupling of exotics vs. $\mu$ term

Decoupling of exotics

\[
X_i \overline{X}_j \quad s_{i_1} \ldots s_{i_n}
\]

vev $\rightarrow$ mass term

We have checked that:

1. exotics’ mass matrices have full rank with

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

2. $s_i$ vevs are consistent with supersymmetry

$\Rightarrow$ Have obtained an MSSM vacuum with $R$-parity

Questions:

$\Rightarrow$ Is there a reason why the Higgs doublets’ mass is much smaller than the exotics’ masses?

$\Rightarrow$ Is there a reason why the Higgs mass is of the order of the weak scale?
A stringy solution to the $\mu$ problem

The pair $h_u - h_d$ are the only fields from $U_3$
A stringy solution to the $\mu$ problem

- The pair $h_u - h_d$ are the only fields from $U_3$
- $h_u h_d$ is ‘neutral’ w.r.t. to the selection rules
A stringy solution to the $\mu$ problem

* The pair $h_u$-$h_d$ are the only fields from $U_3$
* $h_u h_d$ is ‘neutral’ w.r.t. to the selection rules
* As a consequence: for any monomial $\mathcal{M} = s_{i_1} \ldots s_{i_N}$

$$\mathcal{M} h_u h_d \in \mathcal{W} \quad \Leftrightarrow \quad \mathcal{M} \in \mathcal{W}$$
A stringy solution to the $\mu$ problem

- The pair $h_u - h_d$ are the only fields from $U_3$
- $h_u h_d$ is ‘neutral’ w.r.t. to the selection rules
- As a consequence: for any monomial $M = s_{i_1} \ldots s_{i_N}$
  $$M h_u h_d \in W \Leftrightarrow M \in W$$
- We find that
  $$\mu \propto \langle W \rangle$$
A stringy solution to the $\mu$ problem

- The pair $h_u - h_d$ are the only fields from $U_3$.
- $h_u h_d$ is ‘neutral’ w.r.t. to the selection rules.
- As a consequence: for any monomial $M = s_{i_1} \ldots s_{i_N}$

  $$M h_u h_d \in W \quad \Leftrightarrow \quad M \in W$$

- We find that

  $$\mu \propto \langle W \rangle$$

- **question:** why is $\langle W \rangle$ small
We find that \textit{R symmetries} allow us to control the superpotential.
We find that $R$ symmetries allow us to control the superpotential

approximate continuous $R$ symmetries $\sim \langle W \rangle \sim \langle s \rangle^N$
We find that R symmetries allow us to control the superpotential

\[ \langle W \rangle \sim \langle s \rangle^N \]

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

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

We find that \textit{R symmetries} allow us to control the superpotential

\[
\text{approximate continuous } R \text{ symmetries } \sim \langle W \rangle \sim \langle s \rangle^N
\]

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

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

Discrete symmetries imply approximate continuous symmetries
We find that $R$ symmetries allow us to control the superpotential

approximate continuous $R$ symmetries $\sim \langle W \rangle \sim \langle s \rangle^N$

$\blacktriangleright$ In ‘our’ $\mathbb{Z}_6$-II orbifold one has **exact discrete $R$ symmetries**

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

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

$\blacktriangleright$ Discrete symmetries imply approximate continuous symmetries

$\blacktriangleright$ In the ‘vacuum’ discussed so far one obtains

$$\mu \sim \langle W \rangle \sim \langle s \rangle^9 \sim m_{3/2}$$
Stringy solutions to the $\mu$ problem - literature

There exist proposals for precisely this situation.
Stringy solutions to the \(\mu\) problem - literature

There exist proposals for precisely this situation

\[ \mu \text{ from } W \]

Casas, Muñoz (1993)
Stringy solutions to the $\mu$ problem - literature

There exist proposals for precisely this situation

1. $\mu$ from $W$

   Casas, Muñoz (1993)

2. $\mu$ from $K$

   Antoniadis, Gava, Narain, Taylor (1994)

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

Kähler modulus \hspace{1cm} complex structure modulus

leads effectively to the Giudice-Masiero mechanism

Giudice, Masiero (1988)

cf. talk by A. Hebecker
There exist proposals for precisely this situation

1. $\mu$ from $W$

   Casas, Muñoz (1993)

2. $\mu$ from $K$

   Antoniadis, Gava, Narain, Taylor (1994)

Model allows to use both mechanisms (simultaneously)

$\sim$ expect $\mu \sim m_{3/2}$
There exist proposals for precisely this situation

1. $\mu$ from $\mathcal{W}$
Casas, Muñoz (1993)

2. $\mu$ from $K$
Antoniadis, Gava, Narain, Taylor (1994)

Model allows to use both mechanisms (simultaneously)

$\sim$ expect $\mu \sim m_{3/2}$

‘Combination’ of both mechanisms appears phenomenologically viable

for related work see talk by S. Kraml
Stringy solutions to the $\mu$ problem - literature

- There exist proposals for precisely this situation

1. $\mu$ from $W$  \(\text{Casas, Muñoz (1993)}\)

2. $\mu$ from $K$  \(\text{Antoniadis, Gava, Narain, Taylor (1994)}\)
   \(\text{Brignole, Ibáñez, Muñoz (1995-1997)}\)

- Model allows to use both mechanisms (simultaneously)
  \(\sim\) expect $\mu \sim m_{3/2}$

- ‘Combination’ of both mechanisms appears phenomenologically viable
  for related work see talk by S. Kraml

- **note:** there are attractive alternative (though related) explanations of a suppressed $\mu$ term
  \(\text{Buchmüller, Lüdeling, Schmidt (2007)}\)
  \(\text{Buchmüller, Schmidt (2008)}\)
**Gauge-top unification (GTU)**

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

<table>
<thead>
<tr>
<th>Field-theoretic description</th>
<th>State</th>
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<tbody>
<tr>
<td>$U_1 \sim A_5 + iA_6$</td>
<td>$\bar{u}_1 + \ldots$</td>
</tr>
<tr>
<td>$U_2 \sim A_7 + iA_8$</td>
<td>$q_1 + \ldots$</td>
</tr>
<tr>
<td>$U_3 \sim A_9 + iA_{10}$</td>
<td>$h_u + \ldots$</td>
</tr>
</tbody>
</table>

**Renormalizable coupling**

$y_t \bar{u}_1 q_1 h_u$

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

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

\[ \text{SU(5)} \times \text{U(1)} = 10 + 5 + 1 = 16 \]

\[ \pi R_5 \]

\[ \text{SU(6)} \]

\[ \pi R_6 \]

\[ \text{SU(4)} \times \text{SU(2)}_L \times \text{U(1)'} \]

\[ \text{SU(5)} \times \text{U(1)} = 10 + 5 + 1 = 16 \]

see also Hall, Nomura (2004)
Buchmüller, Lüdeling, Schmidt (2007)
GTU in more detail

- Focus on 6D orbifold GUT limit
- For $R_5 \gg R_6$ this is similar to a model by Burdman & Nomura

Burdman, Nomura (2003)

\[
\begin{align*}
SU(5) \times U(1) & \to SU(6) \\
V : 35, H : (20, 20^c) & \to SU(4) \times SU(2)_L \times U(1)' \\
\end{align*}
\]
GTU in more detail

- Focus on 6D orbifold GUT limit

- 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 $\varphi$ and $\varphi^c$ of the bulk hypermultiplet, containing $q_3$ and $\bar{u}_3$, attain non-trivial profiles

GTU in more detail

- Focus on 6D orbifold GUT limit
- 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 $\varphi$ and $\varphi^c$ 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

$y_t$ correlated with $\tan \beta$

$m_{1/2} = 1$ TeV
$m_0 = 1$ TeV
$A_0 = -1$ TeV
Top-down motivation for orbifold GUTs

- $y_t$ correlated with $\tan \beta$

- Reasonable values for $\tan \beta$ seem to require rather anisotropic compactifications

Top-down motivation for orbifold GUTs

- $y_t$ correlated with $\tan \beta$

- Reasonable values for $\tan \beta$ seem to require rather anisotropic compactifications

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

\[ R_5 \approx \frac{1}{M_{\text{GUT}}} \quad \text{and} \quad R_{\geq 6} \approx \frac{1}{M_{\text{string}}} \approx \frac{1}{8.6 \cdot 10^{17} \text{GeV}} \]

- Orbifold GUT limit appears to yield valid intermediate description


Witten (1996)

Hebecker, Trapletti (2004)

cf. talk by A. Hebecker
Two families reside on two equivalent orbifold fixed points

\[ \text{SU}(5) \times U(1) \quad \text{SU}(4) \times SU(2)_L \times U(1)' \]

\[ 10 + \bar{5} + 1 = 16 \]
Comments on the structure of soft masses

- Two families reside on two equivalent orbifold fixed points

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


  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

Comments on the structure of soft masses

- Two families reside on two equivalent orbifold fixed points

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

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

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

Ko, Kobayashi, Park, Raby (2007)
Comments on the structure of soft masses

Two families reside on two equivalent orbifold fixed points.

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

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

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

The singlet VEVs $\langle s_i \rangle$ that generate the Yukawa coupling also break $D_4$. 
Comments on the structure of soft masses

» Two families reside on two equivalent orbifold fixed points

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

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

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

» The singlet VEVs $\langle s_i \rangle$ that generate the Yukawa coupling also break $D_4$

⇒ MFV-like structure of soft masses

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

MFV = Minimal Flavor Violation
Example: soft masses of squark doublets

Ansatz (@ $M_{\text{GUT}}$):

$$\tilde{m}_Q^2 = \alpha_1 \mathbb{1} + \beta_1 Y_u^\dagger Y_u + \beta_2 Y_d^\dagger Y_d + (\beta_3 Y_d^\dagger Y_d Y_u^\dagger Y_u + \text{h.c.})$$
Example: soft masses of squark doublets

Ansatz (@ $M_{\text{GUT}}$):

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

The form of $\tilde{m}_Q^2$ is RG invariant, only the coefficients $\alpha_i$ & $\beta_i$ run.
Example: Running of $\beta_1$

“SPS + MFV”

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

<table>
<thead>
<tr>
<th>SPS Point</th>
<th>$m_0$ (GeV)</th>
<th>$m_{1/2}$ (GeV)</th>
<th>$A$ (GeV)</th>
<th>$\tan \beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>100</td>
<td>250</td>
<td>-100</td>
<td>10</td>
</tr>
</tbody>
</table>
Example: Running of $\beta_1$

```
"SPS + MFV"

\[ \beta_i = \beta_0 @ M_{\text{GUT}} \]
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</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1450 GeV</td>
<td>300 GeV</td>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>
```
Example: Running of $\beta_1$

“SPS + MFV”

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</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>90 GeV</td>
<td>400 GeV</td>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>
Example: Running of $\beta_1$

**Bottom-line:**

- **SUSY flavor problem(s) may be avoided/ameliorated because of stringy $D_4$ flavor symmetry**

- Deviation of $\tilde{m}^2$ from unit matrices at $M_{\text{GUT}}$ might not even be measurable at low energies

<table>
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Summary
We explore possibilities of getting the MSSM from strings
We explore possibilities of getting the MSSM from strings.

The concept of ‘local grand unification’ has led us to beautiful spots.
Summary of features

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

No exotics
Summary of features

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2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times G_{\text{hid}}$
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2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times H_{\text{hid}}$
3. Unification
4. $R$-parity

...but potential problems with dimension 5 proton decay
Summary of features

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

2. $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times \mathcal{G}_{\text{hid}}$

3. unification

4. $\mathcal{R}$-parity

5. solution to the $\mu$-problem
   i.e. well-known solutions to the $\mu$-problem are automatically realized in explicit models

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

$\langle \mathcal{W} \rangle \ll 1$ from approximate $\text{U}(1)_R$ symmetries
Summary of features

➊ $3 \times 16 + \text{Higgs} + \text{nothing}$

➋ $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)_Y \times G_{\text{hid}}$

➌ Unification

➍ $R$-parity

➎ Solution to the $\mu$-problem

➏ Gauge-top unification: $y_t \lesssim g @ M_{\text{GUT}}$, $y_t/g$ related to geometry (anisotropy) & potentially realistic flavor structures à la Froggatt-Nielsen
Summary of features

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6. gauge-top unification
7. Non-Abelian discrete flavor symmetries relaxing/solving the supersymmetric flavor problems
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9. ‘realistic’ hidden sector

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...

...that’s what we got ‘for free’

“stringy surprises”
Mille grazie
See-saw couplings: $W_{\text{see-saw}} = Y_{ij}^{\nu} h_u \ell_i \bar{\nu}_j + M_{ij} \bar{\nu}_i \bar{\nu}_j$
See-saw couplings:

\[ W_{\text{see-saw}} = Y_{ij}^\nu h_u \ell_i \bar{\nu}_j + M_{ij} \bar{\nu}_i \bar{\nu}_j \]

In string models \( M, Y_\nu \sim \langle s^n \rangle \)

Singlet
see-saw couplings: \( W_{\text{see-saw}} = Y_{ij}^\nu h_u \ell_i \bar{\nu}_j + M_{ij} \bar{\nu}_i \bar{\nu}_j \)

in string models \( M, \ Y_\nu \sim \langle s^n \rangle \)

see-saw mass matrix

\[
W_{\text{see-saw}} \xrightarrow{h_u} (\nu, \bar{\nu}) \begin{pmatrix} 0 & y_\nu \nu \\ y_\nu \nu & M \end{pmatrix} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix} \approx \frac{y_\nu^2 \nu^2}{M} \nu \nu + M \bar{\nu} \bar{\nu}
\]
See-saw couplings

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- see-saw mass matrix

\[
W_{\text{see-saw}} \xrightarrow{h_u \rightarrow v} (\nu, \bar{\nu}) \begin{pmatrix} 0 & y_\nu v \\ y_\nu v & M \end{pmatrix} \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix} \approx \frac{y_\nu^2 v^2}{M} \nu \nu + M \bar{\nu} \bar{\nu}
\]

- naive GUT expectation:
  \( m_\nu \sim (100 \text{ GeV})^2 / 10^{16} \text{ GeV} \sim 10^{-3} \text{ eV} \)
See-saw couplings

- see-saw couplings: \( W_{\text{see-saw}} = Y^j_\nu h_u \ell_i \bar{\nu}_j + M_{ij} \bar{\nu}_i \bar{\nu}_j \)
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\]

- naive GUT expectation:
  \( m_\nu \sim (100 \text{ GeV})^2 / 10^{16} \text{ GeV} \sim 10^{-3} \text{ eV} \)

\( \ldots \) suspiciously close to observed values

\[
\sqrt{\Delta m^2_{\text{atm}}} \approx 0.04 \text{ eV} \; \& \; \sqrt{\Delta m^2_{\text{sol}}} \approx 0.008 \text{ eV}
\]
there are $O(100)$ neutrinos ($= R$-parity odd SM singlets)
there are $\mathcal{O}(100)$ neutrinos ($= R$-parity odd SM singlets)

$\mathcal{O}(100)$ contributions to the (effective) neutrino mass operator

\[
m_\nu = \sum \bar{\nu}_\ell \phi \phi \nu_\ell + \bar{\nu} \phi \phi \nu_\ell
\]
there are $\mathcal{O}(100)$ neutrinos (\(\equiv\) R-parity odd SM singlets)

- \(\mathcal{O}(100)\) contributions to the (effective) neutrino mass operator

- effective suppression of the see-saw scale

\[
m_\nu \sim \frac{\nu^2}{M_*} \quad M_* \sim \frac{M_{\text{GUT}}}{10 \ldots 100}
\]

... seems consistent with observation

\[
\left( \sqrt{\Delta m^2_{\text{atm}}} \approx 0.04 \text{ eV} \quad \& \quad \sqrt{\Delta m^2_{\text{sol}}} \approx 0.008 \text{ eV} \right)
\]
Heterotic see-saw

> there are $\mathcal{O}(100)$ neutrinos ($= R$-parity odd SM singlets)

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$$\sqrt{\Delta m_{\text{atm}}^2} \approx 0.04 \text{ eV} \quad \text{and} \quad \sqrt{\Delta m_{\text{sol}}^2} \approx 0.008 \text{ eV}$$

Main conclusion:

See-saw is a generic feature in heterotic MSSM vacua
Heterotic see-saw

there are $O(100)$ neutrinos ($\equiv R$-parity odd SM singlets)

$O(100)$ contributions to the (effective) neutrino mass operator

effective suppression of the see-saw scale

... seems consistent with observation

$$\left(\sqrt{\Delta m_{\text{atm}}^2} \approx 0.04 \text{ eV} \& \sqrt{\Delta m_{\text{sol}}^2} \approx 0.008 \text{ eV}\right)$$

Main conclusion:

See-saw is a generic feature in heterotic MSSM vacua

Note: in $\mathbb{Z}_3$ orbifolds one arrives at a different conclusion
Why is $\langle W \rangle$ small?

Two ingredients:

1. One can show:

   $W$ has $U(1)_R$ symmetry

   $\partial_{\phi_i} W = 0$  \(\sim\)  $W = 0$

Why is $\langle W \rangle$ small?

Two ingredients:

1. One can show:

   $W$ has $U(1)_R$ symmetry

   \[
   \frac{\partial W}{\partial \phi_i} = 0 \implies W = 0
   \]

2. Orbifolds have high-power discrete $R$ symmetries

   $\sim$ approximate $R$ symmetries

   $\sim \langle W \rangle \sim \langle \phi \rangle^N$ with $N$ large

From strings to the MSSM

"Appendix"

Large hierarchies from approximate $R$ symmetries

$\langle W \rangle = 0$ because of $U(1)_R$ (1)


aim: show that

$W$ has $U(1)_R$ symmetry

Consider a superpotential

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

with an exact $R$-symmetry

$W \rightarrow e^{2i\alpha} W$, \hspace{1em} $\phi_j \rightarrow \phi_j' = e^{ir_j \alpha} \phi_j$

where each monomial in $W$ has total $R$-charge 2.
Consider a field configuration $\langle \phi_i \rangle$ with

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

Under an infinitesimal $U(1)_R$ transformation, the superpotential transforms nontrivially

$$W(\phi_j) \to W'(\phi_j') = W(\phi_j) + \sum_i \frac{\partial W}{\partial \phi_i} \Delta \phi_i$$
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$$W(\phi_j) \rightarrow W'(\phi'_j) = W(\phi_j) + \sum_i \frac{\partial W}{\partial \phi_i} \Delta \phi_i$$
\[ \langle W \rangle = 0 \text{ because of } U(1)_R \quad (\text{II}) \]

Consider a field configuration \( \langle \phi_i \rangle \) with

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

Under an infinitesimal \( U(1)_R \) transformation, the superpotential transforms nontrivially

\[
W(\phi_j) \rightarrow \bar{W}(\phi'_j) = W(\phi_j) + \sum_i \frac{\partial W}{\partial \phi_i} \Delta \phi_i = e^{2i \alpha} W
\]

This is only possible if \( \langle W \rangle = 0 \)!

**bottom-line:**

- \( W \) has \( U(1)_R \) symmetry
- \( \frac{\partial W}{\partial \phi_i} = 0 \quad \implies \quad \bar{W} = 0 \)
Comments

1. Relation to Nelson-Seiberg theorem

\[
\begin{align*}
&\text{setting without} \\
&\text{supersymmetric} \\
&\text{ground state} \\
\end{align*}
\xrightarrow{\text{requires}}
\text{U}(1)_R \text{ symmetry}
\]

Nelson & Seiberg (1994)
Relation to Nelson-Seiberg theorem

\[
\begin{align*}
\{ & \text{setting without} \\
& \text{supersymmetric} \\
& \text{ground state} \} \\
\end{align*}
\]

requires \( \rightarrow \)

does not imply \( \leftarrow \)

\( U(1)_R \) symmetry

Nelson & Seiberg (1994)
Comments

1. Relation to Nelson-Seiberg theorem
   \[
   \left\{ \begin{array}{c}
   \text{setting without} \\
   \text{supersymmetric} \\
   \text{ground state}
   \end{array} \right\} \overset{\text{requires}}{\longrightarrow} \U(1)_R \text{ symmetry}
   \begin{array}{c}
   \overset{\text{does not imply}}{\longleftarrow}
   \end{array}
   \]

2. in local SUSY: \( \frac{\partial W}{\partial \phi_i} = 0 \) and \( \langle W \rangle = 0 \) imply \( D_i W = 0 \)
   (That is, a \( \U(1)_R \) symmetry implies Minkowski solutions.)
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1. Relation to Nelson-Seiberg theorem
   
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   \\ 
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2. In local SUSY: \( \frac{\partial W}{\partial \phi_i} = 0 \) and \( \langle W \rangle = 0 \) imply \( D_i W = 0 \)
   
   (That is, a \( \text{U}(1)_R \) symmetry implies Minkowski solutions.)

3. For a continuous \( \text{U}(1)_R \) symmetry we would have
   
   - a supersymmetric ground state with \( W = 0 \) and \( \text{U}(1)_R \) spontaneously broken
   - a problematic \( R \)-Goldstone boson
1 Relation to Nelson-Seiberg theorem

\[ \begin{align*}
\text{setting without} & \quad \text{supersymmetric} \\
\text{ground state} & \quad \Rightarrow \quad \text{requires} \\
\text{\U(1)}_R \text{ symmetry} & \quad \Leftarrow \quad \text{does not imply}
\end{align*} \]

Nelson & Seiberg (1994)

2 in local SUSY: \( \frac{\partial \mathcal{W}}{\partial \phi_i} = 0 \) and \( \langle \mathcal{W} \rangle = 0 \) imply \( D_i \mathcal{W} = 0 \)

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3 for a continuous \( \text{U(1)}_R \) symmetry we would have

- a supersymmetric ground state with \( \mathcal{W} = 0 \) and \( \text{U(1)}_R \) spontaneously broken
- a problematic \( R \)-Goldstone boson

However, the above \( \text{U(1)}_R \)-symmetry appears as an accidental continuous symmetry resulting from an exact discrete symmetry of (high) order \( N \); hence

- Goldstone-Boson massive and harmless
- a nontrivial VEV of \( \mathcal{W} \) of higher order in \( \phi \)
Orbifold breaks $\text{SO}(6) \simeq \text{SU}(4)$ Lorentz symmetry of compact space to discrete subgroup
Origin of high-power discrete $R$-symmetries

- Orbifold breaks $SO(6) \simeq SU(4)$ 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)
Application: moduli stabilization

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

- Race-track
- Kähler stabilization

Casas (1996)
Binétruy, Gaillard & Wu (1996)

non-perturbative corrections to the Kähler potential

\[ 10^{-8} \times \frac{Y}{(m_{3/2} M_p)^2} \]

\[ \text{Re}\ S \]

\[ 0 \quad 2.1 \quad 2.3 \]
Application: moduli stabilization

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

- Race-track
- Kähler stabilization
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Application: moduli stabilization

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

- Race-track
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- etc. . . .
Constant + exponential scheme

 KKLT type proposal

\[ \mathcal{W}_{\text{eff}} = C + A e^{-\alpha S} \]

constant \quad \quad non-perturbative
Constant + exponential scheme

- KKLT type proposal
  \[ W_{\text{eff}} = c + A e^{-\alpha S} \]

- Gravitino mass
  \[ m_{3/2} \sim |c| \]
**Constant + exponential scheme**

- **KKLT type proposal**

\[ \mathcal{W}_{\text{eff}} = c + A e^{-\alpha S} \]

- **Gravitino mass**

\[ m_{3/2} \sim |c| \quad m_{3/2} \overset{\text{I}}{=} \text{TeV} \quad |c| \sim 10^{-15} \]
Constant + exponential scheme

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\[ m_{3/2} \sim |c| \quad \overset{\text{m}_{3/2} \approx \text{TeV}}{\longrightarrow} \quad |c| \sim 10^{-15} \]

- **Philosophy of flux compactifications**: many vacua, in some of them \( c \) might be small by accident
From strings to the MSSM

"Appendix"

Large hierarchies from approximate $R$ symmetries

Constant + exponential scheme

- KKLT type proposal

$$\mathcal{W}_{\text{eff}} = c + A e^{-\alpha S}$$

- Gravitino mass

$$m_{3/2} \sim |c| \quad \xrightarrow{m_{3/2} \approx \text{TeV}} \quad |c| \sim 10^{-15}$$

- Philosophy of flux compactifications: many vacua, in some of them $c$ might be small by accident

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

$$\mathcal{W}_{\text{eff}} = \langle \mathcal{W}_{\text{pert}} \rangle + A e^{-\alpha S}$$

$\langle \mathcal{W}_{\text{pert}} \rangle \sim \langle \phi \rangle^N$

"gaugino condensate"
Embedding into the MiniLandscape

We analyzed a couple of models
We analyzed a couple of models

We find $\langle W_{\text{pert}} \rangle \sim \langle s \rangle^N$ with $N = 9 \ldots 26$
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We find $\langle W_{\text{pert}} \rangle \sim \langle s \rangle^N$ with $N = 9 \ldots 26$.

Assuming that the FI term sets the scale of the $\sim \langle s \rangle$ this leads to

$$\langle W \rangle \sim \langle W_{\text{pert}} \rangle \sim 10^{-O(10)}$$
From strings to the MSSM

**Appendix**

Large hierarchies from approximate $R$ symmetries

Embedding into the MiniLandscape

- We analyzed a couple of models
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- **Note:** the solutions of $F$-term equations are points in field space (no moduli in $s_i$-space)
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**application**: this

- generates a suppressed $\mu$ term
  $$\mu \sim \langle W \rangle \sim m_{3/2}$$
- fixes the gauge coupling / dilaton
Embedding into the MiniLandscape

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**application**: this
  - generates a suppressed \( \mu \) term
    \[ \mu \sim \langle W \rangle \sim m_{3/2} \]
  - fixes the gauge coupling / dilaton

**question**: is the dilaton fixed at realistic values?
Relation between $m_{3/2} \ll M_P$ and the scale of hidden sector strong dynamics

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

$$m_{3/2} \approx \frac{\Lambda^3}{M_P^2}$$

Gravitino mass \quad \text{scale of hidden sector strong dynamics}
Relation between $m_{3/2} \ll M_P$ and the scale of hidden sector strong dynamics

We estimate the scale of hidden sector strong dynamics (i.e. calculate the $\beta$-function)
Properties of the hidden sector

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

\[ \log_{10}(A/\text{GeV}) \]

- # of models
- 2 Wilson line case
**Properties of the hidden sector**

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

![Graph showing the distribution of the scale of hidden sector strong dynamics.](image)

- **2+3 Wilson line case (heavy top)**
Properties of the hidden sector

Distribution of the \textit{(naive)} scale of hidden sector strong dynamics

\begin{itemize}
  \item Note: hidden sector usually \textbf{stronger} coupled
\end{itemize}
Properties of the hidden sector

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

Note: hidden sector usually stronger coupled

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
Yukawa structure

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

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

We find many other configurations with the same characteristics ($\mu \sim m_{3/2}$, all exotics decouple, etc.) but different Yukawa couplings

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

Effective Yukawa couplings are vacuum/moduli dependent
From strings to the MSSM

Yukawa structure

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

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

We find many other configurations with the same characteristics ($\mu \sim m_{3/2}$, all exotics decouple, etc.) but different Yukawa couplings

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

$$
\begin{cases}
\text{hierarchical Yukawa couplings in Nature} \\
\text{do we live close to an orbifold point}
\end{cases}
\quad \leftrightarrow 
\quad \begin{cases}
\text{???}
\end{cases}
$$

Summary