Review on Model Building in Heterotic Orbifolds

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DESY Hamburg

November 8, 2011

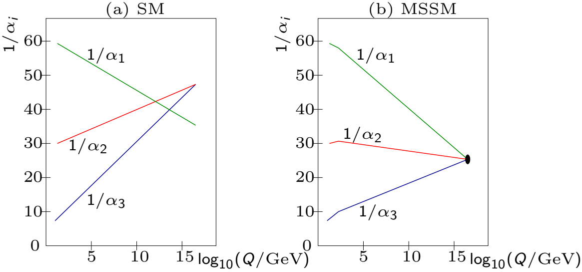
Bethe Forum: LHC, Dark Matter and Unification

in Bonn

Hints towards GUTs

see talk by S. Raby

- Gauge coupling unification



- Charge quantization: one generation fits nicely into rep of SO(10),

  $\mathbf{16} = (\mathbf{3},\mathbf{2})_{1/6} \oplus (\overline{\mathbf{3}},\mathbf{1})_{-2/3} \oplus (\overline{\mathbf{3}},\mathbf{1})_{1/3} \oplus (\mathbf{1},\mathbf{2})_{-1/2} \oplus (\mathbf{1},\mathbf{1})_{1} \oplus (\mathbf{1},\mathbf{1})_{0}$

  (and "predicts" the right-handed neutrino)

$\Rightarrow$ GUTs

Hints away from GUTs?

- What about the Higgs?
- Smallest SO(10) representation containing the Higgs:

$$\mathbf{10} = (\overline{\mathbf{3}}, \mathbf{1})_{1/3} \oplus (\mathbf{3}, \mathbf{1})_{-1/3} \oplus (\mathbf{1}, \mathbf{2})_{-1/2} \oplus (\mathbf{1}, \mathbf{2})_{1/2}$$

  10 contains unwanted triplets! $\rightarrow$ doublet-triplet splitting problem

- μ-problem

$$\mathcal{W} \supset \mu \bar{H} H$$

  $\mu \sim m_{3/2}$ needed, but $\mu \sim M_P$ expected

$\Rightarrow$ Complete vs. split GUT multiplets

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Hints away from GUTs?

- Proton decay via operators, like

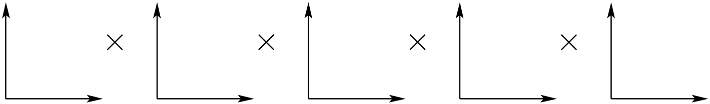
$$\bar{U}\bar{D}\bar{D} \qquad \text{and} \qquad QQQL$$

- Possible solution:
  need large GUT breaking Higgs ($\rightarrow$ matter-parity)

$$\Rightarrow \text{4D GUTS nice but problematic!}$$

Hints towards strings

- Heterotic string: 10D ($E_8 \times E_8$) gauge theory
- Naturally incorporates supersymmetry
- Extra dimensions $\rightarrow$ compactification
- Unification with gravity
- Hope: strings might provide solutions to various problems of MSSM/GUTs



- Heterotic string theory: $E_8 \times E_8$ gauge group in 10D
- Aim: connection to observable world
- Compactify six spatial dimensions on a compact space (e.g. 6-torus, Calabi-Yau)
- 6D Orbifolds: compact space; flat like torus, except for some singularities (called fixed points)
- CFT $\rightarrow$ computability!

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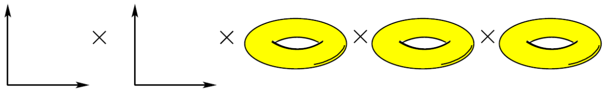

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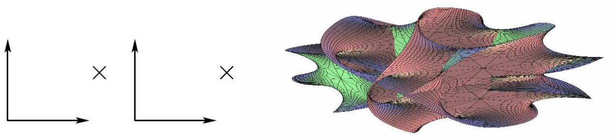

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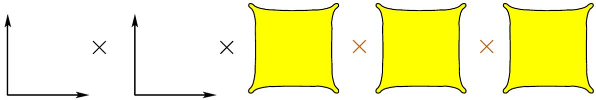

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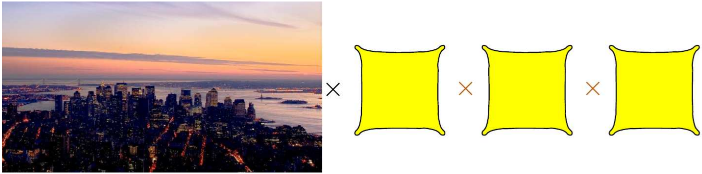

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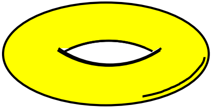
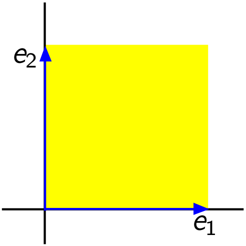
Example: 2D Orbifold $T^2/\mathbb{Z}_2$

Torus T^2



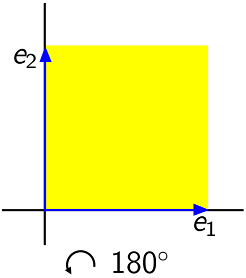
Example: 2D Orbifold $T^2/\mathbb{Z}_2$

Torus $T^2 = \mathbb{R}^2/\Lambda$ with $\Lambda = \{ae_1 + be_2 | a, b \in \mathbb{Z}\}$



Example: 2D Orbifold $T^2/\mathbb{Z}_2$

Torus $T^2 = \mathbb{R}^2/\Lambda$ has $\mathbb{Z}_2$ symmetry



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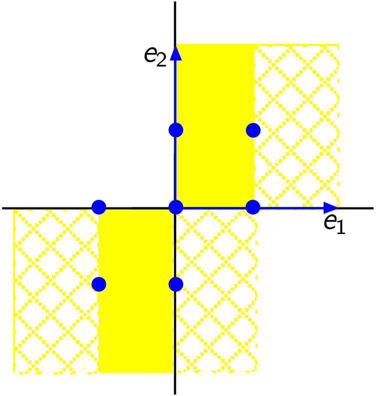
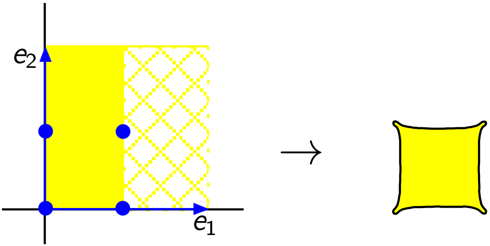


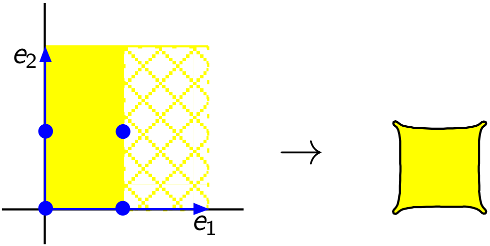
Example: 2D Orbifold $T^2/\mathbb{Z}_2$

$T^2/\mathbb{Z}_2$ as a pillow



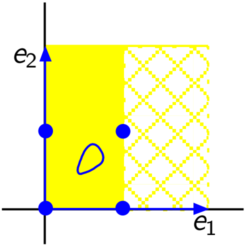
Example: 2D Orbifold $T^2/\mathbb{Z}_2$

$T^2/\mathbb{Z}_2$ as a pillow   Next: put closed strings on orbifold

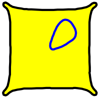


Example: 2D Orbifold $T^2/\mathbb{Z}_2$

$T^2/\mathbb{Z}_2$ with untwisted string

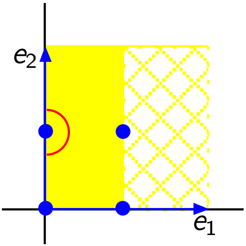


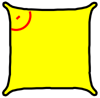
$\longrightarrow$



Example: 2D Orbifold $T^2/\mathbb{Z}_2$

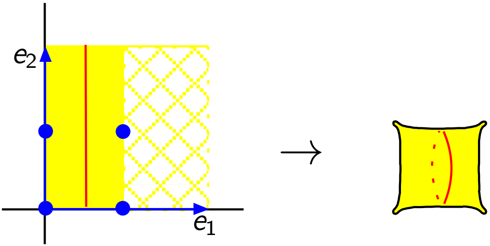
$T^2/\mathbb{Z}_2$ with twisted string





Example: 2D Orbifold $T^2/\mathbb{Z}_2$

$T^2/\mathbb{Z}_2$ with winding string (massive)



Orbifold construction

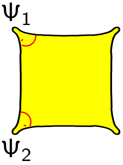
1. Six-torus $T^6 = \mathbb{R}^6/\Lambda$ with $\Lambda = \{n_\alpha e_\alpha | n_\alpha \in \mathbb{Z}\}$
2. $\mathbb{Z}_N$ or $\mathbb{Z}_N \times \mathbb{Z}_M$ symmetry of Λ
3. Orbifold T^6/Λ
4. Compactify heterotic string on orbifold using free CFT with boundary conditions

$\Rightarrow$ untwisted and twisted strings $\Rightarrow$ 4D effective theory

4D effective theory from orbifolds

- $\mathcal{N} = 1$ SUSY in 4D
- 4D gauge group from $E_8 \times E_8$
- Chiral matter
- Discrete symmetries from symmetric nature of orbifold

Symmetries of 4D effective theory



Strings carry discrete and gauge charges that must be conserved:

- (discrete) Space group selection rule (geometric)
- (discrete) R-charge conservation
- Gauge Invariance

$\Rightarrow$ allowed terms in superpotential $\mathcal{W}$

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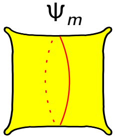

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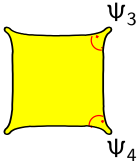

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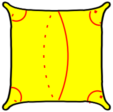

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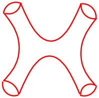

$\Psi_1\Psi_2 \to \Psi_3\Psi_4$

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Symmetries of 4D effective theory

Space group selection rule

- Flavor symmetries like D_4, A_4, $\Delta(54)$

T. Kobayashi, H. P. Nilles, F. Ploger, S. Raby, M. Ratz 2006

- Hierarchy of fermion masses and suppress large flavor changing neutral currents

P. Ko, T. Kobayashi, J. Park, S. Raby 2007

R-charge conservation

- Remnant of 10D Lorentz symmetry
- $\mathbb{Z}_4^R$ to suppress Proton decay and solve μ-problem
see talk by M. Ratz

H. M. Lee, S. Raby, M. Ratz, G. G. Ross, R. Schieren, K. Schmidt-Hoberg, P. K. S. V. 2010

R. Kappl, B. Petersen, S. Raby, M. Ratz, R. Schieren, P. K. S. V. 2010

Couplings in 4D effective theory

- Coupling strength can be computed in principle using CFT, e.g. 3-point coupling of two fermions and a boson

$$\langle V_{-1/2}\; V_{-1/2}\; V_{-1} \rangle$$

S. Hamidi, C. Vafa, 1987
L. Dixon, D. Friedan, E. Martinec, S. Shenker, 1987

- However, in practice not (yet) feasible for higher order
- Better techniques/automation needed!

First attempts e.g. T. Kobayashi, S. Parameswaran, S. Ramos-Sánchez, I. Zavala 2011

Orbifold model-building

- MSSM from $\mathbb{Z}_3$ orbifold

L. Ibanez, J. E. Kim, H. P. Nilles, F. Quevedo 1987
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- Pati-Salam from $\mathbb{Z}_6$-II orbifold

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- Mini-Landscape of MSSMs from $\mathbb{Z}_6$-II orbifold

O. Lebedev, H. P. Nilles, S. Raby, S. Ramos-Sánchez, M. Ratz, P. K. S. V., A. Wingerter 2006-2008

- MSSM from $\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifold with freely-acting involution

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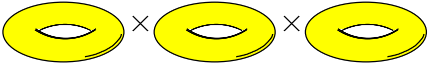
The $\mathbb{Z}_6$-II Orbifold



Orbifold described by:

- Six-torus T^6 with lattice $\Lambda = \mathrm{G}_2 \times \mathrm{SU}(3) \times \mathrm{SO}(4)$
- Discrete symmetry: $\mathbb{Z}_6$ such that $\mathcal{N} = 1$ SUSY
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Het. String: only closed strings. Massless spectrum:

- Boundary conditions: shift V and “Wilson lines” A_α
- untwisted strings: gauge bosons + matter representations
- twisted strings, localized at fixed points: matter representations

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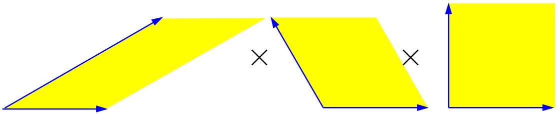

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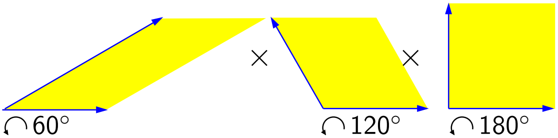

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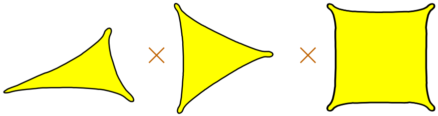

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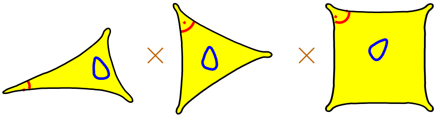

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The $\mathbb{Z}_6$-II Orbifold

- Choose boundary conditions: shift V and "Wilson lines" A_α
- V and A_α quantized

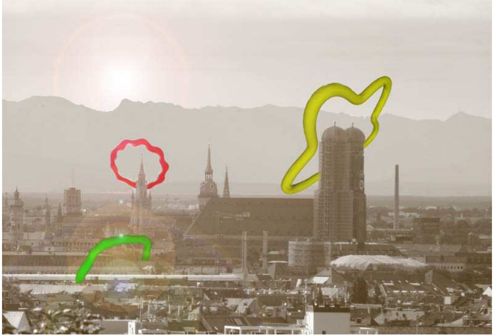
$$NV \in \Lambda_{\mathrm{E}_8\times\mathrm{E}_8} \quad \text{and} \quad N_\alpha A_\alpha \in \Lambda_{\mathrm{E}_8\times\mathrm{E}_8}$$

- Modular invariance like

$$N\left(V^2 - v^2\right) = 0 \mod 2 \quad \text{and} \quad N_\alpha (A_\alpha \cdot Vi) = 0 \mod 2$$

- Parameter space (V, A_α) huge

The string landscape



- Aim: construct the MSSM from string theory.
- But: where to look? Landscape of string vacua is huge.
- Need: a guideline!

Guideline: Local GUTs

- GUT theory realized only in higher dimensions
- Matter in full SO(10)-plets ($\Leftrightarrow$ localization)
- Higgs in split SO(10)-plet ($\Leftrightarrow$ localization)
- In 4D just SM gauge group

Local gauge group

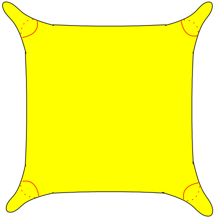
Asaka, Buchmüller & Covi / Kobayashi, Raby & Zhang / Förste, Nilles, P.K.S.V. & Wingerter

- 6 compact dimensions:
  - 4 compact dimensions near string scale $\Rightarrow$ not observable
  - 2 compact dimensions near the GUT scale $\Rightarrow$ GUT in 6D
- Local gauge group $\Leftrightarrow$ Gauge group geography
- Local matter

Local gauge group

Asaka, Buchmüller & Covi / Kobayashi, Raby & Zhang / Förste, Nilles, P.K.S.V. & Wingerter

compactification to 4D



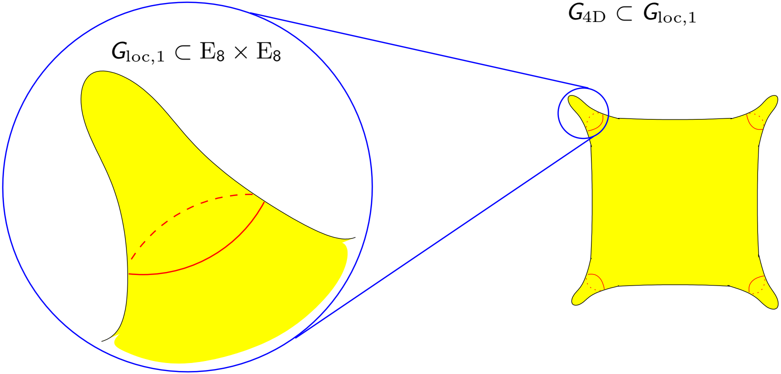
Local gauge group

Asaka, Buchmüller & Covi / Kobayashi, Raby & Zhang / Förste, Nilles, P.K.S.V. & Wingerter

zoom to fixed point g_1

compactification to 4D

$G_{4\mathrm{D}} \subset G_{\mathrm{loc},1}$



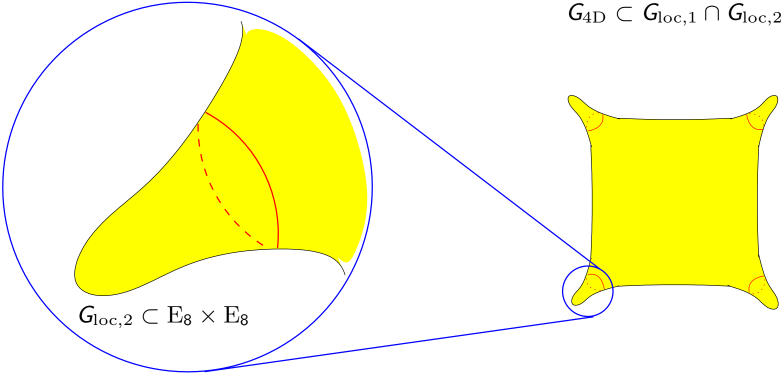
Local gauge group

Asaka, Buchmüller & Covi / Kobayashi, Raby & Zhang / Förste, Nilles, P.K.S.V. & Wingerter

zoom to fixed point g_2

compactification to 4D

$G_{\mathrm{4D}} \subset G_{\mathrm{loc},1} \cap G_{\mathrm{loc},2}$



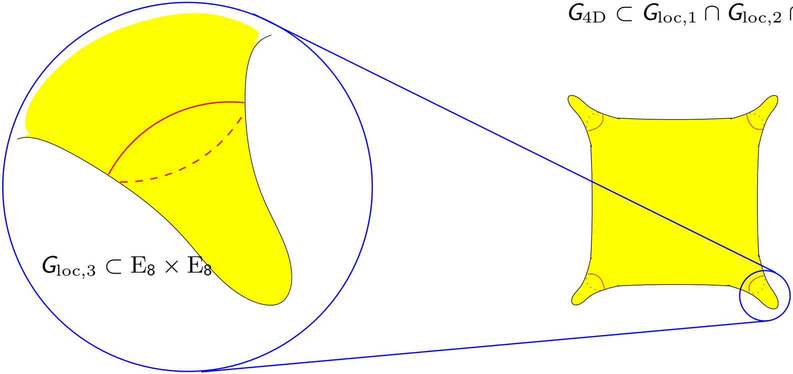
Local gauge group

Asaka, Buchmüller & Covi / Kobayashi, Raby & Zhang / Förste, Nilles, P.K.S.V. & Wingerter

zoom to fixed point g_3

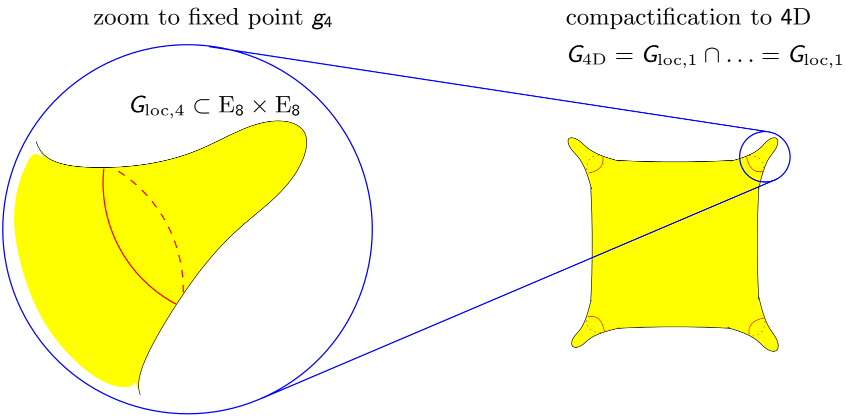
compactification to 4D

$G_{4\mathrm{D}} \subset G_{\mathrm{loc},1} \cap G_{\mathrm{loc},2} \cap G_{\mathrm{loc},3}$



Local gauge group

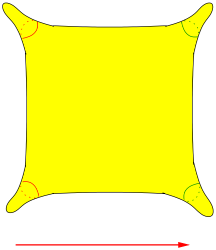
Asaka, Buchmüller & Covi / Kobayashi, Raby & Zhang / Förste, Nilles, P.K.S.V. & Wingerter



Local gauge group

Asaka, Buchmüller & Covi / Kobayashi, Raby & Zhang / Förste, Nilles, P.K.S.V. & Wingerter

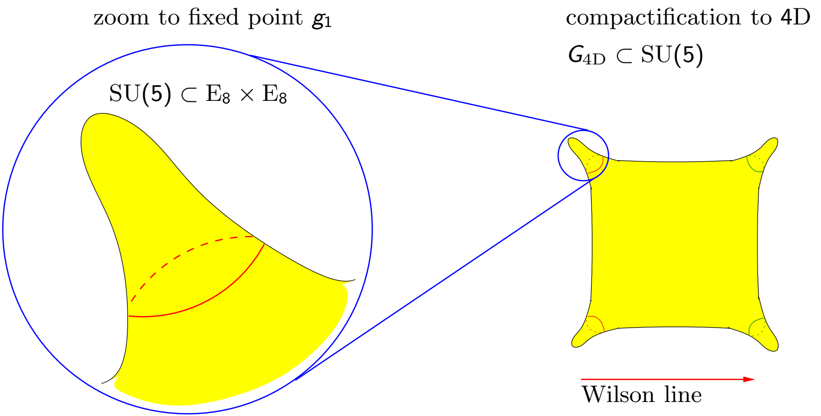
compactification to 4D



Wilson line

Local gauge group

Asaka, Buchmüller & Covi / Kobayashi, Raby & Zhang / Förste, Nilles, P.K.S.V. & Wingerter



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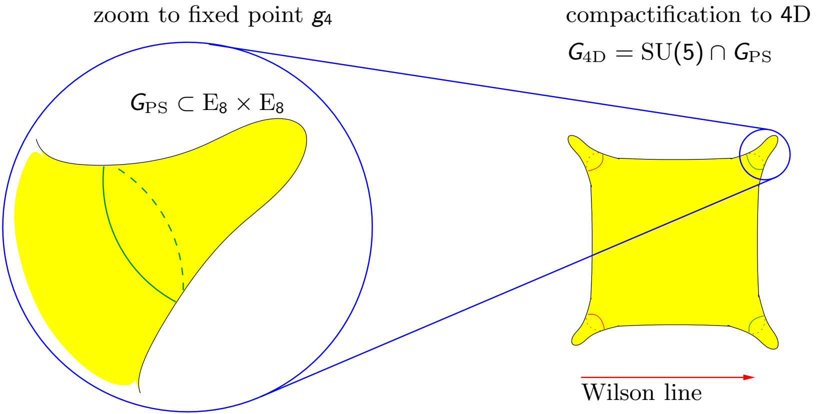
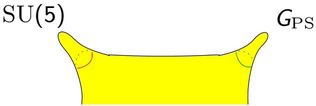


Local gauge group

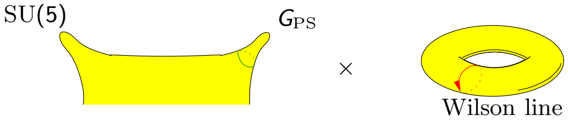
- At each fixed point g_i different parts of $\mathrm{E}_8 \times \mathrm{E}_8$ remain massless $\Rightarrow$ local gauge group
- The local gauge group $G_{\mathrm{loc,i}} \subset \mathrm{E}_8 \times \mathrm{E}_8$ depends on the localization in extra dimensions
- Generic case: in 4D, gauge group broken further $G_{\mathrm{4D}} \subset G_{\mathrm{loc,i}}$

Local matter



- At fixed point g_i: local gauge group $G_{\mathrm{loc,i}}$ and localized matter (twisted strings)
- This matter falls into representations of local gauge group $G_{\mathrm{loc,i}}$
- Generic case: in 4D, some of the local matter is projected out (by non-trivial boundary conditions)

Local matter



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Local SO(10)

- If local gauge group SO(10), local matter can be **16**, **10** or **1**
- We want local **16**-plets as generations of quarks and leptons
- Now going to 4D:
  - we want standard model gauge group
  $$\mathrm{SO}(10) \xrightarrow{\text{4D}} G_{\text{4D}} = \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)_Y$$
  - we want local **16**-plets not projected out
  $$\begin{aligned}\mathbf{16} \quad \xrightarrow{\text{4D}} \quad & (\mathbf{3},\mathbf{2})_{1/6} \oplus (\overline{\mathbf{3}},\mathbf{1})_{-2/3} \oplus (\overline{\mathbf{3}},\mathbf{1})_{1/3} \\ & \oplus (\mathbf{1},\mathbf{2})_{-1/2} \oplus (\mathbf{1},\mathbf{1})_{1} \oplus (\mathbf{1},\mathbf{1})_{0}\end{aligned}$$
  - and eventually local **10**-plets projected out partially
  $$\mathbf{10} \xrightarrow{\text{4D}} (\overline{\mathbf{3}},\mathbf{1})_{1/3} \oplus (\mathbf{3},\mathbf{1})_{-1/3} \oplus (\mathbf{1},\mathbf{2})_{-1/2} \oplus (\mathbf{1},\mathbf{2})_{1/2}$$
- Localization of **16**- and **10**-plets important

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The Search Strategy

- (0) take local–GUT–shifts $V^{\mathrm{SO10},1}$ and $V^{\mathrm{SO10},2}$
- (1) generate all two Wilson line cases
- (2) identify "inequivalent" models
- (3) select models with $G_{\mathrm{SM}} \subset \mathrm{SU}(5) \subset \mathrm{SO}(10)$ (standard GUT hypercharge $\Rightarrow$ gauge coupling unification)
- (4) select models with three net $(\mathbf{3}, \mathbf{2})$
- (5) select models with non–anomalous $\mathrm{U}(1)_Y \subset \mathrm{SU}(5)$
- (6) select models with net 3 SM families + Higgses + vector–like

The Mini-Landscape

criterion	$V^{\mathrm{SO}(10),1}$	$V^{\mathrm{SO}(10),2}$
(2) ineq. models with 2 Wilson lines	22000	7800
(3) SM $\subset$ SU(5) $\subset$ SO(10)	3563	1163
(4) 3 net $(\mathbf{3},\mathbf{2})$	1170	492
(5) non–anomalous $\mathrm{U}(1)_Y \subset \mathrm{SU}(5)$	528	234
(6) 3 generations + vector-like	128	90

O. Lebedev, H. P. Nilles, S. Raby, S. Ramos-Sánchez, M. Ratz, P. K. S. V., A. Wingerter 2006-2008

$\Rightarrow$ fertile region of the landscape

Gaugino Condensation and SUSY breaking

- Hidden sector gauge group: non-abelian with little or no (light) matter $\Rightarrow$ beta-function β
- Gauge interactions become strong at intermediate scale $\Rightarrow$ confinement and gauginos λ condensate:

$$\Lambda \equiv \langle \lambda\lambda \rangle^{1/3} \sim M_{\mathrm{GUT}} \exp\left(-\frac{1}{2\beta} \frac{1}{g^2(M_{\mathrm{GUT}})} \right)$$

where $1/g^2 = \mathrm{Re}S \Rightarrow W \sim \exp\left(-\frac{3}{2\beta} S\right) \quad \Rightarrow \quad S \to \infty$

- (Assume S stabilized using non-perturbative corrections to the Kähler potential)

Casas 1996 / Binetruy, Gaillard & Wu 1996

Gaugino Condensation and SUSY breaking

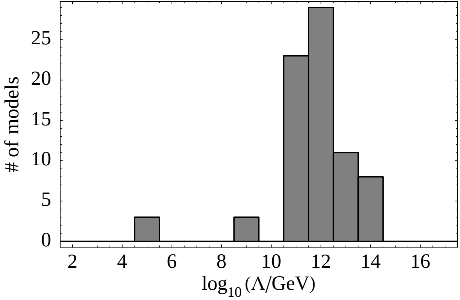
- SUSY breaking by the dilaton F-term

$$F_S \sim \frac{\Lambda^3}{M_{\mathrm{Pl}}}$$

- Communicated to the observable sector by gravity
- If $\Lambda \sim 10^{13}$GeV gravitino mass $m_{3/2} \sim \frac{\Lambda^3}{M_{\mathrm{Pl}}^2} \sim$ TeV
- Significant uncertainties: string threshold corrections, details of dilaton stabilization, ...

Gaugino Condensation and SUSY breaking

- Result: intermediate SUSY breaking



O. Lebedev, H. P. Nilles, S. Raby, S. Ramos-Sánchez, M. Ratz, P. K. S. V., A. Wingerter 2006

- Compare to:

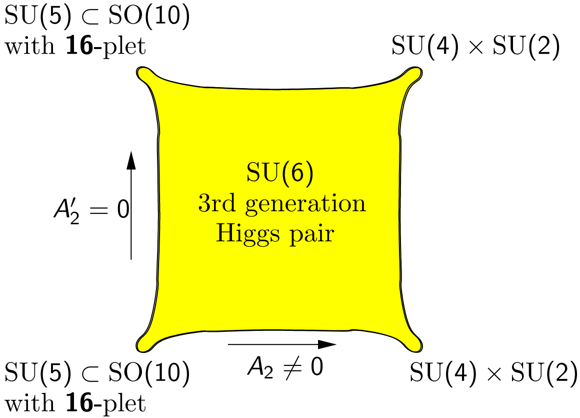
shift	hidden gauge group	$\log_{10}(\Lambda/\mathrm{GeV})$
$V^{\mathrm{SO10},1}$	SO(14)	14
$V^{\mathrm{SO10},2}$	E_7	15

6D orbifold GUT

- Weakly coupled heterotic strings $M_{\text{GUT}} \leftrightarrow M_{\text{string}}$
  $\Rightarrow$ Anisotropic compactification

E. Witten, 1996 and A. Hebecker and M. Trapletti 2005

- GUT is realized in 6D
- For example third torus of model 1A from the Mini-Landscape:



6D orbifold GUT

- Higgs in the bulk:
  - Natural solution of doublet-triplet splitting

    Kawamura 2000 and T. Asaka, W. Buchmüller, L. Covi 2001
  - Gauge-top unification

    P. Hosteins, R. Kappl, M. Ratz, K. Schmidt-Hoberg 2009
  - $\mu \sim \langle W \rangle \sim m_{3/2}$

    J. Casas, C. Munoz 1993

    R. Kappl, H. P. Nilles, S. Ramos-Sánchez, M. Ratz, K. Schmidt-Hoberg, P. K. S. V. 2008

    F. Brümmer, R. Kappl, M. Ratz, K. Schmidt-Hoberg 2010
- $A_2' = 0 \Rightarrow D_4$ flavor symmetry
  1st + 2nd generation **2** of D_4
- $\mathbb{Z}_4^R$ from 10D Lorentz symmetry

Relation to other constructions

- Can these models be obtained from a CY construction? (see talk by S. Groot Nibbelink)

  $\Rightarrow$No, at least not easily!

- Example: Benchmark model 1
  - Resolve orbifold singularity by VEV of twisted state (blow-up mode)
  - E.g. spectrum at fixed point $\left(\theta^3, e_5\right)$: only state labeled $s_9^\pm$, charged under Y, i.e. $(1,1)_{\pm\frac{1}{2}}$
  - In this model full blow-up breaks hypercharge

Relation to other constructions

- $\mathbb{Z}_6$-II Mini-Landscape at special (symmetry enhanced) point in moduli space:
  - Wilson line breaks GUT to SM (locally) at fixed points
  - Some fixed points carry only SM charged states
  - In full blow-up, SM gauge group (e.g. hypercharge) broken at these fixed points

S. Groot Nibbelink, J. Held, F. Ruehle, M. Trapletti, P. K. S. V 2009

- In general, partial blow-up necessary: FI $\neq 0 \Rightarrow$ VEVs $\neq 0$
- Important: full blow-up of Orbifold MSSMs not necessary
- Possibility for full blow-up: non-local GUT breaking

$\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifold with freely-acting involution

- setup:

$$\begin{array}{l} \mathbb{Z}_2 \times \mathbb{Z}_2 \text{ orbifold with 6 generations of } \mathrm{SU}(5) \\ \quad \Big\downarrow \ \text{freely acting } \mathbb{Z}_2 \\ 3 \text{ generations of } \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1) \end{array}$$

- Where freely acting Wilson line induces GUT breaking
- Potentially: one SM singlet per fixed point $\Rightarrow$ full blow-up

$\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifold with freely-acting involution

- Shifts

$$
\begin{aligned}
V_1 &= \left(\frac{5}{4}, -\frac{3}{4}, -\frac{7}{4}, \frac{1}{4}, \frac{1}{4}, -\frac{3}{4}, -\frac{3}{4}, \frac{1}{4}, 0, 1, 1, 0, 1, 0, 0, -1\right) \\
V_2 &= \left(-\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, \frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, -\frac{1}{2}, \frac{1}{2}, \frac{1}{2}, 0, 0, 0, 0, 0, 4\right)
\end{aligned}
$$

- Wilson lines

$$
\begin{aligned}
W_1 &= 0 \\
W_2 &= \left(\frac{5}{4}, \frac{1}{4}, \frac{3}{4}, -\frac{1}{4}, -\frac{1}{4}, \frac{3}{4}, \frac{3}{4}, \frac{3}{4}, -\frac{1}{4}, \frac{3}{4}, \frac{5}{4}, \frac{5}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4}\right) \\
W_3 &= \left(-\frac{3}{4}, -\frac{1}{4}, \frac{1}{4}, \frac{7}{4}, -\frac{1}{4}, -\frac{1}{4}, -\frac{1}{4}, -\frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{1}{4}, \frac{5}{4}, -\frac{3}{4}, \frac{1}{4}, -\frac{3}{4}, \frac{1}{4}\right) \\
W_5 &= \left(-\frac{1}{2}, -\frac{1}{2}, \frac{1}{2}, -\frac{1}{2}, \frac{1}{2}, -\frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}, 0, 0, 0, 0, -\frac{1}{2}, -\frac{1}{2}\right) \\
W_6 &= W_4 = W_2
\end{aligned}
$$

- Freely acting Wilson line

$$
W = \frac{3}{2} W_2
$$

M. Blaszczyk, S. Groot Nibbelink, M. Ratz, F. Ruehle, M. Trapletti, P. K. S. V. 2009

(1) without freely acting Wilson line

- 4D gauge group: $SU(5) \times U(1)^4 \times [SU(4)^2 \times U(1)^2]$
- massless spectrum

15	$(5, 1, 1)$	9	$(\overline{5}, 1, 1)$
6	$(\overline{10}, 1, 1)$	52	$(1, 1, 1)$
6	$(1, 1, 4)$	6	$(1, 1, \overline{4})$
8	$(1, 4, 1)$	8	$(1, \overline{4}, 1)$
2	$(1, 6, 1)$		

- (remark: generically, SU(5) vector-like exotics decouple linear in VEVs!)

(2) with freely acting Wilson line

- 4D gauge group:
  $SU(3) \times SU(2) \times U(1)_Y \times U(1)^4 \times [SU(3) \times SU(2)^2 \times U(1)^4]$
- massless spectrum

3	$(\overline{3}, 2, 1, 1, 1)_{1/6}$	q
3+5	$(3, 1, 1, 1, 1)_{1/3}$	$\overline{d}, \overline{\delta}$
3+4	$(1, 2, 1, 1, 1)_{-1/2}$	$\ell,\ h_d$
3	$(1, 1, 1, 1, 1)_1$	$\overline{e}$
5	$(1, 1, \overline{3}, 1, 1)_0$	$\overline{x}$
6	$(1, 1, 1, 1, 2)_0$	y

3	$(3, 1, 1, 1, 1)_{-2/3}$	$\overline{u}$
5	$(\overline{3}, 1, 1, 1, 1)_{-1/3}$	δ
4	$(1, 2, 1, 1, 1)_{1/2}$	h_u
33	$(1, 1, 1, 1, 1)_0$	s
5	$(1, 1, 3, 1, 1)_0$	x
6	$(1, 1, 1, 2, 1)_0$	z

  Generically, less states compared to $\mathbb{Z}_6$-II
- hypercharge

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

  orthogonal to anomalous direction.

see talk by M. Ratz

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orthogonal to anomalous direction.

see talk by M. Ratz

The C++ orbifolder

http://projects.hepforge.org/orbifolder/

- Automatically constructs inequivalent string models
- Checks anomaly freedom
  (including Green-Schwarz mechanism)
- Identifies string MSSM candidates
- Offers Linux-style command system to analyze the model in detail

H. P. Nilles, S. Ramos-Sánchez, P. K. S. V., A. Wingerter 2011

Conclusion

- Orbifold GUTs in 6D from heterotic string: better than 4D GUTs?
- MSSM from heterotic orbifolds: the Mini-Landscape
- Orbifold compactification $\Rightarrow$ symmetry enhanced point with gauge and discrete symmetries
- Discrete symmetries relevant for phenomenology?
- http://projects.hepforge.org/orbifolder/ or google "orbifolder"