Phenomenology of Heterotic Orbifolds

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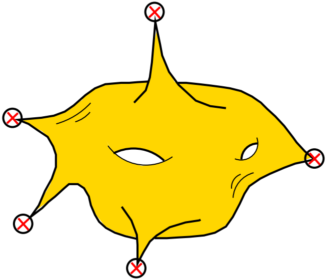
Based on collaborations with:
K.S. Choi, O. Lebedev, H.P. Nilles, S. Raby, M. Ratz, P. Vaudrevange & A. Wingerter
hep-th/0611095, arXiv:0812.2120, arXiv:0902.3070

Heterotic Orbifolds



Dixon, Harvey, Vafa, Witten (1985-86)
Ibáñez, Nilles, Quevedo (1987)
Font, Ibáñez, Quevedo, Sierra (1990)
Katsuki, Kawamura, Kobayashi, Ohtsubo, Ono, Tanioka (1990)
Kobayashi, Raby, Zhang (2004)
Förste, Nilles, Vaudrevange, Wingerter (2004)
Buchmüller, Hamaguchi, Lebedev, Ratz (2004-06)
Kobayashi, Nilles, Plöger, Raby, Ratz (2006)
Faraggi, Förste, Timirgaziu (2006)
Förste, Kobayashi, Ohki, Takahashi (2006)
Kim, Kyae (2006-07)
Choi, Kim (2006-08)
...

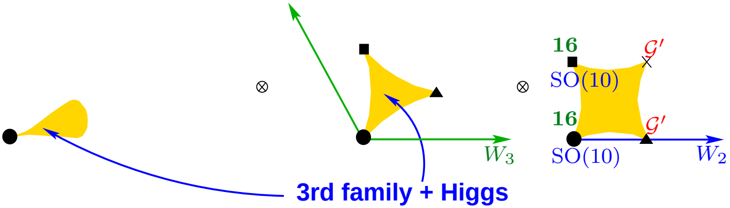
What we know so far...

From the heteroticMini-Landscape

cf. talk by Peter Nilles

Factorizable orbifolds:

$$\mathcal{O} = T^2 \times T^2 \times T^2 \Big/ \mathbb{Z}_6 - \mathrm{II}$$



$$\mathrm{E}_8 \times \mathrm{E}_8 \xrightarrow{\mathcal{O}} \mathcal{G}_{4D} = \mathcal{G}_{SM} \times \mathcal{G}_{\text{hidden}}$$

Lebedev, Nilles, Raby, R-S, Ratz, Vaudrevange, Wingerter (2006-08)

What we know so far...

From the heteroclitic Mini-Landscape

cf. talks by Rolf Kappl, Peter Nilles

- ∼300 MSSM-like orbifolds
  - $\mathcal{G}_{4D} = \mathcal{G}_{SM} \times \mathcal{G}_{\text{hidden}}$
  - $\mathcal{N} = 1$ SUSY vacua
  - 3 SM generations + Higgses + no exotics
  - see-saw neutrino masses
  - gauge coupling unification
  - $y_t \sim g$ @ M_{GUT} — Hosteins, Kappl, Ratz, Schmidt-Hoberg (2009)

    & suppression $y_t < g$ @ low energy
- Most models
  - intermediate scale ~~SUSY~~ favored ☺
  - endowed with local GUTs ☺

Nilles, R-S, Ratz, Vaudrevange (2008)

Further appealing features: $\mu \ll 1$

cf. talk by Michael Ratz

Ingredients:

- *only* one pair of untwisted Higgs doublets
- $\mathcal{W}$ preserves an $accidental$ $\mathrm{U}(1)_R$ @ order N
- vacuum such that $-F_i{}^\dagger = \frac{\partial \mathcal{W}}{\partial s_i} = 0$ (for all singlets s_i)

Consequences:

- $H_u H_d \supset \mathbf{1}$ (gauge & string symm.)

  $\Rightarrow \mu \sim \mathcal{W}(s_i)$
- $\langle \mathcal{W} \rangle = 0$ @ order N

  $\Rightarrow \mu = 0$ & $D\mathcal{W} = 0$
- $\mathrm{U}(1)_R$ *explicitly* broken @ order $M > N$

  $\Rightarrow \langle \mathcal{W} \rangle \sim \mu \sim \langle s_i \rangle^M \ll 1, \qquad \langle s_i \rangle \sim 0.1$

Kappl, Nilles, R-S, Ratz, Vaudrevange (2008)

Strong CP Problem

If there were CP–violation in QCD
$\Rightarrow$ electron dipole moment of neutron… unobserved!

BUT $-\theta F^{\mu\nu}\widetilde{F}_{\mu\nu}$… allowed!

Implying $\theta \leq 10^{-11}$ … why? Baker *et al.* (2006)

An elegant solution: $\mathrm{U}(1)_{\mathrm{PQ}}$

- (QCD–) anomalous & global symmetry
- $\mathrm{U}(1)_{\mathrm{PQ}}$ spontaneously broken
- $\theta = \langle a(x) \rangle \sim 0$, axion: $a(x)$
- axion decay constant F_a

$$10^9 \text{ GeV} \leq F_a \leq 10^{12} \text{ GeV}$$

- highly suppressed $m_a \sim 0$

Acci☺ns

(no, it isn't a typo)

Choi, Nilles, R-S, Vaudrevange (2009)

Accions in Heterotic Orbifolds

In string theory:

- No exact global $\mathrm{U}(1)$
- If $\mathrm{U}(1)$ anomalous, then gauged
- Natural scale close to M_{Pl}

$\Rightarrow$ QCD-axions are elusive in string theory Svrček, Witten (2006)

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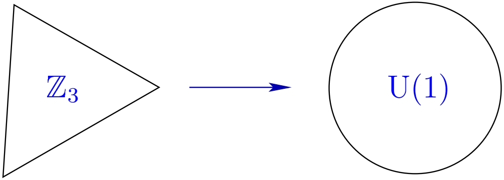
Addressing the strong CP problem amounts to

In heterotic orbifolds:

1. finding $\mathrm{U}(1)_{\mathrm{PQ}}$
2. getting $F_a < M_{\mathrm{Pl}}$
3. guaranteeing large suppression of m_a

Accions: ① Finding $\mathrm{U}(1)_{\mathrm{PQ}}$

stringy discrete symmetries $\rightarrow$ $\mathrm{U}(1)$ *accidental* symmetries of $\mathcal{W}$



- compute $\mathcal{W}$ @ order N
- identify accidental $\mathrm{U}(1)$s of $\mathcal{W}$ — Choi, Kim, Kim (2006)
- verify whether they have $\mathrm{SU}(3)$–$\mathrm{SU}(3)$–$\mathrm{U}(1)_{\mathrm{PQ}}$ anomalies
- identify SM singlets charged under $\mathrm{U}(1)_{\mathrm{PQ}}$,

  $s_i = v_i e^{\mathrm{i}a_i/v_i}$ $\quad a_i$: *accions*
- consistent vacuum (preserving e.g. SUSY)

Accions: ② Lowering F_a

A single $\mathrm{U}(1)_{\mathrm{PQ}}$:

- $\langle\varphi\rangle = v \neq 0 \quad \Rightarrow \quad F_a \sim q_{PQ}\, v/\mathcal{A}$
- $\langle\varphi_i\rangle = v_i \neq 0 \quad \Rightarrow \quad F_a \sim \sum q^i_{PQ} v_i/\mathcal{A}$

Al least one $v_i \sim M_{\mathrm{Pl}}$ ☹

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Alternative: $\mathrm{U}(1)_{\mathrm{P}} \times \mathrm{U}(1)_{\mathrm{Q}}$

- $\langle\varphi_{1,2}\rangle = v_{1,2} \neq 0$

$$\Rightarrow \quad F_a = \frac{v_1\, v_2\, (q^1_P\, q^2_Q - q^1_Q\, q^2_P)}{\sqrt{(q^1_f\, v_1)^2 + (q^2_f\, v_2)^2}} \approx v_2\, \frac{q^1_P q^2_Q - q^1_Q q^2_P}{q^1_f} \qquad (*)$$

Al least one $v_i \sim M_{\mathrm{Pl}} \qquad v_1 > v_2$ ☺

For $\langle\varphi_i\rangle = v_i \neq 0$ & $v_1 > v_2 > v_3 > \ldots$, (*) still holds!! ☺

Accions: ② Lowering F_a

A single $\mathrm{U}(1)_{\mathrm{PQ}}$:

- $\langle\varphi\rangle = v \neq 0 \quad \Rightarrow \quad F_a \sim q_{PQ}\ v/\mathcal{A}$
- $\langle\varphi_i\rangle = v_i \neq 0 \quad \Rightarrow \quad F_a \sim \sum q^i_{PQ} v_i/\mathcal{A}$

Al least one $v_i \sim M_{\mathrm{Pl}}$ ☹

In general: $\mathrm{U}(1)^n_{\mathrm{PQ}}$

$F_a \propto v_n\ \times$ charges

Al least one $v_i \sim M_{\mathrm{Pl}}$ $\quad v_1 > v_2 > \ldots > v_n > \ldots$

intermediate scale v_n possible! ☺

Accions: ③ Verifying small m_a ?

No exact global $\mathrm{U}(1)$ in string theory

$\Rightarrow$ $\mathrm{U}(1)_{\mathrm{PQ}}$ broken *explicitly* @ order $M > N$

The explicit breaking induces an accion mass m_a — Barr, Seckel (1992)

Neutrino-dipole-moment constraint: $m_a \lesssim 3 \times 10^{-7}\ \mathrm{GeV}^2/F_a$

Kim, Carosi (2008)

Sufficient condition for suppressed m_a: $\quad M \geq 12$

Kamionkowsky, March-Russell (1992)

Also achieved if first mass contribution appears at order

$\mathcal{O} \geq 12, \quad \mathcal{O} \geq M > N$ — Choi, Nilles, R-S, Vaudrevange (2009)

Example

Choi, Nilles, R-S., Vaudrevange (2009)

Minilandscape Example with QCD *Accions*

- $\mathcal{G}_{4D} = \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times [\mathrm{SU}(4) \times \mathrm{SU}(2)]$

3	$(\mathbf{3},\mathbf{2};\mathbf{1},\mathbf{1})_{1/6}$	q_i			
9	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{-1/2}$	ℓ_i	6	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_{1/2}$	$\bar{\ell}_i$
3	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{1}$	$\bar{e}_i$			
3	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{-2/3}$	$\bar{u}_i$			
8	$(\overline{\mathbf{3}},\mathbf{1};\mathbf{1},\mathbf{1})_{1/3}$	$\bar{d}_i$	5	$(\mathbf{3},\mathbf{1};\mathbf{1},\mathbf{1})_{-1/3}$	d_i
12	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{1/2}$	s_i^+	12	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_{-1/2}$	s_i^-
2	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{1/2}$	x_i^+	2	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_{-1/2}$	x_i^-

4	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{1})_0$	m_i
2	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{2})_0$	n_i
65	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{1})_0$	s_i^0
12	$(\mathbf{1},\mathbf{1};\mathbf{1},\mathbf{2})_0$	h_i
10	$(\mathbf{1},\mathbf{1};\mathbf{4},\mathbf{1})_0$	w_i
10	$(\mathbf{1},\mathbf{1};\overline{\mathbf{4}},\mathbf{1})_0$	$\bar{w}_i$

- 1 *accidental* $\mathrm{U}(1)_{\mathrm{PQ}}$ + gauge anomalous $\mathrm{U}(1)_A$
- Break $\mathrm{U}(1)_A$, preserve $\mathcal{N}=1$ SUSY & unbroken $\mathrm{U}(1)_{\mathrm{PQ}}$

$$v_1 : \langle s^0_{19}\rangle \sim \langle s^0_{49}\rangle \sim \langle s^0_{52}\rangle \sim \langle s^0_{57}\rangle \sim \langle s^0_{59}\rangle \sim M_{\mathrm{Pl}}$$

- Vacuum that breaks $\mathrm{U}(1)_{\mathrm{PQ}}$ at lower energies:

$$v_2 : \langle s^0_{1}\rangle \sim \langle s^0_{36}\rangle \sim \langle s^0_{37}\rangle \sim 10^{12}\ \text{GeV}$$

In this model

$$F_a \propto v_2 \quad \Rightarrow \quad m_a \sim 10^{-9}\ \text{GeV}^2/F_a \approx 10^{-21}\ \text{GeV}$$ ☺

In few words...

In promising $\mathbb{Z}_6$–II heterotic orbifolds:

QCD axions

- *accidental* $\mathrm{U}(1)$s with QCD–anomalies ✓
- spontaneuos breaking ⇒ accions ✓
- two or more $\mathrm{U}(1)_{\mathrm{PQ}}$ broken ✓

  ⇒ F_a fits bounds ☺
- explicit breaking of $\mathrm{U}(1)_{\mathrm{PQ}}$ @ high orders ✓

  ⇒ suppressed $m_a \sim 0$ ☺