# Reduced rank heterotic string theory without supersymmetry

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# Introduction

# Motivation

➢String theory is a promising candidate for unified theory.

a well-known scenario

**D=10**

string w/ 16 supercharges

e.g. $E_8 \times E_8$ Het.

comp. on $\boldsymbol{X}^6$ →

Calabi-Yau (orbifold) w/ $SU(3)$ holonomy

**D=4**

string w/ 4 supercharges

(MSSM-like model)

SUSY breaking at low-energy

➢But, no signal of low-energy SUSY

→ non-supersymmetric string phenomenology?

(landscape of non-SUSY vacua > landscape of SUSY vacua)

difficulty    very large cosmological constant

in general,    $\Lambda^{(D)} \sim \mathcal{O}(M_s^D)$

How can we obtain small (or vanishing) cosmological constants WITHOUT SUSY?

# Heterotic strings with SUSY

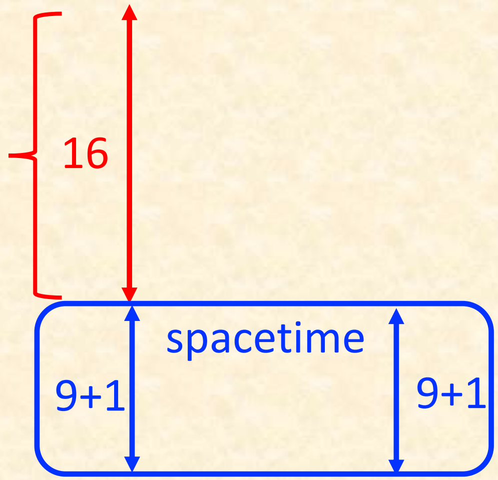
[Gross-Harvey-Martinec-Rohm '85]

- What is heterotic string theory?

➡ closed string theory with different left and right d.o.f.

bosonic string in 26 dim. | L | R | superstring in 10 dim.

$X_L^A(\sigma + t)$
on
$T_L^{16} = \mathbb{R}^{16}/\Gamma_{16}$




$X_L^\mu(\sigma + t)$

$X_R^\mu(\sigma - t)$ $\psi_R^\mu(\sigma - t)$

modular invariance (+ spacetime SUSY)

➡ $\Gamma_{16}$ must be a Euclidian even self-dual lattice

only two inequivalent such lattices in 16 dim.

$\Gamma_{16} = \Gamma_{Spin(32)/\mathbb{Z}_2}$ ($SO(32)$ Het.) or $\Gamma_{16} = \Gamma_{E_8} \oplus \Gamma_{E_8'}$ ($E_8 \times E_8$ Het.)

# Heterotic strings without SUSY (rank 16+d)

- Construction: freely acting $\mathbb{Z}_2$-orbifold

ingredients: three $\mathbb{Z}_2$ generators

- $\gamma_\delta$ : half shift in $T_L^{16}$ ➡ $X_L^A \to X_L^A + \delta^A \quad (2\delta^A \in \Gamma_{16})$
- $\mathbf{T}$ : half shift in $S^1$ ➡ $X^1 \to X^1 + \pi R$
- $(-1)^F$ : $2\pi$ spatial rotation ➡ SUSY breaking

D=10 **SUSY Het.** $\xrightarrow{\gamma_\delta(-1)^F}$ **Non-SUSY Het. (w/ rank 16)**

- Non-SUSY $SO(32)$
- Non-SUSY $SO(16)\times E_8$
- Non-SUSY $SO(16)\times SO(16)$
- Non-SUSY $E_7^2\times SU(2)^2$
- Non-SUSY $SO(24)\times SO(8)$
- Non-SUSY $SU(16)\times U(1)$

[Dixon-Harvey '86]

SUSY Het. $\xrightarrow{\gamma_\delta \mathbf{T}(-1)^F}$ interpolating model; interpolating model $\xrightarrow{R\to\infty}$ SUSY Het.; interpolating model $\xrightarrow{R\to 0}$ Non-SUSY Het.

D=9 **interpolating model (w/ rank 16+1)**

The 1-loop cosmological constant is evaluated as

$$\Lambda^{(9)} \sim \cancel{\frac{\xi}{R^9}(n_F - n_B)} + \mathcal{O}\left(e^{-R}\right)$$

[Itoyama-Taylor '87]

$n_F, n_B$: #(massless fermions, bosons)

$\boxed{n_F = n_B}$

➡ **exponentially suppressed cosmological constant!**

# Heterotic strings without SUSY (rank 8+d)

- Construction: asymmetric $\mathbb{Z}_2$-orbifold

ingredients: three $\mathbb{Z}_2$ generators

- $\mathbf{R}$ : exchange of the two $E_8$ factors ➡ $\Gamma_{E_8} \oplus \Gamma_{E_8'} \to \Gamma_{E_8'} \oplus \Gamma_{E_8}$
- $\mathbf{T}$ : half shift on $S^1$ ➡ $X^1 \to X^1 + \pi R$
- $(-1)^F$ : $2\pi$ spatial rotation ➡ SUSY breaking

$$\begin{tikzcd}
\text{D=10} & E_8 \times E_8 \text{ Het.} \arrow[rr, "\mathbf{R}(-1)^F"] \arrow[d, "\mathbf{RT}"'] \arrow[drr, "\mathbf{RT}(-1)^F"'] & & \text{Non-SUSY } E_8 \text{ Het.} \\
\text{D=9} & \text{CHL string} & & \boxed{\text{Non-SUSY CHL string}} \arrow[ull, dashed, bend right, "R \to \infty"'] \arrow[u, dashed, "R \to 0"']
\end{tikzcd}$$

[Kawai-Lewellen-Tye '86]

CHL string
w/
16 supercharges
reduced rank 8+1

[Chaudhuri-Hockney-Lykken '95]

Non-SUSY CHL string

today's talk

- enhancement to non-simply-laced groups (except for $d = 1$)
- exponentially suppressed c.c.

# *Outline*

- **Review: CHL strings**
- **Non-SUSY CHL strings**
- **Cosmological constant**
- **Summary**

# Review: CHL strings

# Closed strings on orbifolds

[Dixon-Harvey-Vafa-Witten '85]

- (toroidal) orbifold: $T^d/\mathrm{P}$ $(T^d = \mathbb{R}^d/\Gamma)$

untwisted sector

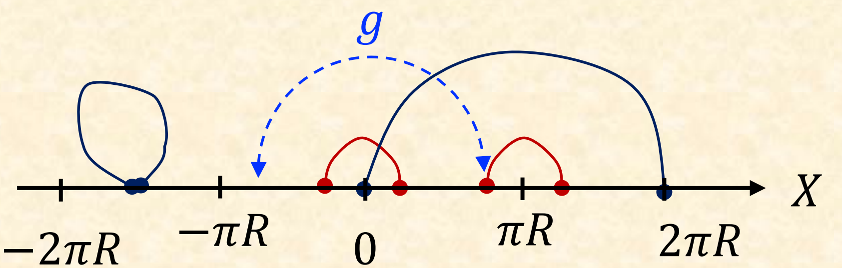
$$X(\sigma + 2\pi) = X(\sigma) + Q \quad (Q \in \Gamma)$$

twisted sector

$$X(\sigma + 2\pi) = gX(\sigma) + Q \quad (g \in \mathrm{P})$$

example: $S^1/\mathbb{Z}_2$ $\quad X = X + 2\pi R$

$g: X \to -X$




- the CHL model

$\boxed{X_\pm^I := (X_L^I \pm X_L^{I+8})/\sqrt{2}}$

$\mathbf{R}$: $(X_L^I, X_L^{I+8}) \to (X_L^{I+8}, X_L^I)$ ⇒ $\mathbf{R}$: $X_\pm^I \to \pm X_\pm^I$ $\quad$ $\mathbf{T}$: $X^1 \to X^1 + \pi R$

untwisted sector

$$X_\pm^I(\sigma + 2\pi) = X_\pm^I(\sigma) + Q_\pm^I \quad \left(Q_\pm^I \in \frac{1}{\sqrt{2}}\Gamma_{E_8}\right)$$

$$X^1(\sigma + 2\pi) = X^1(\sigma) + 2\pi w R \quad (w \in \mathbb{Z})$$

twisted sector

$$X_\pm^I(\sigma + 2\pi) = \pm X_\pm^I(\sigma) + Q_\pm^I$$

$$X^1(\sigma + 2\pi) = X^1(\sigma) + \pi R + 2\pi\tilde{w}R = X^1(\sigma) + 2\pi w R \quad \left(w \in \mathbb{Z} + \frac{1}{2}\right)$$

# Spectrum

- Mass formula
  - Right: $M_R^2 = p_R^2 + \tilde{N}$
  - Left: $M_L^2 = P_L^2 + N - a$

  $N, \tilde{N} \in \mathbb{Z}_{\geq 0}$ $a = \begin{cases} 2 & \text{(untwisted sector)} \\ 1 & \text{(twisted sector)} \end{cases}$

  internal momentum

  $(P_L; p_R) = (\ell_+, p_L; p_R) = (\pi, w, n)\mathcal{E}(G, B, a) \in$ charge lattice w/ (8+d,d)

- Massless spectrum
  - Right: $p_R^2 = 0$ → $\mathbf{8}_V, \mathbf{8}_S$ of the spacetime $SO(8)$
  - Left:

untwisted sector

$P_L^2 = 0$ → gravity multiplet
gauge bosons of $U(1)^{8+d}$

$P_L^2 = 1$ → short roots

$\boxed{P_L^2 = 2 \rightarrow \text{long roots}}$ enhancement to non-simply-laced

twisted sector

$P_L^2 = 1$ → short roots

# Non-SUSY CHL strings

# Partition function

Torus partition function: $Z(\tau) = \mathrm{Tr}\left[e^{-2\pi\tau_2 H_t} e^{-2\pi i \tau_1 P_\sigma}\right]$

- CHL strings (twisted by $\mathbf{RT}$)

$$Z^{(10-d)}_{\rm CHL} = \frac{1}{2} Z_B^{(8-d)} \left(\underbrace{\bar{V}_8}_{\mathbf{8}_V} - \underbrace{\bar{S}_8}_{\mathbf{8}_S}\right) \{\underbrace{Z(\mathbf{1},\mathbf{1}) + Z(\mathbf{1},\mathbf{RT})}_{w^1 \in \mathbb{Z}\quad \text{untw.}} + \underbrace{Z(\mathbf{RT},\mathbf{1}) + Z(\mathbf{RT},\mathbf{RT})}_{w^1 \in \mathbb{Z}+1/2\quad \text{tw.}}\}$$

- Non-SUSY CHL strings (twisted by $\mathbf{RT}(-\mathbf{1})^F$)

$$Z^{(10-d)}_{\mathcal{N}=0} = \frac{1}{2} Z_B^{(8-d)} \{\underbrace{\bar{V}_8}_{\mathbf{8}_V} \underbrace{(Z(\mathbf{1},\mathbf{1}) + Z(\mathbf{1},\mathbf{RT}))}_{\mathbf{RT}\ \text{even}} - \underbrace{\bar{S}_8}_{\mathbf{8}_S} \underbrace{(Z(\mathbf{1},\mathbf{1}) + Z(\mathbf{1},\mathbf{RT}))}_{\mathbf{RT}\ \text{odd}} \quad \text{untw.}$$

$$+ \underbrace{\bar{O}_8}_{\text{scalar}} \underbrace{(Z(\mathbf{RT},\mathbf{1}) - Z(\mathbf{RT},\mathbf{RT}))} - \underbrace{\bar{C}_8}_{\mathbf{8}_C} \underbrace{(Z(\mathbf{RT},\mathbf{1}) + Z(\mathbf{RT},\mathbf{RT}))}\} \quad \text{tw.}$$

$$\Delta_{G_{\mathcal{N}=0}} = \{P_L \in \Delta_{G_{\rm CHL}} | w^1 \in \mathbb{Z}\} \qquad \Delta_{G_{\mathcal{N}=0}} \setminus \Delta_{G_{\rm CHL}} = \{P_L \in \Delta_{G_{\rm CHL}} | w^1 \in \mathbb{Z} + \tfrac{1}{2}\}$$

($\Delta_G$: a set of nonzero roots of a non-Abelian group $G$)

- Orbifold projection for states w/ long roots

$\begin{bmatrix}\text{Bosonic}\\ \text{Fermionic}\end{bmatrix}$ states with $n_1$ $\begin{pmatrix}\text{even}\\ \text{odd}\end{pmatrix}$ survive under the projection.

# Spectrum

- $d = 1 \qquad a = 0 \qquad G_{CHL} = G_{\mathcal{N}=0} = E_8 \times U(1)_l$ (at generic $R$)

  $\mathbf{8}_S$ in the adjoint rep. of the $E_8$

| | $R=1$ | $R=\sqrt{2}$ | | $R=\frac{\sqrt{2}}{\lvert w\rvert}\ (w\in\mathbb{Z}+\frac{1}{2})$ |
|---|---|---|---|---|
| space-time $SO(8)$ reps. | $\mathbf{8}_S$ | $\mathbf{8}_C$ | scalar | scalar |
| $E_8$ reps. | singlet | singlet | adjoint | singlet |
| $U(1)_l$-charge $(w,n)$ | $(\pm1,\pm1)$ | $(\pm\frac{1}{2},\pm1)$ | $(\pm\frac{1}{2},\mp1)$ | $(\pm\sqrt{2}R^{-1},0)$ |

$G_{CHL} = E_8 \times SU(2)$

- $d = 2$

**Example 1.** $E = \begin{pmatrix} 2 & 0 \\ -2 & 1 \end{pmatrix} \quad a_1 = -\frac{1}{6}(-1,1,1,1,1,1,1,-5) \quad a_2 = 0 \quad \to G_{CHL} = C_{10}$

**Example 2.** $E = \begin{pmatrix} 2 & 0 \\ 0 & 1 \end{pmatrix} \quad a_1 = \frac{1}{2}(0,0,0,0,0,0,-1,1) \quad a_2 = \frac{1}{5}(0,0,0,-1,-1,-1,-1,4)$

$(E \coloneqq G - B + a \cdot a) \qquad \to \quad G_{CHL} = A_4 \times C_6$

| | Gauge sym. | $\mathbf{8}_S$ | $\mathbf{8}_C$ | Scalar |
|---|---|---|---|---|
| Example 1 | $C_1 \times C_9$ | $(\mathbf{1},\mathbf{152})$ | $(\mathbf{2},\mathbf{18})$ | $(\mathbf{1},\mathbf{152})\times 4$ |
| Example 2 | $A_4 \times C_2 \times C_4$ | $\mathbf{24}\oplus\mathbf{5}\oplus\mathbf{42}$ | $(\mathbf{4},\mathbf{8})$ | —— |

# Cosmological constant

# Cosmological constant

Background: $S^1 \times T^{d-1}$ ➡ the moduli: $(R, a_1; G', B', a')$

↰ SS mechanism

- cosmological constant ⇔ vacuum energy density

at one-loop

$$\Lambda^{(10-d)} = -\frac{1}{2}\left(4\pi^2\alpha'\right)^{-\frac{10-d}{2}} \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2} Z^{(10-d)}_{\mathcal{N}=0}$$

$R \gg 1$

$$\sim -\frac{2\Gamma\left(\frac{11-d}{2}\right)}{\sqrt{\pi}\left(\pi^{\frac{3}{2}}\sqrt{\alpha'}R\right)^{10-d}} \sum_{n\geq 1}(2n-1)^{d-11}\left(\underbrace{64}_{\text{gravitational sector + KK bosons}} + \underbrace{8\sum_{\substack{p'_R=0 \\ P'^2_L=2}} \cos\left[\pi(2n-1)\rho\cdot a_1\right]}_{\text{gauge sector with long roots } (\rho := \pi - w'a')}\right) + \mathcal{O}(e^{-R})$$

assume

$n_1 = \rho \cdot a_1 \in \mathbb{Z}$

$$\sim \frac{2\Gamma\left(\frac{11-d}{2}\right)}{\sqrt{\pi}\left(\pi^{\frac{3}{2}}\sqrt{\alpha'}R\right)^{10-d}} \sum_{n\geq 1}(2n-1)^{d-11}\left(n_F - n_B\right)$$

$\rho \cdot a_1$ { even → bosonic; odd → fermionic

- $d = 1$ No solutions of $P'^2_L = 2$

$$\Lambda^{(9)} \sim -\frac{48}{\pi^{14}\left(\sqrt{\alpha'}R\right)^9} 2^{-10}\zeta\left(10, \frac{1}{2}\right) 64 < 0$$

# Exponential suppression

The condition for the suppression: $\sum_{\substack{p'_R=0 \\ P'^2_L=2}} \cos\left[\pi(2n-1)\rho\cdot a_1\right] = -8$

- Example in $d = 2$: $S^1 \times S^1$

$$R' = \frac{1}{2}, \quad a' = -\frac{1}{4}\left(0^4, 1^3, -3\right)$$

$p'^2_R = 0, P'^2_L = 2$ → the eight solutions:

$$(w';\pi) = \pm\left(1;0^8\right), \pm\left(1;0^4,\underline{-2,0^2},2\right)$$

$$a_1 = \left(0^6, -1, 1\right)$$

→ $\sum_\rho \cos\left[\pi(2n-1)\rho\cdot a_1\right] = 0 - 8$

- Example in $d = 3$: $S^1 \times T^2$

$$E' = \begin{pmatrix} 2 & 0 \\ 0 & 1 \end{pmatrix}, \quad a_2 = 0, \quad a_3 = \frac{1}{8}\left(1^7, -7\right)$$

$p'^2_R = 0, P'^2_L = 2$ → the sixteen solutions:

$$(w';\pi) = \pm\left(0,1;0^8\right), \pm\left(0,1;\underline{2,0^6},-2\right)$$

$$a_1 = \frac{1}{2}\left(0^6, 7, 1\right)$$

→ $\sum_\rho \cos\left[\pi(2n-1)\rho\cdot a_1\right] = 4 - 12$

# Summary

# Conclusion & Outlook

- The reduced rank non-supersymmetric model is constructed by the asymmetric orbifold twist $\mathbf{RT}(-1)^F$.
- The gauge symmetry can be enhanced to non-simply-laced groups.

  Does a systematic way to explore the moduli space exist?

  (c.f. [Font-Fraiman-Grana-Nunez-Freitas '20 '21])
- Exponential suppression of the cosmological constant is possible maybe at unstable points.

  Is it possible to realize the suppressed cosmological const. with the moduli stabilized?

  Wilson lines, radion

Thank you for your attention!

# **Back up**