New Non-supersymmetric Tachyon-Free Strings

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Based on: 2406.00185 and 2406.00129 with Kaan Baykara, Cumrun Vafa

25 June 2024

String Pheno 2024

String Landscape

Geometric string constructions do lots of the heavy lifting!

Geometric String Landscape

String Landscape

Geometric **String Landscape**

Today

Quasicrystalline orbifolds

[88' Harvey, Moore, Vafa]

Connections?

Non-geometric

Symmetries

Perturbative Narain compactifications $\quad \mathrm{II}^{d+x;d} \hookrightarrow \Gamma^{d+x;d} \subset \mathbb{R}^{d+x;d}$ [86' Narain]

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$\theta_R = \theta_L$

Symmetric Action

$\theta = (\theta_L;\theta_R)$

$\theta_R \neq \theta_L$

Asymmetric Action

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Crystallographic Symmetry

θ_R, θ_L automorphisms

[87' Narain, Sarmadi, Vafa]

Quasicrystalograhic Symmetry

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Quasicrystalographic Symmetry

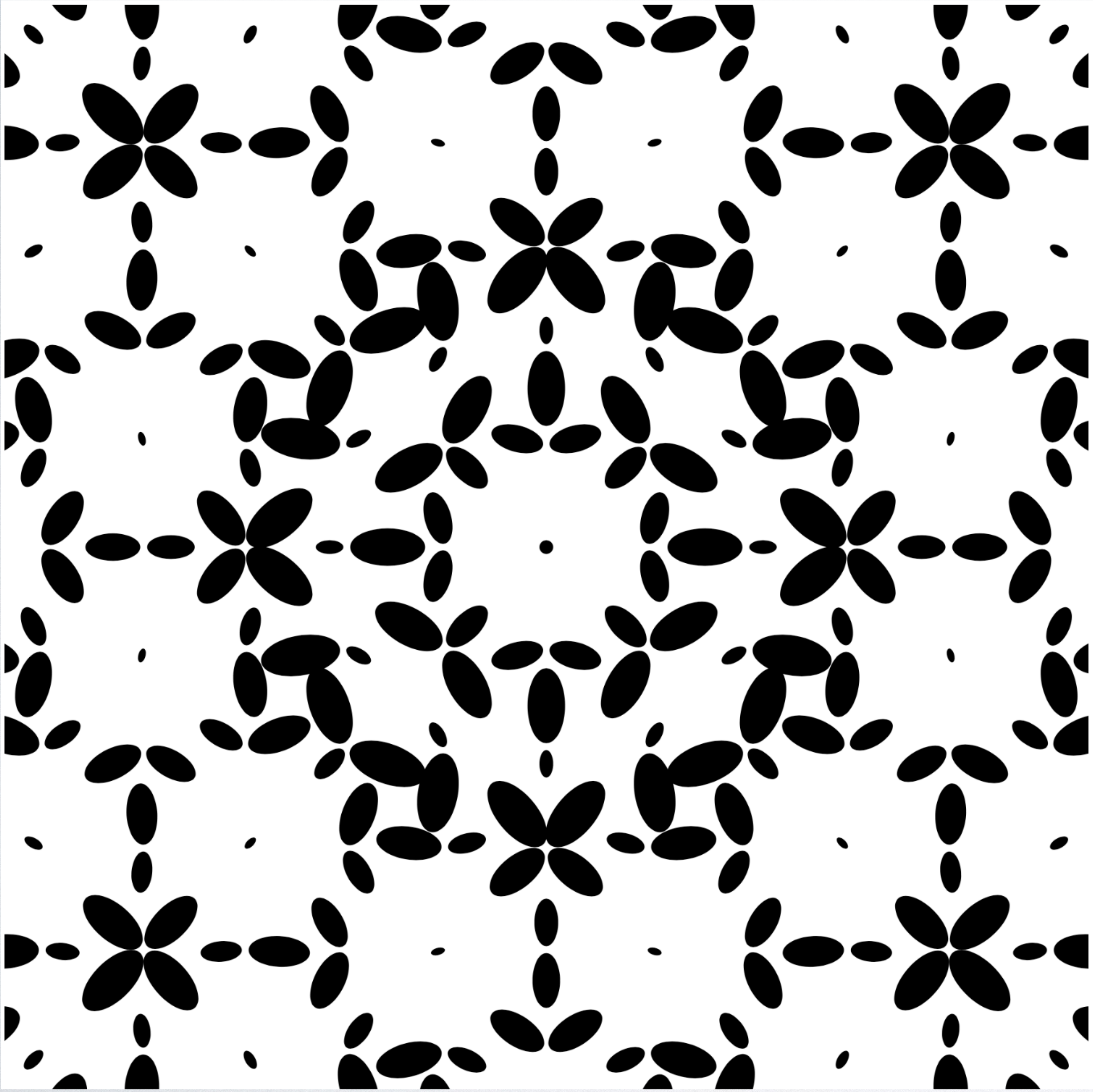
θ_R, θ_L not separately automorphisms

[88' Harvey, Moore, Vafa]

- The location of the symmetry in the target torus $T^d = \mathbb{R}^d / 2\pi\Lambda_d$ is at special locations with G_{ij}, B_{ij} fixed

$$\text{For } \mathbb{Z}_{12} \text{ we have } G_{ij} = \alpha' \begin{pmatrix} \frac{\sqrt{3}}{2} & 0 \\ 0 & \frac{\sqrt{3}}{2} \end{pmatrix}, \; B_{ij} = \alpha' \begin{pmatrix} 0 & \frac{1}{2} \\ -\frac{1}{2} & 0 \end{pmatrix}.$$

So this models are rigid where all internal radii are fixed



Quasicrystalline Symmetry

$$(p_L^1, p_L^2; p_R^1, p_R^2) \in \Gamma_{12}^{2;2}$$

Center of ellipsis: (p_L^1, p_L^2)

Orientation and length: (p_R^1, p_R^2)

No translation symmetry

Quasicrystalline Orbifolds

- Choose the starting point: IIA, IIB, Heterotic
- Choose your symmetry: $\theta = (\exp(2\pi i \phi_L), \exp(2\pi i \phi_R))$
- Find your even self-dual lattice: $\Gamma^{D,D}(\mathfrak{g}) / \Gamma^{D+16,D}(\mathfrak{g})$
- Twist by θ: $[g_L, g_R] = [\exp(2\pi i \phi_L), \exp(2\pi i \phi_R)]$
- Choose the shift: (v_L, v_R)

$$\left.\begin{array}{l} [g_L, g_R] = [\exp(2\pi i \phi_L), \exp(2\pi i \phi_R)] \\ (v_L, v_R) \end{array}\right\} \; |p_L, p_R> \to e^{2\pi i(p_L \cdot v_L - p_R \cdot v_R)} |g_L \cdot p_L, g_R \cdot p_R>$$

- Ensure level matching: $N(E_L - E_R) \in \mathbb{Z}$
- Compute spectrum

Let’s start with 16 supercharges

Where can non-geometric constructions help us?

Supersymmetric Landscape

Possible ranks in 16 Qs

[01' Boer et al]

[20' Montero, Vafa]

[19' Kim, HCT, Vafa]

String islands

Check Hector's talk on Thursday

[98' Dabholkar, Harvey]

[22' Fraiman, Parra de Freitas]

Which geometric conditions are Swampland conditions? ~~Kodaira condition~~

[23' Baykara, Hamada, HCT, Vafa]

Realize all K3 orbifold points

[12' Gaberdiel, Volpato]

Theta angle

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Large discrete gauge symmetries?

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Large discrete gauge symmetries?

First interesting example

K3 sigma model moduli space:

$$\mathscr{M}_{K3} = O(\Gamma^{4,20})\backslash O(4,20)/O(4) \times O(20)$$

RR charges ($\Gamma^{4,20}$)

NSNS B,G fields ($O(4,20)$)

Classify susy preserving automorphisms

[11' Gaberdiel, Volpato]

e.g. orbifold quantum symmetries

[89' Vafa]

First interesting example

K3 sigma model is expected to have the following symmetries:

Co_0-class	<u>1A</u>	<u>2B</u>	2C	<u>3B</u>	3C	4B	<u>4E</u>	4F	<u>5B</u>	5C	6G	6H	6I	<u>6K</u>	6L	6M	<u>7B</u>
dim fix	24	16	8	12	6	8	10	6	8	4	6	6	6	8	4	4	6
$\mathrm{Tr}_{\mathbf{24}}(g)$	24	8	−8	6	−3	8	4	−4	4	−1	−4	4	5	2	−2	−1	3
$\tilde{\phi}(\tau,0)$	24	24	0	24	0	24	24	0	24	0	0	24	24	24	0	0	24

Co_0-class	8D	<u>8G</u>	8H	9C	10F	10G	10H	<u>11A</u>	12I	12L	12N	12O	<u>14C</u>	<u>15D</u>
dim fix	4	6	4	4	4	4	4	4	4	4	4	4	4	4
$\mathrm{Tr}_{\mathbf{24}}(g)$	4	2	−2	3	−2	2	3	2	2	1	−2	2	1	1
$\tilde{\phi}(\tau,0)$	24	24	0	24	0	24	24	24	24	24	0	24	24	24

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K3 sigma model is expected to have the following symmetries:

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$\tilde{\phi}(\tau,0)$	24	24	0	24	0	24	24	0	24	0	0	24	24	24	0	0	24

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$\mathrm{Tr}_{\mathbf{24}}(g)$	4	2	-2	3	-2	2	3	2	2	1	-2	2	1	1
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Toroidal Orbifold

[12' Gaberdiel, Volpato]

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Toroidal Orbifold

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Quasicrystals!!!

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$Q = 16$ Quasicrystalline Orbifolds				
Dimension	Lattice	Twist	IIA	IIB
6	$\Gamma_5^{2,2}\Gamma_5^{2,2}[11]$ $\Gamma_8^{2,2}\Gamma_8^{2,2}[11]$ $\Gamma_{10}^{2,2}\Gamma_{10}^{2,2}[11]$ $2\Gamma_{12}^{2,2}$	$\mathbb{Z}_5 : (1,1;2,2)/5$ $\mathbb{Z}_8 : (1,1;3,3)/8$ $\mathbb{Z}_{10} : (1,1;3,3)/10$ $\mathbb{Z}_{12} : (1,1;5,5)/12$	$\mathcal{N} = (1,1)$ $G + 20V$	$\mathcal{N} = (2,0)$ $G + 21T$

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K3 Moduli space

[89' Eguchi, Ooguri,, Taormina, Yang]

Quasicrystalline orbifold	$\mathcal{Q}$ charges	Co_0 class	$\Gamma^{4;20}$	Symmetries
$\mathbb{Z}_5$	$(1^5, 2^5)/5$	$5C$	HM122	$5^{1+2} : \mathbb{Z}_4$
$\mathbb{Z}_8$	$(1^2, 2^3, 3^2, 4^3)/8$	$8H$	HM143	$\mathbb{Z}_8.\mathbb{Z}_2^3$
$\mathbb{Z}_{10}$	$(1, 2^3, 3^1, 4^3, 5^2)/10$	$10F$	HM159	D_{20}
$\mathbb{Z}_{12}$	$(1, 2, 3^2, 4^3, 5, 6^2)/12$	$12N$	HM157	D_{24}

[89' Vafa] [21' Baykara, Harvey] [15' Hoehn, Mason]

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There are also points in the K3 moduli space that are not quasicrystalline orbifold points, but are dual to heterotic quasicrystalline

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K3 Moduli space

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There are also points in the K3 moduli space that are not quasicrystalline orbifold points, but are dual to heterotic quasicrystalline

They are obtained by the orbifold of the LG model

$$W = z_1^3 + z_2^7 + z_3^{42}$$

[89' Vafa]

Corresponds to a $\mathbb{Z}_{42}$ quasicrystal with $2\Gamma_{42}^{2;10}$

Free action

$Q = 16$ Quasicrystalline Orbifolds				
Dimension	Lattice	Twist	IIA	IIB
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	$\Gamma_8^{2,2}\Gamma_8^{2,2}[11]$	$\mathbb{Z}_8 : (1,1;3,3)/8$	$G + 20V$	$G + 21T$
	$\Gamma_{10}^{2,2}\Gamma_{10}^{2,2}[11]$	$\mathbb{Z}_{10} : (1,1;3,3)/10$		
	$2\Gamma_{12}^{2,2}$	$\mathbb{Z}_{12} : (1,1;5,5)/12$		
5	$\Gamma_5^{2,2}\Gamma_5^{2,2}[11] + \Gamma^{1,1}$	$\mathbb{Z}_5 : (1,1;2,2)/5$	$\mathcal{N} = 2$	
	$\Gamma_8^{2,2}\Gamma_8^{2,2}[11] + \Gamma^{1,1}$	$\mathbb{Z}_8 : (1,1;3,3)/8$	$G + 1V$	
	$\Gamma_{10}^{2,2}\Gamma_{10}^{2,2}[11] + \Gamma^{1,1}$	$\mathbb{Z}_{10} : (1,1;3,3)/10$		
	$2\Gamma_{12}^{2,2} + \Gamma^{1,1}$	$\mathbb{Z}_{12} : (1,1;5,5)/12$		

K3 Moduli space

String Islands?

[98' Dabholkar, Harvey]

[22' Fraiman, Parra de Freitas]

2407.XXX

[Baykara, Parra de Freitas, HCT]

Check Hector's talk on Thursday

Let's go to

↓

0 supercharges

Where can non-geometric constructions help us?

Non-Supersymmetric Landscape

Landscape of tachyon free theories

Minimize number of moduli?

10d Example

- Heterotic $O(16) \times O(16)$ string

[Dixon, Harvey; Alvarez-Gaume, Ginsparg, Moore, Vafa]

positive leading cosmological constant, chiral matter, no tachyons and one neutral scalar

How about in $d < 10$?

- Heterotic $O(16) \times O(16)$ string on S^1 $\rightarrow$ 8 special points with no tachyons and $\Lambda > 0$

[23' Fraiman, Grana, Parra de Freitas, Sethi]

How about in $d = 4$?

4d Non-Susy $\mathbb{Z}_5$ Quasicrystalline orbifold

Massless Spectrum

	$SO(10) \times SU(5) \times SU(3) \times SU(2) \times U(1)^4$ reps	
Sector	Complex scalars	Left handed Weyl fermions
Untwisted	$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,0}$	$9(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,0}$
	$3(\mathbf{16},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,-15}$	$(\mathbf{16},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,-15}$
	$3(\mathbf{10},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,0,0,10}$	$(\mathbf{10},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,0,0,10}$
	$3(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{1})_{-2,-10,-2,0}$	$(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{1})_{-2,-10,-2,0}$
	$3(\mathbf{1},\overline{\mathbf{10}},\mathbf{1},\mathbf{2})_{-1,5,-1,0}$	$(\mathbf{1},\overline{\mathbf{10}},\mathbf{1},\mathbf{2})_{-1,5,-1,0}$
	$3(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{5,-5,5,0}$	$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{5,-5,5,0}$
		$3(\mathbf{16},\mathbf{1},\mathbf{3},\mathbf{1})_{0,0,0,5}$
		$3(\mathbf{1},\mathbf{10},\mathbf{1},\mathbf{1})_{-4,0,-4,0}$
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		$3(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{2})_{3,5,3,0}$
		$3(\mathbf{1},\bar{\mathbf{5}},\mathbf{1},\mathbf{1})_{2,-10,2,0}$
$\hat{g}+\hat{g}^4$		$15(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{-1,-3,-1,12}$
		$15(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{-2,7,1,12}$
		$15(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,7,-3,12}$
		$5(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{1,-3,-5,12}$
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		$5(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{1})_{2,2,2,12}$
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$\hat{g}^2+\hat{g}^3$	$15(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{4,-1,1,4}$	$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{4,-1,1,4}$
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- Narain Lattice: $\Gamma(E_8) \oplus L\Gamma_5^{2,2} \oplus \Gamma_5^{2,2}\Gamma_5^{2,2}$
- Twist by: $\phi = (4,4,4,0^8;2,2,2)/5$
- Shift by: $v = (2,0,3,0,1,4,0,0,4,3,0,3,3,3,4,0)/5$

No tachyon at tree level

4d Non-Susy $\mathbb{Z}_5$ Quasicrystalline orbifold

Massless Spectrum

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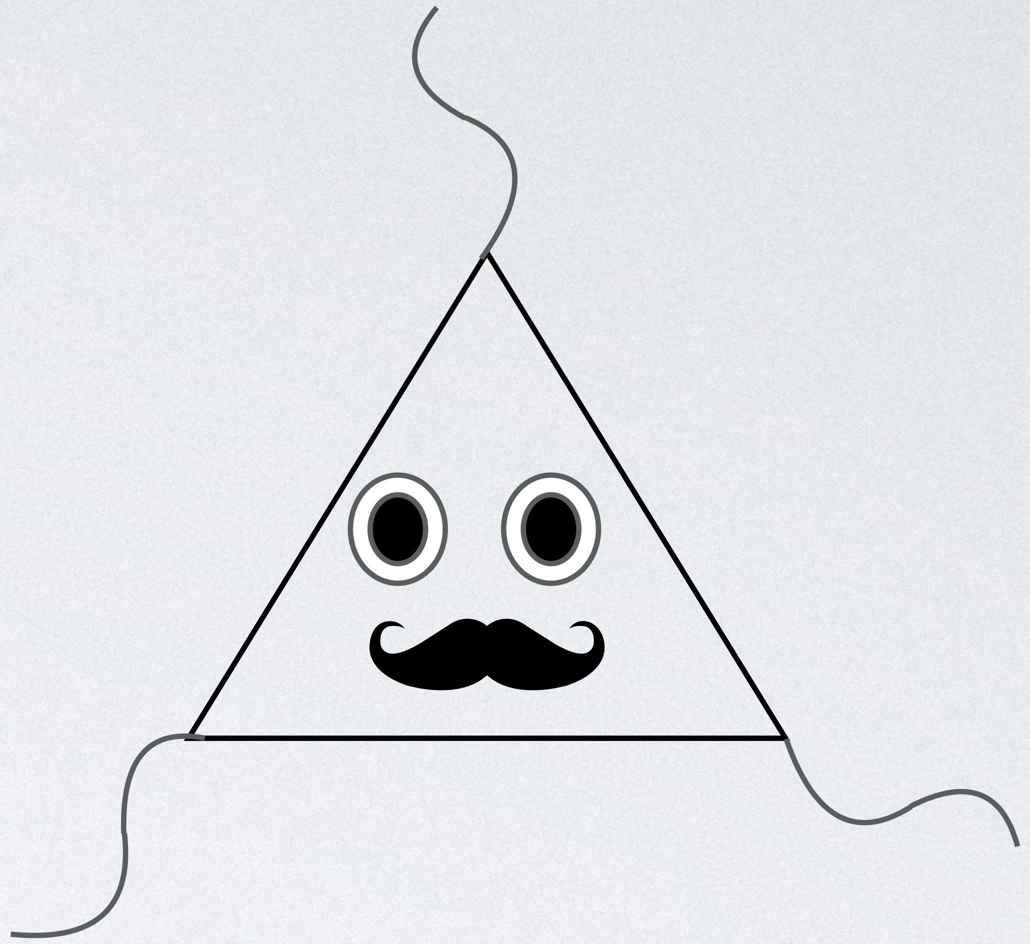
	$15(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{-2,-6,-2,4}$	$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{-2,-6,-2,4}$

Chiral Matter

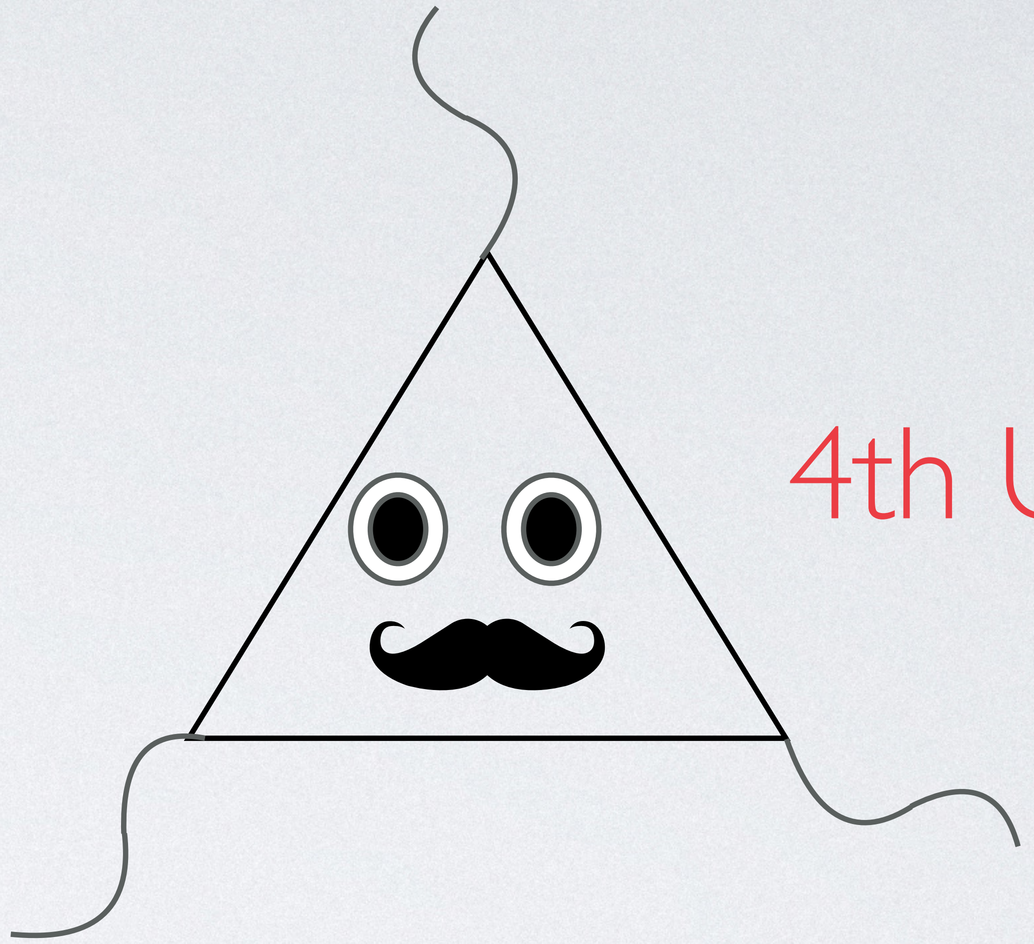


4d Non-Susy $\mathbb{Z}_5$ Quasicrystalline orbifold

Massless Spectrum

	$SO(10) \times SU(5) \times SU(3) \times SU(2) \times U(1)^4$ reps	
Sector	Complex scalars	Left handed Weyl fermions
Untwisted	$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,0}$	$9(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,0}$
	$3(\mathbf{16},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,-15}$	$(\mathbf{16},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,-15}$
	$3(\mathbf{10},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,0,0,10}$	$(\mathbf{10},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,0,0,10}$
	$3(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{1})_{-2,-10,-2,0}$	$(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{1})_{-2,-10,-2,0}$
	$3(\mathbf{1},\overline{\mathbf{10}},\mathbf{1},\mathbf{2})_{-1,5,-1,0}$	$(\mathbf{1},\overline{\mathbf{10}},\mathbf{1},\mathbf{2})_{-1,5,-1,0}$
	$3(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{5,-5,5,0}$	$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{5,-5,5,0}$
		$3(\mathbf{16},\mathbf{1},\mathbf{3},\mathbf{1})_{0,0,0,5}$
		$3(\mathbf{1},\mathbf{10},\mathbf{1},\mathbf{1})_{-4,0,-4,0}$
		$3(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,0,0,-20}$
		$3(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{2})_{3,5,3,0}$
		$3(\mathbf{1},\bar{\mathbf{5}},\mathbf{1},\mathbf{1})_{2,-10,2,0}$
$\hat{g}+\hat{g}^4$		$15(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{-1,-3,-1,12}$
		$15(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{-2,7,1,12}$
		$15(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,7,-3,12}$
		$5(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{1,-3,-5,12}$
		$5(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{-3,-3,3,12}$
		$5(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{1})_{2,2,2,12}$
		$5(\mathbf{1},\bar{\mathbf{5}},\mathbf{1},\mathbf{1})_{2,-3,-1,12}$
		$5(\mathbf{1},\bar{\mathbf{5}},\mathbf{1},\mathbf{1})_{0,-3,3,12}$
		$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{2})_{-1,-3,-1,-8}$
		$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,7,-3,-8}$
		$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{-2,7,1,-8}$
$\hat{g}^2+\hat{g}^3$	$15(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{4,-1,1,4}$	$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{4,-1,1,4}$
	$15(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{2,-1,5,4}$	$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{2,-1,5,4}$
	$15(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{-2,-6,-2,4}$	$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{-2,-6,-2,4}$

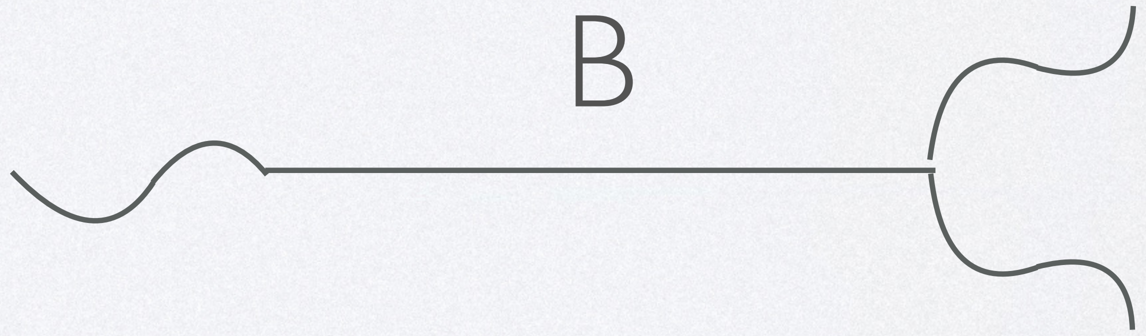
Chiral Matter



4th U(1) is “anomalous”

$$Tr(Q_4) \neq 0,\ Tr(Q_4^3) \neq 0$$

Green-Schwarz mechanism



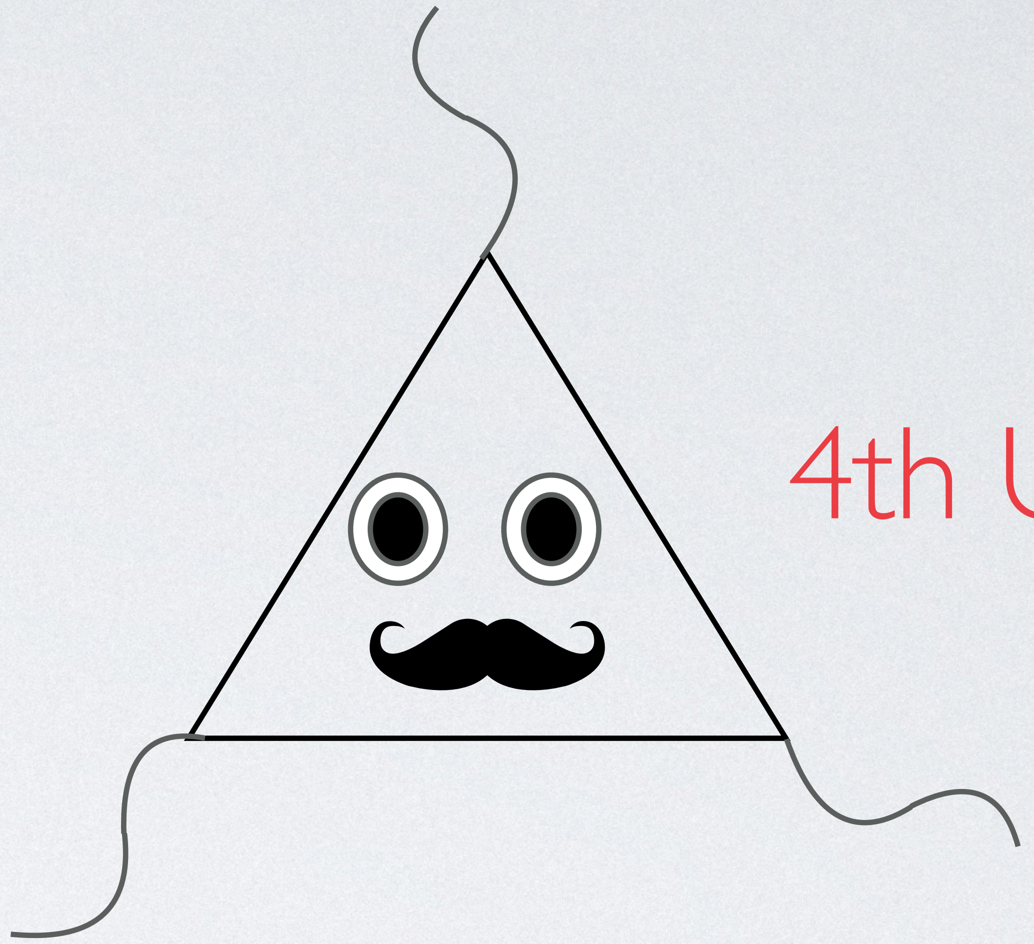
$$B \wedge F_4$$

4d Non-Susy $\mathbb{Z}_5$ Quasicrystalline orbifold

Massless Spectrum

	$SO(10) \times SU(5) \times SU(3) \times SU(2) \times U(1)^4$ reps	
Sector	Complex scalars	Left handed Weyl fermions
Untwisted	$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,0}$	$9(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,0}$
	$3(\mathbf{16},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,-15}$	$(\mathbf{16},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,-15}$
	$3(\mathbf{10},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,0,0,10}$	$(\mathbf{10},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,0,0,10}$
	$3(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{1})_{-2,-10,-2,0}$	$(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{1})_{-2,-10,-2,0}$
	$3(\mathbf{1},\overline{\mathbf{10}},\mathbf{1},\mathbf{2})_{-1,5,-1,0}$	$(\mathbf{1},\overline{\mathbf{10}},\mathbf{1},\mathbf{2})_{-1,5,-1,0}$
	$3(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{5,-5,5,0}$	$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{5,-5,5,0}$
		$3(\mathbf{16},\mathbf{1},\mathbf{3},\mathbf{1})_{0,0,0,5}$
		$3(\mathbf{1},\mathbf{10},\mathbf{1},\mathbf{1})_{-4,0,-4,0}$
		$3(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,0,0,-20}$
		$3(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{2})_{3,5,3,0}$
		$3(\mathbf{1},\bar{\mathbf{5}},\mathbf{1},\mathbf{1})_{2,-10,2,0}$
$\hat{g}+\hat{g}^4$		$15(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{-1,-3,-1,12}$
		$15(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{-2,7,1,12}$
		$15(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,7,-3,12}$
		$5(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{1,-3,-5,12}$
		$5(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{-3,-3,3,12}$
		$5(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{1})_{2,2,2,12}$
		$5(\mathbf{1},\bar{\mathbf{5}},\mathbf{1},\mathbf{1})_{2,-3,-1,12}$
		$5(\mathbf{1},\bar{\mathbf{5}},\mathbf{1},\mathbf{1})_{0,-3,3,12}$
		$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{2})_{-1,-3,-1,-8}$
		$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,7,-3,-8}$
		$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{-2,7,1,-8}$
$\hat{g}^2+\hat{g}^3$	$15(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{4,-1,1,4}$	$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{4,-1,1,4}$
	$15(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{2,-1,5,4}$	$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{2,-1,5,4}$
	$15(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{-2,-6,-2,4}$	$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{-2,-6,-2,4}$

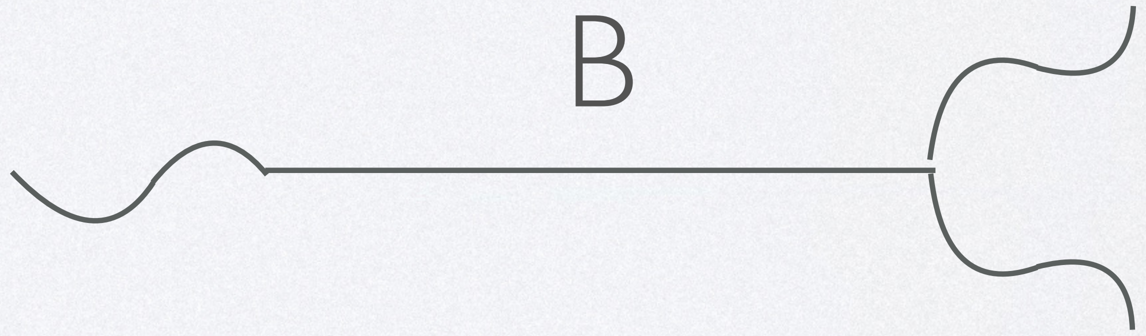
Chiral Matter



4th U(1) is "anomalous"

$$Tr(Q_4) \neq 0, \ Tr(Q_4^3) \neq 0$$

Green-Schwarz mechanism



Massive U(1) at 2-loops

$$B \wedge F_4 \rightarrow (\partial_\mu \theta + M\ A_\mu^4)^2$$

4d Non-Susy $\mathbb{Z}_5$ Quasicrystalline orbifold

Massless Spectrum

	$SO(10)\times SU(5)\times SU(3)\times SU(2)\times U(1)^4$ reps	
Sector	Complex scalars	Left handed Weyl fermions
Untwisted	$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,0}$	$9(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,0}$
	$3(\mathbf{16},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,-15}$	$(\mathbf{16},\mathbf{1},\mathbf{1},\mathbf{1})_{0,0,0,-15}$
	$3(\mathbf{10},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,0,0,10}$	$(\mathbf{10},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,0,0,10}$
	$3(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{1})_{-2,-10,-2,0}$	$(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{1})_{-2,-10,-2,0}$
	$3(\mathbf{1},\overline{\mathbf{10}},\mathbf{1},\mathbf{2})_{-1,5,-1,0}$	$(\mathbf{1},\overline{\mathbf{10}},\mathbf{1},\mathbf{2})_{-1,5,-1,0}$
	$3(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{5,-5,5,0}$	$(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{5,-5,5,0}$
		$3(\mathbf{16},\mathbf{1},\mathbf{3},\mathbf{1})_{0,0,0,5}$
		$3(\mathbf{1},\mathbf{10},\mathbf{1},\mathbf{1})_{-4,0,-4,0}$
		$3(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,0,0,-20}$
		$3(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{2})_{3,5,3,0}$
		$3(\mathbf{1},\bar{\mathbf{5}},\mathbf{1},\mathbf{1})_{2,-10,2,0}$
$\hat{g}+\hat{g}^4$		$15(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{-1,-3,-1,12}$
		$15(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{-2,7,1,12}$
		$15(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,7,-3,12}$
		$5(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{1,-3,-5,12}$
		$5(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2})_{-3,-3,3,12}$
		$5(\mathbf{1},\mathbf{5},\mathbf{1},\mathbf{1})_{2,2,2,12}$
		$5(\mathbf{1},\bar{\mathbf{5}},\mathbf{1},\mathbf{1})_{2,-3,-1,12}$
		$5(\mathbf{1},\bar{\mathbf{5}},\mathbf{1},\mathbf{1})_{0,-3,3,12}$
		$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{2})_{-1,-3,-1,-8}$
		$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{0,7,-3,-8}$
		$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{-2,7,1,-8}$
$\hat{g}^2+\hat{g}^3$	$15(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{4,-1,1,4}$	$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{4,-1,1,4}$
	$15(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{2,-1,5,4}$	$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{2,-1,5,4}$
	$15(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{-2,-6,-2,4}$	$5(\mathbf{1},\mathbf{1},\bar{\mathbf{3}},\mathbf{1})_{-2,-6,-2,4}$

- No Tachyons at tree level
- Chiral Matter
- Positive CC
- One neutral scalar

$$V_{1-loop}(\hat{\phi}) \approx e^{-2\sqrt{2}\hat{\phi}}\left(3.13\times 10^{-2}\right) M_s^4$$

How about in other dimensions?

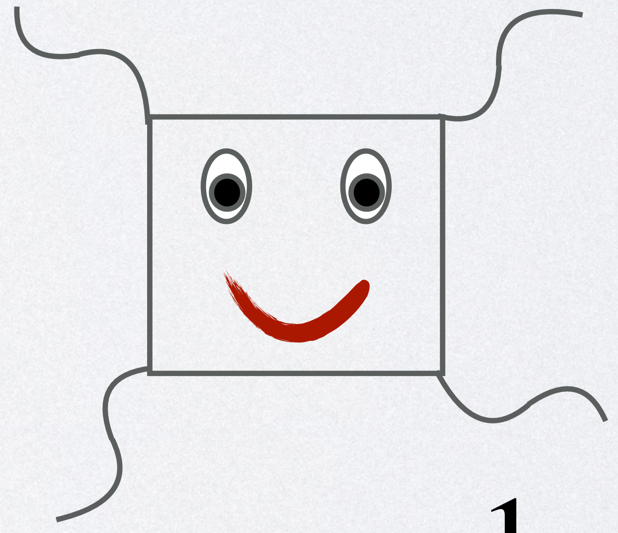
6d Non-Susy $\mathbb{Z}_5$ asymmetric orbifold

Sector	$SU(5) \times SU(5) \times SU(5) \times SU(5) \times U(1)^4$ reps
Untwisted	${}^{R}(\mathbf{10}, \mathbf{5}, \mathbf{1}, \mathbf{1})_{0,0,0,0}$
	${}^{R}(\overline{\mathbf{5}}, \mathbf{10}, \mathbf{1}, \mathbf{1})_{0,0,0,0}$
	${}^{L}(\mathbf{1}, \mathbf{1}, \mathbf{10}, \mathbf{5})_{0,0,0,0}$
	${}^{L}(\mathbf{1}, \mathbf{1}, \mathbf{5}, \overline{\mathbf{10}})_{0,0,0,0}$
	${}^{R}(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-1,3,2,6}$
	${}^{R}(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{0,8,-3,1}$
	${}^{R}(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{1,-7,-3,1}$
	${}^{R}(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-2,-2,2,4}$
	${}^{R}(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{2,-2,2,-4}$
	${}^{L}(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{1,1,4,2}$
	${}^{L}(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{0,-4,-1,7}$
	${}^{L}(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{2,6,-1,-3}$
	${}^{L}(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-1,-9,-1,-3}$
	${}^{L}(\mathbf{1}, \mathbf{1}, \mathbf{1}, \mathbf{1})_{-2,6,-1,-3}$
$\hat{g} + \hat{g}^4$	${}^{R}(\overline{\mathbf{5}}, \mathbf{1}, \mathbf{1}, \mathbf{5})_{0,-4,0,-2}$
	${}^{R}(\overline{\mathbf{5}}, \mathbf{1}, \mathbf{1}, \mathbf{5})_{0,0,2,0}$
	${}^{R}(\overline{\mathbf{5}}, \mathbf{1}, \mathbf{1}, \mathbf{5})_{1,1,-1,-1}$
	${}^{R}(\overline{\mathbf{5}}, \mathbf{1}, \mathbf{1}, \mathbf{5})_{-1,3,0,0}$
	${}^{R}(\overline{\mathbf{5}}, \mathbf{1}, \mathbf{1}, \mathbf{5})_{0,0,-1,3}$
$\hat{g}^2 + \hat{g}^3$	${}^{L}(\mathbf{1}, \mathbf{5}, \mathbf{5}, \mathbf{1})_{1,1,1,-1}$
	${}^{L}(\mathbf{1}, \mathbf{5}, \mathbf{5}, \mathbf{1})_{0,-4,-1,1}$
	${}^{L}(\mathbf{1}, \mathbf{5}, \mathbf{5}, \mathbf{1})_{-1,-1,0,-2}$
	${}^{L}(\mathbf{1}, \mathbf{5}, \mathbf{5}, \mathbf{1})_{0,0,1,3}$
	${}^{L}(\mathbf{1}, \mathbf{5}, \mathbf{5}, \mathbf{1})_{0,4,-1,-1}$

fermions+bosons

- Starting point: Heterotic string
- Narain Lattice: $\Gamma(E_8 \times E_8) \oplus \Gamma^{4;4}(A_4)$
- Twist by: $\phi = (0^{10}; 2,4)/5$
- Shift by: $v = (3,3,1,4,4,1,2,2,4,4,1,1,2,4,2,3,3,3,2,3)/5.$

Chiral Matter ←



$$(2\pi)^4 I_8 = \frac{1}{12} X_4 Y_4$$

6d Non-Susy $\mathbb{Z}_5$ asymmetric orbifold

Sector	$SU(5)\times SU(5)\times SU(5)\times SU(5)\times U(1)^4$ reps
Untwisted	${}^R(\mathbf{10},\mathbf{5},\mathbf{1},\mathbf{1})_{0,0,0,0}$
	${}^R(\overline{\mathbf{5}},\mathbf{10},\mathbf{1},\mathbf{1})_{0,0,0,0}$
	${}^L(\mathbf{1},\mathbf{1},\mathbf{10},\mathbf{5})_{0,0,0,0}$
	${}^L(\mathbf{1},\mathbf{1},\mathbf{5},\overline{\mathbf{10}})_{0,0,0,0}$
	${}^R(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{-1,3,2,6}$
	${}^R(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,8,-3,1}$
	${}^R(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{1,-7,-3,1}$
	${}^R(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{-2,-2,2,4}$
	${}^R(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{2,-2,2,-4}$
	${}^L(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{1,1,4,2}$
	${}^L(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{0,-4,-1,7}$
	${}^L(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{2,6,-1,-3}$
	${}^L(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{-1,-9,-1,-3}$
	${}^L(\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1})_{-2,6,-1,-3}$
$\hat{g}+\hat{g}^4$	${}^R(\overline{\mathbf{5}},\mathbf{1},\mathbf{1},\mathbf{5})_{0,-4,0,-2}$
	${}^R(\overline{\mathbf{5}},\mathbf{1},\mathbf{1},\mathbf{5})_{0,0,2,0}$
	${}^R(\overline{\mathbf{5}},\mathbf{1},\mathbf{1},\mathbf{5})_{1,1,-1,-1}$
	${}^R(\overline{\mathbf{5}},\mathbf{1},\mathbf{1},\mathbf{5})_{-1,3,0,0}$
	${}^R(\overline{\mathbf{5}},\mathbf{1},\mathbf{1},\mathbf{5})_{0,0,-1,3}$
$\hat{g}^2+\hat{g}^3$	${}^L(\mathbf{1},\mathbf{5},\mathbf{5},\mathbf{1})_{1,1,1,-1}$
	${}^L(\mathbf{1},\mathbf{5},\mathbf{5},\mathbf{1})_{0,-4,-1,1}$
	${}^L(\mathbf{1},\mathbf{5},\mathbf{5},\mathbf{1})_{-1,-1,0,-2}$
	${}^L(\mathbf{1},\mathbf{5},\mathbf{5},\mathbf{1})_{0,0,1,3}$
	${}^L(\mathbf{1},\mathbf{5},\mathbf{5},\mathbf{1})_{0,4,-1,-1}$

- No Tachyons at tree level
- One neutral scalar
- Chiral Matter
- Positive CC

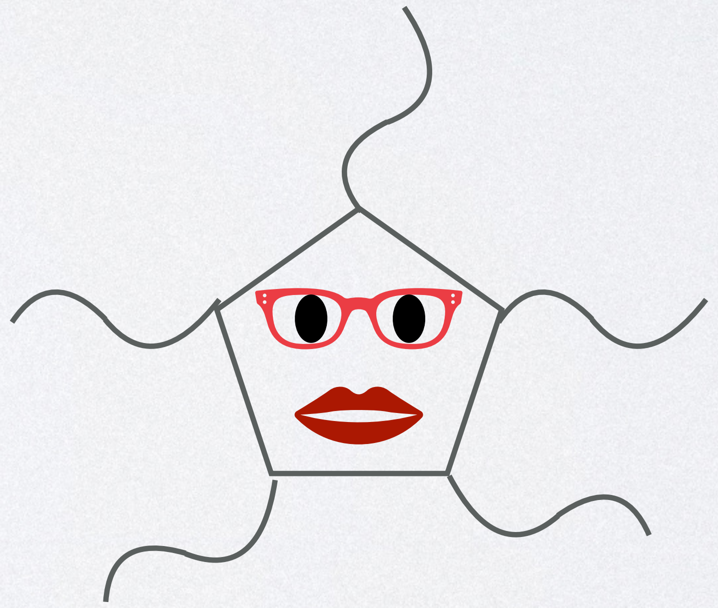
- $V(\hat{\phi})_{1\text{-loop}} \approx e^{-3\hat{\phi}}\left(2.89\times 10^{-3}\right) M_s^6\,.$

8d Non-Susy $\mathbb{Z}_3$ asymmetric orbifold

Sector	$SU(9) \times SU(9) \times U(1)^2$ reps
Untwisted	$(\mathbf{84}, \mathbf{1})_{0,0}$ $(\mathbf{1}, \mathbf{84})_{0,0}$ $(\mathbf{1}, \mathbf{1})_{0,-6}$ $(\mathbf{1}, \mathbf{1})_{-3,3}$ $(\mathbf{1}, \mathbf{1})_{3,3}$
$\hat{g} + \hat{g}^2$	$(\mathbf{9}, \mathbf{9})_{-1,1}$ $(\mathbf{9}, \mathbf{9})_{1,1}$ $(\mathbf{9}, \mathbf{9})_{0,-2}$

- Narain Lattice: $\Gamma(E_8 \times E_8) \oplus \Gamma^{2;2}(A_2)$
- Twist by : $\phi = (0^9; 2/3)$
- Shift by: $v = (2,1,0,2^3,1,2,0,2,0,2^2,0,2^2,1,0)/3$

Chiral Matter



$$(2\pi)^5 I_{10} = \frac{1}{12} X_6 Y_4$$

8d Non-Susy $\mathbb{Z}_3$ asymmetric orbifold

Sector	$SU(9)\times SU(9)\times U(1)^2$ reps
Untwisted	$(\mathbf{84},\mathbf{1})_{0,0}$
	$(\mathbf{1},\mathbf{84})_{0,0}$
	$(\mathbf{1},\mathbf{1})_{0,-6}$
	$(\mathbf{1},\mathbf{1})_{-3,3}$
	$(\mathbf{1},\mathbf{1})_{3,3}$
$\hat{g}+\hat{g}^2$	$(\mathbf{9},\mathbf{9})_{-1,1}$
	$(\mathbf{9},\mathbf{9})_{1,1}$
	$(\mathbf{9},\mathbf{9})_{0,-2}$

- No Tachyons at tree level
- One neutral scalar
- Chiral Matter
- Positive CC :

$$V_{1-loop}(\hat{\phi}) \approx e^{\frac{-8}{\sqrt{6}}\hat{\phi}}\left(1.26\times 10^{-4}\right) M_s^8$$

So we have three theories in 4, 6 and 8 dimensions

We have no tree level tachyons

They all have chiral matter

They all have positive CC

Questions and future direction

Do all tachyon free theories with one neutral scalar have chiral fermions and positive leading order potential?

Duality relation to 10d non-susy strings on T^n?

How many of these theories can we get?

Higher order fate of the theories?

Thank you very much

Construct irreducible unimodular quasicrystals

- Fix the order m of θ then $\phi(m) = r + s$ gives the dimension of the Narain Lattice $\Gamma^{r,s}$

For $m = 12$ we have $\phi(12) = 4$ so it acts irreducibly and crystallographically in 4 dimensions

- Construct lattice with this symmetry and basis $v_n = \theta^{n-1} v$ with $v \in \mathbb{R}^{r,s}$

For $m = 12$ we have the Narain Lattice $\Gamma^{2;2}$ with $v = \frac{1}{\sqrt[4]{3}}(1,0;1,0)$

- Show $\Gamma^{r,s}$ is even and unimodular

General proof

Based on

[20' Bayer-Fluckiger, Taelman]