Scanning the Heterotic String Landscape

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TUM Institute for Advanced Study Garching
and
Universe Cluster Munich

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DESY Theory Workshop 2015

Based on:

- M. Fischer, M. Ratz, J. Torrado and P. V.: 1209.3906, JHEP 1301 (2013) 084
- M. Fischer, S. Ramos-Sánchez and P. V.: 1304.7742, JHEP 1307 (2013) 080
- H. P. Nilles and P. V.: 1403.1597, Mod.Phys.Lett. A30 (2015) 10, 1530008
- S. Groot Nibbelink, O. Loukas, F. Ruehle, P.V.: 1506.00879, PRD 92 (2015) 4, 046002

Motivation

- Connect string theory to particle physics
- Framework: $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic string
- Compactify from 10d to 4d using:
  - orbifolds
  - Calabi-Yaus
- Questions in this talk:
  - How many 6d orbifold geometries are there?
  - What are their common properties for model-building?
  - What is the situation for Calabi-Yau compactifications?

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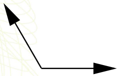
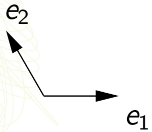
Orbifolds

Lattice Λ



Orbifolds

Lattice Λ spanned by e_1 and e_2



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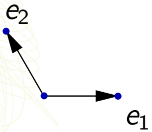

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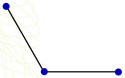

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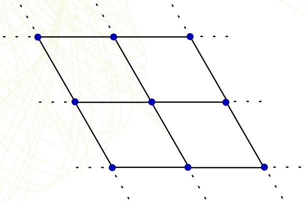
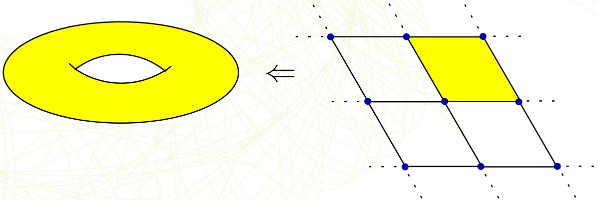


Orbifolds

Lattice $\Lambda \Rightarrow$ torus T^2

T^2 defined by $x \sim x + e_i$ for $x \in \mathbb{R}^2$



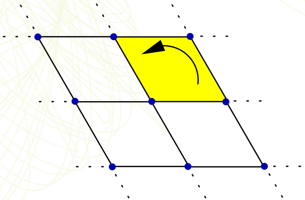
Orbifolds

Lattice $\Lambda \Rightarrow$ torus T^2

P rotational symmetry of Λ

$P = \{1, \theta, \theta^2\} = \mathbb{Z}_3$

$\theta \equiv 120^\circ$



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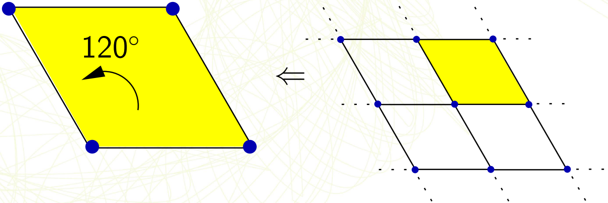
zoom-in:



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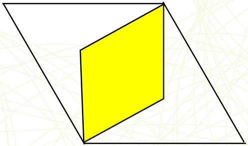
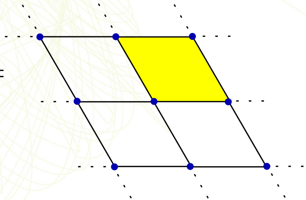
Orbifold T^2/P

$$x \sim \theta x$$



$\Leftarrow$



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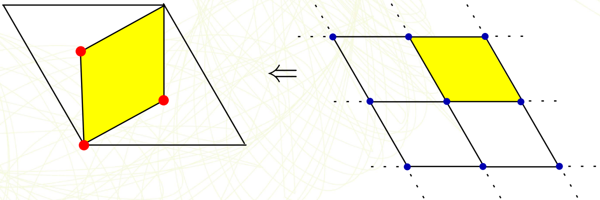
Orbifold T^2/P with 3 fixed points •



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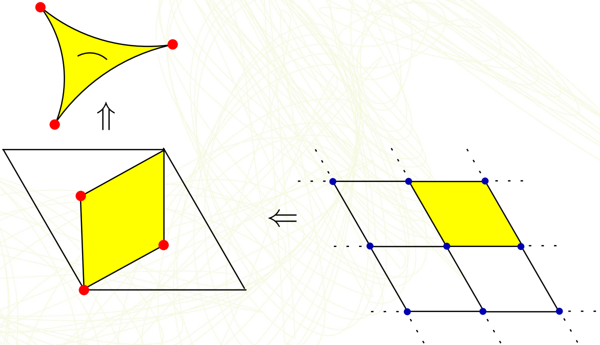

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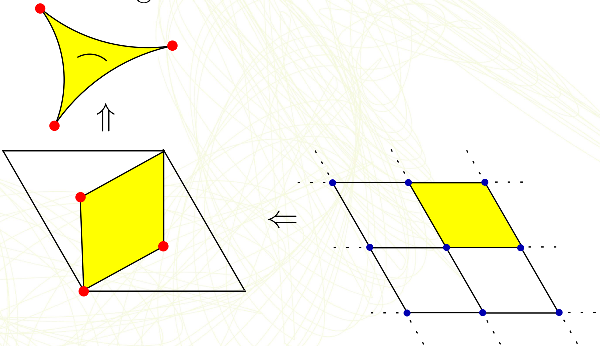
Heterotic string on orbifolds



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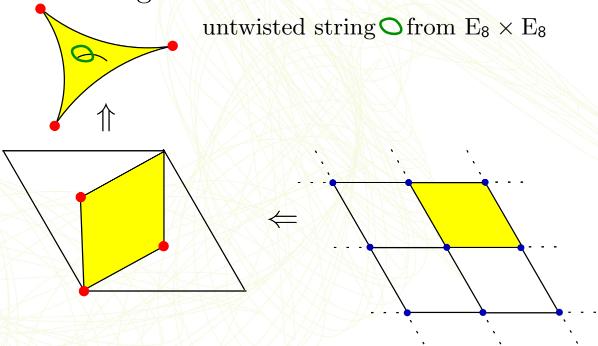

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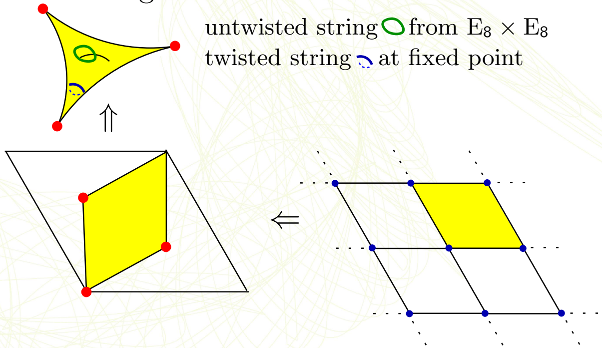
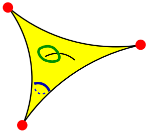


Classification of Orbifolds



in 6D

1) Lattice Λ

2) P rotational symmetry of Λ

$P \;\Leftrightarrow\; \mathcal{N} = 1$ SUSY

3) inlcude roto-translations $x \mapsto \theta x + t$

$\Rightarrow$ Crystallography

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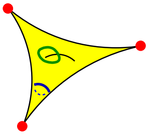

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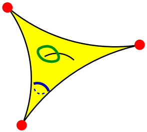
Example in 2d:

1) 17 different tilings

2) $P = \mathbb{Z}_N$ with $N = 2, 3, 4, 6$

E.g. no $\mathbb{Z}_5$ in 2d

Classification of Orbifolds



Results in 6d:

1) 60 point groups P with $\mathcal{N} \geq 1$ SUSY

2) 186 lattices Λ

include roto-translations:

3) 520 inequivalent orbifold geometries in 6d

162 with P abelian

358 with P non-abelian

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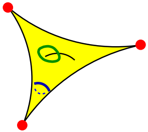

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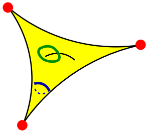

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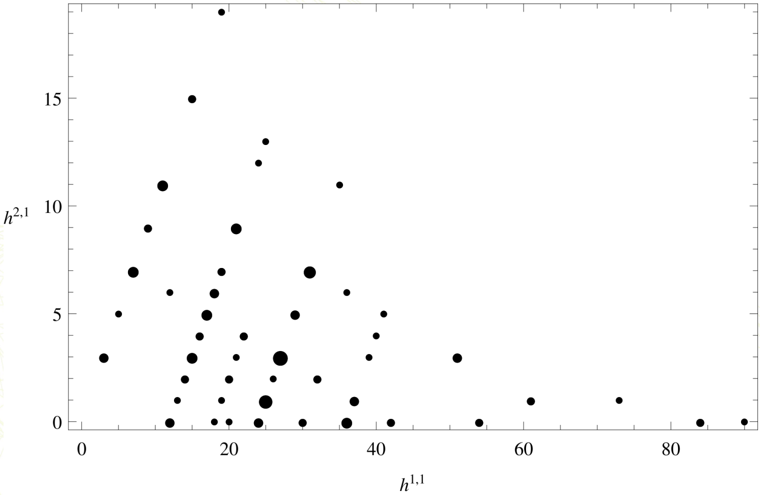
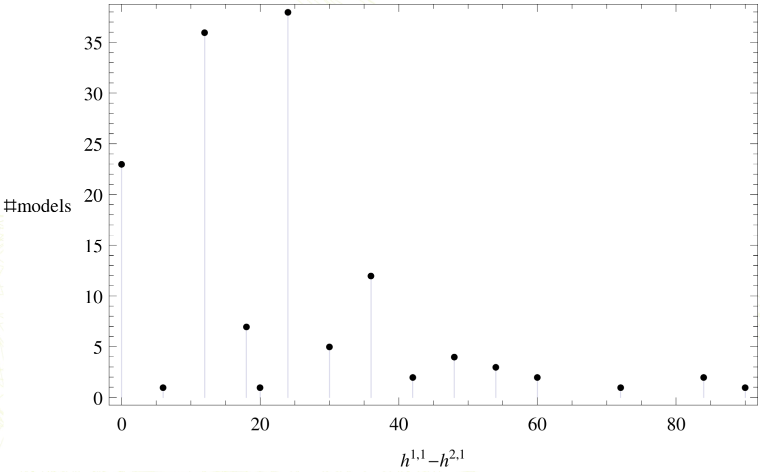
$h^{2,1}$ vs. $h^{1,1}$ for abelian orbifold geometries



M. Fischer, M. Ratz, J. Torrado and P. V. 2012

Number of generations for abelian orbifold geometries

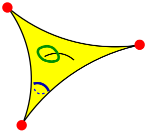


M. Fischer, M. Ratz, J. Torrado and P. V. 2012

Number of generations for abelian orbifold geometries

- $h^{1,1} - h^{2,1}$ always divisible by six
- Only exception: $(h^{1,1}, h^{2,1}) = (20, 0)$
- No geometry with three generations
  $\Rightarrow$ discrete Wilson lines needed for three generations
- computer program "orbifolder" to create and analyse orbifold models with abelian P H.P. Nilles, S. Ramos-Sanchez, P. V. and A. Wingerter 2012

Classification of Orbifolds



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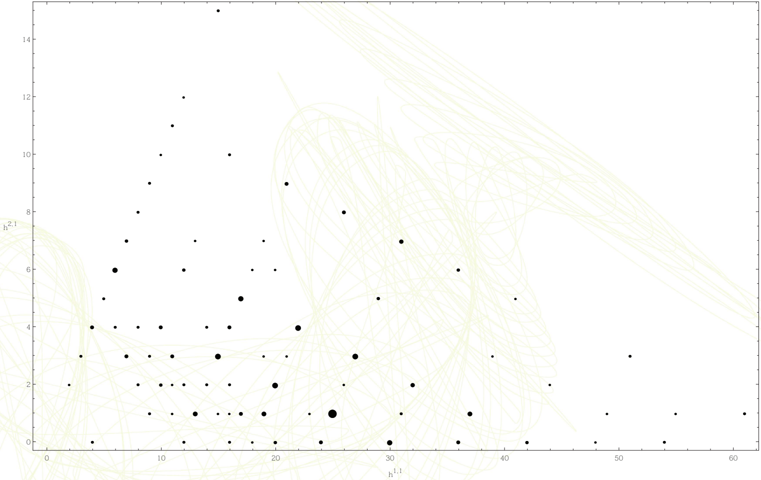
Non-abelian Orbifolds: untwisted Moduli $(h_{\mathbf{U}}^{(1,1)}, h_{\mathbf{U}}^{(2,1)})$

untwisted moduli $(h_{\mathrm{U}}^{(1,1)}, h_{\mathrm{U}}^{(2,1)})$	non-abelian point groups
(2,2)	S_3, D_4, D_6
(2,1)	QD_{16}, $(\mathbb{Z}_4 \times \mathbb{Z}_2) \rtimes \mathbb{Z}_2$, $\mathbb{Z}_4 \times S_3$, $(\mathbb{Z}_6 \times \mathbb{Z}_2) \rtimes \mathbb{Z}_2$, $\mathrm{GL}(2,3)$, $\mathrm{SL}(2,3) \rtimes \mathbb{Z}_2$
(2,0)	$\mathbb{Z}_8 \rtimes \mathbb{Z}_2$, $\mathbb{Z}_3 \times S_3$, $\mathbb{Z}_3 \rtimes \mathbb{Z}_8$, $\mathrm{SL}(2,3){-}\mathrm{I}$, $\mathbb{Z}_3 \times D_4$, $\mathbb{Z}_3 \times Q_8$, $(\mathbb{Z}_4 \times \mathbb{Z}_4) \rtimes \mathbb{Z}_2$, $\mathbb{Z}_3 \times (\mathbb{Z}_3 \rtimes \mathbb{Z}_4)$, $\mathbb{Z}_6 \times S_3$, $\mathbb{Z}_3 \times \mathrm{SL}(2,3)$, $\mathbb{Z}_3 \times ((\mathbb{Z}_6 \times \mathbb{Z}_2) \rtimes \mathbb{Z}_2)$, $\mathrm{SL}(2,3) \rtimes \mathbb{Z}_4$
(1,1)	A_4, S_4
(1,0)	T_7, $\Delta(27)$, $\mathbb{Z}_3 \times A_4$, $\Delta(48)$, $\Delta(54)$, $\mathbb{Z}_3 \times S_4$, $\Delta(96)$, $\Sigma(36\phi)$, $\Delta(108)$, $\mathrm{PSL}(3,2)$, $\Sigma(72\phi)$, $\Delta(216)$

$h^{2,1}$ vs. $h^{1,1}$ for non–abelian orbifold geometries



M. Fischer, S. Ramos-Sánchez and P. V. 2013

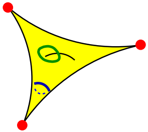
Number of generations for all orbifold geometries

- 65 orbifold geometries with $h^{1,1} = h^{2,1}$

  $\Rightarrow$ always non–chiral using standard heterotic CFT
- Magnetized orbifolds to create chirality in blow–up

  S. Groot Nibbelink and P. V. 2012

The OrbifoldLandscape



1) all $\mathbb{Z}_N$ and some $\mathbb{Z}_N \times \mathbb{Z}_M$ orbifolds

2) use "orbifolder" for MSSM models

we find $\approx$ 12000 MSSM-like models

3) lessons from this OrbifoldLandscape?

- location of matter
- location of Higgs
- flavor symmetries

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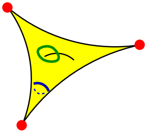

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orbifold		# MSSM	max. # of indep. WLs	# models with 0 indep. vanishing WLs	1	2	3	≥ 4	# MSSM without $\mathrm{U}(1)_{\text{anom}}$
$\mathbb{Z}_3$	(1,1)	0	3	0	0	0	0	0	0
$\mathbb{Z}_4$	(1,1)	0	4	0	0	0	0	0	0
	(2,1)	128	3	128	0	0	0	0	0
	(3,1)	25	2	25	0	0	0	0	0
$\mathbb{Z}_6$-I	(1,1)	31	1	31	0	0	0	0	0
	(2,1)	31	1	31	0	0	0	0	0
$\mathbb{Z}_6$-II	(1,1)	348	3	13	335	0	0	0	1
	(2,1)	338	3	10	328	0	0	0	2
	(3,1)	350	3	18	332	0	0	0	2
	(4,1)	334	2	39	295	0	0	0	3
$\mathbb{Z}_7$	(1,1)	0	1	0	0	0	0	0	0
$\mathbb{Z}_8$-I	(1,1)	263	2	221	42	0	0	0	7
	(2,1)	164	2	123	41	0	0	0	5
	(3,1)	387	1	387	0	0	0	0	27
$\mathbb{Z}_8$-II	(1,1)	638	3	212	404	22	0	0	7
	(2,1)	260	2	92	168	0	0	0	3
$\mathbb{Z}_{12}$-I	(1,1)	365	1	365	0	0	0	0	8
	(2,1)	385	1	385	0	0	0	0	9

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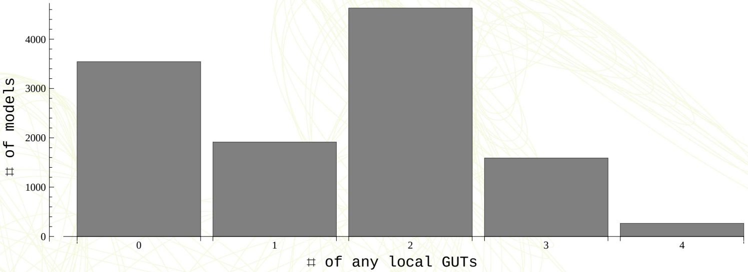
$\mathbb{Z}_{12}$-II	(1,1)	211	2	135	76	0	0	0	3
$\mathbb{Z}_2 \times \mathbb{Z}_2$	(1,1)	101	6	0	59	42	0	0	0
$\mathbb{Z}_2 \times \mathbb{Z}_4$	(1,1)	3632	4	67	2336	1199	30	0	10
$\mathbb{Z}_2 \times \mathbb{Z}_6$-I	(1,1)	445	2	332	113	0	0	0	5
$\mathbb{Z}_2 \times \mathbb{Z}_6$-II	(1,1)	0	0	0	0	0	0	0	0
$\mathbb{Z}_3 \times \mathbb{Z}_3$	(1,1)	445	3	1	369	75	0	0	9
$\mathbb{Z}_3 \times \mathbb{Z}_6$	(1,1)	465	1	441	24	0	0	0	0
$\mathbb{Z}_4 \times \mathbb{Z}_4$	(1,1)	1466	3	11	529	921	5	0	1
$\mathbb{Z}_6 \times \mathbb{Z}_6$	(1,1)	1128	0	1128	0	0	0	0	0
total		11940							102

Local GUTs

Fixed point with local GUT (e.g. SO(10) or SU(5)) and localized matter representation:



H.P. Nilles and P. V. 2014

Locations with split multiplets for Higgs

- Higgs in split GUT representation
- Origin? Location in higher dim. where GUT group is broken, i.e. 10d bulk

H.P. Nilles and P. V. 2014

Calabi-Yau

Complete Intersection Calabi-Yau: CICY 7862

Candelas, Dale, Lutken, Schimmrigk - 1987

- CY X described as hypersurface in product of projective spaces
- Hodge numbers $h_{11} = 4$ and $h_{21} = 68$
  $\Rightarrow$ four divisors: D_i, $i = 1, \dots, h_{11} = 4$
- Non-vanishing triple intersection numbers and second Chern classes:

$$\kappa_{ijk} = \int_X D_i D_j D_k = 2 \quad \text{and} \quad c_{2i} = \int_{D_i} c_2 = 24$$

for $i \neq j \neq k \neq i$ from 1 to $h_{11} = 4$

Line bundle gauge background

- CICY 7862 X with $\mathrm{S}(\mathrm{U}(1)^5) = \mathrm{U}(1)^4$ gauge background.
- Specified by five vectors $k_{(a)} = (k^1_{(a)}, \ldots, k^4_{(a)}) \in \mathbb{Z}^4$, $a = 1, \ldots, 5$:

$$\mathcal{V} = \bigoplus_{a=1}^{5} \mathcal{O}_X\left(k^1_{(a)}, \ldots, k^4_{(a)}\right) \quad \text{with} \quad \sum_{a=1}^{5} k_{(a)} = 0$$

- Alternative description:

$$\frac{\mathcal{F}}{2\pi} = D_i\, H_i \ , \quad H_i = V_i^I\, H_I \quad \text{where}$$

  - D_i with $i = 1, \ldots, h_{11} = 4$: two-forms, Poincaré-dual to the divisors
  - H_I with $I = 1, \ldots, 16$: Cartan generators of $\mathrm{E}_8 \times \mathrm{E}_8$
  - V_i with $i = 1, \ldots, h_{11} = 4$: 16-component line bundle vectors

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  - V_i with $i = 1, \ldots, h_{11} = 4$: 16-component line bundle vectors

Line bundle gauge background

- Write line bundle vector $V_i = (V_i', V_i'')$ for observable and hidden E_8
- Given the five vectors $k_{(a)}$ the corresponding line bundle vectors in the observable E_8 are

$$V_i' = (a_i^5, b_i, c_i, d_i)$$

  (Exponent 5 indicates 5-times repetition)
- Using

$$\begin{pmatrix} a_i \\ b_i \\ c_i \\ d_i \end{pmatrix} = -\frac{1}{2} \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & -1 & 1 \\ -1 & 1 & -1 & 1 \\ -1 & -1 & 1 & 1 \end{pmatrix} \begin{pmatrix} k^i_{(1)} \\ k^i_{(2)} \\ k^i_{(3)} \\ k^i_{(4)} \end{pmatrix}$$

  for $i = 1, \ldots, h_{11}$

Line bundle gauge background

- Choose Model number 2, identifier $\{7862, 4, 5\}$

$$\left(k^i{}_{(a)}\right) = \begin{pmatrix} 1 & 1 & 0 & -1 & -1 \\ -1 & -2 & 0 & 2 & 1 \\ -1 & 0 & -1 & 2 & 0 \\ 1 & 1 & 1 & -3 & 0 \end{pmatrix}$$

Anderson, Gray, Lukas, Palti - 2011

- Corresponding line bundle vectors:

$$\begin{aligned} V_1 &= \left(-\frac{1}{2}^5, \frac{1}{2}, \frac{1}{2}, \frac{3}{2}\right)(0^8) \\ V_2 &= \left(\frac{1}{2}^5, -\frac{3}{2}, -\frac{1}{2}, -\frac{5}{2}\right)(0^8) \\ V_3 &= \left(0^5, -1, -2, -1\right)(0^8) \\ V_4 &= \left(0^5, 2, 2, 2\right)(0^8) \end{aligned}$$

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Line bundle gauge background

- Integrated BIs of the Kalb-Ramond field in the presence of NS5 branes:

$$\begin{aligned} N_i &= N_i' + N_i'' \\ N_i' &= c_{2i} + \kappa_{ijk}\, V_j' \cdot V_k' \\ N_i'' &= c_{2i} + \kappa_{ijk}\, V_j'' \cdot V_k'' \end{aligned}$$

  for all divisors D_i , $i = 1, \ldots, h_{11} = 4$.
- BIs $\Rightarrow$ anomaly cancellation in the 4D EFT
- Unbroken SUSY requires $N_i \geq 0$
- We will choose V_i'' such that $N_i = 0$, i.e. $N_i'' = -N_i'$
- Chiral part of the 4D matter spectrum: multiplicity operator:

$$\mathcal{N} = \frac{1}{6}\, \kappa_{ijk}\, H_i H_j H_k + \frac{1}{12} c_{2i}\, H_i$$

  evaluated on each root p of $\mathrm{E}_8 \times \mathrm{E}_8$ using $H_i(p) = V_i \cdot p$ (and checked with cohomCalg) Blumenhagen, Jurke, Rahn, Roschy - 2010

Infinite set of MSSM-like models?

- BIs with $N_i = 0$ for CICY 7862:

$$24 + \sum_{i \neq j = 1}^{4} V_i \cdot V_j = 0$$

- Allows for infinite number of solutions, e.g.

$$\begin{aligned}
V_1 &= \left(-\frac{1}{2}^5, \frac{1}{2}, \frac{1}{2}, \frac{3}{2}\right)\left(\ 1^4,\ 0, -2,\ 0,\ 0\right)\\
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for all $k \in \mathbb{Z}$

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Infinite set of MSSM-like models?

- Gauge group $SU(5) \times SU(4) \times U(1)^9$
- Chiral spectrum (omitting U(1) charges):

Observable E_8		Hidden E_8	
Mult.	Rep.	Mult.	Rep.
12	$(\overline{\mathbf{5}}, \mathbf{1})$	$12k + 8$	$(\mathbf{1}, \mathbf{4})$
12	$(\mathbf{10}, \mathbf{1})$	$12k + 8$	$(\mathbf{1}, \overline{\mathbf{4}})$
		$4k$	$(\mathbf{1}, \mathbf{6})$
60	$(\mathbf{1}, \mathbf{1})$	$80k + 8$	$(\mathbf{1}, \mathbf{1})$

- Pure, mixed (non-)Abelian gauge and gravitational anomalies cancel for all k via generalized Green-Schwarz mechanism
- One-loop corrected DUY equations satisfied using VEVs of charged fields

Blumenhagen, Honecker, Weigand - 2005

- Order 4 symmetry of $X \Rightarrow$ 3 generation MSSM

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Conclusion

- Complete classification of orbifold geometries with $\mathcal{N} \geq 1$ SUSY (Abelian and non-Abelian)
- $\Rightarrow$ 520 orbifold geometries
- Useful tool for abelian P: "orbifolder"
- The OrbifoldLandscape: $\approx$ 12000 MSSM-like models
- Lessons:
  - Location of matter: local GUTs
  - Location of Higgs: 10d bulk
  - Discrete flavor symmetries
- Calabi-Yau case:
  - MSSM like-models
  - Hidden E_8: infinite set of models? At the boundary of the Kähler cone?