String Pheno in the Heterotic OrbifoldLandscape

Patrick K. S. Vaudrevange

Universe Cluster Munich

July 7th, 2014

String Pheno 2014, Trieste

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

Motivation

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

Motivation

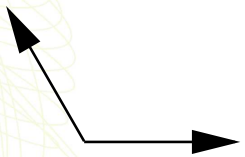
- Connect string theory to particle physics
- Framework: $\mathrm{E}_8 \times \mathrm{E}_8$ heterotic string
- Compactify from 10d to 4d on orbifold
- Questions in this talk:
  - How many 6d orbifold geometries are there?
  - What are their common properties for model-building?

Motivation

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

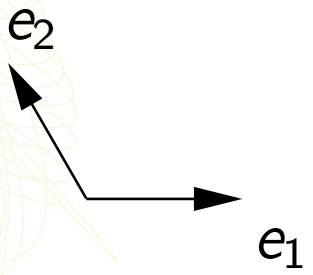
Orbifolds

Lattice Λ



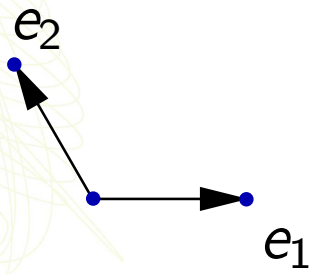
Orbifolds

Lattice Λ spanned by e_1 and e_2



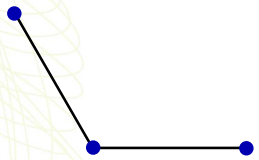
Orbifolds

Lattice Λ spanned by e_1 and e_2



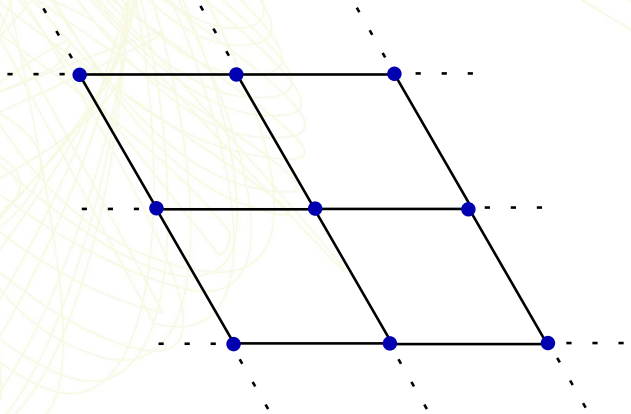
Orbifolds

Lattice Λ



Orbifolds

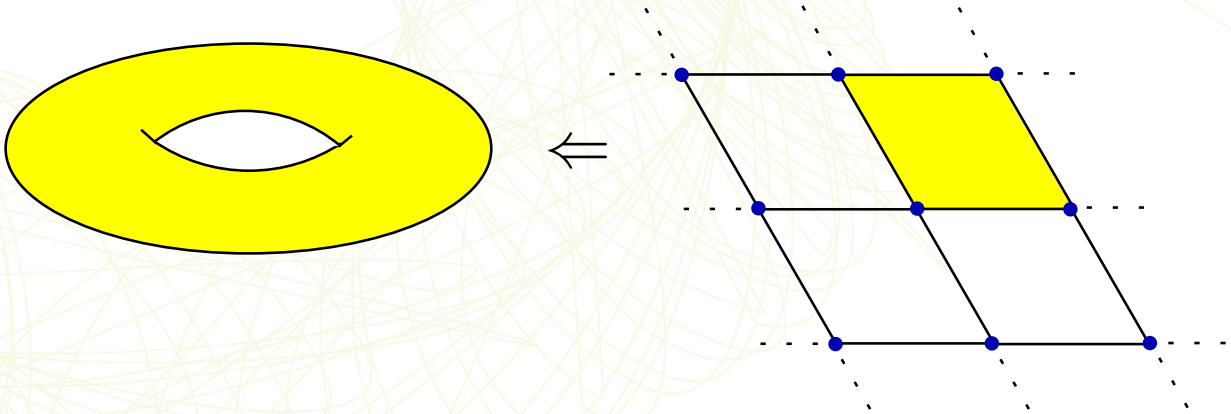
Lattice Λ



Orbifolds

Lattice $\Lambda \Rightarrow$ torus T^2

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



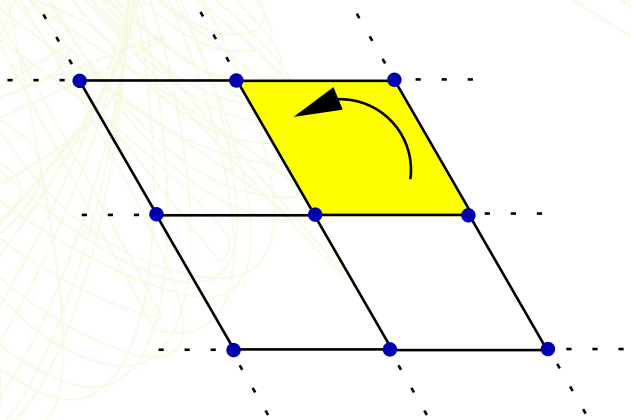
Orbifolds

Lattice $\Lambda \Rightarrow$ torus T^2

P rotational symmetry of Λ

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

$$\theta \equiv 120^\circ$$

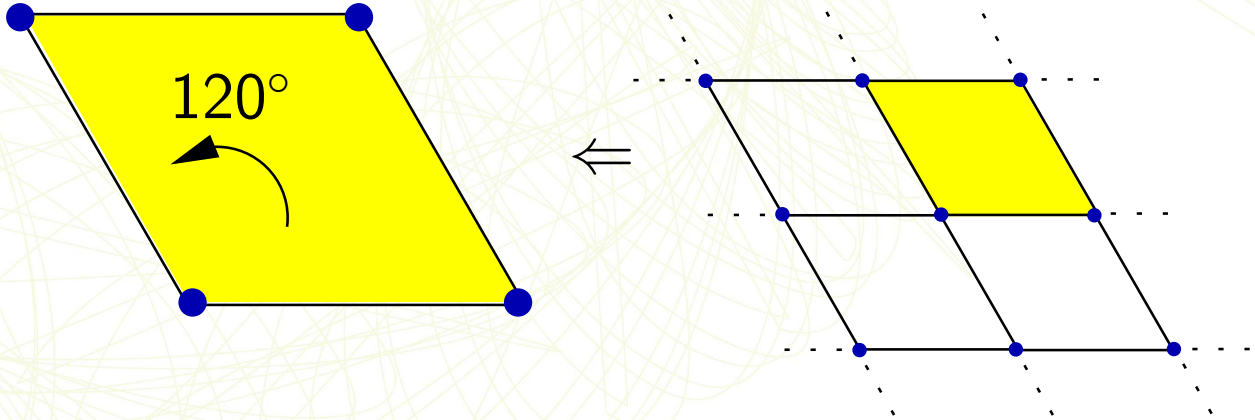


Orbifolds

Lattice $\Lambda \Rightarrow$ torus T^2

P rotational symmetry of Λ

zoom-in:



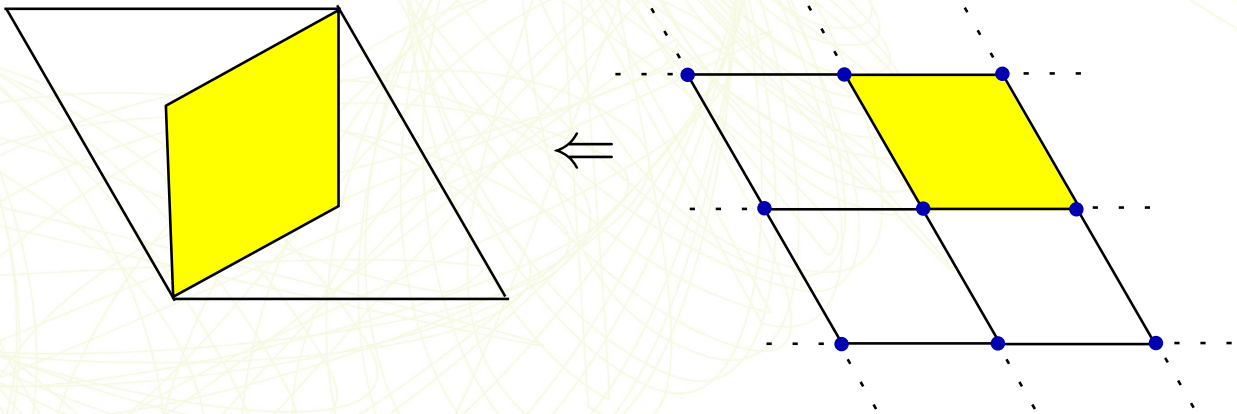
Orbifolds

Lattice $\Lambda \Rightarrow$ torus T^2

P rotational symmetry of Λ

Orbifold T^2/P

$$x \sim \theta x$$

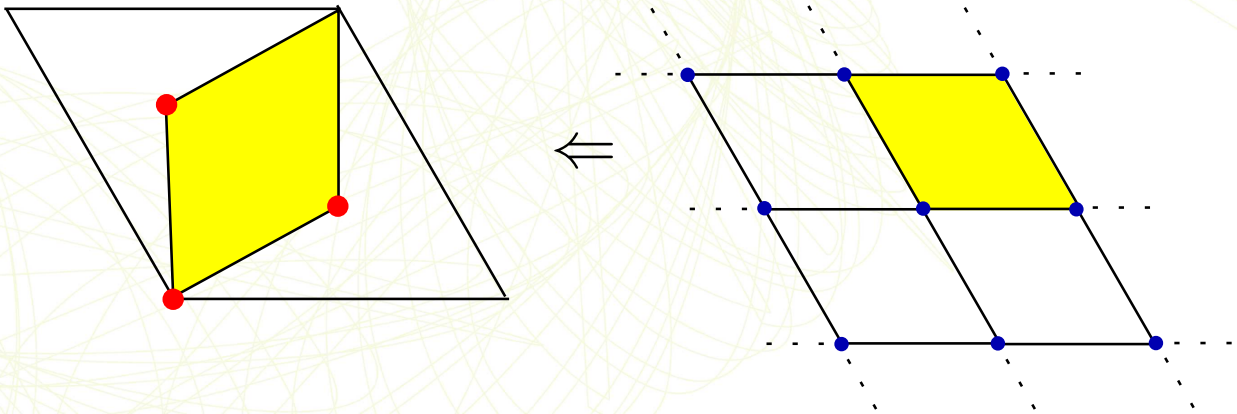


Orbifolds

Lattice $\Lambda \Rightarrow$ torus T^2

P rotational symmetry of Λ

Orbifold T^2/P with 3 fixed points •

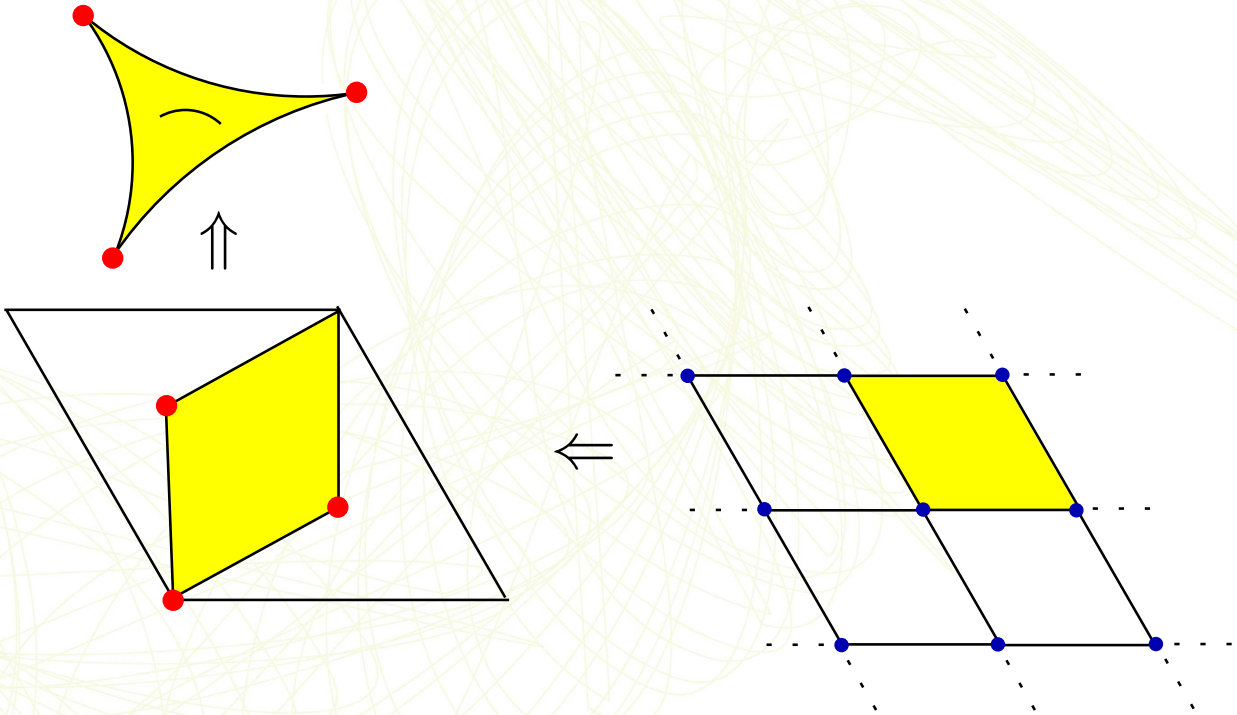


Orbifolds

Lattice $\Lambda \Rightarrow$ torus T^2

P rotational symmetry of Λ

Orbifold T^2/P with 3 fixed points



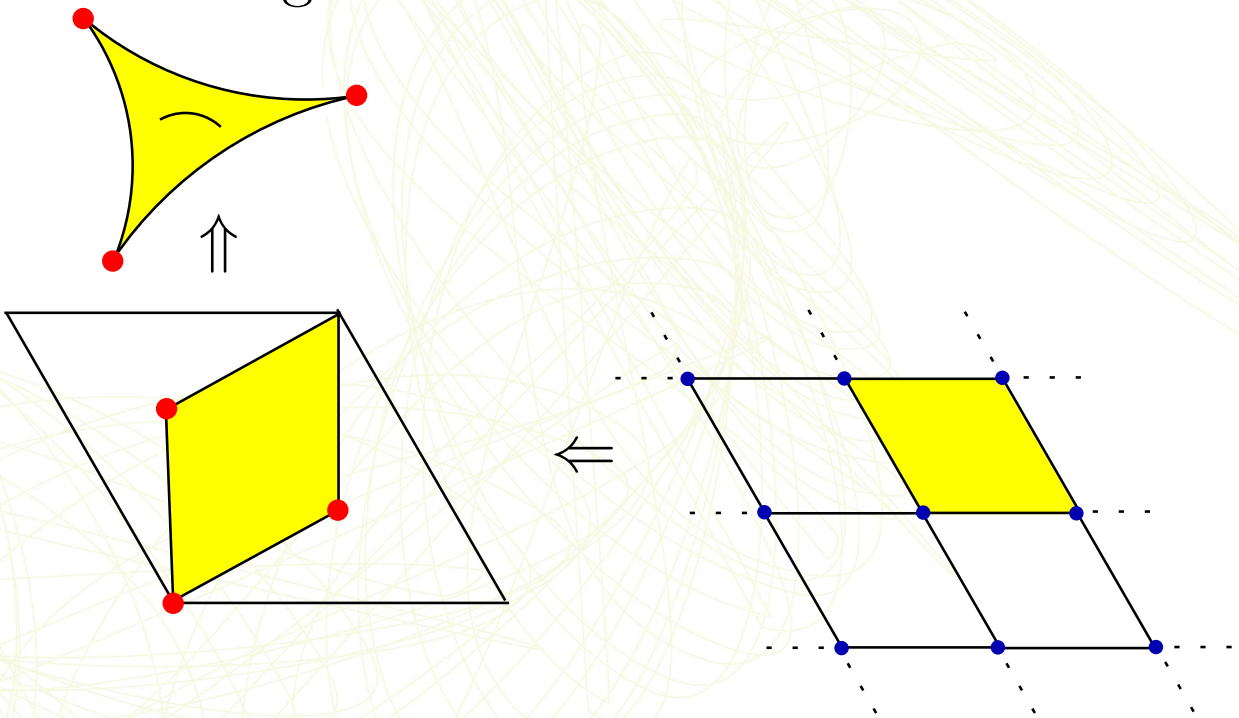
Orbifolds

Lattice $\Lambda \Rightarrow$ torus T^2

P rotational symmetry of Λ

Orbifold T^2/P with 3 fixed points

Heterotic string on orbifolds



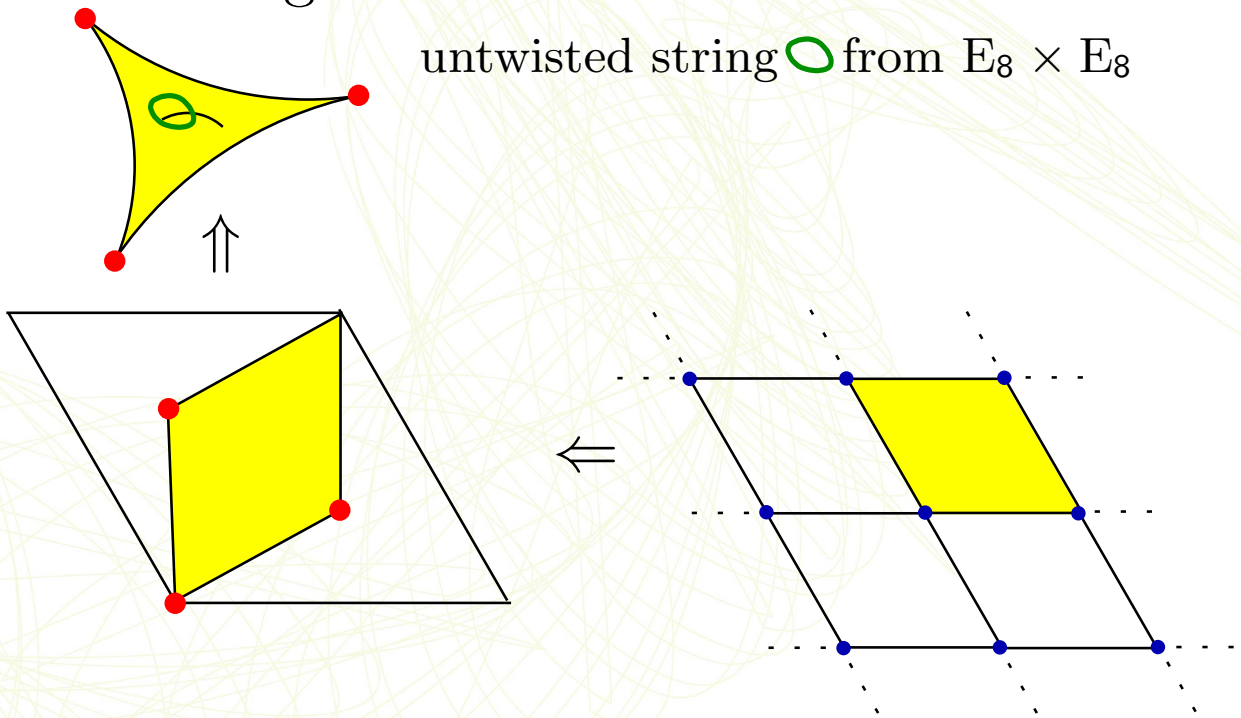
Orbifolds

Lattice $\Lambda \Rightarrow$ torus T^2

P rotational symmetry of Λ

Orbifold T^2/P with 3 fixed points •

Heterotic string on orbifolds



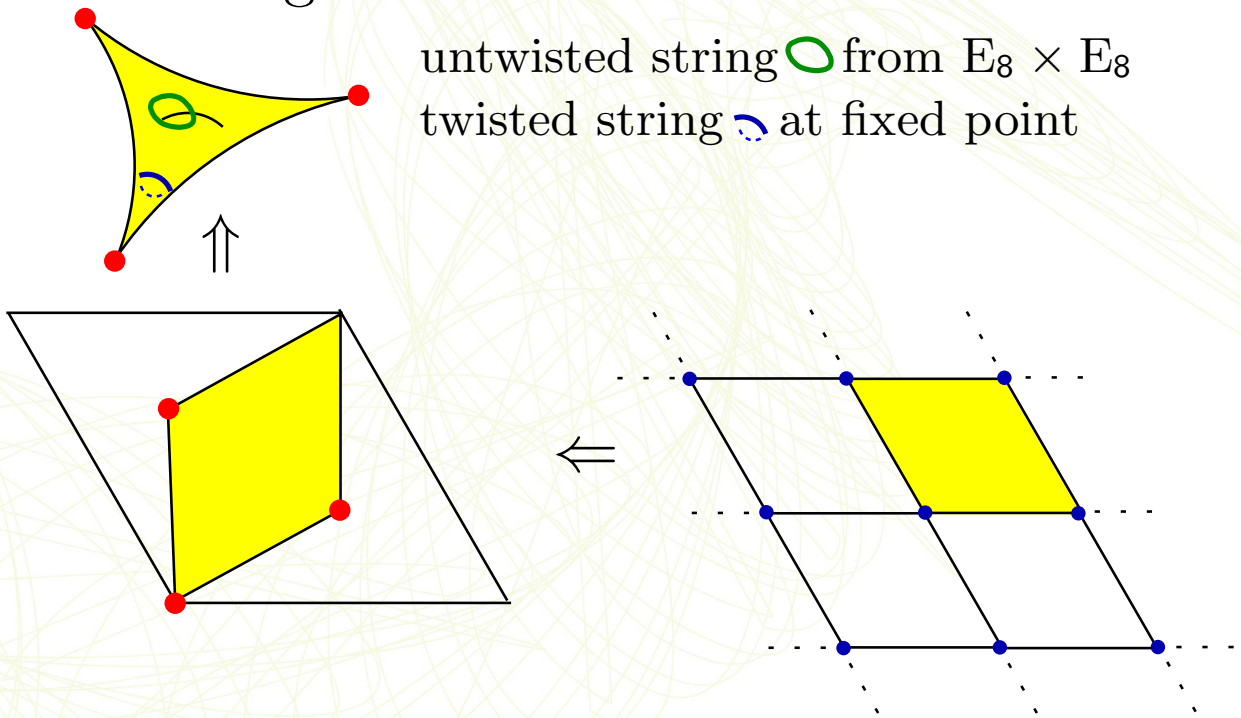
Orbifolds

Lattice $\Lambda \Rightarrow$ torus T^2

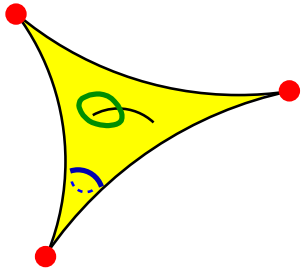
P rotational symmetry of Λ

Orbifold T^2/P with 3 fixed points

Heterotic string on orbifolds



Classification of Orbifolds



in 6D

1) Lattice Λ

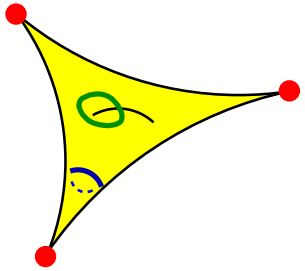
2) P rotational symmetry of Λ

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

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

$\Rightarrow$ Crystallography

Classification of Orbifolds



in 6D

1) Lattice Λ

2) P rotational symmetry of Λ

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

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

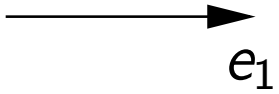
$\Rightarrow$ Crystallography

Example in 2d:

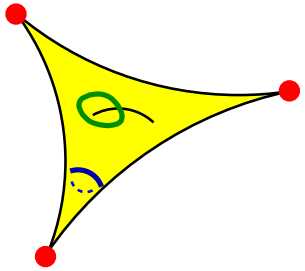
1) 17 different tilings

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

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



Classification of Orbifolds



in 6D

1) Lattice Λ

2) P rotational symmetry of Λ

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

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

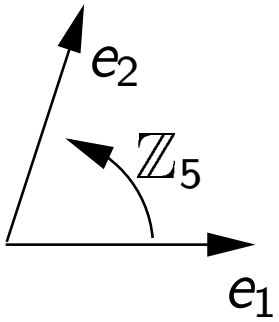
$\Rightarrow$ Crystallography

Example in 2d:

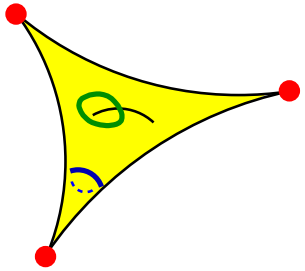
1) 17 different tilings

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

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



Classification of Orbifolds



in 6D

1) Lattice Λ

2) P rotational symmetry of Λ

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

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

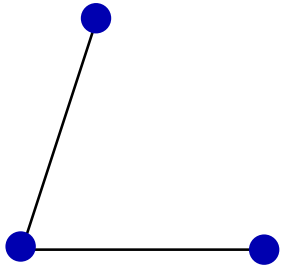
$\Rightarrow$ Crystallography

Example in 2d:

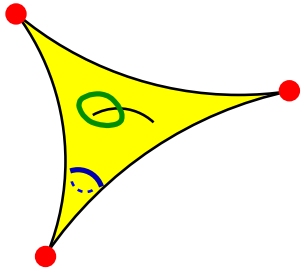
1) 17 different tilings

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

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



Classification of Orbifolds



in 6D

1) Lattice Λ

2) P rotational symmetry of Λ

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

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

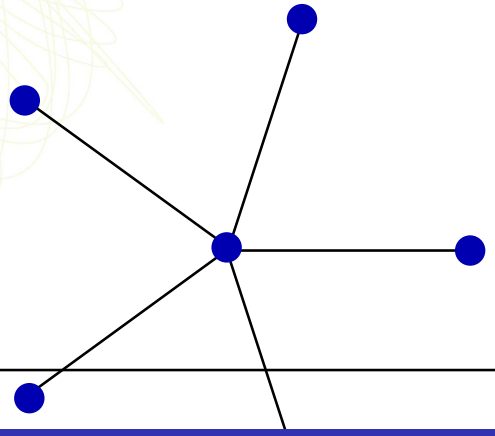
$\Rightarrow$ Crystallography

Example in 2d:

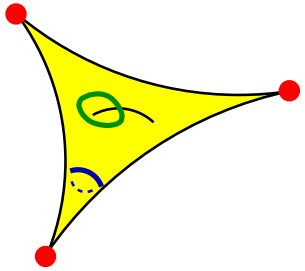
1) 17 different tilings

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

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



Classification of Orbifolds



in 6D

1) Lattice Λ

2) P rotational symmetry of Λ

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

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

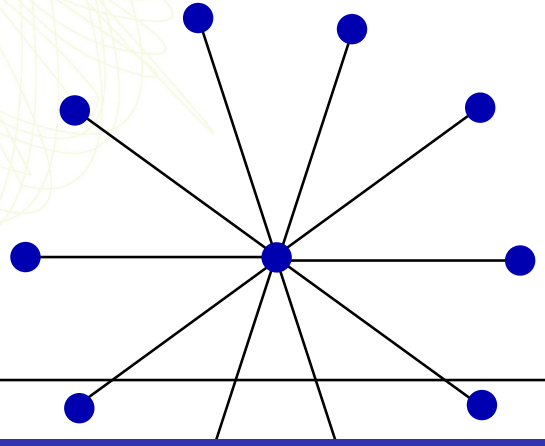
$\Rightarrow$ Crystallography

Example in 2d:

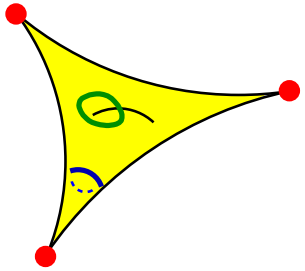
1) 17 different tilings

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

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



Classification of Orbifolds



in 6D

1) Lattice Λ

2) P rotational symmetry of Λ

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

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

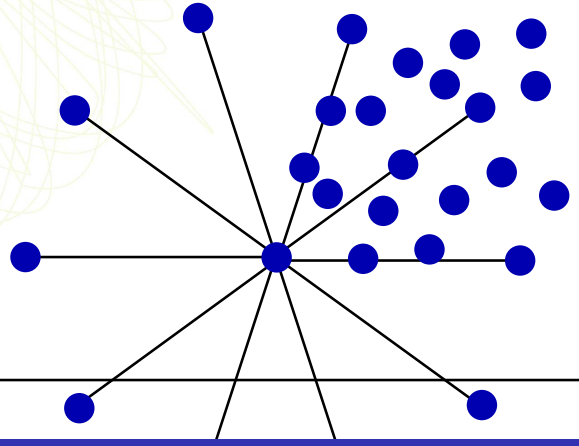
$\Rightarrow$ Crystallography

Example in 2d:

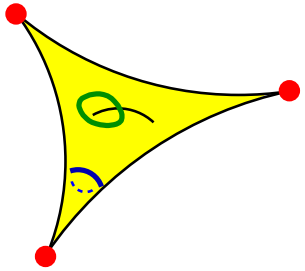
1) 17 different tilings

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

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



Classification of Orbifolds



in 6D

1) Lattice Λ

2) P rotational symmetry of Λ

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

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

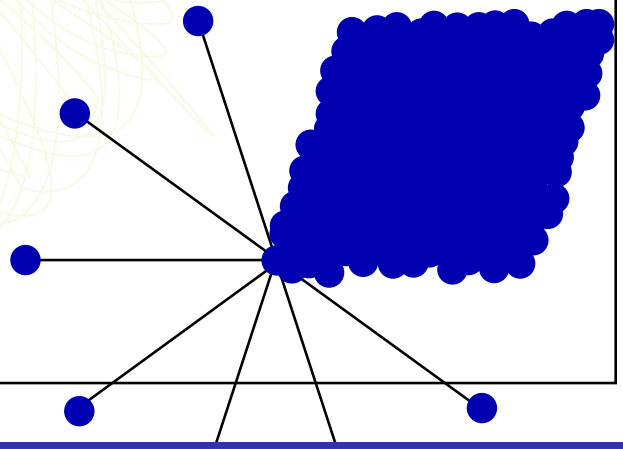
$\Rightarrow$ Crystallography

Example in 2d:

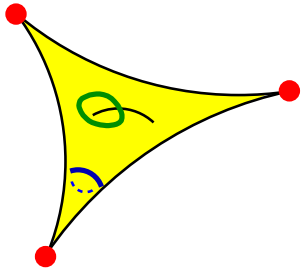
1) 17 different tilings

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

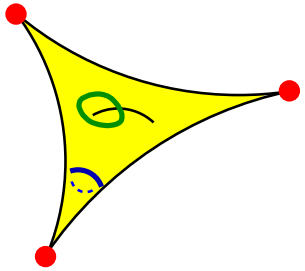
include roto-translations:

3) 520 inequivalent orbifold geometries in 6d

162 with P abelian

358 with P non-abelian

Classification of Orbifolds



Results in 6d:

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

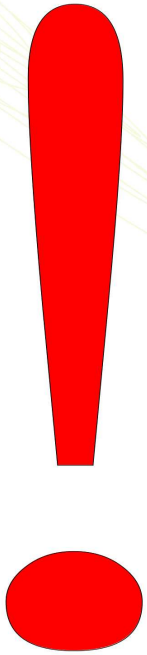
2) 186 lattices Λ

include roto-translations:

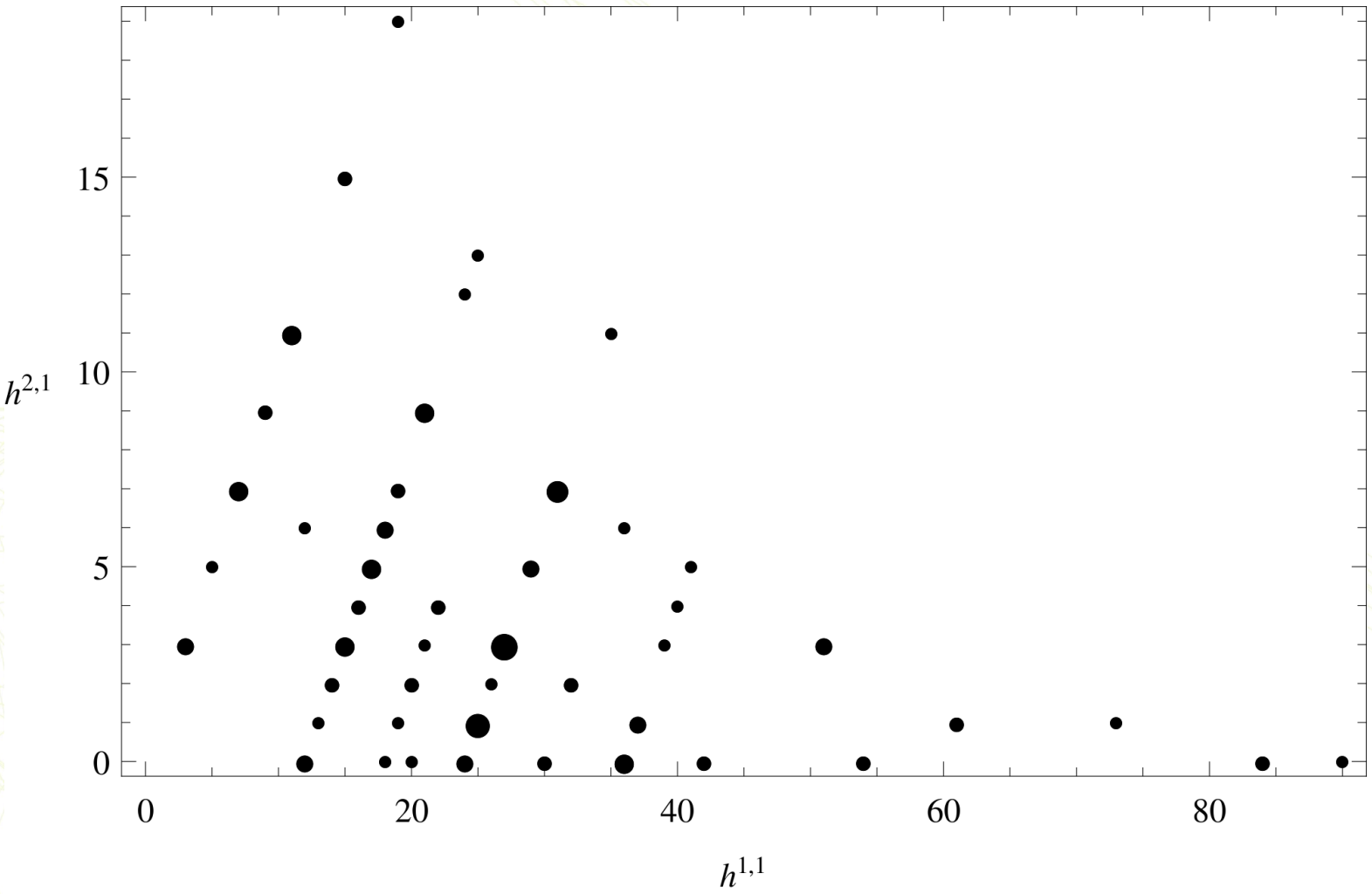
3) 520 inequivalent orbifold geometries in 6d

162 with P abelian

358 with P non-abelian

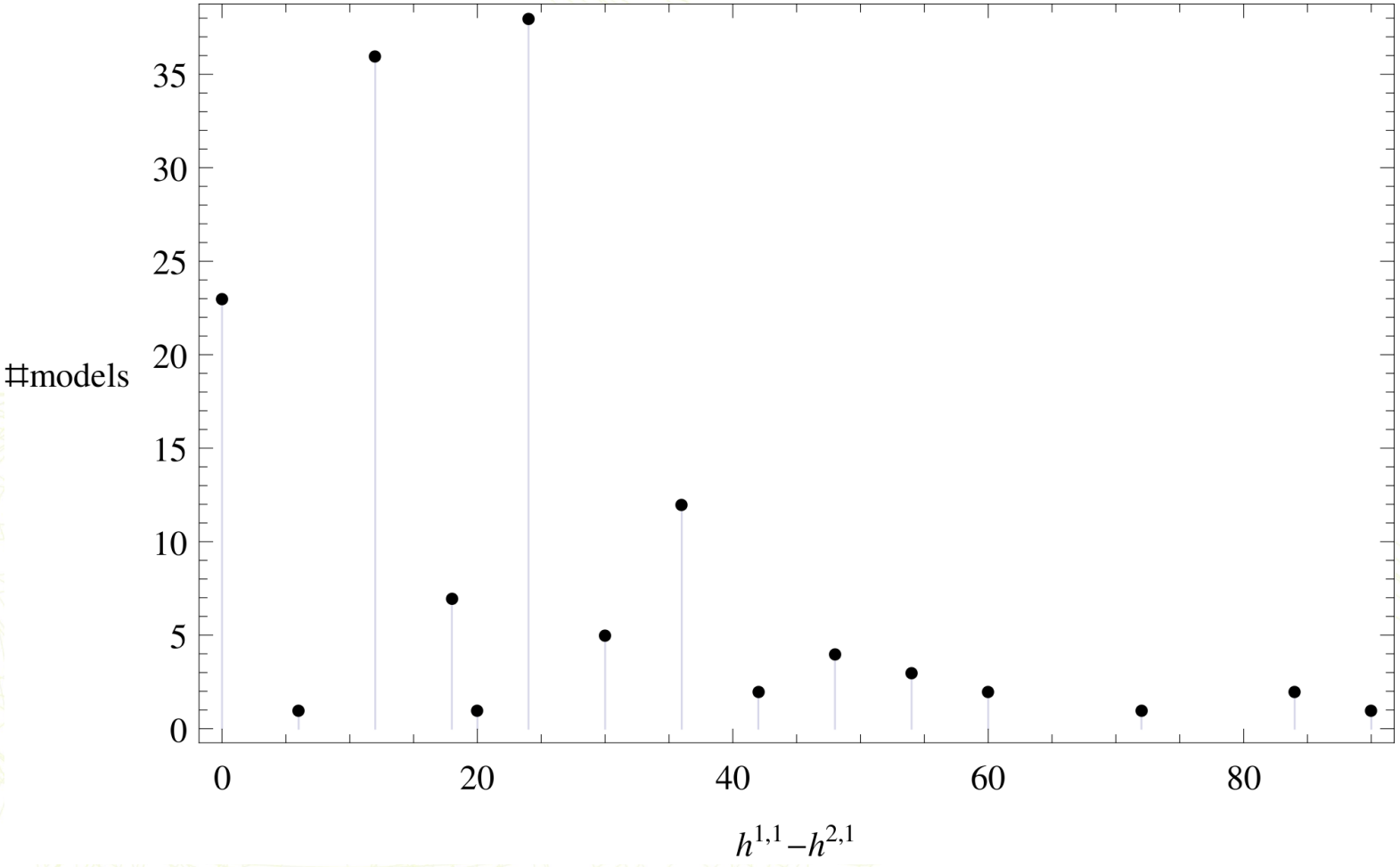


$h^{2,1}$ vs. $h^{1,1}$ for abelian orbifold geometries



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

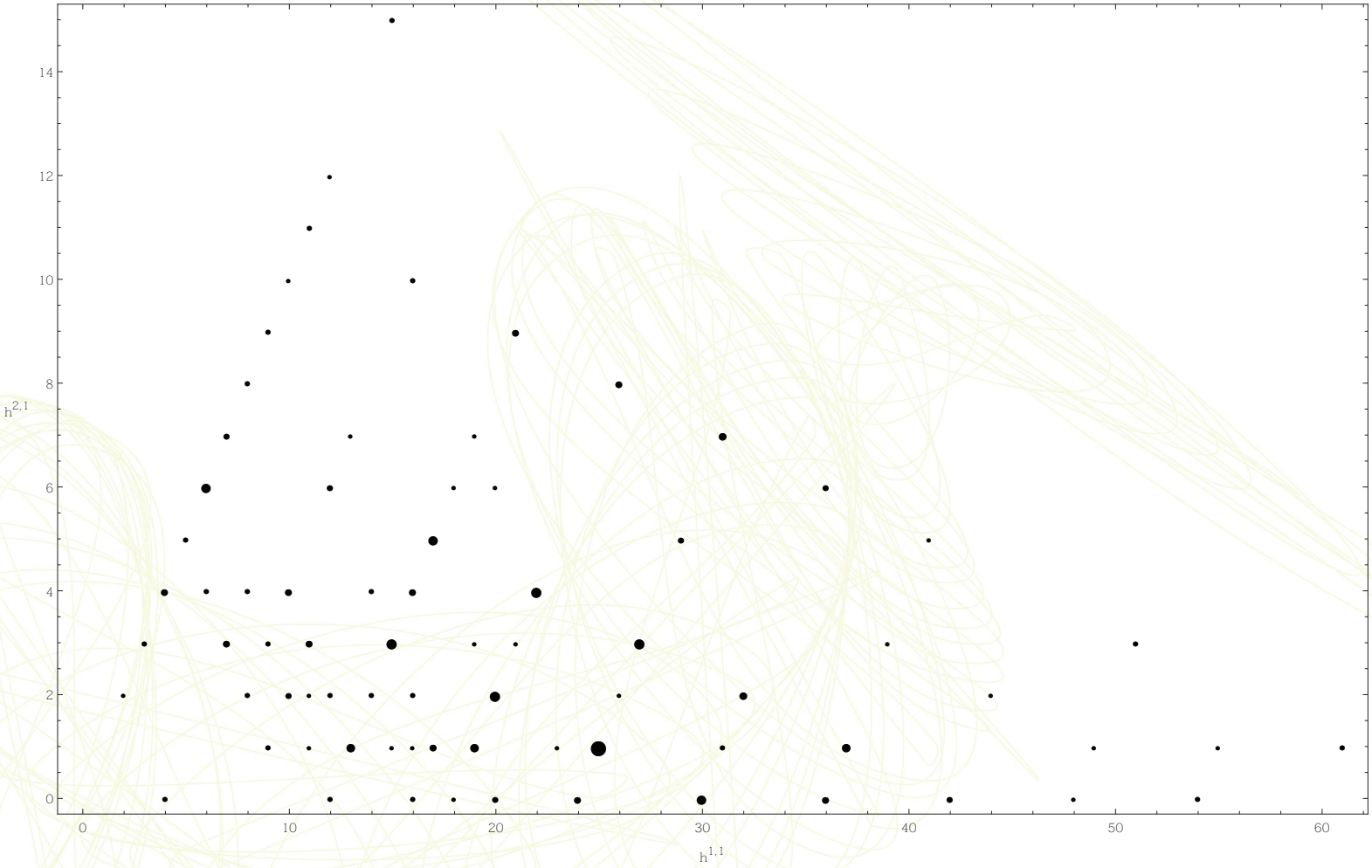
Number of generations for abelian orbifold geometries

- $h^{1,1} - h^{2,1}$ 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

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

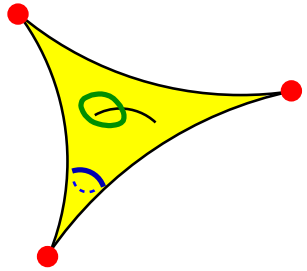
Number of generations for all orbifold geometries

- 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

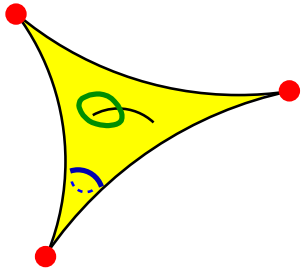
The OrbifoldLandscape



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?

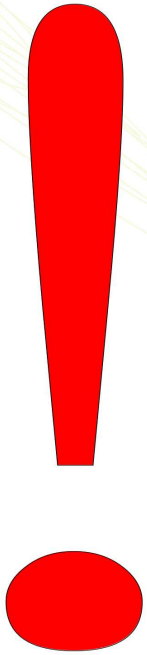
- location of matter
- location of Higgs
- flavor symmetries
- gaugino condensation and SUSY breaking

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
- gaugino condensation and SUSY breaking



The OrbifoldLandscape

orbifold		# MSSM	max. # of indep. WLs	# models with 0 indep. vanishing WLs	1	2	3	≥ 4	# MSSM without $U(1)_{anom}$
$\mathbb{Z}_3$	(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

The OrbifoldLandscape

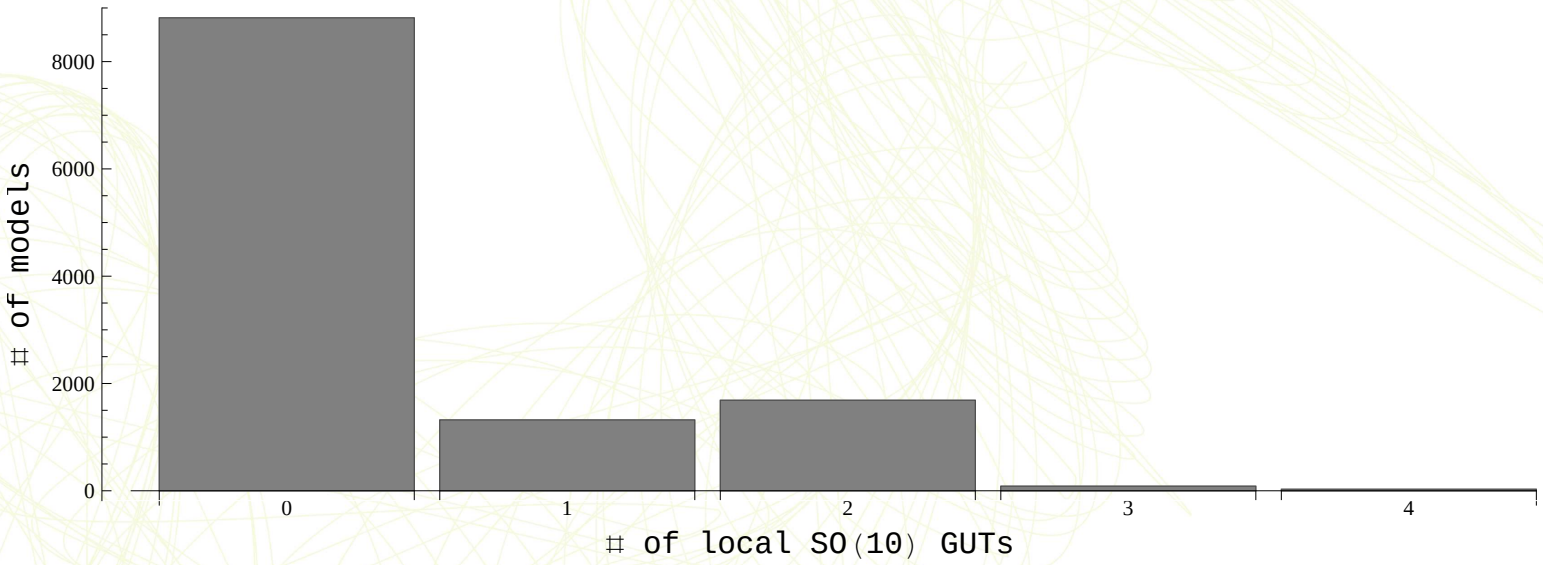
orbifold		# MSSM	max. # of indep. WLs	# models with 0 indep. vanishing WLs	1	2	3	≥ 4	# MSSM without $U(1)_{anom}$
$\mathbb{Z}_3$	(1,1)	0	3	0	0	0	0	0	0
$\mathbb{Z}_4$	(1,1)	0	4	0	0	0	0	0	0
	(2,1)	128	3	128	0	0	0	0	0
	(3,1)	25	2	25	0	0	0	0	0
$\mathbb{Z}_6$-I	(1,1)	31	1	31	0	0	0	0	0
	(2,1)	31	1	31	0	0	0	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

The OrbifoldLandscape

orbifold		# MSSM	max. # of indep. WLs	# models with 0 indep. vanishing WLs	1	2	3	≥ 4	# MSSM without $U(1)_{anom}$
$\mathbb{Z}_{12}$-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

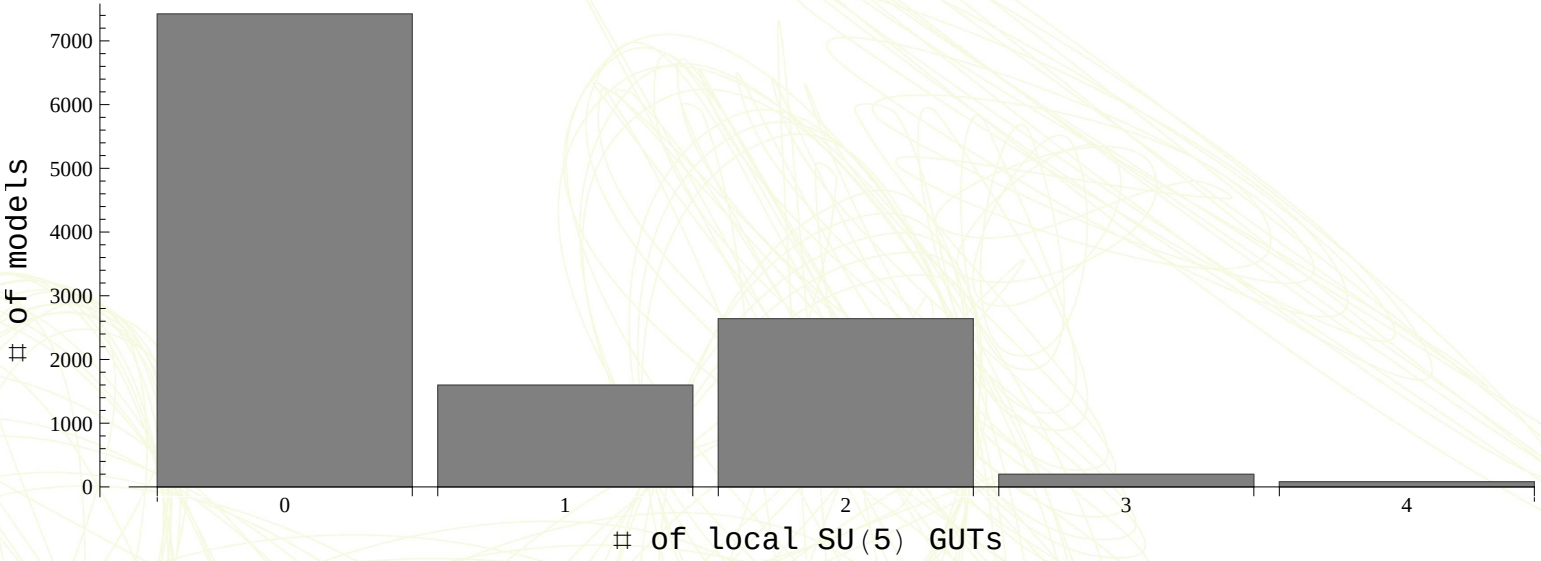
Local $\mathrm{SO}(10)$ GUTs

- Matter in complete GUT representation: **16** of $\mathrm{SO}(10)$
- Origin? Twisted matter at fixed point with enhanced $\mathrm{SO}(10)$ symmetry



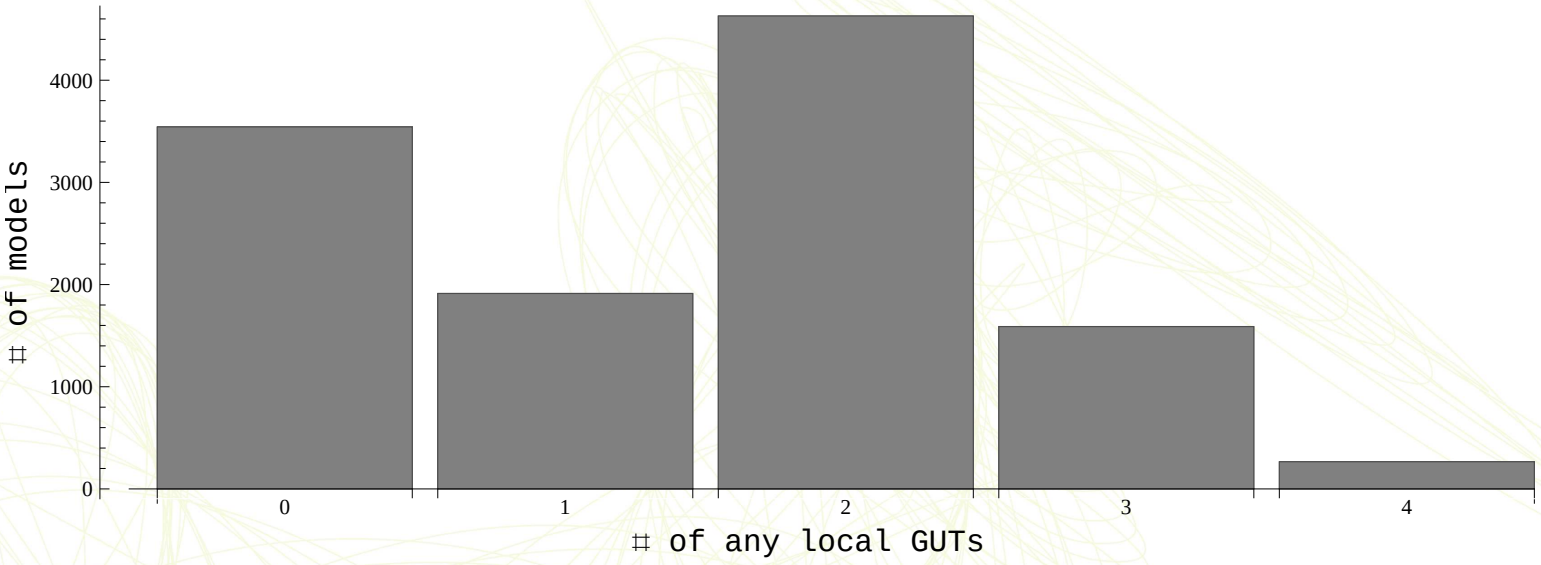
H.P. Nilles and P. V. 2014

Local $\mathrm{SU}(5)$ GUTs



H.P. Nilles and P. V. 2014

Any local GUTs



H.P. Nilles and P. V. 2014

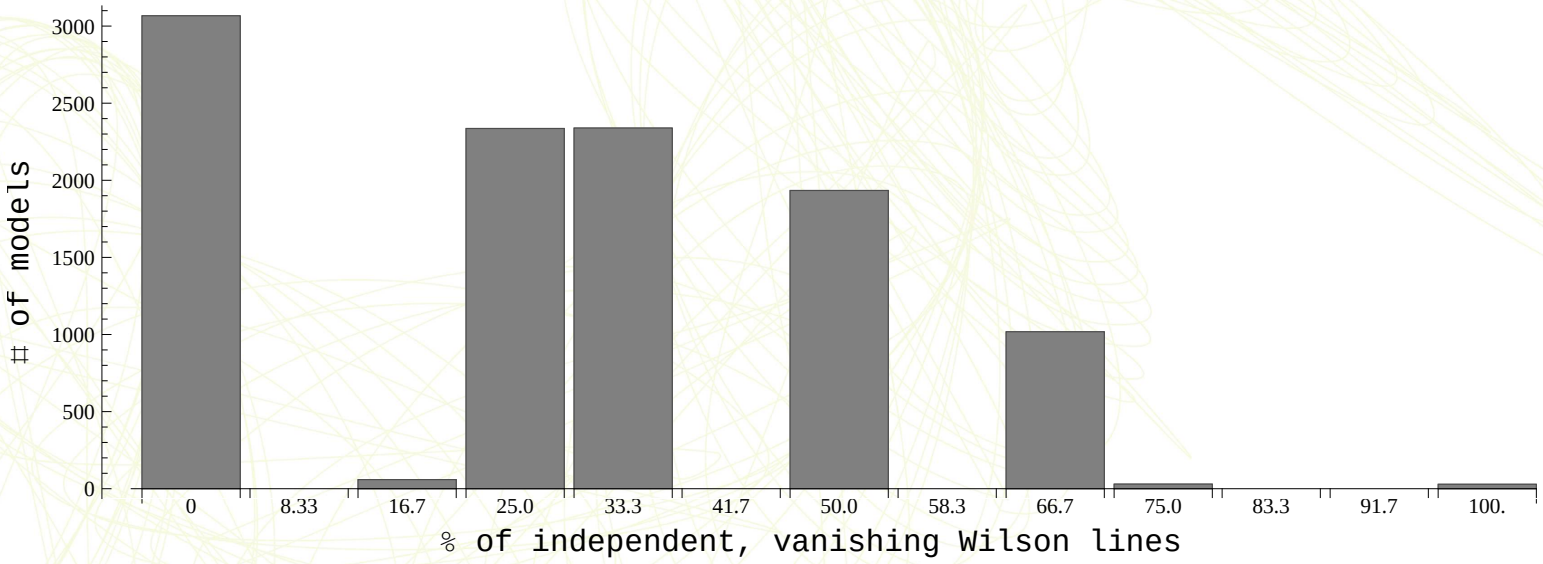
Locations with split multiplets for Higgs

- 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

Flavor symmetries

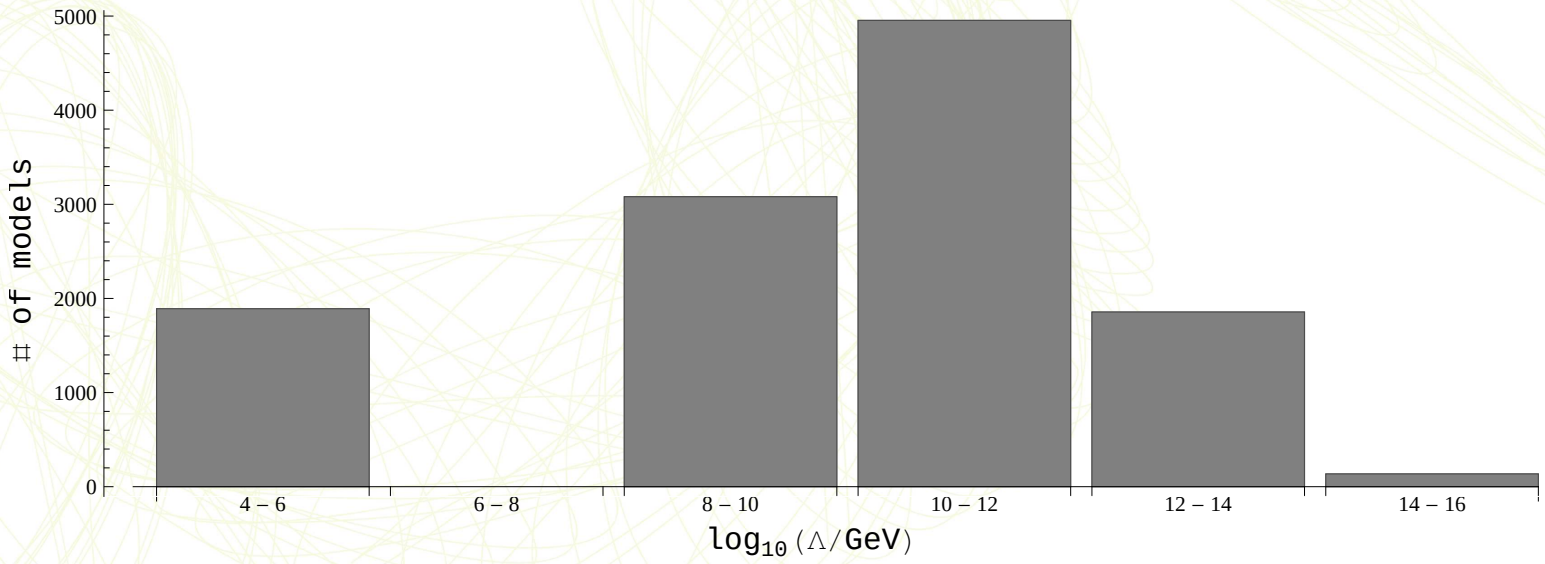
- (Discrete) flavor symmetry from symmetries of orbifold geometry
- Broken by Wilson lines
- If Wilson line vanishes $\Rightarrow$ larger flavor symmetry



H.P. Nilles and P. V. 2014

Scale of Gaugino Condensation

- Hidden sector gauge group from hidden E_8
- "Intermediate" size due to modular invariance
- β-function $\Rightarrow$ strong coupling at intermediate scale Λ
- SUSY breaking by dilaton F term
- Gravity mediation: $m_{3/2} \sim \frac{\Lambda^3}{M_{\mathrm{Pl}}^2}$



H.P. Nilles and P. V. 2014

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
  - Low energy SUSY breaking from hidden sector
- Lessons valid outside heterotic context?

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
  - Low energy SUSY breaking from hidden sector
- Lessons valid outside heterotic context?