Non-supersymmetric heterotic particle physics models

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Based on joint work with

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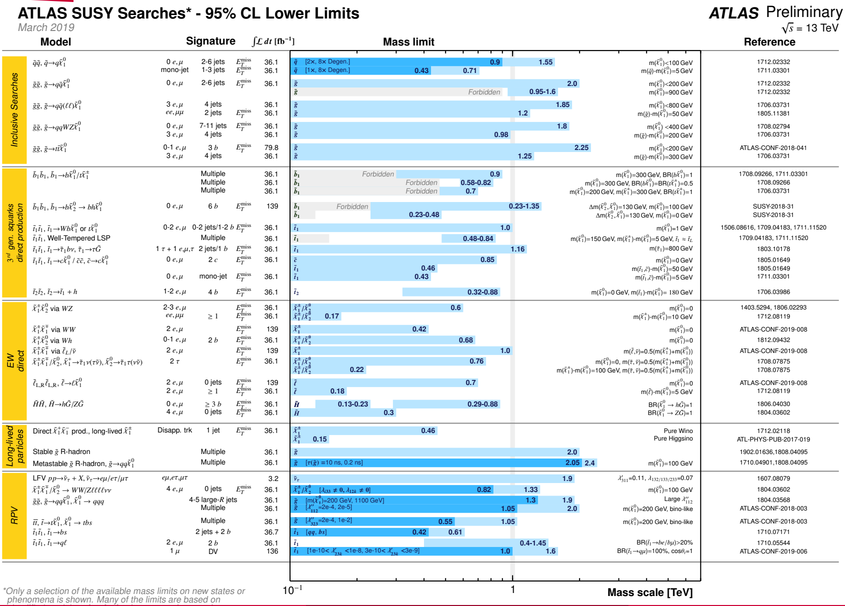
Overview of this talk

1. Motivation
2. Non-supersymmetric heterotic strings
3. Orbifold compactifications
4. Calculable cosmological constant
5. Locally but not globally supersymmetric orbifolds
6. Conclusions

Main motivation: Where is Supersymmetry?



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Main motivating questions:

- **So far no hints for supersymmetry found, what could that mean for string theory?**
- **Can one do string model building without supersymmetry?**
- **Can one understand the value of the cosmological constant in string theory?**

Past works on non-supersymmetric strings

- Non-supersymmetric (orbifolds of) heterotic theories
  Dixon,Harvey'86, Alvarez-Gaume,Ginsparg,Moore,Vafa'86 Itoyahama,Taylor'87, Chamseddine,Derendinger,Quiros'88, Taylor'88, Toon'90, Sasada'95, Font,Hernandez'02
- Misaligned supersymmetric and the supertrace constraints
  Dienes'95
- Free fermionic construction with non-supersymmetric boundary conditions Dienes'94,'06, Faraggi,Tsulaia'07
- Non-supersymmetric orientifold type II theories Sagnotti'95, Angelantonj'98, Blumenhagen,Font,Luest'99, Aldazabal,Ibanez,Quevedo'99
- Vacuum energy cancellation in non-supersymmetric strings
  Kachru,Kumar,Silverstein'99
- Time and space dependent backgrounds from nonsupersymmetric strings Dudas,Mourad,Timirgaziu'02
- Non-supersymmetric RCFTs Gato-Rivera,Schellekens'07

Recent heterotic interest

- Non-supersymmetric heterotic model building on orbifolds and Calabi-Yaus Blaszczyk,SGN,Loukas,Ramos-Sanchez'14, Blaszczyk,SGN,Loukas,Ruehle'15
- Non-tachyonic semi-realistic non-supersymmetric heterotic string vacua Ashfaque,Athanasopoulos,Faraggi,Sonmez'15
- Gauge thresholds in heterotic vacua with and without supersymmetry Angelantonj,Florakis,Tsulaia'15
- Non-renormalization and fermionic symmetries in certain heterotic-string-inspired non-supersymmetric field theories SGN,Parr'16

Recent renewed interest

- Non-supersymmetric heterotic strings with exponentially suppressed cosmological constants Abel,Dienses,Mavroudi'15, Aaronson,Abel,Mavroudi'16, Abel,Stewart'17, Itoyama,Nakajima'19
- Non-supersymmetric asymmetric orbifolds with vanishing cosmological constant Sugawara,Wada'15-'17
- Heterotic strings with positive cosmological constant Florakis,Rizos'16, Rizos'18
- Tension between a vanishing cosmological constant and non-supersymmetric heterotic orbifolds SGN,Loukas,Muetter,Parr,Vaudrevange'17
- Stability and vacuum energy in open string models with broken supersymmetry Abel,Dudas,Lewis,Partouche'18, Partouche'19

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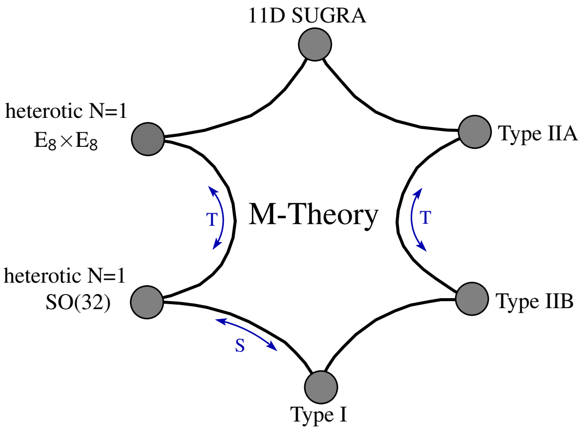
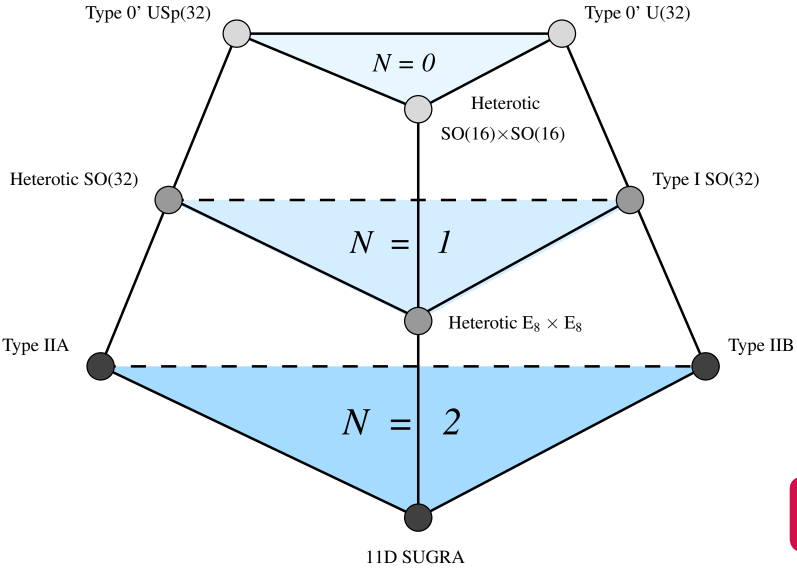
Well-known 10D string theories

The M-theory cartoon displays the modular invariant, anomaly- and tachyon-free 10D string theories:

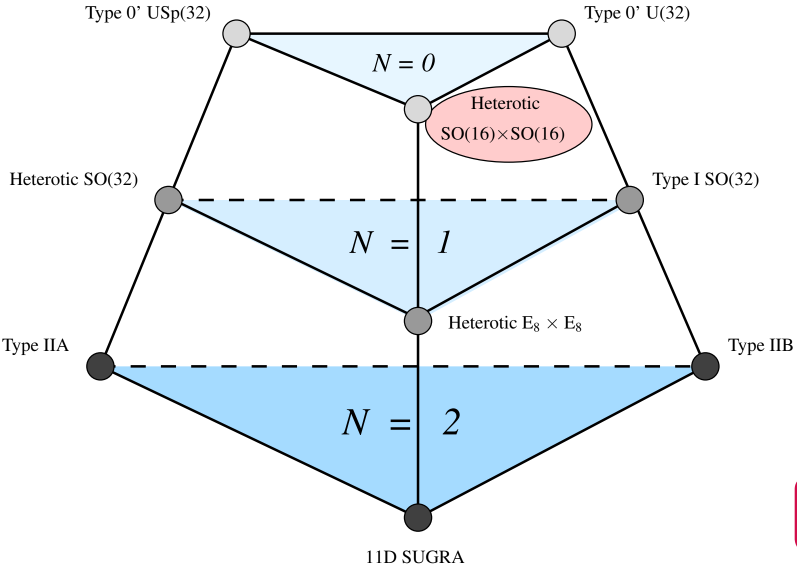


This disregards various non-supersymmetric strings...

10D tachyon-free (non-)supersymmetric strings



10D tachyon-free (non-)supersymmetric strings



10D (non-)supersymmetric heterotic strings

Dixon,Harvey'86

Heterotic theory	SUSY	Tachyons	Fermions
$E_8 \times E_8$	yes	none	Superpartners
$Spin(32)/\mathbb{Z}_2$	yes	none	Superpartners
$SO(16) \times SO(16)$	no	none	$(\mathbf{128};\mathbf{1})_+ + (\mathbf{1};\mathbf{128})_+ + (\mathbf{16};\mathbf{16})_-$
$E_8 \times SO(16)$	no	$(\mathbf{1};\mathbf{16})$	$(\mathbf{1};\mathbf{128}_+)_+ + (\mathbf{1};\mathbf{128}_-)_-$
$(E_7 \times SU(2))^2$	no	$(\mathbf{1},\mathbf{2};\mathbf{1},\mathbf{2})$	$(\mathbf{56},\mathbf{2};\mathbf{1},\mathbf{1})_+ + (\mathbf{1},\mathbf{1};\mathbf{56},\mathbf{2})_+$ $(\mathbf{56},\mathbf{1};\mathbf{1},\mathbf{2})_- + (\mathbf{1},\mathbf{2};\mathbf{56},\mathbf{1})_-$
$SO(24) \times SO(8)$	no	$(\mathbf{1};\mathbf{8}_s)$	$(\mathbf{24};\mathbf{8})_+ + (\mathbf{24};\mathbf{8})_-$
$U(16)$	no	$(\mathbf{1}_{+4}) + (\mathbf{1}_{-4})$	$(\mathbf{120}_{+2})_+ + (\overline{\mathbf{120}}_{-2})_+$
$SO(32)$	no	$(\mathbf{32})$	none

By considering Scherk-Schwarz supersymmetry breaking and Wilson lines on circle (torus) compactifications, one can show that all these theories are continuously connected to each other

Ginsparg,Vafa'87, Nair,Sharpere,Strominger,Wilczek'87

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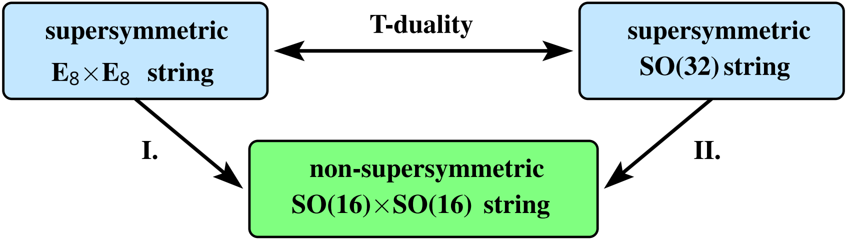
The non-supersymmetric heterotic string

The low-energy spectrum of the non-supersymmetric SO(16)$\times$SO(16) heterotic string reads: Dixon,Harvey'86, Alvarez-Gaume,Ginsparg,Moore,Vafa'86

	Fields	10D space-time interpretation
Bosons	G_{MN}, B_{MN}, ϕ	Graviton, Kalb-Ramond 2-form, Dilaton
	A_M	SO(16)$\times$SO(16) Gauge fields
Fermions	Ψ_+	Spinors in the $(\mathbf{128},\mathbf{1})+(\mathbf{1},\mathbf{128})$
	Ψ_-	Cospinors in the $(\mathbf{16},\mathbf{16})$

Modular invariant, anomaly- and tachyon-free!
But suffers from a non-vanishing dilaton tadpole...

Constructions of the SO(16)×SO(16) string



The SO(16)×SO(16) theory can be obtained by: Dixon,Harvey'86, Alvarez-Gaume,Ginsparg,Moore,Vafa'86

- **I. SUSY breaking orbifolding of the $E_8 \times E_8$ string**
- **II. SUSY breaking orbifolding of the SO(32) string**

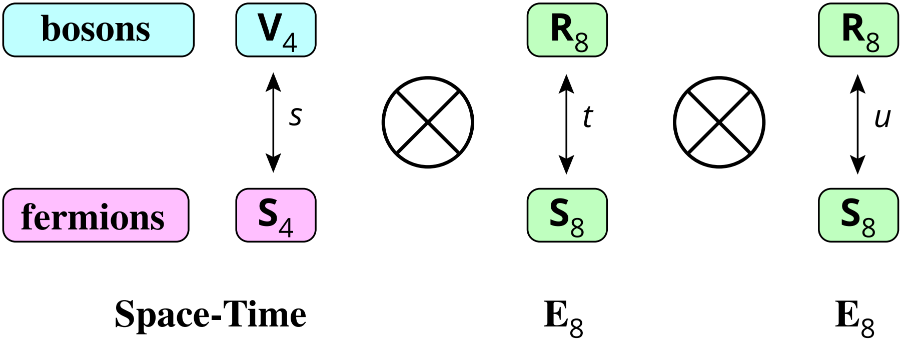
Heterotic weight lattices

The partition function can be viewed as lattice sums over the following lattices:

	Weight lattice	Lattice vectors	Lattice generators
$\mathbf{R}_D$	Root	$n \in \mathbb{Z}^D$, $\sum n_i \in 2\mathbb{Z}$	$\left(\underline{\pm 1^2, 0^{D-2}}\right)$
$\mathbf{V}_D$	Vector	$n \in \mathbb{Z}^D$, $\sum n_i \in 2\mathbb{Z}+1$	$\left(\underline{\pm 1, 0^{D-2}}\right)$
$\mathbf{S}_D$	Spinor	$n \in \mathbb{Z}^D + \frac{1}{2}e_D$, $\sum n_i \in 2\mathbb{Z}$	$\left(\underline{-\frac{1}{2}^{2n}, +\frac{1}{2}^{D-2n}}\right)$
$\mathbf{C}_D$	Cospinor	$n \in \mathbb{Z}^D + \frac{1}{2}e_D$, $\sum n_i \in 2\mathbb{Z}+1$	$\left(\underline{-\frac{1}{2}^{2n+1}, +\frac{1}{2}^{D-2n-1}}\right)$

Spin-structure s as supersymmetry generator

The lattices of the standard $E_8 \times E_8$ theory:

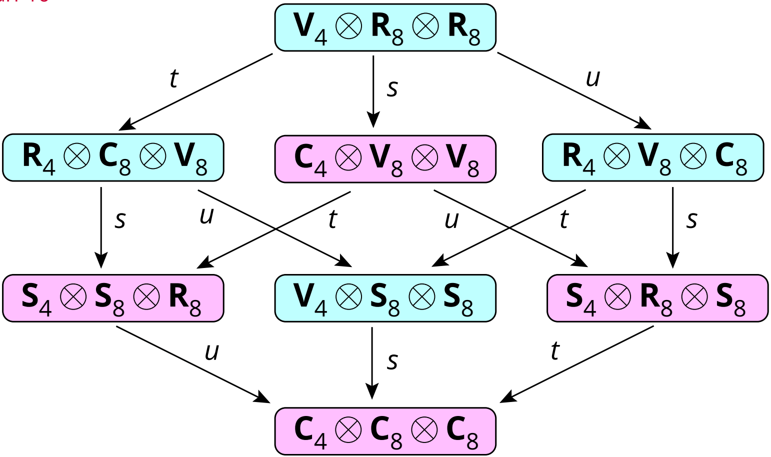


Supersymmetry : $\delta_s A_M^\alpha = \Psi_+^\alpha \,, \qquad \alpha \in E_8 \oplus E_8$

Spin-structures as SUSY-like generators

The lattices of the SO(16)$\times$SO(16) theory:

SGN,Parr’16

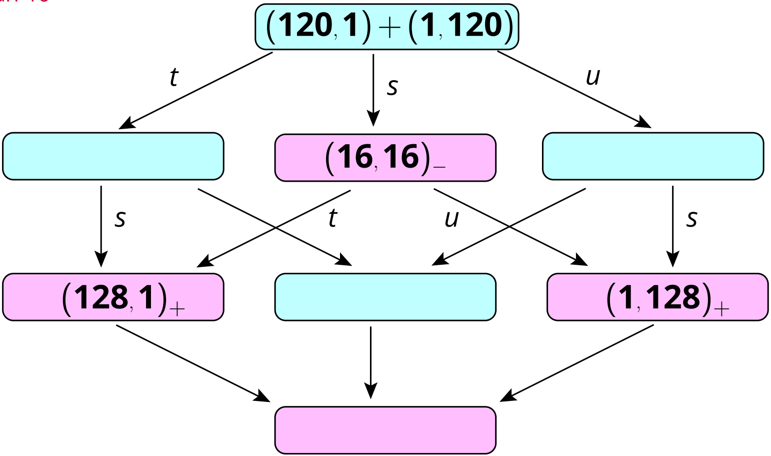


Possible similar fermionic transformations???

Spin-structures as SUSY-like generators

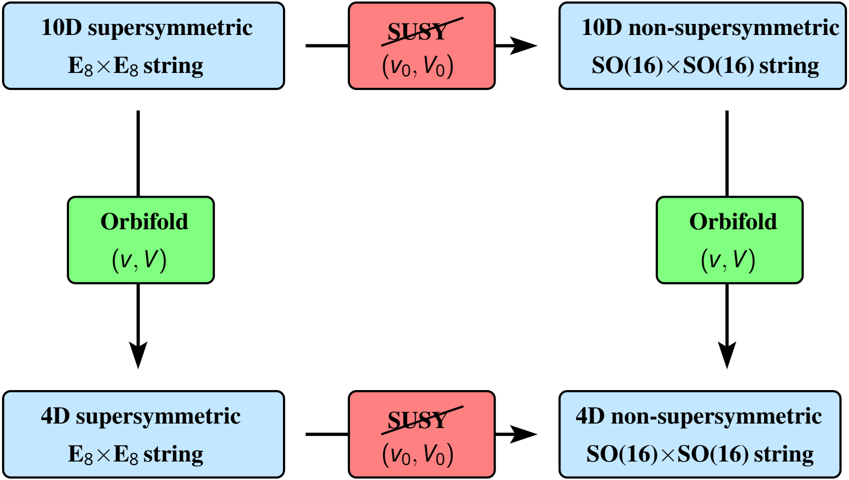
Massless charged states of the SO(16)×SO(16) theory:

SGN,Parr'16



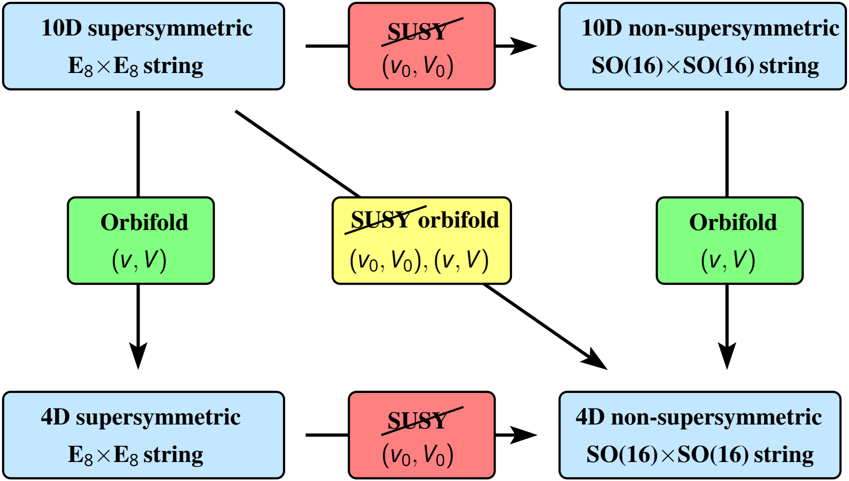
$$\delta_{ts} A_M^{(120,1)} \sim \Psi_+^{(128,1)}\,, \quad \delta_s A_M \sim \Psi_-^{(16,16)}\,, \quad \delta_{us} A_M^{(1,120)} \sim \Psi_+^{(1,128)}$$

SO(16)×SO(16) orbifold models



Orbifold $\mathbb{Z}_N$ twist (v, V) and SUSY breaking $\mathbb{Z}_2$ twist (v_0, V_0)

SO(16)×SO(16) orbifold models



Do a $\mathbb{Z}_2 \times \mathbb{Z}_N$ compactification using the **Orbifolder package**

Nilles,Ramos-Sanchez,Vaudrevange,Wingerter'11

SM-like models scans on CY orbifolds

Orbifold twist	#(geom)	Inequivalent scanned models	Tachyon-free percentage	SM-like tachyon-free models total	one-Higgs	two-Higgs
$\mathbb{Z}_3$	(1)	74,958	100 %	128	0	0
$\mathbb{Z}_4$	(3)	1,100,336	100 %	12	0	0
$\mathbb{Z}_{6\text{-I}}$	(2)	148,950	55 %	59	18	0
$\mathbb{Z}_{6\text{-II}}$	(4)	15,036,790	57 %	109	0	1
$\mathbb{Z}_{8\text{-I}}$	(3)	2,751,085	51 %	24	0	0
$\mathbb{Z}_{8\text{-II}}$	(2)	4,397,555	71 %	187	1	1
$\mathbb{Z}_2 \times \mathbb{Z}_2$	(12)	9,546,081	100 %	1,562	0	5
$\mathbb{Z}_2 \times \mathbb{Z}_4$	(10)	17,054,154	67 %	7,958	0	89
$\mathbb{Z}_3 \times \mathbb{Z}_3$	(5)	11,411,739	52 %	284	0	1
$\mathbb{Z}_4 \times \mathbb{Z}_4$	(5)	15,361,570	64 %	2,460	0	6

Blaszczyk,SGN,Loukas,Ramos-Sanchez'14

On orbifolds single Higgs-doublet models, like the SM, can be constructed! But always contain many other states

Motivation for a vanishing cosmological constant

The cosmological constant Λ is very very tiny: 10^{-120} smaller than its natural scale $\Lambda \sim m_P^4$

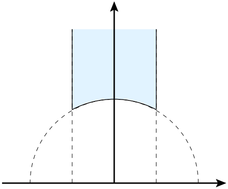
This may be taken as an indication that the cosmological constant should vanish perturbatively to all orders and only arises due to non-perturbative effects

For this to be feasible at least the cosmological constant should vanish at the one-loop level

One-loop cosmological constant

The one-loop heterotic cosmological constant is computed via

$$\Lambda \sim \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2} \mathcal{Z}_{\text{full}}(\tau, \bar{\tau})$$



Given that the integral over the fundamental domain $\mathcal{F}$ can be very complicated, we asked:

Can we construct non-supersymmetric heterotic orbifolds which have a vanishing one-loop partition function?

As there are an infinite number of 6D manifolds, the almost **29 million toroidal orbifolds** Opgenorth,Plesken,Schulz'98 provide a large but trackable testing ground

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Decomposition of the full partition function

The full partition function consists of

$$\mathcal{Z}_{\text{full}} = \mathcal{Z}_{\text{4D Mink.}}\,\mathcal{Z}_{\text{6D int.}} \qquad \mathcal{Z}_{\text{4D Mink.}} = \frac{1}{\tau_2}\left|\frac{1}{\eta^2}\right|^2 \neq 0$$

On orbifolds the internal part Dixon,Harvey,Vafa,Witten'85

$$\mathcal{Z}_{\text{6D int.}} = \frac{1}{|\mathbf{P}|}\sum_{[g,h]=0} \mathcal{Z}_X\begin{bmatrix}g\\h\end{bmatrix}\overline{\mathcal{Z}_\psi\begin{bmatrix}g\\h\end{bmatrix}}\,\mathcal{Z}_Y\begin{bmatrix}g\\h\end{bmatrix}$$

is associated with

- the 6D internal coordinate fields X
- their worldsheet superpartners, the right-moving fermions ψ
- the 16D left-moving gauge degrees of freedom Y

and the sum over all commuting space group element $g, h \in \mathbf{S}$

Orbifolds with vanishing partition functions

Using Riemann identities one can shows that:

$$\mathcal{Z}_\psi \begin{bmatrix} g \\ h \end{bmatrix} = 0 \quad \Leftrightarrow \quad g, h \in \mathbf{S} \text{ share at least one Killing spinor}$$

Hence, all supersymmetric orbifolds have vanish partition functions

And so does any non-supersymmetric toroidal orbifold for which

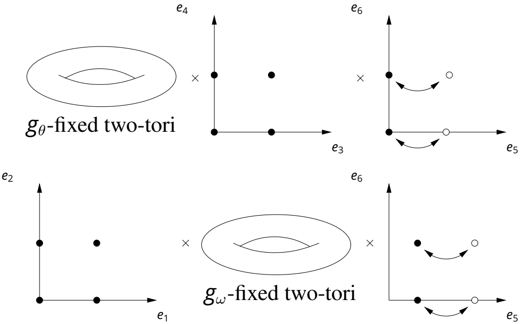
i. a Killing spinor exists *locally* in every commuting (g, h)-sector
ii. but none *globally*

Do such orbifolds exist?

- One would say yes, as there are orbifold examples with different local and non-local supersymmetry breakings

A (non-)local supersymmetry breaking orbifold

The space group **S** the DW(0–2) $\mathbb{Z}_2 \times \mathbb{Z}_2$ orbifold is generated by the elements: $g_\theta = \big(\theta, 0\big)$, $g_\omega = \big(\omega, \frac{1}{2}\, e_5\big)$, $g_i = \big(1, e_i\big)$ Donagi,Wendland'08



- These non-intersecting two-tori preserve different $\mathcal{N} = 2$, but combined only $\mathcal{N} = 1$ supersymmetry
- Less supersymmetry is preserved globally than locally

Classification of toroidal orbifolds

Toroidal orbifolds in 6D have been classified: Opgenorth,Plesken,Schulz'98

- **7,103 $\mathbb{Q}$-classes:**

  Inequivalent point groups **P**: Inequivalent orbifold twists that can act on some 6D lattice Γ

- **85,308 $\mathbb{Z}$-classes:**

  Inequivalent lattices Γ on which these point groups can act

- **28,927,915 affine-classes:**

  Inequivalent space groups **S** (encoding roto-translations)

Among these there are **520** toroidal orbifolds (associated to **60** $\mathbb{Q}$-classes) that preserve at least $\mathcal{N} = 1$ supersymmetry

Fischer,Ratz,Torrado,Vaudrevange'12

Local but not global supersymmetric orbifolds

This classification can be used to identify toroidal orbifolds that admit Killing spinors in all sectors locally but none globally:

# $\mathbb{Q}$-classes	Restriction
7,103	All inequivalent geometrical point groups **P** $\subset$ O(6)
1,616	Orientable geometrical point groups **P** $\subset \mathrm{SO}(6)$
106	No element from **P** rotates in a two-dimensional plane only
63	Each element $\theta \in$ **P** admits a choice with some local Killing spinors
60	Geometrical point group compatible with some global Killing spinors

This leaves orbifolds with 3 candidate $\mathbb{Q}$-classes

SGN,Loukas,Muetter,Parr,Vaudrevange'17

Candidate orbifold geometries

Some properties of the three candidate $\mathbb{Q}$-classes are:

CARAT-index	Point group	Generator relations	Order	Local twist vectors
3375	$\text{Dic}_3 = \mathbb{Z}_3 \rtimes \mathbb{Z}_4$	$\theta_1^4 = \theta_2^3 = \mathbb{1}$, $\theta_2\,\theta_1\,\theta_2 = \theta_1$	12	$\left(\frac{1}{4}, \frac{1}{4}, -\frac{1}{2}\right)$, $\left(\frac{1}{3}, -\frac{1}{3}, 0\right)$
5751	Q_8	$\theta_1^4 = \mathbb{1},\ \theta_1^2 = \theta_2^2$, $\theta_1\,\theta_2\,\theta_1 = \theta_2$	8	$\left(\frac{1}{4}, \frac{1}{4}, -\frac{1}{2}\right)$ $\left(\frac{1}{4}, -\frac{1}{4}, 0\right)$
6737	$SL(2,3)$	$\theta_1^3 = \theta_2^4 = \mathbb{1}$, $(\theta_2\,\theta_1)^2 = \theta_1^2\,\theta_2$	24	$\left(\frac{1}{3}, \frac{1}{3}, -\frac{2}{3}\right)$, $\left(\frac{1}{4}, -\frac{1}{4}, 0\right)$

The local twist vectors, obtained in two different bases, separately indeed preserve some amount of supersymmetry

Candidate orbifold geometries

For these candidate geometries all possible embedding of the point group into spinor space were explicitly constructed:

For all three candidate $\mathbb{Q}$-classes there is at least one point group element that does not preserve any Killing spinor

Hence, there does not exist any non-supersymmetric orbifold for which all point group elements separately preserve some amount of supersymmetry! SGN,Loukas,Muetter,Parr,Vaudrevange'17

Conclusions

The non-supersymmetric heterotic SO(16)$\times$SO(16) string has many fascinating properties

It is possible to construct non-supersymmetric models from string theory that get quite close to the SM of Particle Physics

But it is extremely challenging to obtain string constructions with a very tiny cosmological constant:

There are no non-supersymmetric toroidal orbifolds that preserve some amount of supersymmetry in all sectors locally