Heterotic string model building without supersymmetry

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This talk is based on collaborations with:

Michael Blaszczyk

Orestis Loukas

Ramos-Sanchez

Fabian Ruehle

and publications:

JHEP 1410 (2014) 119 [arXiv:1407.6362]

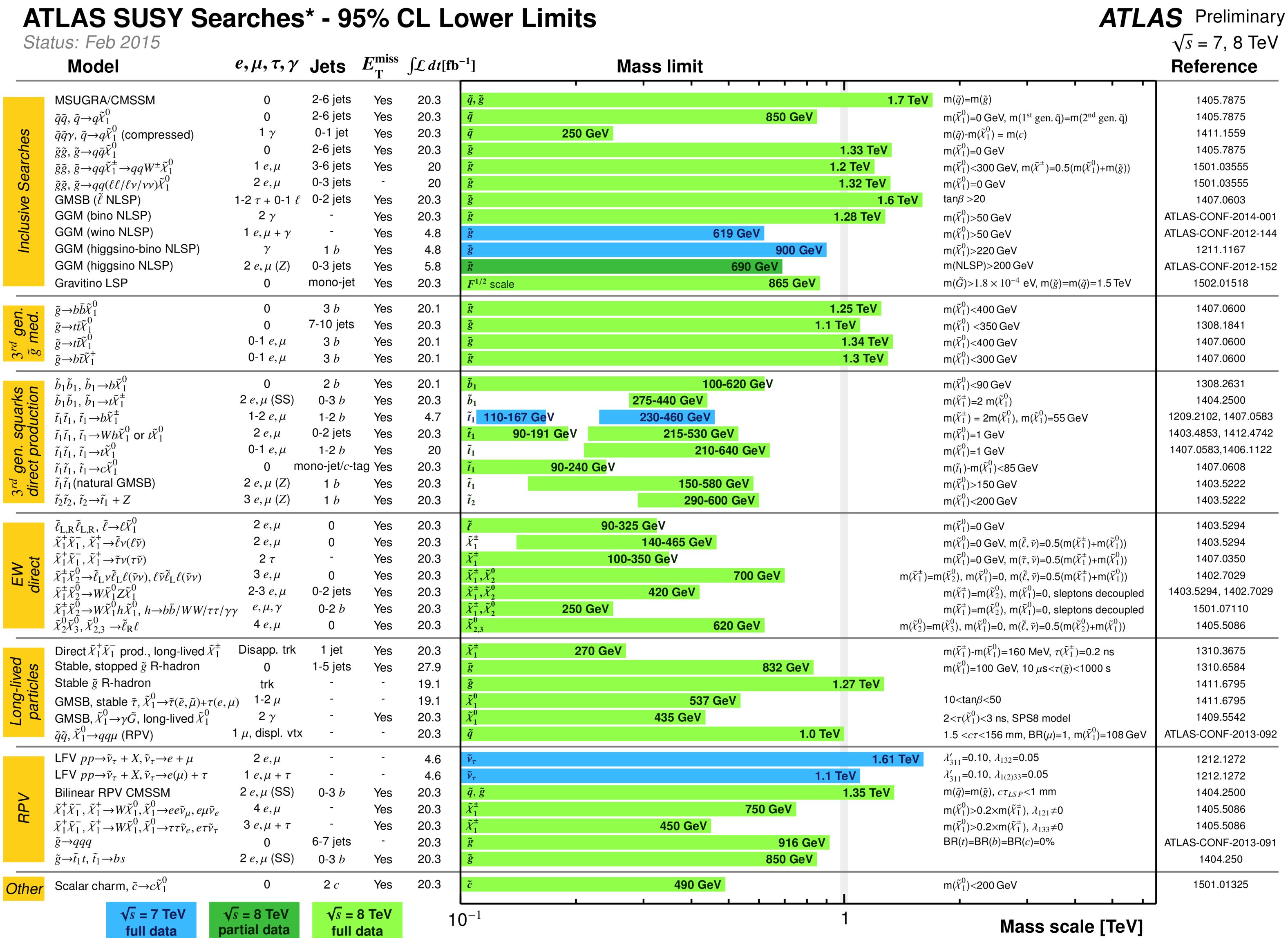
DISCRETE'14 proceedings [arXiv:1502.03604]

JHEP 1510 (2015) 166 [arXiv:1507.06147]

Fortsch.Phys. 63 (2015) 609-632 [arXiv:1507.07559]

and work in progress...

Main motivation: Where is Supersymmetry?



Main motivating questions:

- **So far no hints for supersymmetry found, what if this stays this way?**
- **What could that mean for string theory?**
- **How to describe supersymmetry breaking within string theory?**
- **Can one do string model building without supersymmetry?**

Major issues without supersymmetry

- **Hierarchy problem**
- **Cosmological constant problem**
- **Dilaton tadpole**
- **Tachyons**

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

- 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

- Non-supersymmetric RCFTs

  Gato-Rivera,Schellekens'07

Recent renewed heterotic interest

- Non-supersymmetric heterotic model building

  Blaszczyk,SGN,Loukas,Ramos-Sanchez'14

- Towards a non-supersymmetric string phenomenology

  Abel,Dienses,Mavroudi'15

- Heterotic moduli stabilisation and non-supersymmetric vacua

  Lukas,Lalak,Svanes'15

- Non-tachyonic semi-realistic non-supersymmetric heterotic string vacua

  Ashfaque,Athanasopoulos,Faraggi,Sonmez'15

- Generalised universality of gauge thresholds in heterotic vacua with and without supersymmetry

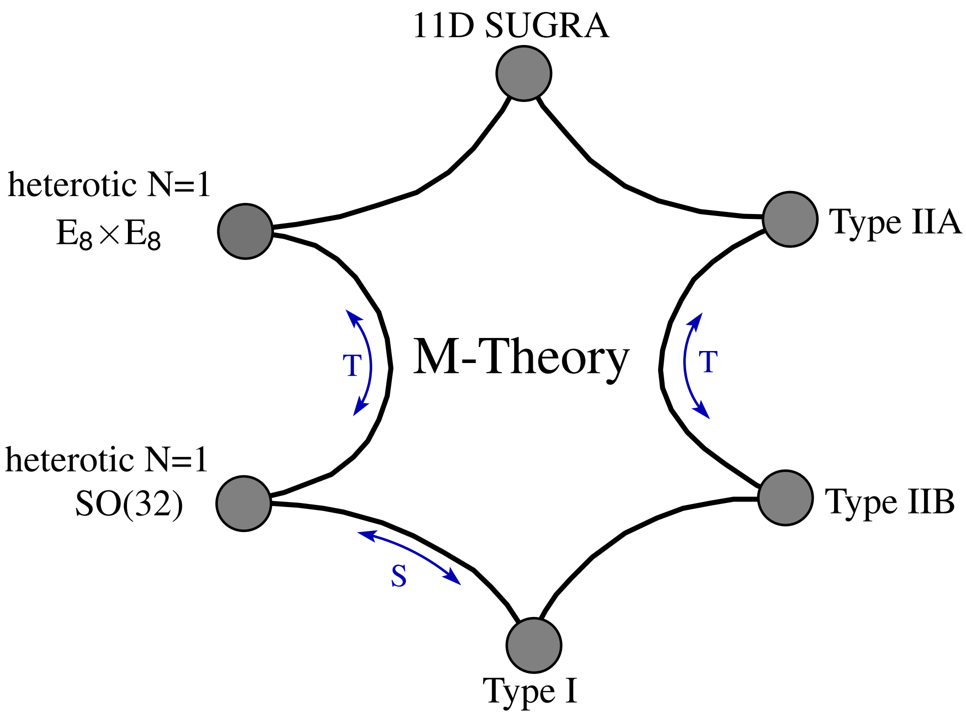
  Angelantonj, Florakis, Tsulaia'15

Overview of this talk

1. Motivation
2. The non-supersymmetric heterotic string
3. Orbifold compactifications
4. Smooth compactifications
5. Tachyons

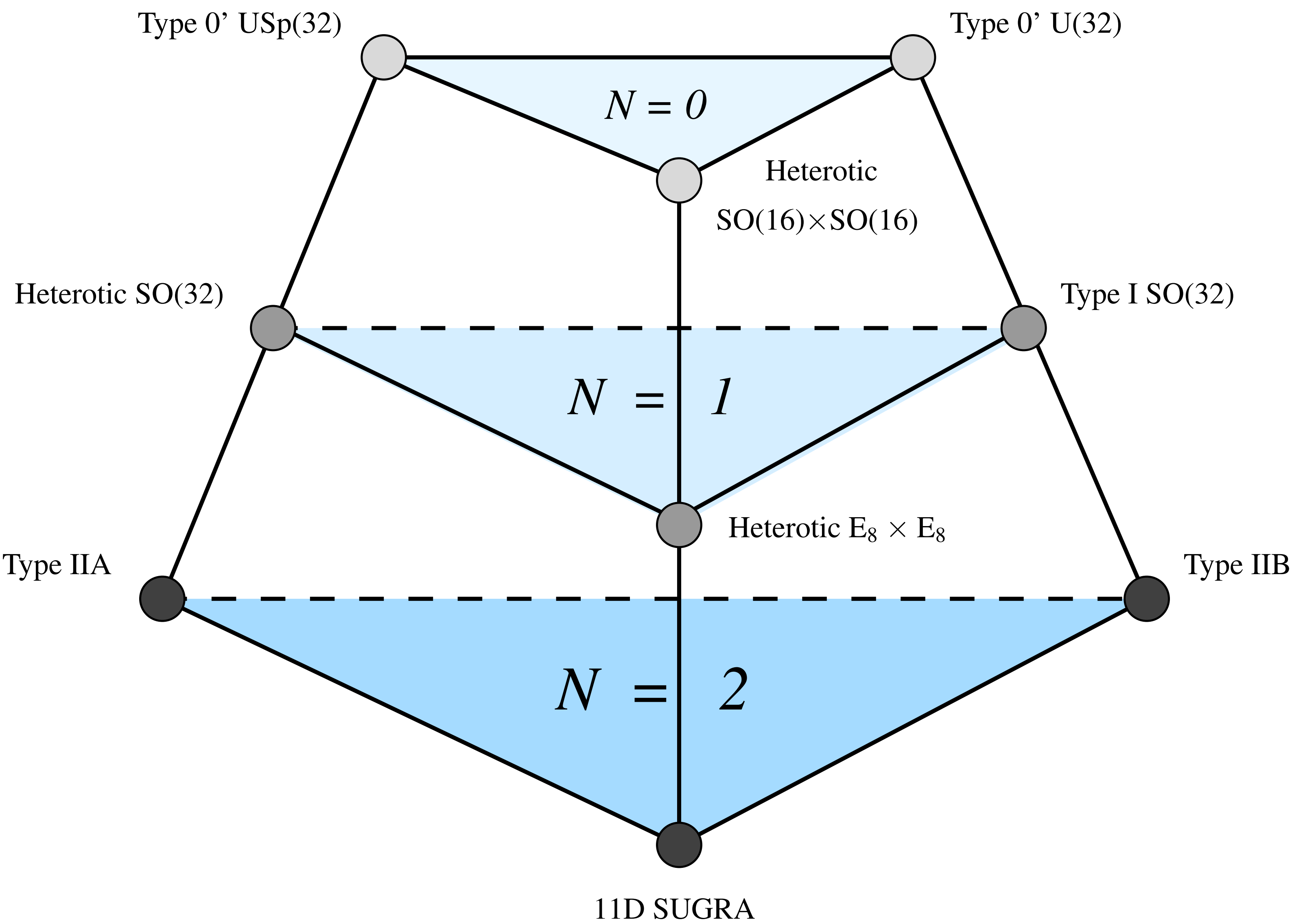
Well-known 10D string theories

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

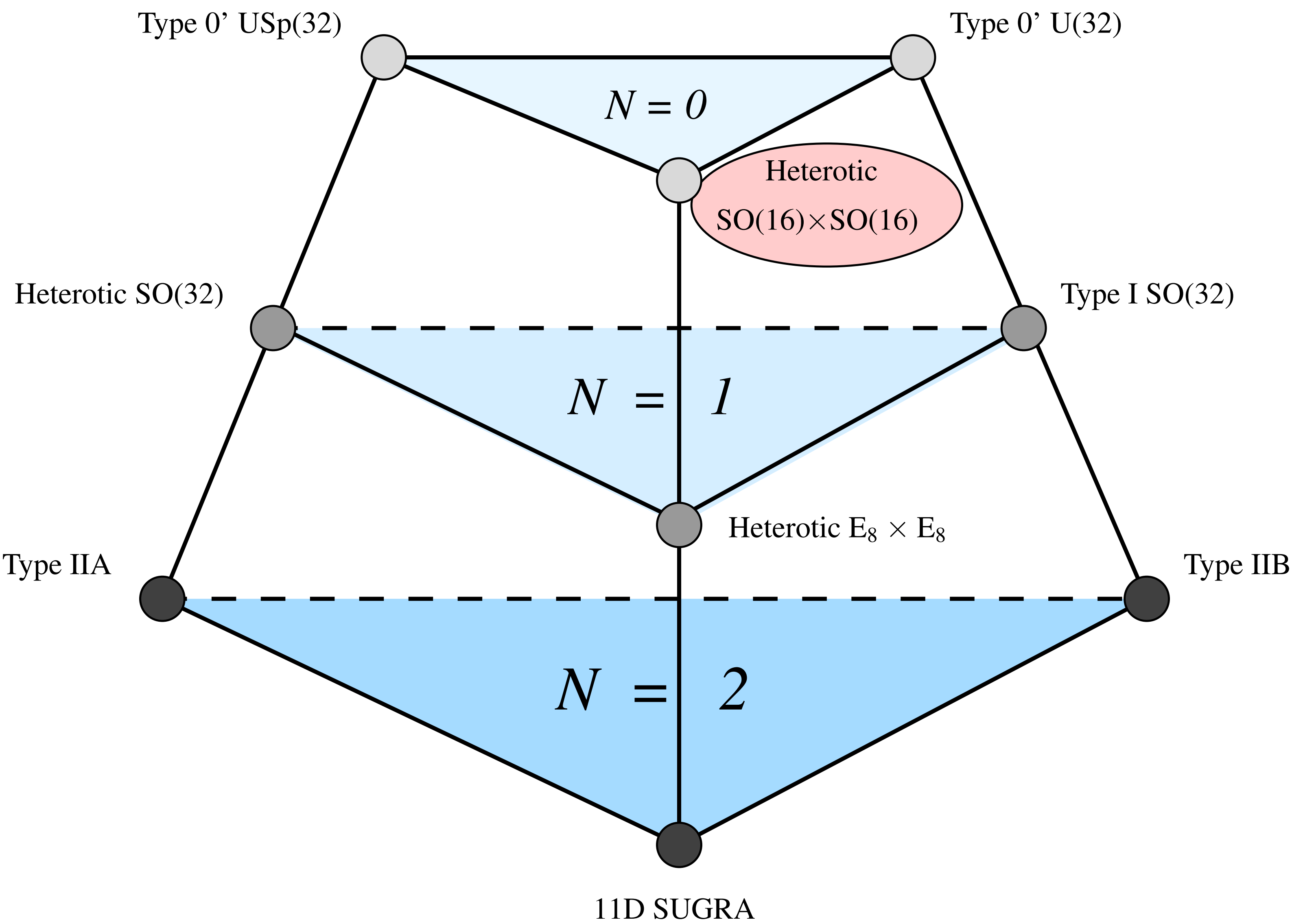


However, it disregards various non-supersymmetric strings...

10D tachyon-free (non-)supersymmetric strings



10D tachyon-free (non-)supersymmetric strings



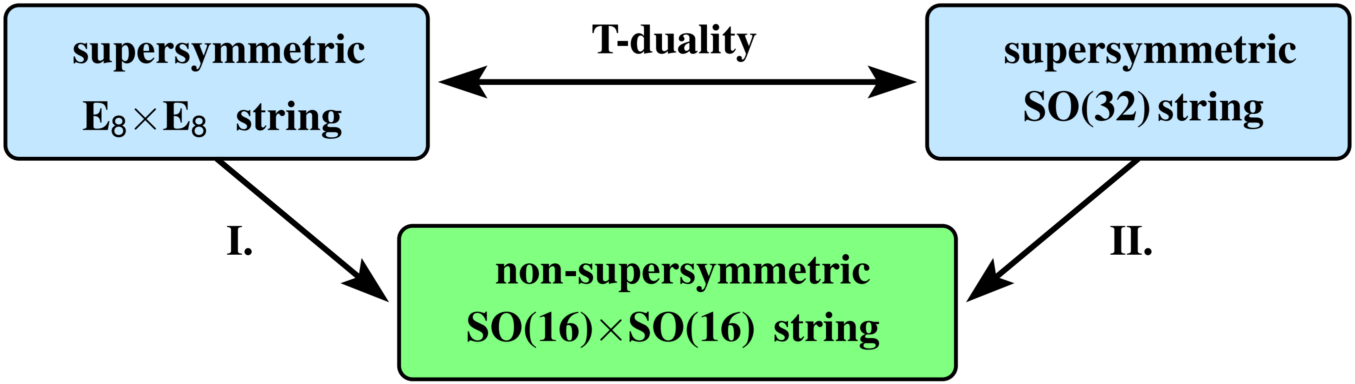
The non-supersymmetric heterotic string

The low-energy spectrum of the non-supersymmetric SO(16)×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)×SO(16) Gauge fields
Fermions	Ψ_+	Spinors in the $(\mathbf{128},\mathbf{1})+(\mathbf{1},\mathbf{128})$
	Ψ_-	Cospinors in the $(\mathbf{16},\mathbf{16})$

This theory is also modular invariant, anomaly- and tachyon-free but obviously not supersymmetric

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**

Untwisted sectors of the SUSY breaking twists:

supersymmetric $E_8\times E_8$ string	I. →	non-supersymmetric $SO(16)\times SO(16)$ string
Graviton, B-field, Dilaton $E_8\times E_8$ Gauge fields		Graviton, B-field, Dilaton $SO(16)\times SO(16)$ Gauge fields
Gravitino, Dilatino $E_8\times E_8$ Gauginos		– $(\mathbf{128},\mathbf{1})_+ + (\mathbf{1},\mathbf{128})_+$

supersymmetric $SO(32)$ strings	II. →	non-supersymmetric $SO(16)\times SO(16)$ strings
Graviton, B-field, Dilaton $SO(32)$ Gauge fields		Graviton, B-field, Dilaton $SO(16)\times SO(16)$ Gauge fields
Gravitino, Dilatino $SO(32)$ Gauginos		– $(\mathbf{16},\mathbf{16})_-$

All states of the $SO(16)\times SO(16)$ theory can be understood as untwisted states of either the $E_8\times E_8$ or $SO(32)$ theory

$E_8\times E_8$ and $SO(16)\times SO(16)$ Partition functions

The partition functions of the non-supersymmetric heterotic $SO(16)\times SO(16)$ and the supersymmetric heterotic $E_8\times E_8$ strings are closely related: Dixon,Harvey'86, Alvarez-Gaume,Ginsparg,Moore,Vafa'86

Introduce SUSY breaking discrete torsion phases :

$$\mathbf{Z}_{E_8^2} = \sum_{\text{spin}} \quad \mathbf{Z}_8^x(\tau,\overline{\tau}) \cdot \widehat{\mathbf{Z}}_4 \left[{s \atop s'}\right](\tau) \cdot \overline{\widehat{\mathbf{Z}}_8 \left[{t \atop t'}\right](\tau)} \cdot \overline{\widehat{\mathbf{Z}}_8 \left[{u \atop u'}\right](\tau)}$$

(where s, t, u label the spin structures) by:

$$\mathbf{Z}_{SO(16)^2} = \sum_{\text{spin}} T \cdot \mathbf{Z}_8^x(\tau,\overline{\tau}) \cdot \widehat{\mathbf{Z}}_4 \left[{s \atop s'}\right](\tau) \cdot \overline{\widehat{\mathbf{Z}}_8 \left[{t \atop t'}\right](\tau)} \cdot \overline{\widehat{\mathbf{Z}}_8 \left[{u \atop u'}\right](\tau)}$$

with torsion phases Blaszczyk,SGN,Loukas,Ramos-Sanchez'14

$$T = (-)^{st'-s't} * \ldots \quad * \quad (-)^{s's+s'+s} * \ldots$$

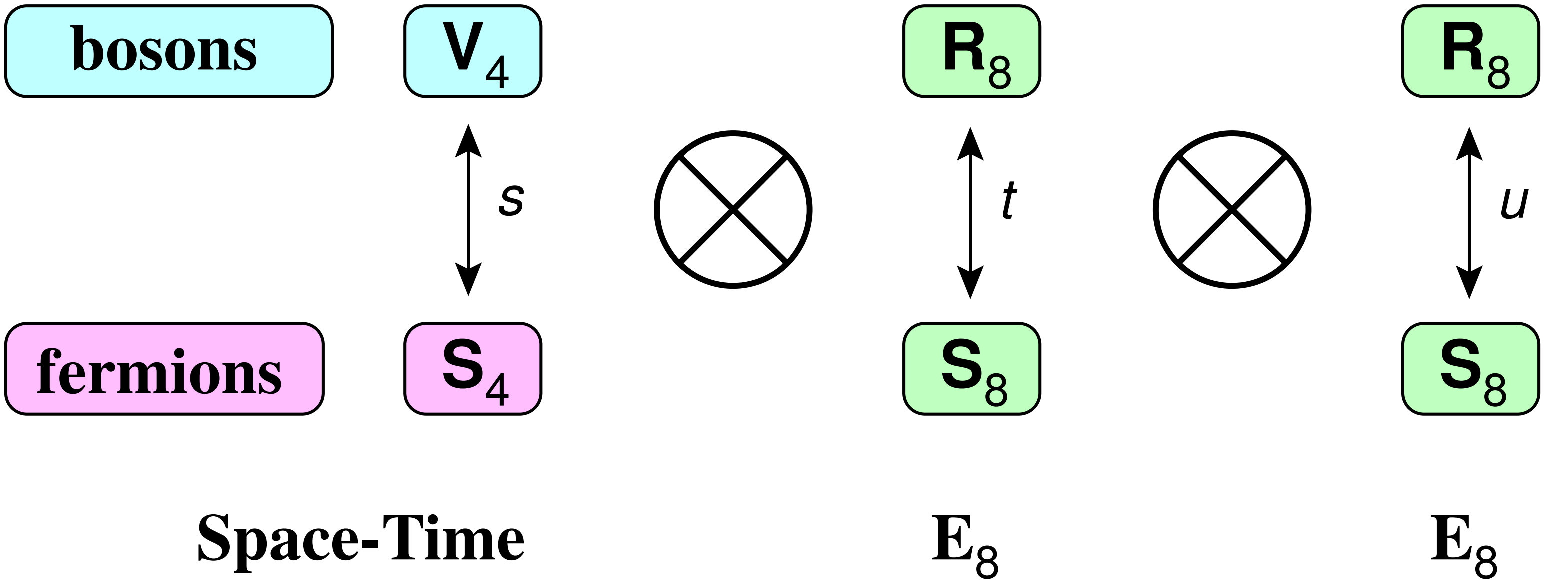
Heterotic weight lattices

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

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

Spin-structure *s* as supersymmetry generator

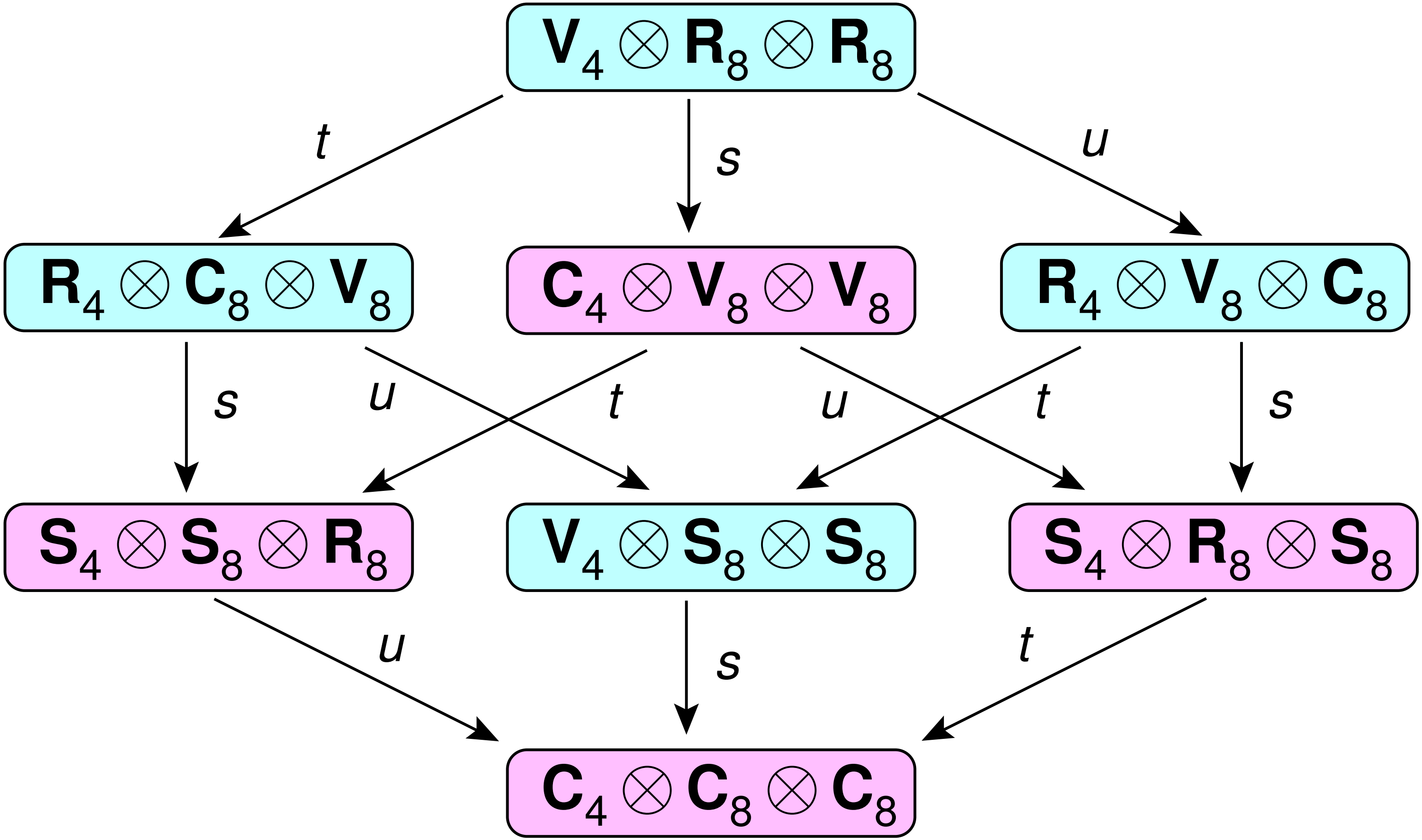
Standard $E_8 \times E_8$ theory:



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

Spin-structures as SUSY-like generators

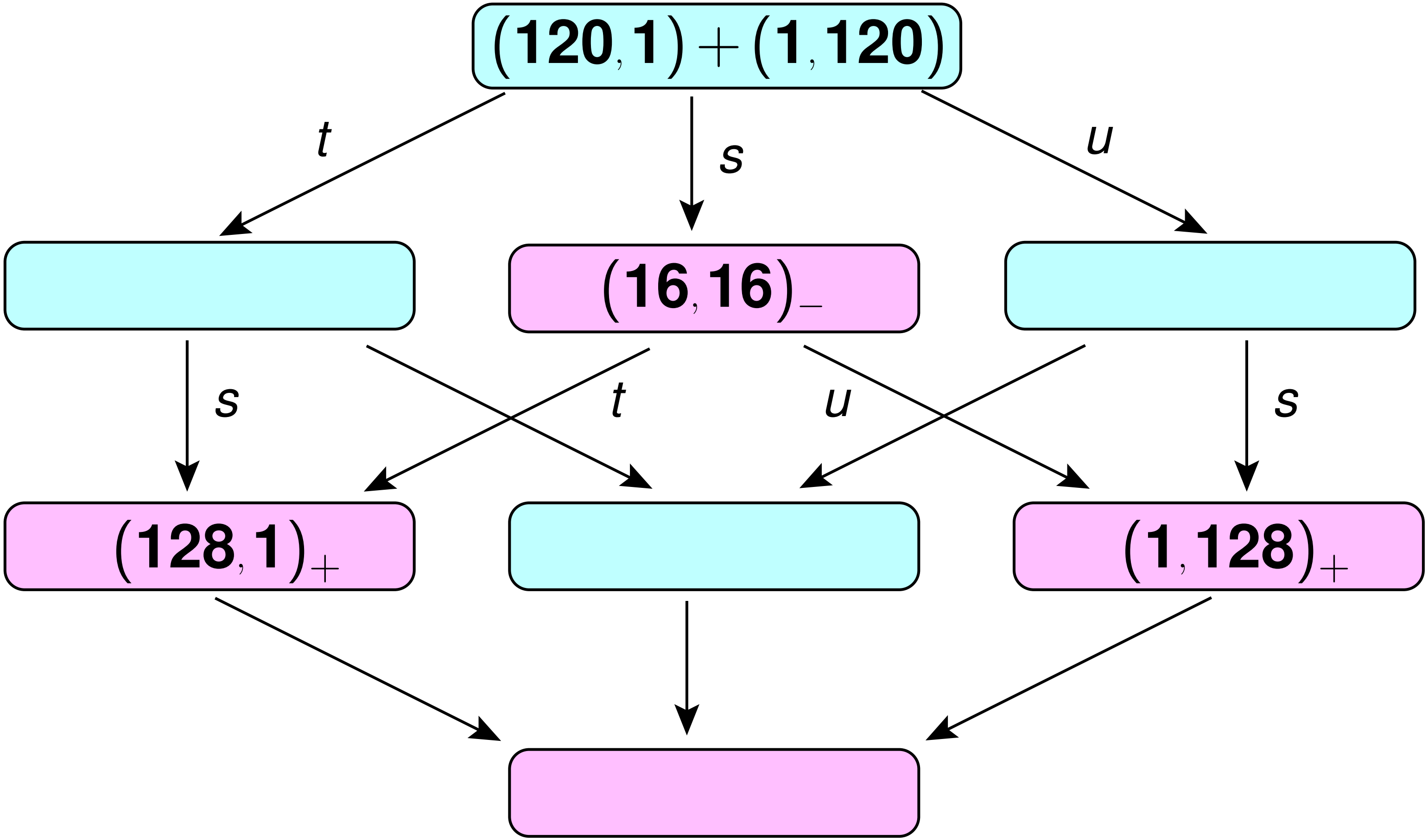
The SO(16)×SO(16) theory:



Possible similar induced transformations ???

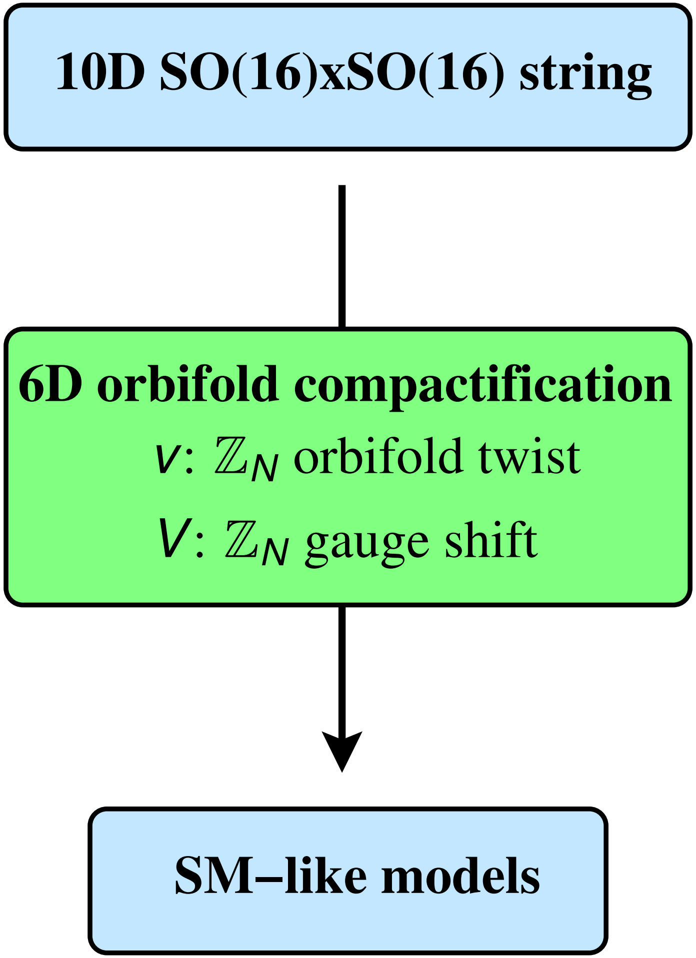
Spin-structures as SUSY-like generators

The SO(16)×SO(16) theory:

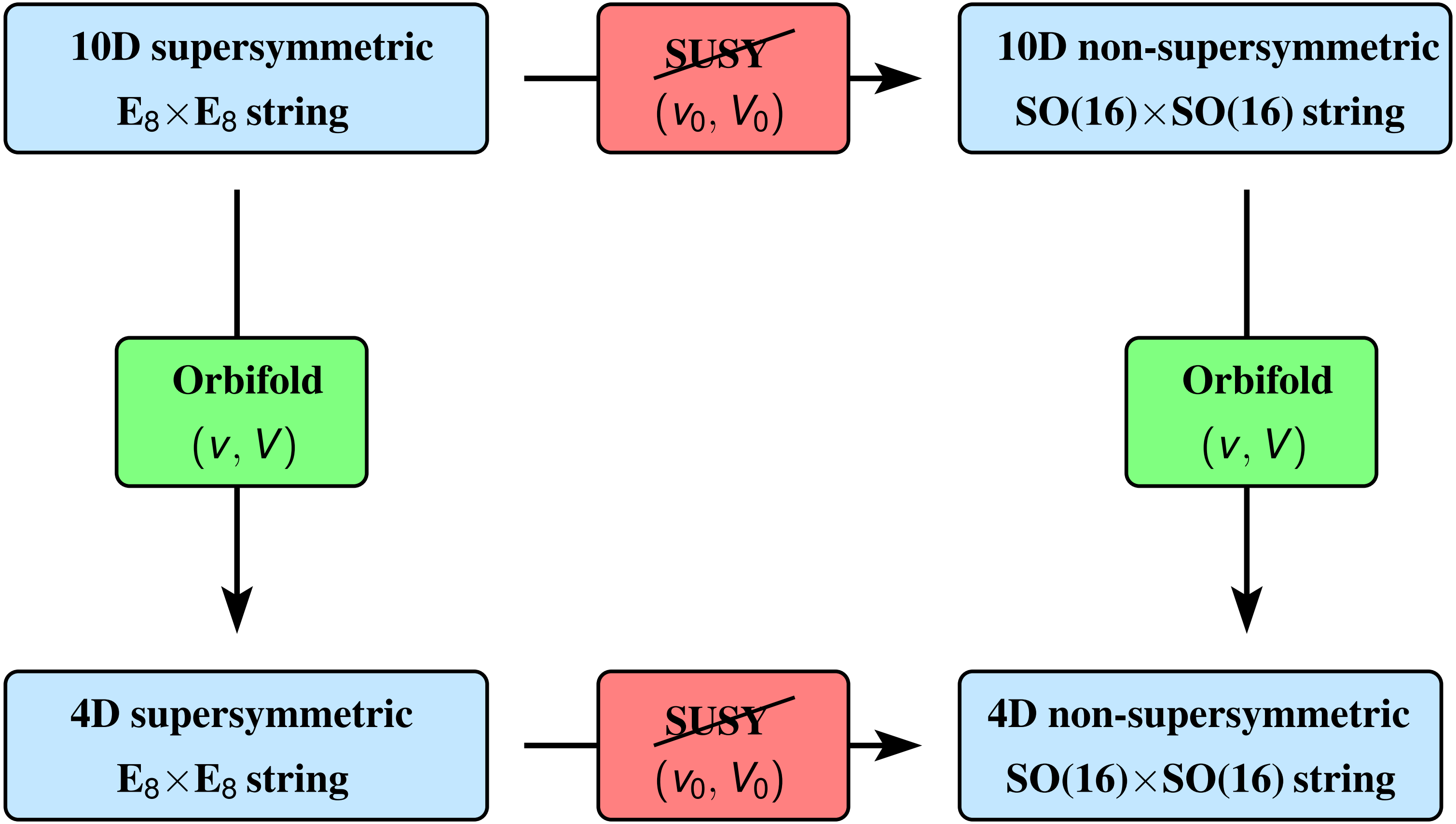


SUSY-like transf. : $\delta_s A_M^{(\mathbf{120},\mathbf{1})} = \Psi_-^{(\mathbf{16},\mathbf{16})}\,, \quad \delta_{st} A_M^{(\mathbf{120},\mathbf{1})} = \Psi_+^{(\mathbf{128},\mathbf{1})}\,, \ldots$

SO(16)×SO(16) orbifolds

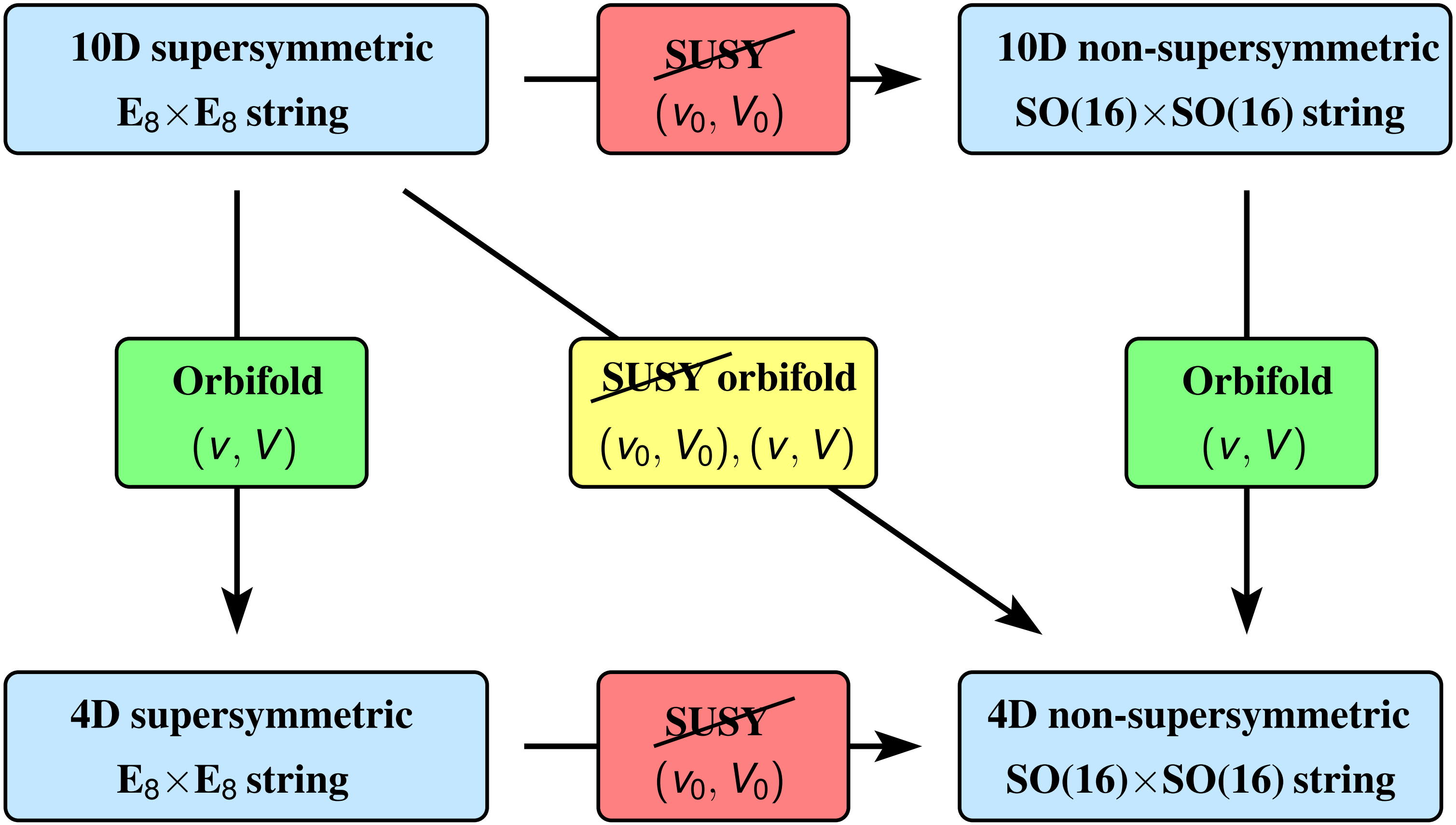


SO(16)×SO(16) orbifolds



SUSY breaking $\mathbb{Z}_2$ twist: $v_0 = (0, 1^3)$, $V_0 = (1, 0^7)(\text{-}1, 0^7)$

SO(16)×SO(16) orbifolds



But then one can do a $\mathbb{Z}_2 \times \mathbb{Z}_N$ orbifold directly...

Twisted tachyons

Tachyons are possible in some twisted sectors of many orbifolds:

Blaszczyk,SGN,Loukas,Ramos-Sanchez'14

Orbifold	Twist	Tachyons	Orbifold	Twists	Tachyons
$T^6/\mathbb{Z}_3$	$\frac{1}{3}(1,1,-2)$	forbidden	$T^6/\mathbb{Z}_2\times\mathbb{Z}_2$	$\frac{1}{2}(1,-1,0)\,;\ \frac{1}{2}(0,1,-1)$	forbidden
$T^6/\mathbb{Z}_4$	$\frac{1}{4}(1,1,-2)$	forbidden	$T^6/\mathbb{Z}_2\times\mathbb{Z}_4$	$\frac{1}{2}(1,-1,0)\,;\ \frac{1}{4}(0,1,-1)$	possible
$T^6/\mathbb{Z}_{6\text{-I}}$	$\frac{1}{6}(1,1,-2)$	possible	$T^6/\mathbb{Z}_2\times\mathbb{Z}_{6\text{-I}}$	$\frac{1}{2}(1,-1,0)\,;\ \frac{1}{6}(1,1,-2)$	possible
$T^6/\mathbb{Z}_{6\text{-II}}$	$\frac{1}{6}(1,2,-3)$	possible	$T^6/\mathbb{Z}_2\times\mathbb{Z}_{6\text{-II}}$	$\frac{1}{2}(1,-1,0)\,;\ \frac{1}{6}(0,1,-1)$	possible
$T^6/\mathbb{Z}_7$	$\frac{1}{7}(1,2,-3)$	possible	$T^6/\mathbb{Z}_3\times\mathbb{Z}_3$	$\frac{1}{3}(1,-1,0)\,;\ \frac{1}{3}(0,1,-1)$	possible
$T^6/\mathbb{Z}_{8\text{-I}}$	$\frac{1}{8}(1,2,-3)$	possible	$T^6/\mathbb{Z}_3\times\mathbb{Z}_6$	$\frac{1}{3}(1,-1,0)\,;\ \frac{1}{6}(0,1,-1)$	possible
$T^6/\mathbb{Z}_{8\text{-II}}$	$\frac{1}{8}(1,3,-4)$	possible	$T^6/\mathbb{Z}_4\times\mathbb{Z}_4$	$\frac{1}{4}(1,-1,0)\,;\ \frac{1}{4}(0,1,-1)$	possible
$T^6/\mathbb{Z}_{12\text{-I}}$	$\frac{1}{12}(1,4,-5)$	possible	$T^6/\mathbb{Z}_6\times\mathbb{Z}_6$	$\frac{1}{6}(1,-1,0)\,;\ \frac{1}{6}(0,1,-1)$	possible
$T^6/\mathbb{Z}_{12\text{-II}}$	$\frac{1}{12}(1,5,-6)$	possible			

Comments:

- when tachyons are possible, they do not necessarily appear
- and tachyons are lifted in full blow-up...

Lifting tachyons by blow-up

State		Sector	Representation
Tachyon	T	θ^1	$(\mathbf{1};\mathbf{1},\mathbf{1},\mathbf{2})$
Blow-up mode	B	θ^2	$(\mathbf{1};\mathbf{1},\mathbf{2}_-,\mathbf{1})$

On general field theoretical grounds we expect that the effective potential for the tachyon t contains the terms

$$V_{\text{eff}} = m_T^2\,|T|^2 + |\lambda|^2\,|B|^2\,|T|^2 + \ldots$$

where $m_T^2 < 0$ is the tachyonic mass

When the blow-up mode B takes a sufficiently large VEV, the tachyon becomes massive

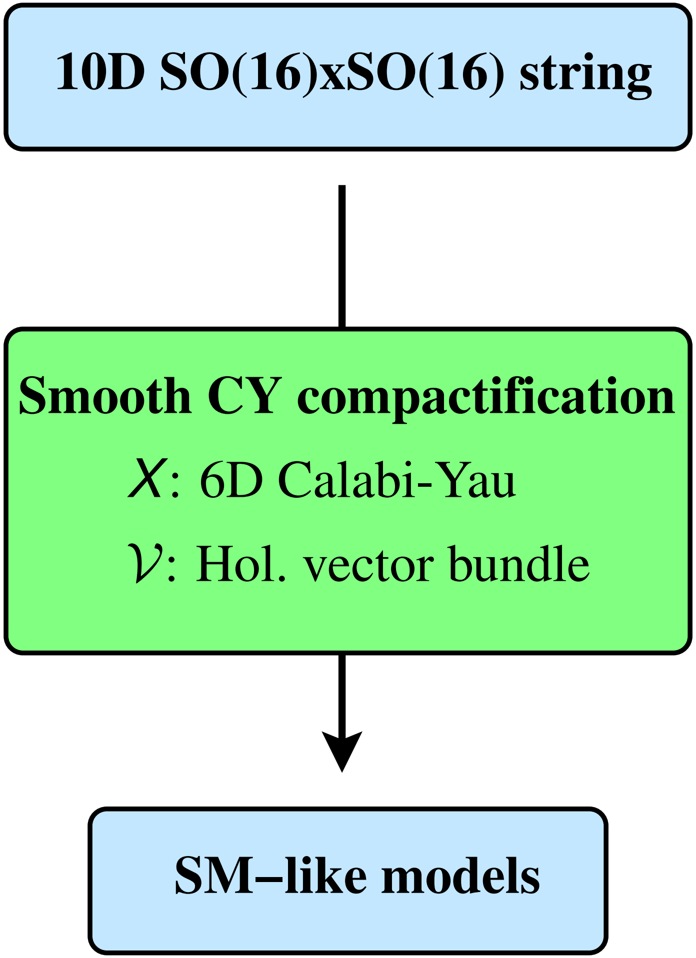
SM-like models scans on CY orbifolds

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 we can construct single Higgs-doublet models, like the SM (not MSSM)!

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



CY backgrounds for SO(16)×SO(16) string

Why consider CY backgrounds for non-SUSY strings?

- **Target space: Avoid tachyons**

  Blaszczyk,SGN,Loukas,Ramos-Sanchez'14

  To leading order there are no tachyon on smooth CY backgrounds in the large volume approximation:

  The Laplace operator $\Delta \sim (i\not{D})^2$ is related to the square of the Dirac operator $i\not{D}$, hence its spectrum is non-negative

- **Worldsheet: U(1)$_R$ symmetry and (2,0) SUSY**

  Hull,Witten'85

- **We can recycle many computational techniques**

SM-like model scans on smooth Calabi-Yaus

Inequivalent SU(5) models for SO(16)×SO(16) theory on smooth CYs										
Geometry		GUT-	Chiral exact			SM-	Chiral exact			
h_{11}	Name (CICY #)	like	Fermi	Scalar	Both	like	Fermi	Scalar	Both	
4	Tetra-quartic (7862)	209,743	281	263	1	1,575,098	2,370	2,000	15	
4	7491, 7522	1,873	0	1	0	14,651	0	11	0	
5	7447, 7487	28,209	901	46	5	149,143	5,154	377	52	
5	6770	65,888	173	85	0	437,327	914	707	0	
5	6715, 6788, 6836, 6927	120	7	0	0	518	89	0	0	
5	6732, 6802, 6834, 6896	460	33	0	0	3,119	275	0	0	
5	6225	72	0	0	0	483	0	0	0	
6	5302	355	22	0	0	1093	66	0	0	
19	Schoen	456,594	5,169	2,745	30	3,002,353	37,276	21,955	237	

SGN,Loukas,Ruehle'15

(CICY classifications Candelas,Dale,Lutken,Schimmrigk'88, Braun'10)

Comments on tachyons and other instabilities

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

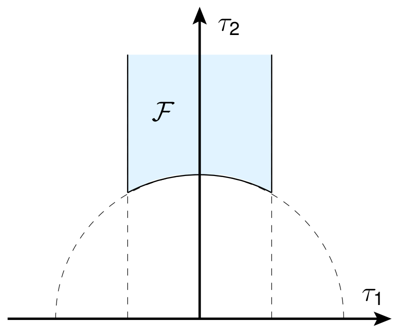
By considering Scherk-Schwarz supersymmetry breaking and Wilson lines on circle (torus) compactifications, one can show that all these theories are continuously connected to each other

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

Comments on the vacuum energy

The vacuum energy is given by

$$V(R) = \int_{\mathcal{F}} \frac{\mathrm{d}^2\tau}{\tau_2^{d/2+1}} Z(R)$$



Without SUSY this will generically non-zero and a potential is being generated for the scalars in the theory.

If the theory contains a level matched tachyon ($m_T^2 < 0$), then this diverges: Kutasov,Seiberg'90

$$V(R) \sim \int_{\mathcal{F}} \frac{\mathrm{d}^2\tau}{\tau_2^{d/2+1}} e^{-2\pi\,\tau_2\, m_T^2}$$

Hence tachyons will be dynamically avoided if there is some deformation direction which can lift tachyons.

Fischler-Susskind mechanism

Fischler,Susskind'86

A non-vanishing vacuum energy implies that the theory possess a non-vanishing dilaton tadpole.

This tadpole can induce tachyons at the two-loop level.

In principle, one should be able to study where the theory goes because of the driving force of this tadpole and expand the theory from the true minimum.

Unfortunately it is unknown how this mechanism should be implemented concretely...

Summary / Outlook

We have seen that studying non-supersymmetric models in string theory is interesting both theoretically and phenomenologically

But there are still many open difficult and fundamental questions here to be addressed...

Thank you!