

# Non-supersymmetric heterotic model building

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based on

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together with:

Michael Blaszczyk (Mainz)

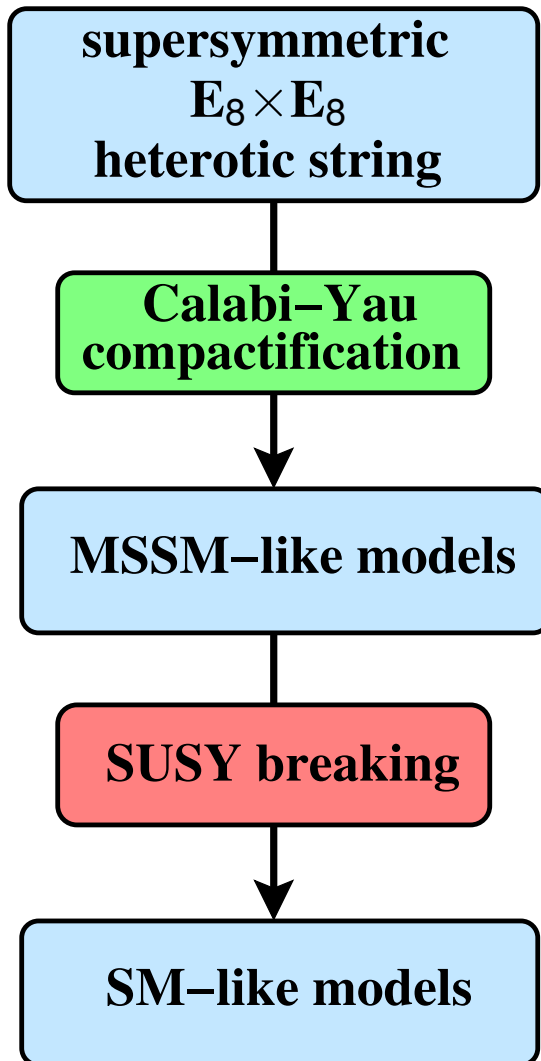
Orestis Loukas (Munich, Athens)

Saul Ramos-Sánchez (Mexico)

# Overview of this talk

- 1 Motivation
- 2 The non-supersymmetric heterotic string
- 3 Smooth Calabi-Yau compactifications
- 4 Orbifold compactifications
- 5 SM-like model searches
- 6 Conclusion

# The conventional heterotic route towards SM



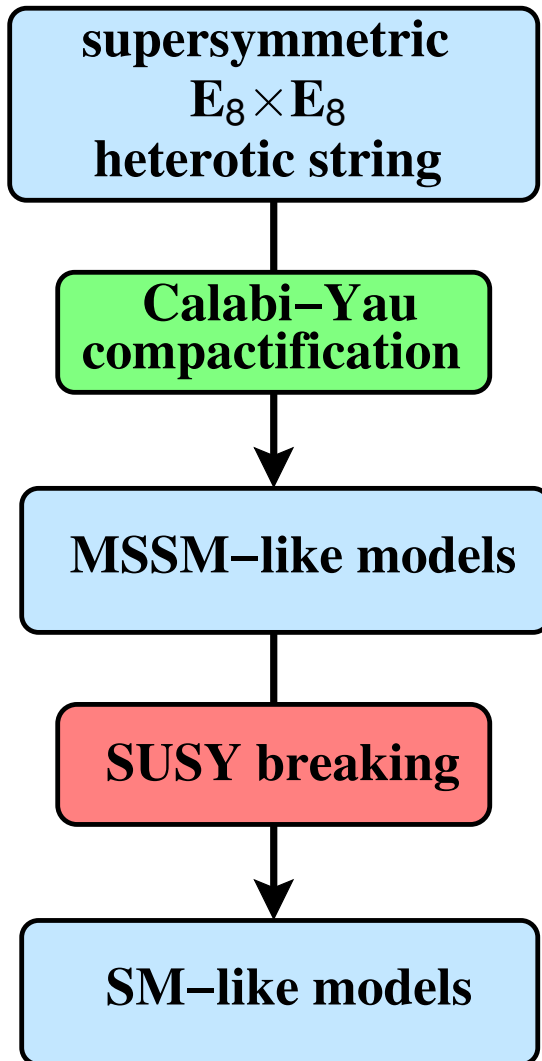
assumes an intermediate MSSM, i.e.:

- a 4D  $\mathcal{N} = 1$  supersymmetric  $SU(3)_C \times SU(2)_L \times U(1)_Y$  gauge theory
- three net chiral generations of quarks and leptons
- at least one Higgs doublet pair

and subsequently some mechanism of SUSY breaking, i.e.:

- order hundred soft parameters
- induced by gauge, gravity, anomaly mediations

# The conventional heterotic route towards SM



obtains 4D MSSM-like models via compactification one has to carefully choose a string background, i.e.:

$$\mathcal{M}^{1,9} \rightarrow \mathcal{M}^{1,3} \times \mathcal{M}^6$$

- a complicated six dimensional Calabi-Yau manifold  $\mathcal{M}^6$ ;  
*Candelas, Horowitz, Strominger, Witten'85*
- supporting a suitable stable holomorphic vector bundle  
(the standard embedding  $E_8 \rightarrow E_6$  leads to a problematic GUT)
- or toroidal orbifolds *Dixon, Harvey, Vafa, Witten'85, Ibanez, Mas, Nilles, Quevedo'87*

# Recent model building results

## MSSM-like models on Calabi–Yaus:

- Stable  $SU(5)$  vector bundles on Schoen manifold  
Donagi,Ovrut,Pantev,Waldram'00, Bouchard,Donagi'05, Braun,He,Ovrut,Pantev'05
- Line bundles on complete intersection Calabi–Yaus  
Anderson,Gray,Lukas,Palti'11

## MSSM-like models on Orbifolds: Vaudrevange,Nilles'14

- $T^6/\mathbb{Z}_{6-II}$  Buchmuller,Hamaguchi,Lebedev,Ratz'05,  
Lebedev,Nilles,Raby,Ramos-Sanchez,Ratz,Vaudrevange,Wingerter'06
- $T^6/\mathbb{Z}_{12-I}$  Kim,Kim,Kyae'07
- $T^6/\mathbb{Z}_2 \times \mathbb{Z}_2$  Blaszczyk,SGN,Ratz,Ruehle,Trapletti,Vaudrevange'09
- $T^6/\mathbb{Z}_4 \times \mathbb{Z}_2$  Mayorga-Pena,Nilles,Oehlmann'12
- $T^6/\mathbb{Z}_{8-I,II}$  SGN,Loukas'13

# But where is supersymmetry?

## ATLAS SUSY Searches\* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s} = 7, 8 \text{ TeV}$

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference	
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$ 1405.7875
	MSUGRA/CMSSM	1 $e, \mu$	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$ ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	any $m(\tilde{q})$ 1.1 TeV	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$ 1405.7875
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1405.7875
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0 \rightarrow q\tilde{q}W\tilde{\chi}_1^0$	1 $e, \mu$	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)<200 \text{ GeV}, m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$ ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell/\nu\nu/\nu\nu)\tilde{\chi}_1^0$	2 $e, \mu$	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ ATLAS-CONF-2013-089
	GMSB ( $\tilde{\ell}$ NLSP)	2 $e, \mu$	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta<15$ 1208.4688
	GMSB ( $\tilde{\ell}$ NLSP)	1-2 $\tau$ + 0-1 $\ell$	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta>20$ 1407.0603
	GGM (bino NLSP)	2 $\gamma$	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0)>50 \text{ GeV}$ ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e, \mu$ + $\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)>50 \text{ GeV}$ ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	$\gamma$	1 $b$	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)>220 \text{ GeV}$ 1211.1167
GGM (higgsino NLSP)	2 $e, \mu$ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\text{NLSP})>200 \text{ GeV}$ ATLAS-CONF-2012-152	
Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{G})>10^{-4} \text{ eV}$ ATLAS-CONF-2012-147	
3 <sup>rd</sup> gen. $\tilde{g}$ med.	$\tilde{g} \rightarrow b\tilde{b}\tilde{\chi}_1^0$	0	3 $b$	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)<400 \text{ GeV}$ 1407.0600
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)<350 \text{ GeV}$ 1308.1841
	$\tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_1^+$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)<400 \text{ GeV}$ 1407.0600
	$\tilde{g} \rightarrow b\tilde{t}\tilde{\chi}_1^+$	0-1 $e, \mu$	3 $b$	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)<300 \text{ GeV}$ 1407.0600
3 <sup>rd</sup> gen. squarks direct production	$\tilde{b}_1\tilde{t}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	0	2 $b$	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)<90 \text{ GeV}$ 1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^0)=2 m(\tilde{\chi}_1^{\pm})$ 1404.2500
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$	1-2 $e, \mu$	1-2 $b$	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)=55 \text{ GeV}$ 1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$	2 $e, \mu$	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)-50 \text{ GeV}, m(\tilde{t}_1)<m(\tilde{\chi}_1^{\pm})$ 1403.4853
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	2 $e, \mu$	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	$m(\tilde{\chi}_1^0)=1 \text{ GeV}$ 1403.4853
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^+$	0	2 $b$	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)<200 \text{ GeV}, m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$ 1308.2631
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^0$	1 $e, \mu$	1 $b$	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1407.0583
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0	2 $b$	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$	0	mono-jet/ $c$ -tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)<85 \text{ GeV}$ 1407.0608
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 $e, \mu$ (Z)	1 $b$	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)>150 \text{ GeV}$ 1403.5222
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 $e, \mu$ (Z)	1 $b$	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)<200 \text{ GeV}$ 1403.5222	
EW direct	$\tilde{\ell}_L, \tilde{\ell}_R, \tilde{\ell} \rightarrow \ell\tilde{\chi}_1^0$	2 $e, \mu$	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ 1403.5294
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow \ell\nu(\ell\nu)$	2 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ 1403.5294
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow \tilde{\tau}\nu(\tilde{\tau}\nu)$	2 $\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	$m(\tilde{\chi}_1^0)=0 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ 1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_L\nu_L(\tilde{\nu}\nu), \tilde{\nu}\tilde{\ell}_L(\tilde{\nu}\nu)$	3 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$ 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^{\pm}Z^0$	2-3 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0, \text{sleptons decoupled}$ 1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow W\tilde{\chi}_1^{\pm}h\tilde{\chi}_1^0$	1 $e, \mu$	2 $b$	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0, \text{sleptons decoupled}$ ATLAS-CONF-2013-093
	$\tilde{\chi}_1^0\tilde{\chi}_2^0, \tilde{\chi}_{2,3}^0 \rightarrow \tilde{\ell}_R\ell$	4 $e, \mu$	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0), m(\tilde{\chi}_1^0)=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$ 1405.5086
	Long-lived particles	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV
Stable, stopped $\tilde{g}$ R-hadron		0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \mu\text{s}<\tau(\tilde{g})<1000 \text{ s}$ 1310.8584
GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$		1-2 $\mu$	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	$10<\tan\beta<50$ ATLAS-CONF-2013-058
GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$ , long-lived $\tilde{\chi}_1^0$		2 $\gamma$	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	$0.4<\tau(\tilde{\chi}_1^0)<2 \text{ ns}$ 1304.6310
$\tilde{q}\tilde{q}, \tilde{\chi}_1^0 \rightarrow q\tilde{q}$ (RPV)		1 $\mu$ , displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	$1.5<c\tau(\tilde{\chi}_1^0)<156 \text{ mm}, \text{BR}(\mu)=1, m(\tilde{\chi}_1^0)=108 \text{ GeV}$ ATLAS-CONF-2013-092
RPV	LFV $pp \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e + \mu$	2 $e, \mu$	-	-	4.6	$\tilde{\nu}_e$ 1.61 TeV	$\lambda'_{311}=0.10, \lambda'_{132}=0.05$ 1212.1272
	LFV $pp \rightarrow \tilde{\nu}_e + X, \tilde{\nu}_e \rightarrow e(\mu) + \tau$	1 $e, \mu$ + $\tau$	-	-	4.6	$\tilde{\nu}_e$ 1.1 TeV	$\lambda'_{311}=0.10, \lambda'_{1233}=0.05$ 1212.1272
	Bilinear RPV CMSSM	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g}), c\tau_{LSP}<1 \text{ mm}$ 1404.2500
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow W\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0 \rightarrow ee\nu_e, e\mu\nu_e$	4 $e, \mu$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 750 GeV	$m(\tilde{\chi}_1^0)>0.2 \times m(\tilde{\chi}_1^{\pm}), \lambda'_{121} \neq 0$ 1405.5086
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}, \tilde{\chi}_1^{\pm} \rightarrow W\tilde{\chi}_1^{\pm}\tilde{\chi}_1^0 \rightarrow \tau\tau\nu_e, e\tau\nu_e$	3 $e, \mu$ + $\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	$m(\tilde{\chi}_1^0)>0.2 \times m(\tilde{\chi}_1^{\pm}), \lambda'_{133} \neq 0$ 1405.5086
	$\tilde{g} \rightarrow q\tilde{q}\tilde{q}$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	$\text{BR}(\ell)=\text{BR}(b)=\text{BR}(c)=0\%$ ATLAS-CONF-2013-091
$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow b s$	2 $e, \mu$ (SS)	0-3 $b$	Yes	20.3	$\tilde{g}$ 850 GeV	1404.2500	
Other	Scalar gluon pair, sgluon $\rightarrow q\tilde{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693 1210.4826
	Scalar gluon pair, sgluon $\rightarrow \tilde{t}\tilde{t}$	2 $e, \mu$ (SS)	2 $b$	Yes	14.3	sgluon 350-800 GeV	ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac $\chi$ )	0	mono-jet	Yes	10.5	$M^*$ scale 704 GeV	$m(\chi)<80 \text{ GeV}$ , limit of $<687 \text{ GeV}$ for D8 ATLAS-CONF-2012-147

$\sqrt{s} = 7 \text{ TeV}$  full data  
 $\sqrt{s} = 8 \text{ TeV}$  partial data  
 $\sqrt{s} = 8 \text{ TeV}$  full data

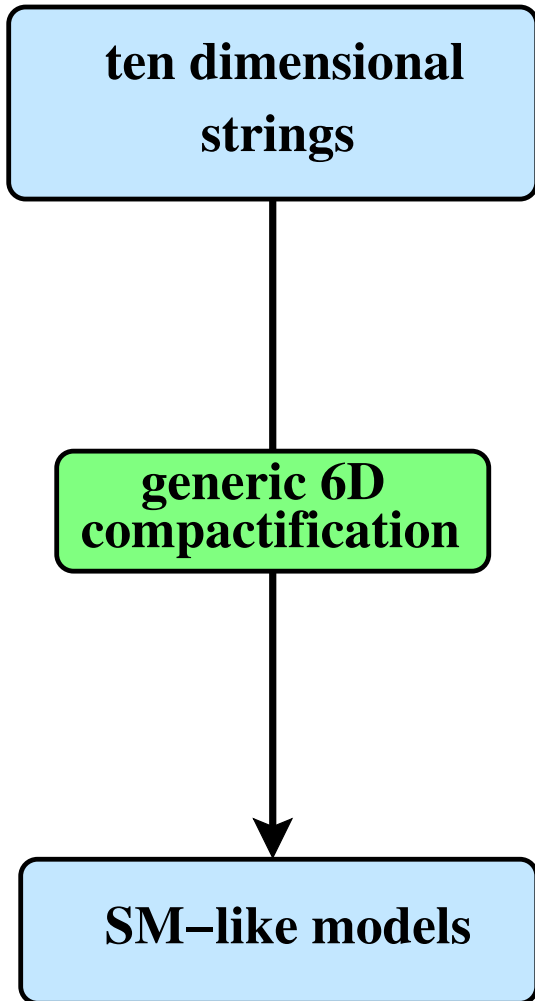
10<sup>-1</sup> 1 Mass scale [TeV]

# Why do (did) we believe in supersymmetry?

Some motivations for supersymmetry:

- hierarchy problem
- unification of gauge couplings
- dark matter candidate
- compelling extension of the Poincaré group
- **gain computational control**

# Maybe we should look for non-supersymmetric string models...



Non-SUSY string models have:

- hierarchy problem
- unstable Higgs mass
- large cosmological constant
- with associated dilaton tadpole
- **tachyons are possible**
- **far less computational control**

Generic 6D compactifications are:

- unclassified number of manifolds
- even the number of toroidal orbifolds is almost 29 million



# Maybe we should look for non-supersymmetric string models...

Previous attempts:

- Free fermionic construction with non-supersymmetric boundary conditions

Dienes'94,'06, Faraggi,Tsulaia'07

- Non-supersymmetric orbifolds of heterotic theories

Chamseddine,Derendinger,Quiros'88, Taylor'88, Toon'90, Sasada'95,  
Font,Hernandez'02

- Non-supersymmetric orientifold type II theories

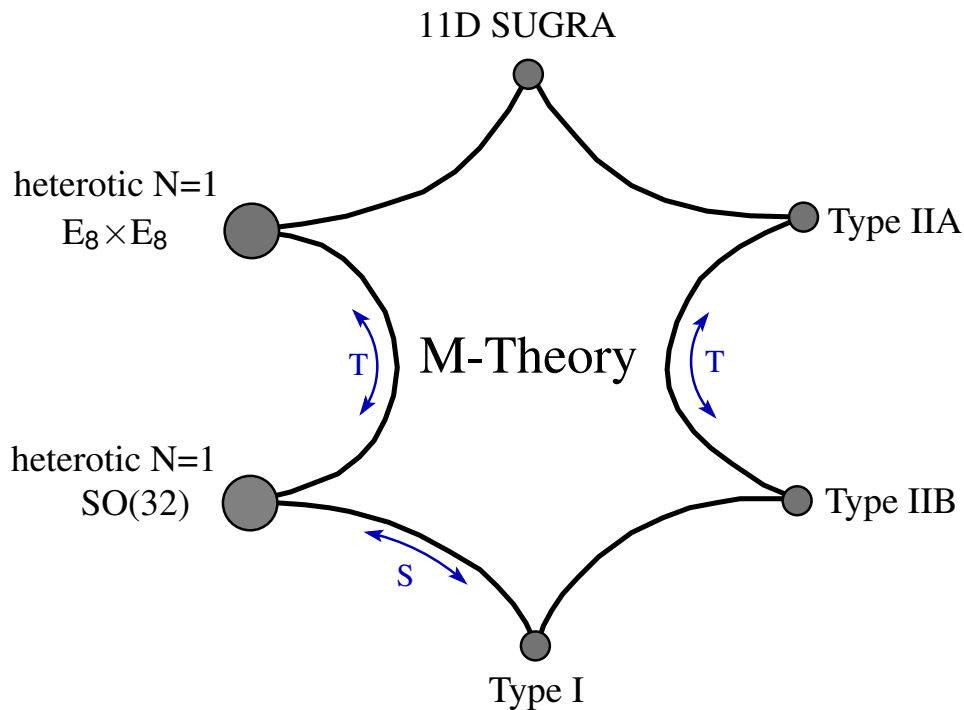
Sagnotti'95, Angelantonj'98 Blumenhagen,Font,Luest'99,  
Aldazabal,Ibanez,Quevedo'99

- Non-supersymmetric RCFTs

Gato-Rivera,Schellekens'07

# Well-known 10D string theories

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



However, it disregards an interesting heterotic string theory...

# The non-supersymmetric heterotic string

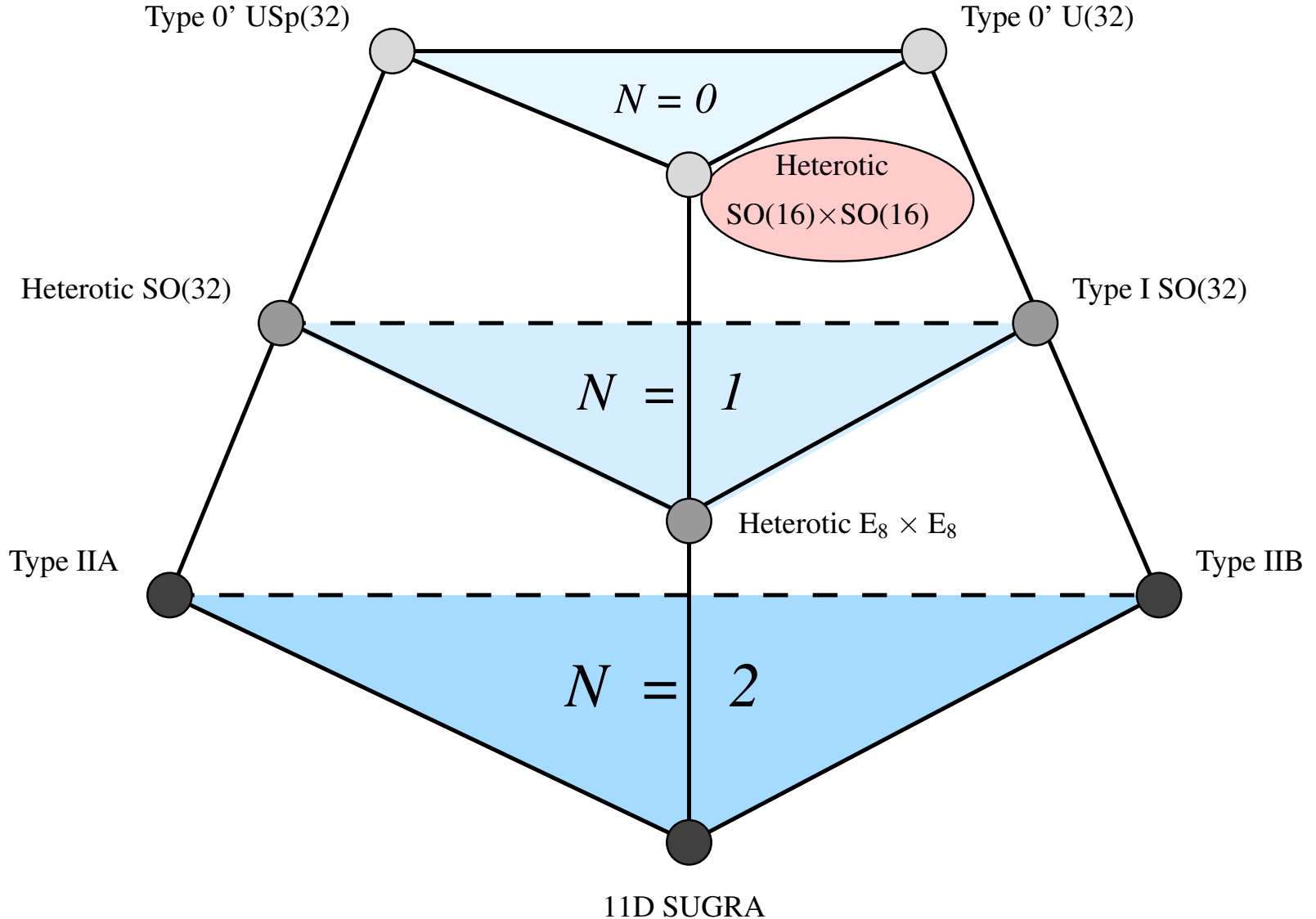
The low-energy spectrum of the N=0 heterotic string reads:

Dixon,Harvey'86, Alvarez-Gaume,Ginsparg,Moore,Vafa'86

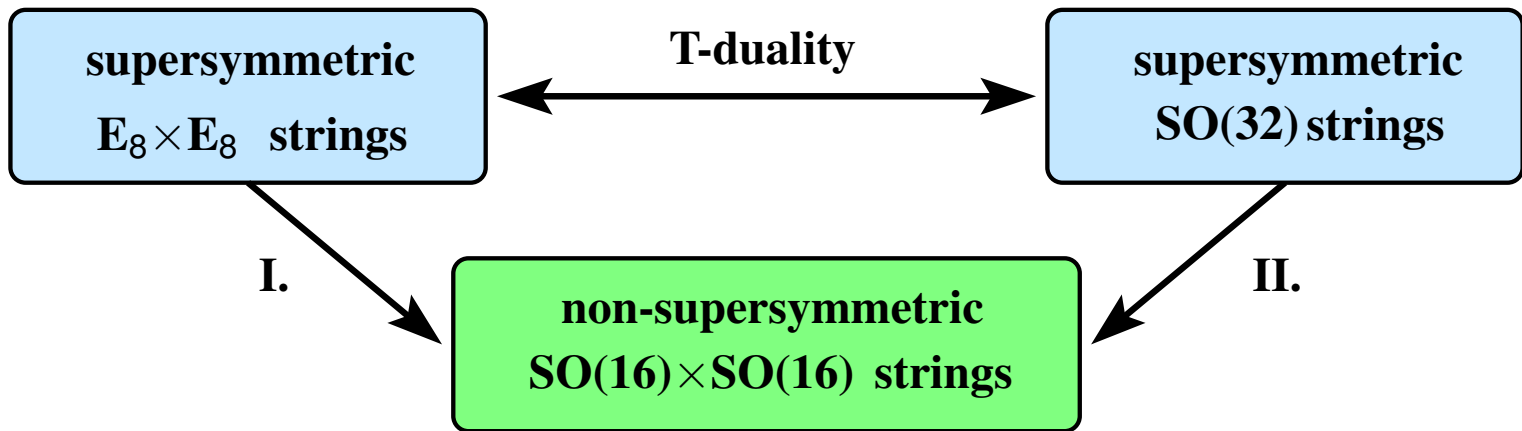
	Fields	10D space-time interpretation
Bosons	$G_{MN}, B_{MN}, \phi$	Graviton, Kalb-Ramond 2-form, Dilaton
	$A_M$	$SO(16) \times SO(16)$ Gauge fields
Fermions	$\psi_+$	Spinors in the $(\mathbf{128}, \mathbf{1}) + (\mathbf{1}, \mathbf{128})$
	$\psi_-$	Cospinors in the $(\mathbf{16}, \mathbf{16})$

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

# 10D tachyon-free (non)SUSY string theories



# Constructions of the $SO(16) \times SO(16)$ string



The  $SO(16) \times SO(16)$  theory thus can be obtained by: [Dixon, Harvey'86](#), [Alvarez-Gaume, Ginsparg, Moore, Vafa'86](#)

- **I. a SUSY breaking orbifolding of the  $E_8 \times E_8$  string :**

using a  $\mathbb{Z}_2$  "orbifold" of twist  $v_0$  and gauge shift  $V_0$ :

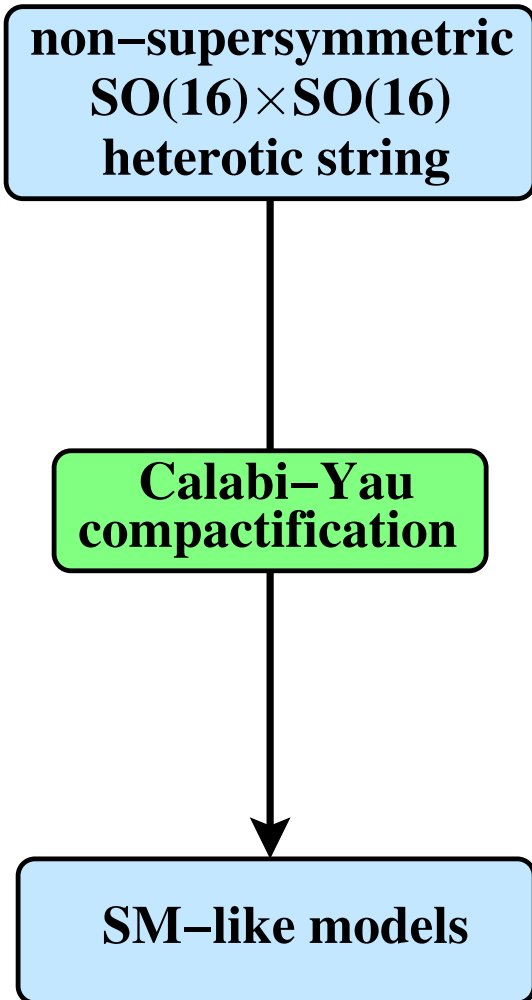
$$v_0 = (0, 1^3), \quad V_0 = (1, 0^7)(-1, 0^7)$$

- **II. a SUSY breaking orbifolding of the  $SO(32)$  string :**

using a  $\mathbb{Z}_2$  "orbifold" twist  $v_0$  and gauge shift  $V_0$ :

$$v_0 = (0, 1^3), \quad V'_0 = (1, 0^7)\left(-\frac{1}{2}, \frac{1}{2}^7\right)$$

# Smooth Calabi-Yau compactifications



We could compactify the  $N=0$  theory on any smooth 6D manifold, but then we lose any computation control...

**We will consider smooth compactifications which would themselves preserve supersymmetry, i.e.:**

Blaszczyk, SGN, Loukas, Ramos-Sanchez'14

- holomorphic vector bundles on Calabi-Yau manifolds
- subject to the Bianchi identities

# Computation of the fermionic spectrum

For the determination of fermionic spectra we can rely on conventional methods

- (representation dependent) index theorems:  $\text{ind}(i\mathcal{D})$
- cohomology theory

In particular, for line bundle backgrounds we may employ the multiplicity operator: [SGN, Trapletti, Walter'07](#)

$$\mathcal{N} = \int \frac{1}{6} \left( \frac{\mathcal{F}_2}{2\pi} \right)^3 - \frac{1}{24} \frac{\mathcal{F}_2}{2\pi} \text{tr} \left( \frac{\mathcal{R}_2}{2\pi} \right)^2$$

evaluated on all fermionic states:

fermions	$\Psi_+$	Spinors in the $(\mathbf{128}, \mathbf{1}) + (\mathbf{1}, \mathbf{128})$
	$\Psi_-$	Cospinors in the $(\mathbf{16}, \mathbf{16})$

# Computation of the bosonic spectrum

On a generic six-manifold I do not know how to determine the spectrum or even the number of zero modes of the Laplace operator  $\Delta$ .

But for a smooth Calabi-Yau manifold  $\mathcal{M}^6$  with a vector bundle we can use that the Laplace operator for complex scalars

$$\Delta \sim (i\mathcal{D})^2$$

is related to the Dirac operator  $i\mathcal{D}$  of the would be gaugino:

bosons	$A_M$	$SO(16) \times SO(16)$ Adjoint gauge fields
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Hence, we can also (representation dependent) indices and cohomology theory to determine the spectra of complex scalars



# No tachyons on Calabi-Yau backgrounds

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

Since on smooth Calabi-Yau backgrounds the Laplace operator  $\Delta$  is related to the square of the Dirac operator  $i\mathcal{D}$ , its spectrum is non-negative

**Hence a major problem of non-supersymmetric model building, tachyons, can be avoided by working on smooth Calabi-Yaus**

# Standard embedding compactifications

In the standard embedding we have the gauge embedding:

$$SO(16) \times SO(16)' \longrightarrow SO(10) \times U(1) \times SO(16)'$$

Hence the standard embedding already gives an **SO(10) GUT!**

Multiplicity	Complex bosons	Chiral fermions
1	—	$(\mathbf{16}; \mathbf{1})_3 + (\overline{\mathbf{16}}; \mathbf{1})_{-3}$ $+ (\mathbf{1}; \mathbf{128})_0 + (\mathbf{10}; \mathbf{16})_0$
$h^{1,1}$	$(\mathbf{10}; \mathbf{1})_2 + (\mathbf{1}; \mathbf{1})_{-4}$	$(\mathbf{16}; \mathbf{1})_{-1} + (\mathbf{1}; \mathbf{16})_{-2}$
$h^{1,2}$	$(\mathbf{10}; \mathbf{1})_{-2} + (\mathbf{1}; \mathbf{1})_4$	$(\overline{\mathbf{16}}; \mathbf{1})_1 + (\mathbf{1}; \mathbf{16})_2$
$h^1(\text{End}(V))$	$(\mathbf{1}; \mathbf{1})_0$	—

The net number of **16** of **SO(10)** is determined by:  $h^{1,1} - h^{2,1}$

# Orbifolding the N=0 theory

A  $\mathbb{Z}_N$  orbifold is defined by the worldsheet boundary conditions:

$$X^i(\sigma + 1) = e^{2\pi i k v_j} X^i(\sigma), \quad \psi^i(\sigma + 1) = e^{2\pi i (\frac{s}{2} + k v_j)} \psi^i(\sigma),$$

$$\lambda'_1(\sigma + 1) = e^{2\pi i (\frac{t}{2} + k V_{1l})} \lambda'_1(\sigma), \quad \lambda'_2(\sigma + 1) = e^{2\pi i (\frac{u}{2} + k V_{2l})} \lambda'_2(\sigma)$$

encoded in a twist  $v$  and gauge shift  $V = (V_1; V_2)$  with:

$$N v_j \equiv 0, \quad N V_{1,2} \in \text{weight lattice of } \mathbf{E}_8$$

# Conditions from modular invariance

We focus  $\mathbb{Z}_N$  orbifold twists that would preserve at least 4D, N=1 supersymmetry if applied to the  $E_8 \times E_8$  theory:

$$v = (v_1, v_2, -v_1 - v_2), \quad \text{like} \quad \left(\frac{1}{3}, \frac{1}{3}, -\frac{2}{3}\right) \quad \text{for} \quad \mathbb{Z}_3$$

We require that we have modular invariant partition function for the orbifolded N=0 theory in the  $\mathbb{Z}_2$  "orbifold" formulation:

$$\frac{N}{2} (V^2 - v^2) \equiv V_0 \cdot V - v_0 \cdot v \equiv 0$$

with

$$v_0 = (1^3), \quad V_0 = (1, 0^7)(-1, 0^7)$$

# Twisted tachyons

Tachyons are possible in some twisted sectors of many orbifolds:

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

However, when tachyons are possible this does not mean that all such orbifold models actually will have tachyons

# Twisted tachyons of a $\mathbb{Z}_{6-1}$ model in blow-up

The  $\mathbb{Z}_{6-1}$  orbifold model spectrum has tachyons:

States	Gauge representations of the spectrum of a tachyonic $\mathbb{Z}_{6-1}$ orbifold
Bosonic tachyons	$3(\mathbf{1}; \mathbf{1}, \mathbf{1}, \mathbf{2})$
Massless chiral fermions	$4(\mathbf{10}; \mathbf{1}) + (\overline{\mathbf{10}}; \mathbf{1}) + 6(\mathbf{5}; \mathbf{1}) + 3(\overline{\mathbf{5}}; \mathbf{1}) + (\mathbf{5}; \mathbf{1}, \mathbf{4}, \mathbf{1}) + 2(\overline{\mathbf{5}}; \mathbf{1}, \mathbf{1}, \mathbf{2}) + (\mathbf{5}; \mathbf{1}, \mathbf{1}, \mathbf{2}) + 2(\overline{\mathbf{5}}; \mathbf{4}, \mathbf{1}, \mathbf{1}) + 12(\mathbf{1}; \mathbf{4}, \mathbf{1}, \mathbf{1}) + 18(\mathbf{1}; \overline{\mathbf{4}}, \mathbf{1}, \mathbf{1}) + 2(\mathbf{1}; \overline{\mathbf{4}}, \mathbf{2}_-, \mathbf{2}) + 2(\mathbf{1}; \mathbf{4}, \mathbf{2}_+, \mathbf{1}) + (\mathbf{1}; \mathbf{6}, \mathbf{2}_-, \mathbf{1}) + (\mathbf{1}; \mathbf{6}, \mathbf{2}_+, \mathbf{1}) + 12(\mathbf{1}; \mathbf{1}, \mathbf{2}_+, \mathbf{2}) + 4(\mathbf{1}; \mathbf{1}, \mathbf{4}, \mathbf{1}) + 36(\mathbf{1}; \mathbf{1}, \mathbf{2}_-, \mathbf{1}) + 30(\mathbf{1}; \mathbf{1}, \mathbf{2}_+, \mathbf{1}) + 11(\mathbf{1}; \mathbf{1}, \mathbf{1}, \mathbf{2}) + 53(\mathbf{1}; \mathbf{1})$
Massless complex scalars	$9(\mathbf{5}; \mathbf{1}) + 2(\overline{\mathbf{5}}; \mathbf{1}) + (\overline{\mathbf{10}}; \mathbf{1}) + (\mathbf{1}; \mathbf{1}, \mathbf{4}, \mathbf{2}) + 30(\mathbf{1}; \mathbf{1}, \mathbf{2}_-, \mathbf{1}) + 12(\mathbf{1}; \mathbf{6}, \mathbf{1}, \mathbf{1}) + 2(\mathbf{1}; \mathbf{4}, \mathbf{1}, \mathbf{2}) + 2(\mathbf{1}; \overline{\mathbf{4}}, \mathbf{4}, \mathbf{1}) + 22(\mathbf{1}; \mathbf{1}, \mathbf{2}_+, \mathbf{1}) + 10(\mathbf{1}; \mathbf{1}, \mathbf{2}_-, \mathbf{2}) + 46(\mathbf{1}; \mathbf{1})$

but its full resolution is free of tachyons:

States	Non-Abelian representations of a blown-up tachyonic orbifold model
Bosonic tachyons	none
Massless chiral fermions	$3(\overline{\mathbf{10}}; \mathbf{1}) + 3(\mathbf{5}; \mathbf{1}) + 6(\overline{\mathbf{5}}; \mathbf{1}) + 2(\overline{\mathbf{5}}; \mathbf{1}, \mathbf{2}_+) + 2(\mathbf{5}; \mathbf{2}_-, \mathbf{1}) + 2(\mathbf{5}; \mathbf{2}_+, \mathbf{1}) + (\mathbf{5}; \mathbf{1}, \mathbf{2}_-) + 2(\mathbf{1}; \mathbf{4}, \mathbf{1}) + 2(\mathbf{1}; \mathbf{1}, \mathbf{4}) + 2(\mathbf{1}; \mathbf{2}_+, \mathbf{2}_+) + 4(\mathbf{1}; \mathbf{2}_+, \mathbf{2}_-) + 2(\mathbf{1}; \mathbf{2}_-, \mathbf{2}_+) + 4(\mathbf{1}; \mathbf{2}_-, \mathbf{2}_-) + 6(\mathbf{1}; \mathbf{2}_+, \mathbf{1}) + 8(\mathbf{1}; \mathbf{2}_-, \mathbf{1}) + 34(\mathbf{1}; \mathbf{1}, \mathbf{2}_+) + 11(\mathbf{1}; \mathbf{1}, \mathbf{2}_-) + 53(\mathbf{1}; \mathbf{1})$
Massless complex scalars	$(\overline{\mathbf{10}}; \mathbf{1}) + 9(\mathbf{5}; \mathbf{1}) + 2(\overline{\mathbf{5}}; \mathbf{1}) + 2(\mathbf{1}; \mathbf{4}, \mathbf{1}) + 2(\mathbf{1}; \mathbf{1}, \mathbf{4}) + 4(\mathbf{1}; \mathbf{2}_+, \mathbf{2}_+) + 2(\mathbf{1}; \mathbf{2}_+, \mathbf{2}_-) + 4(\mathbf{1}; \mathbf{2}_-, \mathbf{2}_+) + 2(\mathbf{1}; \mathbf{2}_-, \mathbf{2}_-) + 43(\mathbf{1}; \mathbf{1})$

# Lifting tachyons by blow-up

State	Sector	Representation
Tachyon $t$	$\theta^1$	$(\mathbf{1}; \mathbf{1}, \mathbf{1}, \mathbf{2})$
Blow-up mode $b$	$\theta^2$	$(\mathbf{1}; \mathbf{1}, \mathbf{2}_-, \mathbf{1})$

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

$$V_{\text{eff}} = -m_t^2 |t|^2 + |\lambda|^2 |b|^2 |t|^2 + \dots$$

where  $m_t^2$  is the tachyonic mass

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

# Orbifold SM-like model searches

Standard Model-like:

- the gauge group contains the SM gauge group with the  $SU(5)$  normalization of the non-anomalous hypercharge  $Y$
- a net number of three generations of chiral fermions
- at least one Higgs scalar field
- vector-like exotic fermions w.r.t. the SM gauge group

Two orbifold models on the same orbifold geometry are equivalent when they have:

- identical massless bosonic and fermionic and possibly tachyonic spectra up to charges under Abelian factors



# Standard Model-like theories

Orbifold		Inequivalent scanned models	Tachyon-free	SM-like tachyon-free models		
twist	#(geom)		percentage	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
$\mathbb{Z}_{6-I}$	(2)	148,950	55 %	59	18	0
$\mathbb{Z}_{6-II}$	(4)	15,036,790	57 %	109	0	1
$\mathbb{Z}_{8-I}$	(3)	2,751,085	51 %	24	0	0
$\mathbb{Z}_{8-II}$	(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

Obtained by implementing the SUSY breaking  $\mathbb{Z}_2$  orbifolding of the  $E_8 \times E_8$  theory in the "Orbifolder package" [Nilles, Ramos-Sanchez,](#)

[Vaudrevange, Wingerter'12](#)

# A Standard Model-like theory with three generations and a single Higgs

Sector	Massless spectrum: chiral fermions / complex bosons
Observable	$3(\mathbf{3}, \mathbf{2})_{1/6} + 3(\bar{\mathbf{3}}, \mathbf{1})_{-2/3} + 6(\bar{\mathbf{3}}, \mathbf{1})_{1/3} + 3(\mathbf{3}, \mathbf{1})_{-1/3} + 3(\mathbf{1}, \mathbf{1})_1 + 5(\mathbf{1}, \mathbf{2})_{-1/2} + 2(\mathbf{1}, \mathbf{2})_{1/2} + 20(\mathbf{1}, \mathbf{1})_{1/2} + 20(\mathbf{1}, \mathbf{1})_{-1/2} + 6(\mathbf{3}, \mathbf{1})_{1/6} + 6(\bar{\mathbf{3}}, \mathbf{1})_{-1/6} + 2(\mathbf{1}, \mathbf{2})_0$
Obs. & Hid.	$3(\mathbf{1}, \mathbf{1}; \mathbf{1}, \mathbf{2})_{1/2} + 3(\mathbf{1}, \mathbf{1}; \mathbf{1}, \mathbf{2})_{-1/2}$
Hidden	$14(\mathbf{1}, \mathbf{2})_0 + 10(\bar{\mathbf{4}}, \mathbf{1})_0 + 6(\mathbf{4}, \mathbf{1})_0 + 3(\mathbf{6}, \mathbf{1})_0 + 2(\mathbf{4}, \mathbf{2})_0 + 71(\mathbf{1})_0$
Observable	$(\mathbf{1}, \mathbf{2})_{-1/2}$ $(\mathbf{3}, \mathbf{1})_{1/6} + (\bar{\mathbf{3}}, \mathbf{1})_{-1/6} + 2(\bar{\mathbf{3}}, \mathbf{1})_{1/3} + 13(\mathbf{1}, \mathbf{2})_0 + 20(\mathbf{1}, \mathbf{1})_{-1/2} + 18(\mathbf{1}, \mathbf{1})_{1/2}$
Obs. & Hid.	$(\mathbf{1}, \mathbf{1}; \mathbf{4}, \mathbf{1})_{1/2} + (\mathbf{1}, \mathbf{1}; \mathbf{4}, \mathbf{1})_{-1/2} + (\mathbf{1}, \mathbf{2}; \mathbf{1}, \mathbf{2})_0$
Hidden	$14(\mathbf{1}, \mathbf{2})_0 + 4(\mathbf{4}, \mathbf{1})_0 + (\mathbf{6}, \mathbf{2})_0 + 23(\mathbf{1})_0$

This model with gauge groups  $G_{\text{obs}} = \text{SU}(3)_C \times \text{SU}(2)_L \times \text{U}(1)_Y$ ,  
 $G_{\text{hid}} = \text{SU}(4) \times \text{SU}(2)$ :

- contains vector-like fermionic and bosonic exotics
- there are states that are charged under both the hidden and the SM gauge group

# Summary

We have studied smooth and orbifold compactifications of the non-supersymmetric heterotic  $SO(16) \times SO(16)$  string

On smooth Calabi-Yau backgrounds we could recycle

- commonly employed techniques to determine both the fermionic and bosonic 4D spectra
- and argue that the  $N=0$  theory never leads to tachyons on smooth Calabi-Yaus

However, twisted tachyons may arise on certain singular orbifolds; in full blow-up they disappear from the spectrum

We have performed SM-like model searches on selected orbifold geometries and found over 12,000 SM-like theories

# Outlook

Some future directions:

- perform non-SUSY model searches on smooth Calabi-Yaus with (line) bundles
- Investigate the cosmological constant in non-SUSY string models
- Investigate the consequences of the destabilizing dilaton tadpole associated to the cosmological constant
- Investigate perturbative and non-perturbative generation of tachyons