Some recent developments in non-Supersymmetric string model building

Stefan Groot Nibbelink

Arnold Sommerfeld Center,
Ludwig-Maximilians-University, Munich

String Pheno, Madrid, June 2015

This talk is based on collaborations with:

Michael Blaszczyk

Orestis Loukas

Ramos-Sanchez

Fabian Ruehle

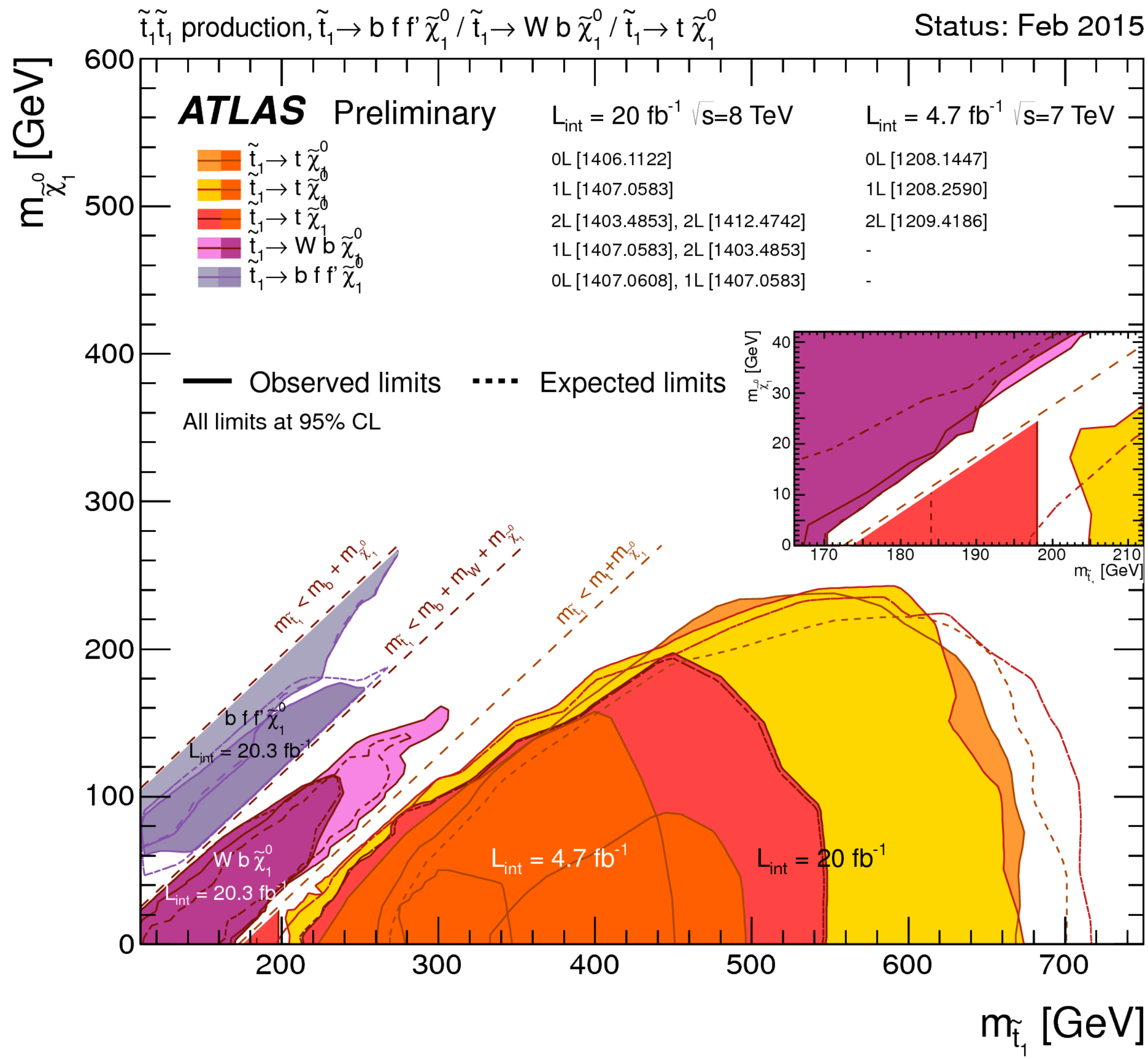
and publications:

JHEP 1410 (2014) 119 [arXiv:1407.6362]

DISCRETE'14 proceedings [arXiv:1502.03604]

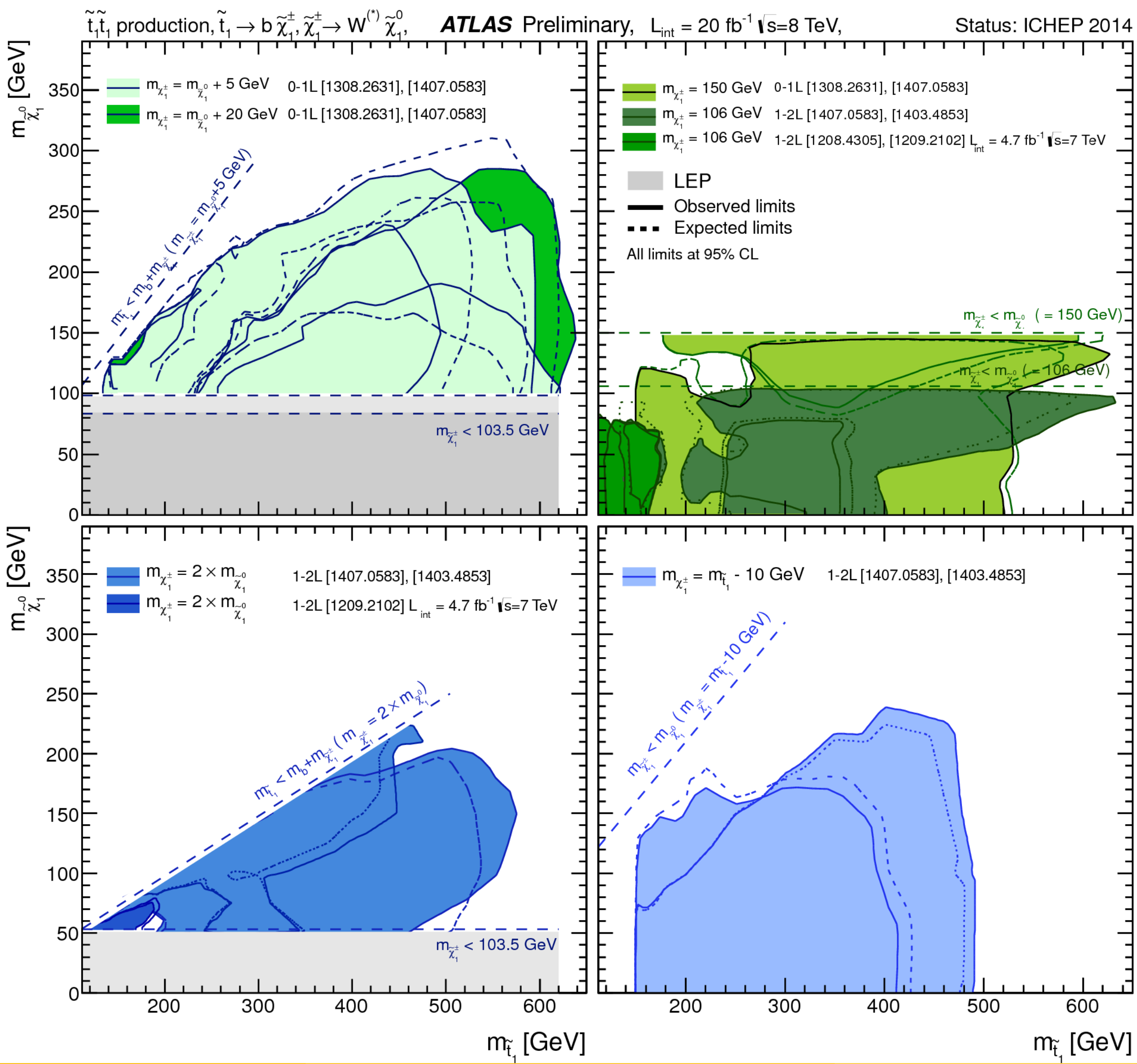
Work(s) in progress [arXiv:1506.?????]

Main motivation: Where is Supersymmetry?



⇒ See talks by Alcaraz, Zwirner

Main motivation: Where is Supersymmetry?



Main motivation: Where is Supersymmetry?

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

ATLAS Preliminary

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

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	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
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}\gamma$, $\tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	1 γ	0-1 jet	Yes	20.3	$\tilde{q}$ 250 GeV	$m(\tilde{q})$-$m(\tilde{\chi}^0_1)$ = m(c)	1411.1559
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	1 e,μ	3-6 jets	Yes	20	$\tilde{g}$ 1.2 TeV	$m(\tilde{\chi}^0_1)$<300 GeV, $m(\tilde{\chi}^\pm)$=0.5($m(\tilde{\chi}^0_1)$+$m(\tilde{g})$)	1501.03555
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}^0_1$	2 e,μ	0-3 jets	-	20	$\tilde{g}$ 1.32 TeV	$m(\tilde{\chi}^0_1)$=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}^0_1)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}^0_1)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}^0_1)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV	$m(\tilde{G})>1.8\times10^{-4}$ eV, $m(\tilde{g})=m(\tilde{q})$=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}^0_1)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}^0_1)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}^0_1)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}^0_1)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}^0_1)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}^\pm_1)$=2 $m(\tilde{\chi}^0_1)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV, 230-460 GeV	$m(\tilde{\chi}^\pm_1)$ = 2$m(\tilde{\chi}^0_1)$, $m(\tilde{\chi}^0_1)$=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 90-191 GeV, 215-530 GeV	$m(\tilde{\chi}^0_1)$=1 GeV	1403.4853, 1412.4742
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to t\tilde{\chi}^0_1$	0-1 e,μ	1-2 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}^0_1)$=1 GeV	1407.0583,1406.1122
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)$-$m(\tilde{\chi}^0_1)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}^0_1)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}^0_1)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}^0_1)$=0 GeV	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}^\pm_1$ 140-465 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 100-350 GeV	$m(\tilde{\chi}^0_1)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1407.0350
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 700 GeV	$m(\tilde{\chi}^\pm_1)$=$m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^\pm_1)$+$m(\tilde{\chi}^0_1)$)	1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 420 GeV	$m(\tilde{\chi}^\pm_1)$=$m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1h\tilde{\chi}^0_1$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}^\pm_1,\tilde{\chi}^0_2$ 250 GeV	$m(\tilde{\chi}^\pm_1)$=$m(\tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1)$=0, sleptons decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}^0_{2,3}$ 620 GeV	$m(\tilde{\chi}^0_2)$=$m(\tilde{\chi}^0_3)$, $m(\tilde{\chi}^0_1)$=0, $m(\tilde{\ell},\tilde{\nu})$=0.5($m(\tilde{\chi}^0_2)$+$m(\tilde{\chi}^0_1)$)	1405.5086
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}^\pm_1$ 270 GeV	$m(\tilde{\chi}^\pm_1)$-$m(\tilde{\chi}^0_1)$=160 MeV, $\tau(\tilde{\chi}^\pm_1)$=0.2 ns	1310.3675
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}^0_1)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$ 1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}^0_1$ 537 GeV	10<$\tan\beta$<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	$\tilde{\chi}^0_1$ 435 GeV	2<$\tau(\tilde{\chi}^0_1)$<3 ns, SPS8 model	1409.5542
	$\tilde{q}\tilde{q}$, $\tilde{\chi}^0_1\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}^0_1)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X$, $\tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 750 GeV	$m(\tilde{\chi}^0_1)$>0.2×$m(\tilde{\chi}^\pm_1)$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}^\pm_1$ 450 GeV	$m(\tilde{\chi}^0_1)$>0.2×$m(\tilde{\chi}^\pm_1)$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	$\tilde{c}$ 490 GeV	$m(\tilde{\chi}^0_1)$<200 GeV	1501.01325

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

10^{-1} 1 **Mass scale [TeV]**

Main motivating questions:

- **So far no supersymmetry found, what if this stays this way?**
- **Can string theory exist without supersymmetry?**
- **What is the supersymmetry breaking mechanism in string theory?**

(Inspired by discussions with Brent Nelson)

Possible scales of supersymmetry breaking:

In light of these bounds there are a couple of options:

- the supersymmetry breaking scale is around a few TeV
- the supersymmetry breaking scale is somewhere between the Planck and electroweak scale
- the supersymmetry breaking happens at the Planck/String scale, i.e. there is no supersymmetry in target space

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 interest

Type-II:

- Non-supersymmetric conifold

  Dymarsky,Kuperstein'12

- Non-SUSY fractional branes

  Kuperstein,Truijen,van Riet'14 $\Rightarrow$ See talks by Puhm,Massai,van Riet

Heterotic:

- Towards a non-supersymmetric string phenomenology

  Abel,Dienses,Mavroudi'15 $\Rightarrow$ See talk by Mavroudi

- Heterotic moduli stabilisation and non-supersymmetric vacua

  Lukas,Lalak,Svanes'15

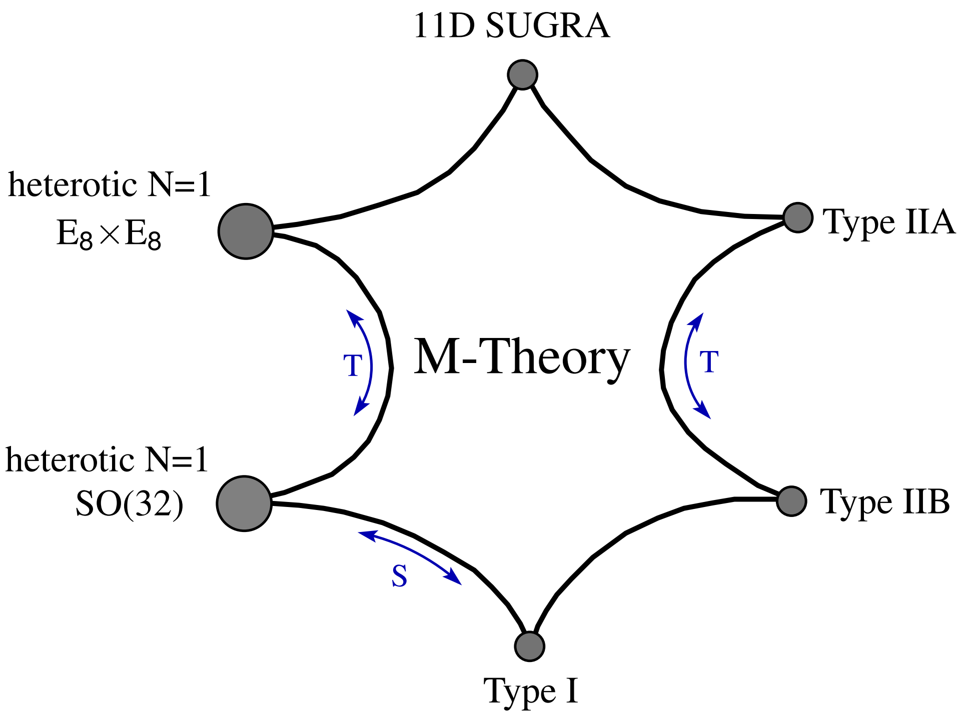
- Non-Tachyonic Semi-Realistic Non-Supersymmetric Heterotic String Vacua Ashfaque,Athanasopoulos,Faraggi,Sonmez'15

  $\Rightarrow$ See talk by Ashfaque

Overview of this talk

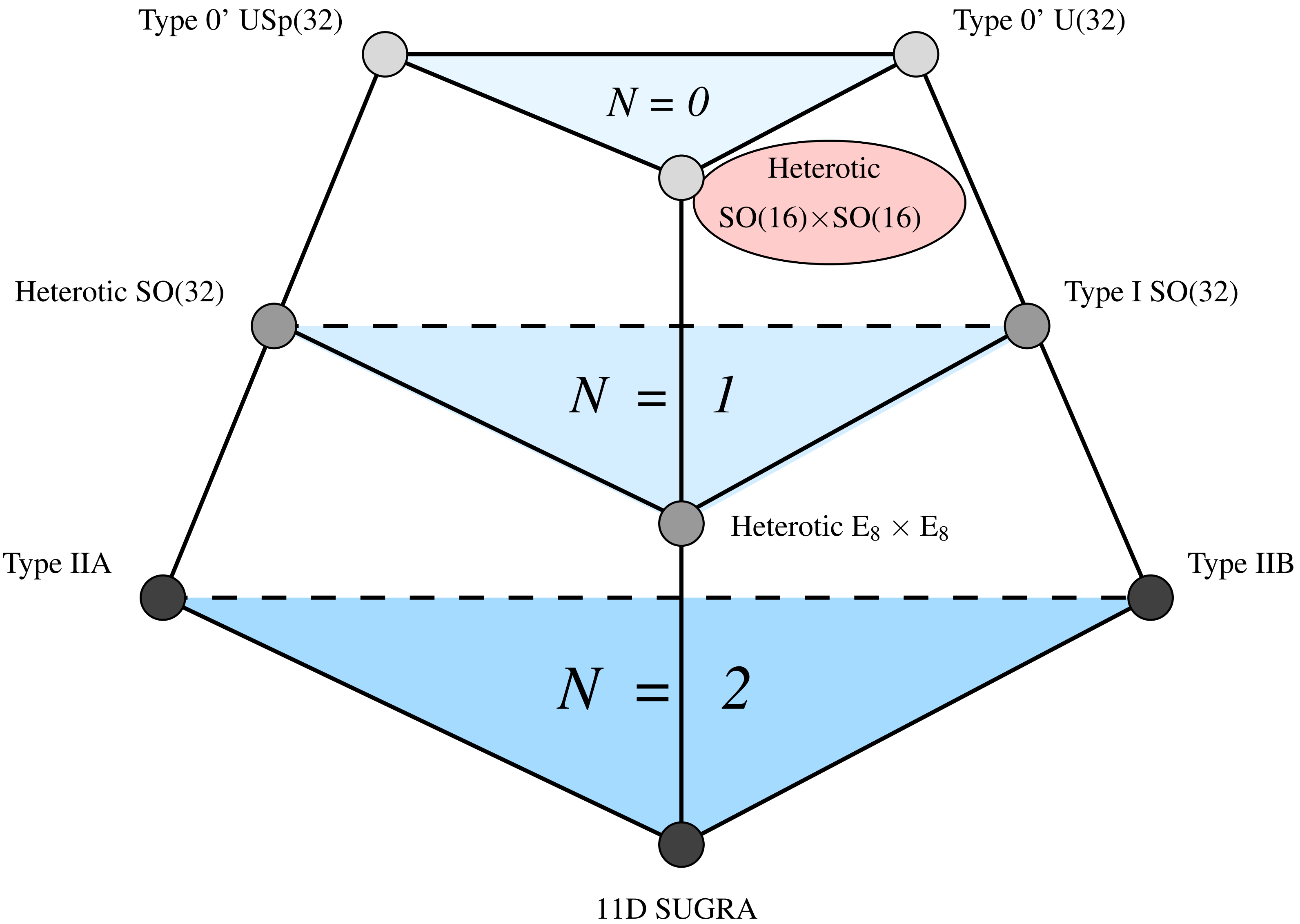
Well-known 10D string theories

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



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 $(\mathbf{16}, \mathbf{16})$

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

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

The partition functions of the non-supersymmetric heterotic SO(16)×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

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

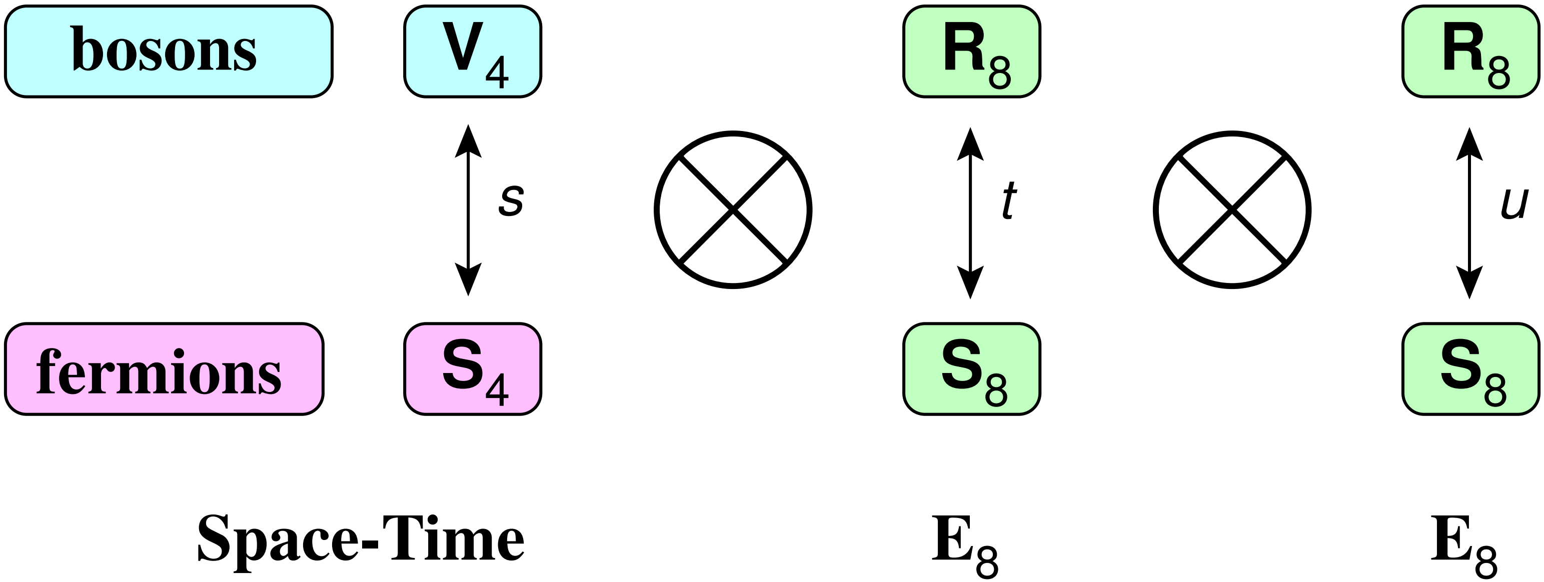
Heterotic weight lattices

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

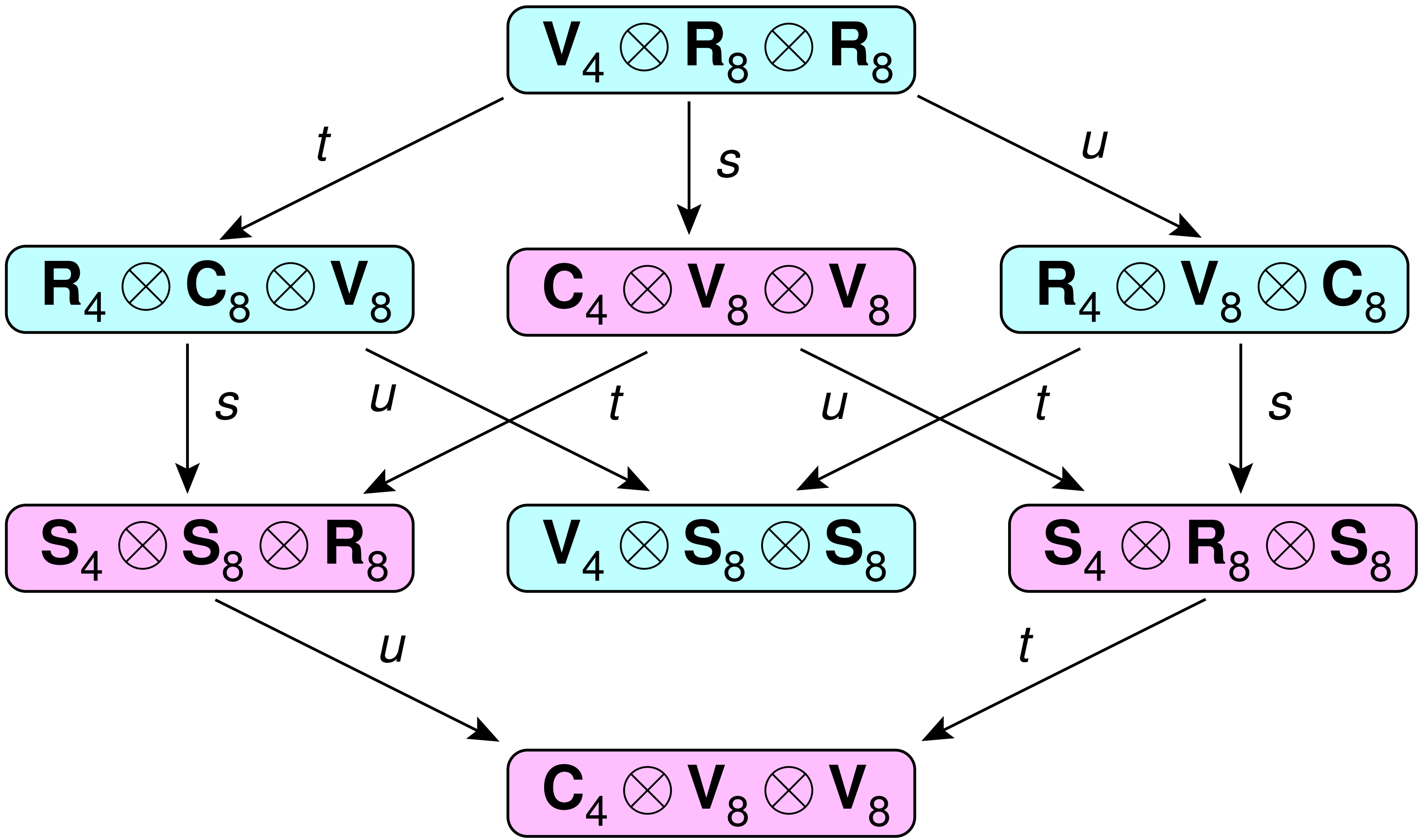
Standard $E_8 \times E_8$ theory:



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

Spin-structures as SUSY-like generators

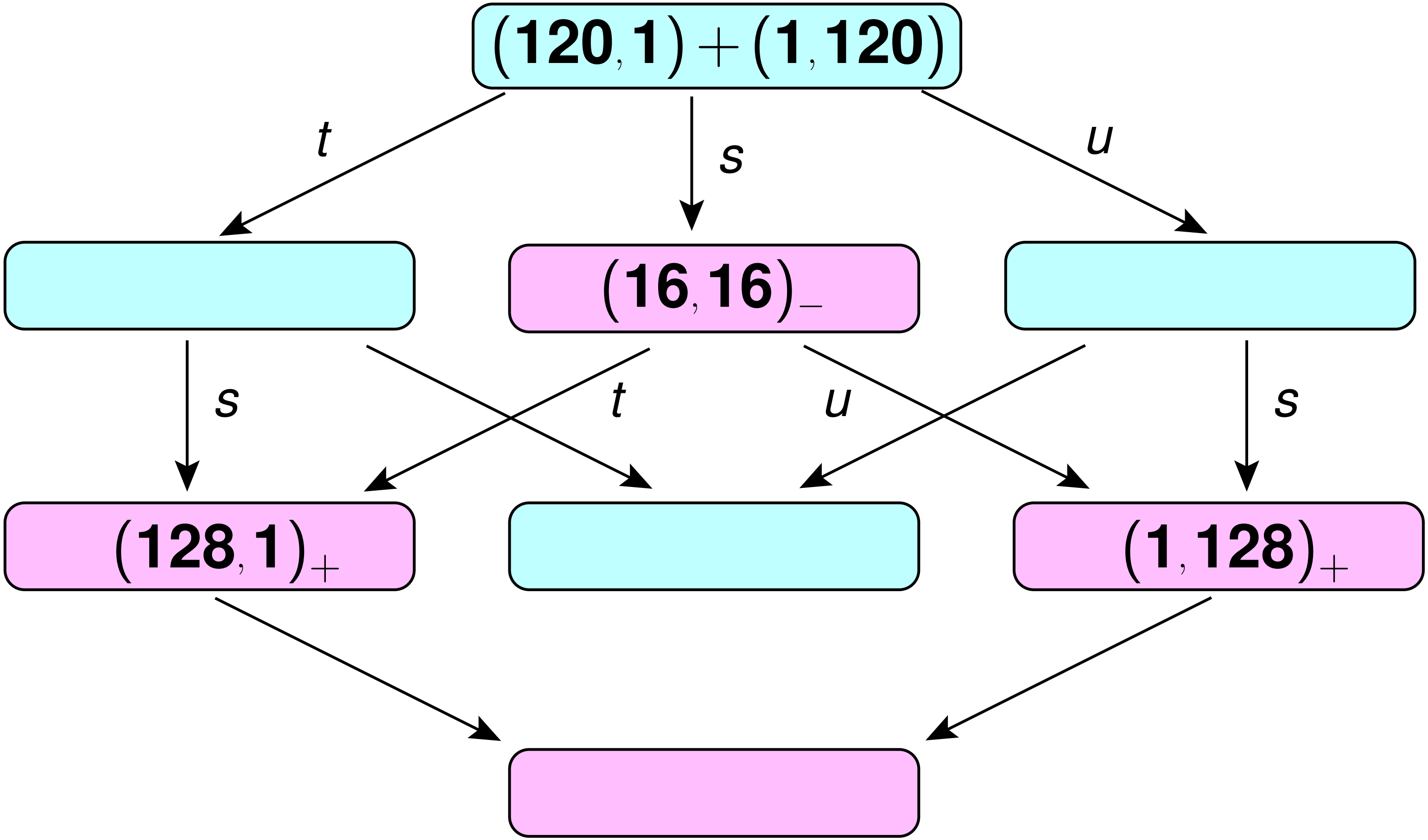
The SO(16)×SO(16) theory:



Possible similar induced transformations ???

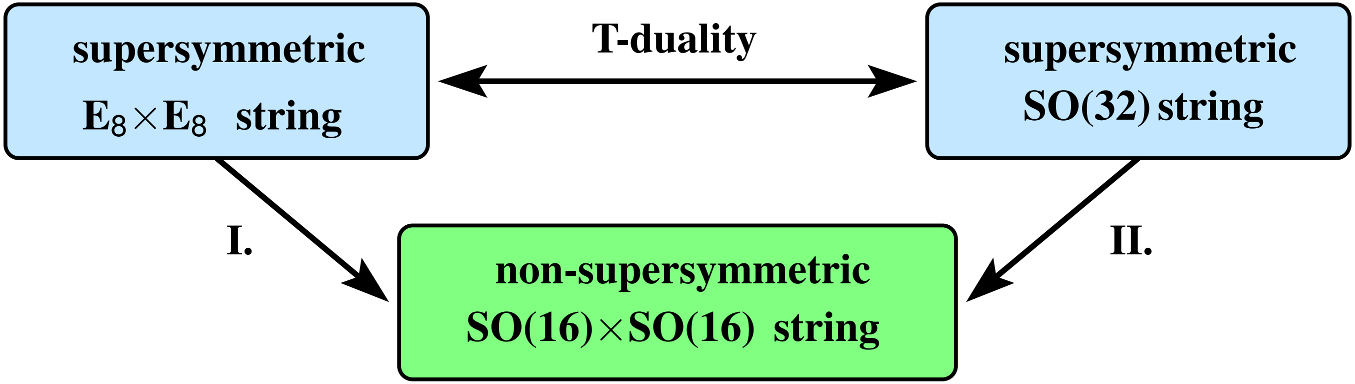
Spin-structures as SUSY-like generators

The SO(16)×SO(16) theory:



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

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 :**

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

  $$v_0 = (0, 1^3)\,, \qquad V_0 = (1, 0^7)(\text{-}1, 0^7)$$

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

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

  $$v_0 = (0, 1^3)\,, \qquad V_0' = (1, 0^7)(\text{-}\tfrac{1}{2}, \tfrac{1}{2}^7)$$

Untwisted sectors of the SUSY breaking twists:

supersymmetric $E_8 \times E_8$ string $\xrightarrow{\text{I.}}$ **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	– $(\mathbf{128},\mathbf{1})_+ + (\mathbf{1},\mathbf{128})_+$

Untwisted sectors of the SUSY breaking twists:

supersymmetric SO(32) strings $\xrightarrow{\text{II.}}$ **non-supersymmetric SO(16)×SO(16) strings**

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

Untwisted sectors of the SUSY breaking twists:

supersymmetric $E_8 \times E_8$ string $\xrightarrow{\text{I.}}$ **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 $\xrightarrow{\text{II.}}$ **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

Anomalies in the SO(16)×SO(16) string

The non-supersymmetric SO(16)×SO(16) string is in between the supersymmetric $E_8 \times E_8$ and SO(32) string:

$$
\begin{aligned}
&(\text{E}_8 \times \text{E}_8 \text{ gauginos})_+ + (\text{SO(32) gauginos})_- = \\
&\quad (\mathbf{Ad\,E_8}, \mathbf{1})_+ + (\mathbf{1}, \mathbf{Ad\,E_8})_+ + (\mathbf{Ad\,SO(32)})_- = \\
&= \cancel{(\mathbf{120}, \mathbf{1})_+} + (\mathbf{128}, \mathbf{1})_+ + \cancel{(\mathbf{1}, \mathbf{120})_+} + (\mathbf{1}, \mathbf{128})_+ \\
&\quad + \cancel{(\mathbf{120}, \mathbf{1})_-} + (\mathbf{16}, \mathbf{16})_- + \cancel{(\mathbf{1}, \mathbf{120})_-} = \\
&= (\mathbf{128}, \mathbf{1})_+ + (\mathbf{1}, \mathbf{128})_+ + (\mathbf{16}, \mathbf{16})_-
\end{aligned}
$$

This is reflected in the structure of the Green-Schwarz mechanism of the SO(16)×SO(16) string:

$$
S_{\text{GS}} = \int B_2\, X_8^{\cancel{\text{SUSY}}}\,, \qquad X_8^{\cancel{\text{SUSY}}} = X_8^{\text{E}_8 \times \text{E}_8} - X_8^{\text{SO(32)}}\,.
$$

Five branes for the SO(16)×SO(16) theory

More questions than answers:

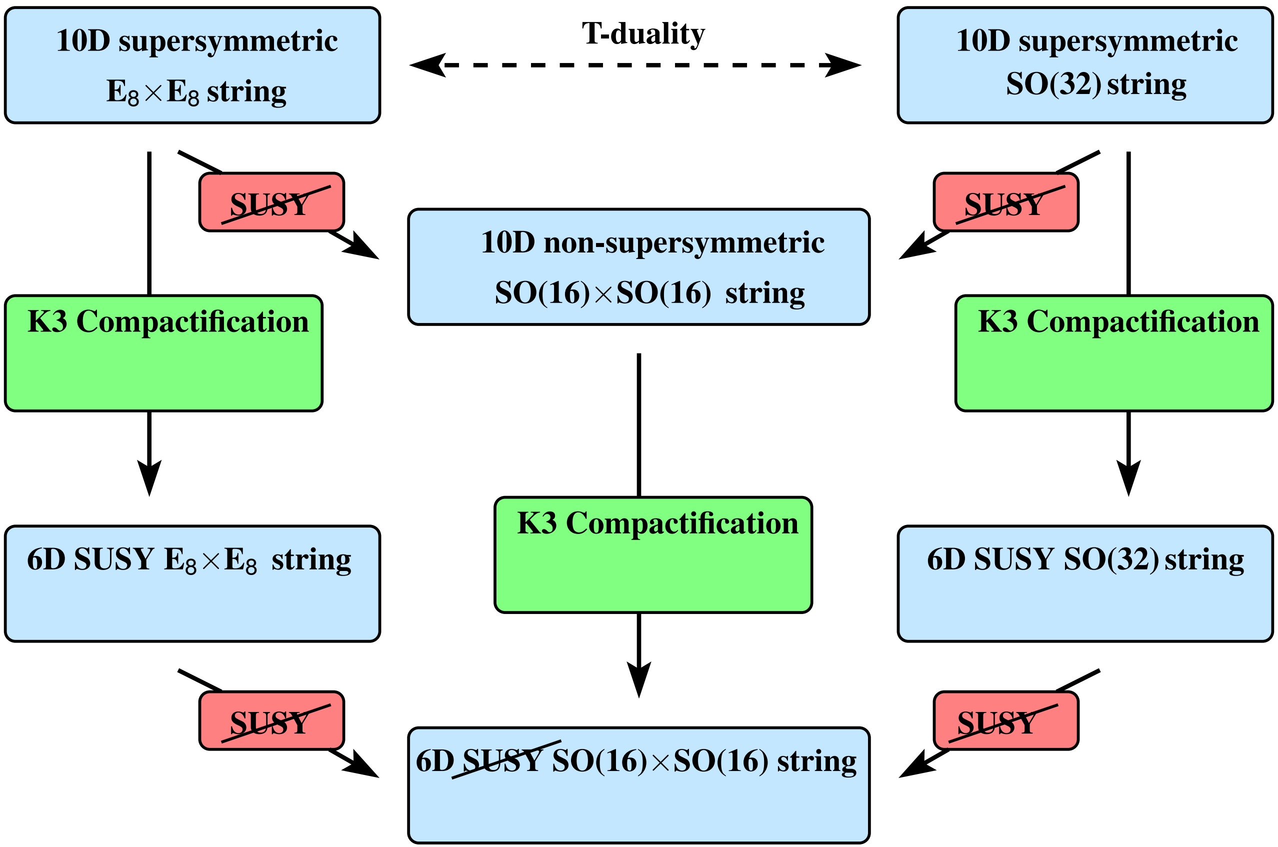
- **What kind of NS5-branes does the SO(16)×SO(16) admit?**
- **Could these branes be in some sense supersymmetric?**
- **Are these branes unstable?**
- **Could they be an additional source for tachyons?**
- **Are these branes consistent?**

Here is a possible suggestion for their construction...

Blaszczyk,SGN,Loukas,Ruehle'15-preliminary

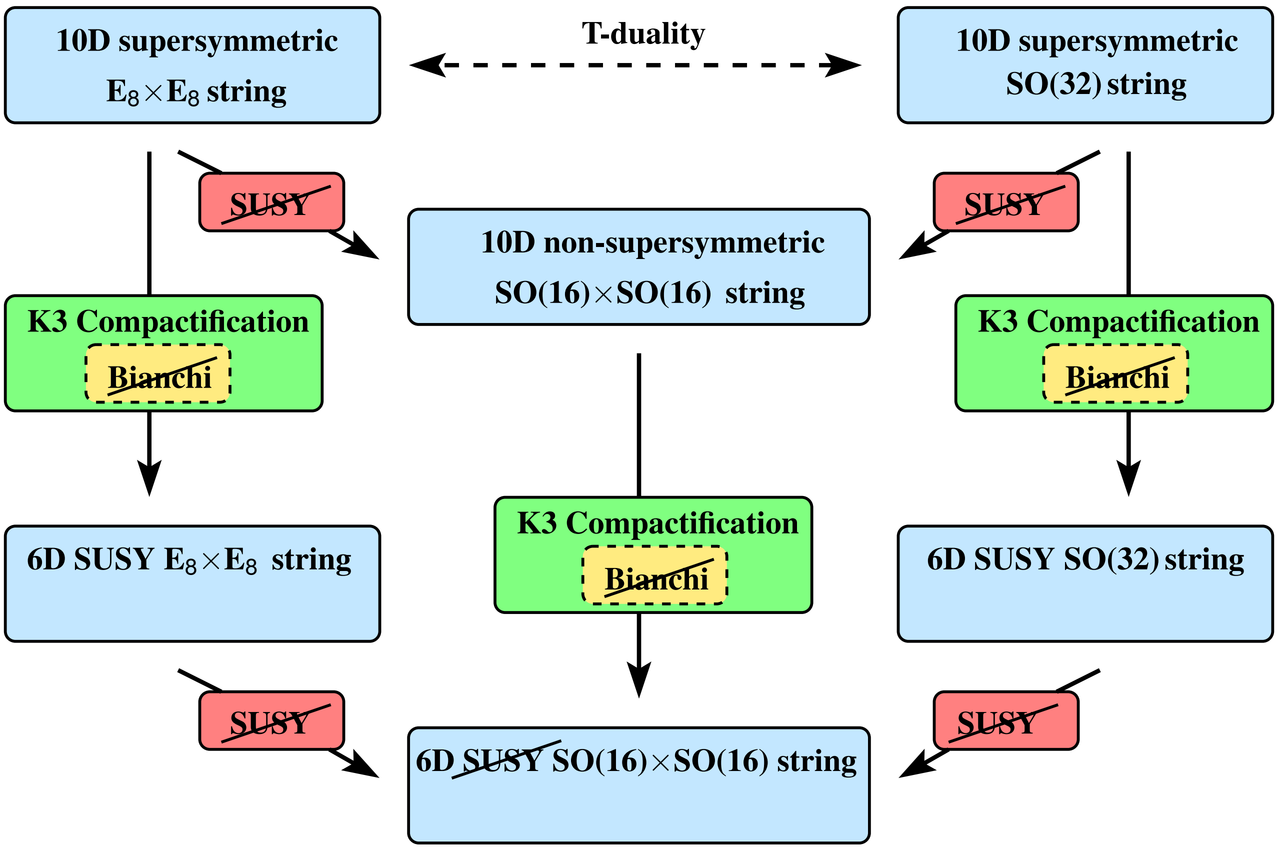
(Inspired by discussions with Anamaria Font, Ralph Blumenhagen)

Three SO(16)×SO(16) compactification routes



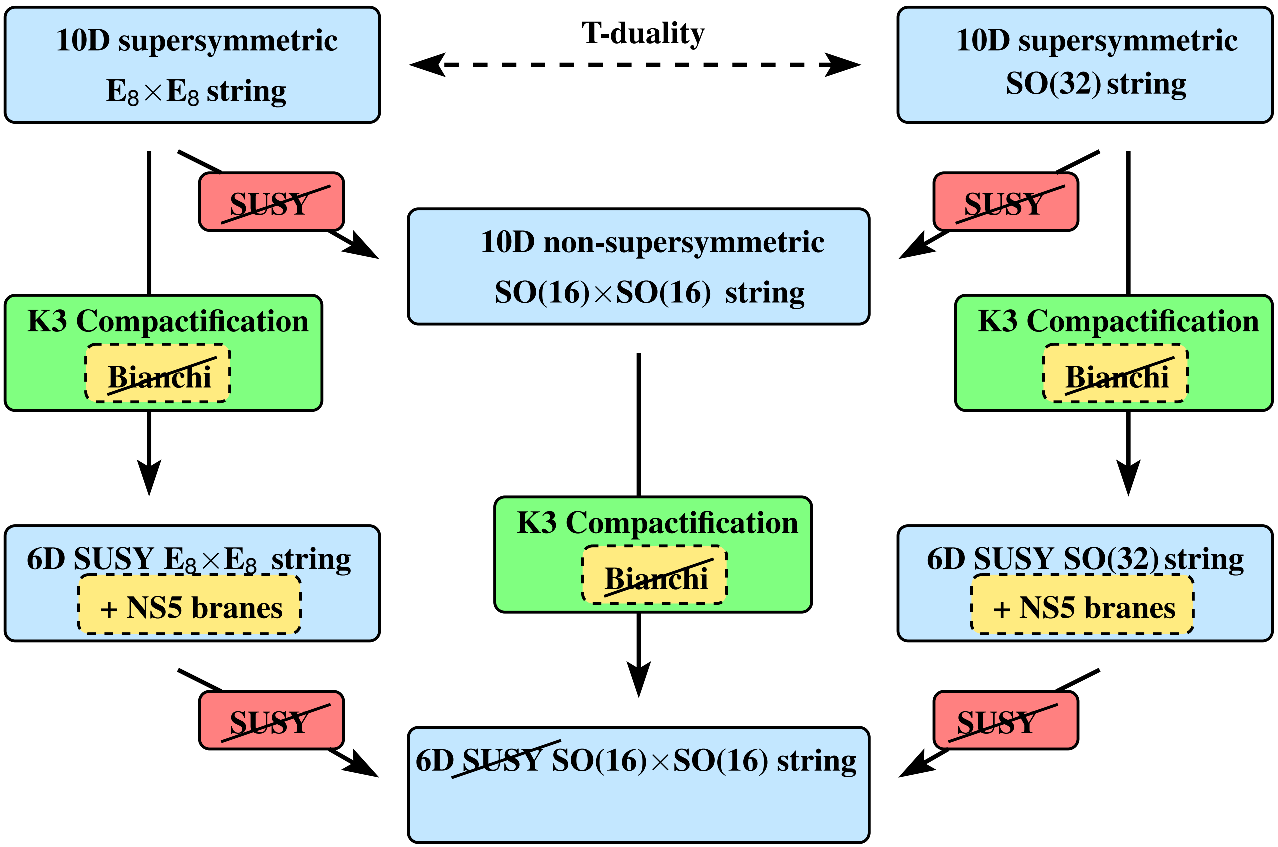
Recall: All SO(16)×SO(16) states can be understood as untwisted ~~SUSY~~-twist sectors of the $E_8 \times E_8$ or SO(32) theory

Three SO(16)×SO(16) compactification routes



When one does K3 compactifications, that violate the Bianchi identity, one has to introduce NS5-branes...

Three SO(16)×SO(16) compactification routes



Five branes for both the E$_8$×E$_8$ and SO(32) are known; by the SUSY breaking twist we can infer the SO(16)×SO(16)-branes

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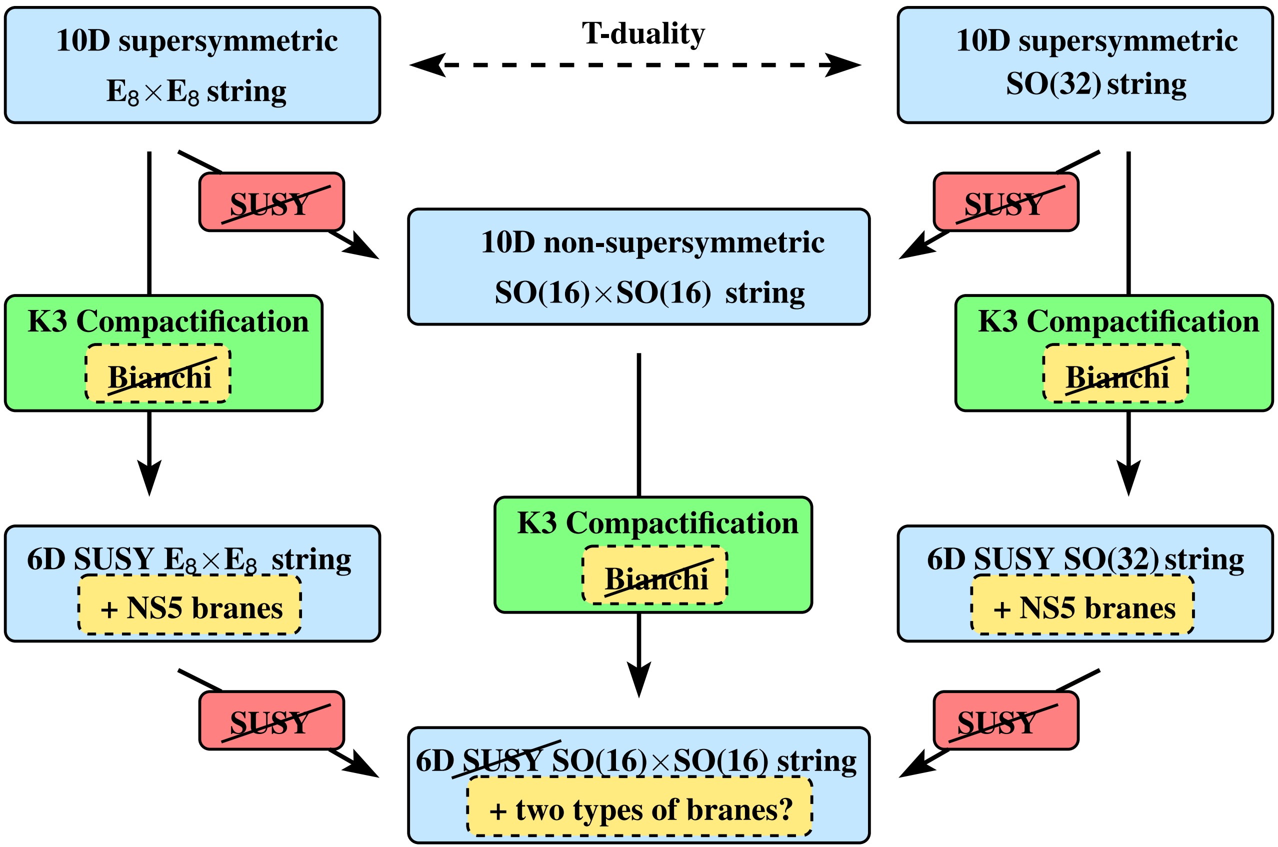

Five branes for both the $E_8 \times E_8$ and SO(32) are known; by the SUSY breaking twist we can infer the SO(16)×SO(16)-branes

Five branes for the SO(16)$\times$SO(16) theory

The spectra on the E$_8\times$E$_8$ and SO(32) NS5 brane:

e.g. Honecker'06

SO(32) NS5-branes		
Sp($2\widetilde{N}$) 6D vector multiplet	Bi-fundamental half-hyper multiplets	Anti-symmetric hyper multiplets
V $([2\widetilde{N}]_2^+)_+$	H $(32;2\widetilde{N})_-$	C $([2\widetilde{N}]_2^-)_-$

E$_8\times$E$_8$ NS5-branes	
Tensor multiplets	Hyper multiplets
T_s	$\mathrm{H}_s\ ,\ \ s=1,\ldots,\tilde{n}$

An extension of the SUSY breaking twist can be found such that all irreducible anomalies cancel.

Blaszczyk,SGN,Loukas,Ruehle'15-preliminary

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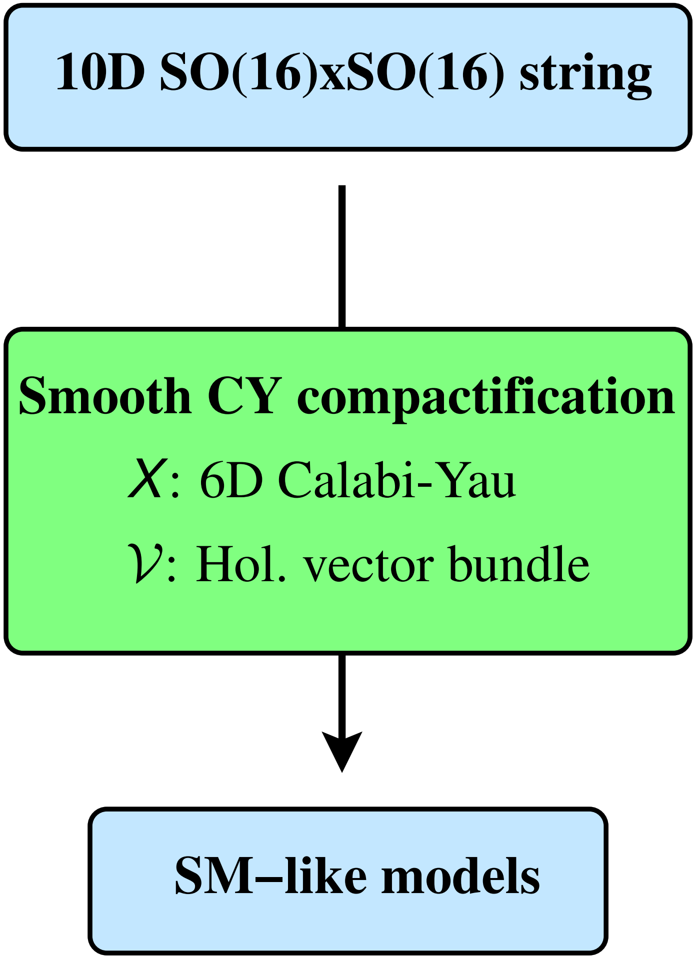
T_s	$H_s\ ,\ s = 1, \ldots, \tilde{n}$

An extension of the SUSY breaking twist can be found such that all irreducible anomalies cancel. Factorization?

Blaszczyk,SGN,Loukas,Ruehle'15-preliminary

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



(We can use the formalism as introduced e.g. in Vaudrevange's talk)

CY backgrounds for SO(16)$\times$SO(16) string

Why consider CY backgrounds for non-SUSY strings?

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

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- **Worldsheet: U(1)$_R$ symmetry**

  The complex structure generates a global U(1)$_R$ symmetry, leading to (2,0) worldsheet SUSY, which is non-anomalous when $c_1(X) = 0$ Hull,Witten'85

Massless fermionic spectrum

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

- (representation dependent) index theorems: ind($i\not{D}$)
- cohomology theory

Hence, we may employ the multiplicity operator to determine the chiral spectrum: SGN,Trapletti,Walter'07, Blaszczyk,SGN,Loukas,Ramos-Sanchez'14

$$\mathcal{N}_{\text{ferm}} = \int_X \Big\{ \frac{1}{6} \Big(\frac{\mathcal{F}_2}{2\pi} \Big)^3 + \frac{c_2(X)}{12} \frac{\mathcal{F}_2}{2\pi} \Big\}$$

evaluated on all fermionic states (keeping track of their chirality):

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

Massless fermionic spectrum

Similarly, the Hirzebruch-Riemann-Roch inspires us to define the multiplicity operator for the massless bosonic spectrum:

Blaszczyk,SGN,Loukas,Ramos-Sanchez'14

$$\mathcal{N}_{\text{bos}} = \int_X \left\{ \frac{1}{6} \left(\frac{\mathcal{F}_2}{2\pi} \right)^3 + \frac{c_2(X)}{12} \frac{\mathcal{F}_2}{2\pi} \right\}$$

evaluated on all bosonic states:

bosons	A_M	SO(16)×SO(16) Adjoint gauge fields

6-generation non-SUSY GUT on CICY 7862

The chiral spectrum of a six generation SU(5) non-SUSY GUT model on the CICY 7862:

	Massless chiral fermions	Massless complex bosons
obs	$8(\overline{10},1,1,1)+2(10,1,1,1)$ $+24(5;1,1,1)+18(\overline{5};1,1,1)$	$16(5;1,1,1)$
hid	$24(1;\overline{3},1,1)+20(1;3,1,1)+2(1;3,2,1)$ $+34(1;1,2,1)28(1;1,1,2)+150(1;1,1,1)$	$16(1;3,1,1)+12(1;\overline{3},1,1)+2(1;\overline{3},2,2)$ $+4(1;1,2,2)+80(1;1,1,1)$

(upstairs spectrum)

Gauge group: $G_{\text{obs}} = \text{SU}(5)$, $G_{\text{hid}} = \text{SU}(3)\times\text{SU}(2)\times\text{SU}(2)$

- This model satisfies the tree-level DUY deep inside the Kähler cone
- This model has vector-like fermionic and bosonic exotics
- By a $\mathbb{Z}_2$ freely acting Wilson line the spectrum becomes...

3-generation SM-like model on CICY 7862

Spectrum of a three generation SM-like model on the CICY 7862:

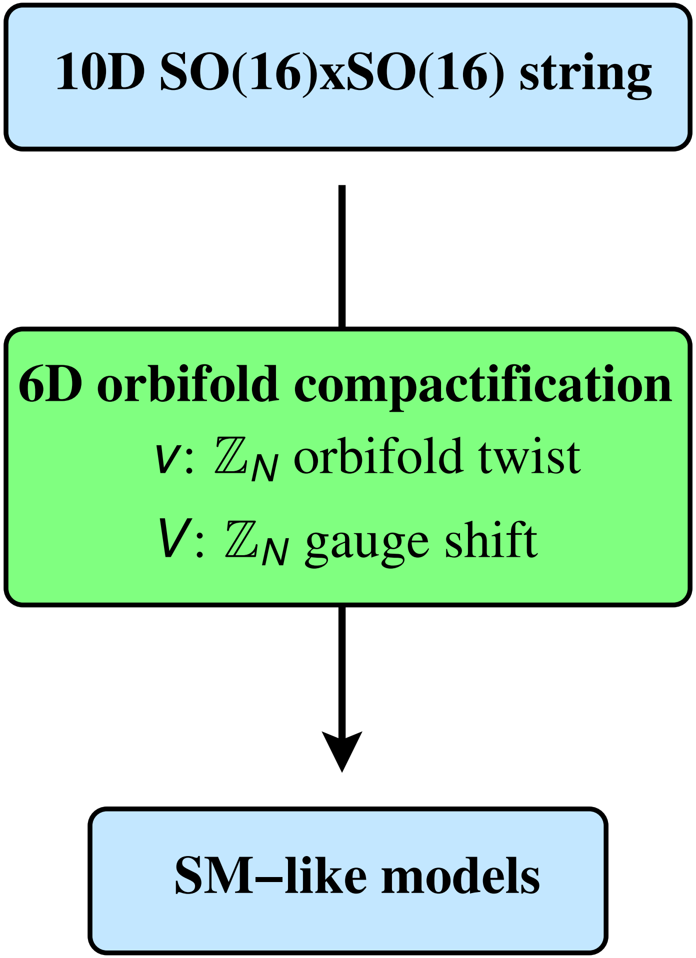
	Massless chiral fermions	Massless complex bosons
obs	$4(\overline{3},2;1,1,1)+(3,2;1,1,1)$ $+16(3,1;1,1,1)+10(\overline{3},1;1,1,1)$ $+21(1,2;1,1,1)$	$8(3,1;1,1,1)+8(1,2;1,1,1)$
hid	$12(1,1;\overline{3},1,1)+10(1,1;3,1,1)+$ $(1,1;3,2,1)+17(1,1;1,2,1)+$ $14(1,1;1,1,2)+80(1,1;1,1,1)$	$(1,1;\overline{3},2,2)+8(1,1;3,1,1)$ $+6(1,1;\overline{3},1,1)+2(1,1;1,2,2)$ $+40(1,1;1,1,1)$

(downstairs spectrum)

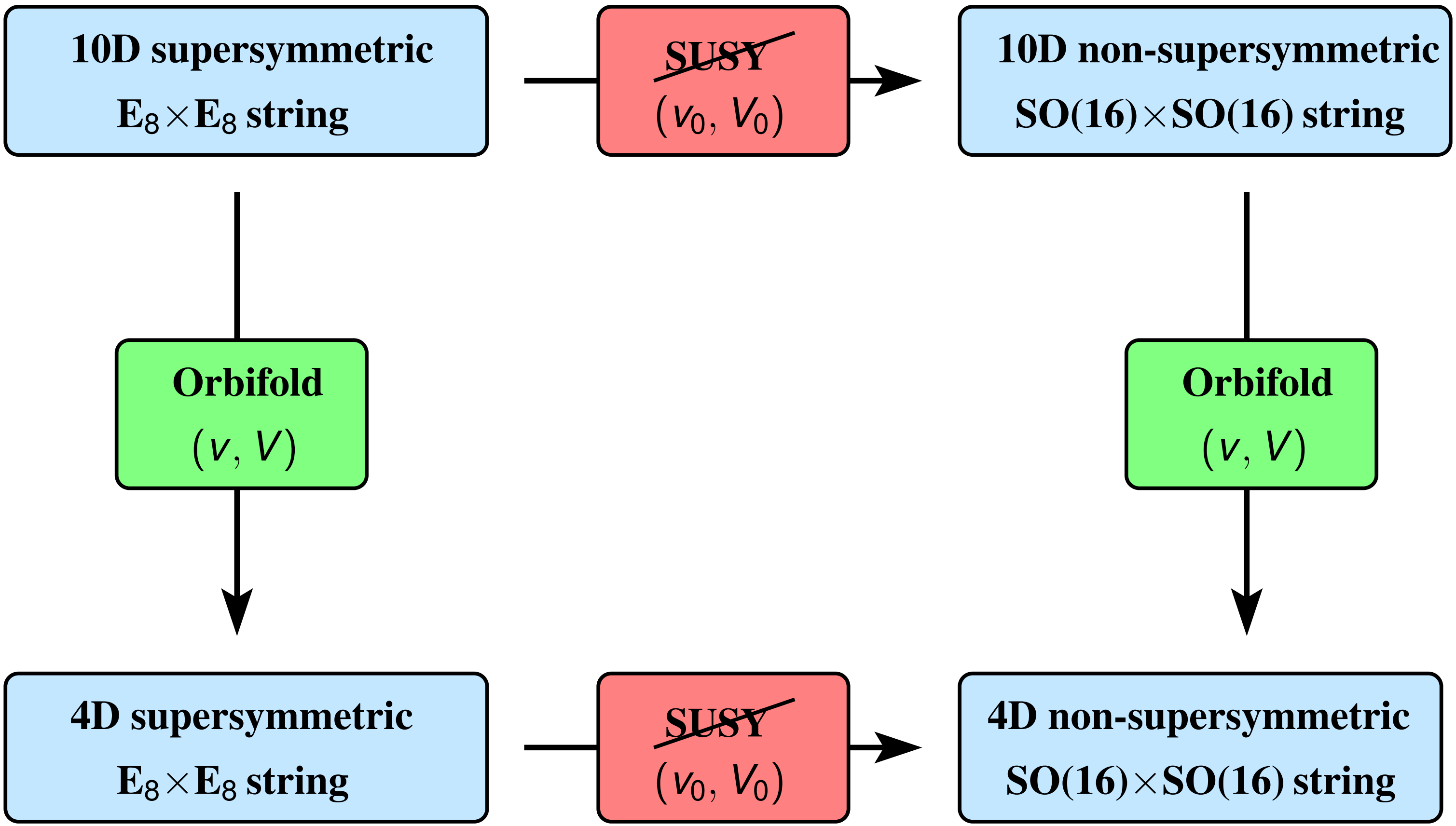
This model has the following features / bugs:

- It has the SM-gauge group: $G_{\text{obs}} = \text{SU}(2)\times\text{SU}(3)\times\text{U}(1)_Y$
- Its spectrum misses potential vector-like states, e.g. Higgs-doublet pairs
- but no doublet-triplet splitting

SO(16)×SO(16) orbifolds

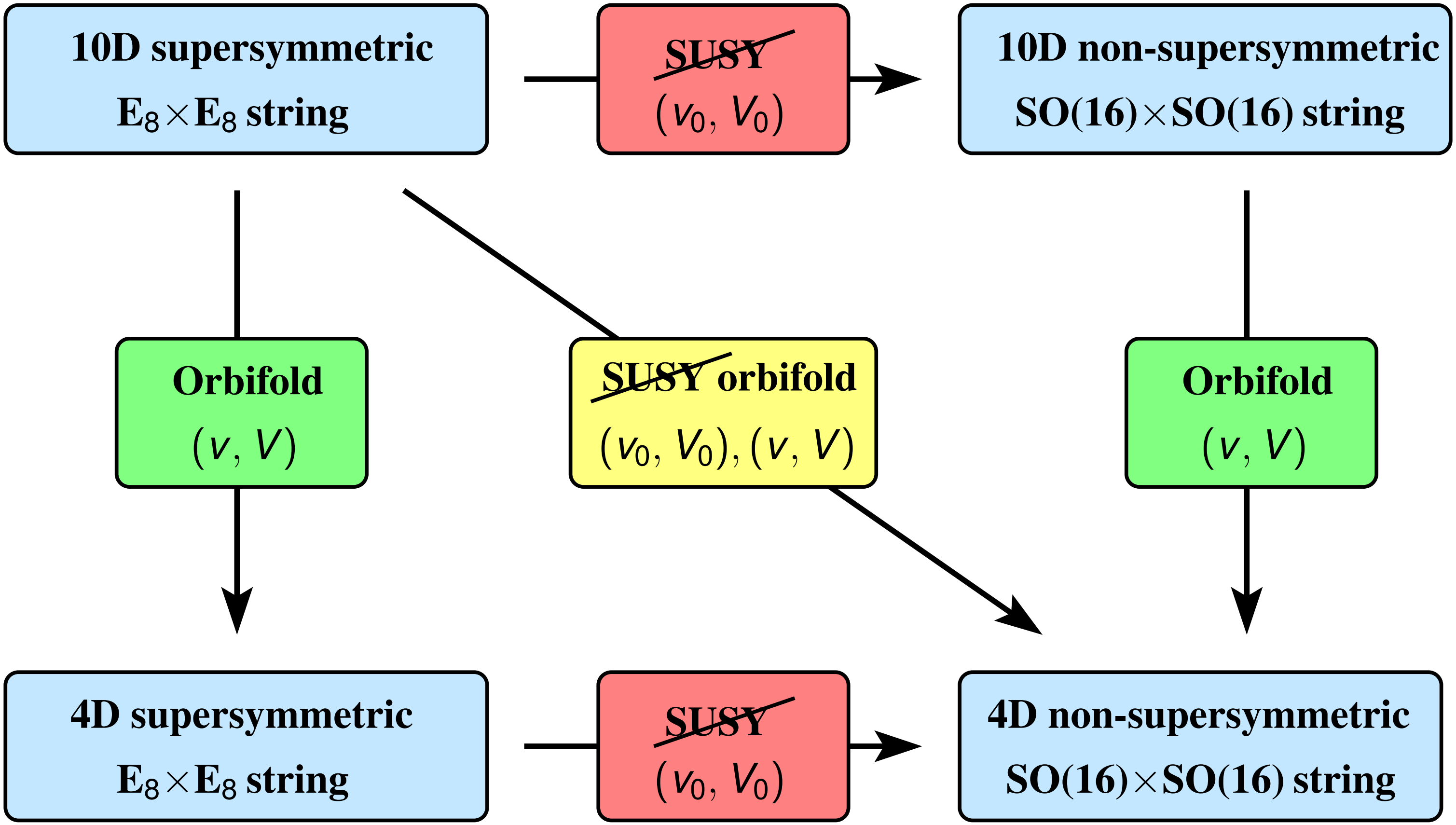


SO(16)$\times$SO(16) orbifolds



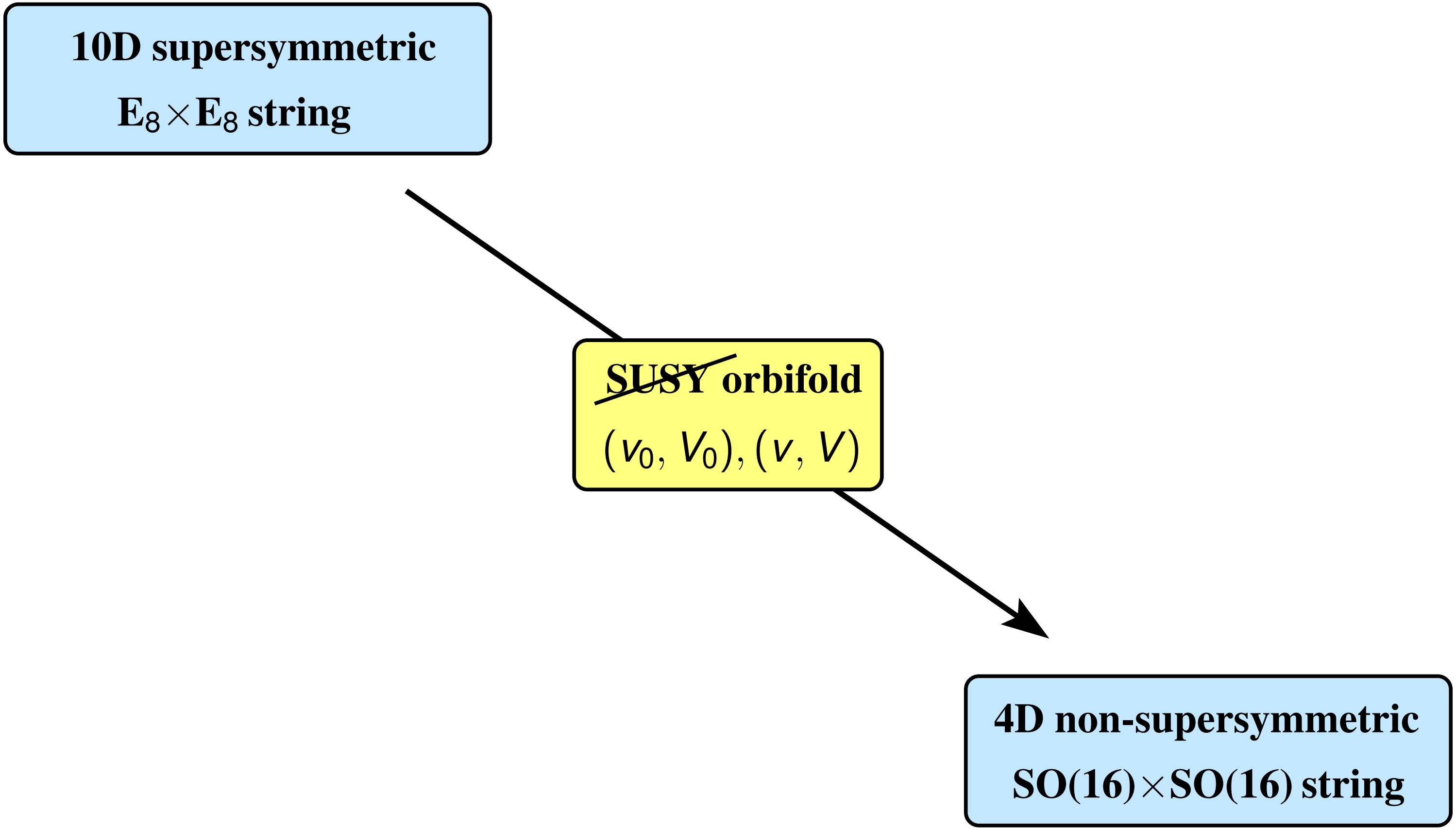
SUSY breaking $\mathbb{Z}_2$ twist: $v_0 = (0, 1^3)\ , \quad V_0 = (1, 0^7)(\text{-}1, 0^7)$

SO(16)×SO(16) orbifolds



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

SO(16)×SO(16) orbifolds



implemented in the "Orbifolder" Nilles,Ramos-Sanchez,Vaudrevange,Wingerter

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

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

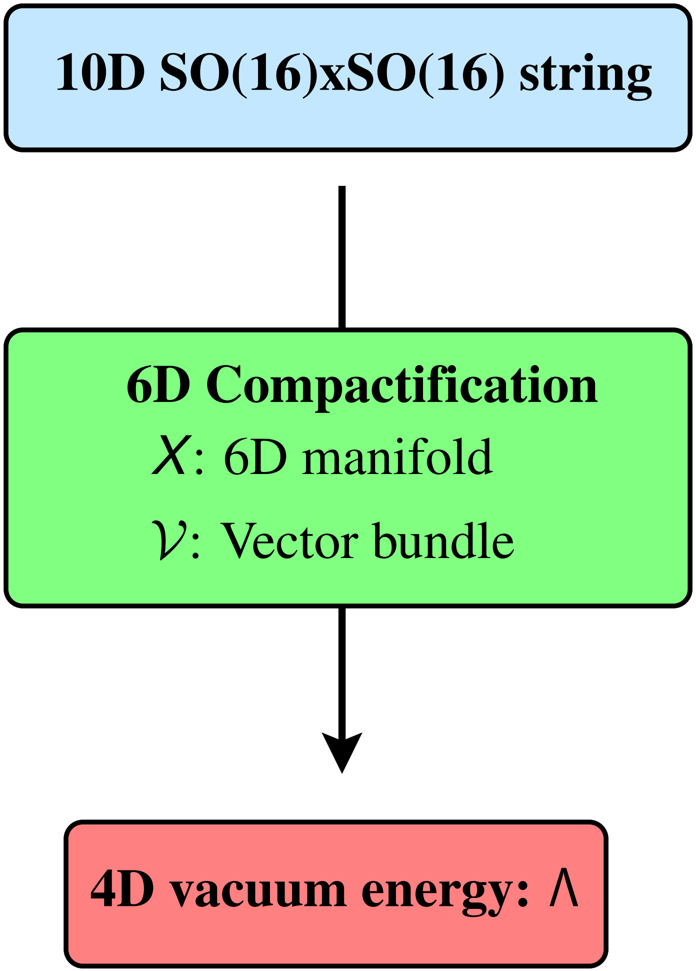
A Standard Model-like theory with three generations and a single Higgs

Sector	Massless spectrum: chiral fermions / complex bosons
Observable	$3(\mathbf{3},\mathbf{2})_{1/6}+3(\overline{\mathbf{3}},\mathbf{1})_{-2/3}+6(\overline{\mathbf{3}},\mathbf{1})_{1/3}+3(\mathbf{3},\mathbf{1})_{-1/3}+3(\mathbf{1},\mathbf{1})_{1}+5(\mathbf{1},\mathbf{2})_{-1/2}$ $+2(\mathbf{1},\mathbf{2})_{1/2}+20(\mathbf{1},\mathbf{1})_{1/2}+20(\mathbf{1},\mathbf{1})_{-1/2}+6(\mathbf{3},\mathbf{1})_{1/6}+6(\overline{\mathbf{3}},\mathbf{1})_{-1/6}+2(\mathbf{1},\mathbf{2})_{0}$
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	$14(\mathbf{1},\mathbf{2})_{0}+10(\overline{\mathbf{4}},\mathbf{1})_{0}+6(\mathbf{4},\mathbf{1})_{0}+3(\mathbf{6},\mathbf{1})_{0}+2(\mathbf{4},\mathbf{2})_{0}+71(\mathbf{1})_{0}$
Observable	$(\mathbf{1},\mathbf{2})_{-1/2}$ $(\mathbf{3},\mathbf{1})_{1/6}+(\overline{\mathbf{3}},\mathbf{1})_{-1/6}+2(\overline{\mathbf{3}},\mathbf{1})_{1/3}+13(\mathbf{1},\mathbf{2})_{0}+20(\mathbf{1},\mathbf{1})_{-1/2}+18(\mathbf{1},\mathbf{1})_{1/2}$
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

Cosmological constant in non-SUSY models



Cosmological constant in non-SUSY models

The vacuum energy and tachyons are closely related which leads to the notion of ”Misaligned SUSY”: Dienes’94,Dienes,Moshe,Myers’95

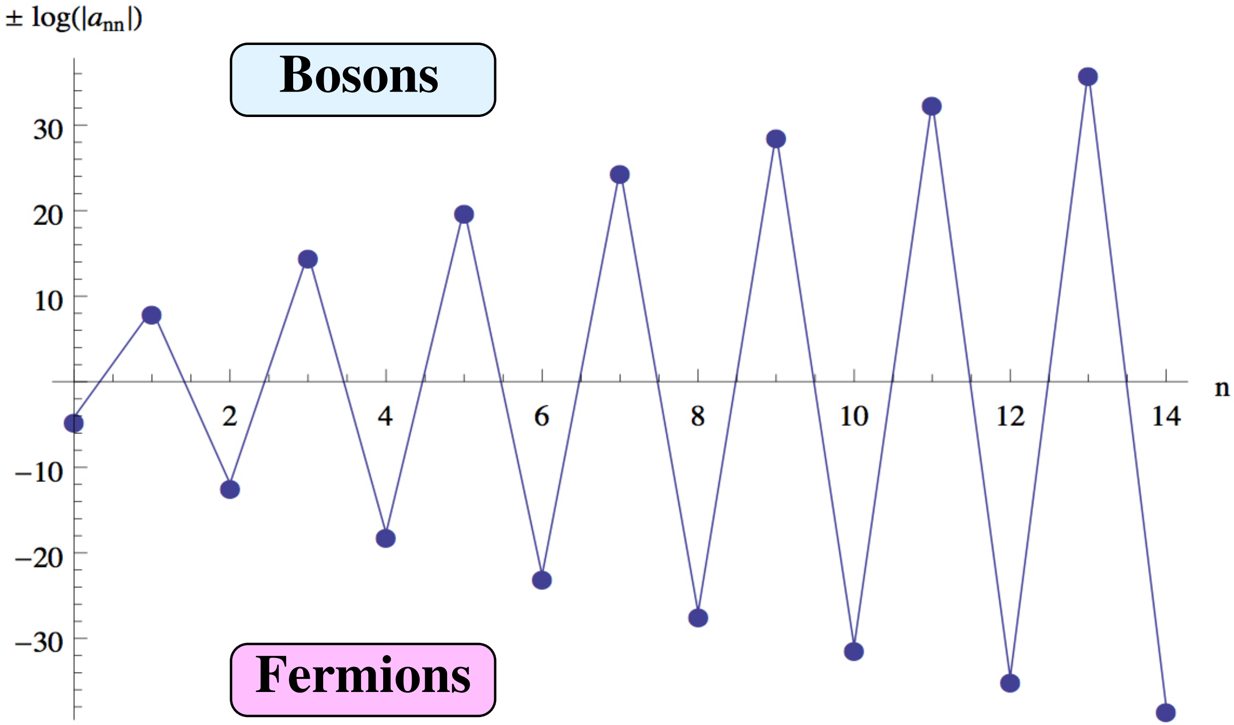
- in the absence of tachyons the vacuum energy is finite
  Kutasov,Seiberg’91
- hence a cancellation between bosonic and fermionic states must happen throughout the whole string towers of states:

$$\mathrm{Str}(1) = 0\,, \qquad \mathrm{Str}(M^2) = -\frac{3}{4\pi}\,\Lambda_{4\mathrm{D}}$$

$$\mathrm{Str}(M^{2\beta}) = \lim_{y\to 0} \sum_{\text{states}} (-)^F\, M^{2\beta}\, e^{-y\alpha' M^2}$$

Cosmological constant in non-SUSY models

$$\Lambda \sim \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^3} \sum_{\text{states}} a_{mn}\, \bar{q}^m q^n$$



(Picture taken from Abel,Dienes,Mavroudi'15)

Interpolating models

To address the issue of the huge cosmological problem, so-called interpolating models may be used: Abel,Dienses,Mavroudi'15

- SUSY breaking implemented by a Scherk-Schwarz on a torus:
  - for $R \to \infty$ the model tends to a SUSY heterotic string theory
  - for $R \to 0$ the model tends to the non-SUSY SO(16)×SO(16) theory
- The number of massless bosons and fermions are equal: $N_B^0 - N_F^0 = 0$

Then the vacuum energy and the resulting dilaton tadpole are exponentially suppressed: Itoyama,Taylor'87

$$\Lambda \sim (N_B^1 - N_F^1) e^{-4\pi R m_1}$$

⇒ See talk by Mavroudi

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Thank you!

What are 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

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

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

States	Gauge representations of the spectrum of a tachyonic $\mathbb{Z}_{6\text{-}I}$ 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	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 is the tachyonic mass

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