Gravity, Strings and Supersymmetry Breaking

SNS Pisa, 3rd April 2025

ASPECT OF SUPERSYMMETRY BREAKING

IN STRING THEORY

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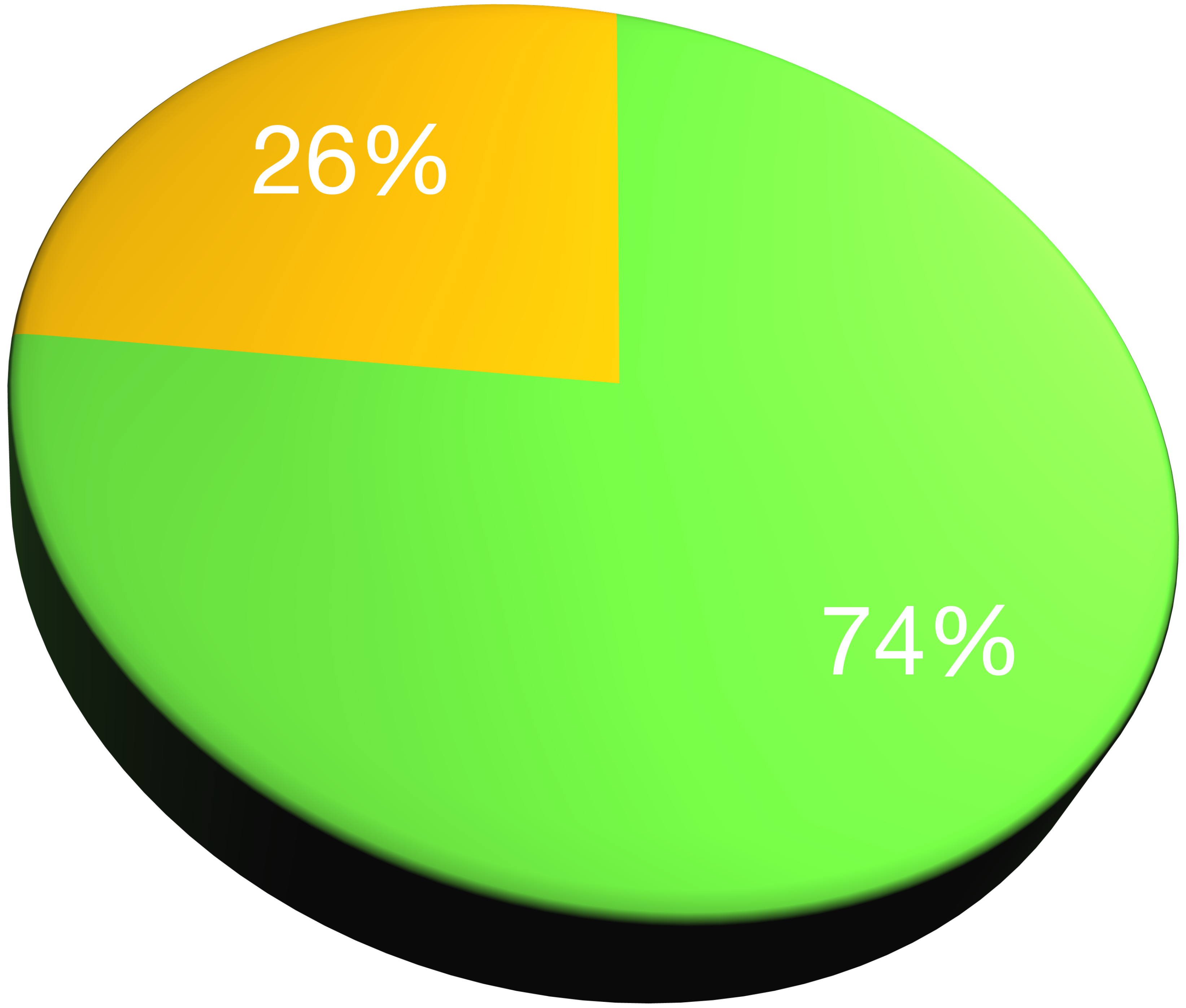
As of today, we don't have any evidence of supersymmetry in Nature

Supersymmetry, if present, must be broken at suitable high energy scales

Absence of supersymmetry raises many questions which may lead to a better understanding of string theory

Perturbative String vacua in D=10



Type IIA

Type IIB

Type I

Heterotic $E_8 x E_8$

Heterotic SO(32)

Type 0A

Type 0B

Sugimoto USp(32)

Type 0B/Ω

Type 0′

Type 0B/Ω″

Type 0A/Ω

Heterotic SO(16)xSO(16)

Heterotic SO(24)xSO(8)

Heterotic $[E_7 xSU(2)]^2$

Heterotic SO(32)

Heterotic $E_8 xSO(16)$

Heterotic SU(16)xU(1)

Heterotic E_8

WAYS TO BREAK SUPERSYMMETRY

Coordinate Dependent Compactifications ❶

Mixing Branes and Orientifold planes ❷

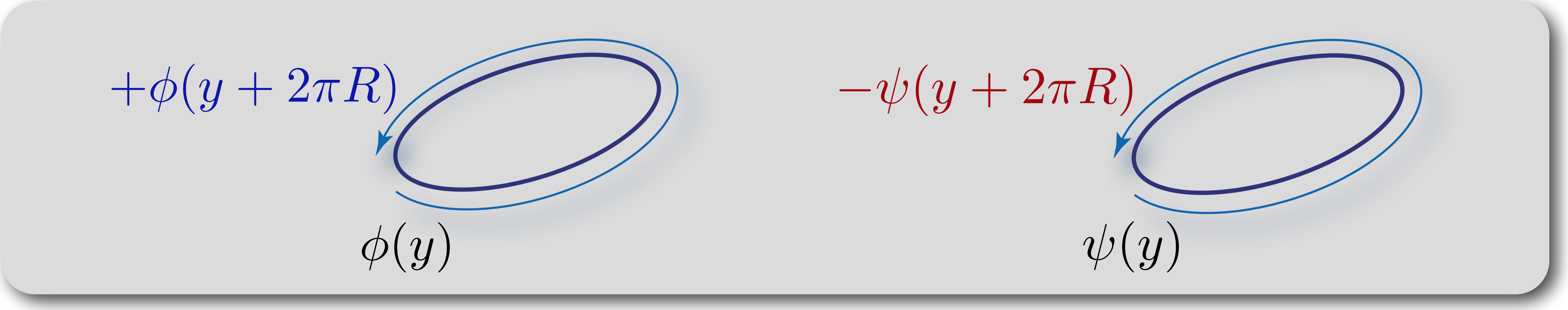
Adding (magnetic) fluxes ③

[Bachas 1995]

Coordinate Dependent Compactifications

Scherk-Schwarz compactification is an elegant way of breaking supersymmetry via compactification [Scherk, Schwarz 1979]

Use symmetries of the action to impose different periodicities for fields in a given supermultiplet



COORDINATE DEPENDENT COMPACTIFICATIONS

Scherk-Schwarz compactification is an elegant way of breaking supersymmetry via compactification

[Scherk, Schwarz 1979]

Use symmetries of the action to impose different periodicities for fields in a given supermultiplet

$$M_\phi^2 = M_0^2 + \left(\frac{n}{R}\right)^2 \qquad M_\psi^2 = M_0^2 + \left(\frac{n+\frac{1}{2}}{R}\right)^2$$

The radius of the circle sets the scale of supersymmetry breaking. SUSY is recovered in the infinite R limit

String theory is very constrained, and any deformation of the spectrum is subject to modular invariance

[Rohm 1984]

[Kounnas, Rostand 1990]

$$\mathscr{Z} \sim \int_{\mathscr{F}} \frac{d^2\tau}{\tau_2^{11/2}} \frac{1}{|\eta|^{16}} \sum_{m,n} \Big[(V_8\bar{V}_8 + S_8\bar{S}_8)\Lambda_{m,2n} - (V_8\bar{S}_8 + S_8\bar{V}_8)\Lambda_{m+\frac{1}{2},2n}$$
$$+ (O_8\bar{O}_8 + C_8\bar{C}_8)\Lambda_{m,2n+1} - (O_8\bar{C}_8 + C_8\bar{O}_8)\Lambda_{m+\frac{1}{2},2n+1} \Big]$$

$$M^2 = -1 + \tfrac{1}{2}R^2$$

The twisted sector (the second line) introduces new states which include KK and winding excitations of the NS-NS vacuum

In a theory of (quantum) gravity, the geometric moduli and the Wilson lines are dynamical fields, and one should study their dynamics to ensure the stability of the construction

Actually, it is expected that in the (pseudo) moduli space non-tachyonic theories are continuously connected to tachyonic ones

[Narain, Sarmadi 1987]
[Nair et al 1987]
[Ginsparg, Vafa 1987]

For instance, this is what happens for the heterotic models upon toroidal compactification

In closed strings, the absence of tachyons is reflected into a distribution of excitations which enjoys ***misaligned supersymmetry*** [Dienes 1994]

$$\mathcal{Z} = \tau_2^{1-D/2} \sum_{i,j} \bar{\chi}_i(\bar{q})\, \mathcal{N}_{ij} \chi_j(q) = \tau_2^{1-D/2} \sum_{m,n} a_{mn}\, \bar{q}^m\, q^n$$

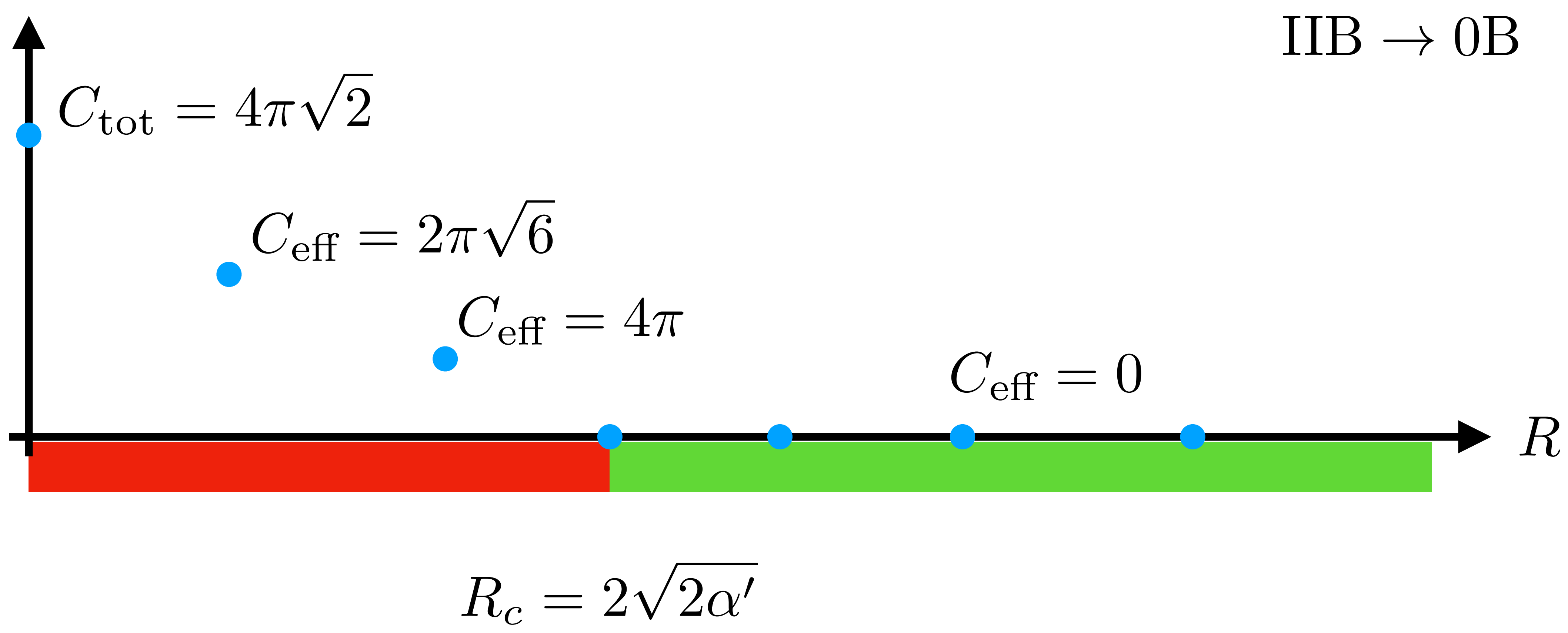
Although, for each sector $\bar{\chi}_i(\bar{q})\, \chi_j(q) \Rightarrow a_{nn}^{(ij)} \sim A n^{-B}\, e^{4\pi C_{\rm tot} \sqrt{n}}$

when the full spectrum is considered

$$\langle a_{nn} \rangle = \sum_{i,j} \mathcal{N}_{ij} a_{nn}^{(ij)} = \sum_{\substack{i,j \\ H_i = \bar{H}_j < 0}} \mathcal{N}_{ij} d_i(0)\, \bar{d}_j(0) \sum_{\ell=1}^{\infty} \tilde{\varphi}_j(\ell)\, e^{\frac{8\pi}{\ell} \sqrt{|H_j|\, n}} \sim e^{4\pi C_{\rm eff} \sqrt{n}}$$

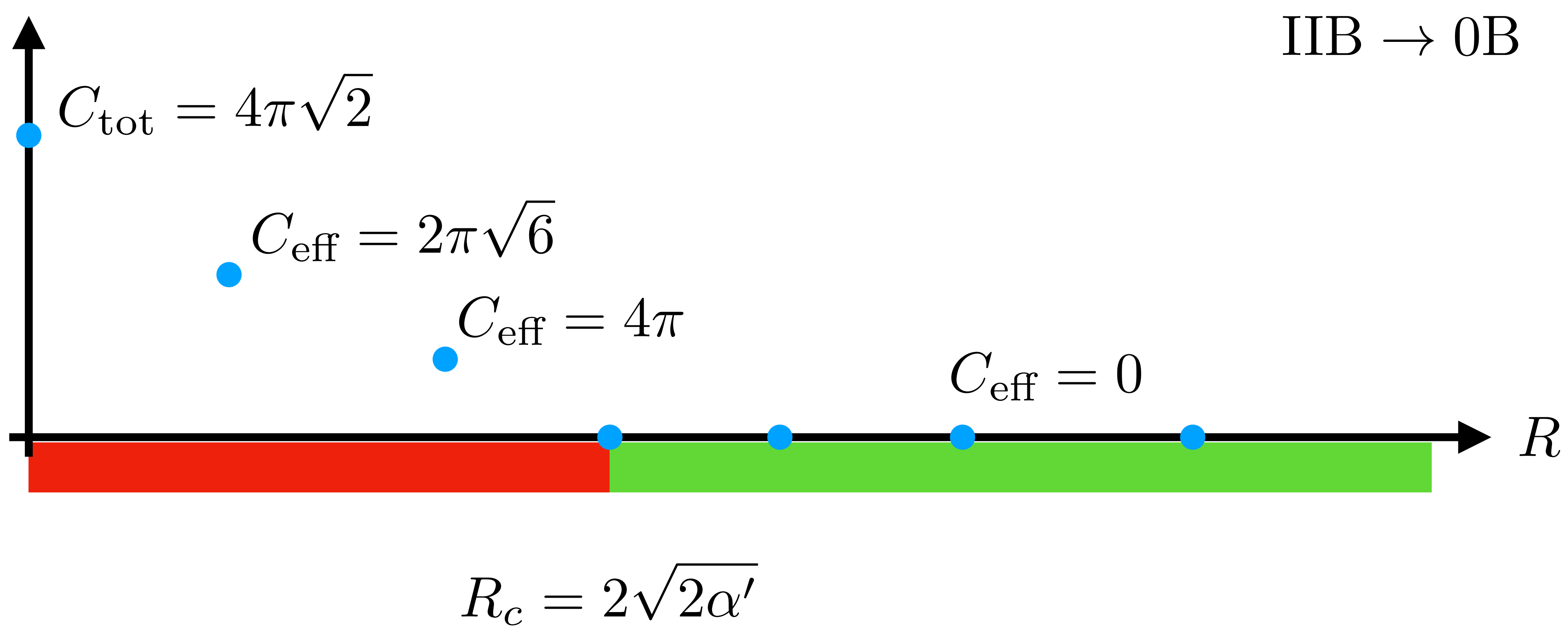
[CA, Florakis, Leone 2023]
[Leone 2023]

The vanishing of the effective central charge implies then classical stability of the string spectrum



Are coordinate-dependent compactifications (Scherk-Schwarz) really a ***deformation*** of the original spectrum?

What happens when we cross the critical point?



Closed string tachyon condensation is not fully understood.
In some cases, a linear dilaton background emerges
and space-time is lower dimensional

[Antoniadis, Derendinger, Kounnas 1999]
[Hellerman, Swanson 2007]
[Kaidi 2020]

How can we avoid tachyons?

Asymmetric orbifolds have been advocated to eliminate geometric moduli and Wilson lines.

However, new moduli typically emerge in the twisted sector which (in principle) can equally deform the vacuum and yield tachyons

After all, most asymmetric orbifold become symmetric (and, thus, geometric) in some dual frame

For example, take the asymmetric Z_4 orbifold

$$Z = X + iY\,, \qquad Z_{\rm L,R} = X_{\rm L,R} + iY_{\rm L,R}$$

$$Z_{\rm L} \to e^{i\pi/2} Z_{\rm L}\,, \qquad Z_{\rm R} \to e^{-i\pi/2} Z_{\rm R}\,.$$

Upon T-duality along the Y direction

$$\tilde{Z}_{\rm L,R} = X_{\rm L,R} + i\tilde{Y}_{\rm L,R} = X_{\rm L,R} \pm iY_{\rm L,R}$$

and the orbifold becomes again ***geometrical***

with all its ***geometrical*** (neutral) moduli

As an example, consider an asymmetric Z_2 orbifold of the SO(16)xSO(16) heterotic string on the SO(8) lattice

[CA, Florakis, Leone, Perugini 2024]

Sector	fields	$SO(16) \times SO(16) \times SO(8)$
Untwisted	$g_{\mu\nu}, B_{\mu\nu}, \phi$	$(\mathbf{1}, \mathbf{1}, \mathbf{1})$
	A_μ	$(\mathbf{120}, \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{120}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}, \mathbf{28})$
	ψ_{L}	$(\mathbf{128}, \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{128}, \mathbf{1})$
	ψ_{R}	$(\mathbf{16}, \mathbf{16}, \mathbf{1})$
Twisted	ψ_{L}	$(\mathbf{128}, \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{128}, \mathbf{1})$
	ψ_{R}	$(\mathbf{16}, \mathbf{16}, \mathbf{1})$
	$4\,\phi$	$(\mathbf{120}, \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{120}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}, \mathbf{28})$
	$4\,A_\mu$	$(\mathbf{1}, \mathbf{1}, \mathbf{1})$

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	A_μ	$(\mathbf{120}, \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{120}, \mathbf{1}) + (\mathbf{1}, \mathbf{1}, \mathbf{28})$
	ψ_{L}	$(\mathbf{128}, \mathbf{1}, \mathbf{1}) + (\mathbf{1}, \mathbf{128}, \mathbf{1})$
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	$4\,A_\mu$	$(\mathbf{1}, \mathbf{1}, \mathbf{1})$

To eliminate these scalars one has to combine the asymmetric orbifold with extra symmetries (*i.e.* outer automorphism)

[CA, Florakis, Leone, Perugini 2024]

Sector	fields	$\mathrm{SO}(16)_2 \times \mathrm{SO}(8)_1$
Untwisted	$g_{\mu\nu}, B_{\mu\nu}, \phi$	$(\mathbf{1}, \mathbf{1})$
	A_μ	$(\mathbf{120}, \mathbf{1}) + (\mathbf{1}, \mathbf{28})$
	$\psi_{\mathrm{L}} + \psi_{\mathrm{R}}$	$(\mathbf{128}, \mathbf{1})$
	ψ_{R}	$(\mathbf{136}, \mathbf{1})$
	$4\phi + \psi_{\mathrm{L}}$	$(\mathbf{120}, \mathbf{1})$
Twisted	$4\phi + \psi_{\mathrm{L}}$	$(\mathbf{120}, \mathbf{1}) + (\mathbf{1}, \mathbf{8}_v + \mathbf{8}_s + \mathbf{8}_c)$
	$4\phi + \psi_{\mathrm{R}}$	$(\mathbf{128}, \mathbf{1})$

Brane Supersymmetry Breaking

[Sugimoto 1999]

[Antoniadis, Dudas, Sagnotti 1999]

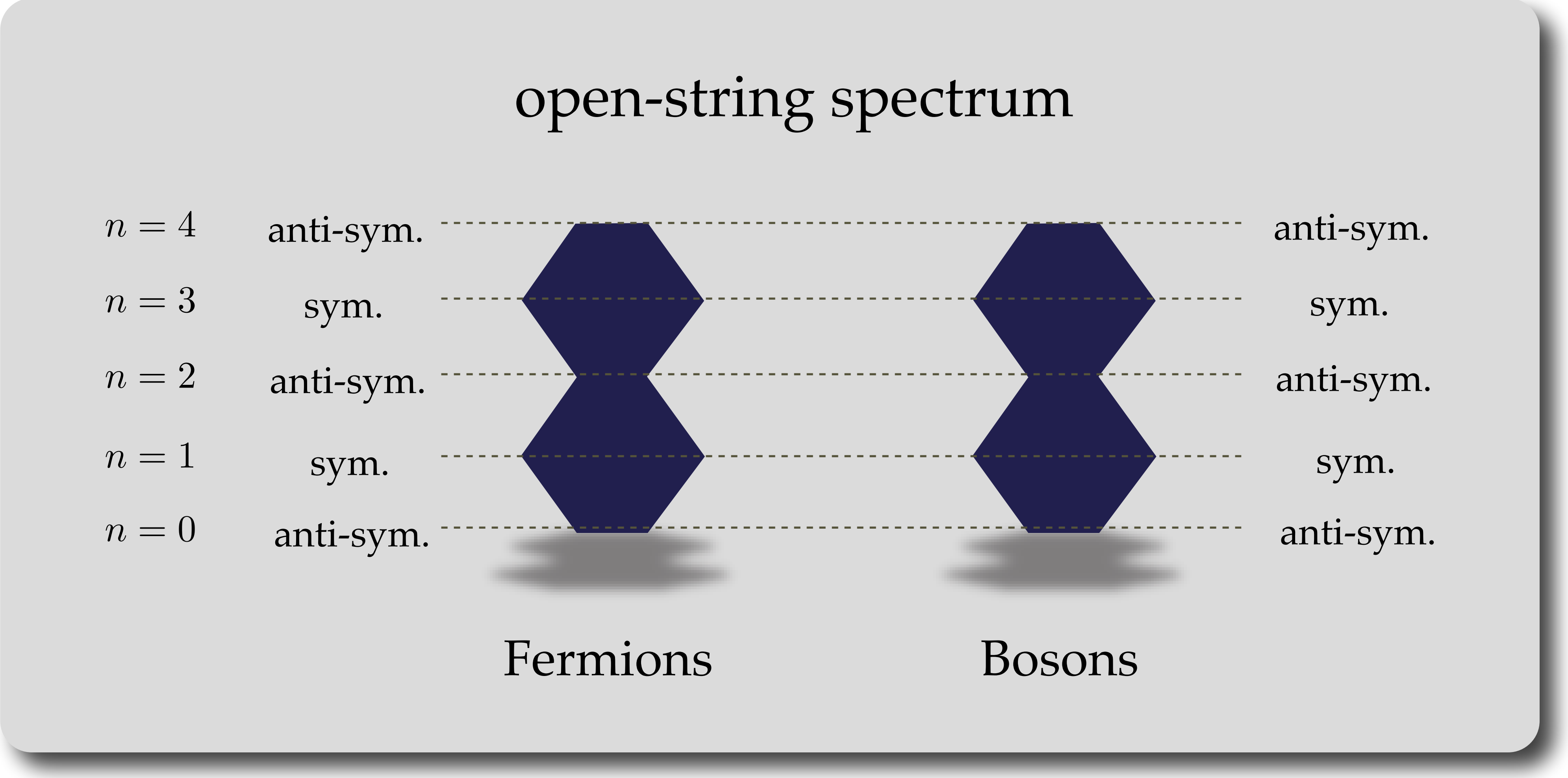
As the name suggests,
it takes place in orientifold models
with branes and orientifold planes

[Sagnotti 1987]

It does not have a counterpart
in heterotic strings

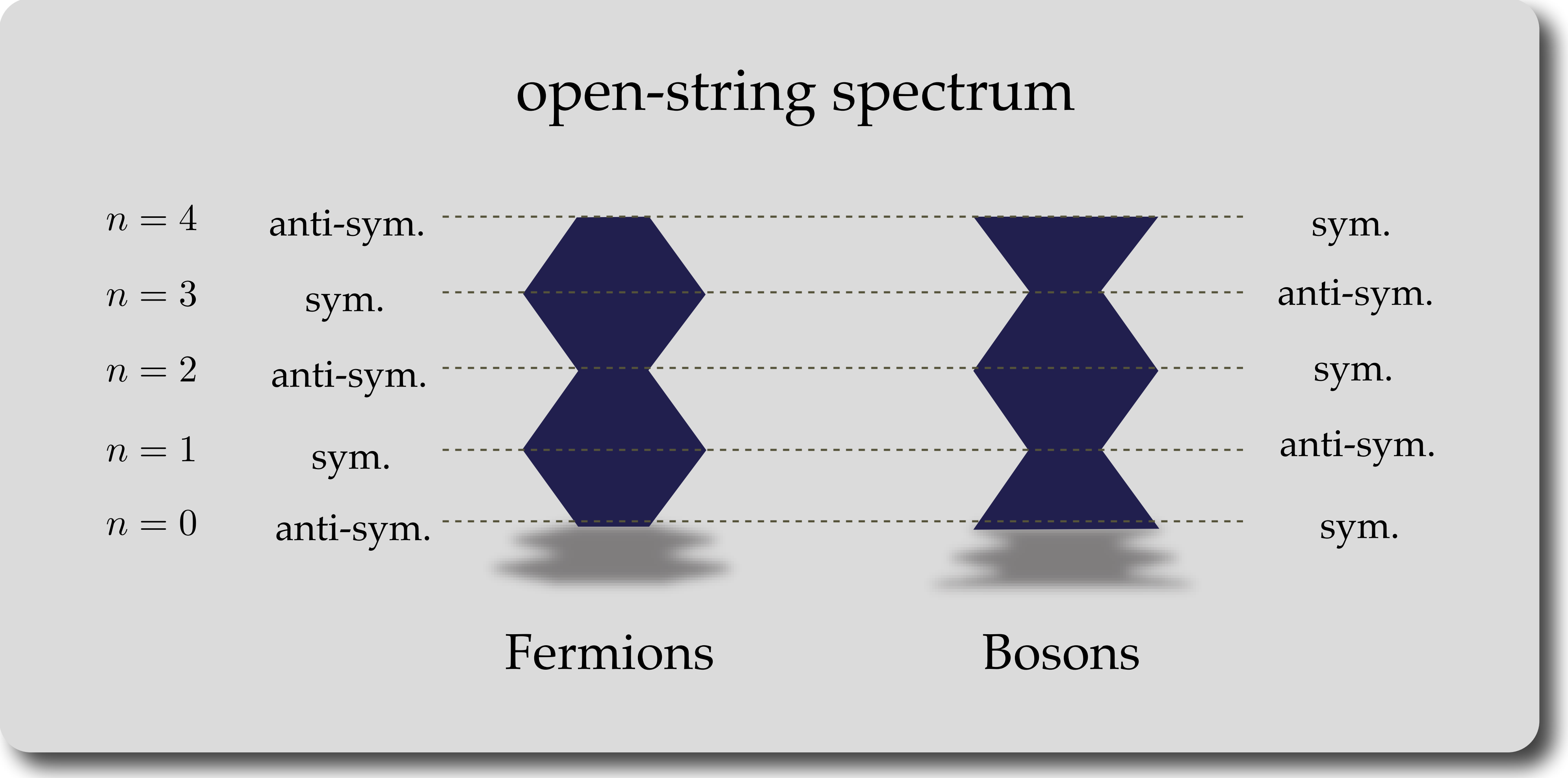
Already in D=10 there are two options:

Supersymmetric type I superstring
G=SO(32)



D9 branes and $O9_-$ planes

Brane Supersymmetry Breaking
G=USp(32)



[Sugimoto 1999]

D9 anti-branes and $O9_+$ planes

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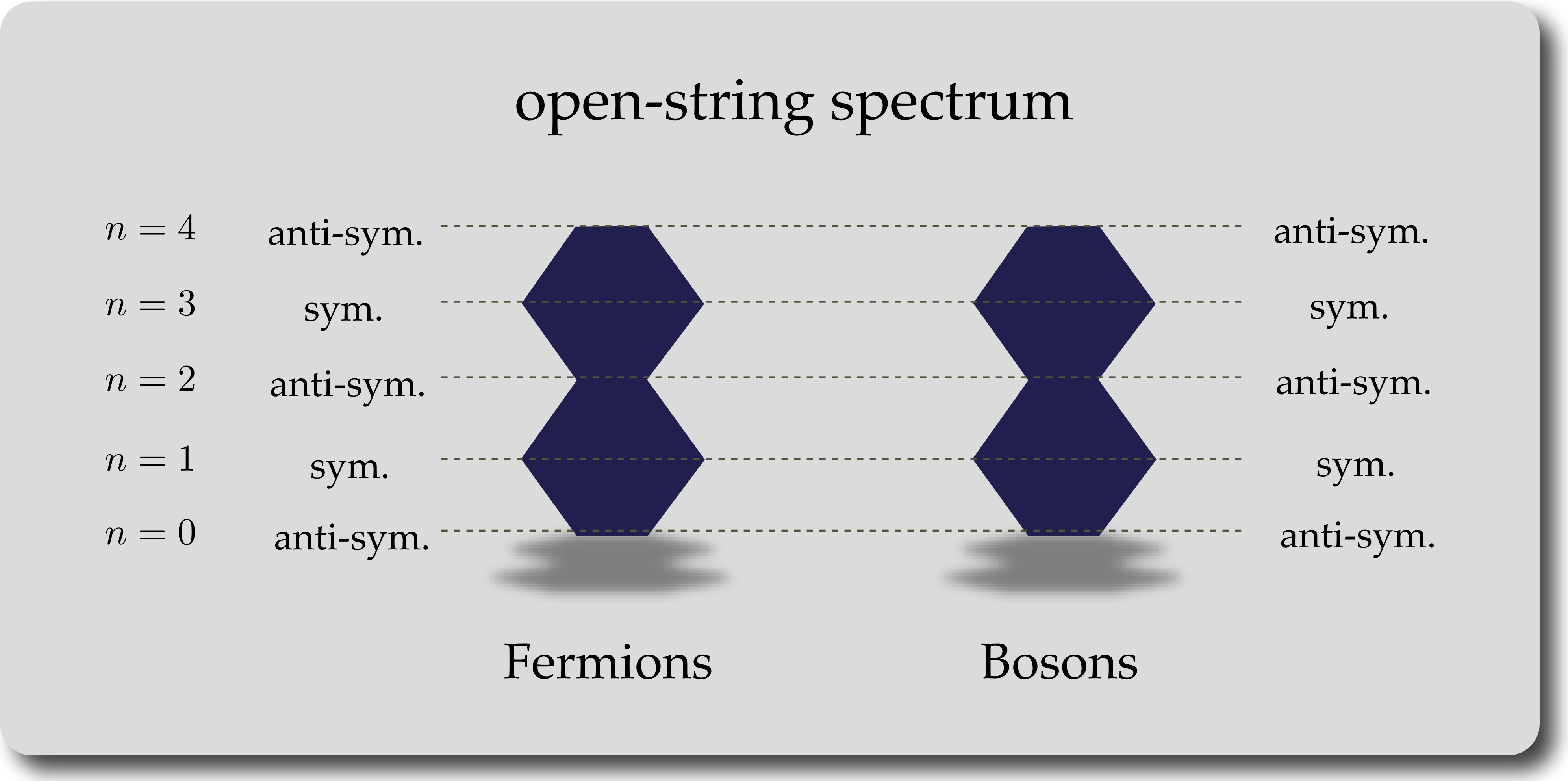
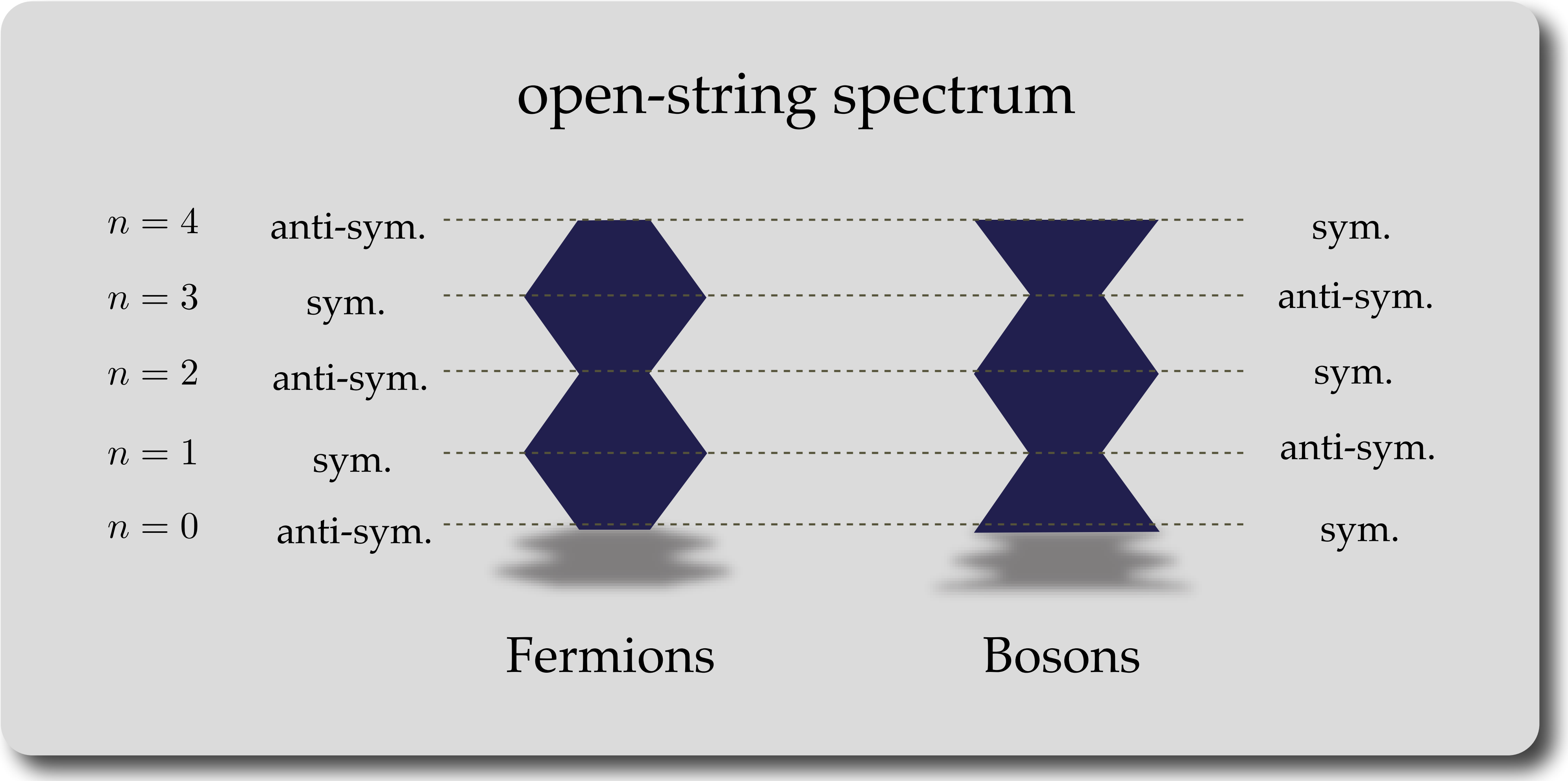


Supersymmetry is exact

Brane Supersymmetry Breaking
G=USp(32)



[Sugimoto 1999]

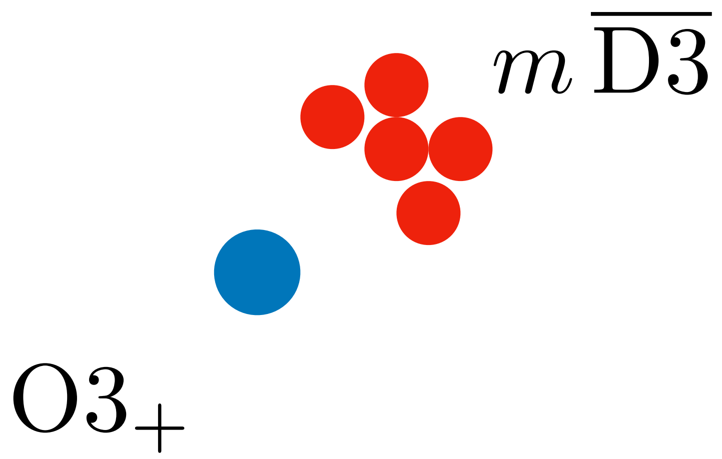
Supersymmetry is hardly broken
(in open strings) at the string scale!

Tree-level dilaton tadpole

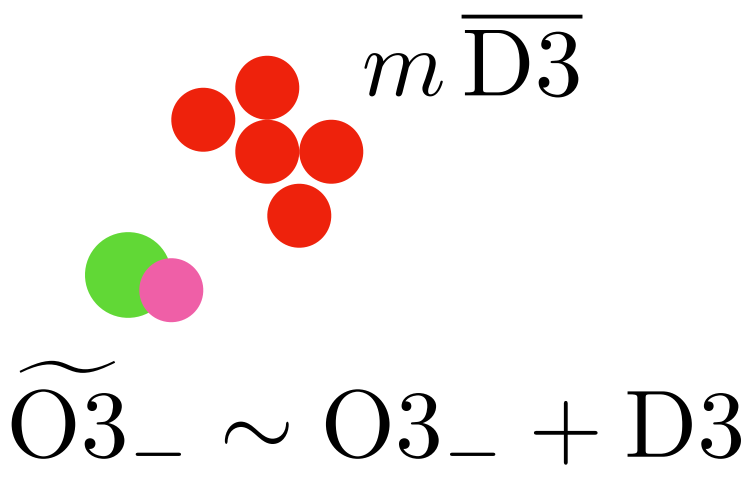
BSB in D=10 after T-dualities

Although tachyon-free by constructions,
there is evidence that these vacua are only metastable,
and could decay into supersymmetric type I superstrings

[CA, Dudas 2007]



The gauge theory is naturally driven towards strong coupling



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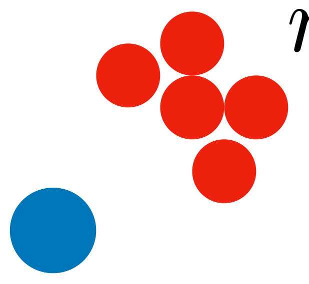

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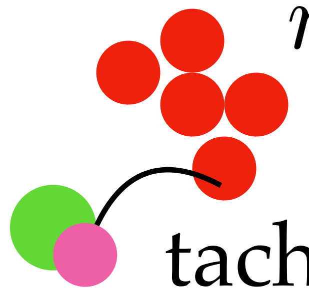

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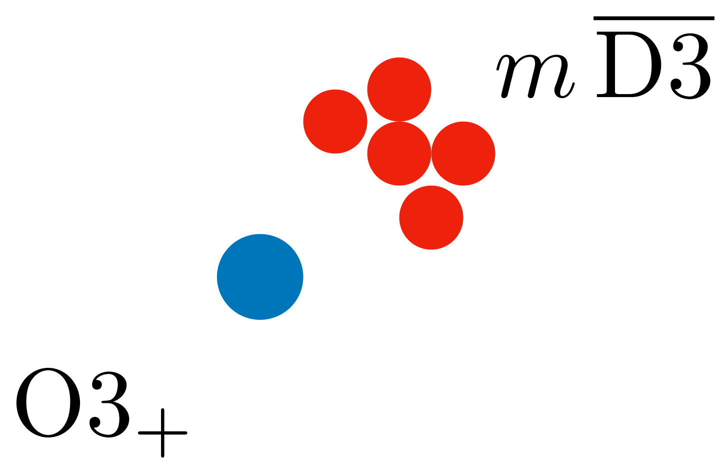

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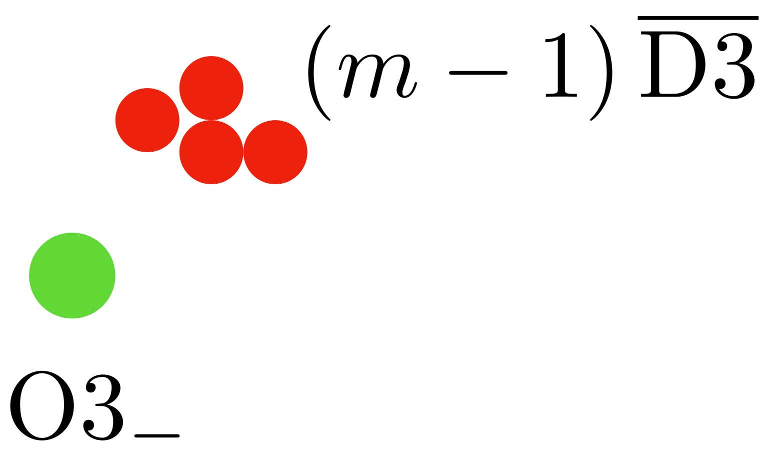


Lower dimensional vacua with BSB

Often, in lower dimensions BSB is not an option but the only vacuum consistent with the orientifold construction

[Antoniadis, Dudas, Sagnotti 1999]

Is this a metastable vacuum?
In the "simple" Z_2 orbifold compactification similar processes might occur

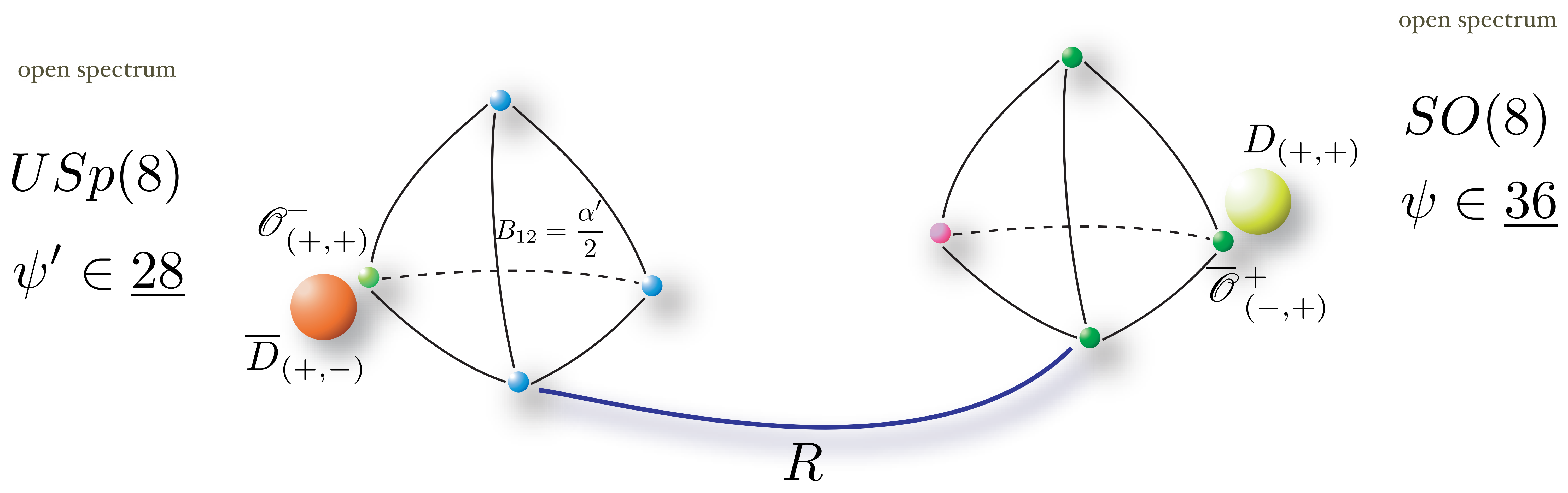
[CA, Dudas 2007]

However, in other orbifold compactifications the cancellation of twisted tadpoles make the model extremely rigid and its fate is far from being obvious

[CA, Condeescu, Dudas, Leone 2024]

❶+❷=DISENTANGLING SCALES

[C.A., Antoniadis; C.A. Cardella]

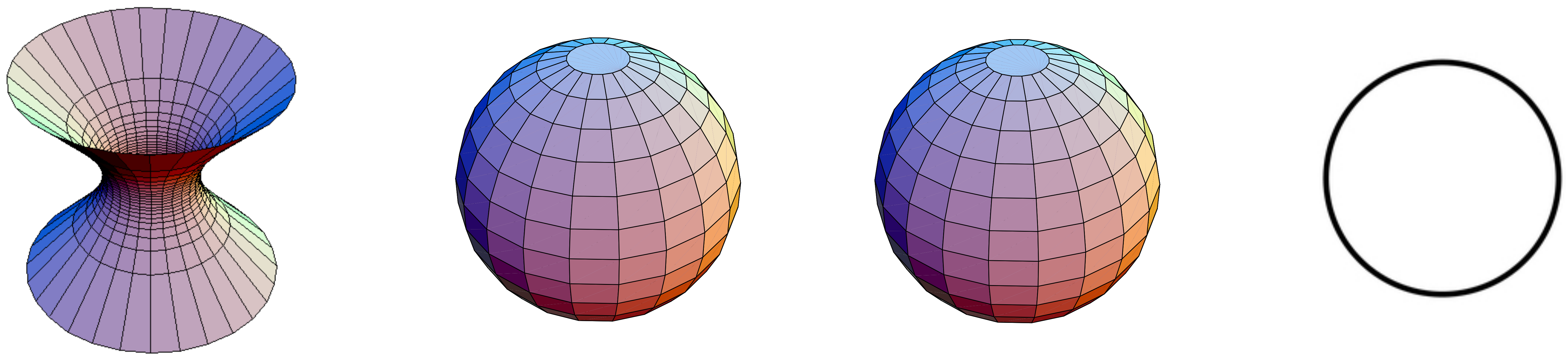


Cosmological constant scale: $\Lambda \sim R^{-4}$

Gaugino mass scale: $M_{\text{gaugino}} \sim 1/\sqrt{\alpha'}$

Which vacuum for BSB (or non-susy) models?

For the SO(16) x SO(16) heterotic theory



$AdS_3 \times S^3 \times S^3 \times S^1$

Is supposed to be a stable vacuum,
even when the one-loop vacuum energy is added

[Baykara, Robbins, Sethi 2023]

Is it really stable in string theory?

Which vacuum for BSB (or non-susy) models?

Whenever supersymmetry is broken a tadpole for the dilaton emerges at some order in perturbation theory

Minkowski is no-longer a vacuum solution.

Spontaneous compactification *à la* Dudas-Mourad?

[Dudas, Mourad 2000]

Fluxes vs vacuum energy can yield (stable) AdS vacua

What are the end-of-the-world branes?

[Basile, Mourad, Raucci, Sagnotti, Tomasiello, …]

THANK YOU

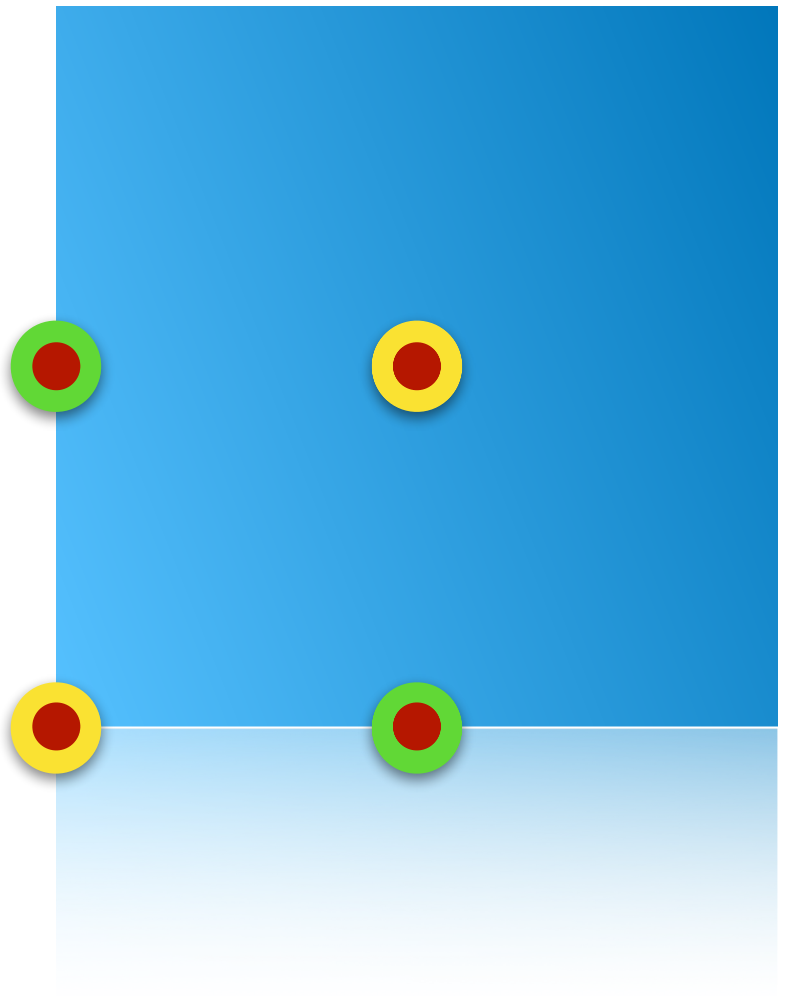
The Klein Bottle Amplitude with BSB

The big difference is that these orientifold planes carry twisted charge.

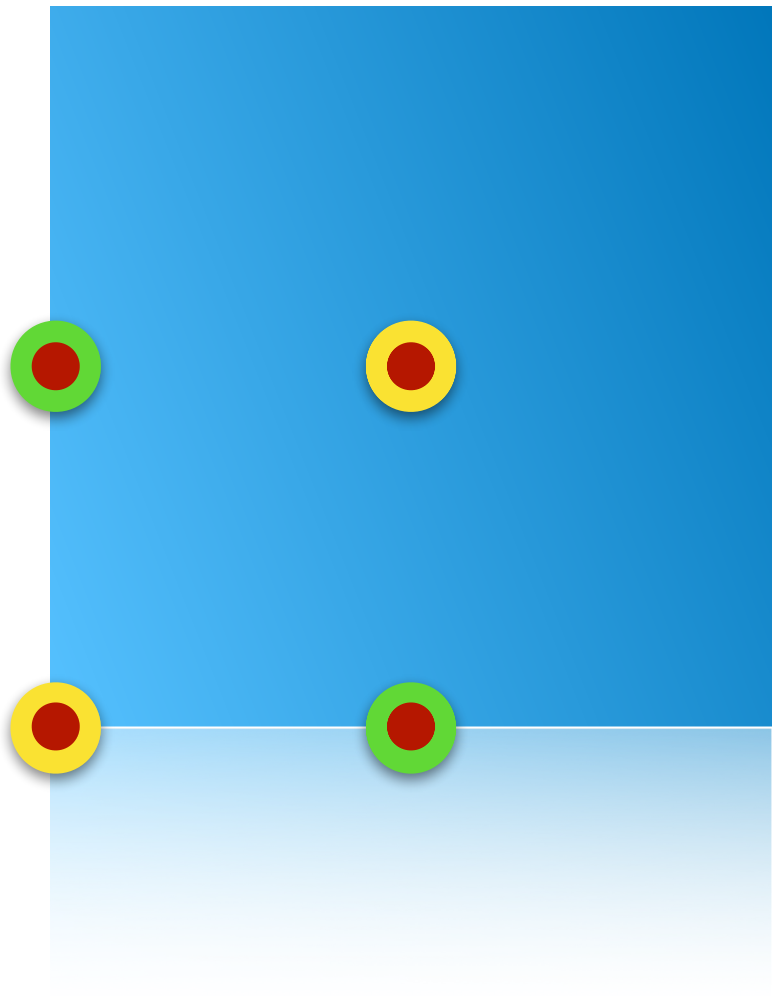
This is possible, because the new orientifold projection yields tensor multiplets from each g^2 fixed point, and a tensor multiplet also contains a non-dynamical (twisted) 6-form

Which O-planes do carry this twisted charge?

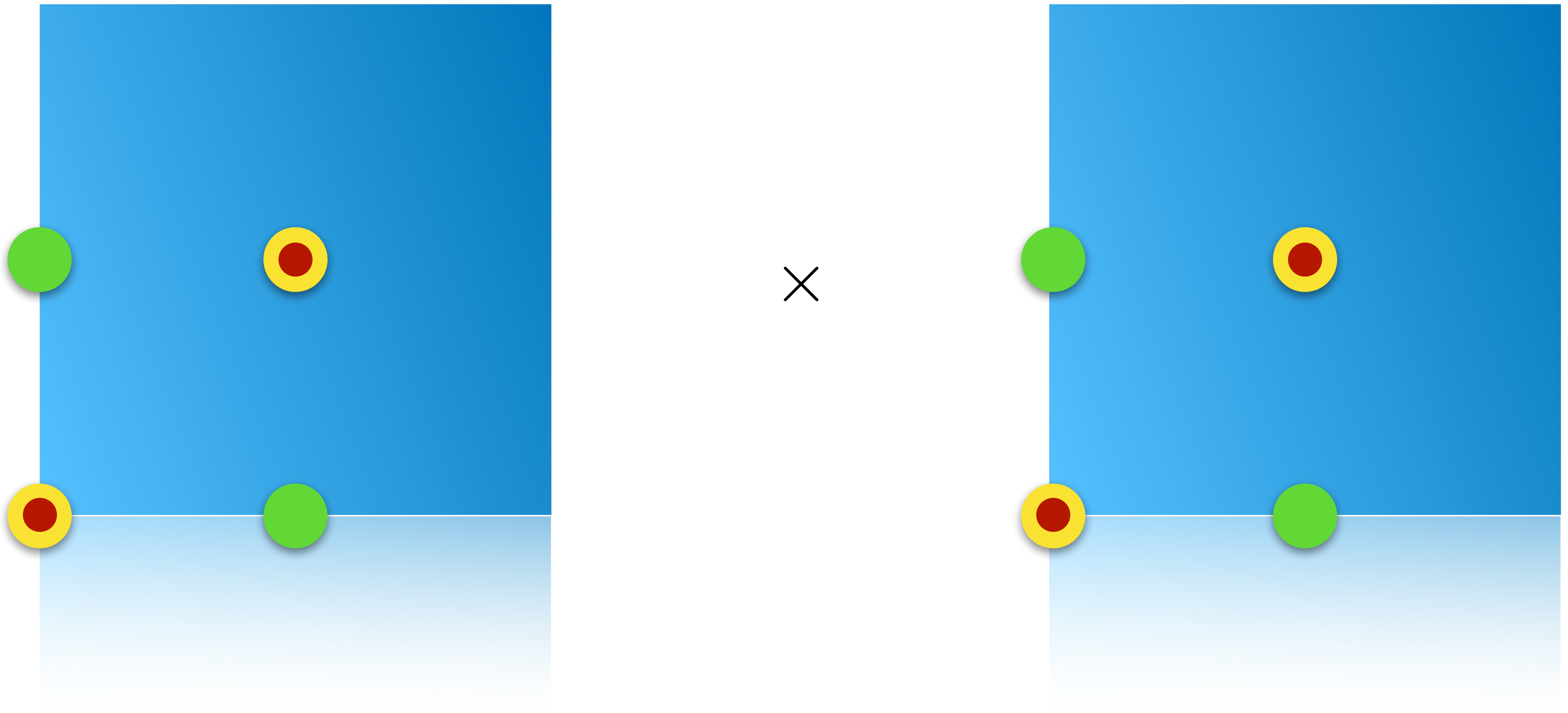
The Klein Bottle Amplitude with BSB



$\times$



The Klein Bottle Amplitude with BSB



Only $\mathbf{Z}_4$ O-planes are *fractional*

$$\tilde{\mathcal{K}} \sim \sum_{a=1}^{4} 2^5\, \chi_{2,0}$$

ADDING D-BRANES. THE LIGHT SPECTRUM

Clearly, this construction calls for *fractional* D9 and anti-D5 branes [ADS 1999]

$$n_1 + n_2 + 2m = 32\,, \qquad \sum_{a=1}^{4} d_{1,a} + d_{2,a} = 32\,, \qquad \text{untwisted}$$

$$n_1 - n_2 = 0\,, \qquad d_{1,a} - d_{2,a} = 0\,, \qquad g{+}g^3 \text{ twisted}$$

$$n_1 + n_2 - 2m = 0\,, \qquad g^2 \text{ twisted, } \mathbb{Z}_2 \text{ f.p.'s}$$

$$n_1 + n_2 - 2m + 4\,\left(d_{1,a} + d_{2,a}\right) = 32\,, \qquad g^2 \text{ twisted, } \mathbb{Z}_4 \text{ f.p.'s}$$

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$$n_1 + n_2 - 2m = 0\,, \qquad g^2 \text{ twisted, } Z_2 \text{ f.p.'s}$$

$$\boxed{4\,(d_{1,a} + d_{2,a}) = 32\,,} \qquad g^2 \text{ twisted, } Z_4 \text{ f.p.'s}$$

Adding D-branes. The Light Spectrum

$$G_{\mathrm{CP}} = \mathrm{SO}(8)^2 \times \mathrm{U}(8)\Big|_9 \times [\mathrm{USp}(4)\times\mathrm{USp}(4)]^4\Big|_{\bar{5}}$$

$$(\mathbf{28},\mathbf{1},\mathbf{1};\vec{\mathbf{1}},\vec{\mathbf{1}}) + (\mathbf{1},\mathbf{28},\mathbf{1};\vec{\mathbf{1}},\vec{\mathbf{1}}) + (\mathbf{1},\mathbf{1},\mathbf{64};\vec{\mathbf{1}},\vec{\mathbf{1}}) + \sum_{a=1}^{4}(\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{6}_a,\mathbf{1}_a) + (\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1}_a,\mathbf{6}_a)$$ LH fermion

$$(\mathbf{8},\mathbf{1},\bar{\mathbf{8}};\vec{\mathbf{1}},\vec{\mathbf{1}}) + (\mathbf{1},\mathbf{8},\mathbf{8};\vec{\mathbf{1}},\vec{\mathbf{1}})$$ Hyper

$$\sum_{a=1}^{4}(\mathbf{8},\mathbf{1},\mathbf{1};\mathbf{4}_a,\mathbf{1}_a) + (\mathbf{1},\mathbf{8},\mathbf{1};\mathbf{1}_a,\mathbf{4}_a)$$ LH (half) fermion

$$\sum_{a=1}^{4}(\mathbf{1},\mathbf{1},\mathbf{8}+\bar{\mathbf{8}};\mathbf{4}_a,\mathbf{1}_a) + (\mathbf{1},\mathbf{1},\mathbf{8}+\bar{\mathbf{8}};\mathbf{1}_a,\mathbf{4}_a)$$ real scalar

ADDING D-BRANES. THE LIGHT SPECTRUM

$$G_{\mathrm{CP}} = \mathrm{SO}(8)^2 \times \mathrm{U}(8)\Big|_9 \times [\mathrm{USp}(4) \times \mathrm{USp}(4)]^4\Big|_{\bar{5}}$$

$$(\mathbf{28},\mathbf{1},\mathbf{1};\vec{\mathbf{1}},\vec{\mathbf{1}}) + (\mathbf{1},\mathbf{28},\mathbf{1};\vec{\mathbf{1}},\vec{\mathbf{1}}) + (\mathbf{1},\mathbf{1},\mathbf{64};\vec{\mathbf{1}},\vec{\mathbf{1}}) + \sum_{a=1}^{4}(\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{6}_a,\mathbf{1}_a) + (\mathbf{1},\mathbf{1},\mathbf{1};\mathbf{1}_a,\mathbf{6}_a)$$

LH fermion

$$\boxed{(\mathbf{8},\mathbf{1},\bar{\mathbf{8}};\vec{\mathbf{1}},\vec{\mathbf{1}}) + (\mathbf{1},\mathbf{8},\mathbf{8};\vec{\mathbf{1}},\vec{\mathbf{1}})}$$

Hyper

$$\sum_{a=1}^{4}(\mathbf{8},\mathbf{1},\mathbf{1};\mathbf{4}_a,\mathbf{1}_a) + (\mathbf{1},\mathbf{8},\mathbf{1};\mathbf{1}_a,\mathbf{4}_a)$$

LH (half) fermion

$$\boxed{\sum_{a=1}^{4}(\mathbf{1},\mathbf{1},\mathbf{8}+\bar{\mathbf{8}};\mathbf{4}_a,\mathbf{1}_a) + (\mathbf{1},\mathbf{1},\mathbf{8}+\bar{\mathbf{8}};\mathbf{1}_a,\mathbf{4}_a)}$$

real scalar

Adding Defects. D1 and D5′ branes

$$G_{\mathrm{CP}} = \mathrm{SO}(8) \times \mathrm{SO}(8) \times \mathrm{U}(8)\Big|_{9} \times [\mathrm{USp}(4) \times \mathrm{USp}(4)]^4\Big|_{\bar{5}}$$

$$G_{\mathrm{D1}} = \mathrm{SO}(r_1) \times \mathrm{SO}(r_2) \times \mathrm{U}(r)$$

$$G_{\mathrm{D5'}} = \mathrm{USp}(r_1) \times \mathrm{USp}(r_2) \times \mathrm{U}(r)$$

Anomaly inflow is cancelled on defects by a unitary theory [Kim, Shiu, Vafa 2019]

Witten interpretation of branes seems to fail [Witten 1995]

D5′ branes ***are*** instantons for D9′s

D5 branes ***are not*** instanton for D9′s

D1 branes ***are not*** instanton for D5′s