Uncovering the Non-supersymmetric Heterotic String Landscape

Bernardo Fraiman

IFT(UAM-CSIC) and CERN

String Phenomenology (25-06-**2024**)

Centro Culturale Altinate - San Gaetano - Padova

Based on:

- [2307.13745] [BF, M. Graña, H. Parra de Freitas, S. Sethi]
- Upcoming work: [BF, H. Parra de Freitas]

Some things being worked on:

- [BF, M. Graña, H. Parra de Freitas]
- [BF, I. Ruiz, I. Valenzuela]
- [S. Baines, V. Collazuol, BF, M. Graña, D. Waldram]

Why *non-SUSY?*

String theory **supersymmetric landscape** has been heavily studied (most of it still **unknown**)

Underlying **structure** for large number of space-time dimensions and supercharges.

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Let's **break** SUSY and find out!

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It is possible to **break** SUSY at the **string scale**

Recent resurgence in interest:

[Abel, Acharya, Aldazabal, Angelantonj, Basile, Baykara, Condeescu, Cribiori, Debray, Delgado, Diaz Avalos, Dudas, Faraggi, Florakis, Font, BF, Graña, Itoyama, Kaidi, Koga, Lanza, Leone, Matyas, Montero, Nakajima, Narain, Parameswaran, Parra de Freitas, Percival, Raucci, Robbins, Sagnotti, Sethi, Tarazi, Tonioni, Vafa, Wrase, etc.]

Most of the structure of SUSY landscape can be generalized under certain SUSY breakings!

More compactifications, richer spectra

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Possible **ISSUES?**

- Tachyons

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Why is this? Try to **identify** general **patterns!**

[BF, Graña, Parra de Freitas, Sethi ’23,
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Heterotic theories in 10D:

[Dixon, Harvey; Alvarez-Gaume, Ginsparg, Moore, Vafa; Kawai, Lewellen, Tye; Seiberg, Witten ’86]

Theory	Gauge symmetry	Tachyons
HE	$E_8 \times E_8 \ltimes \mathbb{Z}_2$	0
HO	$\frac{Spin(32)}{\mathbb{Z}_2}$	0
$O(16) \times O(16)$	$\frac{Spin(16)^2}{\mathbb{Z}_2} \ltimes \mathbb{Z}_2$	0
E_8	E_8	1
$U(16)$	$\frac{SU(15)\times U(1)}{\mathbb{Z}_2} \ltimes \mathbb{Z}_2$	2
$(E_7 \times SU(2))^2$	$\frac{(E_7\times SU(2))^2}{\mathbb{Z}_2} \ltimes \mathbb{Z}_2$	4
$O(24) \times O(8)$	$\frac{Spin(24)\times Spin(8)}{\mathbb{Z}_2}$	8
$E_8 \times O(16)$	$E_8 \times Spin(16)$	16
$O(32)$	$Spin(32)$	32

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Massless **bosons**: G, B, ϕ plus gauge fields in the adjoint of the corresponding gauge group

Massless **fermions**: (e.g. O(16) x O(16))
Half of them transform in the spinor rep. of only one SO(16), or the other.
and the rest transform in the bi-fundamental rep. of SO(16) x SO(16)

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Non-SUSY theories **include a quantum potential**:

$$\int d^{10}x \sqrt{-g}\, \boldsymbol{\Lambda} \qquad \boldsymbol{\Lambda}_{1-\text{loop}} = \int \frac{d^2\tau}{\tau_2^2} \boldsymbol{Z}(\tau)$$

$\boldsymbol{\Lambda} > 0$ for known non-tachyonic **rigid** theories [Baykara, Tarazi, Vafa '24]

$\boldsymbol{\Lambda} \to -\infty$ when **tachyons**

O(16) x O(16) on S^1

space-time fermion number

order 2 shift in E8+E8 lattice

HE theory with holonomy $(-1)^F(-1)^{2\pi\cdot\delta}$ → **Breaking of SUSY**

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9D

Classical moduli space:

Radius **R**

16-dimensional Wilson line $\boldsymbol{A_i}$

Parameter space: $O(\Gamma_{(17,1)})\backslash O(17,1)/O(17)$

(T-duality group)

(different from the SUSY case)

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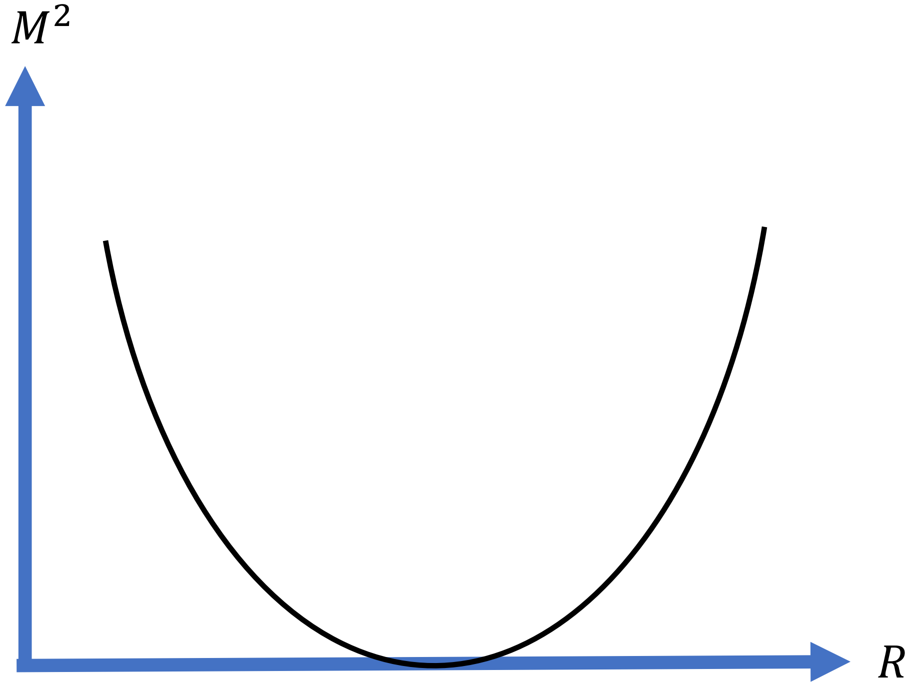
States separated in **sectors**:

- Untwisted: $\boldsymbol{\Gamma_v}$ (gauge **bosons**, appear at boundaries)
  $\boldsymbol{\Gamma_s}$ (**fermions**)
- Twisted: $\boldsymbol{\Gamma_c}$ (**fermions**)
  $\boldsymbol{\Gamma_0}$ (**scalars** or **tachyons**)

Gauge bosons

$$M^2_{\text{gauge boson}} \geq 0$$

$M^2_{\text{gauge boson}} = 0$ could happen in the bulk or in the boundary of parameter space



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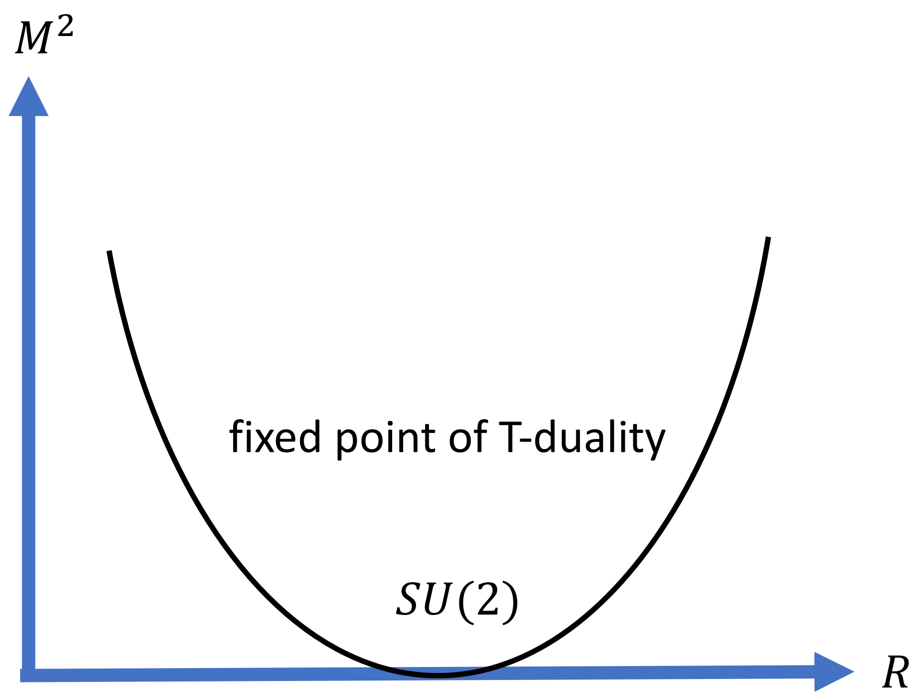

Enhancement to **non-abelian** symmetry.

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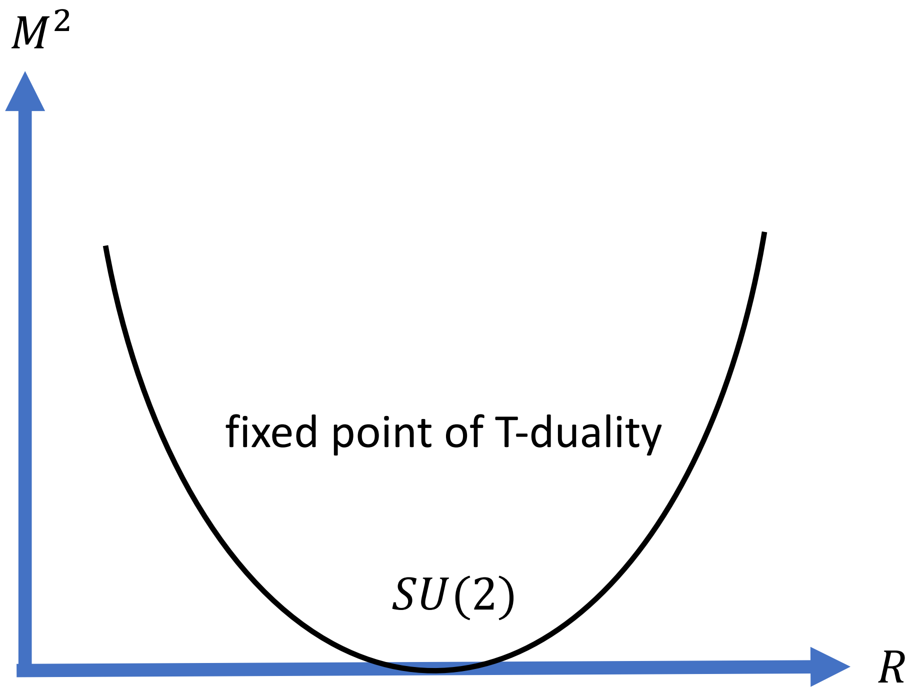

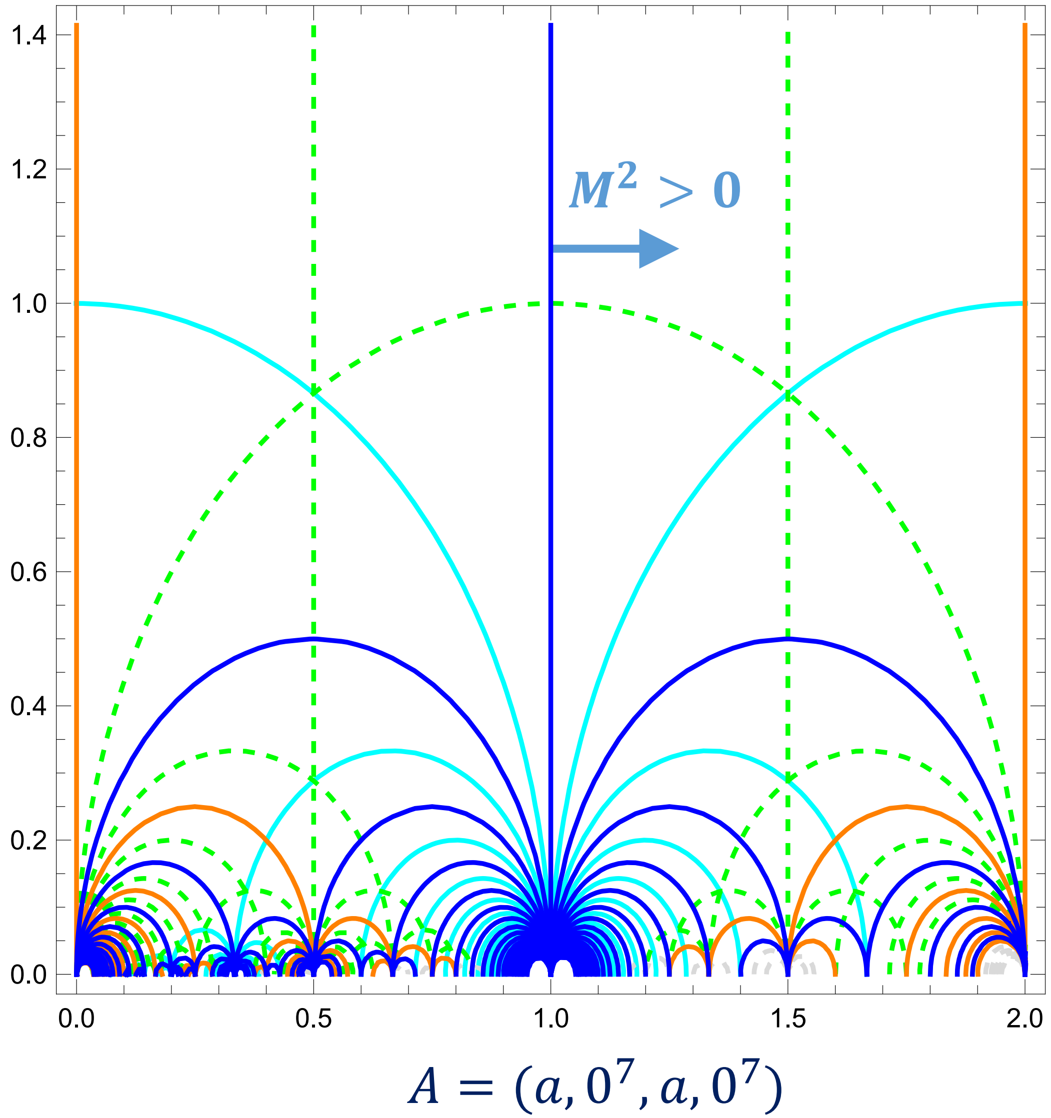

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Classification from embeddings in Γ_{charge}

Full rank: [BF, Graña, Parra de Freitas, Sethi '23]

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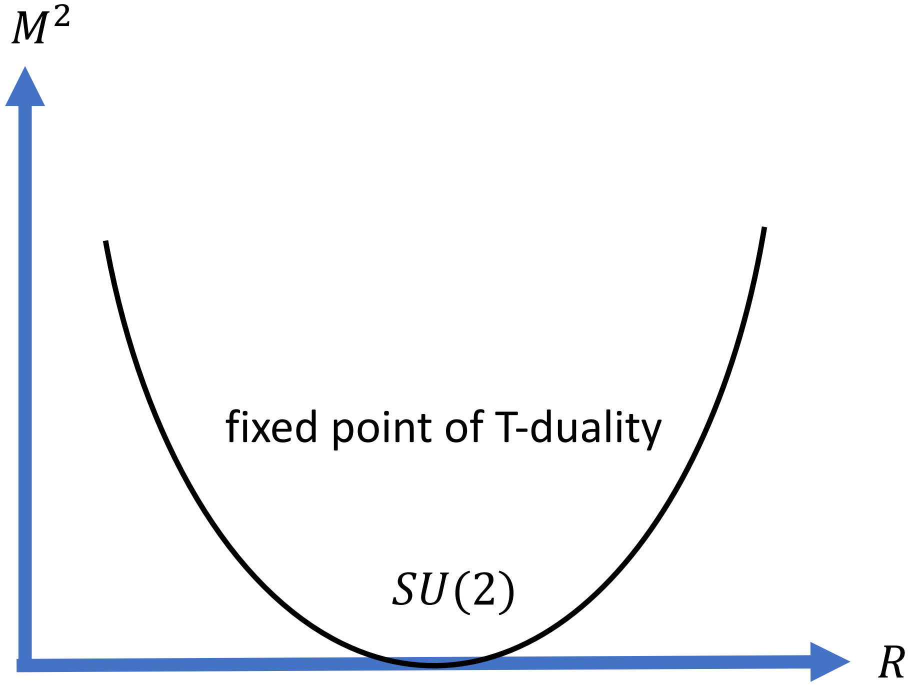

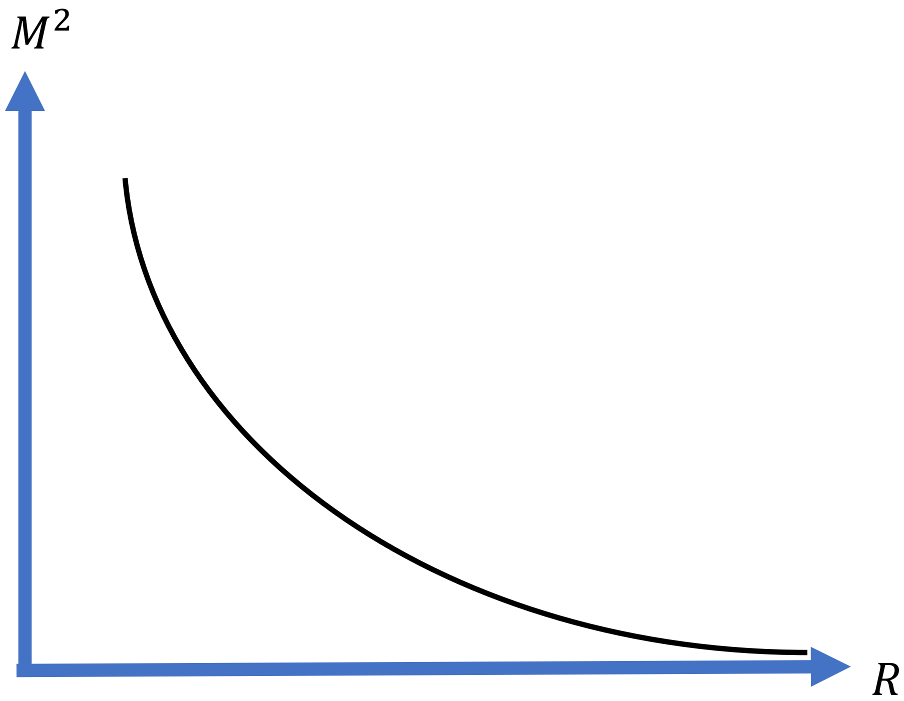

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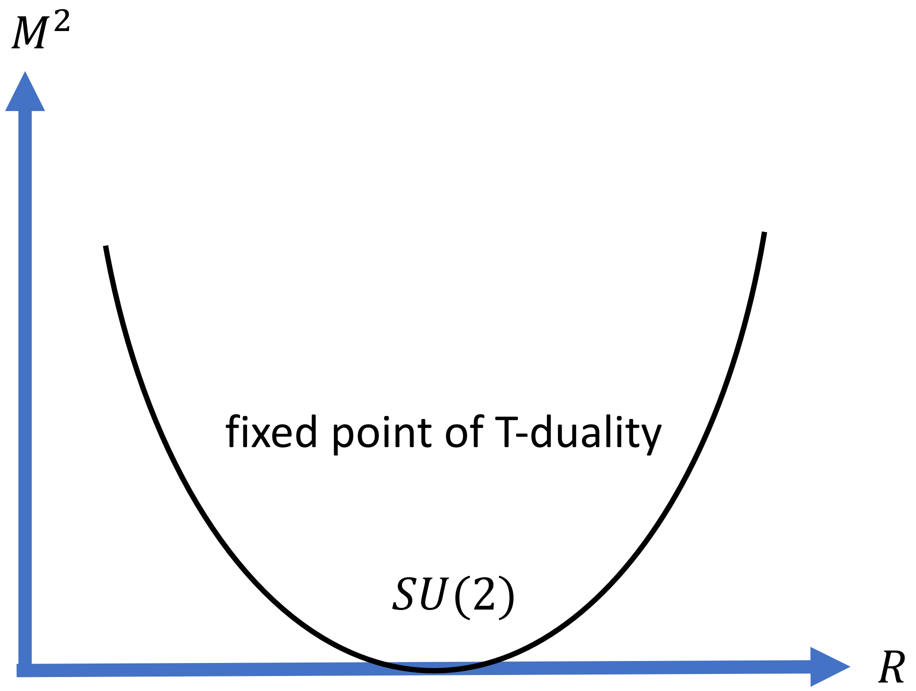

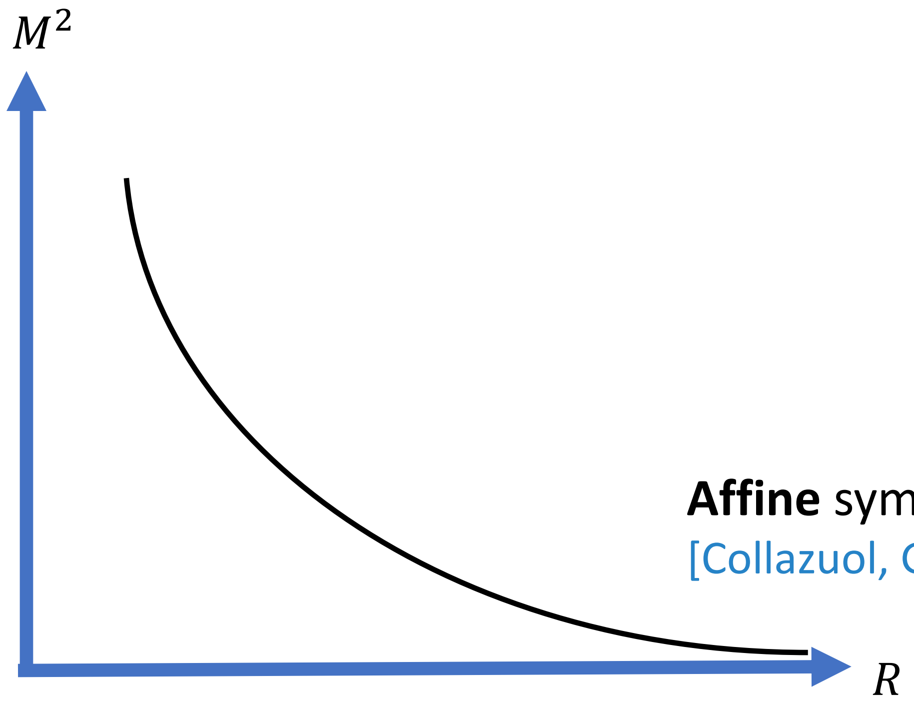

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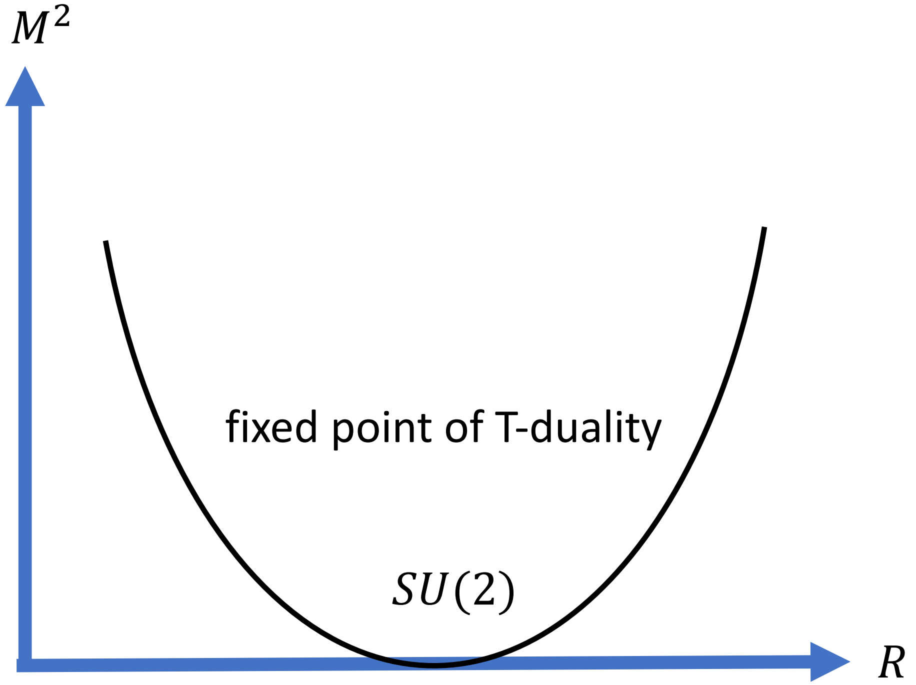

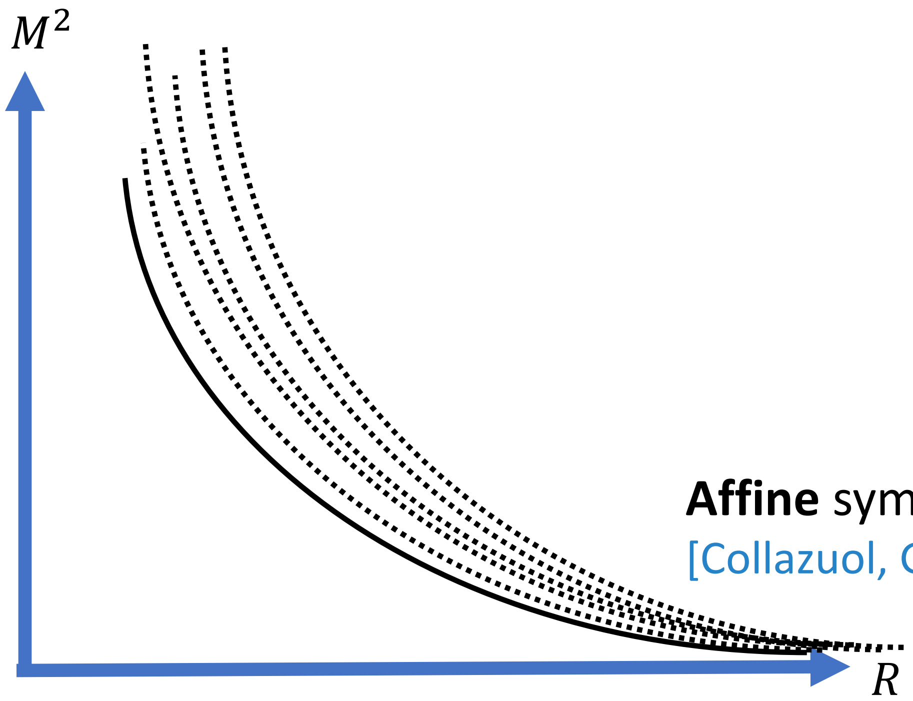

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(distance conjecture [Ooguri, Vafa, '07])

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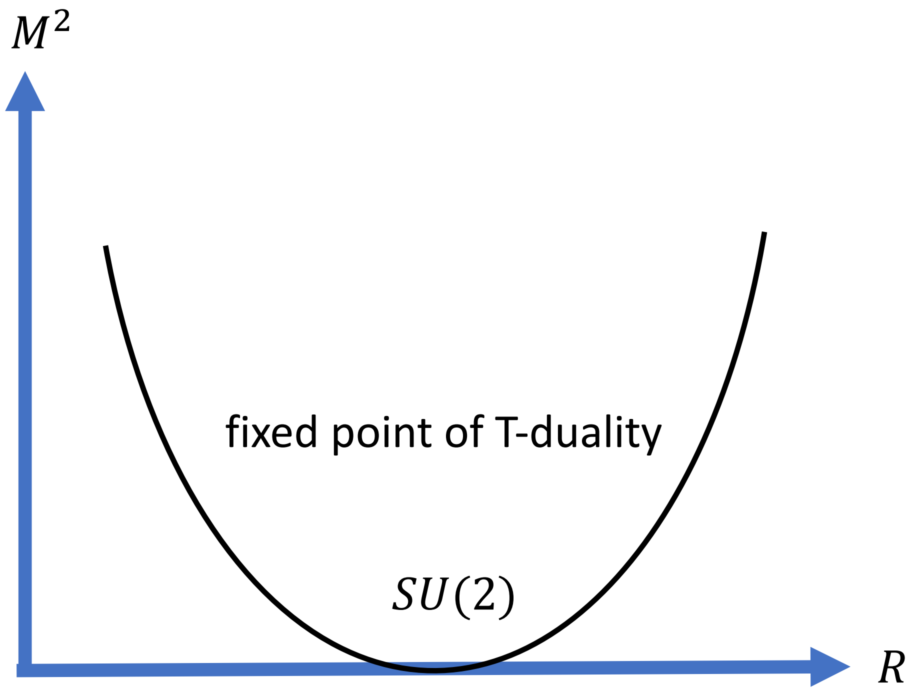

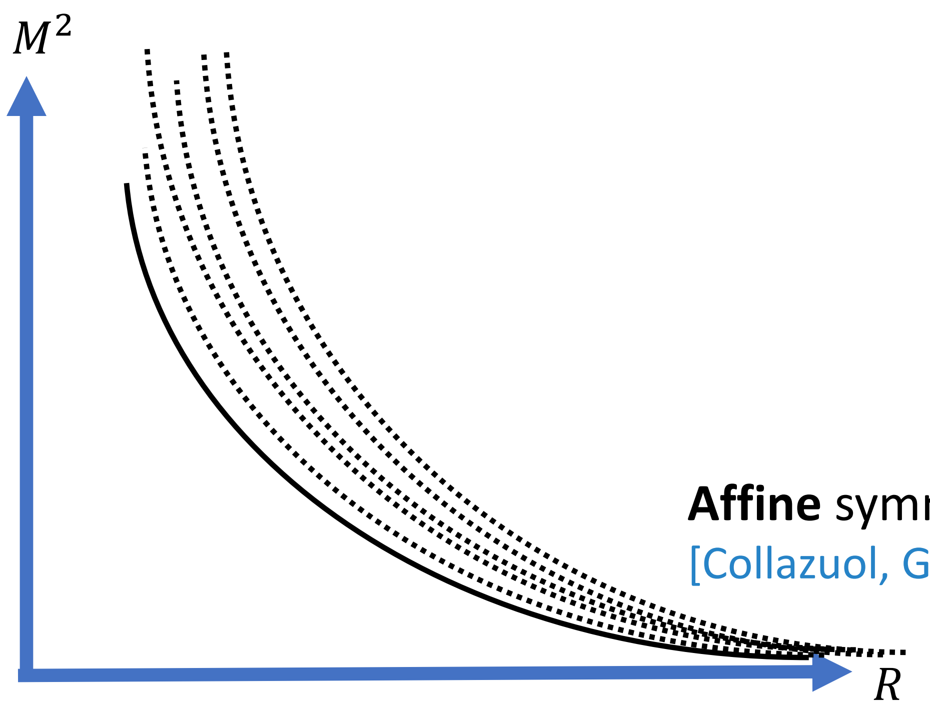

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Related swampland conjectures in
non-SUSY setup? [BF, Ruiz, Valenzuela WIP]

Fermions:

very similar* to gauge bosons

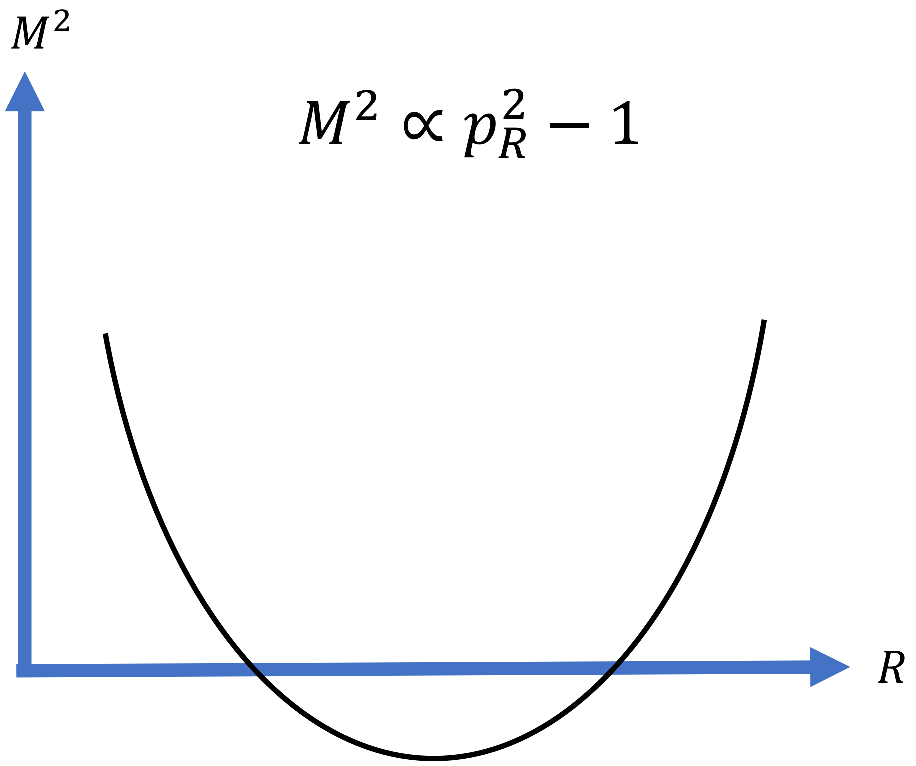
*they do not necessarily become massless at fixed points of T-duality

What about the tachyons?

Tachyons

M^2_{scalar}? Can be negative at some regions

$M^2_{\text{scalar}} = M^2_{\min} < 0$ could happen in the bulk or in the boundary of parameter space



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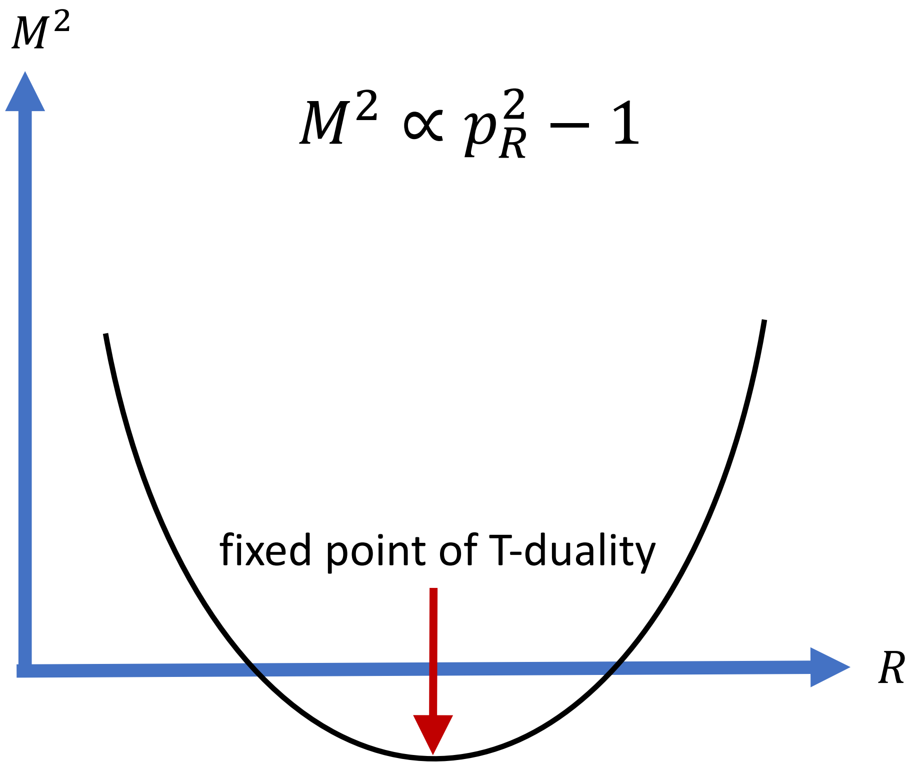
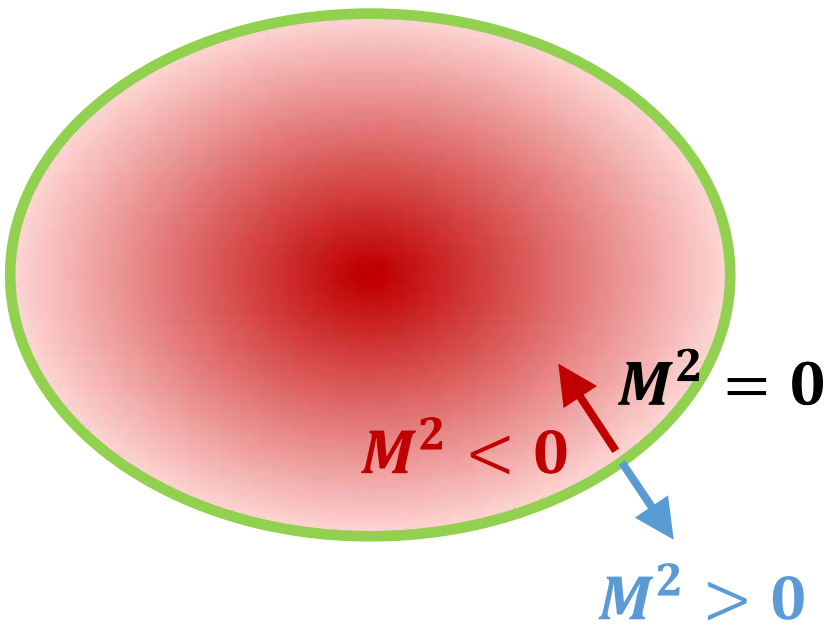


Tachyons if $p_R^2 < 1$
massless scalars if $p_R^2 = 1$



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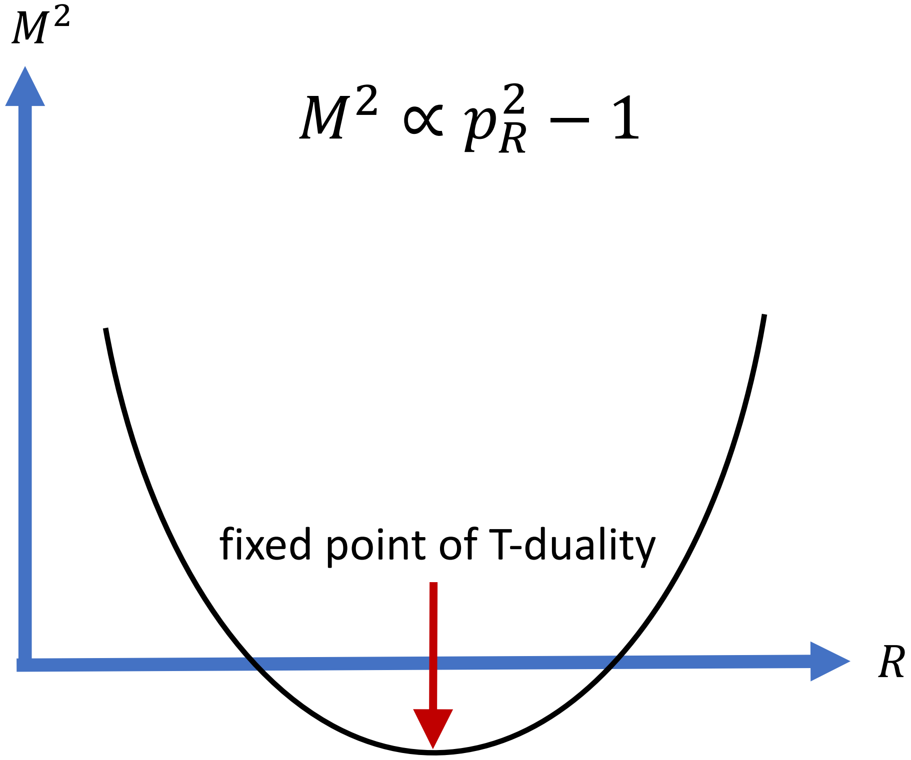

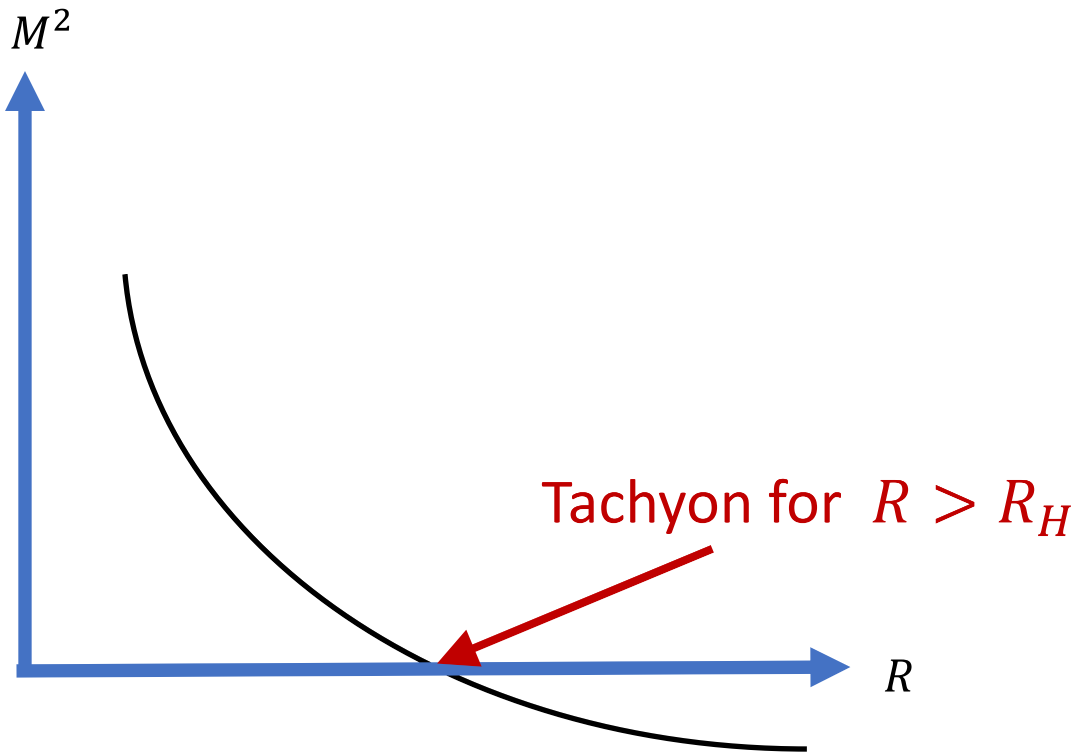

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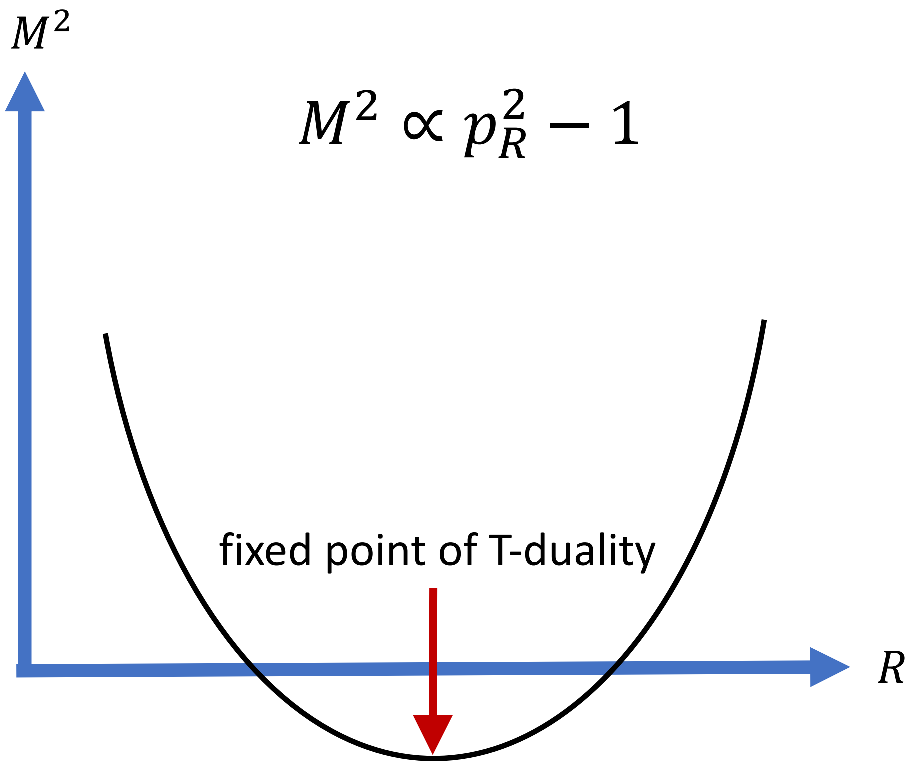

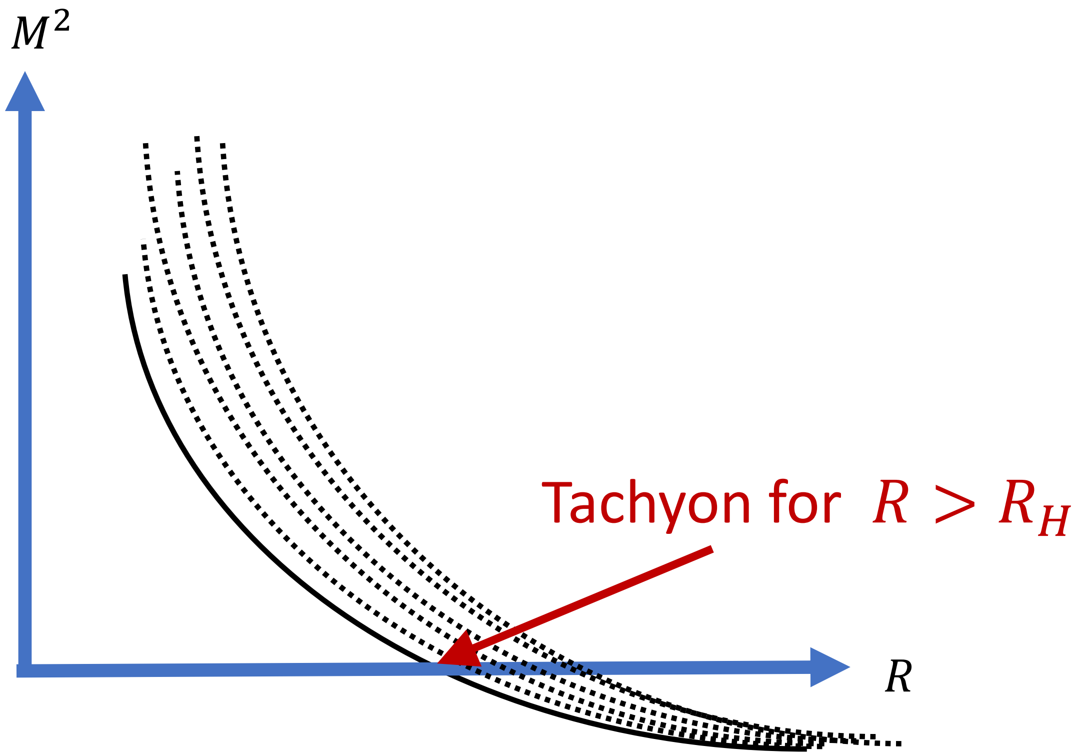

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Part of an **infinite tower** of tachyons becoming **extremal**.
They signal **a tachyonic** higher dim. theory!

What happens to the quantum potential after compactifying?

Is it still positive?
Is there some minimum?

One-loop potential

$$\boldsymbol{\Lambda}_{1-\text{loop}}(\mathrm{R},\mathrm{A}) = \int \frac{d^2\tau}{\tau_2^2} \boldsymbol{Z}(\tau, R, A)$$

Quantum potential now depends on compact **geometry (R,A)**

$$\boldsymbol{Z} \sim \sum q^{p_L^2(R,A)} \bar{q}^{p_R^2(R,A)}$$

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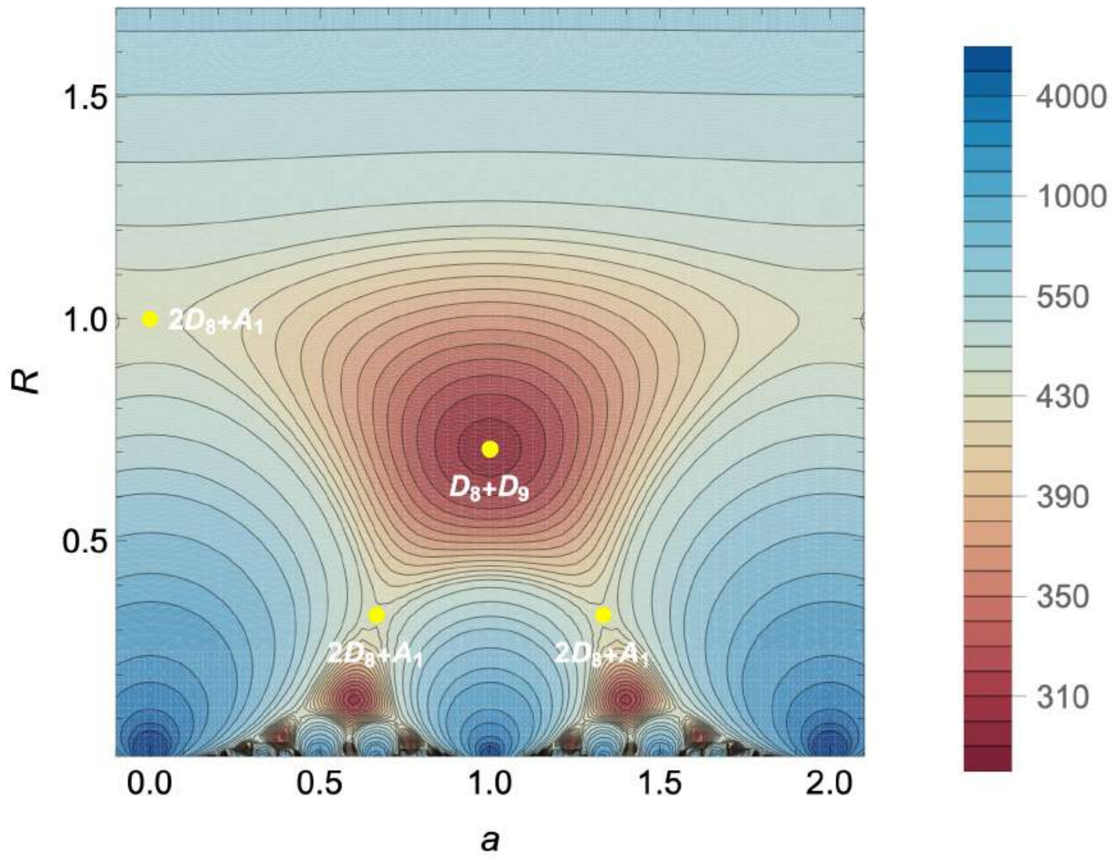
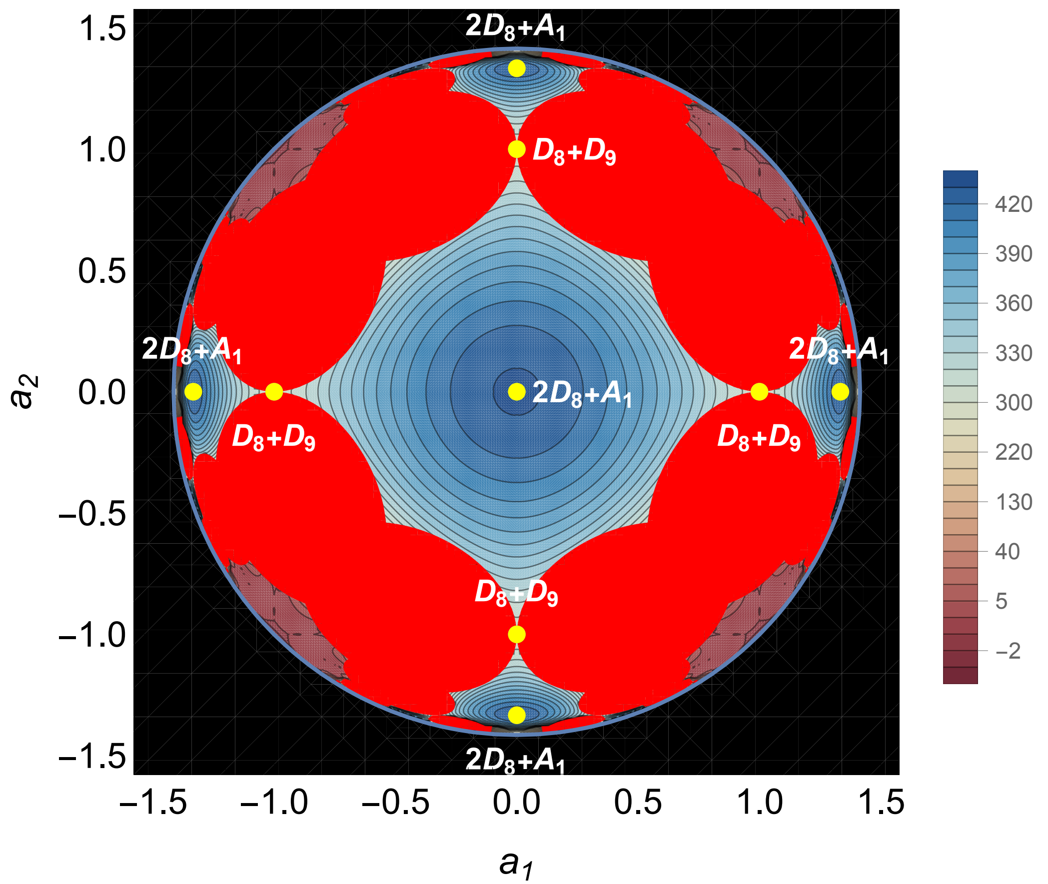
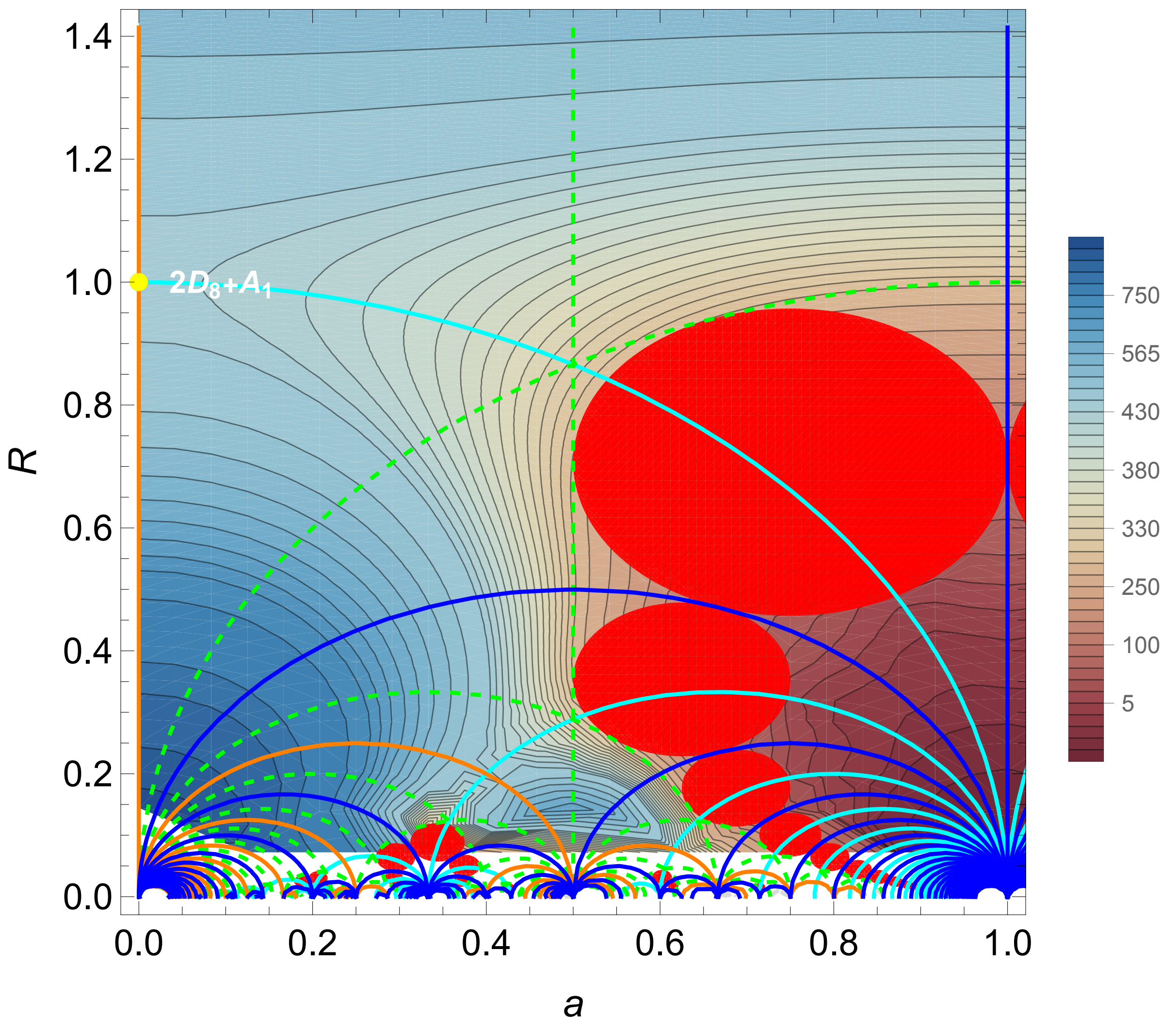




Bosons, fermions and scalars give finite contributions, tachyons make it diverge.

$$A = (a, 0^7, a, 0^7)$$



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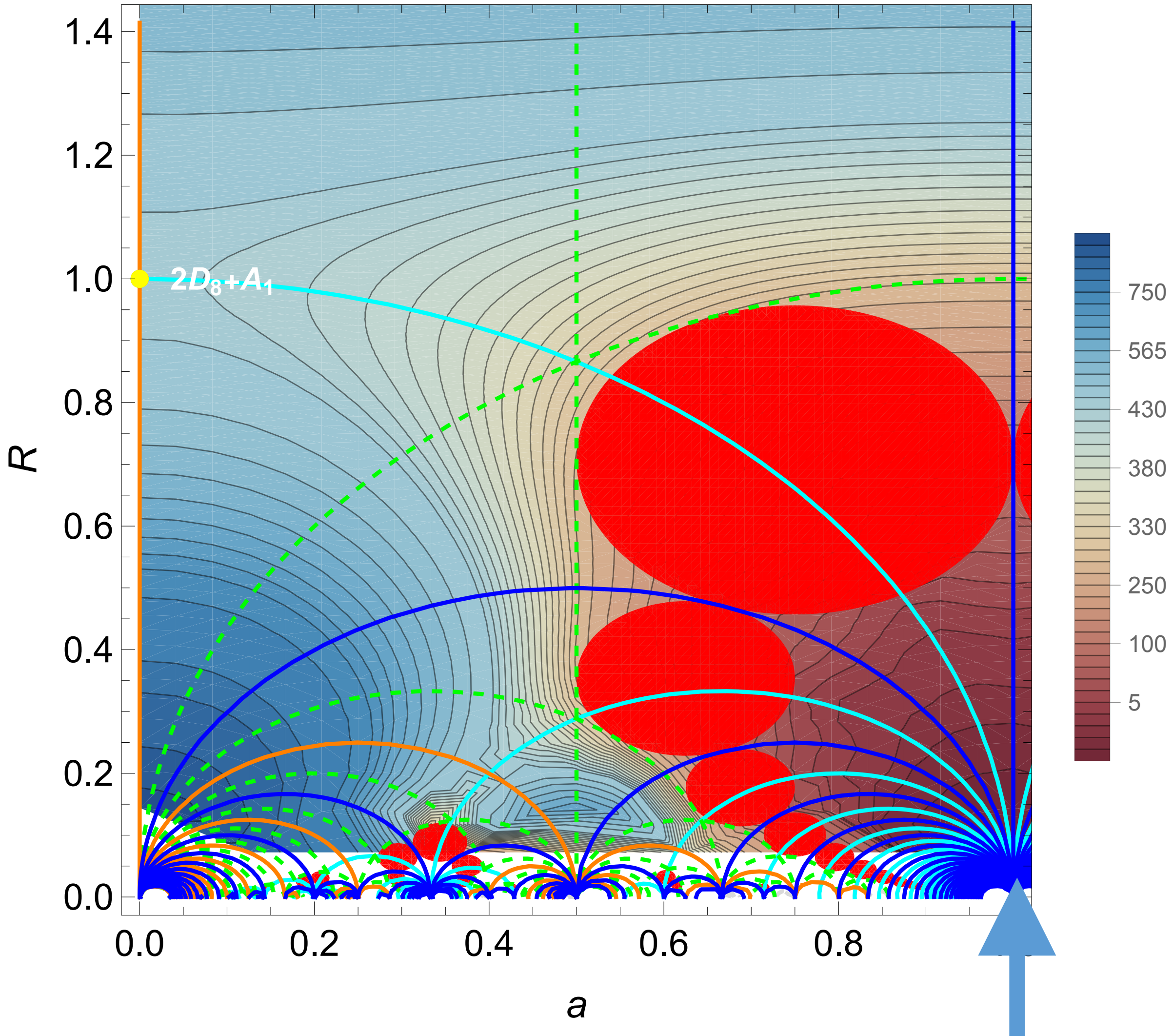

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SO(32) SUSY string

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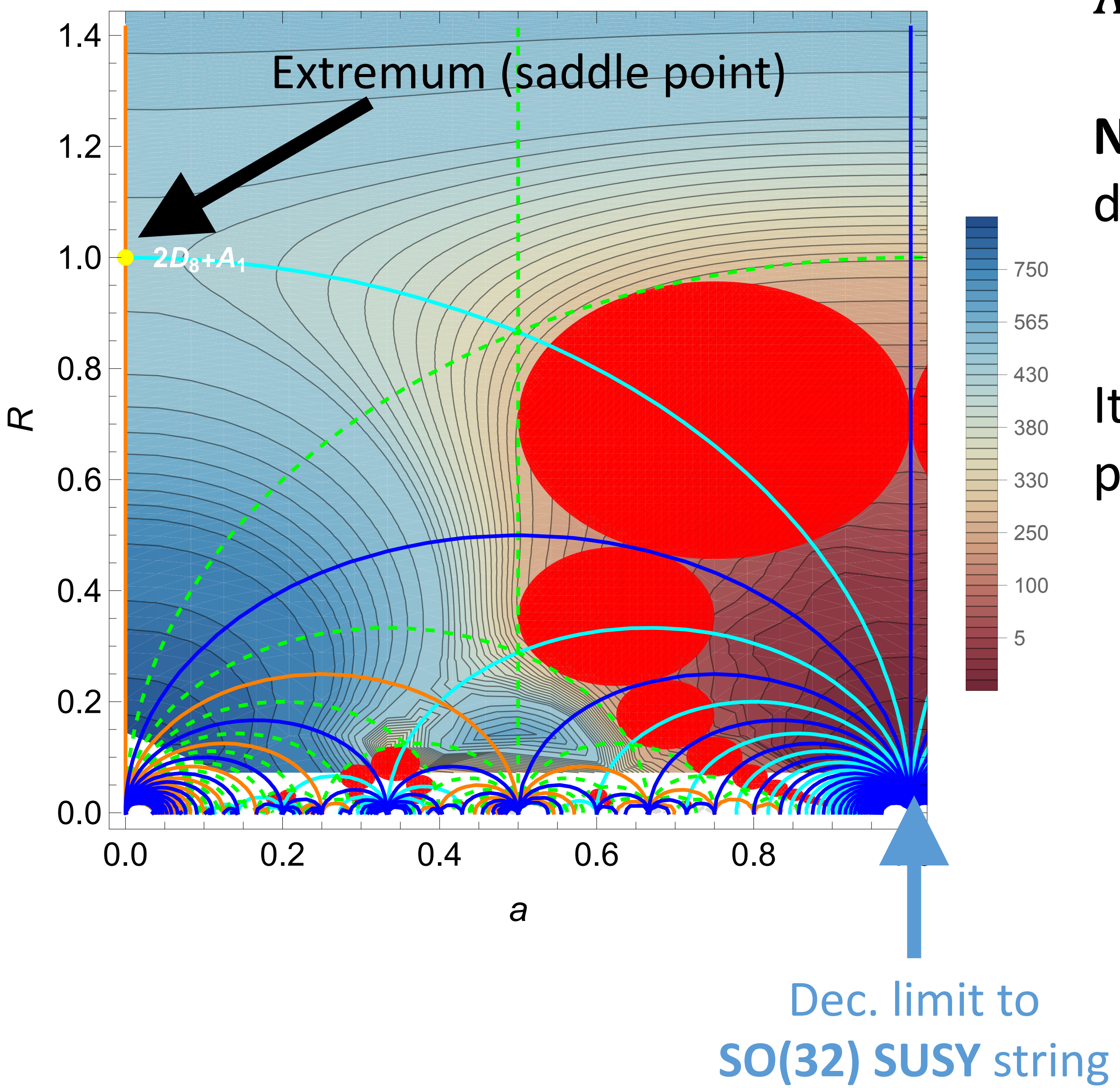

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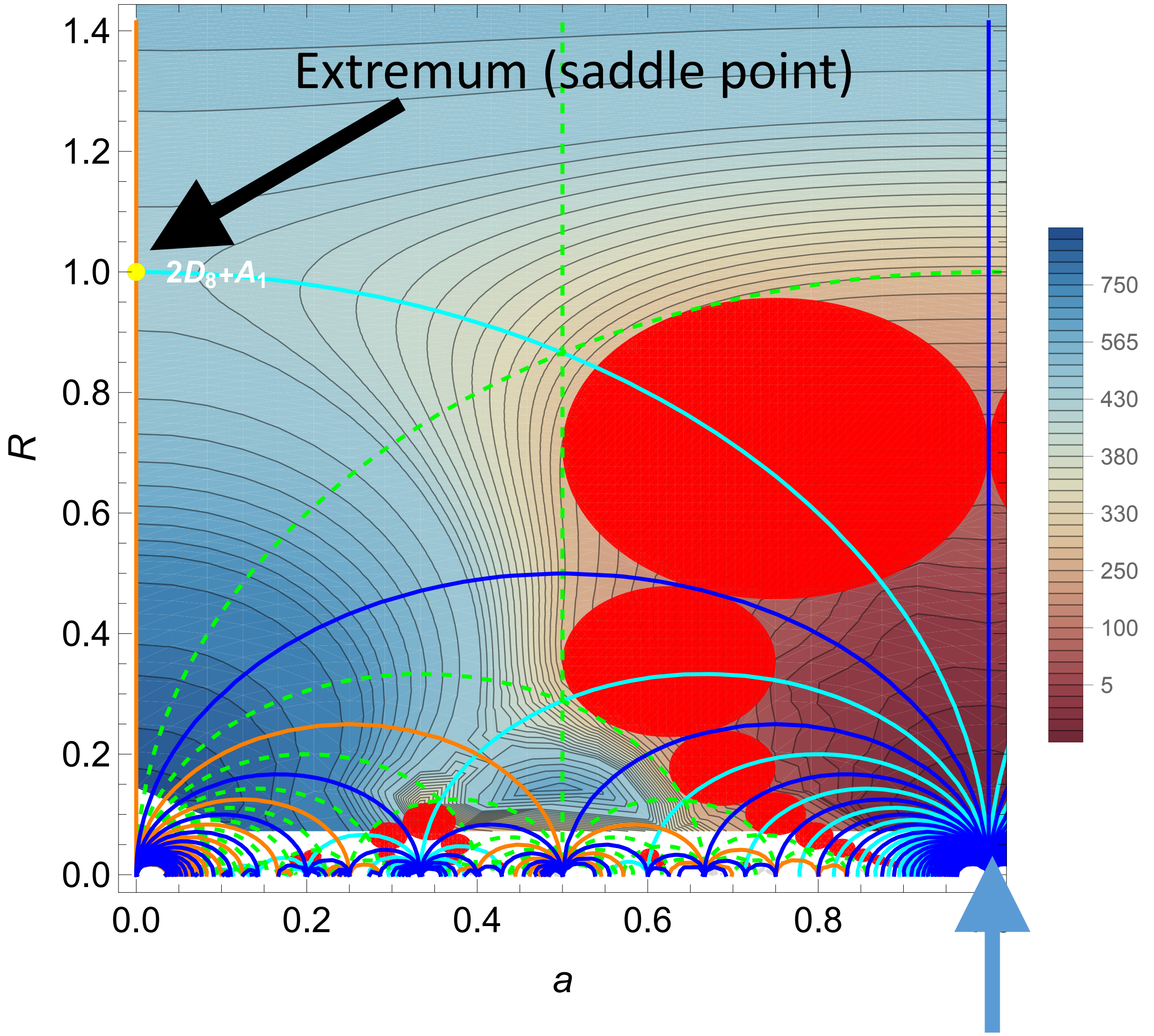

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All extrema found to be **unstable**

[BF, Graña, Parra de Freitas, Sethi '23]

Satisfy **dS conjecture** $\dfrac{\min(\nabla_i \nabla_j V)}{V} \leq -O(1)$

[Andriot '18] [Ooguri, Palti, Shiu , Vafa '18]

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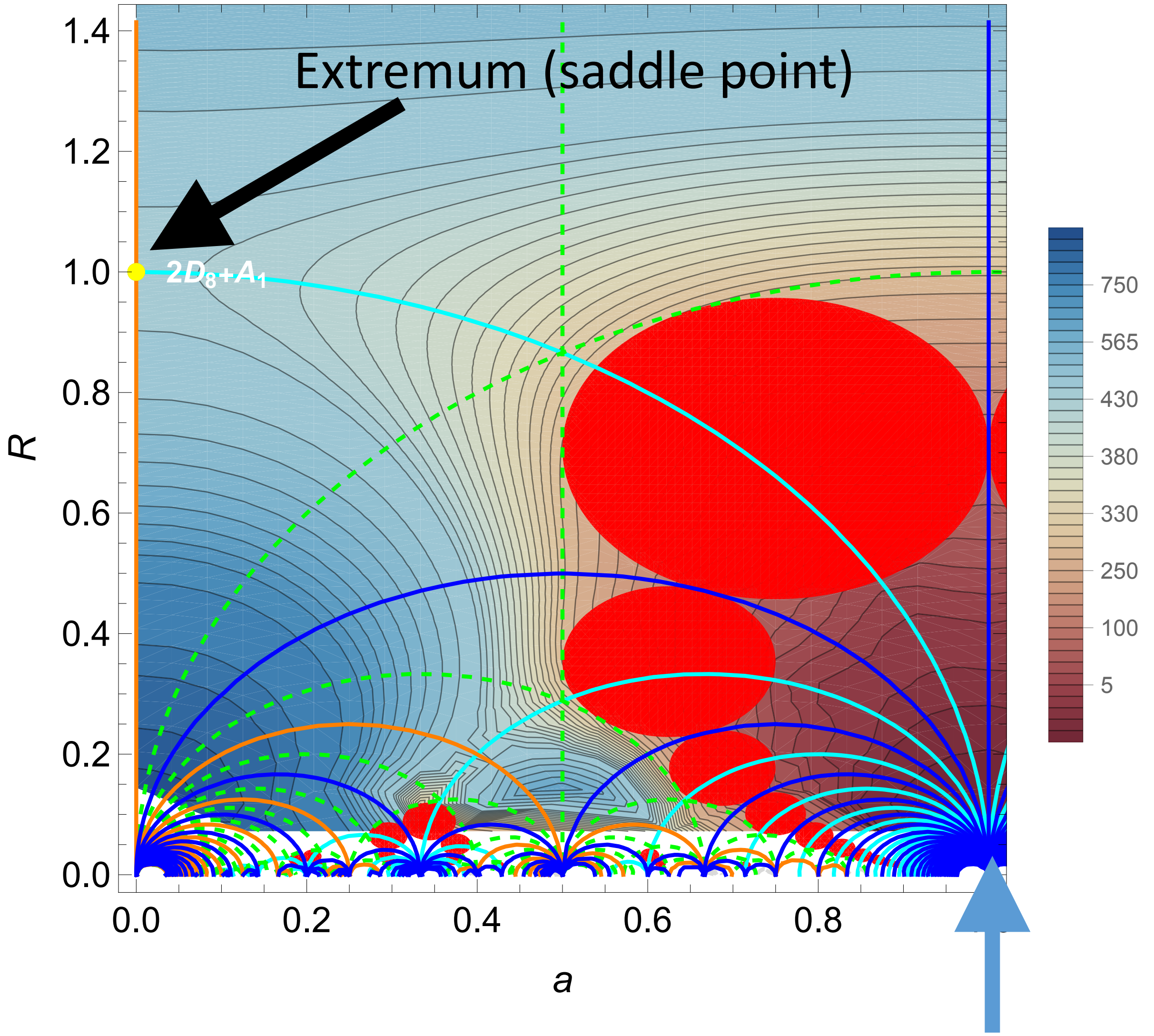

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[Ginsparg, Vafa '87]

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[BF, Graña, Parra de Freitas, Sethi '23]

Satisfy **dS conjecture** $\dfrac{\min(\nabla_i \nabla_j V)}{V} \le -O(1)$

[Andriot '18] [Ooguri, Palti, Shiu , Vafa '18]

D < 9: more extrema… still **not minima**?

[BF, Graña, Parra de Freitas WIP]

How many theories appear as decompactification limits?

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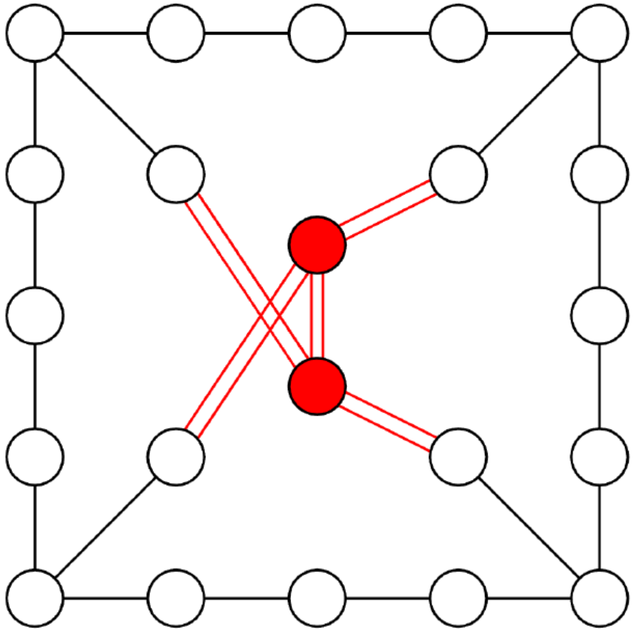
8 (all rank 16 theories in 10D)

Affine subdiagrams of EDD:



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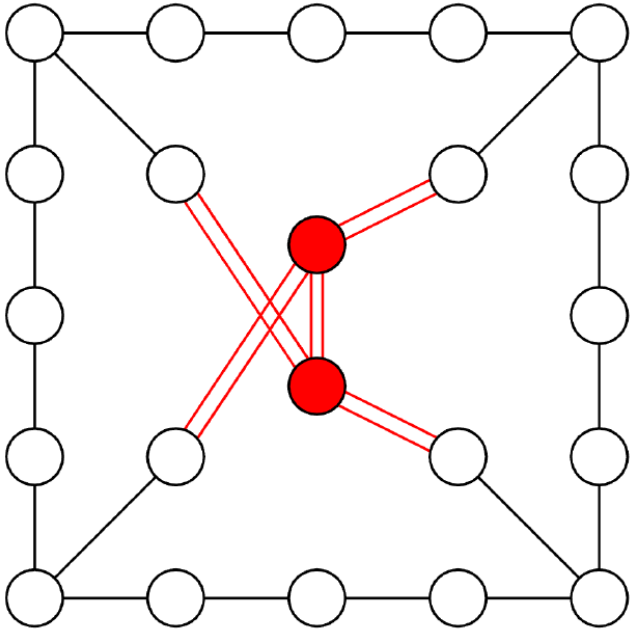

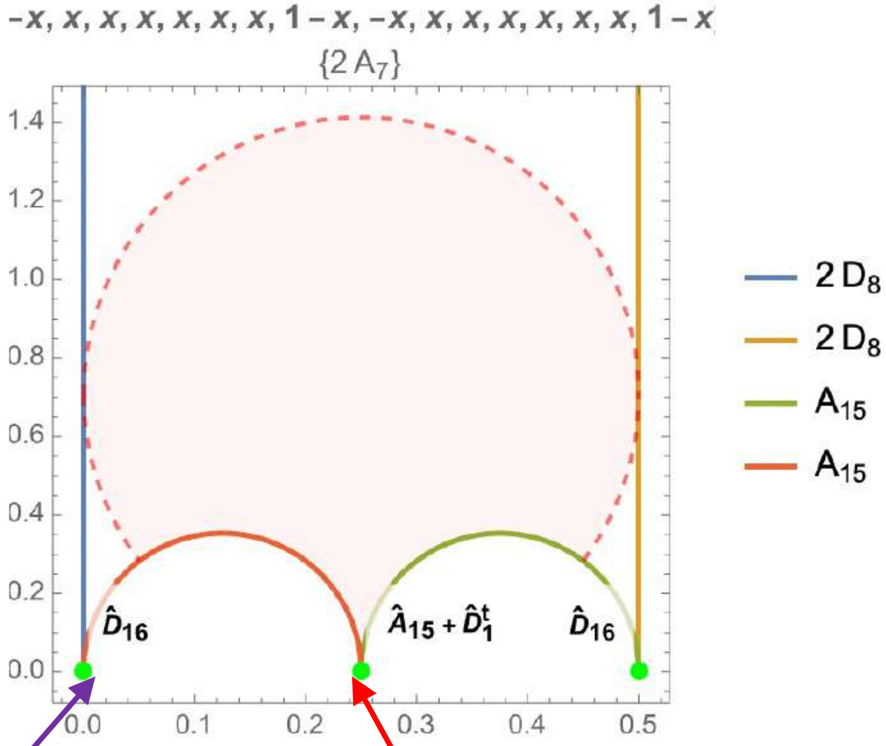

SUSY restoration!

Tachyonic U(16) theory!

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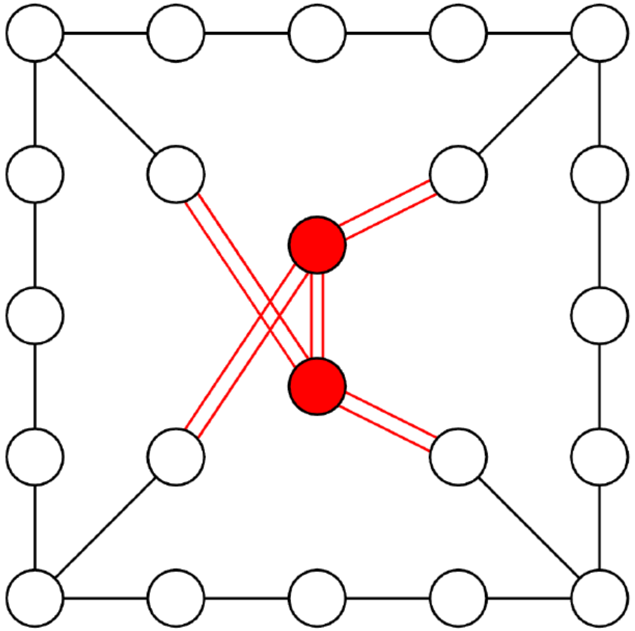
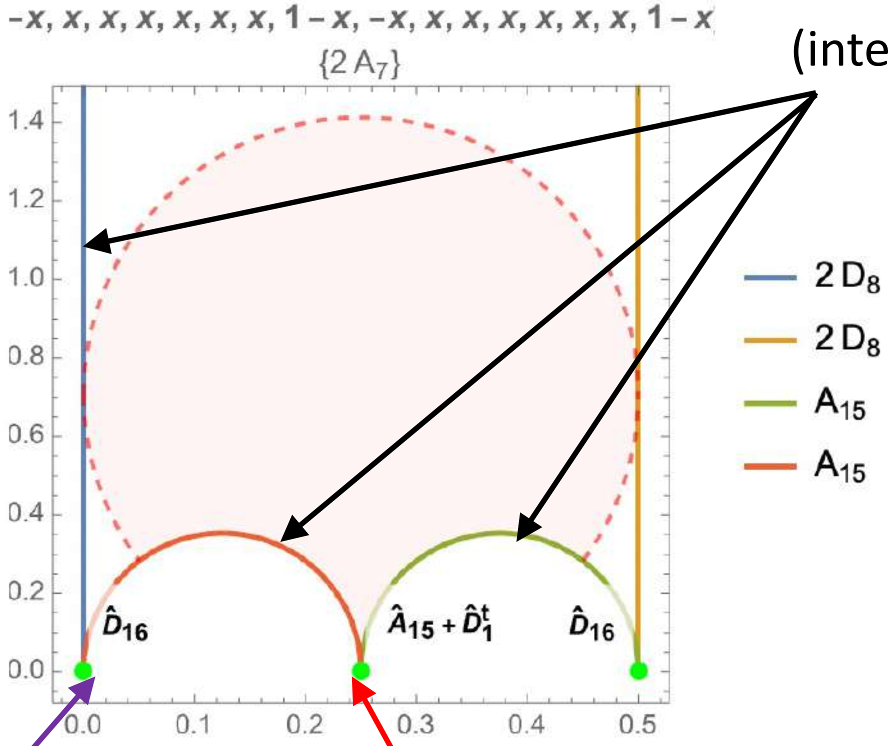


Geodesics
(interpolating models)



Classification and description will appear in [BF, Ruiz, Valenzuela WIP]

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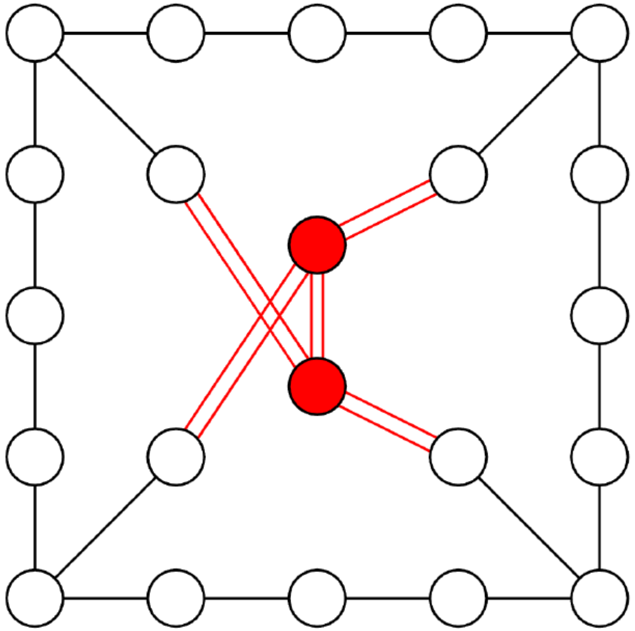

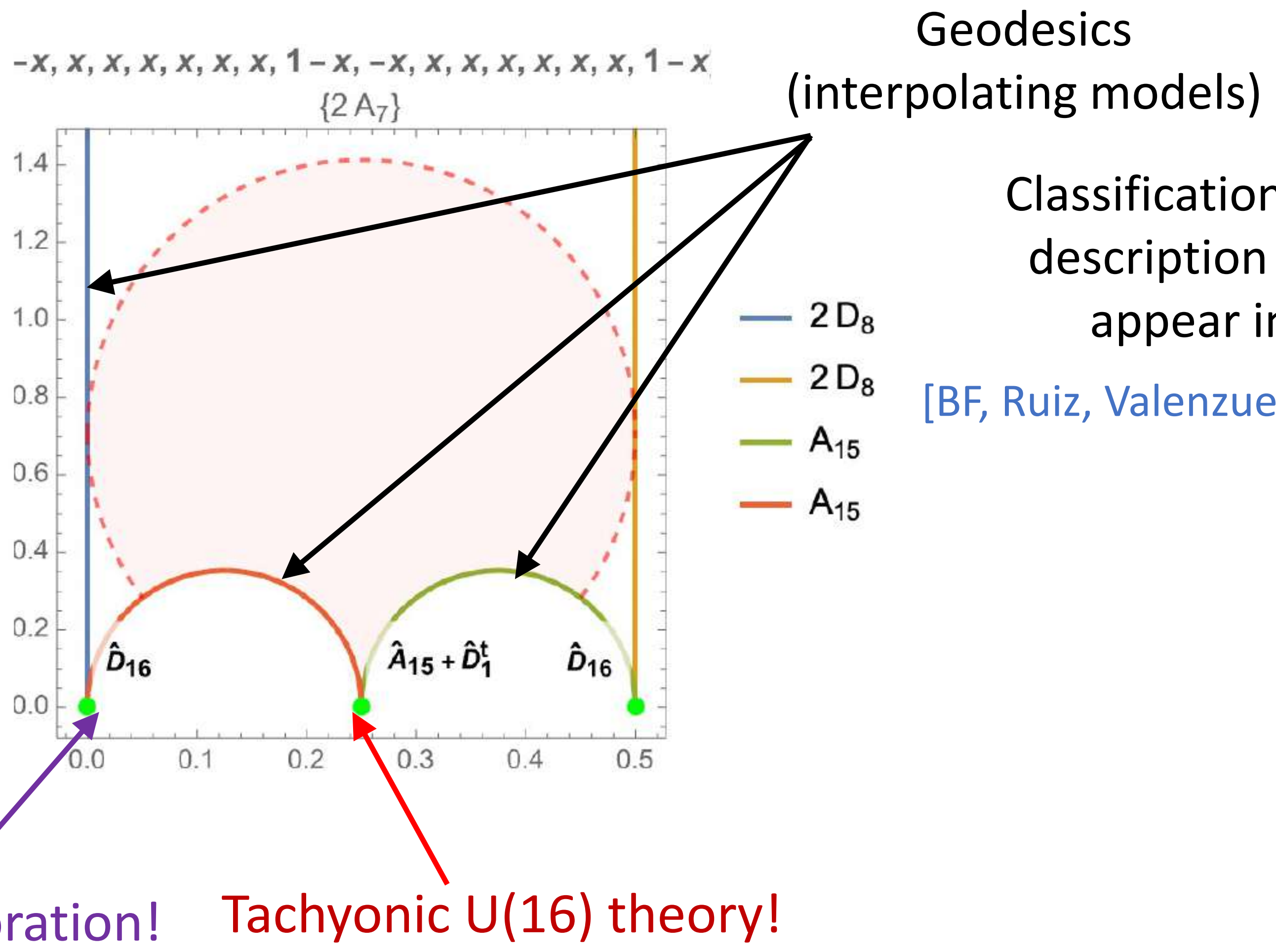

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[BF, Ruiz, Valenzuela WIP]

Equivalence classes of **geodesics** --> **points at infinity**

[Baines, Collazuol, BF, Graña, Waldram]

Veronica Collazuol's talk on Thursday

Rank reduced non-SUSY theories

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Compactifying on torus gives more and more **parameters**

Compactifying on orbifolds gives **less parameters** (compared to full rank)

e.g. CHL string [Chaudhuri, Hockney, Lykken '95]

→ **more likely for stable points to exist!**

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→ **more likely for stable points to exist!**

Systematic SUSY vacua construction carried out long ago [de Boer et al '01]

New non-SUSY theory with reduced rank found [Nakajima '23]

(without generic tachyons)

Can the **SUSY structures** and **properties** be **generalized** to **non-SUSY string compactifications?**

Systematic approach for non-SUSY theories

9D $\boldsymbol{O(16)\times O(16)}$ **non-SUSY string**

10D $\boldsymbol{E_8\times E_8}$ **SUSY string**

SS reduction:
$(-1)^F$ holonomy along some cycle
(breaks SUSY)

[Scherk, Schwarz ‘79]

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9D **CHL SUSY rank reduced string**

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[Scherk, Schwarz '79]

Rank reduction orbifold:
Holonomy (e.g. $\mathbb{Z}_2$) along some cycle, acting on internal CFT (e.g. $E_8 \times E_8 \to E_8$)
(reduces rank of gauge symmetries, reduces number of parameters)

[Chaudhuri, Polchinski '95]

10D $E_8 \times E_8$ SUSY string → 9D $O(16)\times O(16)$ non-SUSY string

→ 9D CHL SUSY rank reduced string

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[Chaudhuri, Polchinski '95]

We combine the two: SUSY **breaking** and rank **reduction**

Many possibilities already in 9D, even more for lower dimensions!

Non-SUSY theories where the rank is reduced by **8:**

- E_8 string $(\mathrm{D} \leq 10) \rightarrow$ Generic tachyons
- B_{IIb} string $(\mathrm{D} \leq 9) \rightarrow$ Some tachyon-free regions, some tachyonic regions
- B_{IIa} string $(\mathrm{D} \leq 9) \rightarrow$ Generic tachyons
- B_{I} string $(\mathrm{D} \leq 8) \rightarrow$ Some tachyon-free regions, some tachyonic regions

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Parameter space: $\frac{\mathrm{O}(8+d,d)}{O(\Gamma_{(8+d,d)}) \times O(8+d) \times O(d)}$, with $\Gamma_{(8+d,d)}$ depending on the theory

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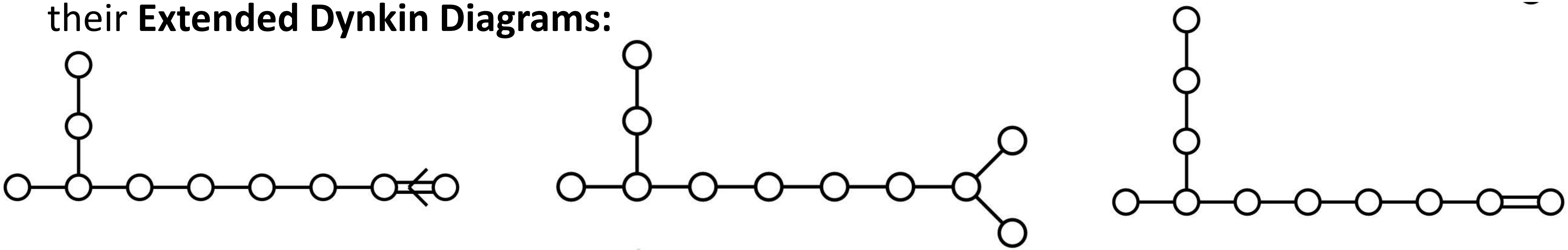
For **9D** we can get all maximal **enhancement** points and their symmetries constructing their **Extended Dynkin Diagrams:**



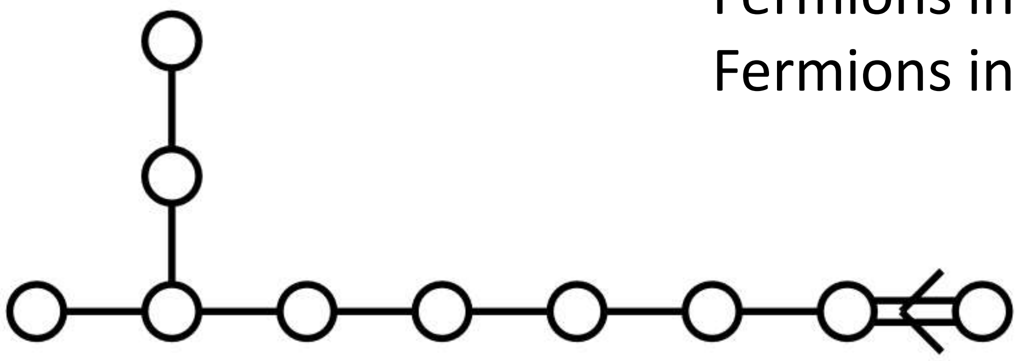
For $\boldsymbol{D \leq 8}$ it is done by finding embeddings in the **charge lattice** and respecting the conditions for the charges imposed by the **holonomies**.

Is the matter content similar to the O(16)xO(16) case?

(Fermions transforming in the spinor or bi-fundamental representatons of the gauge group).

Matter content

$\boldsymbol{E_8}$ theory on a circle (9D)



Gauge bosons with maximal enhancement $E_{8-n} \times Sp(n+1)$,

Fermions in the **adjoint** of E_{8-n}

Fermions in the **antisymmetric traceless** rep. of $Sp(n+1)$

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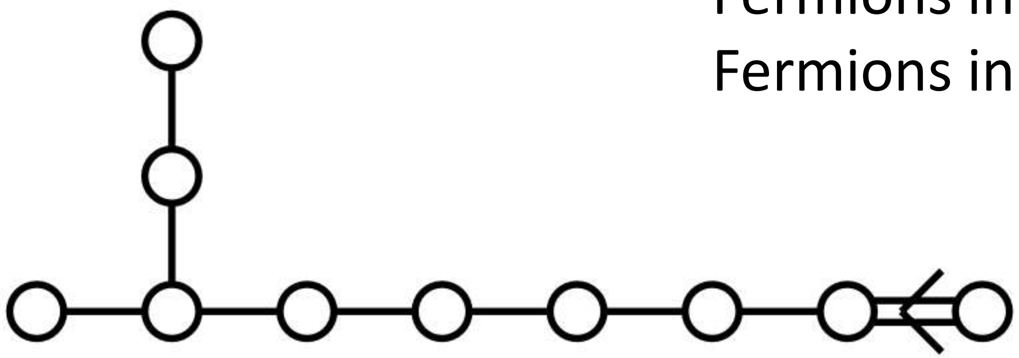
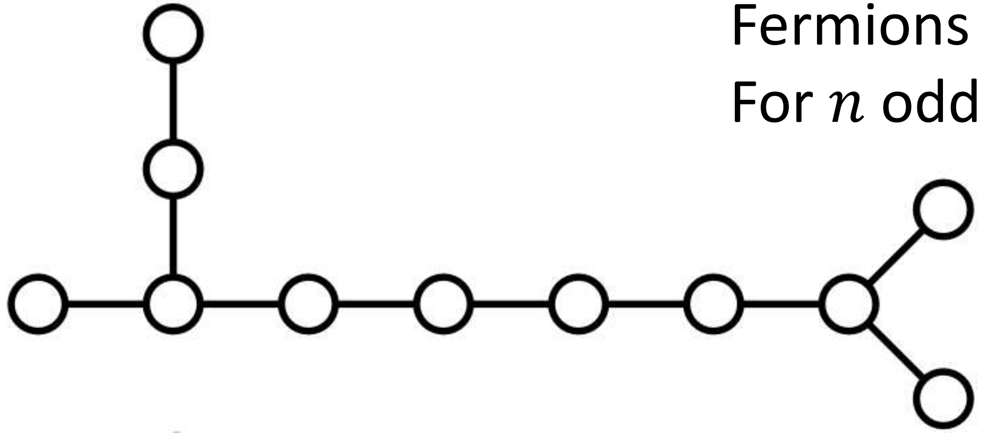
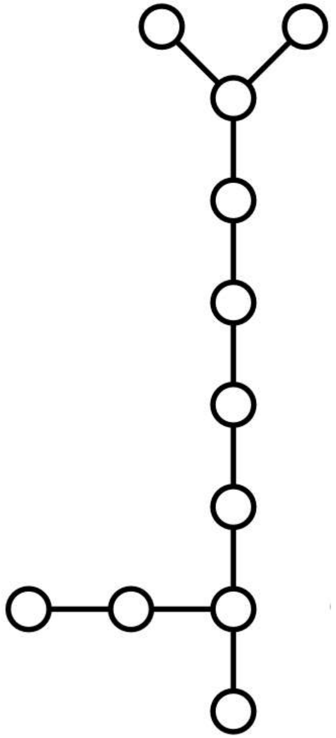


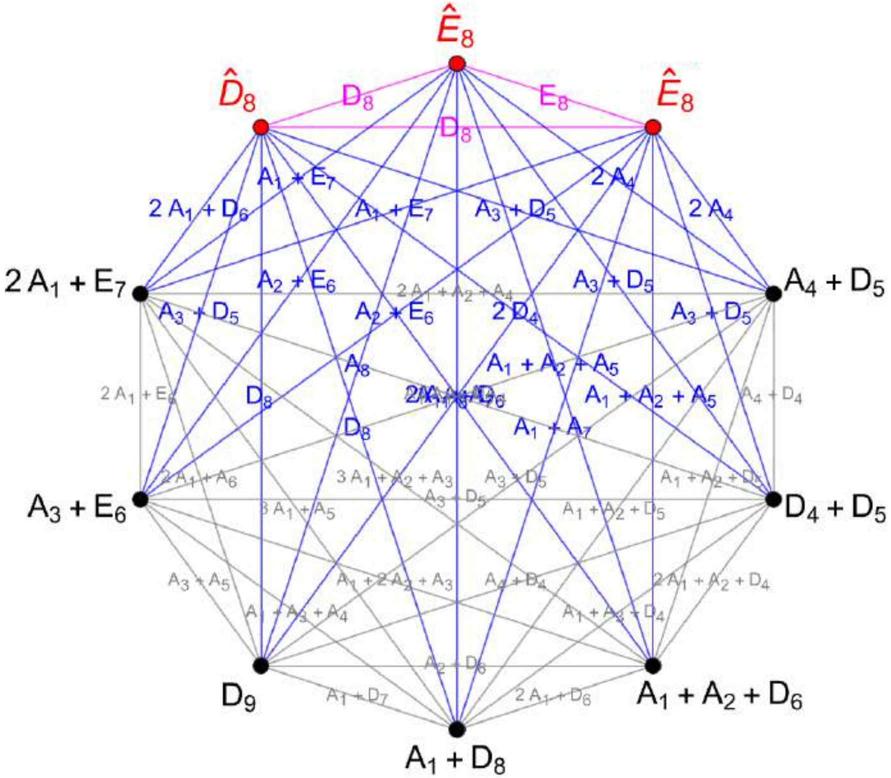
BIIb theory (9D)

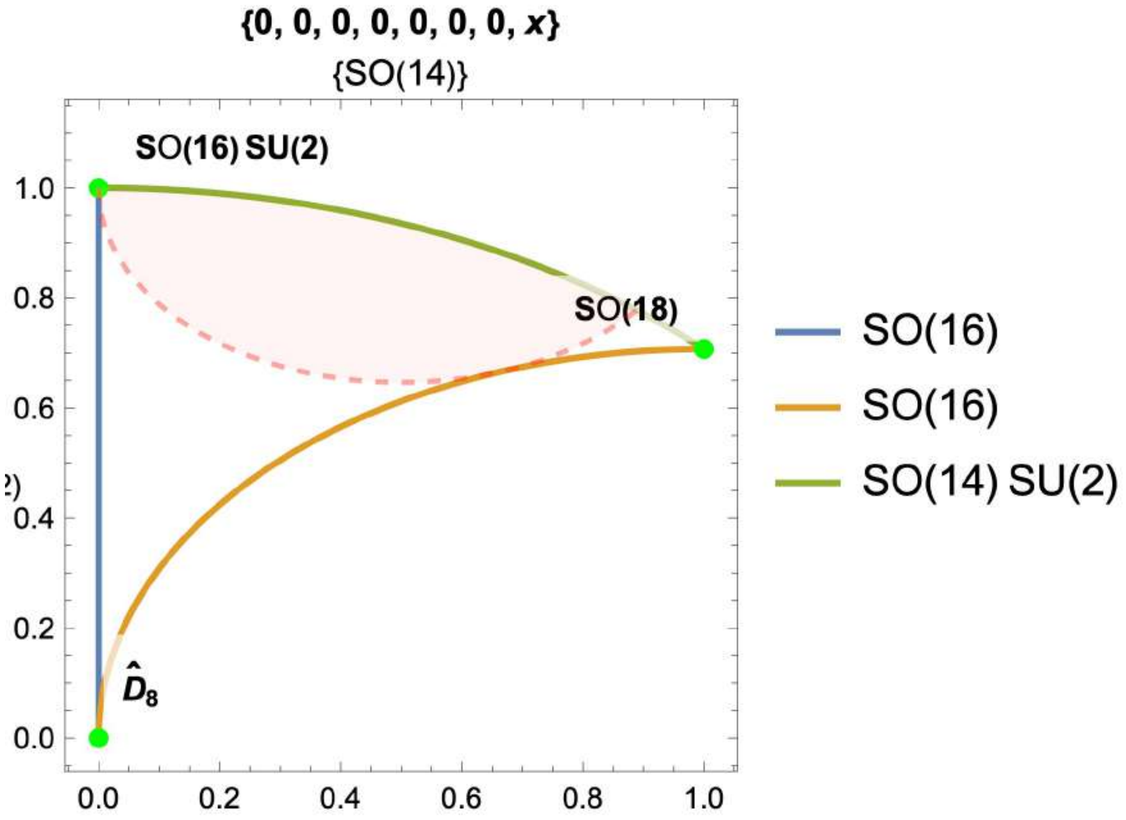
Gauge bosons with maximal enhancement $E_{8-n} \times SO(2n+2)$,
Fermions in the **adjoint** of E_{8-n}
Fermions in the **symmetric traceless** rep. of $SO(2n+2)$
For n odd, there are spinors in some **(bi)fundamental** rep.



B_{IIb} string in 9D:



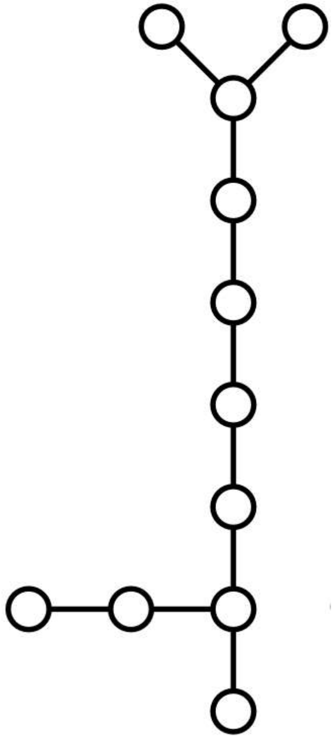


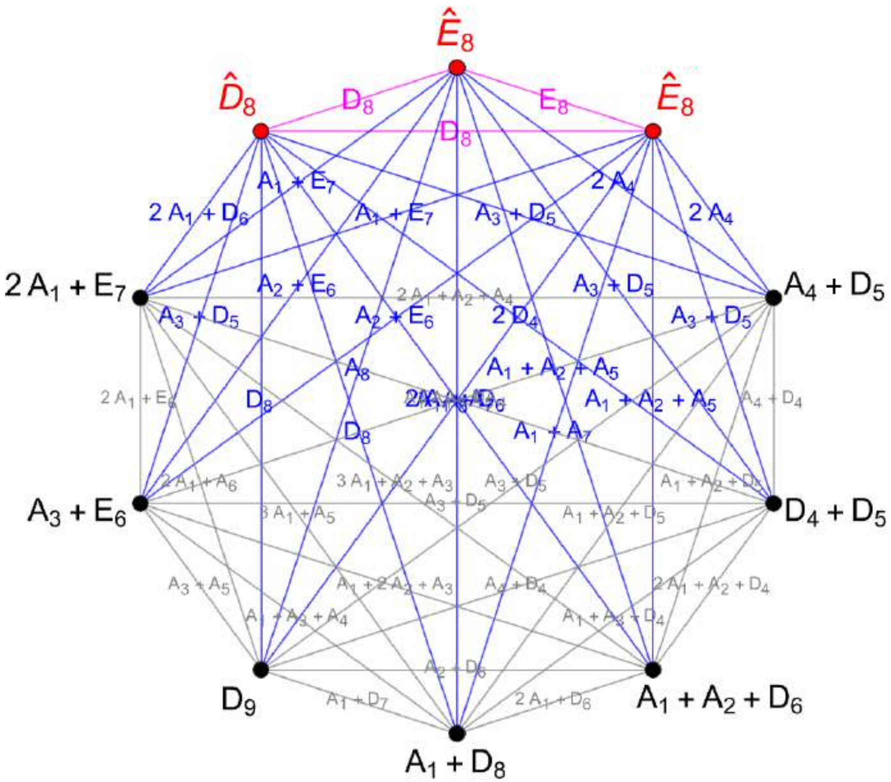


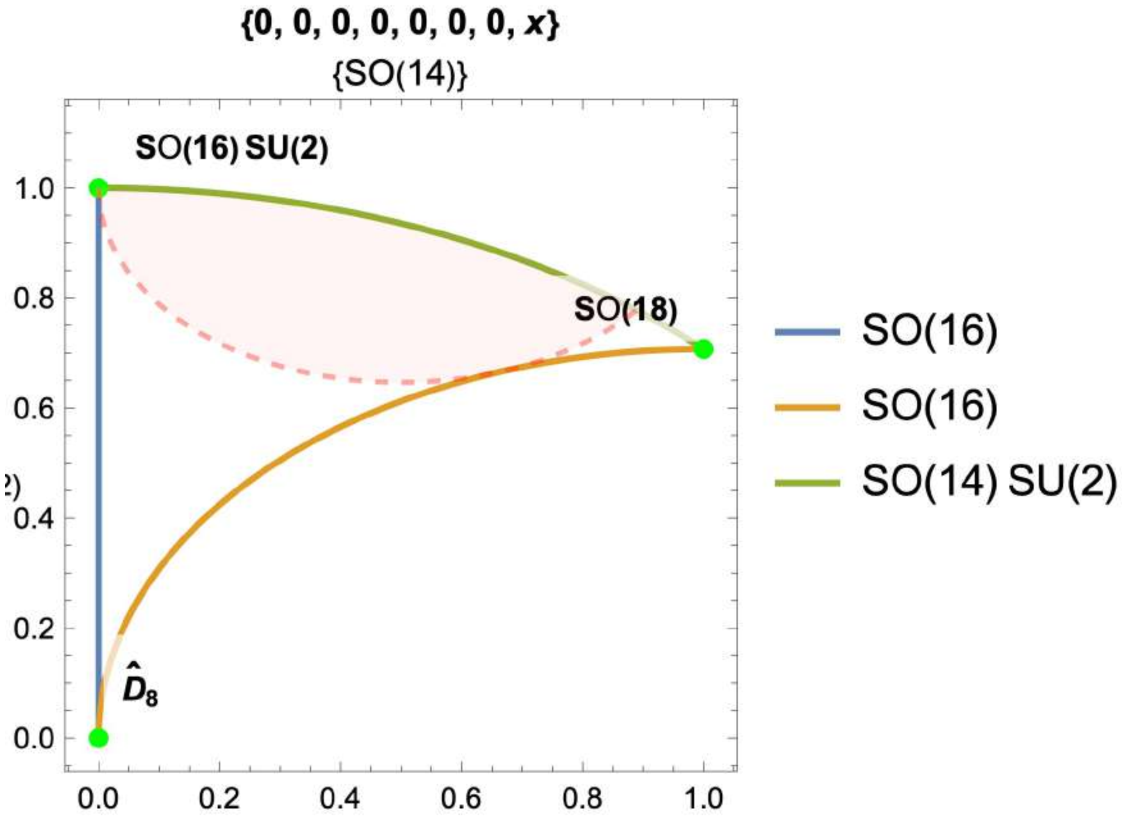
7 maximal enhancements

3 points at infinity. Are the two points with $\hat{E}_8$ equivalent?

B_{IIb} string in 9D:







7 maximal enhancements

3 points at infinity. Are the two points with $\hat{E}_8$ equivalent? → **No!**

10D decomp.:

- **O(16)xO(16)** string
- $\boldsymbol{E_8 \times E_8}$ string
- $\boldsymbol{E_8}$ string

B_{IIb}: One-loop potential

Only **2** tachyon-free maximal enhancements:

- **SO(16) x SU(2)** with $\Lambda \sim 312$ (massless scalars → knife-edge)

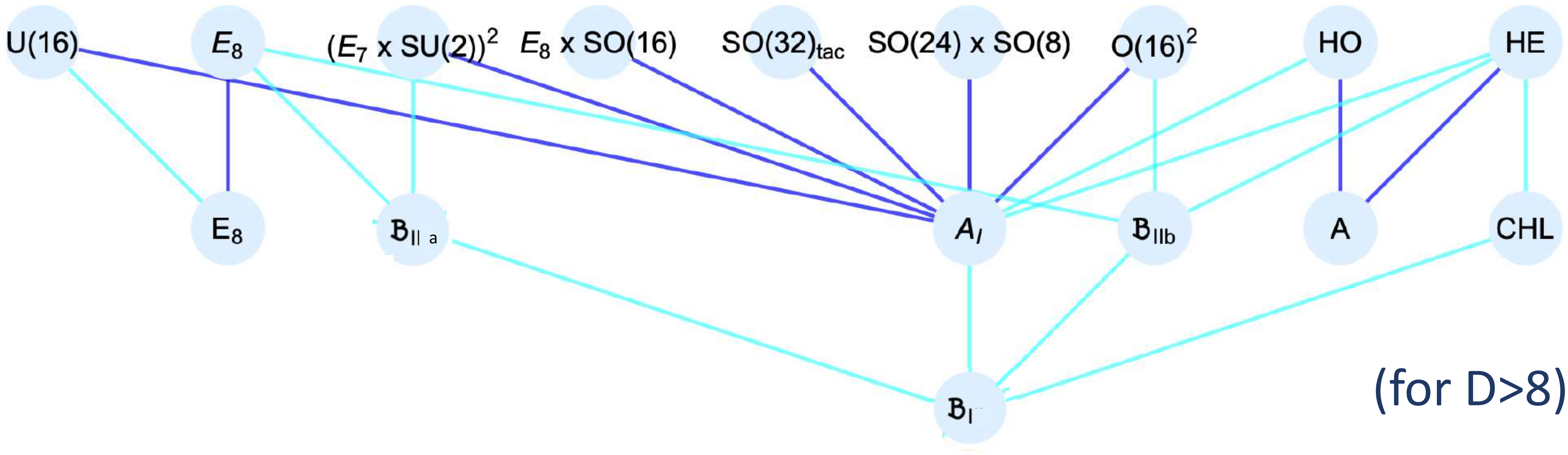
- **SO(18)** with $\Lambda \sim 308$ (no massless scalars)

Same order of magnitude as in 9D O(16)xO(16) string.

No minima, but could be used to **construct stable vacua.**

Many more possibilities when compactifying to lower dimensions.

By analyzing infinite distance limits, we discover connections between new and old theories:



(for D>8)

- T-dual descriptions of same theory.
- Interpolating models connecting higher-dimensional theories

Conclusions and Outlook

- Novel corners in the **non-SUSY** landscape can be reached using **known** and **simple** techniques

- Subset of theories with rank reduced by **8**: interesting features:

→ **symplectic** groups at 10D, fermions transforming in **sym** and **anti-sym traceless rep**.
→ interpolating models, **new** constructions
→ **freezing** relations between full rank SUSY and some of the reduced rank non-SUSY theories [WIP]

- One-loop **potential** behaves similar to the full-rank cases: could be **stabilized**

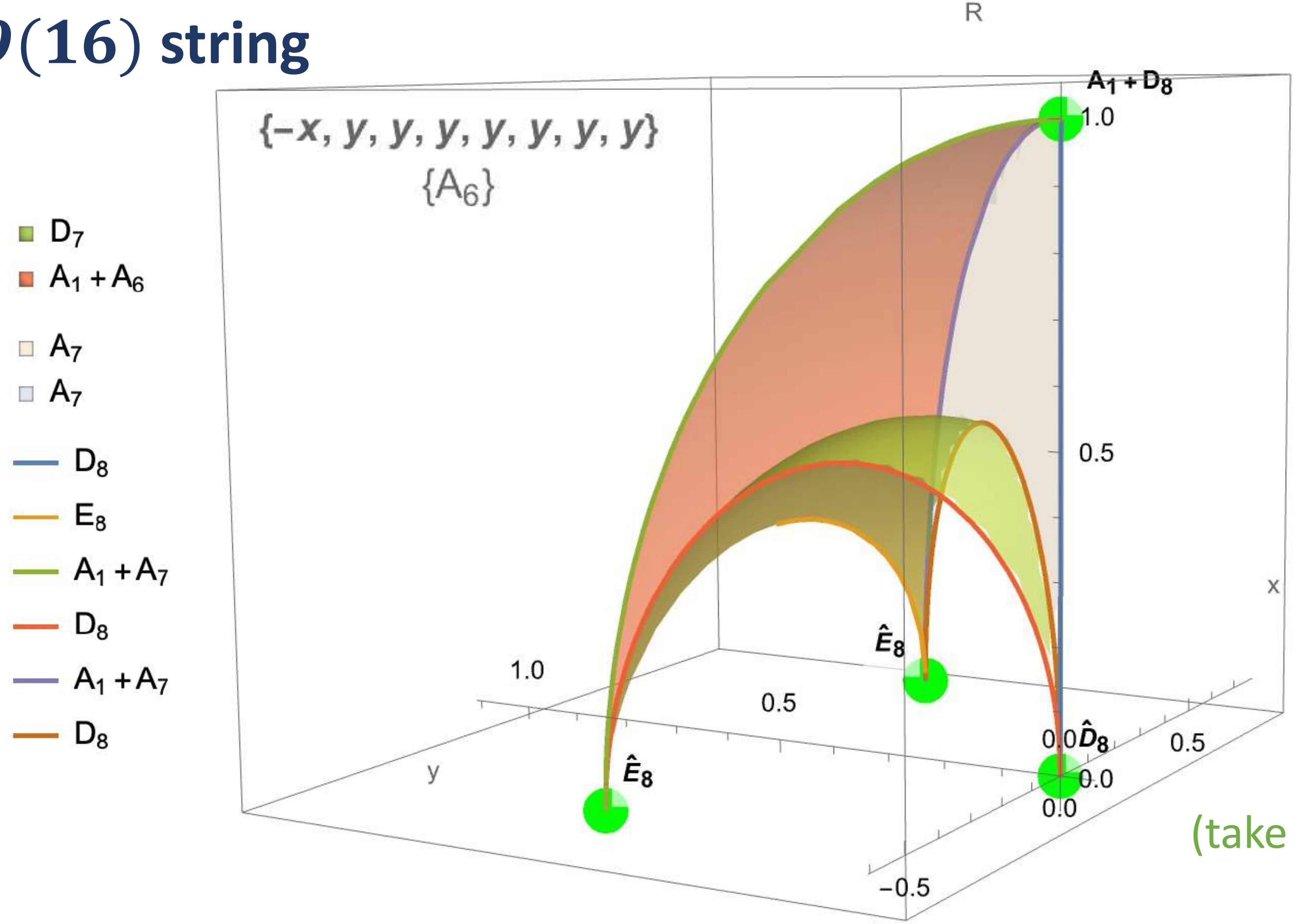
- Structure of **SUSY** landscape → **non-SUSY** counterparts

Grazie mille!

Gauge symmetry	A	N_v	N_s	N_c	N_0	N_t	Λ
$SU(5)\times SO(10)$	$\left(0^3,\frac{1}{5}^4,\frac{4}{5}\right)$	76	78	0	0	30	-∞
$SO(8)\times SO(10)$	$\left(0^4,\frac{1}{4}^3,\frac{3}{4}\right)$	80	80	80	0	16	-∞
$SU(2)\times SU(3)\times SO(12)$	$\left(0^2,\frac{1}{6}^5,\frac{5}{6}\right)$	84	88	64	0	52	-∞
$SU(2)\times SO(16)$	$\left(\frac{1}{8}^7,-\frac{7}{8}\right)$	130	138	128	128	0	312
$SO(18)$	$\left(\frac{1}{6}^7,\frac{5}{6}\right)$	160	170	0	0	0	308
$E_6\times SU(4)$	$\left(0^5,\frac{1}{3}^2,\frac{2}{3}\right)$	100	98	0	0	8	-∞
$E_7\times SU(2)^2$	$\left(0^6,\frac{1}{2}^2\right)$	146	142	112	224	4	-∞
$E_8\times SO(2)$	$\left(0^8\right)$	256	250	0	0	2	-∞

$R=\sqrt{1-A^2}$, Λ in units of $(4\pi^2\alpha')^{-\frac{9}{2}}$

$\boldsymbol{O(16)}$ string



Decomp. limits to 10D:

- **O(16)xO(16)** string
- $\boldsymbol{E_8 \times E_8}$ string
- $\boldsymbol{E_8}$ string

(take limit on partition function)

O(16)xO(16) on $\mathbb{Z}_2$-orbifold $\equiv$ HE on asym. orbifold $\equiv$ E_8 on asym. orbifold

CHL string can be obtained as the HE compactified on S^1 with the $\mathbb{Z}_2$ holonomy: $\begin{cases} R: & E_8 \times E_8' \to E_8' \times E_8 \\ T: & x^9 \to x^9 + \pi R \end{cases}$

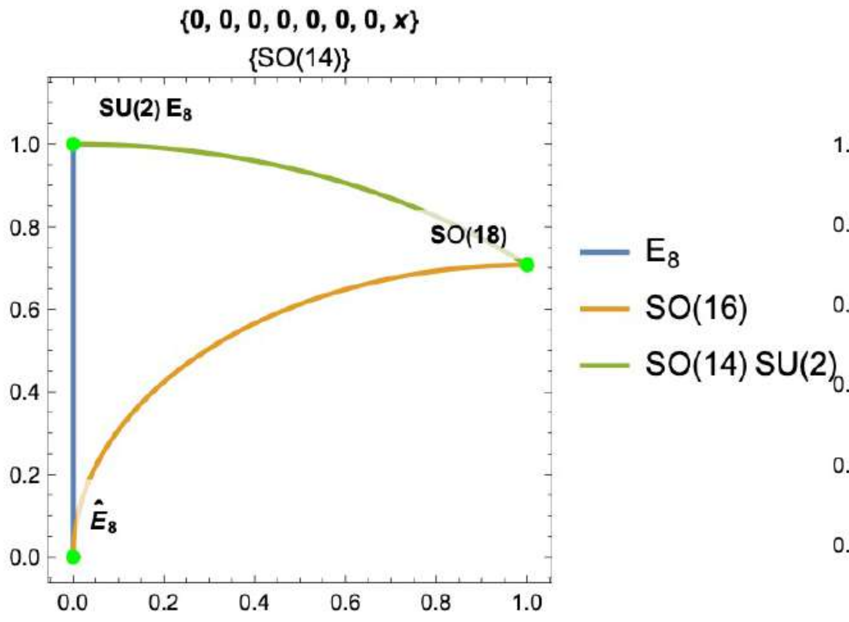
$|\varphi\rangle_{\text{untwisted}} = \frac{|w,n,\pi,\pi'\rangle + (-1)^n |w,n,\pi',\pi\rangle}{\sqrt{2}}$

$|\varphi\rangle_{\text{twisted}} = \left|w + \frac{1}{2}, n, \frac{\pi}{2}, \frac{\pi}{2}\right\rangle$

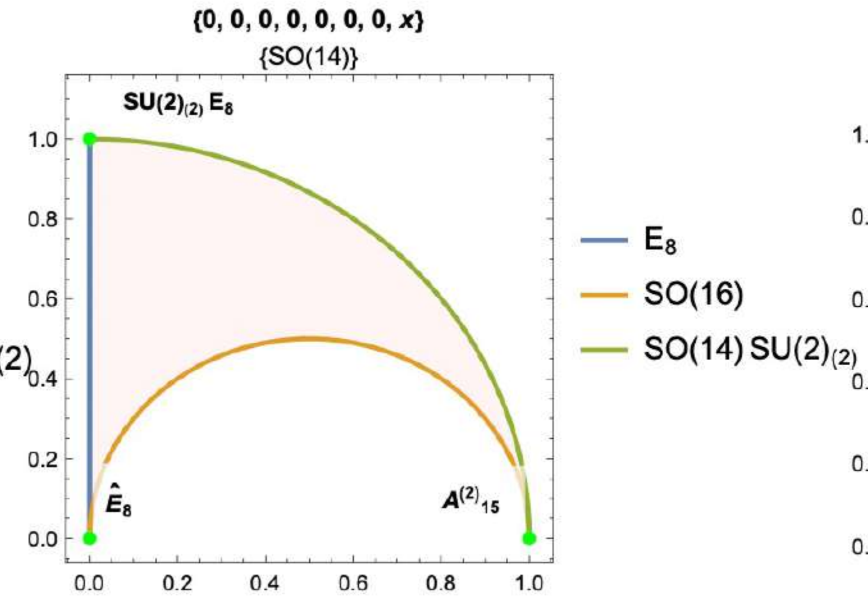
$\mathcal{B}_{IIb}$ **string** can be obtained as the $O(16) \times O(16)$ compactified on S^1 with the $\mathbb{Z}_2$ holonomy: $\begin{cases} R: & SO(16) \times SO(16)' \to SO(16)' \times SO(16) \\ T: & x^9 \to x^9 + \pi R \end{cases}$

$|\varphi\rangle_{\text{untwisted}} = \frac{|w,n,\pi,\pi'\rangle \pm (-1)^n |w,n,\pi',\pi\rangle}{\sqrt{2}}$ with $+$ $(-)$ for gauge bosons (spinors).

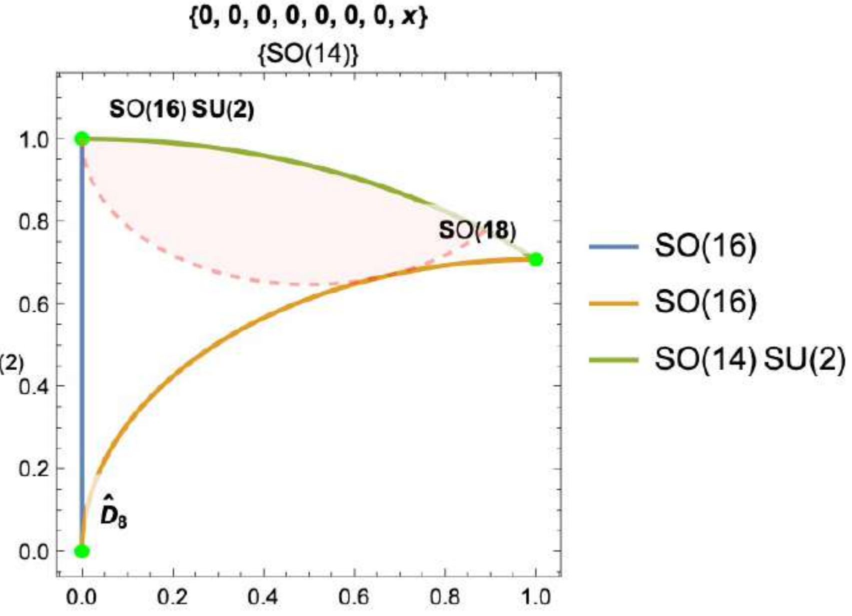
$|\varphi\rangle_{\text{twisted}} = \left|w + \frac{1}{2}, n, \frac{\pi}{2}, \frac{\pi}{2}\right\rangle$ for scalars and co-spinors.



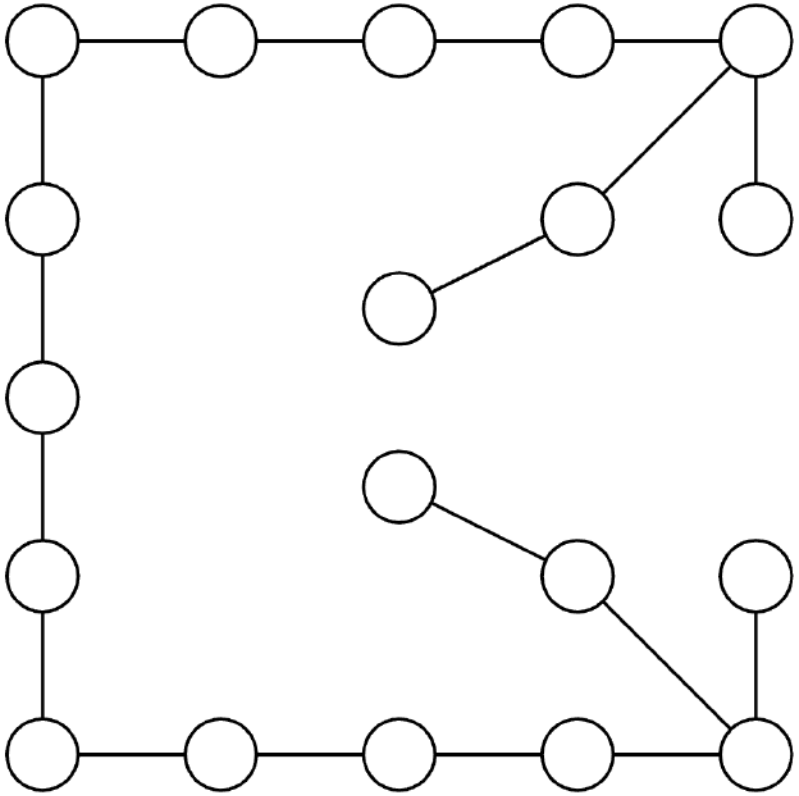
CHL

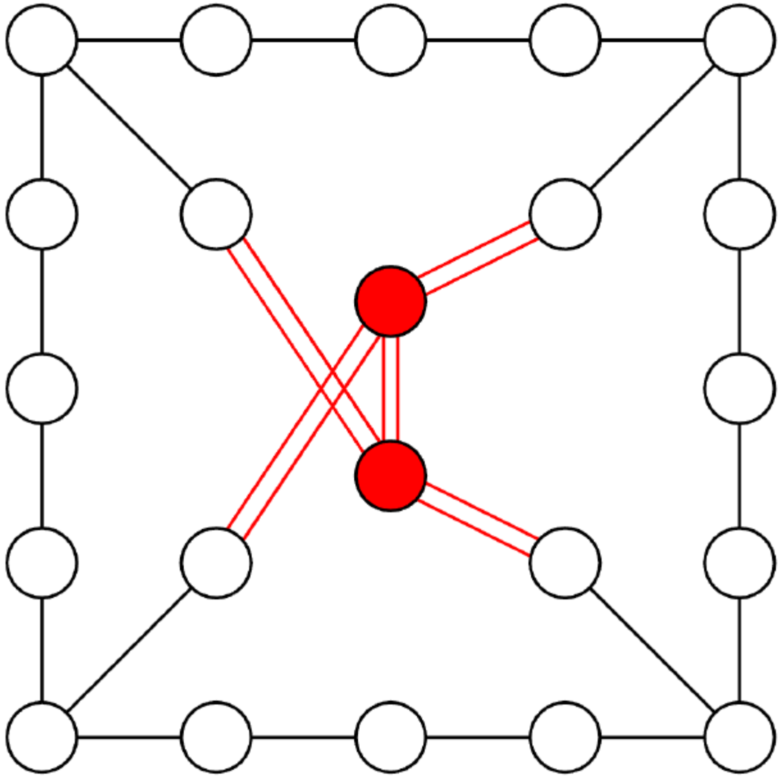


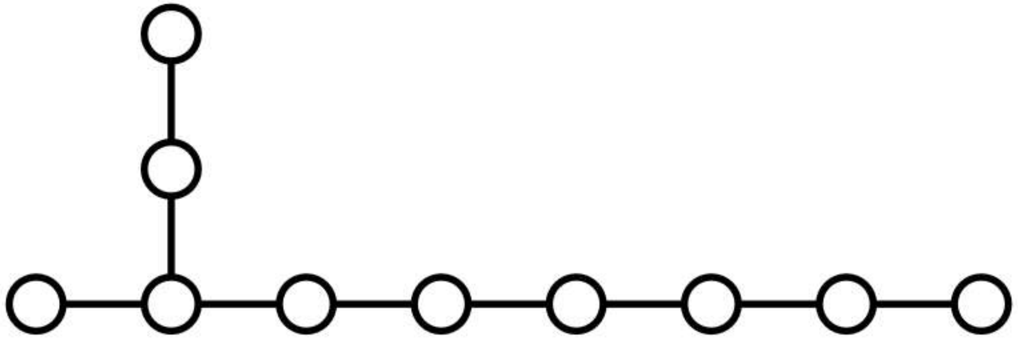
E_8

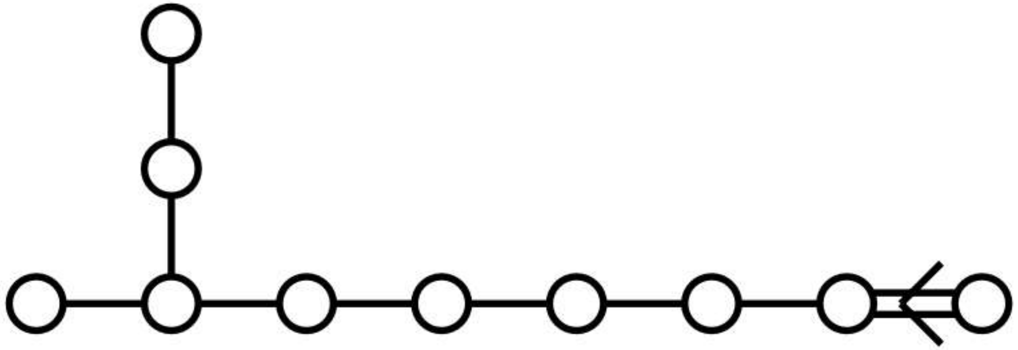


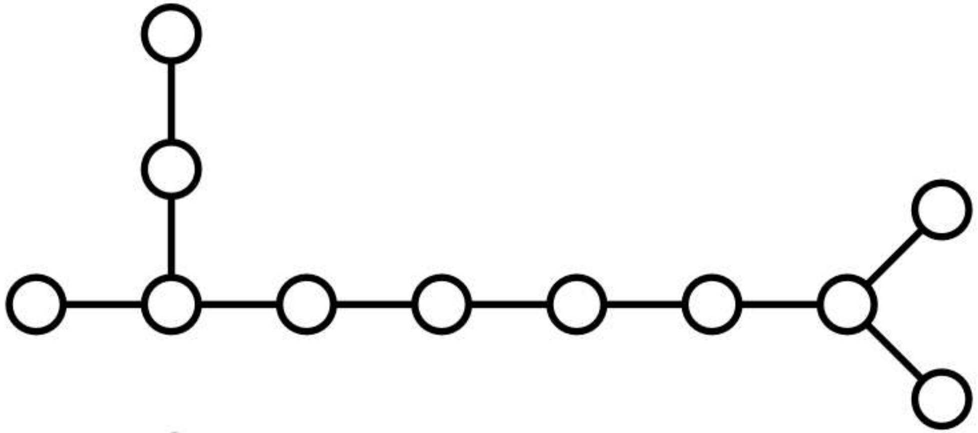
$\mathcal{B}_{IIb}$

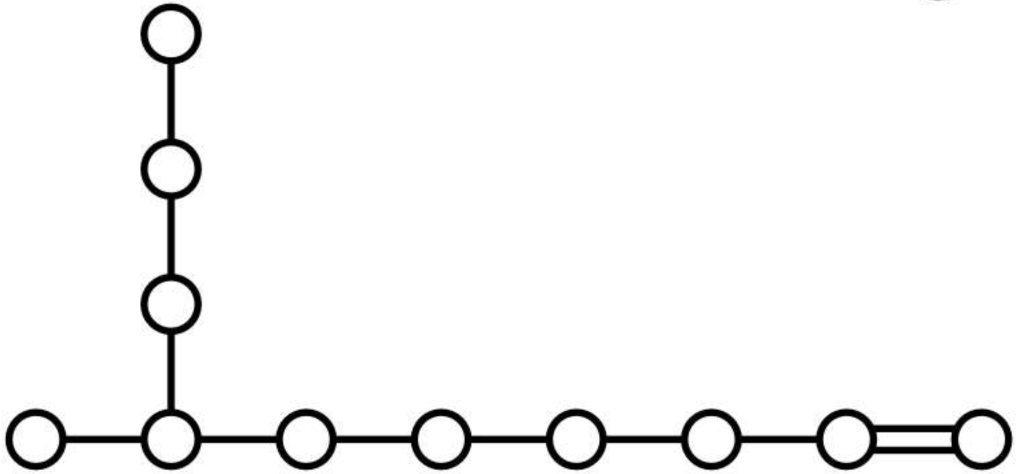






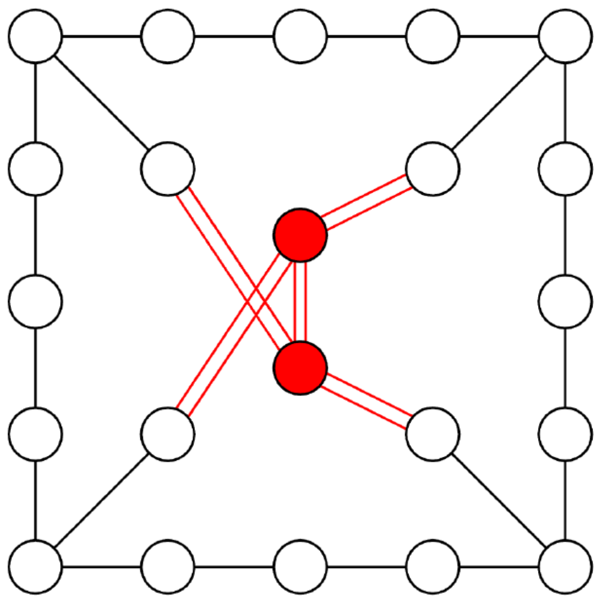


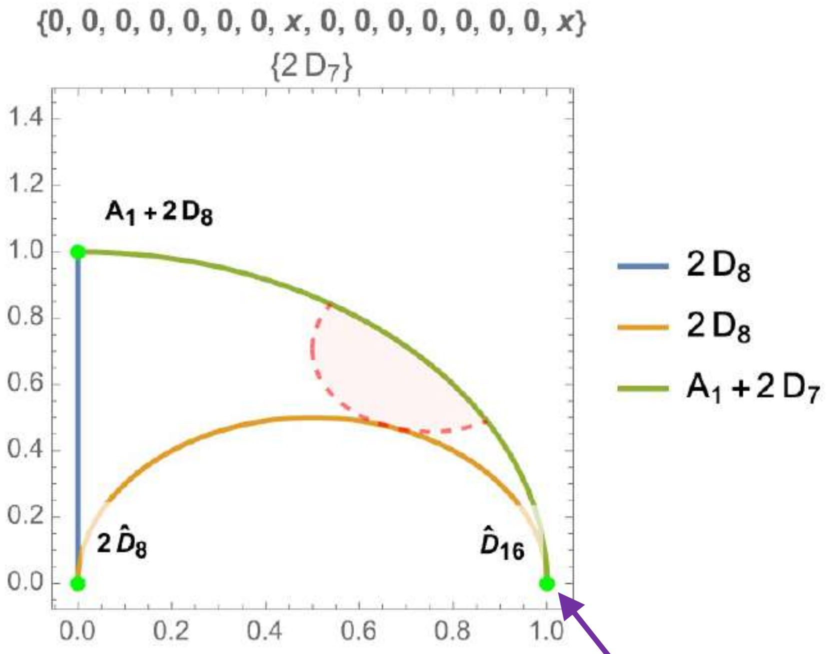


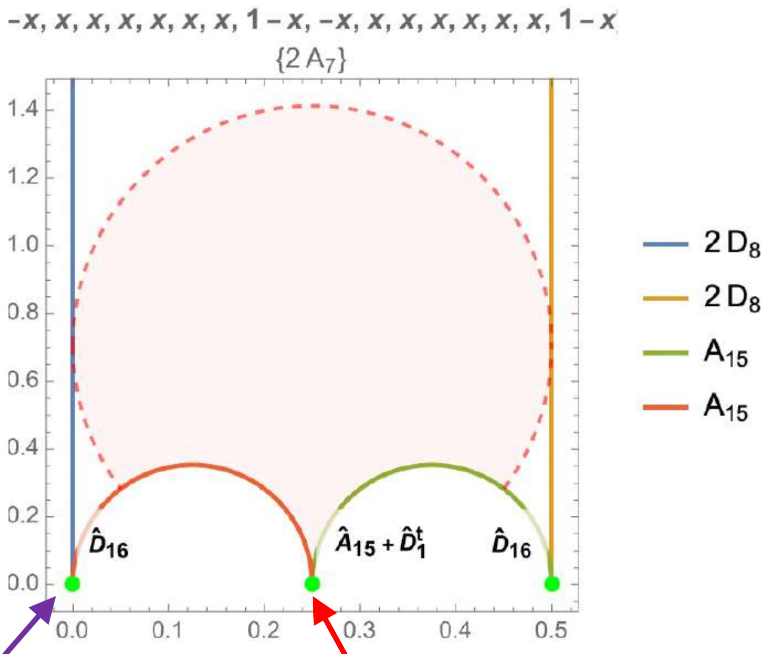


Infinite distance limits

8 points at infinity (**decompactification** limits to all the rank 16 10D strings)







SUSY restoration!

Tachyonic U(16) theory!

WL	v	s	c	0
$\left(0^{16}\right)$	$[A_1 + 2D_8\,;\mathbb{Z}_2]$	$(1,128,1)$ $(1,1,128)$	$(1,16,16)$	none
$\left(\frac{1}{2}^2, 0^{14}\right)$	$[A_1 + A_2 + D_6 + D_8\,;\mathbb{Z}_2]$	$(2,1,32,1)$ $(1,1,1,128)$	(1,1,12,16)	none
$\left(\frac{1}{2}^3, 0^{13}\right)$	$A_4 + D_5 + D_8$	(1,1,128)	(1,10,16)	none
$\left(\frac{1}{2}^3, 0^5, \frac{1}{2}^3, 0^5\right)$	$[A_7 + 2D_5\,;\mathbb{Z}_4]$	none	$(1,10,10)$ $(70,1,1)$	none
$\left(1, 0^{15}\right)$	$D_8 + D_9$	(1,128)	(16,18)	$(128,1) \times 2$
$\left(\frac{1}{2}^4, 0^{12}\right)$	$[D_4 + D_5 + D_8\,;\mathbb{Z}_2]$	$(1,1,128)$ $(8,10,1)$	(8,1,16)	$(8,16,1) \times 2$
$\left(\frac{1}{2}^2, 0^6, \frac{1}{2}^2, 0^6\right)$	$[2A_1 + A_3 + 2D_6\,;\mathbb{Z}_2^2]$	$(2,1,1,32,1)$ $(1,2,1,1,32)$	$(1,1,1,12,12)$ $(2,2,6,1,1)$	$(2,1,1,32,1) \times 2$ $(1,2,1,1,32) \times 2$
$\left(\frac{1}{2}^5, 0^3, \frac{1}{4}^7, \text{-}\frac{1}{4}\right)$	$[A_{11} + E_6\,;\mathbb{Z}_3]$	none	none	$(143,1) \times 2$ $(1,78) \times 2$

Maximal enhancements

Group	R^2	Wilson line	Λ	$\lambda(H_\Lambda) \times R^2$
$\left[Spin(16)^2\right]/\mathbb{Z}_2 \times SU(2)$	1	0^{16}	431.354	$\text{-}306^{16}, 831$
$\left[Spin(16) \times Spin(12) \times SU(2)\right]/\mathbb{Z}_2 \times SU(3)$	$\frac{3}{4}$	$0^{14}, \frac{1}{2}^{2}$	383.516	$\text{-}307^{15}, 544^{2}$
$Spin(16) \times Spin(10) \times SU(5)$	$\frac{5}{8}$	$0^{13}, \frac{1}{2}^{3}$	359.196	$\text{-}569^{5}, \text{-}256^{8}, 355^{4}$
$\left[Spin(10)^2 \times SU(8)\right]/\mathbb{Z}_4$	$\frac{1}{4}$	$0^{4}, \frac{1}{2}^{4}, \frac{1}{4}^{8}$	303.778	$\text{-}195^{17}$
$Spin(18) \times Spin(16)$	$\frac{1}{2}$	$0^{15}, 1$	305.013	$\text{-}1283^{8}, 588^{9}$
$\left[Spin(16) \times Spin(10) \times Spin(8)\right]/\mathbb{Z}_2$	$\frac{1}{2}$	$0^{12}, \frac{1}{2}^{4}$	305.013	$\text{-}1283^{4}, \text{-}347^{8}, 588^{5}$
$\left[Spin(12)^2 \times SU(4) \times SU(2)^2\right]/\mathbb{Z}_2^2$	$\frac{1}{2}$	$0^{6}, \frac{1}{2}^{2}, 0^{6}, \frac{1}{2}^{2}$	305.013	$\text{-}1283^{2}, \text{-}347^{12}, 588^{3}$
$\left[E_6 \times SU(12)\right]/\mathbb{Z}_3$	$\frac{1}{8}$	$0^{3}, \frac{1}{2}^{5}, \text{-}\frac{1}{4}, \frac{1}{4}^{7}$	180.426	$\text{-}72^{17}$