Non-supersymmetric heterotic strings: gauge symmetry enhancement and one-loop cosmological constant in toroidal compactifications

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Work in collaboration with

Bernardo Fraiman, Hector Parra De Freitas, Savdeep Sethi

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see also Bernardo's talk on Thursday

String phenomenology 2023, Daejeon

Motivation Non-SUSY O(16) x O(16) heterotic string

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- Here we'll look at T^d compactifications (and in particular S^1)

Motivation for T^d compactifications

- Rich phenomenon of gauge symmetry enhancement at special points in mod space

  -for SUSY heterotic: full classification of gauge symmetries for $d \leq 4$

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- Same for non SUSY?

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- Local minima, maxima or saddle points?

Non-susy heterotic string: bosonic formulation

- Start from the $E_8 \times E_8$ (susy) heterotic $\pi \in \Gamma_8 \oplus \Gamma_8$ heterotic momenta

- quotient by $\beta = \underset{\overset{\uparrow}{\text{R}}}{\overset{\overset{\text{NS}}{\downarrow}}{\pm}} (-1)^{2\,\pi \cdot \delta}$

(breaks susy)

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- add twisted sector

R: $\Gamma^+ + \delta = \{(v;v),(c;c)\}$

NS: $\Gamma^- + \delta = \{(v;c),(c;v)\}$

Non-susy heterotic string

- Four sectors

  - untwisted sectors $\Gamma_v = \Gamma^+ = \{(0;0),(s;s)\}$

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All 6 non-susy heterotic theories (of rank 16) are dual upon circle compactification!

Ginsparg, Vafa 87

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$$p_{L,16} = \pi + A\omega$$

$$p_L = \frac{1}{\sqrt{2}R}\left[n - \left(-R^2 + \tfrac{1}{2}A^2\right)\omega - \pi \cdot A\right]$$

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- Massless states (with $P \neq 0$)

$P_L^2 = 2\,;\, p_R^2 = 0\,,$	$\bar{N} = \frac{1}{2}$	NS sector	$P \in \Gamma_v$	gauge fields
	$\bar{N} = 0$	R sector	$P \in \Gamma_s$	"gauginos" (spinors of pos chirality)
$P_L^2 = 2\,;\, p_R^2 = 0\,,$	$\bar{N} = 0$	R sector	$P \in \Gamma_c$	spinors of negative chirality

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gauge fields

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scalars

Compactifications on S^1

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$N = 1\,, P_L^2 = 0\,;\, p_R^2 = 1\,,\quad \bar{N} = 0$ NS sector $\quad P \in \Gamma_0$ right-moving vectors

Compactifications on S^1

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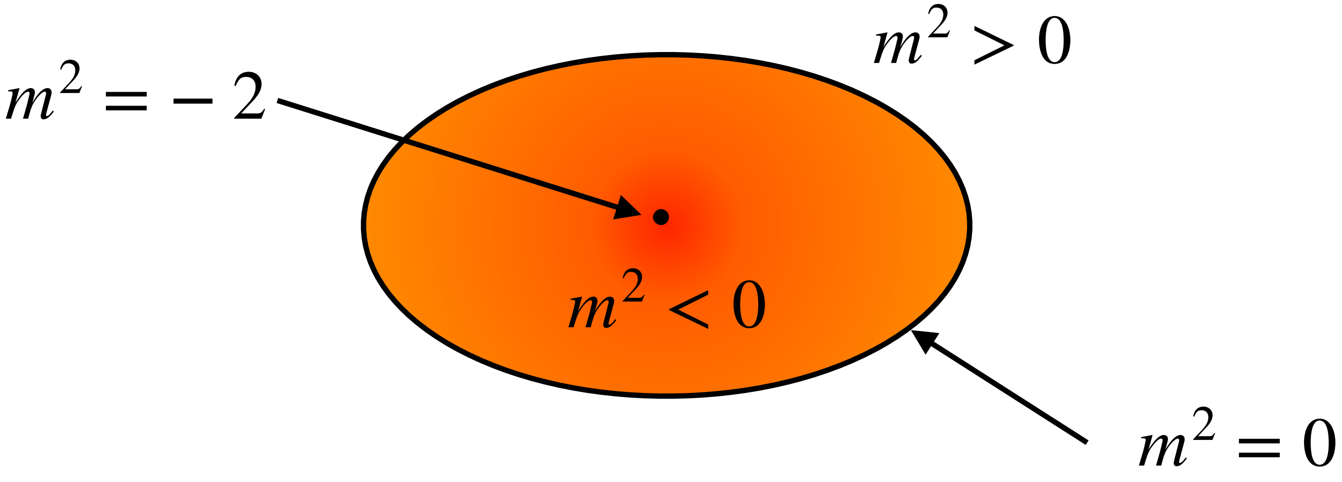
- Tachyons!

  - a region of moduli space has tachyons if there are states in Γ_0:

$$P_L^2 = 1 + p_R^2 \ ; \quad 0 \leq p_R^2 < 1 \qquad\qquad m^2 = -2\,(1 - p_R^2)$$



Gauge symmetry enhancement

- Untwisted + twisted massless states

$$p_R = 0 \Rightarrow n = \left(R^2+\tfrac{1}{2}A^2\right)\omega + \pi \cdot A \in \mathbb{Z}$$

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generic A generic R	$U(1)_L^8 \times U(1)_L^8 \times U(1)_L \times U(1)_R$ no spinors (twisted or untwisted), no massless scalars
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Gauge symmetry enhancement

- Untwisted + twisted massless states $p_R = 0 \Rightarrow n = \left(R^2 + \frac{1}{2}A^2\right)\omega + \pi \cdot A \in \mathbb{Z}$

generic A generic R	$U(1)_L^8 \times U(1)_L^8 \times U(1)_L \times U(1)_R$ no spinors (twisted or untwisted), no massless scalars
rational A generic R	$G_1 \times U(1)_L^{8-k_1} \times G_2 \times U(1)_L^{8-k_2} \times U(1)_L \times U(1)_R$ $\quad G_1, G_2 \subseteq SO(16)$ ADE maybe $\left\{\begin{array}{l}\text{pos. chirality spinors in (spinor,1) of some factor of } G_1, G_2 \\ \text{negative chirality spinors in (fund, spinor)}\end{array}\right.$ no massless scalars
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rational A rational R^2	$G \times U(1)^{17-k}_L \times U(1)_R$ maybe { more positive chirality spinors more negative chirality spinors massless scalars	$G_1 \times G_2 \subseteq G$, ADE

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may be: tachyons in all situations

Maximal (G : rank 17) enhancements

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- 107 in total

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L
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$SO(16) \times SO(10) \times SU(5)$
$SO(10) \times SO(10) \times SU(8)$
$SO(16) \times SO(18)$
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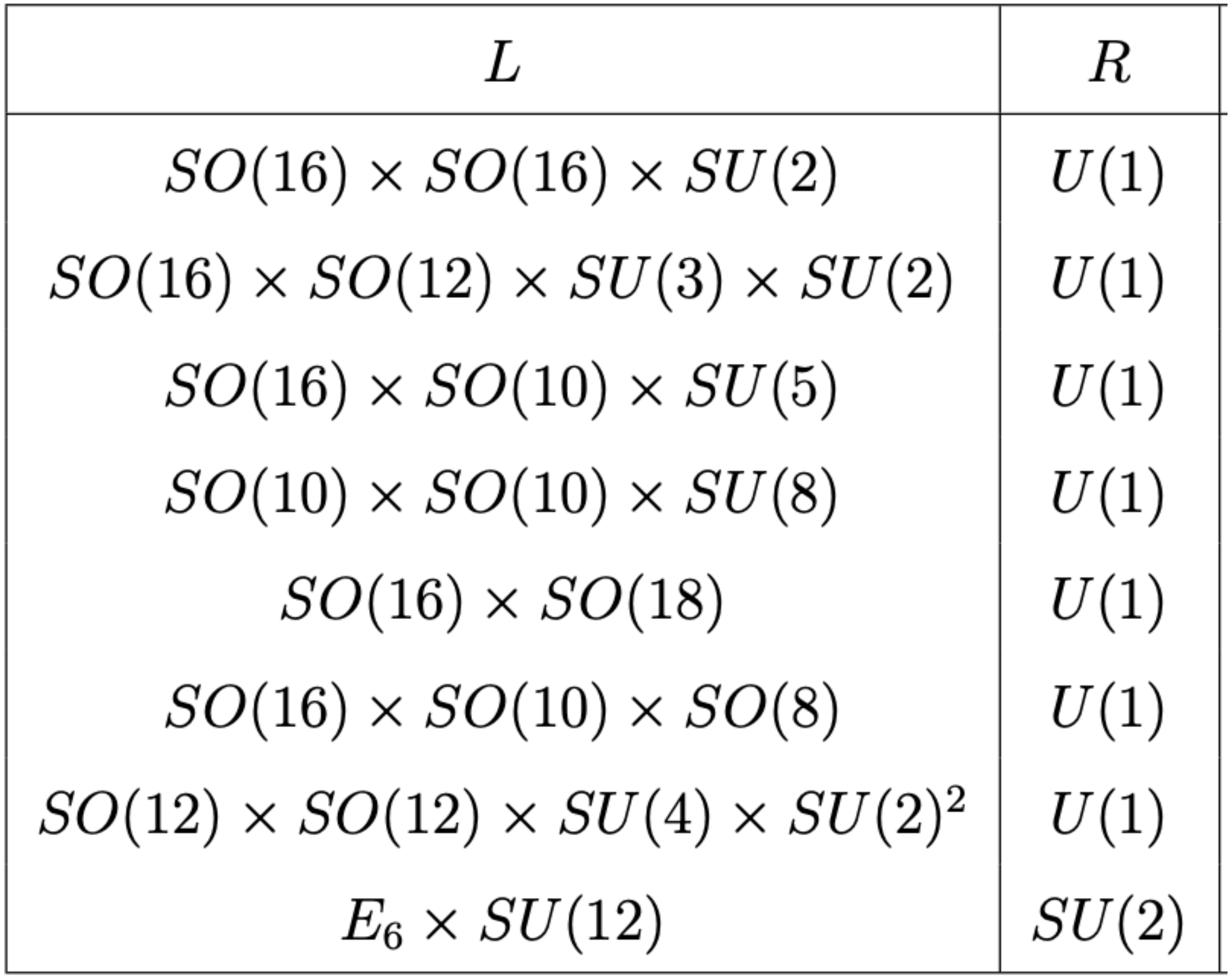

L	R
$SO(16) \times SO(16) \times SU(2)$	$U(1)$
$SO(16) \times SO(12) \times SU(3) \times SU(2)$	$U(1)$
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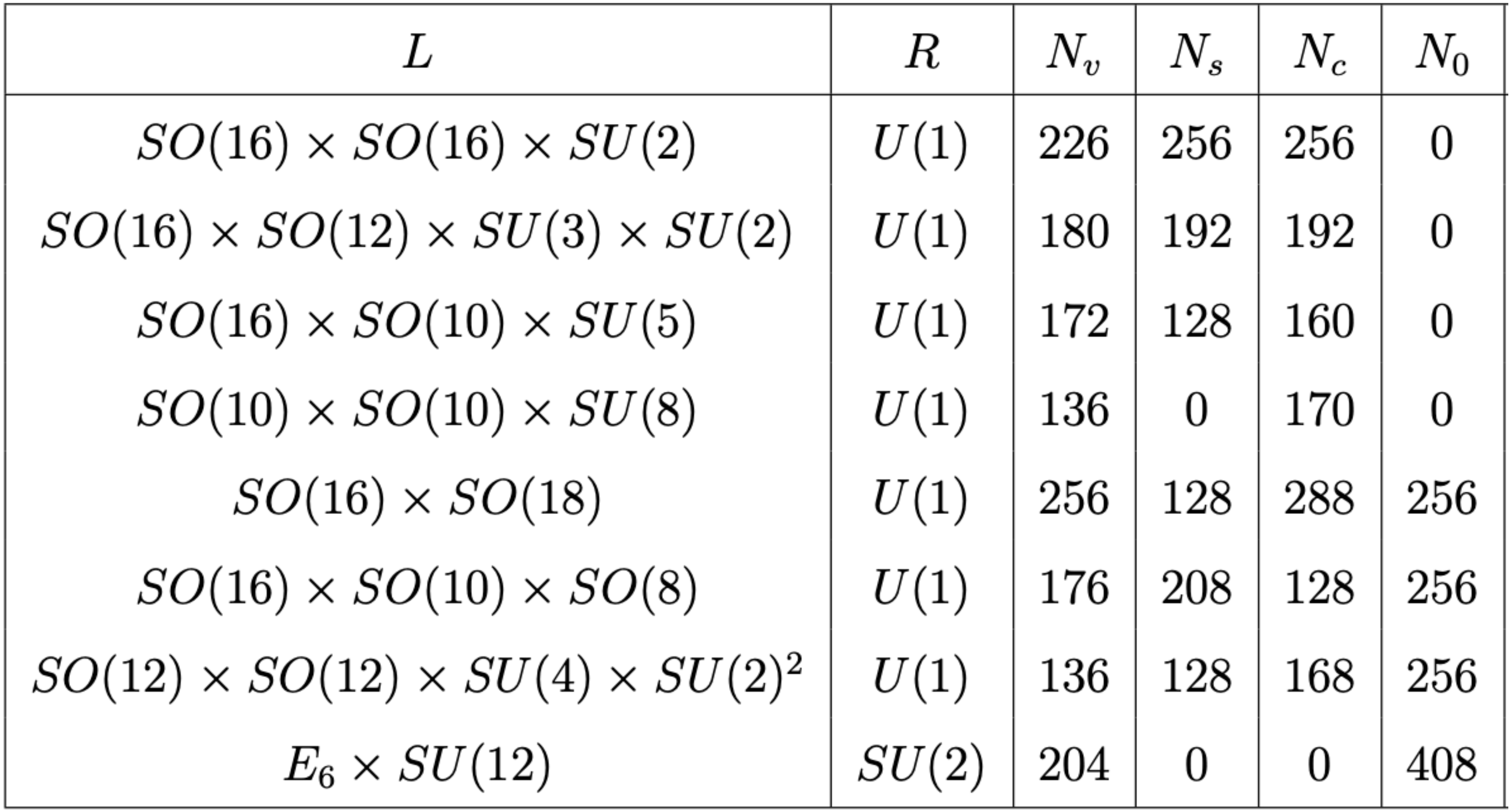

L	R	N_v	N_s	N_c	N_0
$SO(16) \times SO(16) \times SU(2)$	$U(1)$	226	256	256	0
$SO(16) \times SO(12) \times SU(3) \times SU(2)$	$U(1)$	180	192	192	0
$SO(16) \times SO(10) \times SU(5)$	$U(1)$	172	128	160	0
$SO(10) \times SO(10) \times SU(8)$	$U(1)$	136	0	170	0
$SO(16) \times SO(18)$	$U(1)$	256	128	288	256
$SO(16) \times SO(10) \times SO(8)$	$U(1)$	176	208	128	256
$SO(12) \times SO(12) \times SU(4) \times SU(2)^2$	$U(1)$	136	128	168	256
$E_6 \times SU(12)$	$SU(2)$	204	0	0	408

Maximal (G : rank 17) enhancements

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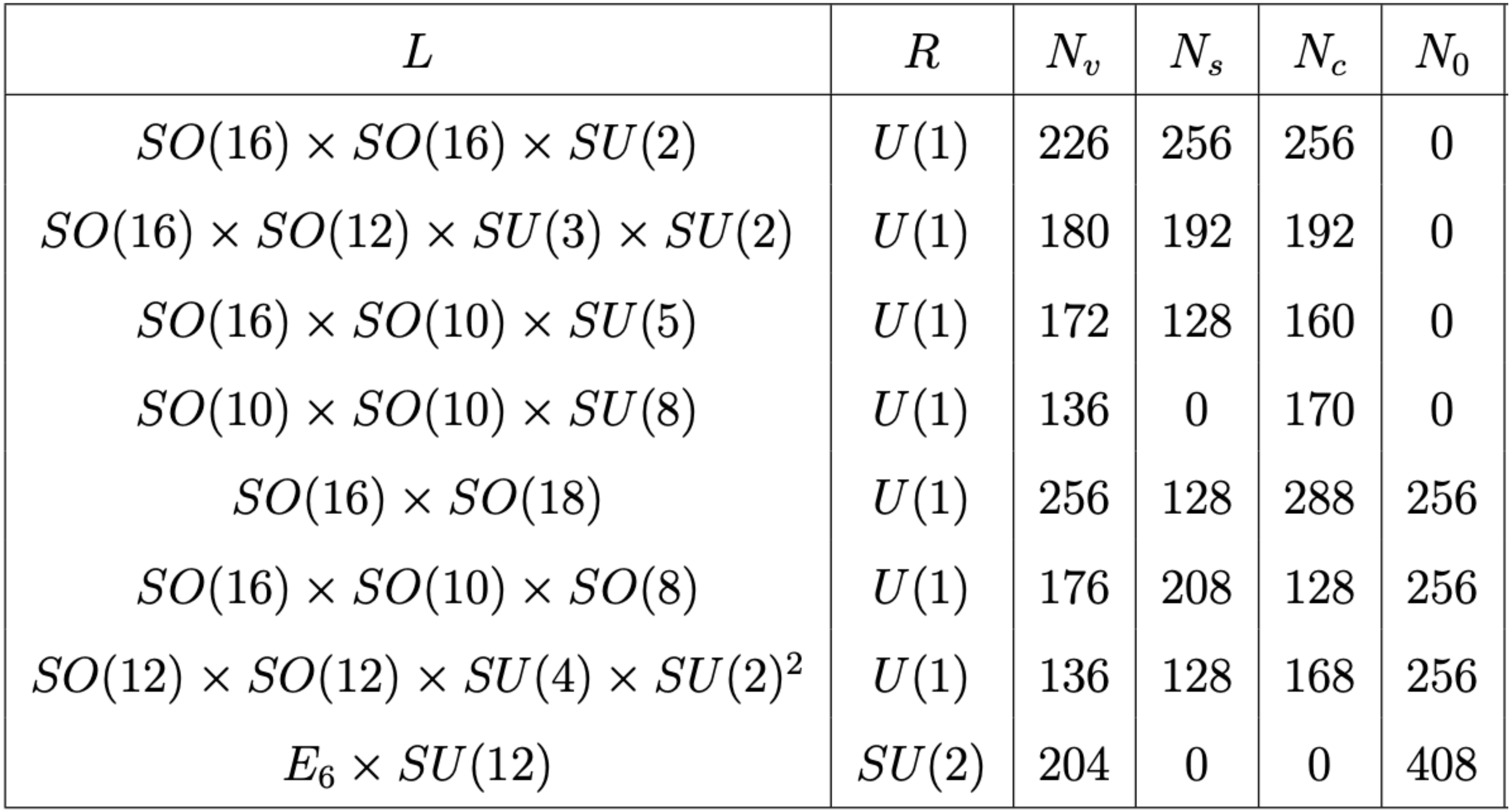
when moving slightly away in mod space

some become tachyonic



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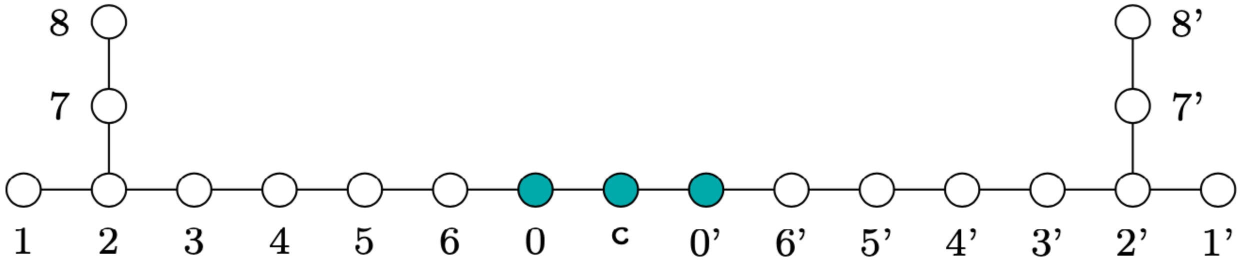
All (maximal and non-maximal) enhancements from Extended Dynkin Diagram

- In SUSY case: all gauge groups, point/region where they occur & fundamental domain of moduli space from Extended Dynkin Diagram

Goddard, Olive 85

Cachazo, Vafa 00



● momentum and/or winding on circle

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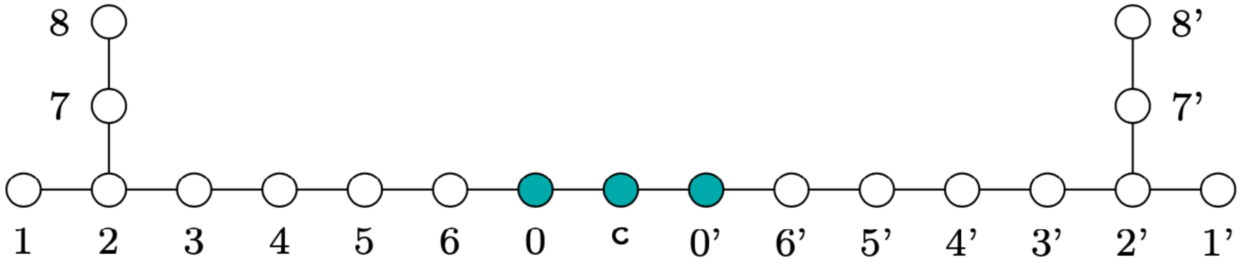
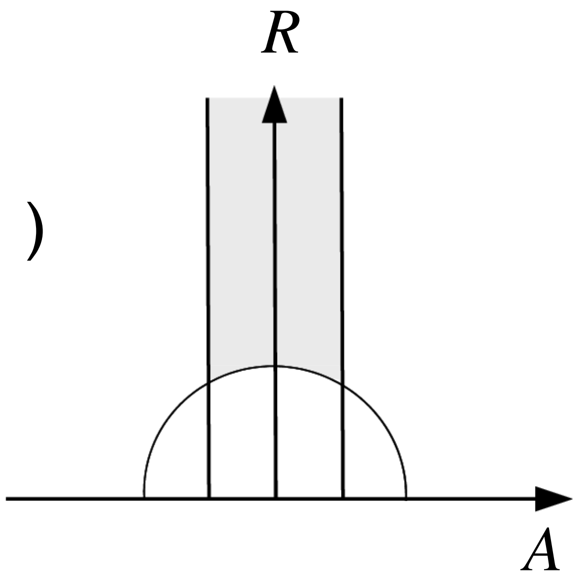


● momentum and/or winding on circle

- 19 nodes, associated to 19 Weyl reflections in $\Gamma_{17,1}$
- Each node corresponds to a boundary in mod space (e.g. ● c : $R^2+\frac{1}{2}A^2 = 1$)
- Allows to get fundamental region



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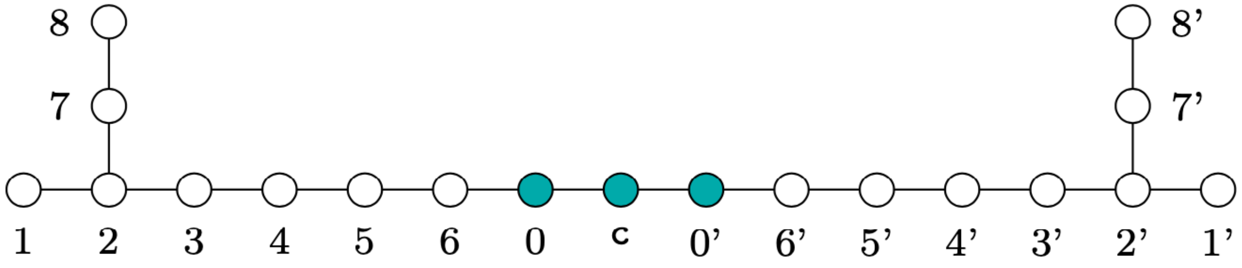

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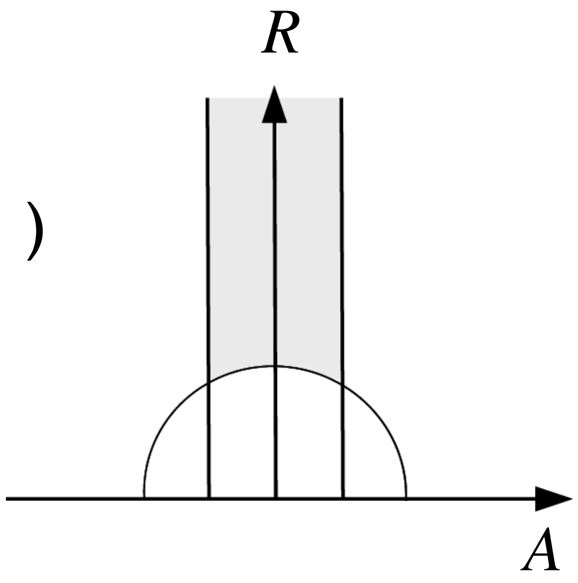

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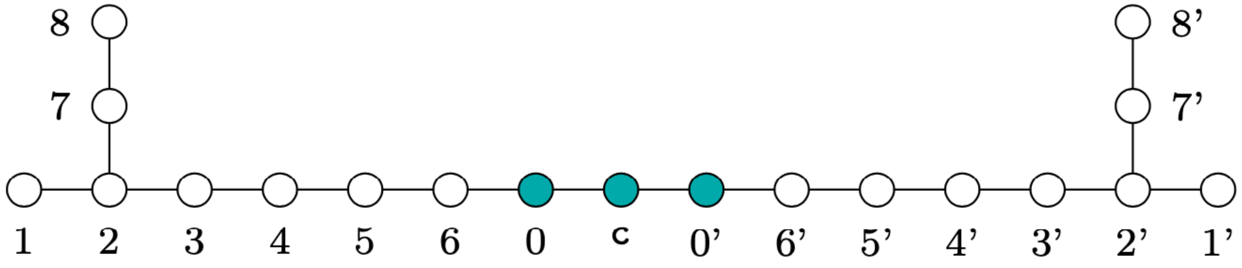

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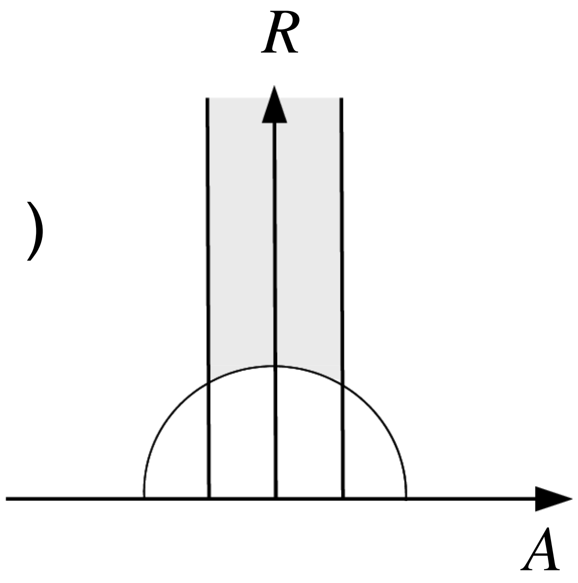

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- What about non-SUSY case??

- We found an Extended Dynkin Diagram for non SUSY heterotic!

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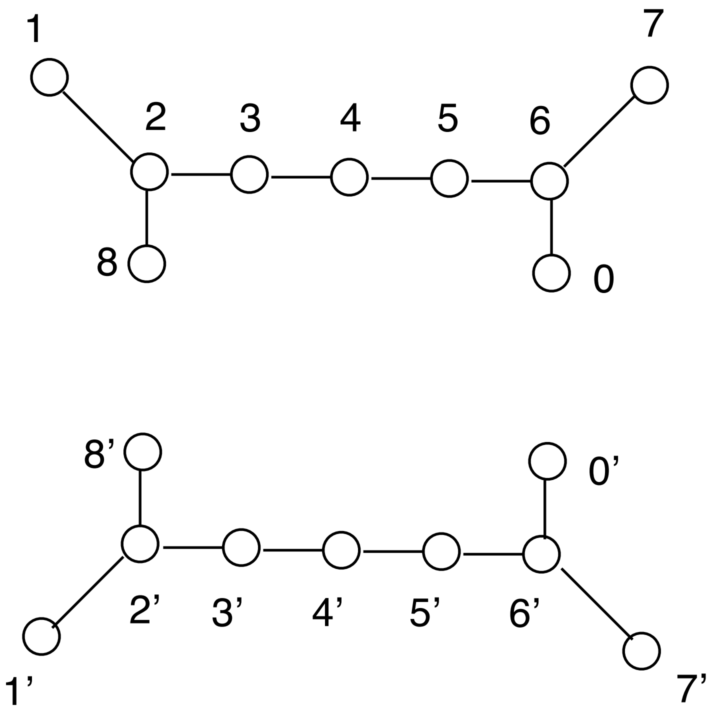

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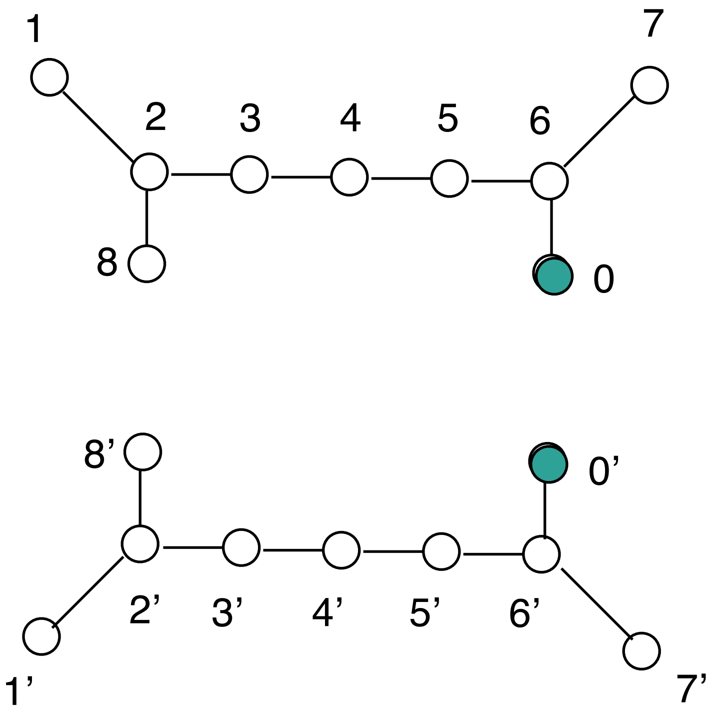

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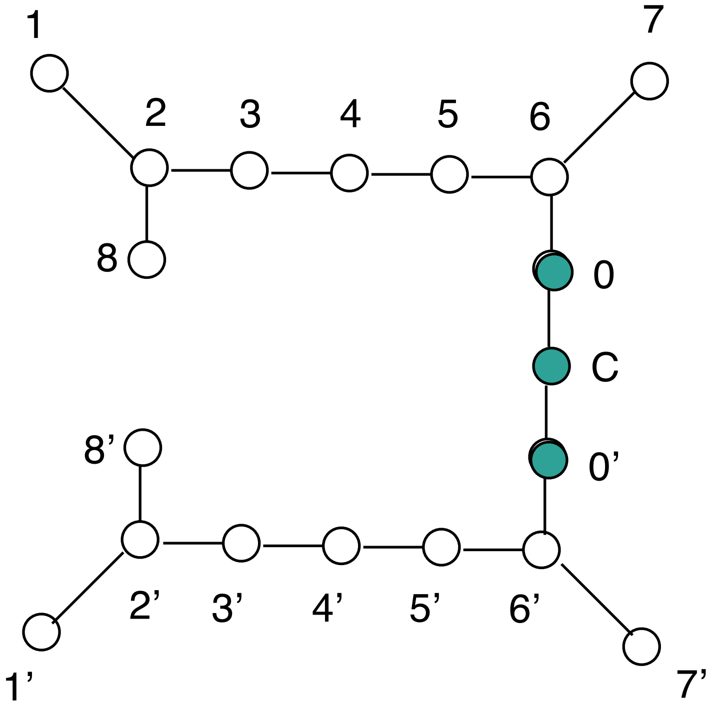

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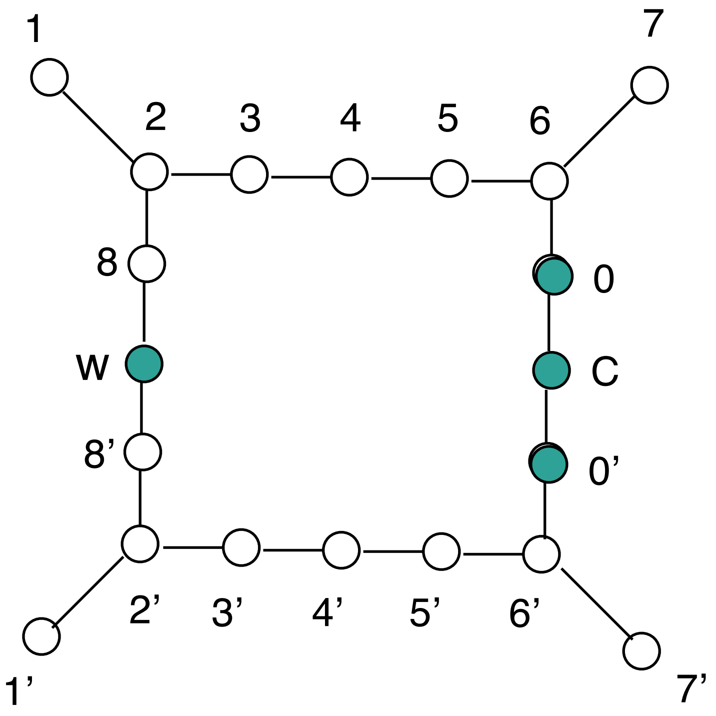

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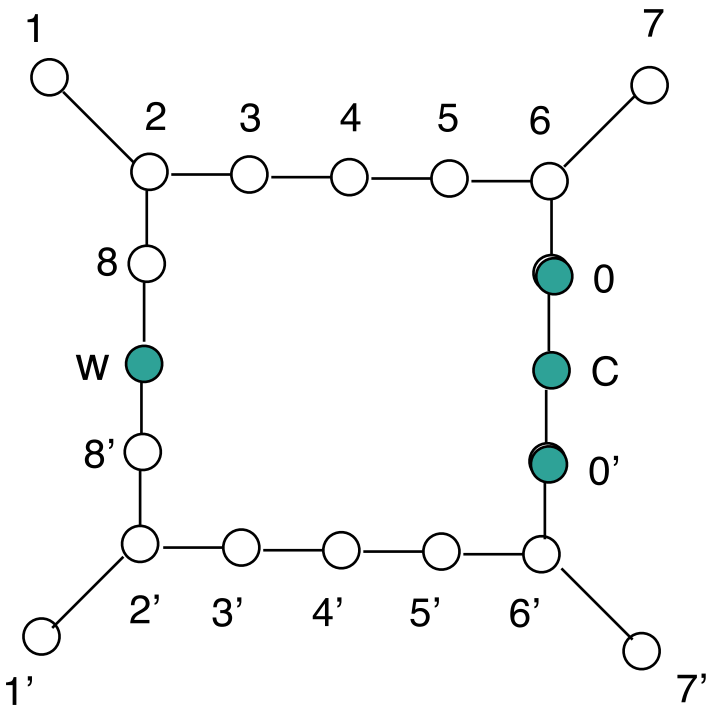

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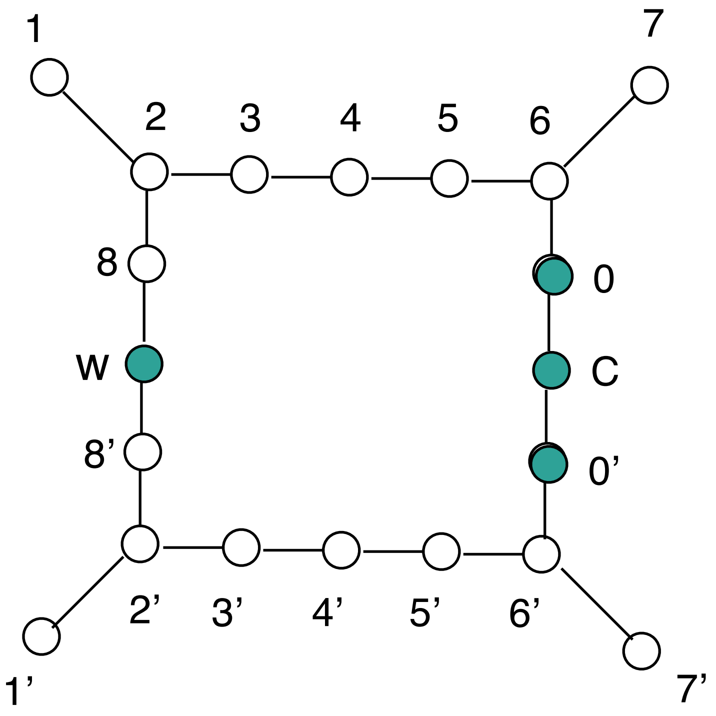

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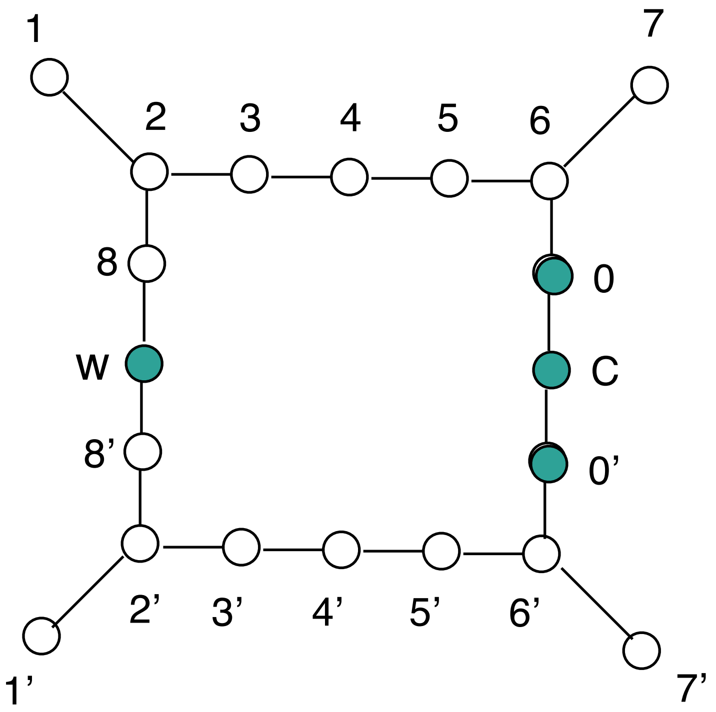

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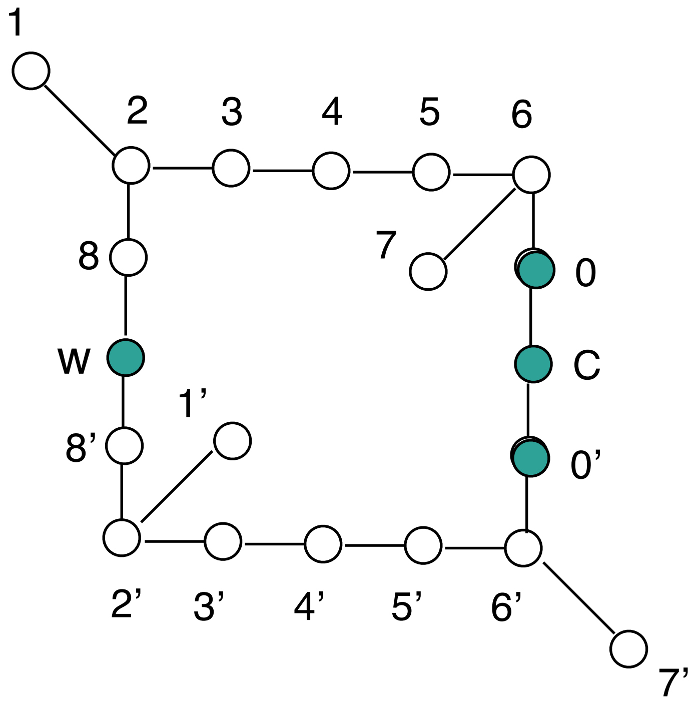

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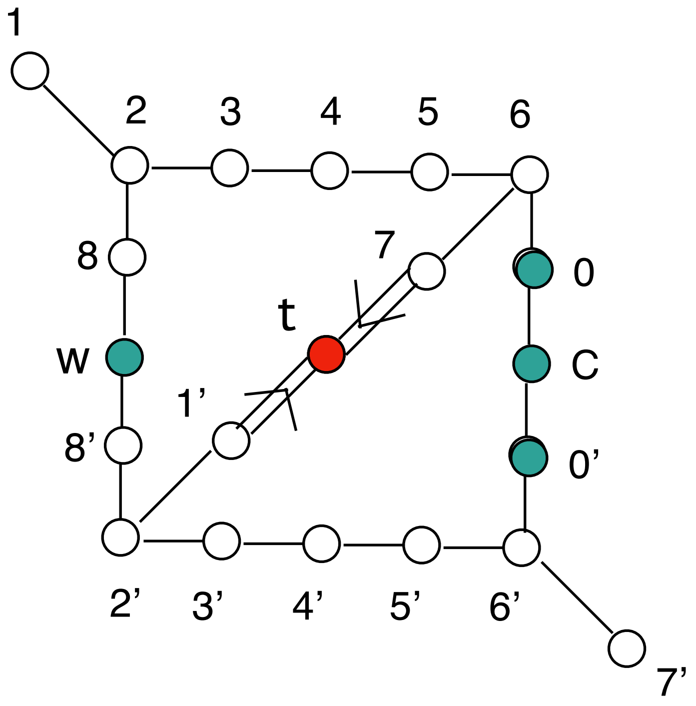

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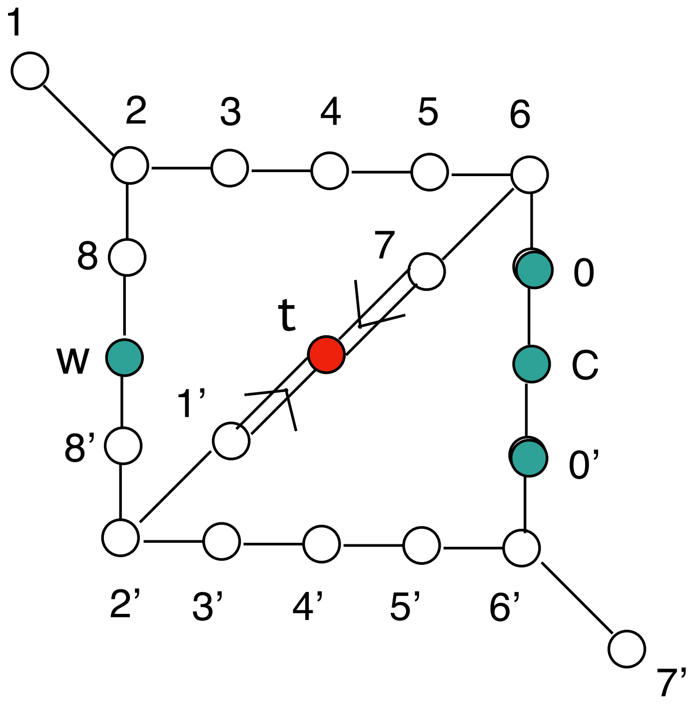

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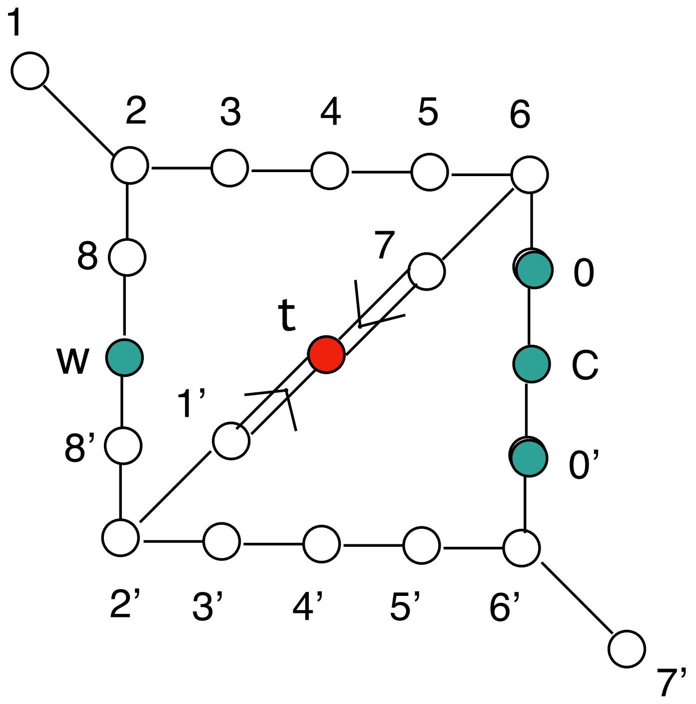

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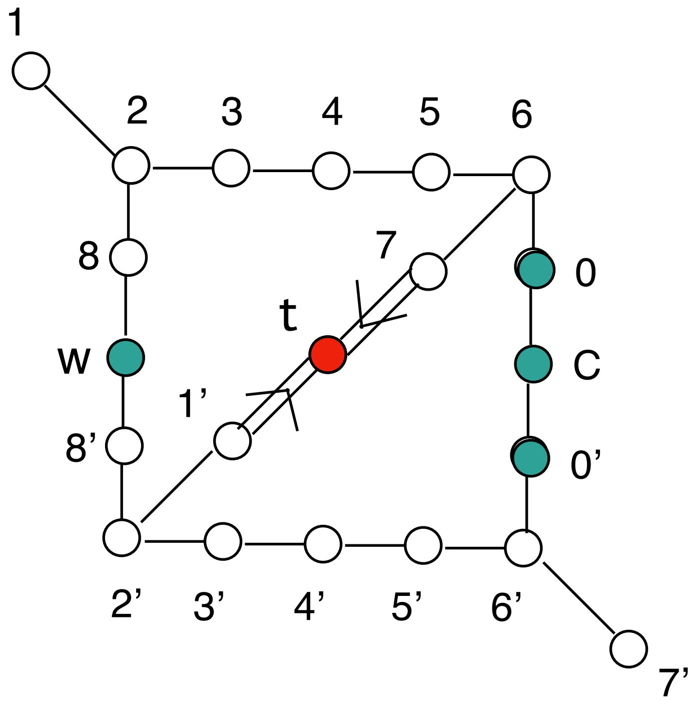

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  - It does not encode the 6 decompactification limits to the 6 non-SUSY heterotic theories

see Fraiman and Collazuol's talk

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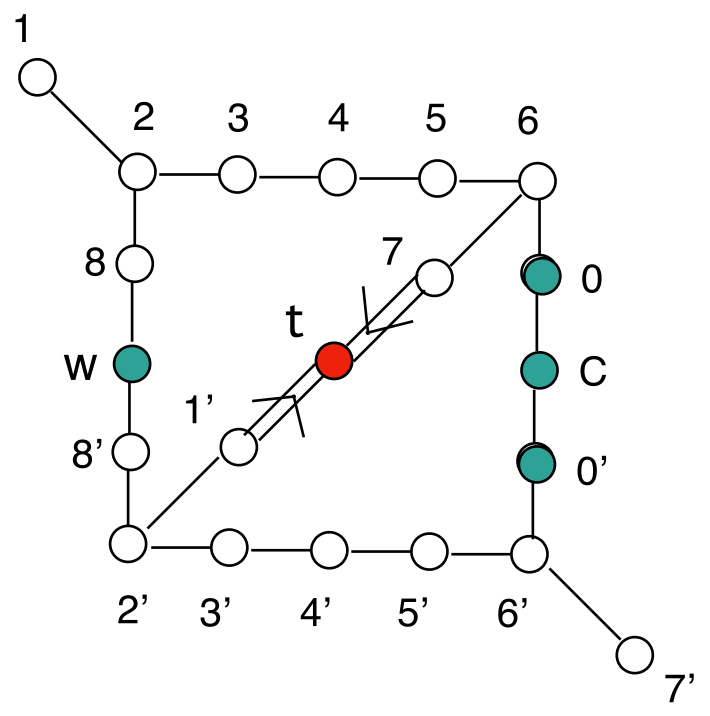

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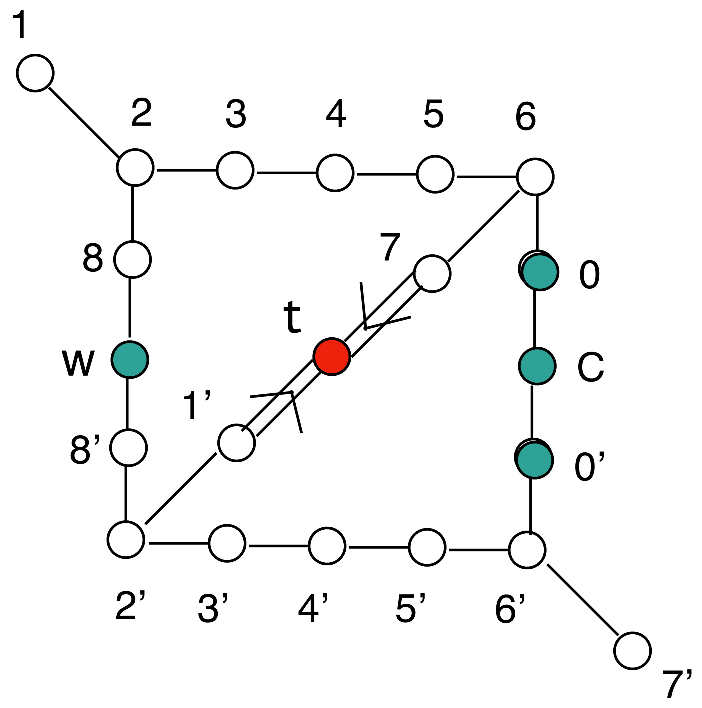

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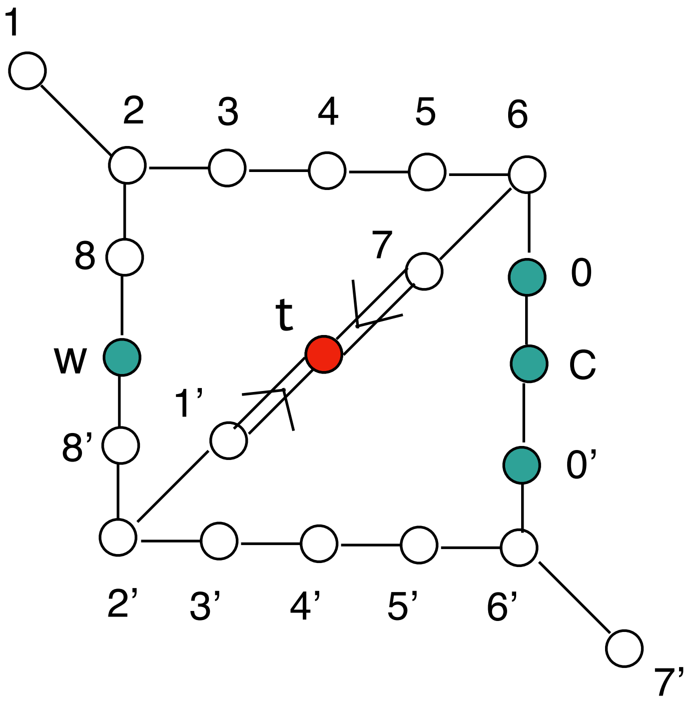
  - Not needed for all practical purposes 😅

see Fraiman and Collazuol's talk

Classification of all non-Abelian gauge symmetry from EDD



- Every non-Abelian group of rank k from deleting 21-k nodes

- Surface (of codimension k) in mod space where a given group appears

  -require the k eqs of remaining nodes (e.g. if $\underset{\text{C}}{●}$ remains $\Rightarrow R^2+\frac{1}{2}A^2 = 1$)

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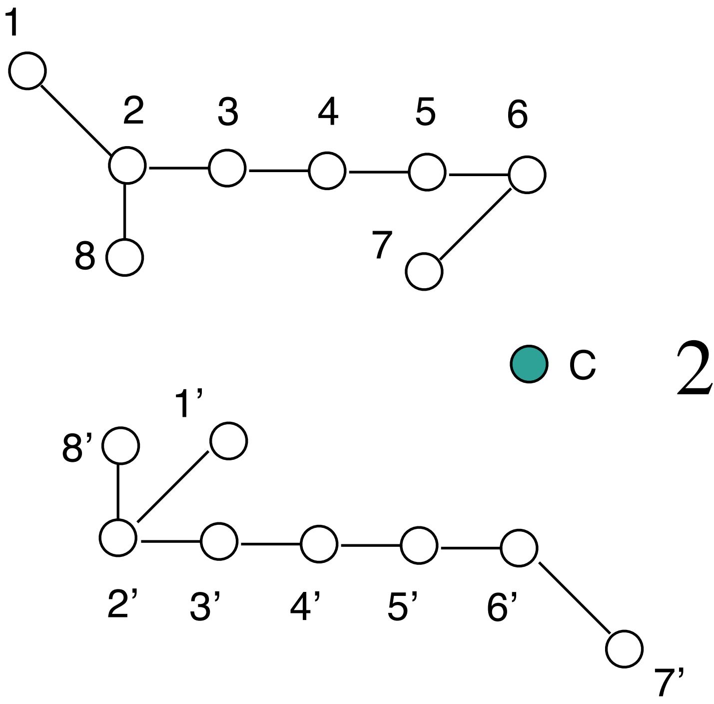

$2D_8 + A_1$

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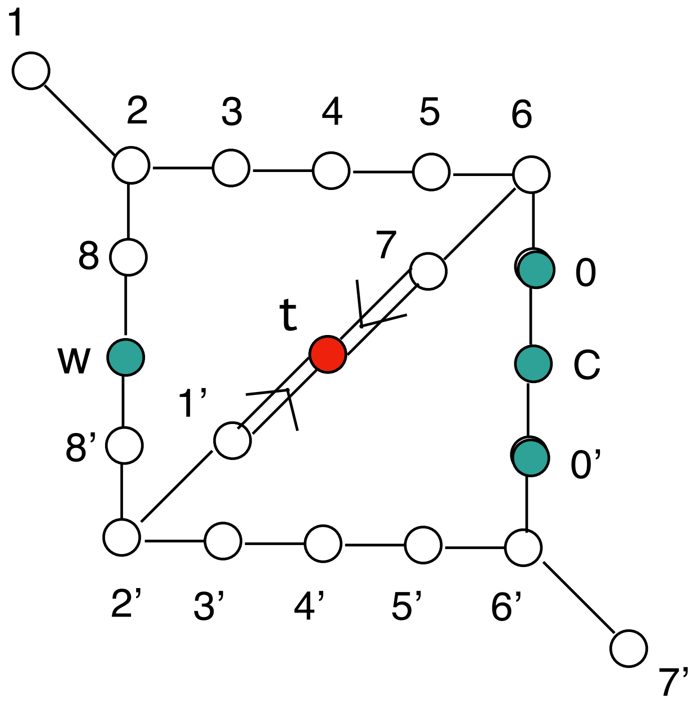

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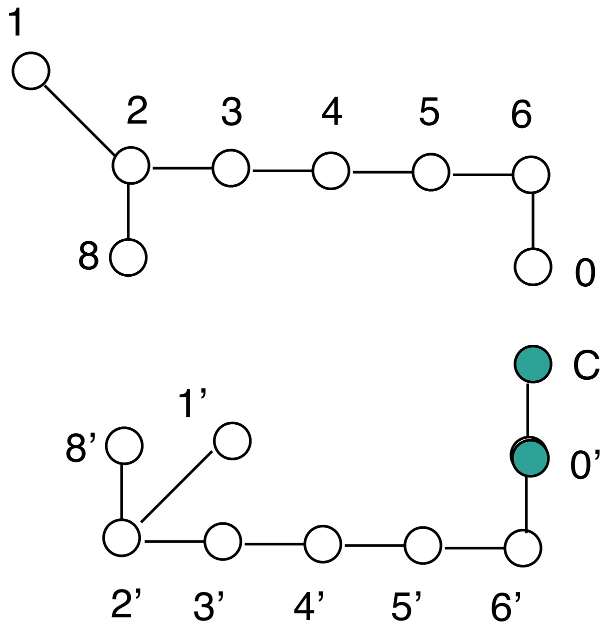

$D_8 + D_9$

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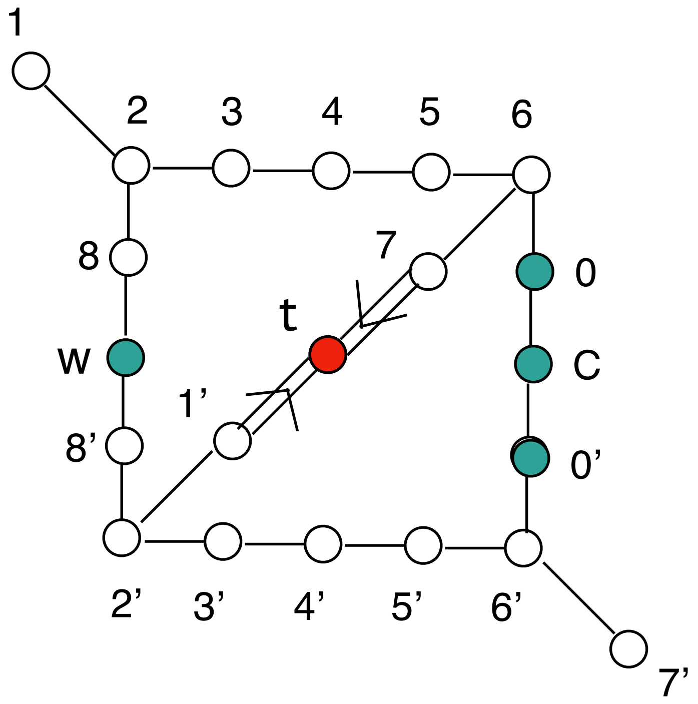

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C

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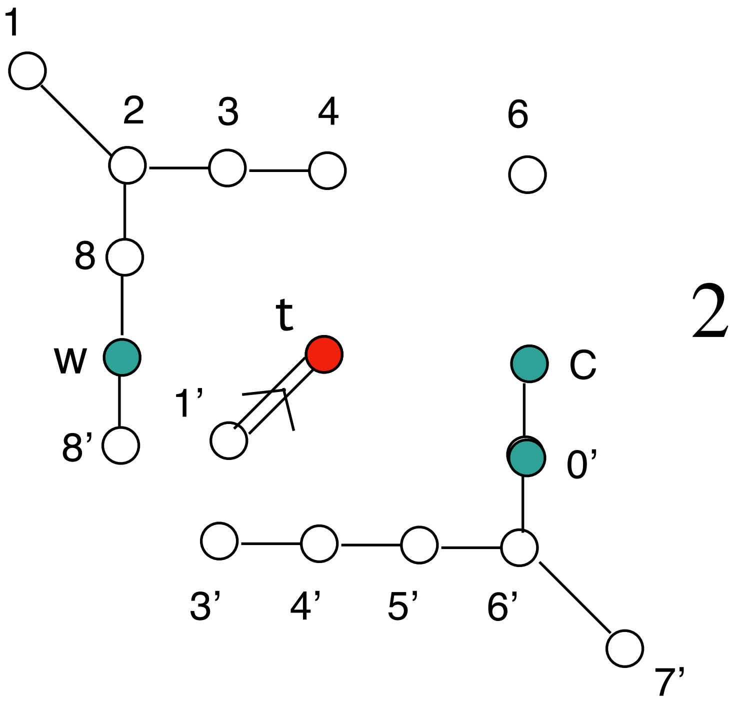

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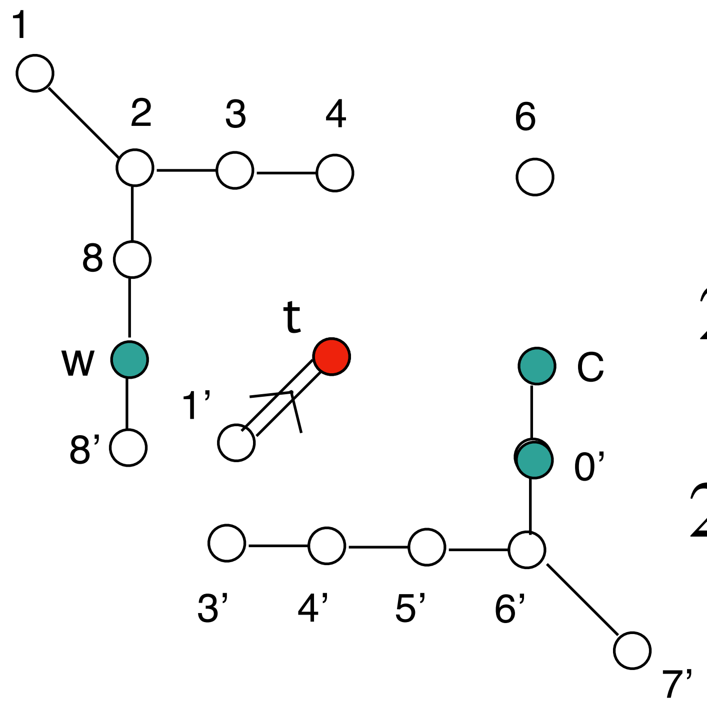

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$$\Downarrow$$
$$2E_7 + A_1 + D_2$$ & tachyon

- Every non-Abelian group of rank k from deleting 21-k nodes

- Surface (of codimension k) in mod space where a given group appears

  -require the k eqs of remaining nodes (e.g. if $\underset{\text{C}}{\bullet}$ remains $\Rightarrow R^2 + \frac{1}{2}A^2 = 1$)

Cosmological constant

- Non-SUSY ⇒ quantum potential for the moduli

$$\Lambda_{1-\mathrm{loop}}(R,A) = \int_{F_0} \frac{d^2\tau}{2\tau_2^2}\,\mathbf{Z}(\tau,R,A) \qquad \mathbf{Z} \sim \sum_{Z\in\Gamma} q^{\frac{P_L^2}{2}}\,\bar{q}^{\frac{p_R^2}{2}} \qquad q = e^{2\pi i\tau}$$

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- Before computing it, look at derivatives

$$\mathbf{Z} \sim \sum_{Z\in\Gamma} q^{\frac{p_L^2}{2}} \bar{q}^{\frac{p_R^2}{2}} = \sum_{Z\in\Gamma} e^{i\pi\tau_1 <Z|Z>} e^{-2\pi\tau_2\, p_R^2(R,A)}$$

$$\nabla_{R,A}\mathbf{Z} \sim \sum_{Z\in\Gamma} e^{i\pi\tau_1 <Z|Z>} e^{-2\pi\tau_2 p_R^2} \underbrace{p_R \nabla p_R}$$

compute & get it's odd in p_R

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- At points in moduli space of maximal (rank d+16) enhancement

Ginsparg,, Vafa 86

$$\forall Z\in\Gamma \qquad \underset{p_R(Z) = -p_R(Z')}{Z \xrightarrow{\text{Weyl reflection}} Z'} \quad \Rightarrow \quad \nabla\mathbf{Z} = 0 \quad \Rightarrow \quad \nabla\Lambda = 0$$

at ALL loops!

Cosmological constant

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we found counterexamples

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Weyl reflection

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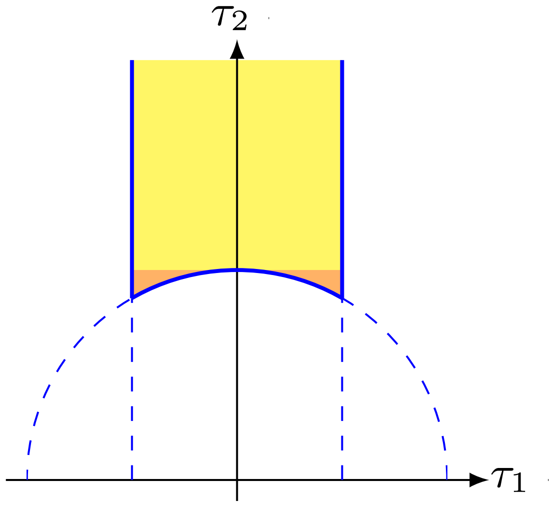
at ALL loops!

- Points of maximal enhancement $\Rightarrow$ $\nabla\Lambda = 0$ $\qquad \nabla^2\Lambda = 0\,?$

$\cancel{\Leftarrow}$ we found counterexamples

Computing cosmological constant



- One-loop cosmological constant for non susy heterotic

$$\Lambda_{1-\text{loop}}(R,A) = \int_{F_0} \frac{d^2\tau}{\tau_2^2} Z(\tau,R,A) \qquad \text{with} \qquad Z = Z^{8-d}\left(Z_s + Z_c - Z_v - Z_0\right)$$

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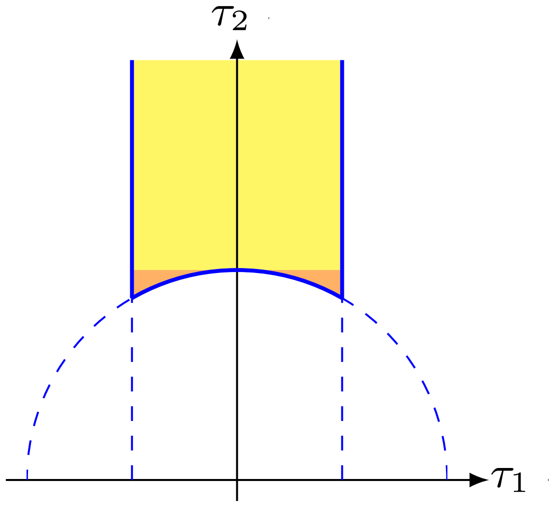
Computing cosmological constant



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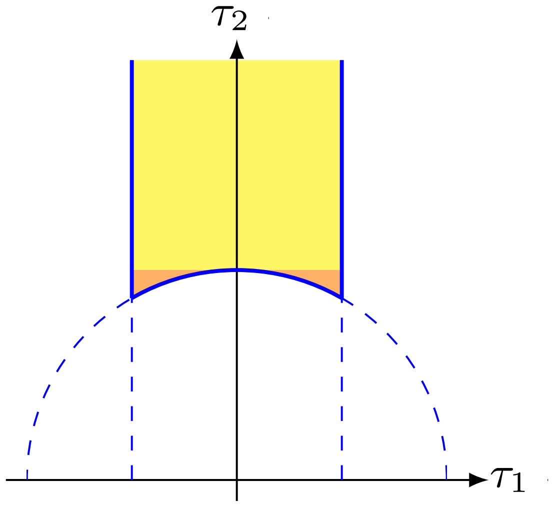
only positive powers

Computing cosmological constant



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Finite contribution from states with

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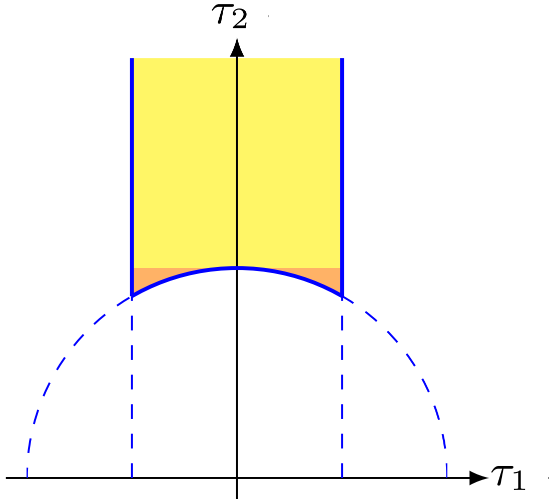
Computing cosmological constant



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↑

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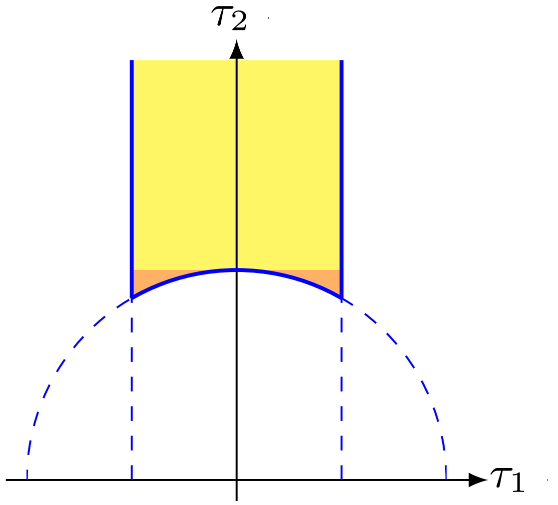

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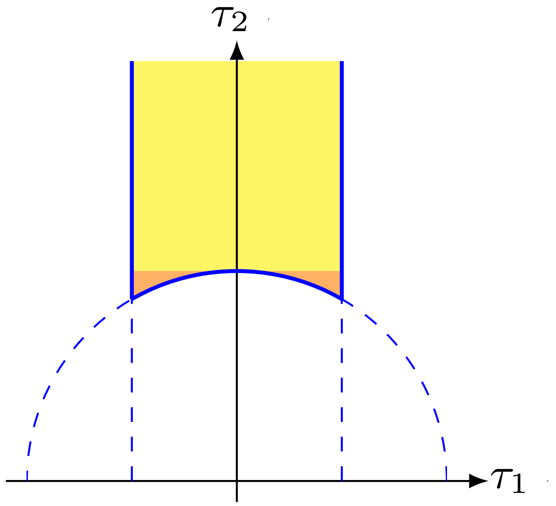
Infinite contribution only from tachyons

Computing cosmological constant



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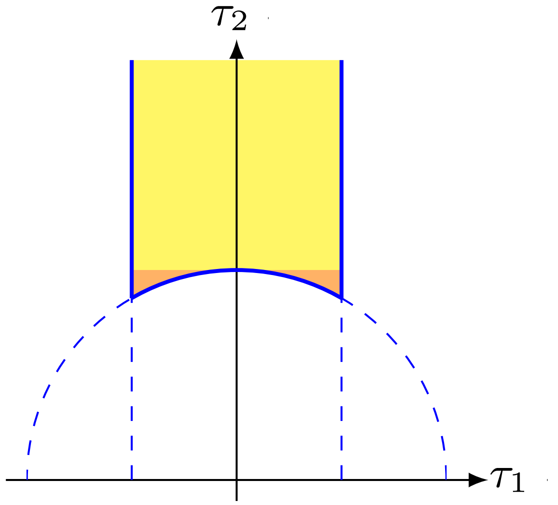
- If tachyons $\Rightarrow\ \Lambda = -\infty$

Computing cosmological constant



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$$\Lambda_{m=0} = 28.1 + 1.1\,(N_s + N_c - N_v) - 0.1 N_0 \;\; + \mathcal{O}(10^{-4})\,(N_f - N_b)$$

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L	N_v	N_s	N_c	N_0	$\Lambda_{m=0}$
$SO(16) \times SO(16) \times SU(2)$	226	256	256	0	341.6
$SO(16) \times SO(12) \times SU(3) \times SU(2)$	180	192	192	0	251.8
$SO(16) \times SO(10) \times SU(5)$	172	128	160	0	155.4
$SO(10) \times SO(10) \times SU(8)$	136	0	170	0	65.6
$SO(16) \times SO(18)$	256	128	288	256	168.7
$SO(16) \times SO(10) \times SO(8)$	176	208	128	256	168.7
$SO(12) \times SO(12) \times SU(4) \times SU(2)^2$	136	128	168	256	168.7
$E_6 \times SU(12)$	204	0	0	408	-243.7

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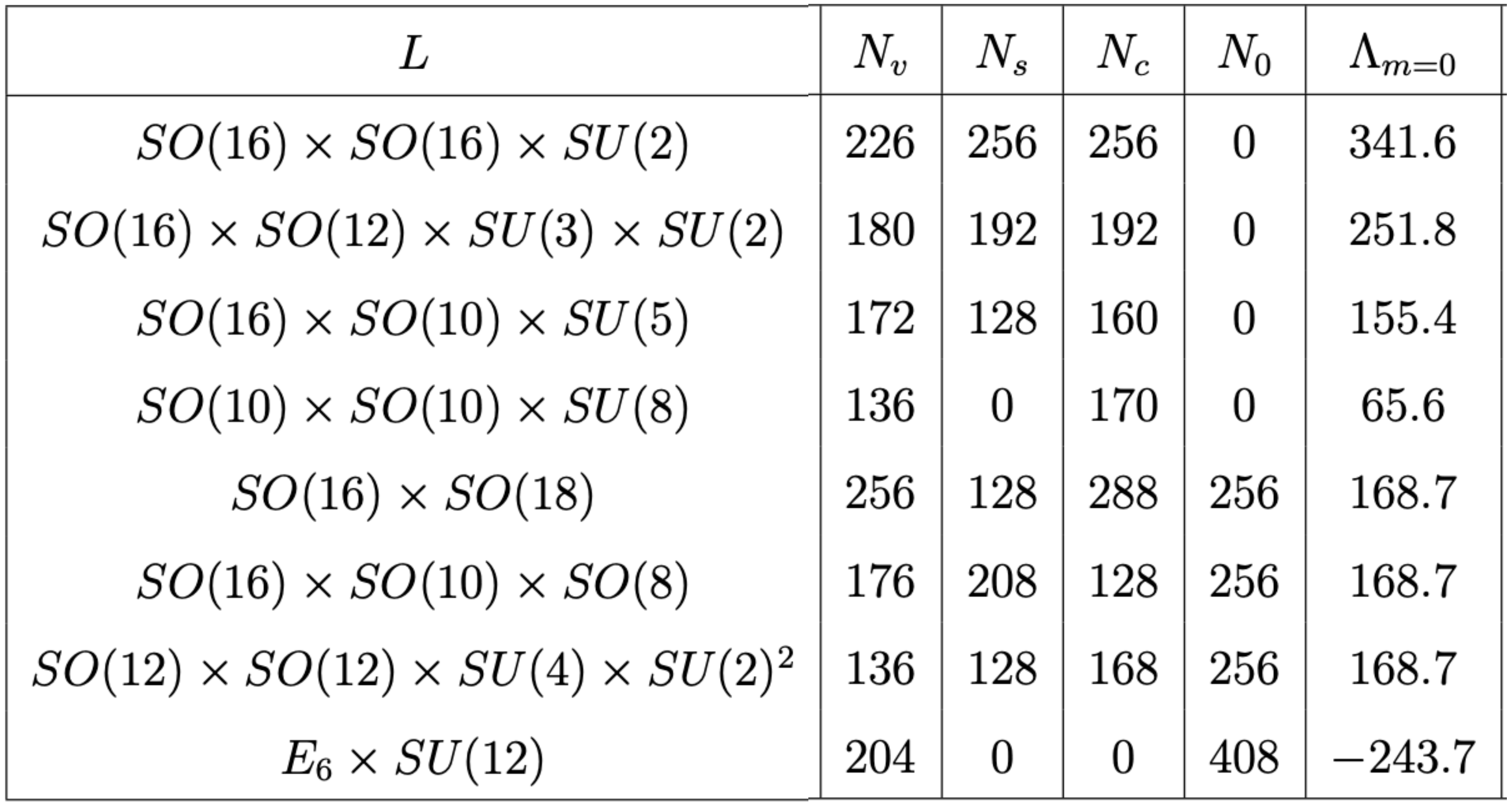

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- Light states can correct this quite significantly

Cosmological constant: results

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$SO(16)\times SO(16)\times SU(2)$	226	256	256	0	341.6	431.4
$SO(16)\times SO(12)\times SU(3)\times SU(2)$	180	192	192	0	251.8	383.5
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$SO(10)\times SO(10)\times SU(8)$	136	0	170	0	65.6	303.8
$SO(16)\times SO(18)$	256	128	288	256	168.7	305.0
$SO(16)\times SO(10)\times SO(8)$	176	208	128	256	168.7	305.0
$SO(12)\times SO(12)\times SU(4)\times SU(2)^2$	136	128	168	256	168.7	305.0
$E_6\times SU(12)$	204	0	0	408	-243.7	180.4

- Light states can correct this quite significantly

Cosmological constant at points of tachyon-free maximal enhancement

L	Λ
$SO(16) \times SO(16) \times SU(2)$	431.4
$SO(16) \times SO(12) \times SU(3) \times SU(2)$	383.5
$SO(16) \times SO(10) \times SU(5)$	359.2
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ALL positive!

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ALL positive!

- What happens at the vicinity?

- Bernardo Fraiman will show beautiful plots of the cosmological constant for 2d slices in mod space

Cosmological constant at points of tachyon-free maximal enhancement

massless scalars that get tachyonic when
moving in certain directions in mod space

L	Λ	N_0
$SO(16)\times SO(16)\times SU(2)$	431.4	0
$SO(16)\times SO(12)\times SU(3)\times SU(2)$	383.5	0
$SO(16)\times SO(10)\times SU(5)$	359.2	0
$SO(10)\times SO(10)\times SU(8)$	303.8	0
$SO(16)\times SO(18)$	305.0	256
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knife edge

ALL positive!

Ginsparg-Vafa

knife edge:

Capitol Peak near Aspen

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L	Λ	N_0	$\nabla^2\Lambda \times R^2$
$SO(16) \times SO(16) \times SU(2)$	431.4	0	$-306^{16}, 831$
$SO(16) \times SO(12) \times SU(3) \times SU(2)$	383.5	0	$-307^{15}, 544^{2}$
$SO(16) \times SO(10) \times SU(5)$	359.2	0	$-569^{5}, -256^{8}, 355^{4}$
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local maximum

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saddle points

local maximum

knife edge

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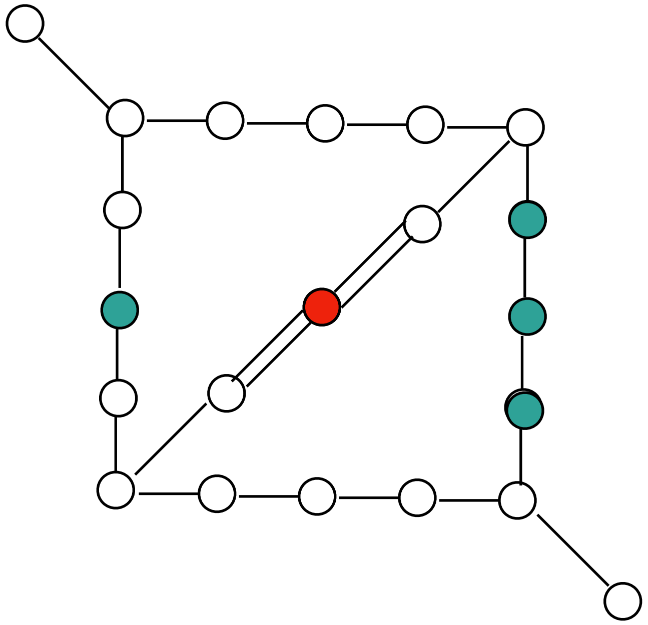

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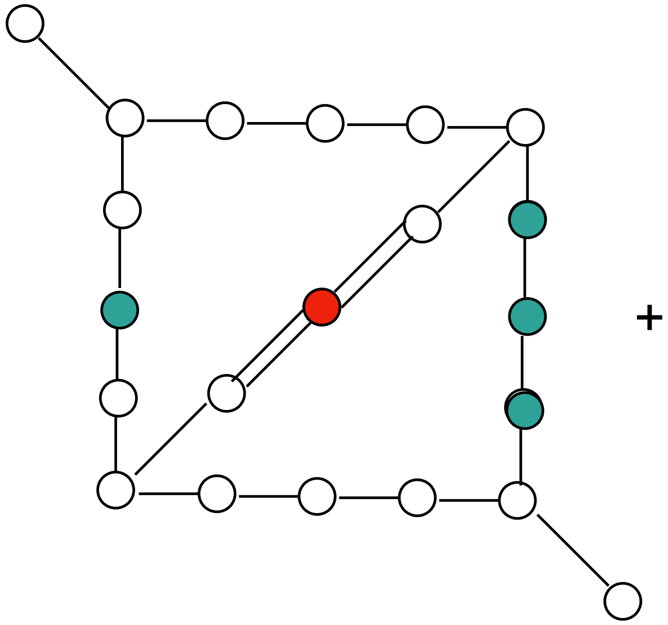

+ other tachyon node

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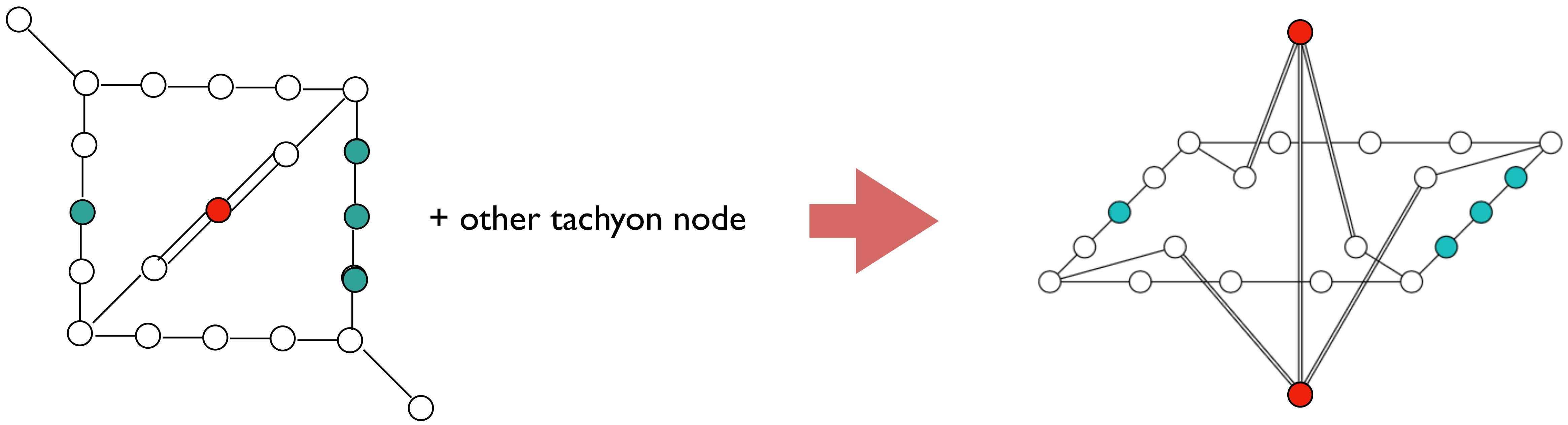

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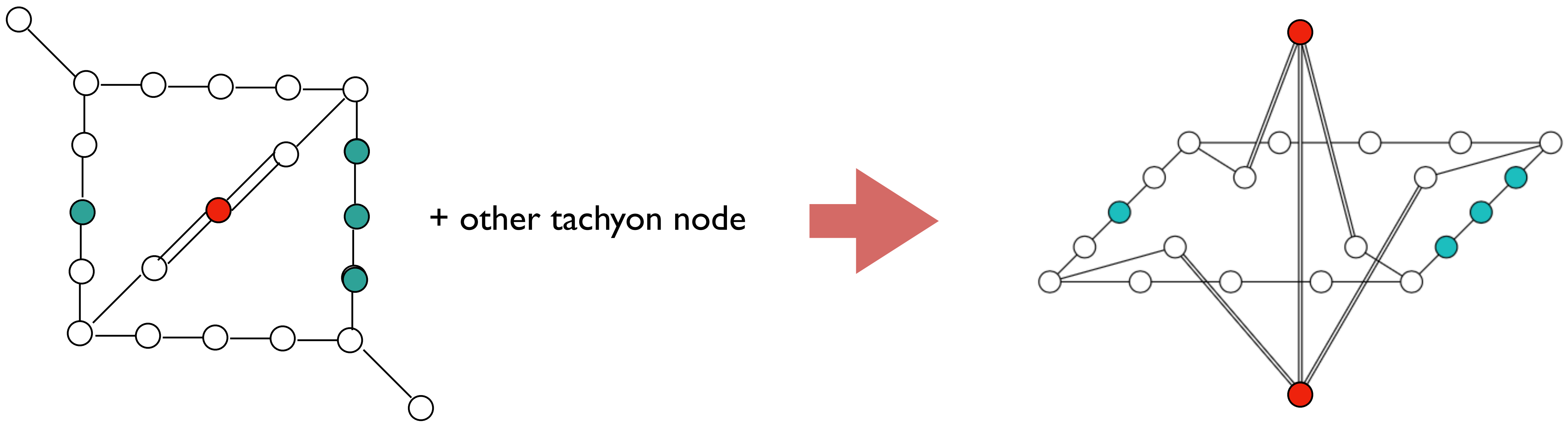

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- 107 maximal enhancements (delete 4 nodes from diagram on the left)

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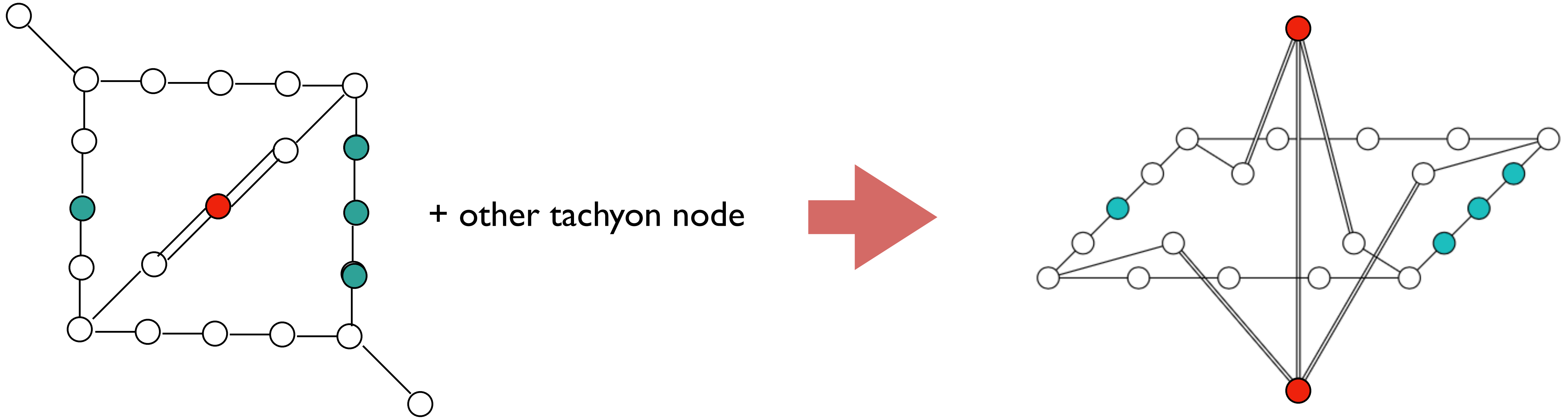

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see Fraiman's talk

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$$\text{knife edges}\ \left\{\begin{array}{l} SO(16)\times SO(18) \\ SO(16)\times SO(10)\times SO(8) \\ SO(12)\times SO(12)\times SU(4)\times SU(2)^2 \\ E_6\times SU(12) \end{array}\right.$$

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local maximum $SO(10)\times SO(10)\times SU(8)$

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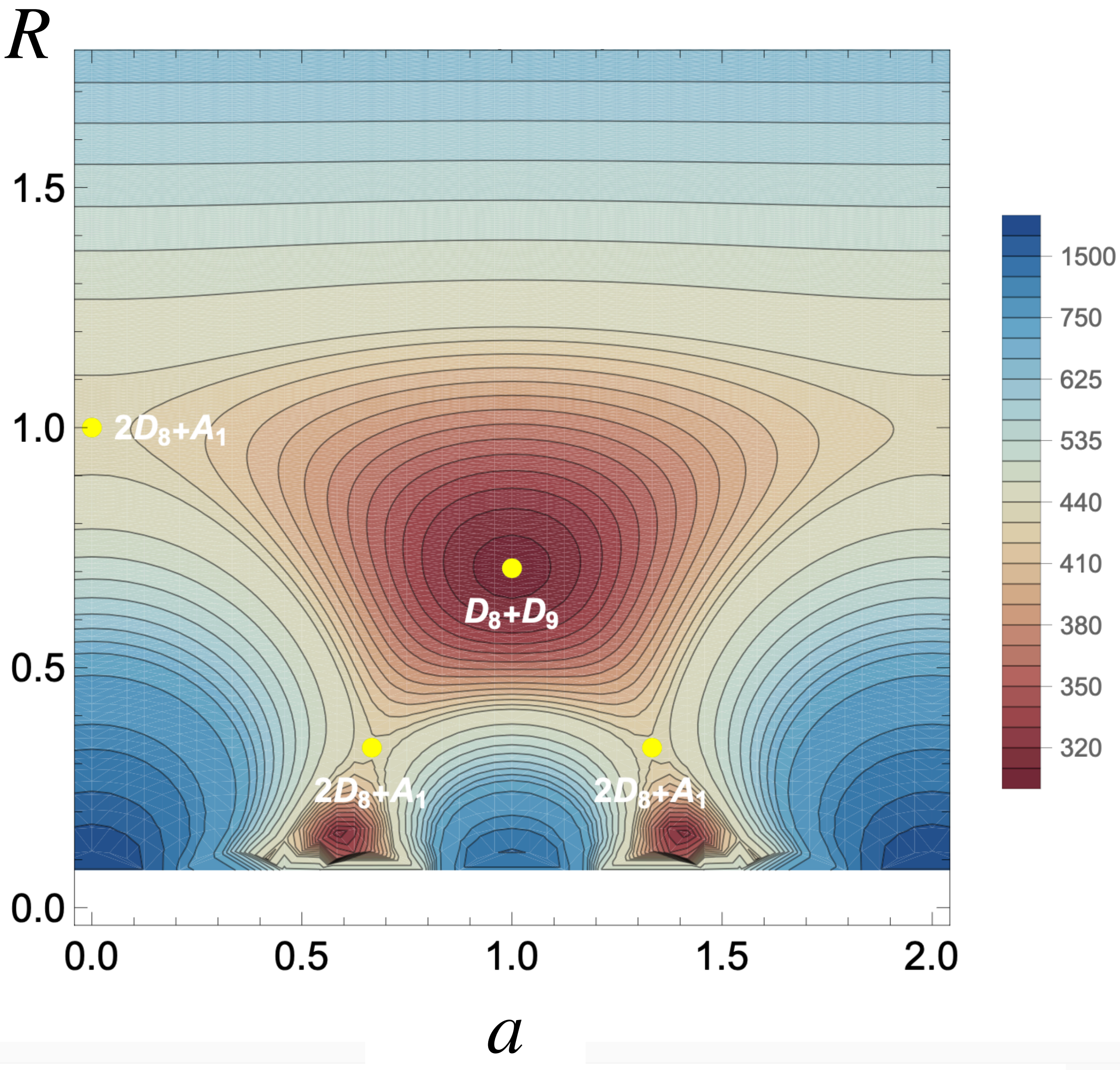
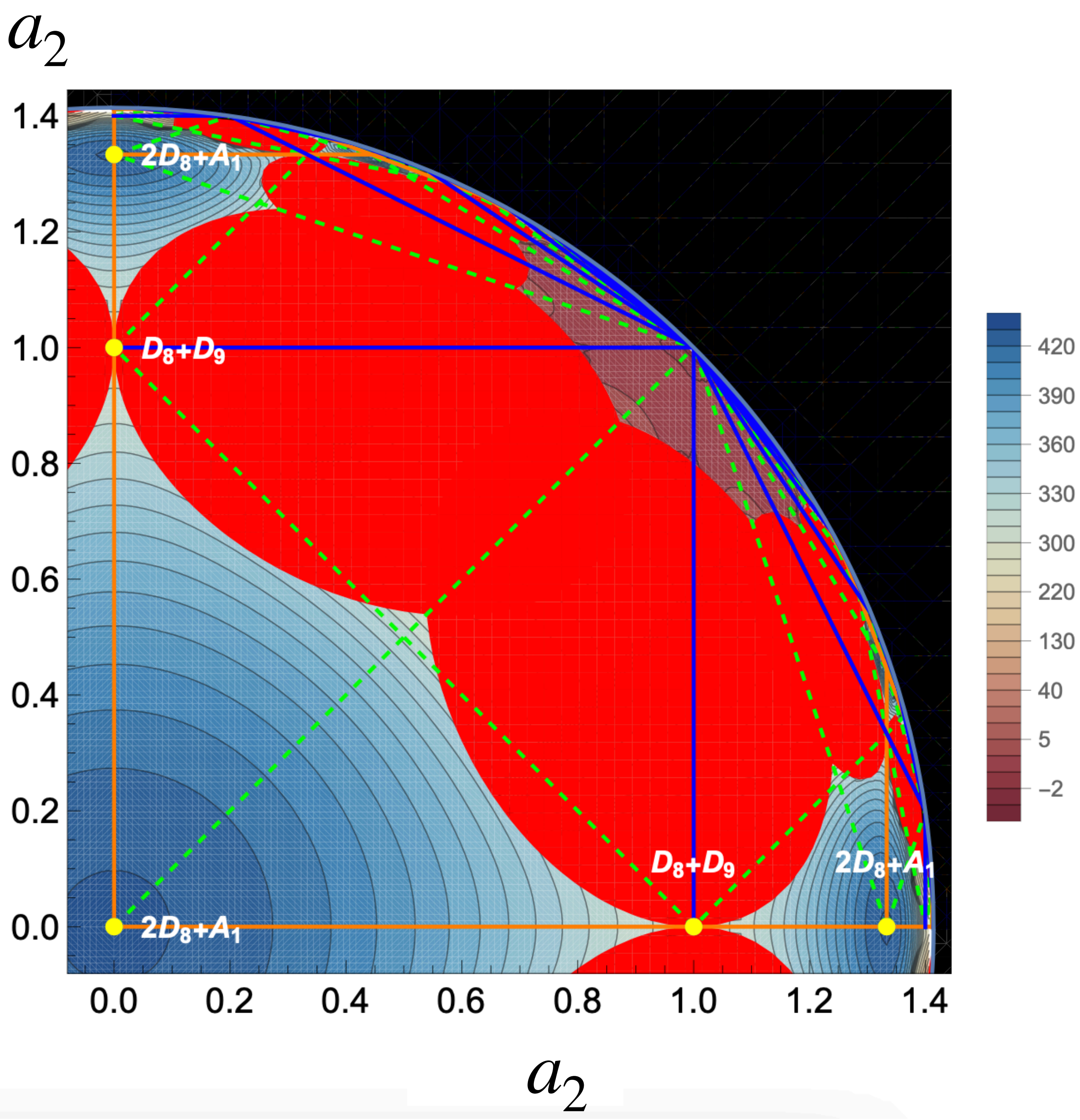
To be continued…

Thank you!



$A = (a, 0^{15})$



$A = (a_1, 0^7, a_2, 0^7)$

$R^2 = 1 - \frac{1}{2} A^2$