Connected Vacua of Heterotic Orbifold

Based on
1901.11194 with Tatsuo Kobayashi (Hokkaido U)
1710.07617 with Soo-Jong Rey (Seoul National U)

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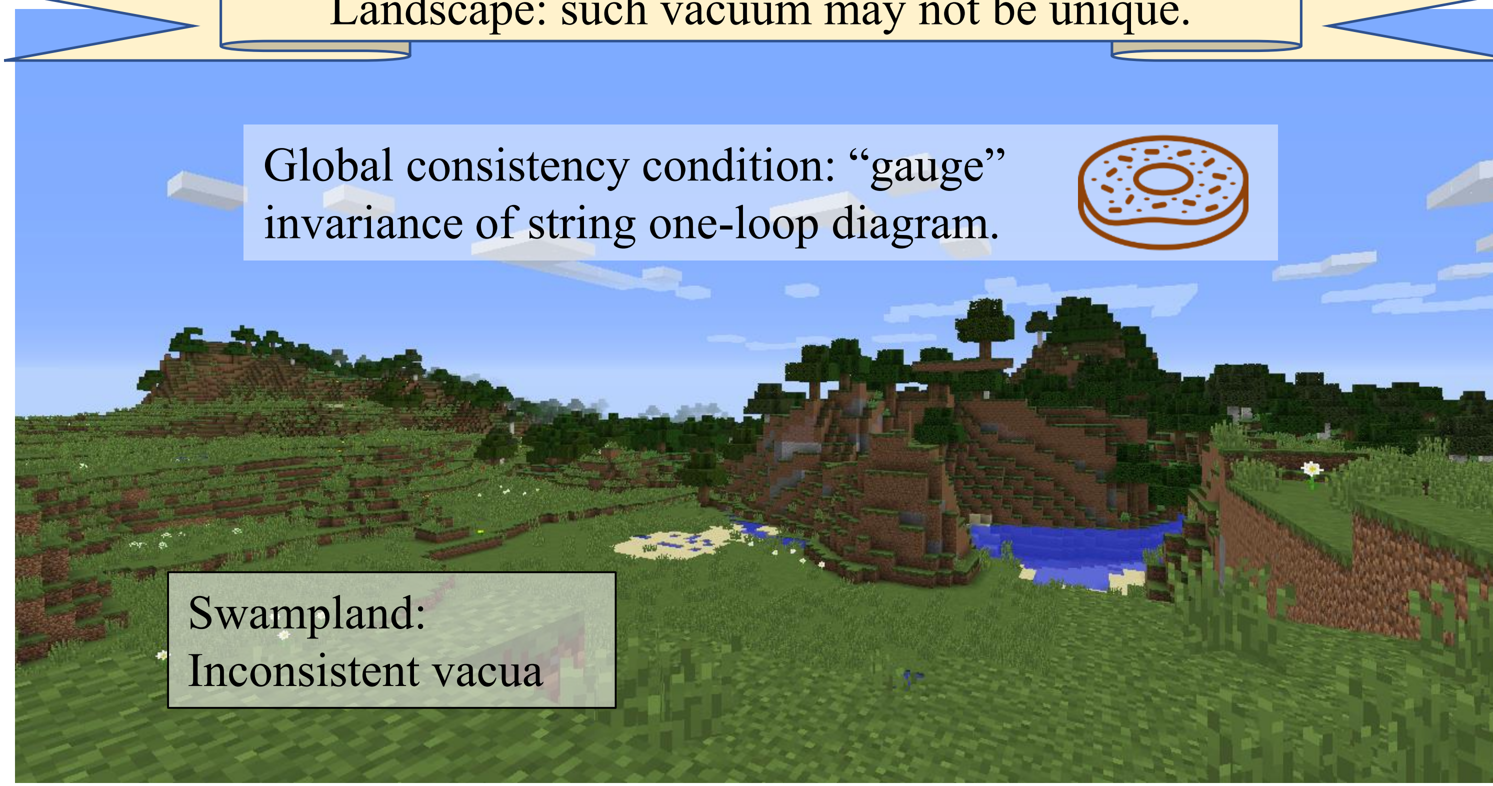
Goal

- String pheno: to find the vacuum for the Standard Model

Landscape: such vacuum may not be unique.



Global consistency condition: “gauge” invariance of string one-loop diagram.

Swampland:
Inconsistent vacua

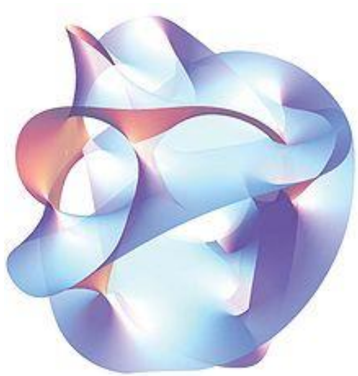
Claim: Many “different” vacua are connected.

- Guided by global consistency cond.
- Protected by SUSY.

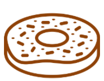
SM from string theory

Large symmetry predicted by string theory

e.g. heterotic string: 10D, $N = 4$ SUSY, $E_8 \times E_8$ SYM



Symmetry breaking associated with geometric symmetry of extra dimension

Global consistency condition 

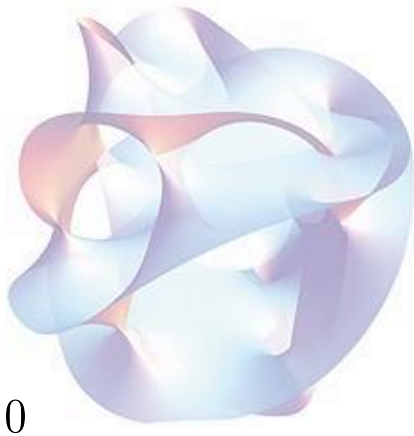
Small observed symmetry of SM

4D, $N = 1$ SUSY, $SU(3) \times SU(2) \times U(1)$ with observed fields.

Internal space and background gauge field

[Candelas, Horowitz, Strominger, Witten 85. 86]

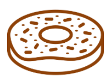
We want $N_{4D} = 1$ or $N_{6D} = (1,0)$ SUSY.



$\delta\psi_m = \nabla_m \epsilon$ Ricci-flat Kahler (Calabi-Yau) manifold

$\delta\lambda = \Gamma^{mn} F_{mn} \epsilon$ Holomorphic vector bundle satisfying Hermitian YM Eq.

6D: $*_4 F_{mn} = - F_{mn}$ anti-self-dual.

Global consistency  $dH = d^2 B + \mathrm{tr}\, R \wedge R - \mathrm{Tr}\, F \wedge F = 0$

inst $k = 24$

Spectrum: Instantons with a struct group G.
$SO(32)$ or $E_8 \times E_8$ broken to H, $[H,G] = 0$.
Matter: zero modes under G-background.

Toroidal orbifold

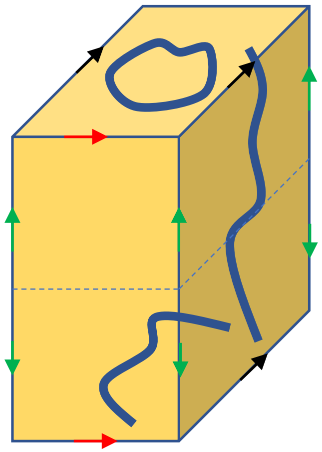
[Dixon, Harvey, Vafa, Witten 85, 86]
…
[KSC, Kim 03]
[Kobayashi, Raby, Zhang 04]
[Buchmuller, Hamaguchi, Lebedev, Ratz 06]
[Kim, Kyae 07]
…

- A torus modded out by discrete action $T^4/\mathbf{Z}_N$.
- $\mathbf{Z}_N : (z^1, z^2) \to (e^{2\pi i \phi_1} z^1, e^{2\pi i \phi_2} z^2), \quad \phi = \left(\frac{1}{N}, -\frac{1}{N}\right)$

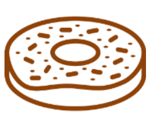
- Associate twist with $\mathbf{Z}_N$ boundary condition.
  Shift vector V = 1/N (0 0 … 1 1… N-1).
- Twisted string: closed string up to $\mathbf{Z}_N$.
  String well behaved at singular points.

$$\frac{(P+jV)^2}{2} + \tilde{N}_L^{(j)} + E_0^{(j)} = 0$$

$$E_0^{(j)} = -1 + \frac{1}{2}\sum_{a=1}^{2} j\phi_a (1 - j\phi_a)$$



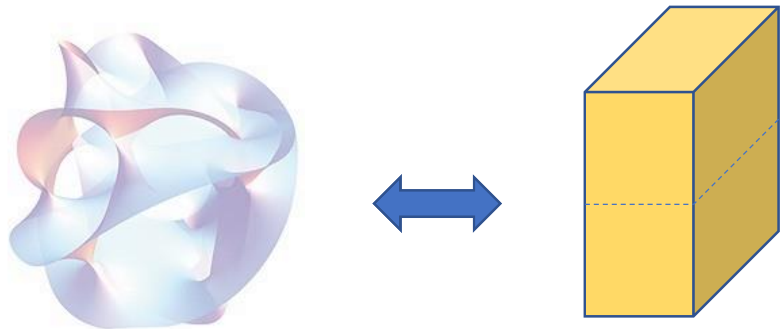
- Modular invariance of the partition function



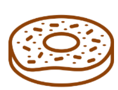
$$\frac{V^2}{2} - \frac{\phi^2}{2} \equiv 0 \mod \frac{1}{N}$$

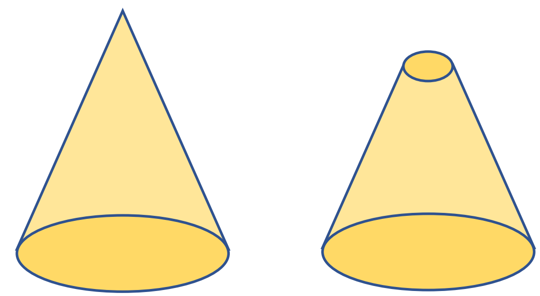
Orbifold as singular limit Calabi-Yau

- Singular limit of Calabi-Yau manifold. Ex. K3 = $T^4/\mathbf{Z}_N$.
- Each fixed point: ALE space $\mathbf{R}^4/\mathbf{Z}_N$.



- Blow up → smooth ALE space.
- Flat background connection at "infinity" = shift vector.
- Structure group is $U(1)^r$:
  - r rank of the maximal torus. $SO(16)$x$SO(16)$ or $SO(32)$.
  - $k_{\mathrm{U}} = 3(n_1+n_2)$ ($\mathbf{Z}_3$) [Intriligator 97]
  - k_{T} = # twisted vectors of $SO(n_0)$ [KSC, Kobayashi 19]
- Gluing $\mathbf{R}^4/\mathbf{Z}_N$'s: shift vector with Wilson lines
- Instanton number $k_{\mathrm{U}} + k_{\mathrm{T}} = 24$





Orbifold with 5-branes

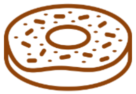
- Heterotic string sources B_{MN} $$\int_{1+1} B_{MN}$$
- 5-branes provides magnetic sources $$\int_{5+1} B^{\mathrm{m}}_{MNPQRS}, \quad *dB \sim dB^{\mathrm{m}}$$

[Aldazabal, Font, Ibanez, Uranga, Violero 98]

- Same worldsheet CFT
  with modified zero point energy.
- Extra gauge group, different twisted string
- More vacua with different spectra

$$\frac{(P+jV)^2}{2} + \tilde{N}_L^{(j)} + E_0^{(j)} + \Delta E_0 = 0$$

$$\frac{V^2}{2} - \frac{\phi^2}{2} + \Delta E_0 \equiv 0 \mod \frac{1}{N}$$



$$\Delta E_0 = \frac{n}{54}$$

[Sagnotti 92] [Seiberg, Witten96] … [KSC, Rey 17]

- Modular invariance with 5-branes $k + n = 24$

[KSC, Kobayashi 19]

- Proof of the relations:
  CFT description, ΔE_0 vs n.
- Transition of vacua

Small instanton into 5-branes

Some instantons can be emitted [Polchinski, Witten 95] [Witten 96]

- becomes 5-branes
- recovering large gauge group.

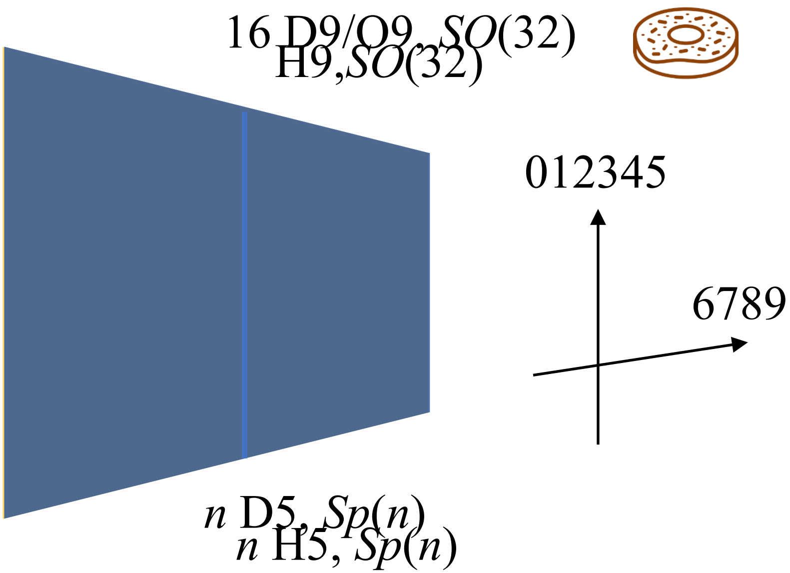
$SO(32)$ heterotic ~ Type I string ~ Type IIB string / Ω

Bound state: instanton $*_4 F = - F$.

- Moduli space = ADHM $\frac{1}{8\pi^2}\int \mathrm{tr} F \wedge F = n.$
- Higgs branch = growing size
- $SO(32)$ broken to smaller group

Heterotic string

Reverse process



D9-D5 string: bifundamental

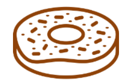
Transitions: example $SO(32)$ het on T^4/Z_3

$U(8) \times SO(16)$
$V = 1/3\,(1\ 1\ 1\ 1\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0)$

$U: (\mathbf{8}, \mathbf{16}) + (\mathbf{28}, \mathbf{1}) + 2(\mathbf{1}, \mathbf{1})$

$T: 9(\mathbf{28}, \mathbf{1}) + 18(\mathbf{1}, \mathbf{1})$

$k_U = 3 \cdot 8 = 24$
$k_T = 0$



$V = V_1 + V_2$
$V_1 = 1/3\,(1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0)$ daughter shift vector
$V_2 = 1/3\,(0\ 0\ 1\ 1\ 1\ 1\ 1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0)$ emitted instantons

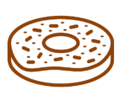
$U(2) \times SO(28) \times Sp(18)$
$V_1 = 1/3\,(1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0)$

$U: (\mathbf{2}, \mathbf{28}; \mathbf{1}) + 3(\mathbf{1}, \mathbf{1}; \mathbf{1})$

$T: 9(\mathbf{1}, \mathbf{1}; \mathbf{1}) + 18(\mathbf{1}, \mathbf{1}; \mathbf{1})$

$NP: \frac{1}{2}(\mathbf{1}, \mathbf{28}; \mathbf{36}) + (\mathbf{2}, \mathbf{1}; \mathbf{36})$

$k_U = 3 \cdot 2 = 6$
$k_T = 0$



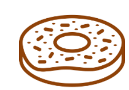
$n = 3 \cdot 6 = 18$ instantons emitted
and became 5-branes: extra $Sp(18)$
Anomaly free

$U(2) \times SO(28)$
$V_1 = 1/3\,(1\ 1\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0)$

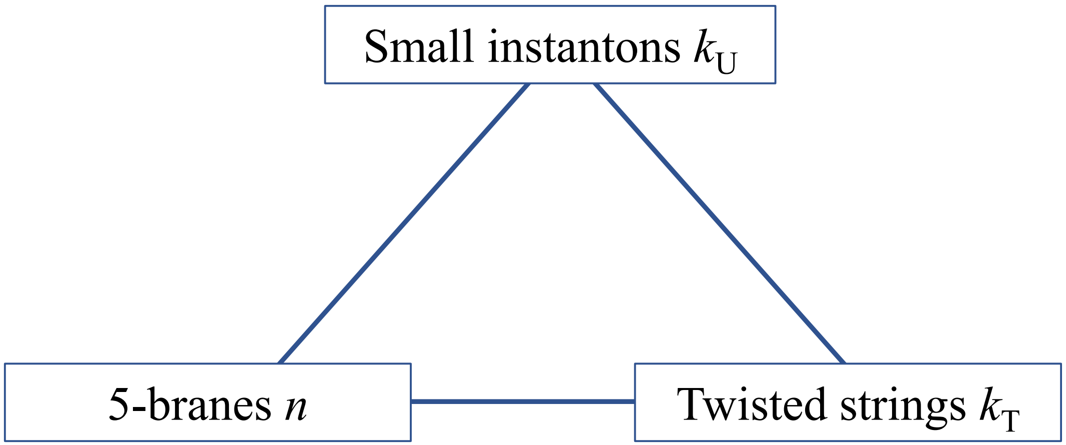
$U: (\mathbf{2}, \mathbf{28}) + 3(\mathbf{1}, \mathbf{1})$

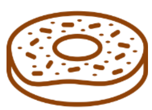
$T: 9(\mathbf{2}, \mathbf{28}) + 18(\mathbf{1}, \mathbf{1}) + 45(\mathbf{1}, \mathbf{1})$

$k_U = 3 \cdot 2 = 6$
$k_T = \#$ vectors $= 18$



Transitions

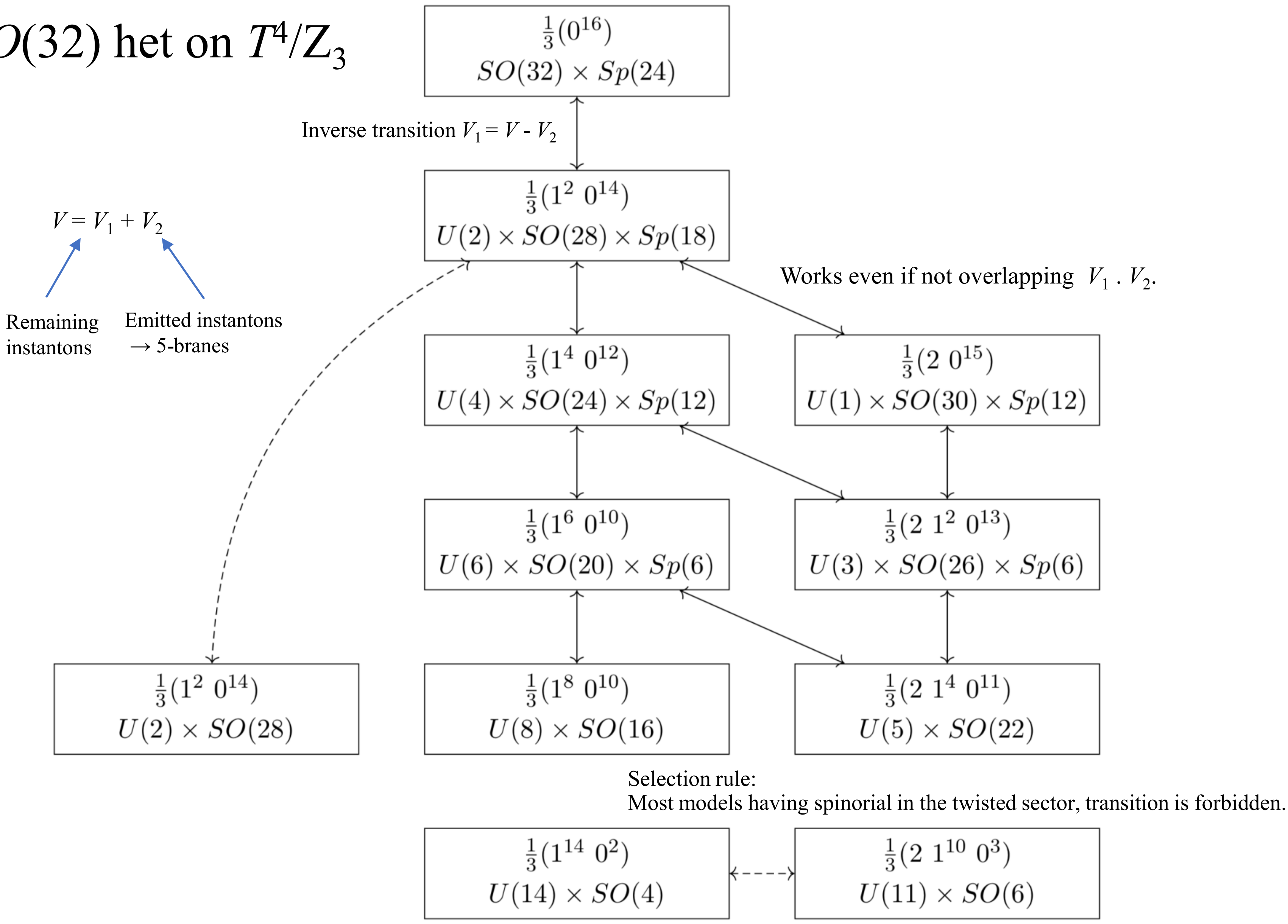




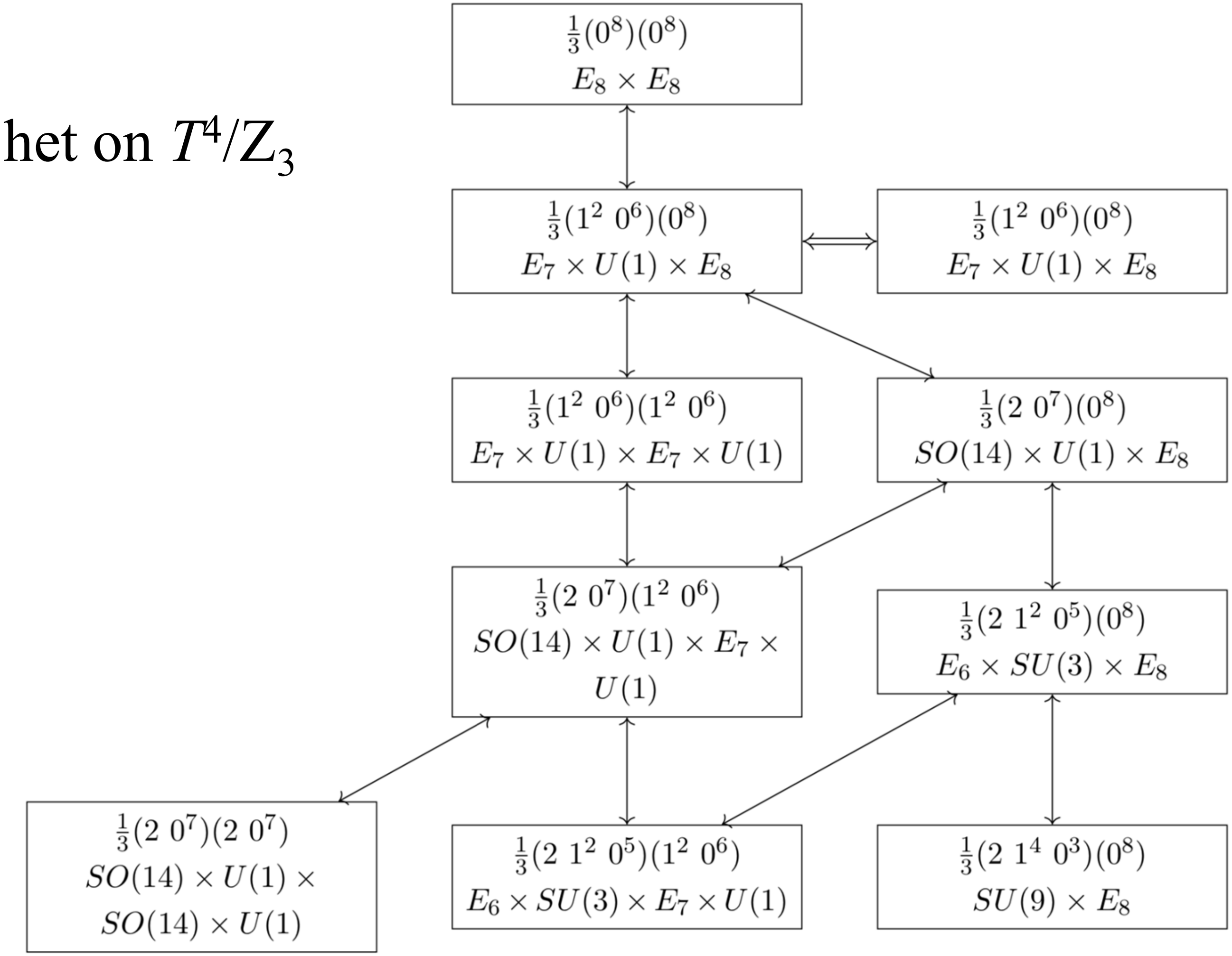
Invariant $k_U + k_T + n = 24$.

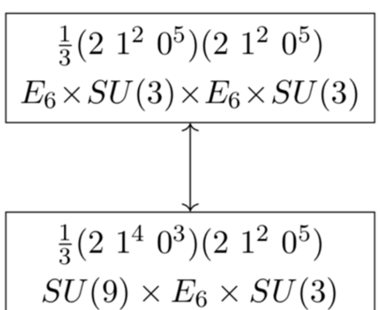
- Fixed points: 5+1 dimensional defect = branes.

$SO(32)$ het on T^4/Z_3



$E_8 \times E_8$ het on T^4/Z_3





In $E_8 \times E_8$, no extra gauge group from 5-branes

Worldsheet CFT with 5-branes

- Every non-perturbative vacua are inherited from perturbative vacua.

$$V = V_1 + V_2$$

Remaining instantons (V_1)   Emitted instantons → 5-branes (V_2)

- Worldsheet CFT

$$\frac{1}{2}m_L^2 = \frac{(P+V_1+V_2)^2}{2} + \tilde{N} + E_0 \quad \text{perturbative}$$

$$= \frac{(P+V_1)^2}{2} + \tilde{N} + E_0 + \Delta E_0 \quad \text{non-perturbative}$$

- GSO Projection

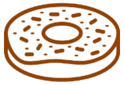
$$e^{2\pi i\left(\tilde{N}-N+(P+V)\cdot V-(s+\phi)\cdot\phi-\frac{1}{2}\left(V^2-\phi^2\right)\right)}$$

$$e^{2\pi i\left(\tilde{\mathrm{N}}-\mathrm{N}+(P+V_1)\cdot V_1-(s+\phi)\cdot\phi-\frac{1}{2}\left(V_1^2-\phi^2\right)+\Delta E_0\right)}$$

$$\Delta E_0 = V_1 \cdot V_2 + \frac{1}{2}V_2^2 = \frac{n}{54}$$

Modified zero point energy

- The same CFT description!

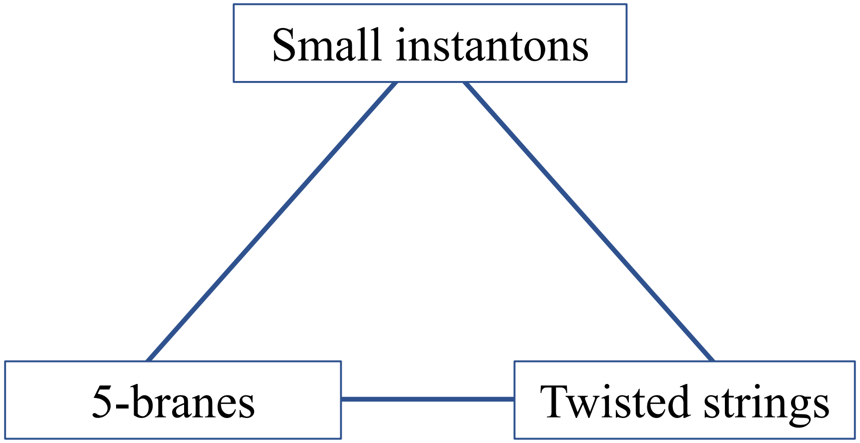
- Modular invariance 

$$\frac{V^2}{2} - \frac{\phi^2}{2} + \Delta E_0 \equiv 0 \quad \mathrm{mod}\ \frac{1}{N}$$

- Instanton # $k_1 + k_2 + n = 24$.

Conclusion

- Heterotic string on orbifolds in the presence of 5-branes.
    - Spectrum, GSO projection and consistency conditions.
- Phase transitions



- Many vacua with different gauge groups and spectra are connected.
- Not all. How general?
    - Branching of twisted string spectrum.