Constructions of Non-SUSY String Vacua With Vanishing Cosmological Constant

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Introduction

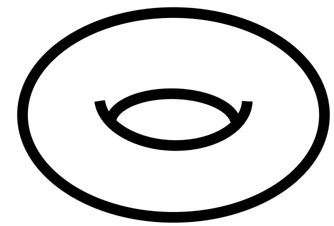
What's cosmological constant?

Cosmological const. = vacuum energy density

$$\Lambda_{\text{1-loop}} \sim \sum \left[\text{1-loop vacuum diagram}\right]$$

Cosmological Constant in String Theory

Torus partition function



Torus, moduli τ

$$\Lambda = \frac{1}{V_d}\int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2}\, Z_{\rm torus}(\tau)$$
$$= \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2}\, \frac{1}{\tau_2^{\frac{d-2}{2}}} \sum_{(i,\tilde{i})\in\mathcal{H}_\perp} D(h_i,\tilde{h}_{\tilde{i}})\, q^{h_i-\frac{1}{2}}\, \overline{q^{\tilde{h}_{\tilde{i}}-\frac{1}{2}}}$$

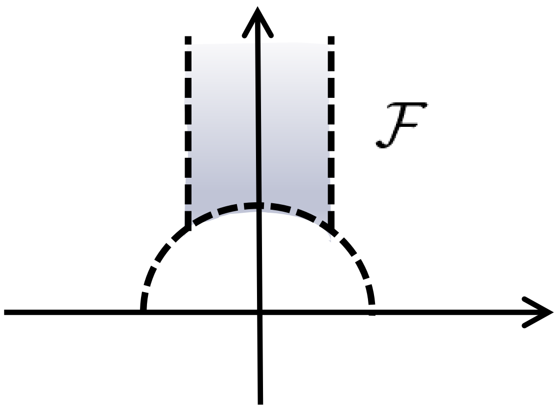
$$(q \equiv e^{2\pi i\tau})$$

Cosmological Constant in String Theory

Modular invariance

$$Z_{\text{torus}}\left(-\frac{1}{\tau}\right) = Z_{\text{torus}}(\tau), \qquad Z_{\text{torus}}(\tau+1) = Z_{\text{torus}}(\tau)$$

⇒ integration region :



‘cosmological constant problem’

$$\Lambda_{\text{observation}} \ll M^4_{\text{SUSY breaking}}$$

→ suggests a vacuum with (nearly) vanishing cosmological constant without SUSY?

→ We want to obtain a ‘hint’ to resolve this issue in string theory.

Non-SUSY with $\Lambda = 0$?

Two possibilities

(1) $Z(\tau) \equiv 0$, but no supercharges exist.

1st part

(2) $Z(\tau) \not\equiv 0$, but $\Lambda = 0$

2nd part

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Asymmetric Orbifolds

as

Non-SUSY String Vacua with Vanishing Cosmological Constant

How to break SUSY?

Orbifolding by $(-1)^{F_L}$

$\left(F_L \right.$: left-moving space-time fermion number $\left. \right)$

→ Removes massless Ramond states in the untwisted sector. (break SUSY?)

→ But, new massless Ramond states emerge in the twisted sector. (eventually, SUSY)

How to break SUSY?

Orbifolding by $(-1)^{F_L} \otimes \mathcal{T}_{2\pi R}$

shift operator

'Scherk-Schwarz Compactification'

Lightest Ramond states in the twisted sectors get massive. (No supercharge can appear.)

SUSY breaking

Non-SUSY Model with $\Lambda = 0$

Non-SUSY string vacua (type II)
with vanishing
1-loop cosmological constant

[Kachru, Kumar, Silverstein 1998], [Kachru, Silverstein 1998], [Kachru, Silverstein 1998]

Asymmetric orbifold defined by the orbifold group:

$$G = \langle f, g \rangle$$

f, g do not commute. → Non-abelian orbifold

f → includes $(-1)^{F_R}$ and (chiral) shift op.

→ break all the right-moving SUSY

g → includes $(-1)^{F_L}$ and (chiral) shift op.

→ break all the left-moving SUSY

→ **Non-SUSY in total**

However, for instance,

$$f\,\underset{1}{\square} = g\,\underset{1}{\square} = 0,$$

※ $f\,\underset{g}{\square}$ is not allowed because f and g do not commute with each other.

The 1-loop cosmological constant (torus partition function) strictly vanishes.

Bose-fermi cancelation without SUSY

Clever, but looks complicated…

Closely related studies :

[Harvey 1998]

[Shiu, Tye 1998]

[Blumenhagen, Gorlich 1998]

[Angelantonj, Antoniadis, Forger 1999]

[Aoki, D'Hoker, Phong 2003]

....

Non-SUSY Model with $\Lambda = 0$

My studies

[Satoh, Y.S, Wada 2015]

[Y.S, Wada 2016]

[Satoh, Y.S, Uetoko 2017]

[Y.S, Uetoko 2018]

[Aoyama, Y.S 2020]

[Aoyama, Y.S 2021]

Non-SUSY Model with $\Lambda = 0$

[Satoh, Y.S, Wada 2015] [Y.S, Wada 2016]

- Realized by simpler orbifold actions.

  (only single generator in the orbifold group)

- Each building block $Z_{(a,b)}(\tau)$ separately vanishes.

  (bose-fermi cancellation in each sector)

[Satoh, Y.S, Uetoko 2017] [Y.S, Uetoko 2018]

- Extensions to open string sector.

Non-SUSY Model with $\Lambda = 0$

[Aoyama, Y.S 2020] (type II)

[Aoyama, Y.S to appear] (hetero)

- Asymmetric orbifolds of Gepner models

  (first attempt of non-toroidal model)

- Each building block $Z_{(a,b)}(\tau)$ does not necessarily vanish.

  (bose-fermi cancellation among the different twisted sectors)

Non-SUSY Model with $\Lambda = 0$

Nevertheless, we cannot construct the space-time supercharges as well-defined conserved quantities on the world-sheet.

Crucial point :

The sector which can contain the candidates of space-time supercharges is twisted w.r.t both the left and right movers, while the conserved charges should be chiral operators.

Non-SUSY Vacua with Vanishing Cosmological Constant : part 2

[Satoh, Y.S 2022]

Non-SUSY Model with $\Lambda = 0$: part 2

Two possibilities

(1) $Z(\tau) \equiv 0$, but no supercharges exist.

(2) $Z(\tau) \not\equiv 0$, but $\Lambda = 0$

no bose-fermi cancellation

Non-SUSY Model with $\Lambda = 0$: part 2

It seems very difficult to construct the string vacua with such property…

[Moore 1987] `Atkin-Lehner symmetry'

⇒

It is possible to construct such vacua in particle theories with infinite number of mass spectra.

Non-SUSY Model with $\Lambda = 0$: part 2

[Satoh, Y.S 2022]

Start with some SUSY string vacuum $\mathcal{M}_0$

'SS-type' compactification by $\boldsymbol{g} := g \otimes \mathcal{T}_{2\pi\epsilon}$

g does not commute with any supercharges

$\mathcal{T}_{2\pi\epsilon}$: shift operator

⇒ 'particle theory' $\mathcal{M}[\epsilon]$

orbifold projection without twisted sectors

※ SUSY is recovered when taking $\epsilon \longrightarrow \infty$

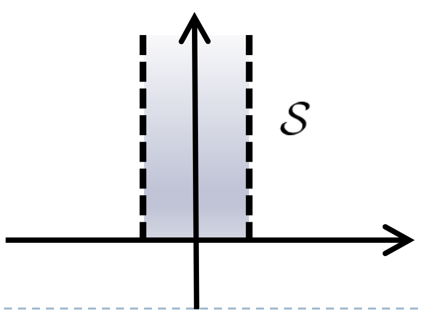
$$\boldsymbol{Z}_{\mathcal{M}[\epsilon]}(\tau) \propto \sum_{m\in\mathbb{Z}} \mathrm{Tr}_{\mathcal{M}_0}\left[\boldsymbol{g}^m\, q^{L_0-\frac{c}{24}}\overline{q^{\tilde{L}_0-\frac{c}{24}}}\right] \neq 0$$

no bose-fermi cancellation

$$\Lambda_{\mathcal{M}[\epsilon]} \equiv \frac{1}{V_D}\int_{\mathcal{S}} \frac{d^2\tau}{\tau_2^2}\, \boldsymbol{Z}_{\mathcal{M}[\epsilon]}(\tau)$$
$$= \int_0^\infty \frac{d\ell}{\ell}\,(2\pi\alpha'\ell)^{-\frac{D}{2}} \sum_{i\in\mathcal{H}[\mathcal{M}[\epsilon]]} D(m_i)\, e^{-2\pi\ell\frac{\alpha'}{2}m_i^2}$$

(D : dim of non-compact space-time)

Particle



We require the conditions (* *) for $\mathcal{M}_0$, g

$$\sum_{a,b} Z_{(a,b)}(\tau) = 0, \quad \text{while} \quad \sum_{b} Z_{(0,b)}(\tau) \neq 0,$$

+ some physically reasonable conditions

Under the conditions (* *) ,

we can prove $$\lim_{\epsilon \to +0} \Lambda_{\mathcal{M}[\epsilon]} = 0, \quad \text{for } {}^{\forall} D \geq 1$$

More precisely, $$\Lambda_{\mathcal{M}[\epsilon]} \sim \epsilon^{2D} M_{\rm SUSY}^{D} \sim \epsilon^{D} M_s^{D}$$

$$(\; M_{\rm SUSY} \sim \epsilon^{-1} M_s \;)$$

while one naively estimates

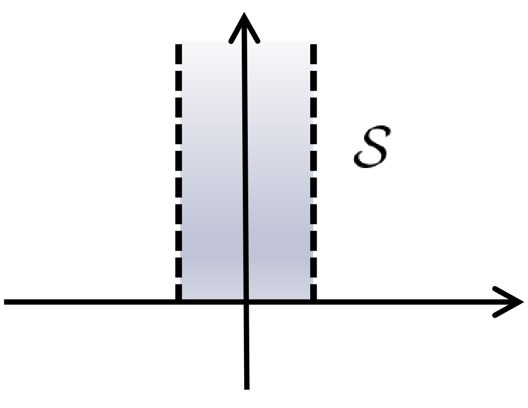
$$\Lambda_{\mathcal{M}[\epsilon]} \sim M_{\rm SUSY}^{D} \sim \epsilon^{-D} M_s^{D}$$

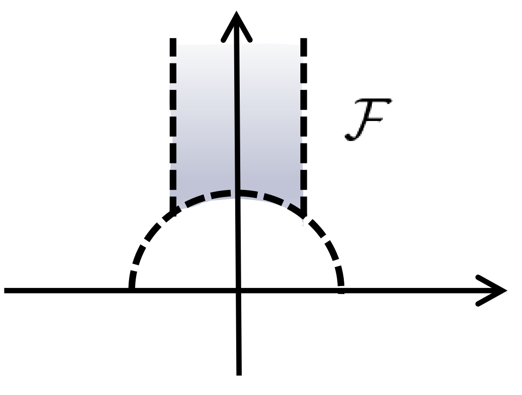
Crucial point :

'Polchinski's trick' [Polchinski 1986]

$$\int_{\mathcal{S}} \frac{d^2\tau}{\tau_2^2} \sum_{m\in\mathbb{Z}} Z_{(0,m)}(\tau) = \int_{\mathcal{F}} \frac{d^2\tau}{\tau_2^2} \sum_{w,m\in\mathbb{Z}} Z_{(w,m)}(\tau)$$

(assume $Z_{(0,0)}(\tau) \equiv 0$)





The concrete examples satisfying the conditions (＊ ＊) have been made up based on the asymmetric orbifolds of SUSYstring vacua associated to the Lie algebra Lattice (Englert Neveu Lattice).

[Satoh-Y.S. 2022]

Higher loop corrections to CC ?

We expect the similar suppressions by powers of ϵ in the higher loop contributions to CC, based on the modular argument for the Riemann surfaces with higher genera.
($\longrightarrow$ should be strictly confirmed)

Summary

Summary

- Non-SUSY string vacua with $Z(\tau) \equiv 0$

→ can be constructed by asymmetric ('non-geometric') orbifold.

toroidal and non-toroidal models. (asymmetric orbifolds of Gepner models.)

Summary

- Vanishing CC with $Z(\tau) \neq 0$

→ seems difficult to realize in string theory, but it could be possible as particle vacua.

(further studies needed : higher loop corrections, interactions, …)

Thank you very much for listening.