A journey through the non supersymmetric landscape

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Motivation

String Theory provides the best candidate for an unified theory of quantum gravity.

- In this framework **supersymmetry** occupies a prominent place, both theoretically and phenomenologically.
- Despite this, we do not observe supersymmetry within the energy ranges of current experiments.
- Therefore it is crucially important to investigate the consistency and the structure of String Theories where supersymmetry is absent, both in spacetime and branes.

Goals of this talk

~~SUSY~~ theories are (perturbative) anomaly free ⚠ → Sugimoto: possible brane anomaly

[Alvarez-Gaume, Ginsparg, Moore, Vafa '86/ Dixon, Harvey '86/ Sagnotti '95,'97/ Sugimoto '99/ Dudas, Mourad '01, Sagnotti '02]

1. Verify anomaly cancellation via inflow on the branes' worldvolume.
2. Study the structure of the gauge group and hints of new dualities to heterotic strings.
3. Constrain 10d $Sp(16)/\mathbb{Z}_2$ gravitational QFTs by means of anomaly cancellation.

The $SO(16)^2$ heterotic theory endows a discrete topological term in the spacetime action

[Tachikawa, Zhang '24]

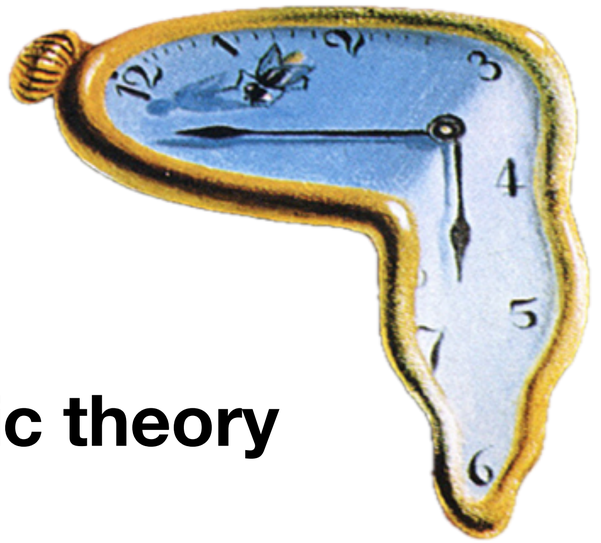
4. Prove the consistency of a tentative NS5-brane spectrum.

[Basile, Debray, Delgado, Montero '23]

Present my latest study on Type II ~~SUSY~~ orbifolds with zero 1-loop cosmological constant.

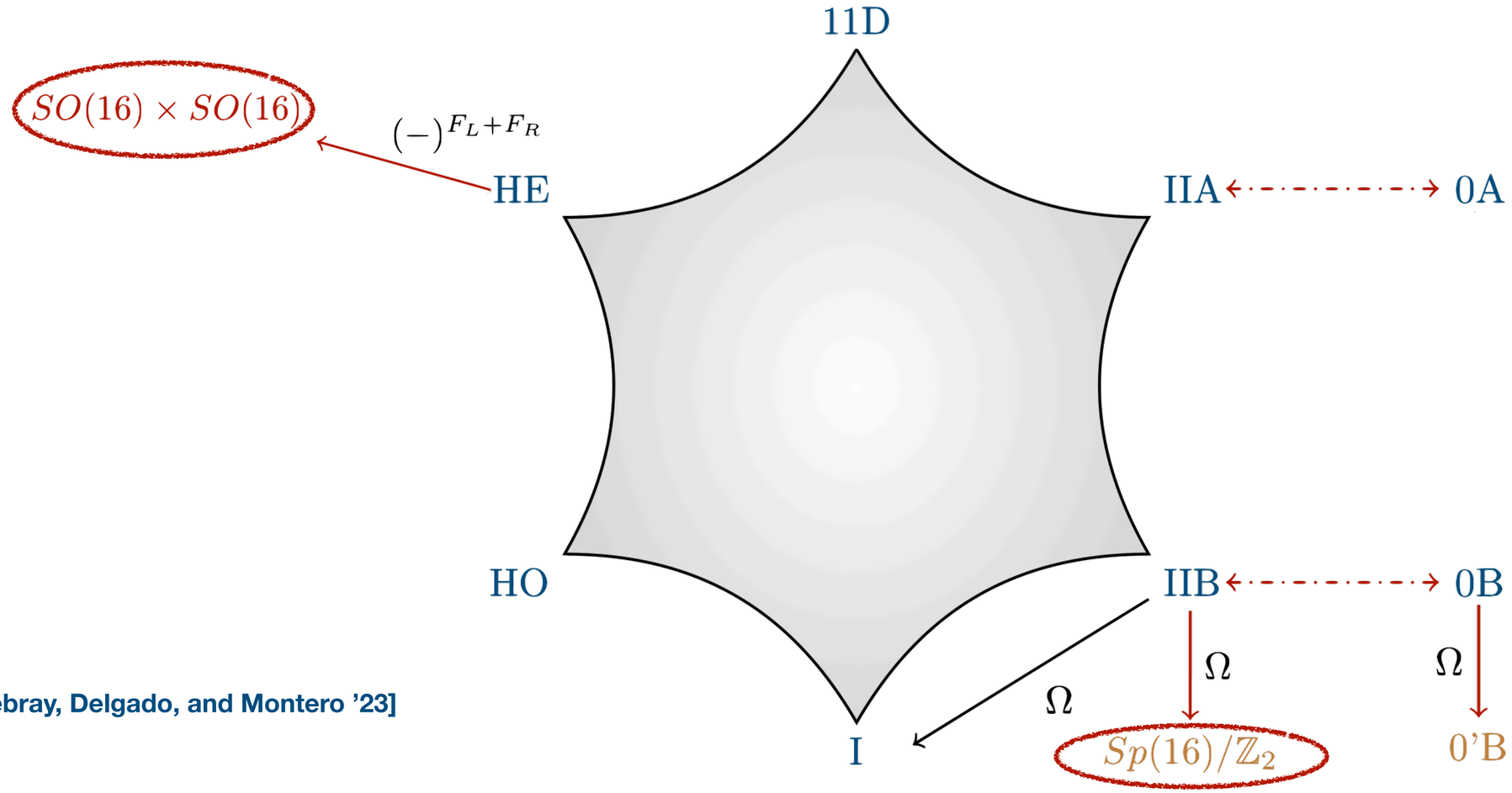
Outline

1. ~~SUSY~~ Strings & Anomalies
2. The structure of the Sugimoto model
3. Discrete topological term in the ~~SUSY~~ heterotic theory
4. ~~SUSY~~ asymmetric orbifolds



1. ~~SUSY~~ Strings & Anomalies

Non-supersymmetric String Theories



[Basile, Debray, Delgado, and Montero '23]

There are 3 non-supersymmetric 10d models without tachyons: Sagnotti, Sugimoto and the heterotic model.

[Sagnotti '95/ Sagnotti '97]

[Sugimoto '99]

[Alvarez-Gaume, Ginsparg, Moore, Vafa '86/ Dixon, Harvey '86]

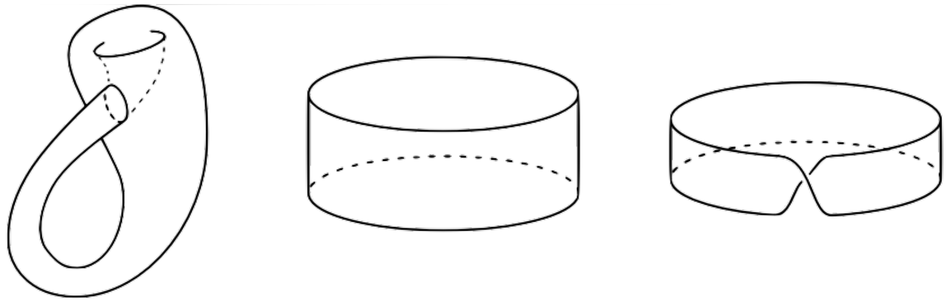
Sugimoto model

The (other) orientifold of Type IIB

- Anomaly cancellation: $O9 + 16\bar{D}9$

  $\Longrightarrow$ Brane supersymmetry breaking

  [Antoniadis, Dudas, Sagnotti '99/ Angelantonj '00/ Aldazabal, Uranga '99/ Angelantonj, Antoniadis, D'Appollonio, Dudas, A. Sagnotti '00]



Klein bottle Annulus Möbius strip

- Open string sector: $\mathfrak{sp}(16)$ gauge algebra.

- Chiral massless spectrum: Gravitino, Dilatino and **495 + 1** (anti-symmetric).

- Two dual RR gauge fields B_2 and $B_6 \Longrightarrow$ charged $D1$ and $D5$- branes.

~~SUSY~~ Heterotic Theory

The $SO(16) \times SO(16)$ is the only 10d ~~SUSY~~ heterotic theory without the tachyon.

The supersymmetric heterotic theories are both endowed of

- Spacetime gauge group
  - HE with $E_8 \times E_8$
  - HO with $Spin(32)/\mathbb{Z}_2$
- NS5-branes
  - rank-k E-string
  - $\mathfrak{sp}(k)$ [Mourad '97]
- Green-Schwarz mechanism in spacetime

The ~~SUSY~~ chiral spectrum can be understood as a subtraction of the SUSY ones:

$$I_{12}^{SO(16)^2} = I_{12}^{HO} - I_{12}^{HE}$$

Green-Schwarz mechanism & anomaly inflow

A general d-dimensional anomaly polynomial can be written as

$$I_{d+2} = X_{d+2} + X_2 \wedge X_d + X_4 \wedge X_{d-2} + \dots$$

Terms of the form $\int B_p \wedge X_{d-p}$ may cancel the anomaly if the polynomial factorizes and

[Green, Schwarz '84/ Sagnotti '92]

$$\delta_\varepsilon B_p = X_p^{(1)} \Leftrightarrow dH_{p+1} = X_{p+2}$$

String structure for p=2

Lower dimensional defects host chiral QFT that may be anomalous.

The coupling term contributes to the anomaly with an **inflow**

$$\int_{W_p} B_p \,.$$

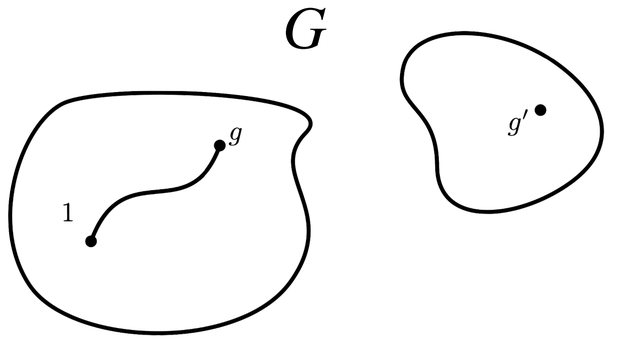
Consistency ⇔ matching between worldvolume anomaly and inflow.

[Callan, Harvey '85/ Blum, Harvey '94/ Freed, Harvey, Minasian, Moore '98/ Lawrie, Schäfer-Nameki, Weigand '17/ Kim, Shiu, Vafa '19/ Angelantonj, Bonnefoy, Condeescu, Dudas '20/ Martucci, Risso, Weigand '23/ Hamada, Vafa '21/ Bedroya, Hamada, Montero, Vafa '21…]

Global anomalies

We have discussed perturbative anomalies, related to “small” gauge transformations.

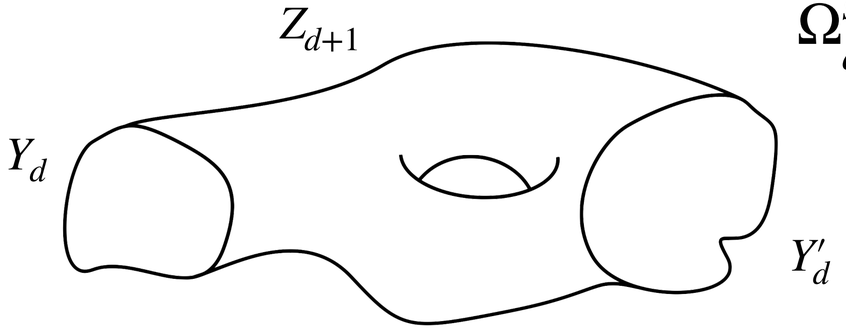
The treatment of “large” gauge transformations is more involved.



These led to global anomalies, encoded in the homotopy groups [Witten ’82]

$$\pi_d(G)$$

Modern understanding: Dai-Freed anomalies and bordism groups. [Garcìa-Etxebarria, Montero ’18/ Hsieh ’18]



$$\Omega^{spin}_{d+1}(BG) = \frac{\{\text{Mfld w/ properties}\}}{\sim}$$

Anomaly inflow

Gauge group topology
&
Dualities

Bottom-up anomaly constraints

2. The structure of the Sugimoto model

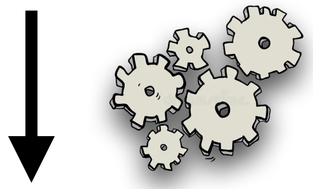
[V.L., L. Lin ’24]

Brane anomalies in the Sugimoto model

From open string amplitudes we can read the brane's spectrum:

D1

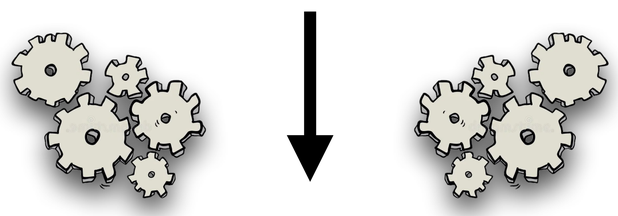
Chirality	$\mathfrak{so}(8)_T$	$\mathfrak{sp}(16)_B$	$\mathfrak{sp}(n)_W$
$(+)$	$\mathbf{8}_c$	$\mathbf{1}$	$\square$
$(-)$	$\mathbf{8}_s$	$\mathbf{1}$	$\square\square$
$(+)$	$\mathbf{1}$	$\mathbf{32}$	$\square$



$$I_4 = nX_4 \xrightarrow{\text{descent}} -\delta S_{D1}\,.$$

D5

Chirality	$\mathfrak{so}(4)_T$	$\mathfrak{sp}(16)_B$	$\mathfrak{so}(n)_W$
$(+)$	$\mathbf{2}_c$	$\mathbf{1}$	$\square$
$(-)$	$\mathbf{2}_s$	$\mathbf{1}$	$\square\square$
$(+)$	$\mathbf{1}$	$\mathbf{32}$	$\square$



$$I_8 = nX_8 + \big(X_4 + n\chi(N)\big) \wedge Y_4 \xrightarrow{\text{descent}} -\delta S_{D5}\,.$$

Anomaly inflow cancels $D1$ and $D5$ brane anomaly $\Longrightarrow$ Sugimoto model is (perturbative) anomaly free!

Furthermore, the Sugimoto model has no global anomalies.

[Basile, Debray, Delgado, and Montero '23]

Investigating the Gauge Group

The 10d spectrum of Sugimoto is invariant under the $\mathbb{Z}_2$-center of $Sp(16)$.

Problem:

Do the (bifundamental) representations on the branes change this situation?

Workflow:

- Canonically quantize these modes on the brane.
- Consider the branching products invariant under the worldvolume gauge algebra.
- Check if the corresponding spacetime representations break the $\mathbb{Z}_2$ center.

D1- and D5-branes' mode quantization

As for the D0 in Type I, we quantize the bifundamental on the D1-brane:

[Witten '23]

$$(\mathbf{32},\mathbf{2n})\ \text{of}\ \mathfrak{sp}(16)_B \oplus \mathfrak{sp}(n)_W \xrightarrow{\text{Quantization}} \{\chi_{i,\alpha},\chi_{j,\beta}\} = \omega_{ij}\omega_{\alpha\beta} \xrightarrow{\text{Indices rearrangement}} \{\chi_I,\chi_J\} = \delta_{IJ}$$

This is a Clifford algebra over the vector **64n** of $\mathfrak{so}(64n)$, associated with the branching:

$$\mathfrak{so}(4mn) \supset \mathfrak{sp}(m) \oplus \mathfrak{sp}(n), \qquad \mathbf{4mn} \to (\mathbf{2m},\mathbf{2n})$$

Physical states ≡ singlets

Then, the Hilbert space of the D1-brane accounts for the spinor representations.

The computation for the D5-brane modes is analogous.

We decompose the equivalence classes of the spinors using the projection matrix.

[Yamatsu '20]

D1 and D5 worldvolume gauge-invariant irreps **must** be also invariant under $\mathbb{Z}_2$.

Duality to Heterotic Strings?

We have found strong evidence that the 10d gauge group of Sugimoto is $Sp(16)/\mathbb{Z}_2$.

In SUSY strings Type I $\overset{\text{S-duality}}{\longleftrightarrow}$ $Spin(32)/\mathbb{Z}_2$ heterotic.

S duality:

$$\Lambda_r \longleftrightarrow \Lambda_{cr} \implies \mathfrak{sp}(16) \text{ S-dual algebra } \mathfrak{g} = \mathfrak{so}(33)$$

$$\Lambda_c \longleftrightarrow \Lambda_{cc} \implies Sp(16)/\mathbb{Z}_2 \text{ S-dual group } \hat{G} = Spin(33)$$

This algebra/group does not appear as the gauge symmetry in ~~SUSY~~ heterotic theories.

BUT trough the embedding $\mathfrak{so}(33) \supset \mathfrak{so}(32), \quad \mathbf{528} \to \mathbf{496} \oplus \mathbf{32}$

$Spin(32)$ ~~SUSY~~ heterotic string is a candidate to be the possible S-dual of Sugimoto.

[Fraiman, Grana, Parra De Freitas, Sethi '24]

[See also Basile '23]

Bottom-up constraints for $Sp(16)/\mathbb{Z}_2$ theories

Consider the set of chiral 10d ~~SUSY~~ $Sp(16)/\mathbb{Z}_2$ theories coupled to gravity.

No 1-form symmetry anomaly. [Apruzzi, Dierigl, Lin '20/ Cvetič, Dierigl, Lin, Zhang '20]

$$I_{12} = n_{\mathbf{1}} I_{12\,\mathbf{1}} + n_g I_{12\,g} + n_{\square\atop\square} I_{12\,\square\atop\square} + n_{\square\square} I_{12\,\square\square}.$$

Green-Schwarz: • $X_{12} = 0 \implies n_{\square\square} = 0$ and $n_{\mathbf{1}} = 495 n_g - 496 n_{\square\atop\square}$

$\tilde{X}_4 = \frac{1}{2}\left[trR^2 - \beta trF^2\right]$

• Imposing $I_{12} = \tilde{X}_4 \wedge \tilde{X}_8 \implies n_g = n_{\square\atop\square}$ and $\beta = 1$.

⚠ For the structure of $Sp(16)/\mathbb{Z}_2$ this is the only possible factorization $\implies \exists B_2$ and charged 1 and 5 branes

Anomaly inflow: anomaly cancellation requires $n_{\square\atop\square} = 1$

The only possible 10d realization of $Sp(16)/\mathbb{Z}_2$ is the Sugimoto model! 🏅

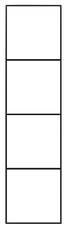
Consistency of tentative $Sp(16)/\mathbb{Z}_2$ models

Extending our search of $Sp(16)/\mathbb{Z}_2$ models by enlarging the set of matter representations.

Allow for higher rank representations of $Sp(16)/\mathbb{Z}_2$, both in space-time and world-volume.

$$I_{12} = n_{\mathbf{1}} I_{12\,\mathbf{1}} + n_g I_{12\,g} + n_{\square\atop\square} I_{12\,\square\atop\square} + n_{\square\square} I_{12\,\square\square} + \ldots$$

❌ Obstruction to GS mechanism

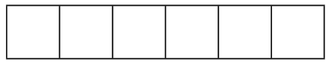


$\beta = \frac{4095}{3071}$

✅ Anomaly cancellation in space-time

❌ Obstruction to anomaly inflow onto 1-brane

$\beta = -2, -4$



✅ Anomaly cancellation in space-time

✅ Anomaly inflow onto 1-brane

❌ Obstruction to anomaly inflow onto 5-brane

3. Discrete topological term in the ~~SUSY~~ Heterotic theory

[I. Basile, V.L. ’25]

Discrete topological term

[Tachikawa, Zhang '24]

Global counterpart of the Green-Schwarz mechanism, classified by

$$\Omega_{10}^{String} = \mathbb{Z}_2 \times \mathbb{Z}_3$$

We consider a ten-dimensional theory with a Green-Schwarz mechanism

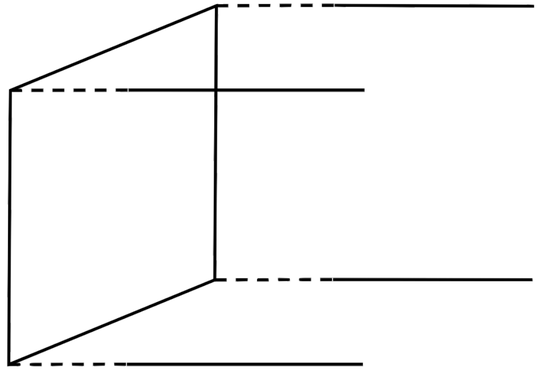
$$\int_{M_{10}} B_2 \wedge Y = \int_{M_{10}} H_3 \wedge CS[Y]$$

If we choose M_{10} as

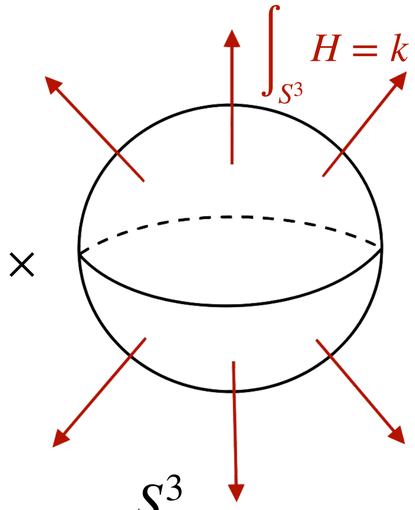
$S^3 \hookrightarrow M_{10} \longrightarrow N_7 \cong \mathbb{R}_{>0} \times N_6'$ with H-flux

we recover the inflow onto the NS5-brane

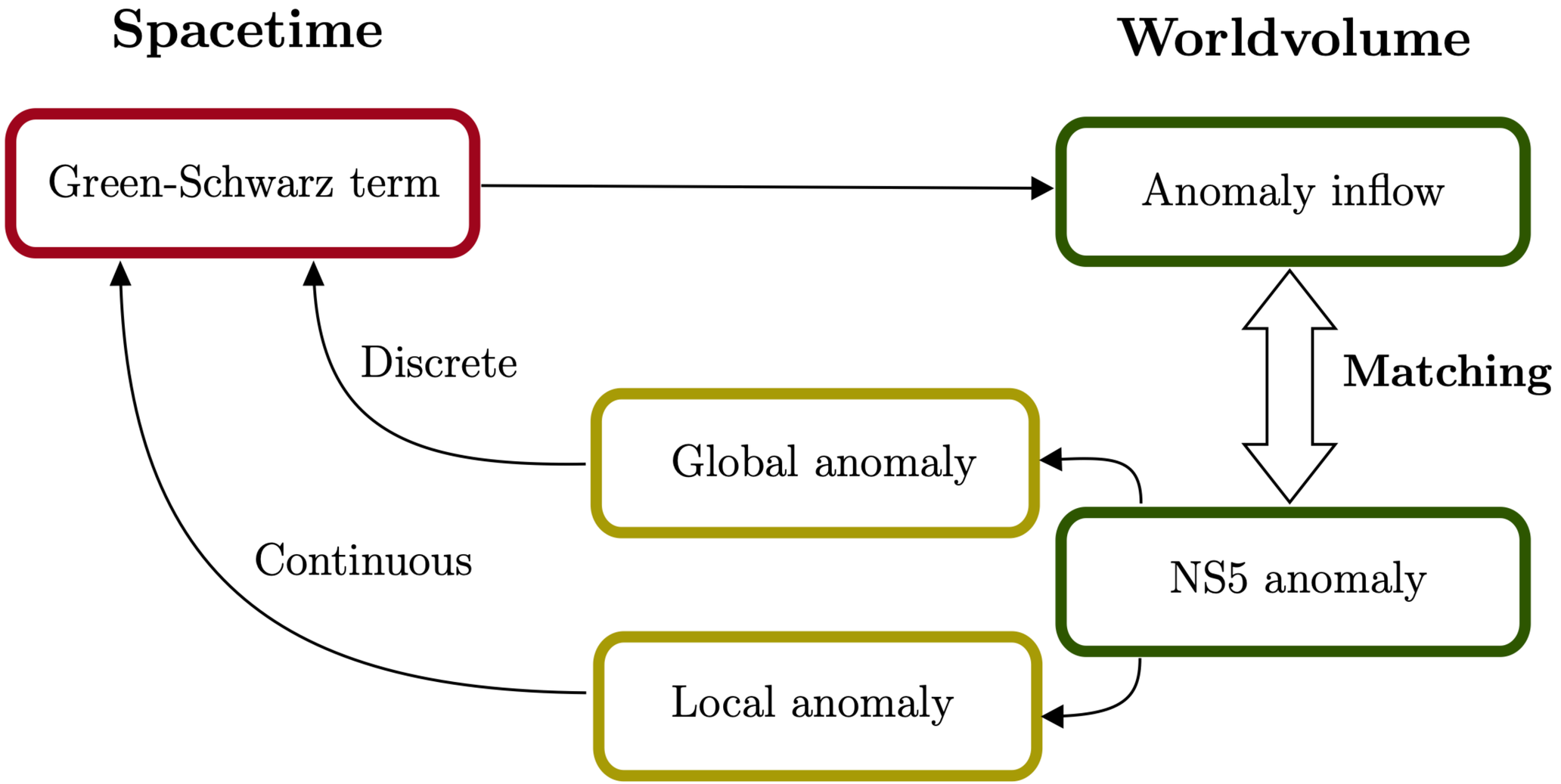
$$k \int_{N_7} CS[Y]$$



$N_7 \cong \mathbb{R}_{>0} \times N_6'$



Strategy


Spacetime
Worldvolume
Green-Schwarz term
Anomaly inflow
Discrete
Matching
Global anomaly
NS5 anomaly
Continuous
Local anomaly

The global anomaly

Our aim is to compute the global anomaly of the NS5 worldvolume theory.

These objects break the spacetime Lorentz symmetry to

$$SO(1,9) \longrightarrow SO(1,5) \times SO(4) \cong SO(1,5) \times SU(2)_R \times SU(2)_L$$

"R-symmetry"

The $SU(2)_R$ bundle is enough to detect the discrete topological term.

The global anomaly of $SU(2)$ is encoded by

$$\pi_6(SU(2)) = \mathbb{Z}_{12} \qquad \text{but with the spin structure} \qquad \Omega_7^{spin}(BSU(2)) = 0$$

Global anomaly on the NS5 $\Leftrightarrow$ Introduction of H_3 with $dH_3 = Z_4$

Evaluation [Tachikawa, Zhang '24]

We have an $SU(2)$ theory with a 6d Green-Schwarz mechanism:

$$I_8 = Z_4 \wedge W_4 \quad \text{with} \quad -\int_{N_6'} B_2 \wedge W_4 \qquad \text{where} \qquad I_8 = I_8^{Spin(32)/\mathbb{Z}_2} - I_8^{E_8 \times E_8}$$

[Ohomori, Shimizu, Tachikawa '14]

The perturbative anomaly is cancelled but the global one remains:

$$X = \eta[\mathscr{M}_7, Z_4 W_4] - \int_{\mathscr{M}_7} H_3 \wedge W_4$$

Using a standard method to compute it, we find

$$X = \frac{t}{12} \quad \text{and} \quad t = 8 \pmod{12}$$

Our approach

We consider a general $SU(2)$ spectrum providing the anomaly

$$I_8 = n_{\mathbf{1}} I_{\mathbf{1}} + n_{\mathbf{2}} I_{\mathbf{2}} + n_{\mathbf{3}} I_{\mathbf{3}} + n_{SD} I_{SD}$$

Factorization
+
Matching with the proposed spectrum

[Basile, Debray, Delgado, and Montero '23]

$$\Longrightarrow \quad \begin{cases} n_{SD} = -1\,, \\ n_{\mathbf{1}} = 32 + 13 n_{\mathbf{3}}\,, \\ n_{\mathbf{2}} = -2 - 8 n_{\mathbf{3}}\,. \end{cases}$$

We compute the global anomaly and find

$$t = 124 + 36 n_{\mathbf{3}} \cong 4 \pmod{12}$$

The analysis with the $SO(16) \times SO(16)$ bundle gives no further restrictions and suggests

$$n_{\mathbf{3}} = 0.$$

3. ~~SUSY~~ asymmetric orbifolds

[M. Montero, V.L., M. Tartaglia ’26]

~~SUSY~~ asymmetric orbifolds

A toroidal orbifold T^n/Γ is the quotient space of an n-torus by a finite isometry group Γ:

$$g \in \Gamma\,, \quad g|p_L, p_R\rangle = e^{2\pi i(-v_L\cdot p_L + v_R\cdot p_R)}|\theta_L\, p_L, \theta_R\, p_R\rangle \qquad (v_L, v_R) \text{ shifts, } (\theta_L, \theta_R) \text{ twists}$$

$L = R$

Symmetric orbifolds

[Dixon, Harvey, Vafa, Witten '85/86]

$L \neq R$

Asymmetric orbifolds

[Narain, Sarmadi, Vafa '87]

Considering Type II compactifications with $n = 6$, the one-loop cosmological constant is

$$\Lambda_1 \sim \int_{\mathcal{F}} \frac{d^2\tau}{\mathrm{Im}\tau}\mathcal{Z}(\tau,\bar\tau) \qquad \mathcal{Z}_{\text{orbifold}}(\tau,\bar\tau) = \frac{1}{N}\sum_{(f,g)}\mathcal{Z}[f,g] \quad \text{with} \quad fgf^{-1}g^{-1} = 1$$

If each commuting pair (f, g) preserves some supercharge, but not the same in all sectors

4d ~~SUSY~~ model with $\Lambda_1 = 0$.

~~SUSY~~ asymmetric orbifolds II

Besides some $\mathbb{Z}_2 \times \mathbb{Z}_2$ models, there is a lack of knowledge about these theories.

[Kachru, Kumar, Silverstein '98/ Harvey '98/ Shiu, Tye '98/ Angelantonj, Antoniadis, Forger '99/ Angelantonj, Cardella '04/ Satoh, Sugawara, Wada '15/ Ayoama, Sugawara '20]

We search for orbifold groups Γ with an action on the supercharges such that

1. $\forall g_i \in \Gamma$ has an invariant subspace $\Longrightarrow$ each sector preserves a supercharge
2. No global invariant subspace + invariant base torus $\Longrightarrow$ no SUSY
3. $(1, g_i)$ are the only commuting pairs $\Longrightarrow$ avoid contributions like $\mathcal{Z}[f, g] \neq 0$

1. and 2. $\Longrightarrow$ $\mathbb{Z}_3 \times \mathbb{Z}_3, \mathbb{Z}_4 \times \mathbb{Z}_4$ 3. $\Longrightarrow$ add shifts $\Longrightarrow$ anomalies! 

No-go for these models

New models

To find new models we have to drop the requirement of the invariant base torus

$\Longrightarrow$ check explicitly the absence of gravitini in twisted sectors, one by one!

We find **240** $\mathbb{Z}_3 \times \mathbb{Z}_3$ and **1125** $\mathbb{Z}_4 \times \mathbb{Z}_4$ actions.

Explicit examples: have a look at the paper!

You will also find two non-Abelian models, $S_3 \times \mathbb{Z}_3$ and D_6.

We are currently classifying non-abelian actions, stay tuned!

Conclusions

- The Sugimoto model is consistent and $Sp(16)/\mathbb{Z}_2$ naturally emerges as gauge group.
- The tentative spectrum of the NS5-brane gives a correct topological term.
- We observed a different $\mathbb{Z}_3$ value computing the DTT from the worldvolume.
- We found new ~~SUSY~~ asymmetric orbifolds with $\Lambda_1 = 0$.

Outlook

- Net of dualities and string universality also in the ~~SUSY~~ landscape?
- The subtraction of the spectra is structural feature of the ~~SUSY~~ theory?
- M-theoretical embedding of the ~~SUSY~~ heterotic theory?
- New models with non-abelian groups? What about Λ_n?

Thank you!
ありがとう!