Embedding the Salam-Sezgin model in type II

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- Talk aims:

  - 1: Briefly review consistent truncations and explain how our approach for constructing them is novel.

  - 2: Review the Salam-Sezgin model and why it is interesting.

  - 3: Explain how we embed the model in type II supergravity and give some examples.

- Allow me to frame things...

The utility of consistent truncations

- String theory is a fantastic frame work for studying physical problems
  - It is the leading contender for unifying gravity standard model forces
  - Allows for microscopic description of black holes
  - AdS/CFT allows one to probe gauge theories with string theory
- But strings live in $d = 10$, the world around us $d = 4$, SCFTs $d \leq 6$!
  - one needs to do something with the extra dimensions
- Conceptually this isn't really a problem
  - String pheno perspective, extra dimensions are small, yet to be observed
  - AdS/CFT perspective, extra dimensions capture symmetries of gauge dual
- There are problems on a technical level
  - Constructing solutions in gravity is hard, and difficulty scales with d
  - Usually need compact/bounded extra dimensions
- Useful to have an effective description in lower dimensions
- A very powerful tool in this regard are consistent truncations

So what is a consistent truncation?

A consistent truncation is essentially a map between theories of different dimensionality

- This is an old idea that goes back to Kaluza-Klein

  - 5d pure gravity on $\mathcal{M}_4 \times S^1 \quad \Rightarrow \quad$ 4d Einstein-Maxwell+dilaton theory

- In general EOM of theory in d dimensions imply those of $d+n$ dimensional theory

  - fields of low dim theory embedded into higher in the form

$$ds^2_{d+n} = \sqrt{\Delta} ds^2_d + ds^2(\mathrm{B}^n)$$

  - Δ can contain dim d scalars and B^n scalars and vectors

  - Fluxes also dim d tensors.

- In strings context if B^n is compact then n dimensions are taken care of

  - allows one to construct and study solutions in dim d

  - vast simplification

- But one needs a consistent truncations in hand

  - Actually constructing an embedding is challenging

Truncations from string dimensions

Consistent truncations of 10 and 11d supergravity to **gauged supergravities** have had much utility

- Usually these are of one of two types:

- Consistent truncations to maximally supersymmetric gauged supergravities :

  - Truncations to the theories with 32 supercharges

  - Large gauge symmetries must be respected by embedding

  - Constructed with Scherk-Schwarz procedure on $\mathrm{B}^n = \mathrm{S}^n$

  - Examples include truncations of 11d on S^4 and S^7, IIB on S^5 and IIA on S^6

  - Full non linear embedding still very challenging to construct:

  Ex: S^5 truncation proposed in 1985, full embedding found in 2015 [Baguet-Hohm-Samtleben]

- Consistent truncations to minimal gauged supergravities:

  - Typically truncations to theories with U(1) gauge symmetry and gauge field $\mathcal{A}$

  - Minimal fields turned on, so comparatively easy to embed

  - Often simply need to modify AdS vacua by housing $\mathcal{A}$ within existing S^1

  - Truncations of type II and 11d based on AdS_5 vacua are fully known. Other AdS_d only partially.

What about other cases?

There are many more gauged supergravities than these, but how to construct their higher dim embeddings?

- Truncations to maximal greatly benefited from developments in exceptional field theory
  - Used for full non-linear embedding of $d = 5$ maximal into type IIB
  - Have lead to truncations to half maximally supersymmetric gauged supergravities
  - But seems like not well suited for matter coupled minimal theories
- Truncations to minimal supergravities usually proceed by brute force
  - Minimal fields makes this tractable
  - Often there are no scalars making things particularly "easy"
  - Difficult to brute force inclusion of additional matter multiplets
- There is an exception: Embedding of minimal $d = 5$ into type IIA [Couzens-NTM-Passias]
  - This utilised bispinor techniques to embed the gauged and ungauged theories.
  - Very systematic: Geometric conditions for supersymmetry imply most of the embedding
  - Seems like same approach should work for matter coupled minimal theories
- This talk: I will show this is indeed the case, lifting the Salam-Sezgin model

- **The Salam-Sezgin model**
  - Generalities of the model
  - Why it is interesting
  - Geometric conditions for suspersymmetry
- **Embedding Salam-Sezgin into $d = 10$**
  - What is already known
  - Uplift recipe
  - Constraints on embedding manifolds
- **Example embeddings**
  - Some gauged and ungauged uplifts
- **Conclusions**

The Salam-Sezgin model

The Salam-Sezgin model, or $d = 6$ Einstein-Maxwell gauged supergravity, is not minimal

- Contains a gauge coupling g and the following multiplets (write Bosons only)

$$\text{Gravity}: \ (g^{(6)}_{\mu\nu},\ \mathcal{G}^-), \qquad \text{Tensor}: \ (\varphi,\ \mathcal{G}^+), \qquad \text{Vector}: \ \mathcal{A}$$

- where $\star\mathcal{G}^\pm = \pm\mathcal{G}^\pm$ such that $\mathcal{G} = \mathcal{G}^+ + \mathcal{G}^-$ is a generic 3-form.

- Inclusion of tensor multiplet allows for a "true" action for the theory

$$S = \int d^6x\sqrt{-g^{(6)}}\left[R - (\partial\varphi)^2 - 2e^{2\varphi}\mathcal{G}^2 - 2e^{\varphi}\mathcal{F}^2 - 2g^2e^{-\varphi}\right]$$

- where $\mathcal{F} = d\mathcal{A}$ and $\mathcal{G} = d\mathcal{B} + \mathcal{A}\wedge\mathcal{F}$.

- Theory is interesting for several reasons:

- The vacuum is not AdS_6

- The $e^{-\varphi}g^2$ term can yield positive cosmological constant.

- Action also has following symmetries (in addition to trombone sym):

- Scaling symmetry: $(\mathcal{G},\ e^{-\varphi},\ \mathcal{F},\ g) \to (\lambda\mathcal{G},\ \lambda e^{-\varphi},\ \lambda^{\frac{1}{2}}\mathcal{F},\ \lambda^{-\frac{1}{2}}g)$

- Follows that $d\varphi = 0$ equivalent to $\varphi = 0$

- When $g = \mathcal{F} = 0$ "S-duality": $(\mathcal{G},\ e^{2\varphi}\star_6\mathcal{G},\ \varphi) \to (-e^{2\varphi}\star_6\mathcal{G},\ -\mathcal{G},\ -\varphi)$

The Salam-Sezgin model: Generalities

- Supersymmetry is chiral *i.e* $\mathcal{N} = (1,0)$, in the absence of fermions, amounts to

$$\left(\mathcal{F} - ige^{-\varphi}\right)\zeta_- = 0, \quad \left(d\varphi - e^{\varphi}\mathcal{G}\right)\zeta_- = 0, \quad (\nabla_\mu - ig\mathcal{A}_\mu)\zeta_- + \frac{1}{4}e^{\varphi}\mathcal{G}\gamma_\mu\zeta_- = 0$$

  - ζ_- negative chirality Weyl spinor. Note that $\mathcal{F} = 0 \Rightarrow g = 0$

Some notable solutions include:

- Gravity multiplet only (ungauged): $\mathrm{AdS}_3\times \mathrm{S}^3$ black-string near horizon
  - Relevance to microstate counting, superstrata etc
- Gravity + vector: $\mathrm{Mink}_4\times \mathrm{S}^2$ solution [Salam, Sezgin]
  - Provides explicit chiral $\mathcal{N} = 1$ Mink_4 solution, *c.f* CY_3 compactions of type II
- Gravity + tensor + vector: Dionic-string solutions [Güven, Liu, Pope, Sezgin]
  - Some supersymmetric some not
- Gravity + tensor + vector: Two parameter $\mathrm{AdS}_3 \times$ [squashed S^3]
  - near horizon of the former case, spectrum shows scale separation with and without supersymmetry [Proust, Samtleben, Sezgin]

Crucial to our uplift method are geometric conditions of supersymmetry in $d = 6$

- Chiral spinor in 6d Lorenzian $\Rightarrow$ SU(2)$\ltimes\mathbb{R}^4$-structure

$$ds^2 = g^{(6)}_{\mu\nu} dx^\mu dx^\nu = 2kv + ds^2(\mathrm{M(SU(2))})$$

  - (k, v) null 1-forms $(J,\ \Omega)$ real and holomorphic SU(2)-structure 2-forms

- Bi-spinors are useful for making supersymmetry geometric

  - map to forms under Clifford map, in dim d

$$\not{\Psi} = \epsilon_1 \otimes \overline{\epsilon}_2 = \frac{1}{2^{[\frac{d}{2}]}} \sum_{n=0}^{d} \overline{\epsilon}_2 \gamma_{\mu_n \dots \mu_1} \epsilon_1 \gamma^{\mu_1 \cdots \mu_n} \to \Psi = \frac{1}{2^{[\frac{d}{2}]}} \sum_{n=0}^{d} \overline{\epsilon}_2 \gamma_{\mu_n \dots \mu_1} \epsilon_1 dx^{\mu_1 \cdots \mu_n}$$

- For the case at hand this leads to

$$\not{\psi}^{(6)}_- = \zeta_- \otimes \overline{\zeta}_-, \qquad \tilde{\not{\psi}}^{(6)}_- = \zeta_- \otimes \overline{\zeta^c_-},$$

$$\psi^{(6)}_- = -\frac{1}{8} k \wedge e^{-iJ}, \qquad \tilde{\psi}^{(6)}_- = \frac{1}{8} k \wedge \Omega$$

- One can then derive constraints on these forms that imply spinoral supersymmetry conditions

The Salam-Sezgin model: Supersymmetry as geometric conditions

- This is an exercise in G-structure torsion classes, technical...
- We find the following is necessary and sufficient for supersymmetry

$$\nabla_{(\mu}k_{\nu)} = 0, \qquad \mathcal{L}_k\varphi = 0, \qquad \iota_k\mathcal{F} = 0,$$

$$e^{-\varphi}d\psi_-^{(6)} = \frac{1}{8}\iota_k(\mathcal{G} - \star_6\mathcal{G}), \qquad d\tilde{\psi}_-^{(6)} = 2gi\mathcal{A}\wedge\tilde{\psi}_-^{(6)},$$

$$\iota_k(\mathcal{G} + \star_6\mathcal{G}) = -8e^{-\varphi}d\varphi\wedge\psi_1^{(6)},$$

$$\mathcal{F}\wedge\psi_1^{(6)} = \frac{1}{8}\iota_k\star_6\mathcal{F} + ige^{-\varphi}\psi_3^{(6)}, \quad \mathcal{F}\wedge\psi_3^{(6)} = ige^{-\varphi}\psi_5^{(6)},$$

$$v\wedge\Omega\wedge\Big[d(k\wedge v - iJ) + 2e^{\varphi}\mathcal{G}\Big] = 0,$$

$$v\wedge\Big[\mathrm{Im}\left(d\Omega\wedge\overline{\Omega}\right) - 2k\wedge J\wedge dv - 4(g\mathcal{A}\wedge J\wedge J - e^{\varphi}\mathcal{G}\wedge J)\Big] = 0,$$

- In particular $k^\mu\partial_\mu$ is a null Killing vector.
- conditions hold in general, tuning off g or the vector or tensor multiplet not problematic.

Embedding Salam-Sezgin into $d = 10$

Embedding Salam-Sezgin into $d = 10$: What is already known

There are previous works that lift Salam-Sezgin or its ungauged limit

- There is a F-theory uplift of $d = 6$ supergravity coupled to arbitrary vectors, tensor and hypers [Bonett-Grimm]

  - This contains the **UNGAUGED** Salam-Sezgin model as a special case

  - Uplift is a bit implicit

- There is a type IIB uplift with $g \neq 0$ [Cvetic, Gibbons, Pope]

$$ds^2 = \sqrt{\cosh(2\rho)}g^{(6)}_{\mu\nu}dx^\mu dx^\nu + \frac{e^{\varphi}}{2g^2}\sqrt{\cosh(2\rho)}\Big[d\rho^2 + d\phi_1^2 + \frac{\cosh^2\rho}{\cosh(2\rho)}(d\phi_2 - g\mathcal{A})^2$$

$$+ \frac{\sinh^2\rho}{\cosh(2\rho)}(d\phi_3 + g\mathcal{A})^2\Big], \qquad e^{-\Phi} = \frac{1}{\sqrt{\cosh(2\rho)}}e^{-\varphi}, \qquad (\mathcal{F},\ \mathcal{G}) \in F_3$$

  - Derived through a singular reduction of $d = 7$ maximal and its S^4 uplift

  - Note: $\mathrm{U}(1)^3$ isometry of ∂_{ϕ_i} in which $\mathcal{A}$ appears twice!

- However this uplift has issues:

  - The internal manifold is not compact/bounded

  - In fact as $\rho \to \infty$ the uplift of $\mathrm{Mink}_4\times\mathrm{S}^2$ approaches linear dilaton vacuum at infinity

Our general uplift philosophy is that

1. Embedding into type II should preserve $d = 10$ supersymmetry when $d = 6$ holds
2. Bosonic fields of type II should only depend on $d = 6$ data through

$$(g^{(6)}_{\mu\nu},\ \mathcal{F},\ \mathcal{G},\ \varphi), \quad D\phi = d\phi + V + \mathcal{A}$$

- in particular, should not depend on anything that requires ζ_- to define.

- This leads us to an embedding ansatz of the form

$$ds^2 = e^{2A} g^{(6)}_{\mu\nu} + ds^2(\mathrm{M}_4), \qquad H = H_3 + H_0\mathcal{G} + \tilde{H}_0 e^{2\varphi} \star_6 \mathcal{G} + H_1 \wedge \mathcal{F} + H_2 \wedge d\varphi,$$

$$F_\pm = (1 + \star\lambda)\left(f_\pm + e^{2A}\mathcal{F} \wedge g_\pm + e^{3A}\mathcal{G} \wedge g_\mp + e^{5A} \star_6 d\varphi \wedge h_\mp\right),$$

$$\epsilon^1 = \zeta_- \otimes \eta^1_- + \text{m.c}, \qquad \epsilon^2 = \zeta_- \otimes \eta^2_\pm + \text{m.c}$$

- When $g \neq 0$ we require

$$ds^2(\mathrm{M}_4) = ds^2(\mathrm{M}_3) + e^{2C} D\phi^2, \qquad \text{Only one U(1)}$$

- We are totally agnostic about embedding of $d = 6$ dilaton

- *i.e.* above internal fields and $d = 10$ dilaton Φ have function-like dependence on φ

Embedding Salam-Sezgin into $d = 10$: How embedding in performed

To deal with $d = 6 \Rightarrow d = 10$ supersymmetry make use of existing work [Tomasiello]

- Type II supersymmetry can be phrased in terms of bilinears

$$K = \frac{1}{2}(K_1 + K_2), \quad \tilde{K} = \frac{1}{2}(K_1 - K_2), \quad \Psi_\pm = \epsilon_1 \otimes \bar{\epsilon}_2, \quad K_{1,2} = \frac{1}{32}\bar{\epsilon}_{1,2}\Gamma_M \epsilon_{1,2} dX^M$$

- Geometric conditions for supersymmetry are

$$d\tilde{K} = \iota_K H, \quad \nabla^{(10)}_{(M} K_{N)} = 0, \quad d_H(e^{-\Phi}\Psi_\pm) = -(\tilde{K} \wedge + \iota_K) F_\pm$$

+ Some "pairing constraints"

- where in particular $K^M \partial_M$ is a null/time-like Killing vector.

- For the case at hand

$$16K = e^{2A} k, \quad 16\tilde{K} = e^{2A} \cos\beta k,$$

$$\Psi_\pm = \mp 2\Big(e^A \psi_1^{(6)} \wedge \mathrm{Re}\psi_\mp + e^{3A} i\psi_3^{(6)} \wedge \mathrm{Im}\psi_\mp + e^{3A}\mathrm{Re}(\tilde{\psi}_-^{(6)} \wedge \tilde{\psi}_\mp) + e^{5A}\psi_5^{(6)} \wedge \mathrm{Re}\psi_\mp\Big)$$

- where $(\psi_\mp, \tilde{\psi}_\mp)$ are internal $d = 4$ bi-linears/polyforms

Embedding Salam-Sezgin into $d=10$: How embedding in performed

- We can then extract constraints on internal fields and bilinears that imply $d=10$ supersymmetry

  - *i.e.*

  $$0 = d_H(e^{-\Phi}\Psi_\pm) + (\tilde{K}\wedge + \iota_K)F_\pm = \sum_i \Big[\text{6d data}\Big]_i \wedge \Big[\text{4d data}\Big]_i \quad \Rightarrow \quad \Big[\text{4d data}\Big]_i = 0$$

  - Horrible computation, but easily implemented in mathematica, result is is a bit long

- Internal bilinears take the following forms in IIA and IIB respectively

$$\psi_- = \frac{1}{4}e^A \sin\beta \overline{U}\wedge e^{\frac{1}{2}W\wedge\overline{W}}, \quad \tilde{\psi}_- = \frac{1}{4}e^A \sin\beta W \wedge e^{-\frac{1}{2}U\wedge\overline{U}},$$

$$\psi_+ = \frac{1}{4}e^A \sin\beta e^{i\alpha}e^{-ij}, \quad \tilde{\psi}_+ = -\frac{1}{4}e^A \sin\beta\omega$$

  - where $(j,\ \omega)$ span an SU(2)-structure and $(U,\ W)$ a complex vielbein on M_4.

- Thus solving supersymmetry fixes M_4 and other details of embedding

  - actual result depends on what $d=6$ fields are turned on

  - given a choice there are actually distinct classes of embedding

- $g\neq 0$ requires that $\tilde{\psi}_\mp$ is charged under ∂_ϕ: $\mathcal{L}_{\partial_\phi}\tilde{\psi}_\mp = in\tilde{\psi}_\mp$

  i.e. the isometry in which $\mathcal{A}$ is "housed"

- General conditions (evaluated with $\mathcal{A} = 0$ if $\mathcal{A}$ in M_4)

$$2n = g, \quad e^{2\varphi}\tilde{H}_0 - H_0 - 2e^{2A+\varphi}\cos\beta = 0,$$

$$d_{H_3}(e^{3A-\Phi}\mathrm{Im}\psi_\mp) - d\varphi \wedge H_2 \wedge \mathrm{Im}\psi_\mp = \pm\frac{1}{4}ge^{4A-\varphi}\star_4\lambda(g_\pm),$$

$$d_{H_3}(e^{3A-\Phi}\tilde{\psi}_\mp) - e^{3A-\Phi}H_2 \wedge d\varphi \wedge \tilde{\psi}_\mp = 0, \quad \frac{1}{8}e^{3A-\varphi}(1+\star_4\lambda)g_\mp = \mp e^{A-\Phi}\mathrm{Re}\psi_\mp,$$

$$d_{H_3}(e^{5A-\Phi}\mathrm{Re}\psi_\mp) \mp \frac{1}{4}e^{6A}\star_4\lambda(f_\pm) + ge^{3A-\Phi-\varphi}\Big(H_1 \wedge \mathrm{Im}\psi_\pm - \iota_{\partial_\phi}\mathrm{Im}\psi_\pm\Big)\Big|_{d\varphi\to 0} = 0,$$

$$d_{H_3}(e^{A-\Phi}\mathrm{Re}\psi_\mp) - d\varphi \wedge \Big[\pm\frac{1}{8}e^{3A-\varphi}(1-\star_4\lambda)g_\mp$$
$$\mp\frac{1}{4}e^{3A}\cos\beta\star_4\lambda(h_\mp) + e^{A-\Phi}H_2 \wedge \mathrm{Re}\psi_\pm\Big] = \mp\frac{1}{4}e^{2A}\cos\beta f_\pm,$$

- Conditions to be imposed when certainly multiplets are non trivial

$$\textbf{Tensor}: \quad \frac{1}{4}e^{5A-\varphi}\Big(h_\mp - e^{-\varphi}\cos\beta\star_4\lambda(g_\mp)\Big) = \pm e^{A-\Phi}\tilde{H}_0\mathrm{Re}\psi_\mp$$

$$\partial_\varphi(e^{2A}\sin\beta) = 0, \quad \partial_\varphi(e^{4A-2\Phi}\sqrt{\det g_4}) = 0,$$

$$\textbf{Vector}: \quad \frac{1}{4}e^{4A}(\cos\beta + \star\lambda)g_\pm = \pm e^{A-\Phi}\Big(H_1 \wedge \mathrm{Re}\psi_\mp - \iota_{\partial_\phi}\mathrm{Re}\psi_\mp\Big)$$

Example embeddings

Example embeddings: Gravity+vector with $g = 0$

There exists a universal embedding for gravity+vector multiplets with $g = 0$:

- Assuming $\mathcal{A}$ does not enter M_4 we find:

$$ds^2 = e^{2A} g^{(6)}_{\mu\nu} dx^\mu dx^\nu + ds^2(\text{M}_4), \quad H = H_3 - 2e^{2A}\cos\beta \mathcal{G} + d(e^{4A}) \wedge \mathcal{F},$$

$$F_\pm = \left(1 + e^{4A}\mathcal{F}\right) \wedge f_\pm \mp 8e^{A-\Phi}\mathcal{G} \wedge \text{Re}\psi_\mp + e^{6A}\,(\text{vol}_6 - \star_6 \mathcal{F}) \wedge \star_4 \lambda(f_\pm),$$

- Internal fields can be those of ANY supersymmetric Mink_6 sol^n in type II obeying

$$d(e^{2A}\cos\beta) = 0, \quad d_{H_3}(e^{3A-\Phi}\tilde{\psi}_\mp) = 0, \quad d_{H_3}(e^{3A-\Phi}\text{Im}\psi_\mp) = 0,$$

$$d_{H_3}(e^{A-\Phi}\text{Re}\psi_\mp) = \mp\frac{1}{4}e^{2A}\cos\beta f_\pm, \quad d_{H_3}(e^{5A-\Phi}\text{Re}\psi_\mp) = \pm\frac{1}{4}e^{6A} \star_6 \lambda(f_\pm)$$

- Contains separate classes of solution:

- IIA: D8-D6-NS5 brane system [Imamura], [Legramandi,Tomasiello]

- IIB: F-theory class+ 3-forms: M_4 base of elliptically fibered CY_3 [?]

- IIB: D5 branes back-reacted on CY_2 [Lust, Patalong, Tsimpis]

- All contain bounded M_4 examples

- Adding a tensor multiplet constrains classes, but doesn't Kill them.

Example embeddings: IIB uplift of full Salam-Sezgin

There are 3 classes of embeddings with $g \neq 0$ with tensor and vector multiplets

- The simplest is in type IIB with only RR 3-form:

$$ds^2 = \frac{g}{\sqrt{\partial_\rho \Delta}} \left[g^{(6)}_{\mu\nu} dx^\mu dx^\nu + \frac{2}{g^2} e^{\varphi} \left(D\phi^2 + \frac{(\partial_\rho \Delta)^2}{4} \left(d\rho^2 + e^{2\Delta}(dx_1^2 + dx_2^2) \right) \right) \right],$$

$$e^{-\Phi} = \sqrt{\partial_\rho \Delta} e^{-\varphi}, \qquad D\phi = -\frac{1}{2} \star_2 d\Delta + g\mathcal{A}, \qquad (\mathcal{F},\ \mathcal{G}) \in F_3$$

- Embeddings are governed by a Toda-like equation

$$2(\partial_{x_1}^2 + \partial_{x_2}^2)\Delta + \partial_\rho^2 e^{2\Delta} = 2(\partial_\rho e^{\Delta})^2$$

  - All $d = 10$ EOM implied by this and $d = 6$ ones
  - Note: Deformation of eq^n defining CY_2's with charged U(1) isometry

- Have reduced embedding Salam-Sezgin to solving 1 PDE
  - So does it have solutions leading to bounded M_4?
  - Yes, simple separation of variables ansatz $e^{\Delta} = p(\rho) e^{\mu(x_1, x_2)}$ leads to

$$M_4 = H_2/\Gamma \times S^1 \times [\text{bounded interval}]$$

  - singularity that we don't recognise, but believe this can be improve on

- **Have derived embedding formulae for Salam-Sezgin and all its limits**
  - cases with $g = 0$ fully classified
  - $g \neq 0$ still work in progress, but preliminary results look promising
  - Also IIA and F-theory like classes
  - Bounded embeddings with physical singularities? Will report on status soon

- **Serves as a proof of concept for non minimal uplifts using bispinor techniques**
  - Works very systematically, many other interesting theories to uplift:
  - SU(2) gauged Salam-Sezgin model
  - $d = 5$ minimal gauged supergravity coupled to abelian vector multipets
  - $d = 4$ $\mathcal{N} = 2$ gauged supergravity + matter

Thank you