Towards Simple de Sitter Vacua

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Based on:


Puzzles of two accelerating phases

Early universe: Inflation

Current universe: Dark Energy
A landscape of string vacua?
The KKLT Menu

Antipasti

**Fluxes** stabilize complex structure moduli; Kahler moduli remain unfixed.

Entree

**Non-perturbative effects** (D7 gauge instantons or ED3 instantons) stabilize the Kahler moduli.

Desserts

**Anti-branes** to “uplift” vacuum energy.

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Before placing your order, please inform your server if a person in your party has a food allergy.

* Consuming raw meat and eggs may increase your risk of food borne illness, especially if you have certain medical conditions.

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Kachru, Kallosh, Linde, Trivedi
In fine print ....

• **Non-perturbative effects:** difficult to compute *explicitly*. Most work aims to illustrate their existence, rather than to compute the actual contributions:

\[
W_{np} = Ae^{-a\rho} \quad \Rightarrow \quad W_{np} = A(\zeta_i)e^{-a\rho}
\]

Moreover, the full moduli dependence is suppressed.

• **Anti D3-branes:** backreaction on the 10D SUGRA proves to be very challenging.

[DeWolfe, Kachru, Mulligan];[McGuirk, GS, Sumitomo];[Bena, Grana, Halmagyi], [Dymarsky], ...
Minimalism describes movements in various forms of art and design, especially visual art and music, where the work is stripped down to its most fundamental features. As a specific movement in the arts it is identified with developments in post-World War II Western Art, most strongly with American visual arts in the late 1960s and early 1970s. Prominent artists associated with this movement include Donald Judd, Agnes Martin and Frank Stella. It is rooted in the reductive aspects of Modernism, and is often interpreted as a reaction against Abstract Expressionism and a bridge to Postmodern art practices.
Towards simple de Sitter vacua

- Explicitly computable within classical SUGRA.
- Absence of np effects, and explicit SUSY breaking localized sources, e.g., anti-branes.
- Solve 10D equations of motion (c.f., 4D EFT).
- (For now) content with simple dS solutions w/o requiring a realistic cc & SUSY breaking scale: explicit models help address conceptual issues.
Our Ingredients

❖ **Fluxes:** contribute *positively* to energy and tend to make the internal space *expands*:

\[
S = -\frac{1}{2p!} \int_6 \sqrt{g_6} F_{\mu_1...\mu_{p+1}} F^{\mu_1...\mu_{p+1}}
\]

❖ **Branes:** contribute *positively* to energy and tend to *shrink* the internal space (reverse for O-plane which has negative tension):

\[
S = -T_{brane} \int_{brane} \sqrt{g_{brane}}
\]

❖ **Curvature:** Positively (negatively) curved spaces tend to shrink (expand) and contribute a negative (positive) energy:

\[
\int_{10} \sqrt{|g_{10}|} R_{10} = \int_4 \sqrt{g_4} \left( \int_6 \sqrt{g_6} R_4 + \int_6 \sqrt{g_6} R_6 \right)
\]
Universal Moduli

Consider metric in 10D string frame and 4d Einstein frame:

\[ ds_{10}^2 = \tau^{-2} ds_4^2 + \rho ds_6^2, \quad \tau \equiv \rho^{3/2} e^{-\phi}, \]

\( \rho, \tau \) are the \textit{universal moduli}.

The various ingredients contribute to \( V \) in some specific way:

\[ V_R = U_R \rho^{-1} \tau^{-2}, \quad U_R(\varphi) \sim \int \sqrt{g_6} (-R_6), \]

\[ V_H = U_H \rho^{-3} \tau^{-2}, \quad U_H(\varphi) \sim \int \sqrt{g_6} H^2, \]

\[ V_q = U_q \rho^{3-q} \tau^{-4}, \quad U_q(\varphi) \sim \int \sqrt{g_6} F_q^2 > 0 \]

\[ V_p = U_p \rho^{p-6} \tau^{-3}, \quad U_p(\varphi) = \mu_p \text{ Vol}(M_{p-3}). \]

The full 4D potential \( V(\rho,\tau,\varphi_i) = V_R + V_H + V_q + V_p. \)
Consider Type IIA string theory with intersecting D6-branes/O6-planes in a Calabi-Yau space:

a popular framework for building the Standard Model (and beyond) from string theory. See [Blumenhagen, Cvetic, Langacker, GS]; [Blumenhagen, Kors, Lust, Stieberger]; [Marchesano]; ... for reviews.
No-go Theorem(s)

- For Calabi-Yau, $V_R = 0$, we have: $V = V_H + \sum_q V_q + V_{D6} + V_{O6}$

- The universal moduli dependence leads to an inequality:

$$-\rho \frac{\partial V}{\partial \rho} - 3\tau \frac{\partial V}{\partial \tau} = 9V + \sum_q qV_q \geq 9V$$

- This excludes a de Sitter vacuum:

$$\frac{\partial V}{\partial \rho} = \frac{\partial V}{\partial \tau} = 0 \text{ and } V > 0$$

as well as slow-roll inflation since $\epsilon \geq \mathcal{O}(1)$.

- More general no-goes were found for Type IIA/B theories with various D-branes/O-planes. [Haque, GS, Underwood, Van Riet, 08]; [Danielsson, Haque, GS, van Riet, 09]; [Wrase, Zagermann, 10].

- In some cases: further no-goes on stability. [GS, Sumitomo]
Evading these no-goes: **O-planes** [introduced in any case because of [Gibbons; de Wit, Smit, Hari Dass; Maldacena,Nunez]], fluxes, often also *negative curvature*. [Silverstein + above cited papers]

Classical AdS vacua from IIA flux compactifications with D6/O6 were found [Derendinger et al; Villadoro et al; De Wolfe et al; Camara et al].

Minimal ingredients needed for dS [Haque, GS, Underwood, Van Riet]:

1) O6-planes 2) Romans mass 3) H-flux 4) Negatively curved internal space.
Generalized Complex Geometry

- Interestingly, such extensions were considered before in the context of generalized complex geometry (GCG).

- Among these GCG, many are negatively curved (e.g., twisted tori), at least in some region of the moduli space [Lust et al; Grana et al; Kachru et al; ...].

- Attempts to construct explicit dS models were made soon after no-goes [Haque, GS, Underwood, Van Riet]; [Flauger, Paban, Robbins, Wrase]; [Caviezel, Koerber, Lust, Wrase, Zagermann]; [Danielsson, Haque, GS, van Riet]; [de Carlos, Guarino, Moreno]; [Caviezel, Wrase, Zagermann]; [Danielsson, Koerber, Van Riet]; ....

- We report on the result of a systematic search within a broad class of such manifolds [Danielsson, Haque, Koerber, GS, van Riet, Wrase].
Two Approaches

SUSY broken @ or above KK scale

SUSY broken below KK scale

Do not lead to an effective SUGRA in dim. reduced theory

Silverstein, 07; Andriot, Goi, Minasian, Petrini, 10; Dong, Horn, Silverstein, Torroba, 10; ...

Lead to a 4d SUGRA (N=1):
[This talk]

- Spontaneous SUSY state
- Potentially lower SUSY scale
- Much more control on the EFT
- c.f. dS searches within SUGRA
10d vs 4d

We advocate 10d point of view, so why consider 4d V(ρ,τ)?

It can be shown [Danielsson, Haque, GS, Van Riet]:

\[ \Box \phi = 0 = \sum_n \frac{a_n}{2n!} e^{a_n \phi} F_n^2 \pm \frac{p - 3}{4} e^{(p-3)\phi/4} |\mu_p| \delta(\Sigma), \]

and trace of

\[ R_{ab} = \sum_n \left( -\frac{n - 1}{16n!} g_{ab} e^{a_n \phi} F_n^2 + \frac{1}{2(n - 1)!} e^{a_n \phi} (F_n)_{ab}^2 + \frac{1}{2} (T_{ab}^{loc} - \frac{1}{8} g_{ab} T^{loc}) \right), \]

(upon smearing of sources) are equivalent to \( \partial_\rho V = \partial_\tau V = 0 \) & trace of \( R_{\mu\nu} \) equation just gives def. of \( V \); a useful first pass.

When backreaction of localized sources cannot be ignored (more later), 10d eoms are harder to solve, a warped 4D EFT is needed. [Giddings, Maharana], [Koerber, Martucci]; [GS, Torroba, Underwood, Douglas]; ...
Search Strategy

- **GCG:** natural framework for N=1 SUSY compactifications when backreaction from fluxes are taken into account.

- Type IIA SUSY AdS vacua arise from specific SU(3) structure manifolds [Lust, Tsimpis];[Caviezel et al];[Koerber, Lust, Tsimpis]; ...

- Modify the AdS ansatz for the fluxes (which solves the flux eoms from the outset) and search for dS solutions.

- Spontaneously SUSY breaking state in a 4D SUGRA: powerful results & tools from SUSY, GCG.
SU(3) Structure

- SUSY implies the existence of a nowhere vanishing internal 6d spinor $\eta_+$ (and complex conjugate $\eta_-$).

- Characterized by a real 2-form $J$ and a complex 3-form $\Omega$:

$$J = \frac{i}{2\|\eta\|^2} \eta_+^{\dag} \gamma_{i_1 i_2} \eta_+ dx^{i_1} \wedge dx^{i_2}$$

$$\Omega = \frac{1}{3!\|\eta\|^2} \eta_+^{\dag} \gamma_{i_1 i_2 i_3} \eta_+ dx^{i_1} \wedge dx^{i_2} \wedge dx^{i_3}$$

satisfying $\Omega \wedge J = 0$, $\Omega \wedge \Omega^* = (4i/3) J \wedge J \wedge J = 8i \text{ vol}_6$.

- $J$, $\Omega$ define SU(3) structure, not SU(3) holonomy: generically $dJ \neq 0$ and $d\Omega \neq 0$. 
SU(3) Structure

• Build an almost complex structure:

\[ I^l_k = c \varepsilon^{m_1 m_2 \ldots m_5 l} (\Omega_R)_{km_1 m_2} (\Omega_R)_{m_3 m_4 m_5} \quad \text{for which } J \text{ is of (1,1) and } \Omega \text{ is of (3,0) type.} \]

• The metric then follows:

\[ g_{mn} = -I^l_m J_{ln} \]

• The global existence of these forms implies the structure group of the frame bundle to be SU(3).
### SU(3) Torsion Classes

The non-closure of the exterior derivatives characterized by:

\[
dJ = \frac{3}{2} \text{Im} (\mathcal{W}_1 \Omega^*) + \mathcal{W}_4 \wedge J + \mathcal{W}_3
\]

\[
d\Omega = \mathcal{W}_1 J \wedge J + \mathcal{W}_2 \wedge J + \mathcal{W}_5^* \wedge \Omega
\]

<table>
<thead>
<tr>
<th>Torsion classes</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mathcal{W}_1 = \mathcal{W}_2 = 0)</td>
<td>Complex</td>
</tr>
<tr>
<td>(\mathcal{W}_1 = \mathcal{W}_3 = \mathcal{W}_4 = 0)</td>
<td>Symplectic</td>
</tr>
<tr>
<td>(\mathcal{W}_2 = \mathcal{W}_3 = \mathcal{W}_4 = \mathcal{W}_5 = 0)</td>
<td>Nearly Kähler</td>
</tr>
<tr>
<td>(\mathcal{W}_1 = \mathcal{W}_2 = \mathcal{W}_3 = \mathcal{W}_4 = 0)</td>
<td>Kähler</td>
</tr>
<tr>
<td>(\text{Im} \mathcal{W}_1 = \text{Im} \mathcal{W}_2 = \mathcal{W}_4 = \mathcal{W}_5 = 0)</td>
<td>Half-flat</td>
</tr>
<tr>
<td>(\mathcal{W}_1 = \text{Im} \mathcal{W}_2 = \mathcal{W}_3 = \mathcal{W}_4 = \mathcal{W}_5 = 0)</td>
<td>Nearly Calabi-Yau</td>
</tr>
<tr>
<td>(\mathcal{W}_1 = \mathcal{W}_2 = \mathcal{W}_3 = \mathcal{W}_4 = \mathcal{W}_5 = 0)</td>
<td>Calabi-Yau</td>
</tr>
<tr>
<td>(\mathcal{W}_1 = \mathcal{W}_2 = \mathcal{W}_3 = 0, (1/2)\mathcal{W}_4 = (1/3)\mathcal{W}_5 = -dA)</td>
<td>Conformal Calabi-Yau</td>
</tr>
</tbody>
</table>
Half Flat Manifolds

- For the SU(3) structure manifold to be compatible with the orbifold/orientifold symmetries we consider (more later):
  \[ dJ = \frac{3}{2} W_1 \Omega_R + W_3, \]
  \[ d\Omega_R = 0, \]
  \[ d\Omega_I = W_1 J \wedge J + W_2 \wedge J, \]

  \( W_{1,2,3} \) are real

- \( W_{1,2,3} \) is a scalar, a (1,1) form, & a (1,2) +(2,1) form satisfying:
  \[ W_2 \wedge J \wedge J = 0, \]
  \[ W_2 \wedge \Omega = 0, \]
  \[ W_3 \wedge J = 0, \]
  \[ W_3 \wedge \Omega = 0 \]

- Ricci tensor can be expressed explicitly in terms of \( J, \Omega \) and the torsion forms [Bedulli, Vezzoni].
Universal Ansatz

- In terms of the universal forms:  \[ \{ J, \Omega, W_1, W_2, W_3 \} \]

one finds a natural ansatz for the fluxes:

\[
\begin{align*}
e^\Phi \hat{F}_0 &= f_1, \\
e^\Phi \hat{F}_2 &= f_2 J + f_3 \hat{W}_2, \\
e^\Phi \hat{F}_4 &= f_4 J \wedge J + f_5 \hat{W}_2 \wedge J, \\
e^\Phi \hat{F}_6 &= f_6 \text{vol}_6, \\
H &= f_7 \Omega_R + f_8 \hat{W}_3, \\
j &= j_1 \Omega_R + j_2 \hat{W}_3.
\end{align*}
\]

- Universal ansatz: forms appear in all SU(3) structure (in this case, half flat) manifolds.

- Also the ansatz for the SUSY AdS vacua in [Lust, Tsimpis]
O-planes

To simplify, we take the **smeared** approximation:

\[ \delta \rightarrow \text{constant} \]

i.e., we solve the eoms in an “average sense”. If backreaction is ignored, eoms are not satisfied pointwise [Douglas, Kallosh].

Finding backeacted solutions with localized sources proves to be challenging (more later) [Blaback, Danielsson, Junghans, Van Riet, Wrase, Zagermann].

The Bianchi identity becomes:

\[ d\hat{F}_2 + H \hat{F}_0 = -j, \quad e^{\Phi} j = j_1 \Omega_R + j_2 \hat{W}_3. \]

The source terms of smeared O-planes in dilaton/Einstein eoms can be found in [Koerber, Tsimpis, 07].
Finding Solutions

- The dilaton/Einstein/flux eoms and Bianchi identities can be expressed as algebraic equations (skip details).
- To find solutions other than the SUSY AdS, impose constraints:

\[
d\hat{W}_2 = c_1 \Omega_R + d_1 \hat{W}_3,
\]
\[
\hat{W}_2 \wedge \hat{W}_2 = c_2 J \wedge J + d_2 \hat{W}_2 \wedge J,
\]
\[
d \star_6 \hat{W}_3 = c_5 J \wedge J + c_3 \hat{W}_2 \wedge J,
\]
\[
\frac{1}{2} (\hat{W}_{3 i k l} \hat{W}_{3 j}^{k l})^+ = d_4 J_{i k} \hat{W}_2^{k j}.
\]

for some c’s and d’s.
Finding Solutions

$W_3 = 0$

$|W_1|^2$ (dashed), $|W_2|^2$

$W_2 = 0$

$\Lambda$ (dashed), $M_{\rho}^2, M_{\tau}^2$

[Danielsson, Haque, GS, Van Riet]

[Danielsson, Koerber, Van Riet]
Universal de Sitter

- Bottom-up approach: we found necessary constraints on fluxes & torsion classes for universal dS solutions, a useful first step.

- Next: explicit geometries, stabilization of model-dependent moduli, flux quantization, unsmeared sources, etc.

- Homogenous spaces (group/coset spaces) seem a promising first trial: can explicitly construct SU(3) structure.
Example

Bottom-up constraints (with $W_2=0$) can be satisfied with an explicit model: an SU(2) x SU(2) group manifold.

This realizes a solution obtained by 4d SUGRA approach [Caviezel, Koerber, Kors, Lust, Wrase, Zagermann]

Unfortunately, out of 14 scalars, one is tachyonic! 😞

[Danielsson, Koerber, Van Riet]
Focus on homogenous spaces \((G/H, H \subseteq SU(3))\) where we can explicitly construct the SU(3) structure.

We cover all group manifolds, by classifying 6d groups.
A coframe of left-invariant forms: \( g^{-1}dg = e^a T_a \)

that obeys the Maurer-Cartan relations: \( de^a = -\frac{1}{2} f^a_{\ bc} e^b \wedge e^c \)

From these MC forms, we can construct \( J, \Omega \), and the metric:

\[
ds^2 = M_{ab} e^a \otimes e^b
\]

Levi’s theorem: \( \mathfrak{g} = \mathfrak{s} \ltimes \mathfrak{r} \)

semisimple \( \mathfrak{S} \); radical \( \mathfrak{r} \) = largest solvable ideal

Ideal: \( [\mathfrak{g}, \mathfrak{i}] \subseteq \mathfrak{i} \).

Solvable: \( \mathfrak{g}^n = [\mathfrak{g}^{n-1}, \mathfrak{g}^{n-1}] \) vanishes at some point
Group Manifolds

- Semi-simple:

<table>
<thead>
<tr>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mathfrak{so}(3) \times \mathfrak{so}(3))</td>
</tr>
<tr>
<td>(\mathfrak{so}(3) \times \mathfrak{so}(2, 1))</td>
</tr>
<tr>
<td>(\mathfrak{so}(2, 1) \times \mathfrak{so}(2, 1))</td>
</tr>
<tr>
<td>(\mathfrak{so}(3, 1))</td>
</tr>
</tbody>
</table>

- Semi-direct product of semi-simple algebra & radical:  \(\mathfrak{g} = \mathfrak{s} \ltimes \mathfrak{r}\)

<table>
<thead>
<tr>
<th>Case</th>
<th>Representations</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mathfrak{so}(3) \ltimes \rho \mathfrak{u}(1)^3)</td>
<td>(\rho = 1 \oplus 1 \oplus 1) and (\rho = 3)</td>
</tr>
<tr>
<td>(\mathfrak{so}(3) \ltimes \rho \mathfrak{Heis}_3)</td>
<td>(\rho = 1 \oplus 1 \oplus 1)</td>
</tr>
<tr>
<td>(\mathfrak{so}(3) \ltimes \rho \mathfrak{iso}(2))</td>
<td>(\rho = 1 \oplus 1 \oplus 1)</td>
</tr>
<tr>
<td>(\mathfrak{so}(3) \ltimes \rho \mathfrak{iso}(1, 1))</td>
<td>(\rho = 1 \oplus 1 \oplus 1)</td>
</tr>
<tr>
<td>(\mathfrak{so}(2, 1) \ltimes \rho \mathfrak{u}(1)^3)</td>
<td>(\rho = 1 \oplus 1 \oplus 1), (\rho = 1 \oplus 2) and (\rho = 3)</td>
</tr>
<tr>
<td>(\mathfrak{so}(2, 1) \ltimes \rho \mathfrak{Heis}_3)</td>
<td>(\rho = 1 \oplus 1 \oplus 1) and (\rho = 1 \oplus 2)</td>
</tr>
<tr>
<td>(\mathfrak{so}(2, 1) \ltimes \rho \mathfrak{iso}(2))</td>
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<td>(\rho = 1 \oplus 1 \oplus 1)</td>
</tr>
</tbody>
</table>

Unimodular algebra: 

\[ f^a_{\ ab} = 0, \text{ for all } b \]

necessary condition for non-compact group space to be made compact.

[Danielsson, Haque, Koerber, GS, Van Riet, Wrase]
## Group Manifolds

### Solvable groups:

<table>
<thead>
<tr>
<th>Name</th>
<th>Algebra</th>
<th>$O_5$</th>
<th>$O_6$</th>
<th>$Sp$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathfrak{g}_{1,4} \oplus \mathbb{R}^4$</td>
<td>$(q_1q_3, q_2, 0, 0, 0, 0)$, $q_1, q_2 &gt; 0$</td>
<td>14, 15, 16, 24, 25, 26, 34, 35, 36</td>
<td>123, 145, 166, 156, 245, 246, 256, 345, 346, 356</td>
<td>✓</td>
</tr>
<tr>
<td>$\mathfrak{g}_{1,5} \oplus \mathbb{R}^4$</td>
<td>$(-23, 13, 0, 0, 0, 0)$</td>
<td>14, 15, 16, 24, 25, 26, 34, 35, 36</td>
<td>123, 145, 166, 156, 245, 246, 256, 345, 346, 356</td>
<td>✓</td>
</tr>
<tr>
<td>$\mathfrak{g}<em>{1,1} \oplus \mathfrak{g}</em>{1,4}^*$</td>
<td>$(-23, 0, 0, q_1q_6, q_2q_6, 0)$, $q_1, q_2 &gt; 0$</td>
<td>14, 15, 16, 24, 25, 26, 34, 35, 36</td>
<td>-</td>
<td>✓</td>
</tr>
<tr>
<td>$\mathfrak{g}<em>{1,1} \oplus \mathfrak{g}</em>{1,5}^*$</td>
<td>$(-23, 0, 0, -56, 46, 0)$</td>
<td>14, 15, 16, 24, 25, 26, 34, 35, 36</td>
<td>-</td>
<td>✓</td>
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<tr>
<td>$\mathfrak{g}<em>{1,6} \oplus \mathfrak{g}</em>{1,5}^*$</td>
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<tr>
<td>$\mathfrak{g}<em>{1,4} \oplus \mathfrak{g}</em>{1,4}^*$</td>
<td>$(q_1q_3, q_2, 13, 0, q_1q_6, q_2q_6, 0)$, $q_1, q_2 &gt; 0$</td>
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<td>-</td>
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<td>14, 15, 16, 24, 25, 26, 34, 35, 36</td>
<td>-</td>
<td>✓</td>
</tr>
</tbody>
</table>

$\mathfrak{g}_{1,6}^T, \mathfrak{g}_{1,5}^T \oplus \mathbb{R}^2$

<table>
<thead>
<tr>
<th>Name</th>
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<th>$O_6$</th>
<th>$Sp$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathfrak{g}_{1,6}^T \oplus \mathbb{R}^2$</td>
<td>$(-23, q_1q_3, q_2q_4, 0, 0, 0)$, $q_1, q_2 &gt; 0$</td>
<td>14, 15, 16, 24, 25, 26, 34, 35, 36</td>
<td>145, 146, 256, 356</td>
<td>-</td>
</tr>
<tr>
<td>$\mathfrak{g}_{1,5}^T \oplus \mathbb{R}^2$</td>
<td>$(-23, -34, 24, 0, 0, 0)$</td>
<td>14, 15, 16, 24, 25, 26, 34, 35, 36</td>
<td>145, 146, 256, 356</td>
<td>-</td>
</tr>
<tr>
<td>$\mathfrak{g}_{1,6}^{T,1} \oplus \mathbb{R}^2$</td>
<td>$(q_1q_3, q_2, 25, q_1q_6, q_2q_6, 0, 0)$, $q_1, q_2 &gt; 0$</td>
<td>14, 15, 16, 24, 25, 26, 34, 35, 36</td>
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<td>✓</td>
</tr>
<tr>
<td>$\mathfrak{g}_{1,13} \oplus \mathbb{R}^2$</td>
<td>$(25, 0, q_1q_5, q_2q_5, 0, 0)$, $q_1, q_2 &gt; 0$</td>
<td>14, 15, 16, 24, 25, 26, 34, 35, 36</td>
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<td>$\mathfrak{g}_{1,14} \oplus \mathbb{R}^2$</td>
<td>$(q_1q_3, q_2, 25, q_1q_6, q_2q_6, 0, 0)$, $q_1, q_2 &gt; 0$</td>
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</tr>
<tr>
<td>$\mathfrak{g}_{1,15} \oplus \mathbb{R}^2$</td>
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<td>14, 15, 16, 24, 25, 26, 34, 35, 36</td>
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<td>✓</td>
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<tr>
<td>$\mathfrak{g}_{1,17} \oplus \mathbb{R}^2$</td>
<td>$(q_1q_3, q_2, 25, q_1q_6, q_2q_6, 0, 0)$, $q_1, q_2 &gt; 0$</td>
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<td>✓</td>
</tr>
<tr>
<td>$\mathfrak{g}_{1,18} \oplus \mathbb{R}^2$</td>
<td>$(-25, -35, 15, -45, 0, 0, 0)$</td>
<td>14, 15, 16, 24, 25, 26, 34, 35, 36</td>
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</tr>
<tr>
<td>$\mathfrak{g}_{1,3} \oplus \mathbb{R}^2$</td>
<td>$(-26, -36, 0, q_1q_6, q_2q_6, 0, 0)$, $q_1, q_2 &gt; 0$</td>
<td>24, 25, 134, 135, 346</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>$\mathfrak{g}_{1,9} \oplus \mathbb{R}^2$</td>
<td>$(-26, -36, 0, -56, 46, 0, 0)$</td>
<td>24, 25, 134, 135, 346</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

[Turkowski]; [Andriot, Goi, Petrini, Minasian]; [Grana, Minasian, Petrini, Tomasiello]
Orientifolding

- dS critical point of effective N=1 SUGRA from group manifolds.
- Orbifolding further by discrete $\Gamma \subset SU(3)$.
- Among the Abelian orbifolds of (twisted) $T^6$, only two $Z_2 \times Z_2$ orientifolds can evade $\epsilon \geq O(1)$ [Flauger, Paban, Robbins, Wrase]
- Consider $Z_2 \times Z_2$ orientifolds of the group spaces we classified.

\[
\theta_1 : \begin{cases} 
    e^1 &\rightarrow -e^1 \\
    e^2 &\rightarrow -e^2 \\
    e^3 &\rightarrow e^3 \\
    e^4 &\rightarrow -e^4 \\
    e^5 &\rightarrow e^5 \\
    e^6 &\rightarrow -e^6 
\end{cases}, \quad \theta_2 : \begin{cases} 
    e^1 &\rightarrow -e^1 \\
    e^2 &\rightarrow e^2 \\
    e^3 &\rightarrow -e^3 \\
    e^4 &\rightarrow e^4 \\
    e^5 &\rightarrow -e^5 \\
    e^6 &\rightarrow -e^6 
\end{cases}, \quad \sigma : \begin{cases} 
    e^1 &\rightarrow e^1 \\
    e^2 &\rightarrow e^2 \\
    e^3 &\rightarrow e^3 \\
    e^4 &\rightarrow -e^4 \\
    e^5 &\rightarrow -e^5 \\
    e^6 &\rightarrow -e^6 
\end{cases}
\]

[Other $Z_2 \times Z_2$ orientifold has a different $\sigma$]
Constructing SU(3) Structure

- **O-planes:** \( j_6 = j_A e^{456} + j_B e^{236} + j_C e^{134} + j_D e^{125} \)

- **J and \( \Omega_R \) are odd under orientifolding:**
  \[
  J = a e^{16} + b e^{24} + c e^{35}, \\
  \Omega_R = v_1 e^{456} + v_2 e^{236} + v_3 e^{134} + v_4 e^{125},
  \]

- **The metric fluxes are even:**
  \[
  \begin{align*}
  d e^1 &= f^1_{23} e^{23} + f^1_{45} e^{45}, \\
  d e^3 &= f^3_{12} e^{12} + f^3_{46} e^{46}, \\
  d e^5 &= f^5_{14} e^{14} + f^5_{26} e^{26}, \\
  d e^2 &= f^2_{13} e^{13} + f^2_{56} e^{56}, \\
  d e^4 &= f^4_{36} e^{36} + f^4_{15} e^{15}, \\
  d e^6 &= f^6_{34} e^{34} + f^6_{25} e^{25}.
  \end{align*}
  \]

- **Metric g and \( \Omega_I \) can be expressed in terms of the “moduli”:**
  \[
  g = \frac{1}{\sqrt{v_1 v_2 v_3 v_4}} \left( a v_3 v_4, -b v_2 v_4, c v_2 v_3, -b v_1 v_3, c v_1 v_4, a v_1 v_2 \right)
  \]
  \[
  \sqrt{v_1 v_2 v_3 v_4} = -abc
  \]
  \[
  \Omega_I = \sqrt{v_1 v_2 v_3 v_4} \left( v^{-1}_1 e^{123} + v^{-1}_2 e^{145} - v^{-1}_3 e^{256} - v^{-1}_4 e^{346} \right)
  \]
Constructing SU(3) Structure

✦ Parity under orientifolding implies \( \text{Im } W_1 = \text{Im } W_2 = W_4 = W_5 = 0 \)

⇒ Half-flat SU(3) Structure Manifold

✦ Construct the remaining torsion classes:

\[
\begin{align*}
W_1 &= -\frac{1}{6} \ast_6 (dJ \wedge \Omega_I), \\
W_2 &= -\ast d\Omega_I + 2W_1 J, \\
W_3 &= dJ - \frac{3}{2} W_1 \Omega_R.
\end{align*}
\]

✦ Search for dS solutions satisfying constraints obtained earlier.
Challenges

- In all models, there are at least one tachyon among the left-invariant modes! (generic? c.f. [Gomez-Reino, Louis, Scrucca], …)

- Flux quantization:

  Pictorially

  For SU(2)xSU(2) examples, can explicitly check flux quantization demands solutions outside SUGRA.

- Backreaction of localized sources:

  \[ R_6 = \frac{1}{4} T_6 - \frac{3}{4} T_4 \]

  Douglas, Kallosh

  constant negative curvature

  localized negative tension

  See [Blaback, Danielsson, Junghans, Van Riet, Wrase, Zagermann]
de Sitter solutions are hard to find

In candidate vacua, tachyons seem ubiquitous
Perhaps $10^{500}$ different uplifted vacua
No-go theorems for de Sitter vacua/inflation from string theory, and the minimal ingredients to evade them.

Motivate dS construction from SU(3) structure manifolds.

Bottom-up approach: de Sitter ansatz.

A systematic search for dS vacua within a broad class of group manifolds that admit an explicit construction of SU(3) structure.

dS solutions hard to come by; even for solutions found, tachyons seem ubiquitous. Other issues: backreaction, flux quantization.

Some future directions: further no-goes [GS, Sumitomo]; warping/inhomogeneous effects, search for more general models, e.g., SCTV [Larfors, Lust, Tsimpis; see Tsimpis’s talk], other dimensions, ...
Local Organizing Committee:
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