The effective theory of type IIA AdS$_4$ compactifications on nilmanifolds and cosets

Based on: 0804.0614 (*PK, Tsimpis, Lüst*), 0806.3458 (*Caviezel, PK, Körs, Lüst, Tsimpis, Zagermann*)

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- Type IIB orientifold with D3/D7-branes on conformal CY: well-studied

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- Geometric fluxes: deviation from Calabi-Yau
- Other application: type IIA on $\mathrm{AdS}_4 \times \mathbb{CP}^3$
    - AdS/CFT *Aharony, Bergman, Jafferis, Maldacena* M2-branes

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Type IIA susy vacua with AdS_4 space-time

Lüst, Tsimpis

- RR-forms: Romans mass $F_0 = m$, F_2, F_4,
  NSNS 3-form: H, dilaton: Φ
- SU(3)-structure: J, Ω

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  - Geometric flux i.e. non-zero torsion classes:

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

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

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  - Form-fluxes:

$$
\begin{aligned}
H &= \frac{2m}{5} e^{\Phi} \mathrm{Re}\Omega \\
F_2 &= \frac{f}{9} J + F_2' \\
F_4 &= f \mathrm{vol}_4 + \frac{3m}{10} J \wedge J
\end{aligned}
$$

AdS$_4$ superpotential W:

$$\nabla_\mu \zeta_- = \frac{1}{2} W \gamma_\mu \zeta_+ \quad \text{definition}$$

$$W e^{i\theta} = -\frac{1}{5} e^{\Phi} m + \frac{i}{3} e^{\Phi} f$$

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- Automatically satisfied except for

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- Bianchi:

$$e^{2\Phi} m^2 = \mu + \frac{5}{16}\left(3|\mathcal{W}_1|^2 - |\mathcal{W}_2|^2\right) \geq 0$$
$$w_3 = -ie^{-\Phi} d\mathcal{W}_2 \Big|_{(2,1)+(1,2)}$$

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- Smearing:

$$j^6 = T_{O6}\,\delta(x^4,x^5,x^6)\,dx^4 \wedge dx^5 \wedge dx^6 \to T_{Op}\,c\,dx^4 \wedge dx^5 \wedge dx^6$$

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$$O6: \qquad dx^4 \rightarrow -dx^4\,, \quad dx^5 \rightarrow -dx^5\,, \quad dx^6 \rightarrow -dx^6$$

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  - $B, H, F_2, \mathrm{Re}\,\Omega$ odd, $F_0, F_4, \mathrm{Im}\,\Omega$ even

Calabi-Yau solution

- Calabi-Yau solution *Acharya, Benini, Valandro*

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- Torus orientifolds

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What about equations of motion?

IIA: *Lüst,Tsimpis*, IIB: *Gauntlett, Martelli, Sparks, Waldram*
With sources: *PK, Tsimpis* 0706.1244
Under mild conditions (subtleties time direction):

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- Bulk supersymmetry conditions
- Bianchi identities form-fields with source
- Supersymmetry conditions source = generalized calibration conditions *PK; Martucci, Smyth*

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imply

- Einstein equations with source
- Dilaton equation of motion with source
- Form field equations of motion

Some older solutions

- Nearly-Kähler: only $\mathcal{W}_1 \neq 0$ *Behrndt, Cvetič*
  SU(2)×SU(2) and the coset spaces $\frac{G_2}{SU(3)}$, $\frac{Sp(2)}{S(U(2)\times U(1))}$, $\frac{SU(3)}{U(1)\times U(1)}$

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- Iwasawa manifold *Lüst, Tsimpis*:
  - A certain nilmanifold or twisted torus
    $=$ a group manifold associated to a nilpotent algebra
  - Left-invariant forms e^i obeying Maurer-Cartan relation:

$$de^i = -\frac{1}{2} f^i{}_{jk} e^j \wedge e^k$$

  - Singular limit of T^2 bundle over K3

Group manifolds

SU(3)-structures with J, Ω constant in terms of left-invariant forms on a group manifold: fertile source of examples

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$\Rightarrow$ algebraic relations

- SU(2)$\times$SU(2)
- Nilmanifolds (divide discrete group: compact)
  - Only Iwasawa & torus
  - Needs smeared orientifolds
- Solvmanifolds (compact?): no solution
- Extend to cosets

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Coset manifolds

Tomasiello: $\mathcal{W}_2 \neq 0$ on two examples $\frac{\mathrm{Sp}(2)}{\mathrm{S}(\mathrm{U}(2)\times\mathrm{U}(1))}$, $\frac{\mathrm{SU}(3)}{\mathrm{U}(1)\times\mathrm{U}(1)}$

PK, Lüst, Tsimpis: classification

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- Condition left-invariance p-form ϕ: constant and components

$$f^j{}_{a[i_1} \phi_{i_2 \ldots i_p]j} = 0$$

Type IIA AdS$_4$ susy vacua on coset manifolds

PK, Lüst, Tsimpis 0804.0614

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# of parameters	2	4	4	3	2	4
$\mathcal{W}_2 \neq 0$	No	Yes	Yes	Yes	No	Yes
$j^6 \propto \mathrm{Re}\Omega$	Yes	No	Yes	Yes	Yes	No

Note: geometric flux: $\mathcal{W}_1 \neq 0, \mathcal{W}_2 \neq 0$

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Parameters:

- Geometric: scale and shape

$$J = ae^{12} + be^{34} + ce^{56}$$

Scale a and shape $\rho = b/a, \sigma = c/a$:

- Orientifold charge μ

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Generalization

- SU(3)×SU(3) susy ansatz: 10d → 4d

$$\begin{aligned}\epsilon_1 &= \zeta_+ \otimes \eta_+^{(1)} + \text{(c.c.)} \\ \epsilon_2 &= \zeta_+ \otimes \eta_\mp^{(2)} + \text{(c.c.)}\end{aligned}$$

for IIA/IIB

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  but neither a zero angle nor a right angle Type: (0,1)
- dynamic SU(3)×SU(3)-structure: angle changes, type may change

SU(3)×SU(3)-structure susy equations

Graña, Minasian, Petrini, Tomasiello

$$
\begin{aligned}
d_H\left(e^{4A-\Phi}\mathrm{Im}\,\Psi_1\right) &= 3e^{3A-\Phi}\mathrm{Im}\,(W^*\Psi_2) + e^{4A}\tilde{F}\\
d_H\left[e^{3A-\Phi}\mathrm{Re}\,(W^*\Psi_2)\right] &= 2|W|^2 e^{2A-\Phi}\mathrm{Re}\,\Psi_1\\
d_H\left[e^{3A-\Phi}\mathrm{Im}\,(W^*\Psi_2)\right] &= 0\\
d_H\left(e^{2A-\Phi}\mathrm{Re}\,\Psi_1\right) &= 0\,.
\end{aligned}
$$

with

$$
\begin{aligned}
d_H &= d + H\wedge\\
\Psi_1 &= \Psi_\mp\,, \qquad \Psi_2 = \Psi_\pm\\
\not{\Psi}_+ &= \frac{8}{|\eta^{(1)}||\eta^{(2)}|}\eta_+^{(1)}\otimes\eta_+^{(2)\dagger}\,, \quad \not{\Psi}_- = \frac{8}{|\eta^{(1)}||\eta^{(2)}|}\eta_+^{(1)}\otimes\eta_-^{(2)\dagger}\,.
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$$d_H\left[e^{3A-\Phi}\mathrm{Re}\,(W^*\Psi_2)\right] = 2|W|^2 e^{2A-\Phi}\mathrm{Re}\,\Psi_1$$
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$$d_H\left(e^{2A-\Phi}\mathrm{Re}\,\Psi_1\right) = 0\,.$$

Example: strict SU(3)-structure in IIA

$$\Psi_1 = \Psi_- = -\Omega\,, \qquad \Psi_2 = \Psi_+ = e^{-i\theta}e^{iJ}$$

leads to susy equations *Lüst, Tsimpis*

SU(3)×SU(3)-structure susy equations

Graña, Minasian, Petrini, Tomasiello

$$d_H\left(e^{4A-\Phi}\mathrm{Im}\,\Psi_1\right) = 3e^{3A-\Phi}\mathrm{Im}\left(W^*\Psi_2\right) + e^{4A}\tilde{F}$$
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Generalizations: no-go theorems

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  with the Mukai pairing $\langle \phi_1, \phi_2 \rangle = \phi_1 \wedge \alpha(\phi_2)|_{\text{top}}$
  and α reverses the indices of a form

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  $\Rightarrow c$ not everywhere non-vanishing

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Generalizations: conclusion of no-go theorems

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- Example: type IIB static SU(2) on nilmanifold 5.1 (table of *Graña, Minasian, Petrini, Tomasiello*)
- Type IIA: only strict SU(3) or dynamic SU(3)×SU(3) for which $d\left(e^{2A-\Phi}\eta^{(2)\dagger}\eta^{(1)}\right) \neq 0$

Low energy effective theory: nilmanifolds

Torus (IIA), nilmanifold 5.1 (IIB), Iwasawa (IIA): T-dual to each other

- Calculation mass spectrum
  - Using effective 4D sugra techniques
  - For Iwasawa & torus: direct KK reduction of equations of motion
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- Result for $M^2/|W|^2$

Complex structure	$-2, -2, -2$
Kähler & dilaton	$70, 18, 18, 18$
Three axions of δC_3	$0, 0, 0$
δB & one more axion	$88, 10, 10, 10$

Issue: decoupling KK tower

- Consistency approximation: $g_s \ll 1, l_s/L_{\text{int}} \ll 1$

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  - Can be tuned with orientifold charge μ:

$$e^{2\Phi} m^2 = \mu + \frac{5}{16} \left(3|\mathcal{W}_1|^2 - |\mathcal{W}_2|^2\right) \approx 0$$

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  - Can be arranged for torus, Iwasawa, nilmanifold 5.1
  - Harder for coset examples

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Low energy theory: superpotential and Kähler potential

We use the superpotential of *Graña, Louis, Waldram; Benmachiche, Grimm; PK, Martucci*
Generalizes *Gukov, Vafa, Witten*

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$$\mathcal{W}_{\mathsf{E}} = \frac{-i}{4\kappa_{10}^2}\int_M \langle \underbrace{\Psi_2 e^{\delta B}}_{\mathcal{Z}}, \hat{F} + i\, d_{\hat{H}}(\underbrace{e^{\delta B} e^{-\Phi}\,\mathrm{Im}\,\Psi_1 - i\delta C}_{\mathcal{T}})\rangle$$

$\mathcal{Z}, \mathcal{T}$ holomorphic coordinates,

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$\mathcal{Z}, \mathcal{T}$ holomorphic coordinates, and the Kähler potential

$$\mathcal{K} = -\ln i \int_M \langle \mathcal{Z}, \bar{\mathcal{Z}} \rangle - 2 \ln i \int_M \langle e^{-\Phi} \Psi_1, e^{-\Phi} \bar{\Psi}_1 \rangle + 3 \ln (8\kappa_{10}^2 M_P^2)$$

where $e^{-\Phi} e^{\delta B} \Psi_1$: function of $\mathrm{Re}\,\mathcal{T} = e^{-\Phi} e^{\delta B} \mathrm{Im}\,\Psi_1$ *Hitchin*.

Superpotential and Kähler potential: SU(3)

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Expansion:

$$J_c = J - i\delta B = (k^i - ib^i) Y_i^{(2-)} = t^i Y_i^{(2-)}$$

$$e^{-\Phi} \mathrm{Im}\,\Omega + i\delta C_3 = (u^i + ic^i) e^{-\hat{\Phi}} Y_i^{(3+)} = z^i e^{-\hat{\Phi}} Y_i^{(3+)}$$

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- If $W = M_P^{-1} \langle \mathcal{W}_{\mathsf{E}} \rangle \neq 0$ i.e. AdS$_4$ compactification
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Mass spectrum from quadratic terms

Low energy theory: cosets

- For all cosets (but not for SU(2)×SU(2)): all moduli stabilized at tree level

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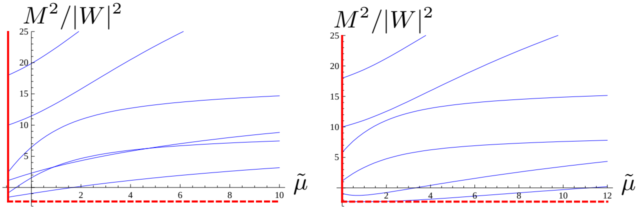

(a) $\sigma = 1$ (b) $\sigma = \frac{2}{5}$

Movie

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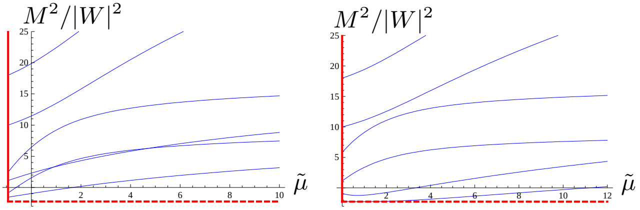

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- $\tilde{\mu}$ big enough: all mass-squared positive

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Nearly-Calabi Yau limit

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  Twistor bundle description more appropriate *Xu*

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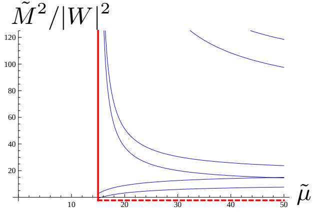

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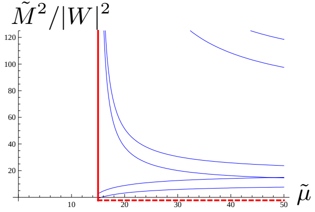

- Light modes: $\tilde{M}^2/|W|^2 = (-38/49, 130/49)$

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Inflation

No-go theorem modular inflation IIA
Hertzberg, Kachru, Taylor, Tegmark

- Dependence on volume-modulus ρ and dilaton-modulus τ
- Ingredients: form-fluxes, D6-branes & O6-planes
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  - not possible for $\frac{G_2}{SU(3)}$, possible for all other cosets and SU(2)×SU(2)

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Conclusions

- Tractable models with geometric flux: nilmanifold & coset models
- Other models: e.g. twistor bundles with negative σ
- Uplift: uplifting term or look for dS minimum e.g. *Silverstein*
- Study inflation

Conclusions

- Tractable models with geometric flux: nilmanifold & coset models
- Other models: e.g. twistor bundles with negative σ
- Uplift: uplifting term or look for dS minimum e.g. *Silverstein*
- Study inflation

The end. . . The end. . . The end. . .

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