On/off scale separation

George Tringas

Laboratoire d'Annecy-le-Vieux de Physique Théorique (LAPTh)

May 24, 2023

French Strings Meeting, Annecy

Based on

1. F. Farakos, G. T and T. Van Riet, "No-scale and scale-separated flux vacua from IIA on G2 orientifolds," [2005.05246].
2. **F. Farakos, M. Morittu, G. T, "On/off scale separation," [2304.14372].**

Introduction

Motivation-Goal

Construct EFTs with Einstein gravity from string theory.

↓

An elementary starting point is the construction of vacua.

Einstein equations at the vacuum:

$$S = \int d^{\mathrm{d}}x\sqrt{-g}\left(\frac{1}{2}R + \cdots + V(\phi)\right) \xrightarrow[\Lambda \equiv \mathrm{V}(\phi^0)]{\nabla_\phi V|_{\phi^0}=0} R_{mn} - \frac{1}{2}Rg_{mn} + \Lambda g_{mn} = 0 \quad (1)$$

In this analysis we are looking for consistent AdS vacua:

$$\Lambda < 0 \quad (2)$$

We construct such vacua from string theory and check their consistency.

Why AdS?

We would like our EFT to have:

- Stabilized moduli
- Quantized fluxes (Requirement for string theory origin)
- No tachyons
- Make the extra dimensions not detectable: Scale separation $\frac{L_{KK}^2}{L_\Lambda^2} \to 0$

de-Sitter from string theory?

U. H. Danielsson and T. Van Riet "What if string theory has no de Sitter vacua?,"[1804.01120].

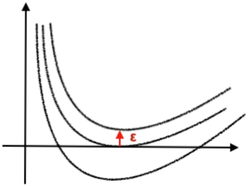
D. Andriot "Open problems on classical de Sitter solutions,"[1902.10093].

Classical limit

- Weak coupling $g_s = e^\phi \ll 1$: string loops neglected
- Large volume: α' corrections sub-leading

AdS vacua from string theory seem to have such properties

O. DeWolfe, A. Giryavets, S. Kachru and W. Taylor, "Type IIA moduli stabilization,"[0505160].



Three dimensional AdS

Three-dimensional EFTs cannot physically describe our Universe

$$M_{10} = M_3 \times X^7 \ : \ \ 10d \text{ Type IIA supergravity} \rightarrow 3d \text{ EFT}$$

but can provide us with information about the existence of EFTs with "good" properties from string theory

- 3d constructions are simpler than 4d
- The validity of AdS_3 vacua can be checked with CFT_2 which is better understood.
- Test conjectures in 3d too.
- Important for 3d de-Sitter uplifts.

Classical SUSY (and non-SUSY!?) AdS$_3$ solutions with: moduli stabilization, flux quantization and parametric scale separation

F. Farakos, G. T and T. Van Riet, "No-scale and scale-separated flux vacua from IIA on G2 orientifolds,"[2005.05246].

Scale separation

Scale separation: Kaluza-Klein scale to be separated from the curvature radius of the external space

$$\frac{L_{KK}^2}{L_\Lambda^2} \to 0\,.$$

This is a naive estimation for **parametric** separation of scales (decoupling), in other worlds, to make extra dimensions not detectable.

- Assume the metric ansatz

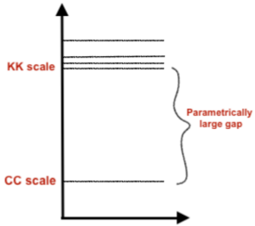
$$\mathrm{d}s_{10}^2 = e^{2\alpha\upsilon}\mathrm{d}s_3^2 + e^{2\beta\upsilon}\left(\tilde{r}_1^2\mathrm{d}y_1^2 + \dots\right)$$

- For a $10d$ scalar assume $\phi(x,y_1) = \sum_n \phi_n(x)cos[2\pi n y_1]$

$$L_{KK}^{-2} \sim m^2 \sim \frac{e^{-16\beta\upsilon}}{\tilde{r}_1^2}\,, \qquad L_\Lambda^{-2} \sim \langle V\rangle$$

- For unbounded flux f we have:

$$\frac{L_{KK}^2}{L_\Lambda^2} \sim f^{-c}$$



Swampland conjectures

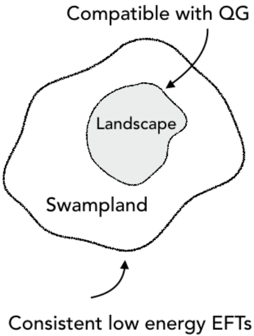
The notion of a consistent EFT can be understood as follows

Effective field theory space:

- Landscape: Consistent
  EFTs that **can** be UV-completed to quantum gravity

Conjectures:

- SUSY AdS conjecture $\Lambda \to 0$ then light KK modes
  D. Lüst, E. Palti, C. Vafa "AdS and the Swampland," [1906.05225]
- Distance conjecture: $m \sim m_0 e^{-\gamma \Delta}$
  H. Ooguri, C. Vafa "On the Geometry of the String Landscape and the Swampland,"[0605264]. H. Ooguri, E. Palti, G. Shiu, C. Vafa "Distance and de Sitter Conjectures on the Swampland,"[1810.05506].
- non-SUSY AdS
  instabilities, dS swampland conjecture, WGC etc...



3d vacua in Type IIA

From G2-manifold to Toroidal orbifold

A G2-manifold is characterized by the **fundamental three-form**

$$\Phi = e^{127} - e^{347} - e^{567} + e^{136} - e^{235} + e^{145} + e^{246}\,,$$

We choose the internal manifold X_7 to be a **seven-torus** with the orbifold Γ:

$$X_7 = \frac{T^7}{\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2}\,, \qquad y^m \sim y^m + 1 \tag{3}$$

with specific $\mathbb{Z}_2$ involutions

$$\begin{aligned} \Theta_\alpha :\; & y^m \to (-y^1, -y^2, -y^3, -y^4, y^5, y^6, y^7)\,, \\ \Theta_\beta :\; & y^m \to (-y^1, -y^2, y^3, y^4, -y^5, -y^6, y^7)\,, \\ \Theta_\gamma :\; & y^m \to (-y^1, y^2, -y^3, y^4, -y^5, y^6, -y^7)\,, \end{aligned} \tag{4}$$

The vielbein of the torus $e^m = r^m \mathrm{d}y^m$

$$\Phi = s^i \Phi_i\,, \qquad \Phi_i = \left(dy^{127}, -dy^{347}, -dy^{567}, dy^{136}, -dy^{235}, dy^{145}, dy^{246}\right)\,, \tag{5}$$

where the s^i are the **metric/structure moduli** related to the seven-torus **radii** r^m

$$e^{127} = s^1 \Phi_1 \;\to\; s^1 = r^1 r^2 r^7\,,\ \text{etc.} \tag{6}$$

Orientifolds

Target space involutions for the sources (fixed points)

$$\sigma_{\text{O2}}: \; y^m \to (-y^1, -y^2, -y^3, -y^4, -y^5, -y^6, -y^7), \qquad \sigma_{\text{O6}_i}: \sigma_{\text{O2}}\Gamma\,. \tag{7}$$

In total we have 7 different directions for O6-planes

	y^1	y^2	y^3	y^4	y^5	y^6	y^7
O6_α	$\otimes$	$\otimes$	$\otimes$	$\otimes$	–	–	–
O6_β	$\otimes$	$\otimes$	–	–	$\otimes$	$\otimes$	–
O6_γ	$\otimes$	–	$\otimes$	–	$\otimes$	–	$\otimes$
$\text{O6}_{\alpha\beta}$	–	–	$\otimes$	$\otimes$	$\otimes$	$\otimes$	–
$\text{O6}_{\beta\gamma}$	–	$\otimes$	$\otimes$	–	–	$\otimes$	$\otimes$
$\text{O6}_{\gamma\alpha}$	–	$\otimes$	–	$\otimes$	$\otimes$	–	$\otimes$
$\text{O6}_{\alpha\beta\gamma}$	$\otimes$	–	–	$\otimes$	–	$\otimes$	$\otimes$

Table: O6-planes localized positions "-" and warped directions $\otimes$ in the internal space.

We get 3d N=1 minimal effective supergravity :

Type IIA supercharges : $\mathbf{32} \xrightarrow{\Gamma \text{ orbifold}} \mathbf{4} \xrightarrow{\text{O2-plane}} \mathbf{2}$ real

The 3d effective theory

The 3d bosonic effective action has the form

$$e^{-1}\mathcal{L}_{EFT} = \frac{1}{2}R_3 - \frac{1}{4}(\partial x)^2 - \frac{1}{4}(\partial y)^2 - \frac{1}{4}\text{vol}(\tilde{X}_7)^{-1}\int_7 \Phi_i \wedge \tilde{\star}\Phi_j \partial\tilde{s}^i\partial\tilde{s}^j - V \tag{8}$$

The scalar potential in 3d supergravity is given by

$$V(x, y, \tilde{s}^i) = G^{IJ}\partial_I P \partial_J P - 4P^2 \tag{9}$$

We guess superpotential which gives the 3d effective potential

$$P = \frac{e^y}{8}\left[e^{\frac{x}{\sqrt{7}}}\int \tilde{\star}\Phi \wedge H_3\,\text{vol}(\tilde{X}_7)^{-\frac{4}{7}} + e^{-\frac{x}{\sqrt{7}}}\int \Phi \wedge F_4\,\text{vol}(\tilde{X}_7)^{-\frac{3}{7}}\right] + \frac{F_0}{8}\,e^{\frac{1}{2}y - \frac{\sqrt{7}}{2}x}$$

The fluxes H_3 and F_4 are expanded on the Φ_i and Ψ_i basis

$$H_3 = \sum_{i=1}^{7} h^i \Phi_i\,, \qquad F_4 = \sum_{i=1}^{7} f^i\,\Psi_i\,, \tag{10}$$

Tadpole cancellation – Flux ansatz

The relevant tadpole:

$$\int_7 \mathrm{d}F_6 = 0 = \int_7 (F_{4,q} + F_{4,f}) \wedge H_3 + (2\pi)^7 \int_7 (N_{\mathrm{O2}}\mu_{\mathrm{O2}} + N_{\mathrm{D2}}\mu_{\mathrm{D2}}) j_7 \tag{11}$$

We have studied to following ansatz for the fluxes:

Flux	isotropic F. Farakos, G. T, T. Van Riet, [2005.05246].	anisotropic F. Farakos, M. Morittu, G. T, [2304.14372].
h_3^i	$h\,(1,1,1,1,1,1,1)$	$h\,(1,1,1,1,1,1,0)$
$f_{4,q}^i$	0	$q\,(0,0,0,0,0,0,-1)$
$f_{4,f}^i$	$f\,(-1,-1,-1,-1,-1,-1,+6)$	$f\,(-1,-1,-1,-1,-1,+5,0)$

- Cancel O2 with $N_{\mathrm{D2}} = 2^4$
- The tadpole cancels while the flux "f" remains unconstrained:

$$\int_7 H_3 \wedge F_{4,q} = 0 \times (-q) = 0\,, \qquad \int_7 H_3 \wedge F_{4,f} = -5hf + 5hf = 0\,.$$

Scaling of the fluxes

For the anisotropic flux ansatz we evaluate the superpotential

$$\frac{P}{(2\pi)^7} = \frac{e^{y+\frac{x}{\sqrt{7}}}}{8} h \sum_{i=1}^{6} \frac{1}{\tilde{s}^i} + \frac{e^{y-\frac{x}{\sqrt{7}}}}{8} \left[f \left(-\sum_{i=1}^{5} \tilde{s}^i + 5\tilde{s}^6 \right) - q\tilde{s}^7 \right] + \frac{m}{8} e^{\frac{y-\sqrt{7}x}{2}} \quad (12)$$

Method: Assume the fluxes of the fields having the following scaling:

$$f \sim N\,, \quad q \sim N^Q\,, \quad e^y \sim N^Y\,, \quad e^x \sim N^X\,, \quad \tilde{s}^a \sim N^S\,. \quad (13)$$

The scaling of the fluxes becomes:

$$Y = -\frac{9}{2} - 7S\,, \quad X = \frac{\sqrt{7}}{2}(1+2S)\,, \quad Q = 1 + 7S\,. \quad (14)$$

- We have created an anisotropic scaling to T^7 radii :

$$\{r_i^2\}_{i=1,3,5,7} \sim N^{\frac{7+11S}{8}} \times N^{3S}\,,$$
$$\{r_i^2\}_{i=2,4,6} \sim N^{\frac{7+11S}{8}} \times N^{-2S}\,,$$

Large volume, Weak coupling and Scale separation

Large volume: $$r_i^2 = e^{2\beta v}\tilde{r}_i^2 \gg 1 \;\rightarrow\; -\frac{1}{5} < S < \frac{1}{3}\,. \tag{15}$$

Weak coupling: $$g_s = e^{\phi} \sim N^{-\frac{3+7S}{4}} < 0 \;\rightarrow\; S > -\frac{3}{7}\,. \tag{16}$$

Scale separation: $$\{r_i\}_{i=1,3,5,7} : \qquad \frac{L^2_{KK,i}}{L^2_{\Lambda}} \sim N^{-1}\,, \tag{17}$$

$$\{r_i\}_{i=2,4,6} : \qquad \frac{L^2_{KK,i}}{L^2_{\Lambda}} \sim N^{-1-7S}\,, \tag{18}$$

"on-off"

- Large volume, Weak coupling, **Scale separation** : $S = 0 \quad (or \;\; Q = 1)$
- Large volume, Weak coupling, **broken-Scale separation** : $-\frac{1}{5} < S \leq -\frac{1}{7}$

For **broken scale separation** $L^2_{KK,i} \sim L^2_{\Lambda}$ we consider:

$$S = -\frac{1}{7}(1+\epsilon)\,, \qquad 1 \gg \epsilon > 0\,. \qquad (or \;\; Q = 0) \tag{19}$$

Moduli stabilization

The supersymmetric equations reduce to the following system:

$$\frac{\partial P}{\partial x} = \frac{\partial P}{\partial y} = \frac{\partial P}{\partial \tilde{s}^a} = 0 \quad \Rightarrow \quad \begin{cases} 0 & = c - a\sigma^5 + 5\sigma^5\tau^7 \, , \\ 0 & = c - a\sigma^4\tau - \sigma^6\tau \, , \\ 0 & = -3b + 2a\left(\frac{5}{\sigma} + \frac{1}{\tau}\right) \, , \\ 0 & = \frac{b}{2} + a\left(\frac{5}{\sigma} + \frac{1}{\tau}\right) + \left(-5\sigma + 5\tau - \frac{c}{\sigma^5\tau}\right) \, , \end{cases} \tag{20}$$

$$\text{where} \qquad c = \frac{q}{f} \, . \tag{21}$$

$$\text{the system is solved for} \qquad a = \frac{h}{f} e^{\frac{2x}{\sqrt{7}}} \, , \quad b = \frac{m_0}{f} e^{-\frac{y}{2} - \frac{5x}{2\sqrt{7}}} \, . \tag{22}$$

c	a	b	$\langle \tilde{s}^a \rangle = \sigma$	$\langle \tilde{s}^6 \rangle = \tau$
10^{-1}	0.298843	2.44476	0.884523	0.151095
10^{-3}	0.0801704	1.26626	0.458136	0.078259
10^{-6}	0.0111396	0.472009	0.170775	0.0291718
10^{-9}	0.00154785	0.175946	0.0636578	0.0108741

Canonical masses

Canonical masses and dimensions of dual operators

$$\text{Eigen}\left[\langle K_{IJ}\rangle^{-1}\frac{\langle V_{IJ}\rangle}{|\langle V\rangle|}\right] = m^2L^2\,, \qquad \Delta[\Delta-(d-1)] = m^2L^2 \tag{23}$$

c	Eigen$[V_{IJ}/\lvert\langle V\rangle\rvert]$
1	$\{231.942, 17.314, 3.8722, 3.4185, 0.8569, 0.8569, 0.8569, 0.8569\}$
10^{-1}	$\{438.227, 23.672, 5.441, 3.510, 1.654, 1.654, 1.654, 1.654\}$
10^{-3}	$\{1606.81, 65.710, 7.403, 6.167, 6.167, 6.167, 6.167, 3.523\}$
10^{-6}	$\{11505., 436.001, 44.384, 44.384, 44.384, 44.384, 8.065, 3.525\}$
10^{-9}	$\{82741.6, 3105.15, 319.429, 319.429, 319.429, 319.429, 8.155, 3.525\}$

$$\mathbf{m^2L^2}\ :\ \{49.778, 8.178, 6.347, 2.589, 2.589, 2.589, 2.589, 1.966\}$$

$$\Delta = \{8.126, 4.029, 3.710, 2.894, 2.894, 2.894, 2.894, 2.722\}$$

Interpolating between flux vacua

Probe D4-brane

So far we have constructed "disconnected" Scale-separated and non-Scale separated vacua.

Interpolate between vacua : Introduce a space-filling prode D4-brane G. Shiu, F. Tonioni, V. Van Hemelryck, T. Van Riet "AdS scale separation and the distance conjecture," [2212.06169].

	t	x	z	y^2	y^4	y^6	y^1	y^3	y^5	y^7
D4	$\otimes$	$\otimes$	$\otimes$	$\circledast$	$\circledast$	$-$	$-$	$-$	$-$	$-$
Φ_7	$-$	$-$	$-$	$\otimes$	$\otimes$	$\otimes$	$-$	$-$	$-$	$-$
$F_{4,q} \sim q\Psi_7$	$-$	$-$	$-$	$-$	$-$	$-$	$\otimes$	$\otimes$	$\otimes$	$\otimes$

Table: The D4-branes fills the AdS_3 and wraps 2-cycles inside the 3-cycle Φ_7.

$$\mathrm{d}F_4 = Q_{\mathrm{D4}}\delta(\psi - \psi_0)\mathrm{d}\psi \wedge \Psi_7 \quad \rightarrow \quad \Delta F_4 = Q_{\mathrm{D4}}\theta(\psi - \psi_0)\Big|_{\psi_1<\psi_0}^{\psi_2>\psi_0}\Psi_7 \tag{24}$$

- D4-brane with co-dimension 1 induces a change to F_4 flux on either side of the brane.
- A scalar field describes the position of the D4 inside the compact geometry.
- A scalar field displacement changes the F_4-flux.

Open string modulus

Let ψ depend on the external coordinates:

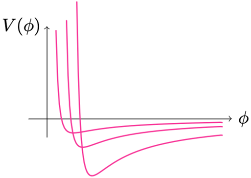
$$\mathrm{d}s^2_{\mathrm{D4}} = \left(e^{2\alpha\upsilon} g^{(3)}_{\mu\nu} + s_7^{\frac{2}{3}} R^2 \partial_\mu\psi\partial_\nu\psi\right) \mathrm{d}x^\mu \mathrm{d}x^\nu + s_7^{\frac{2}{3}} \left(\mathrm{d}R^2 + R^2(\sin\psi)^2 \mathrm{d}\omega^2\right) , \qquad (25)$$

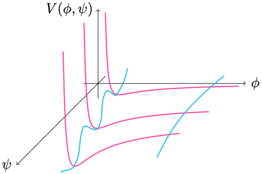
The action:

$$S_{\mathrm{D4}} \sim -\frac{T_4}{8} \int \mathrm{d}^3x \sqrt{-g^{(3)}}\, e^{\frac{\phi}{4}+3\alpha\upsilon} s_7^{\frac{2}{3}} \int_{R_-}^{R_+} \int_{\omega_-}^{\omega_+} R\sin\psi \sqrt{1 + \frac{4 s_7^{\frac{2}{3}} e^{-2\alpha\upsilon} R^2}{(2\pi)^{14}} (\partial\psi)^2} + \ldots$$

The potential for ψ gets the following form

$$V(\psi) \supset \frac{T_4}{8} e^{\frac{\phi}{4} - 21\beta\upsilon} s_7^{2/3} \sin\psi \qquad (26)$$





Scalar potentials with discrete choice of fluxes are connected through ψ direction.

The distance conjecture

The scalar field space metric components:

$$g_{\psi\psi} = 2ck\tilde{s}_7^{\frac{4}{3}} e^{\frac{\phi}{4} - 3\alpha v} \sin\psi\,, \qquad g_{\phi\phi} = g_{vv} = \frac{1}{2}\,, \qquad g_{\tilde{s}^a\tilde{s}^a} = \frac{1+\delta_{ab}}{2\tilde{s}^a\tilde{s}^b}\,. \tag{27}$$

Flux values: h, m_0 fixed,

- Scale separated $q = f = (2\pi)^3 N$
- Deviating from scale separation $q = (2\pi)^3 N$ and $f = (2\pi)^3(N+1)$

After redefinitions

$$\Delta \sim \int_0^1 \mathrm{d}\xi \sqrt{\frac{1}{h_2^2}\left[\left(\frac{\mathrm{d}h_1}{d\xi}\right)^2 + \left(\frac{\mathrm{d}h_2}{d\xi}\right)^2\right] + \left(\frac{\mathrm{d}u_2}{d\xi}\right)^2 + \left(\frac{\mathrm{d}u_3}{d\xi}\right)^2 + \left(\frac{\mathrm{d}u_4}{d\xi}\right)^2} \tag{28}$$

and for the geodesic path we have

$$\Delta \sim \sqrt{d_1^2 + d_3^2 + d_5^2 + d_7^2} \tag{29}$$

Requiring $\frac{m}{m_0} \sim e^{-\gamma\Delta}$ for one jump we get $\gamma \sim \mathcal{O}(1)$.

Conclusion

Conclusion slide

- We constructed minimal classical SUSY three-dimensional AdS_3 vacua compactified on G2 spaces with
  - Scale-separation
  - Moduli stabilization
  - Flux quantization
- For specific flux ansatz we cancelled the tadpoles and created an anisotropy to the scaling of the radii.
- We constructed new vacua with scale separation and broken scale separation while remaining at the supergravity regime.
- Introduced a D4 to interpolate between those vacua and verified the distance conjecture.

Thank you!

The scalar potential

A general scalar potential of Type IIA on G2 oriantifolds has the form

$$V = F(\tilde{s}^a)\, e^{2y - \frac{2}{\sqrt{7}}x} + H(\tilde{s}^a)\, e^{2y + \frac{2}{\sqrt{7}}x} + C\, e^{y - \sqrt{7}x} - T(\tilde{s}^a)\, e^{\frac{3}{2}y - \frac{5x}{2\sqrt{7}}x} \tag{30}$$

The coefficients depends on the flux choice. For the "on/off" setup given by

$$\begin{aligned}
F_4 \quad &: \quad F = \frac{f_4^2}{16}\left(\sum_{a=1}^{6}(\tilde{s}^a)^2 + \prod_{a=1}^{6}(\tilde{s}^a)^{-2}\right), \\
H_3 \quad &: \quad H = \frac{h_3^2}{16}\left(\sum_{a=1}^{6}(\tilde{s}^a)^{-2} + \prod_{a=1}^{6}(\tilde{s}^a)^{2}\right), \\
F_0 \quad &: \quad C = \frac{m^2}{16}, \\
O6/\overline{D6} \quad &: \quad T = \frac{h_3 m}{8}\left(\sum_{a=1}^{6}\frac{1}{\tilde{s}^a} + \prod_{a=1}^{6}\tilde{s}^a\right),
\end{aligned} \tag{31}$$

Results

We used Type IIA down to 3d with Romans mass and smeared sources and found

- *Stabilized moduli*
- *Parametric Scale-separation*
- *Parametric Large volume and weak coupling*
- *No-tachyons*

$$\langle V \rangle = -\frac{1}{64a^6b^4}\left(6\sigma^2 + \frac{36}{\sigma^{12}}\right)\frac{m^4h^6}{f^8} \,. \quad (32)$$

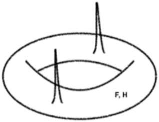
$$\frac{L^2_{KK}}{L^2_{\Lambda}} \sim f^{-1} \,, \quad g_s = e^{\phi} \sim f^{-\frac{3}{4}} \,, \quad \mathrm{vol}(X_7) = e^{7\beta u} \sim f^{\frac{49}{16}} \quad (33)$$

We employ the Hessian of the potential to verify that the BF bound is satisfied, no tachyons.

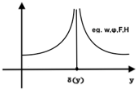
Smearing process

Localized sources:

- The density is locally distributed by singular function $\delta(y)$.
- Strong backreaction
  → Non-trivial field profile close to the locii, $F \sim F_0 + 1/r + \ldots$

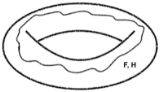


Localized source



Smeared sources:

- Smeared sources are distributed all over the cycles $j(y)$.
- The fields *ignore* local backreaction : Trivial profile
- Lead to consistent truncation.



Smeared source