On/off scale separation

George Tringas

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

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String Pheno 23, IBS Daejeon

Based on

1. F. Farakos, G. T , 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

EFT from String theory

Construct EFTs with Einstein gravity from string theory

$\downarrow$

Elementary starting point: Vacuum construction

We would like our EFT to have:

- Stabilized moduli
- Quantized fluxes
- Not detectable extra dimensions: Scale separation $\frac{L_{KK}^2}{L_\Lambda^2} \to 0$

de-Sitter from string theory?

Danielsson, Van Riet [1804.01120]. , Andriot [1902.10093].

Classical limit

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

AdS$_4$ vacua from massive Type IIA have such properties:

DeWolfe, Giryavets, Kachru, Taylor, [0505160].

Three dimensional AdS

Three-dimensional EFTs cannot physically describe our Universe but can provide us with information about the existence of EFTs from string theory with "good" properties

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

- 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.
- 3d de-Sitter uplifts?

Classical SUSY AdS_3 solutions with moduli stabilization, flux quantization and parametric scale separation:
Farakos, G. T, Van Riet [2005.05246] , Van Hemelryck, [2207.14311]

Scope 1: Find well controlled vacua with broken and non-broken scale separation.

Scale separation

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

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

estimation for **parametric** decoupling of scales.

- Assume the metric ansatz

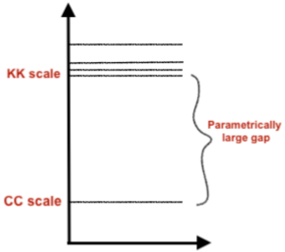
$$\mathrm{d}s_{10}^2 = e^{2\alpha\upsilon}\mathrm{d}s_3^2 + e^{2\beta\upsilon}\left(\tilde{r}_1^2\mathrm{d}y_1^2 + \dots\right)$$

- For a $10d$ scalar $\phi(x_\mu, y_1, \dots)$

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

- For unbounded flux f we have:

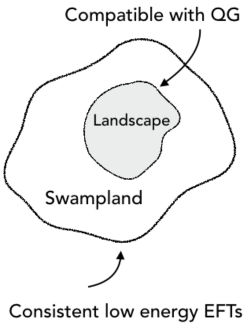
$$\frac{L_{KK}^2}{L_\Lambda^2} \sim f^{-c}$$



Swampland conjectures

Consistent EFT can be understood as follows:

EFTs that **can** be UV-completed to quantum gravity. (Landscape)



Relevant conjecture:

- SUSY AdS conjecture $\Lambda \to 0$ then light KK modes
- Distance conjecture: $m \sim m_0 e^{-\gamma\Delta}$ with $\gamma \sim \mathcal{O}(1)$ and $\Delta > \mathcal{O}(1)$

Ooguri, Vafa [0605264]. Gautason, Van Hemelryck, Van Riet, [1810.08518] Lüst, Palti, Vafa "AdS and the Swampland," [1906.05225] Ooguri, Palti, Shiu, Vafa [1810.05506].

Scope 2: measure the distance from broken scale separated to scale separate vacua.

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:

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

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

$$\Phi = s^i \Phi_i ,$$

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

$$e^{127} = s^1 \Phi_1 \ \rightarrow \ s^1 = r^1 r^2 r^7 \ , \ \text{etc.}$$

Target space involutions for the sources (fixed points)

$$\sigma_{\mathrm{O2}} : \ y^m \to -y^m , \qquad \sigma_{\mathrm{O6}_i} : \sigma_{\mathrm{O2}} \Gamma \quad i = 1, \ldots, 7.$$

We get 3d N=1 minimal effective supergravity :

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

The 3d effective theory

The 3d bosonic effective action has the form

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

with **2+6** moduli in total

$$x, y \ : \ \text{universal}\,, \quad \tilde{s}^i \ : \ \text{metric deformations}\,.$$

We guess superpotential which gives the 3d effective potential

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

The fluxes are expanded on the invariant basis

$$H_3 = \sum_{i=1}^{7} h^i \Phi_i\,, \qquad F_4 = \sum_{i=1}^{7} f^i\,\Psi_i\,, \qquad F_0 = m\,.$$

Tadpole cancellation – Flux ansatz

The relevant tadpole:

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

We have studied to following ansatz for the fluxes:

Flux	isotropic Farakos, G. T, Van Riet, [2005.05246].	anisotropic Farakos, 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 $N_{\mathrm{D2}} = 2^4$
- Tadpole cancels while "f" and "q" remain 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

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

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

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

The scaling of the fluxes becomes:

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

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

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

Constraints on the scaling

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

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

Scale separation:

$$\{r_i\}_{i=1,3,5,7} : \quad \frac{L^2_{KK,i}}{L^2_{\Lambda}} \sim N^{-1}$$

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

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

Moduli stabilization

The supersymmetric equations reduce to the following system:

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

where $c = \frac{q}{f}$,

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

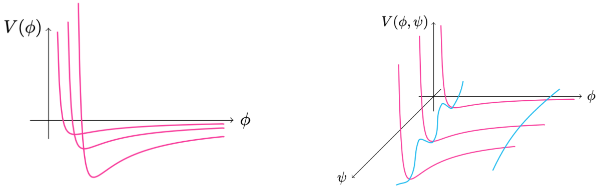
c	a	b	$\langle \tilde{s}^a \rangle = \sigma$	$\langle \tilde{s}^6 \rangle = \tau$
10^{-1}	0.298843	2.44476	0.884523	0.151095
10^{-3}	0.0801704	1.26626	0.458136	0.078259
10^{-6}	0.0111396	0.472009	0.170775	0.0291718
10^{-9}	0.00154785	0.175946	0.0636578	0.0108741

Interpolating between flux vacua

Probe D4-brane

Interpolate between vacua : Shiu, Tonioni, Van Hemelryck, Van Riet [2212.06169]

- D4 with co-dimension 1 induces a change to F_4 flux on either side of the brane
- A open strong modulus displacement changes the F_4-flux.



Scalar potentials with discrete choice of fluxes are connected through ψ direction.
Image: Shiu, Tonioni, Van Hemelryck, Van Riet [2212.06169]

<u>Distance calculation</u>

Flux values: $h = (2\pi)^2 16, \quad m_0 = (2\pi)^{-1}, \; f = (2\pi)^3 10^5,$

$$c = \frac{q}{f} = \frac{(2\pi)^3}{(2\pi)^3 10^5} \xrightarrow{\text{non scale sep. to scale sep}} \frac{(2\pi)^3(1+N^Q)}{(2\pi)^3 10^5}$$

and moduli space: $\mathbb{H}^2 \times \mathbb{R}^3$, we explicitly find

$$m^{\phi}_{KK}(Q=1) = m_{KK}(Q=0)e^{-\gamma\Delta} \quad \rightarrow \quad \gamma \approx 0.127$$

Conclusion

Conclusion slide

- We constructed minimal classical SUSY 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.
- New vacua with scale separation and broken scale separation while remaining at classical supergravity regime.
- Introduced a D4 to interpolate between those vacua and verified the distance conjecture.

Thank you!

Orientifolds

The $\mathbb{Z}_2$ involutions are

$$\Theta_\alpha : \; y^m \to (-y^1, -y^2, -y^3, -y^4, y^5, y^6, y^7)\,,$$
$$\Theta_\beta : \; y^m \to (-y^1, -y^2, y^3, y^4, -y^5, -y^6, y^7)\,,$$
$$\Theta_\gamma : \; y^m \to (-y^1, y^2, -y^3, y^4, -y^5, y^6, -y^7)\,,$$

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$_\alpha$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	−	−	−
O6$_\beta$	$\otimes$	$\otimes$	−	−	$\otimes$	$\otimes$	−
O6$_\gamma$	$\otimes$	−	$\otimes$	−	$\otimes$	−	$\otimes$
O6$_{\alpha\beta}$	−	−	$\otimes$	$\otimes$	$\otimes$	$\otimes$	−
O6$_{\beta\gamma}$	−	$\otimes$	$\otimes$	−	−	$\otimes$	$\otimes$
O6$_{\gamma\alpha}$	−	$\otimes$	−	$\otimes$	$\otimes$	−	$\otimes$
O6$_{\alpha\beta\gamma}$	$\otimes$	−	−	$\otimes$	−	$\otimes$	$\otimes$

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

Canonical masses

Canonical masses and dimensions of dual operators

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

c	Eigen$[V_{IJ}/|\langle V\rangle|]$
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}	$\{82741.6, 3105.15, 319.429, 319.429, 319.429, 319.429, 8.155, 3.525\}$

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

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