Massive IIA vacua with dynamical open strings

Padova, StringPheno 2024

Based on:

2406.15310 [hep-th]

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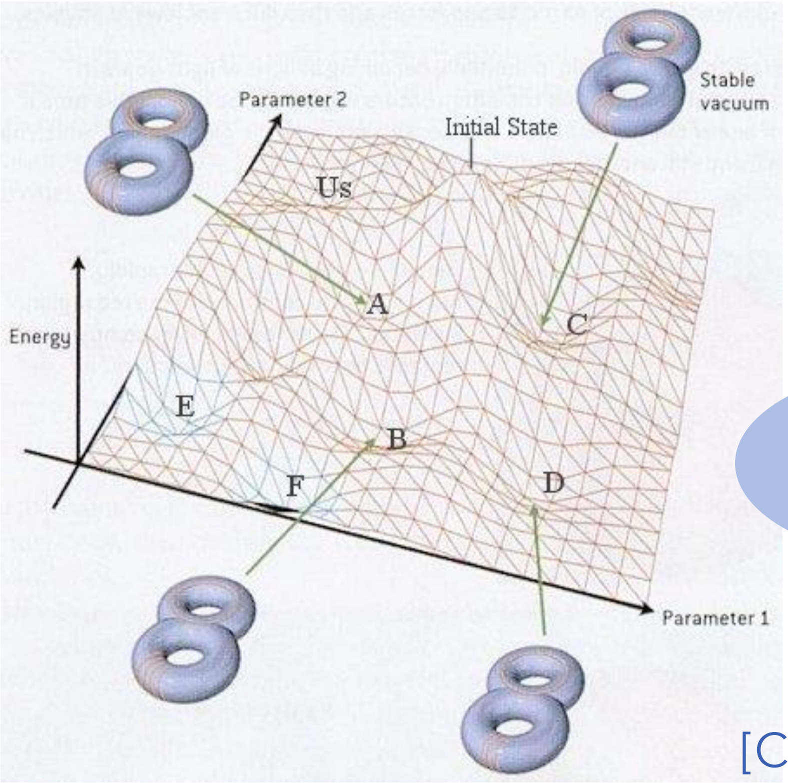
Outline

- Introduction & Motivation
- Review of Op/Dp systems
- Gauged half-maximal 4D supergravity theories
- A comment on Swampland constraints
- Non-Abelian brane actions & reductions thereof
- An explicit example: mIIA with O6/D6
- Vacua analysis
- Perturbative control

Flux Compactifications

Strings on $\mathcal{M}_{1,9-d} \times \mathcal{M}_d$ $\longrightarrow$ Gravity $(10-d)$ + Scalars $\{\phi^I\}$



[Credits: American Physics Society, 2002]

Vacuum:

$$\begin{cases} \phi^I &= \phi^I_0 \qquad \text{(vev's)} \\ \Lambda_{\text{eff}} &= V(\phi_0) \qquad \text{(effective c.c.)} \end{cases}$$

Perturbative Stability:

$$\left(m^2\right)^I{}_J = \partial^I \partial_J V|_{\phi_0} \begin{cases} \overset{!}{\geq} 0 & \text{(Mkw, dS)} \\ \overset{!}{\geq} m^2_{\text{BF}} & \text{(AdS)} \end{cases}$$

Why open strings? (we need D-branes…)

A HARD question because…

- Effectively working **at finite alpha prime** and hence it is not well understood…

A RELEVANT question because…

- It may determine the **ultimate string Landscape** (open+closed strings need to be consistently coupled in a quantum regime)
- It may shed a light on **AdS/CFT** beyond decoupling limit

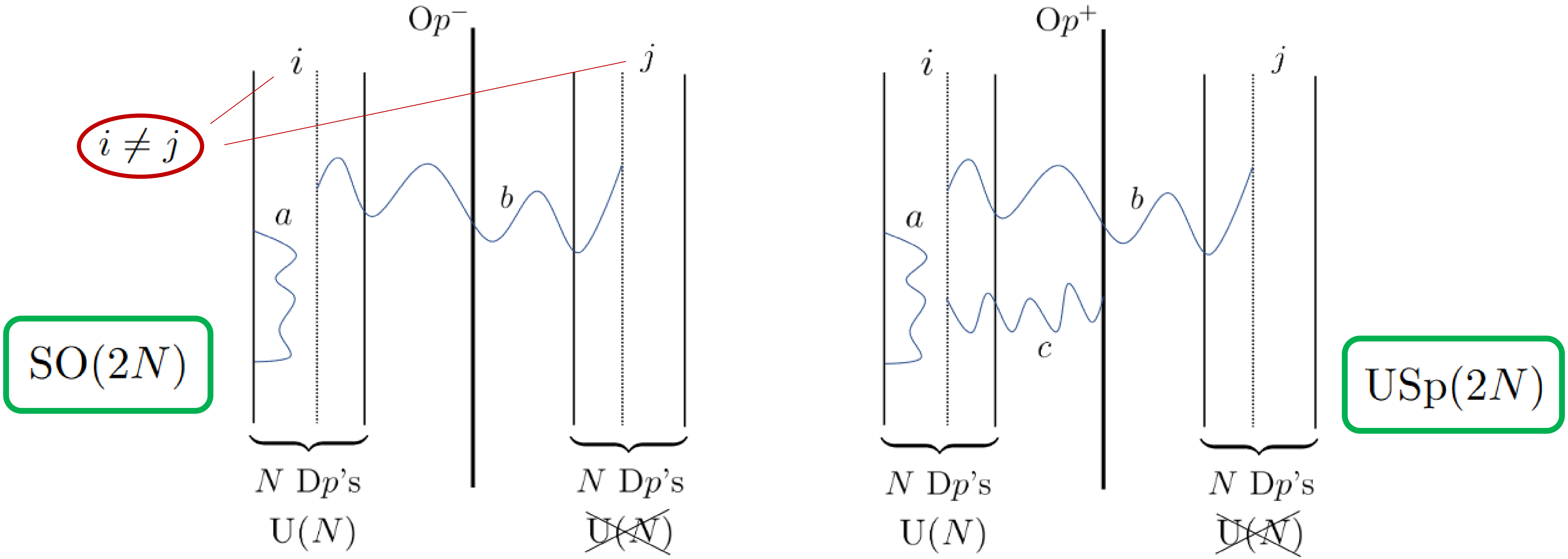
Non-perturbative formulations?

String Field Theory may give a hope?

Today:

Be happy with an **EFT** description

A recap on O*p*/D*p* configurations



UV finiteness in **flat space**, in **absence of fluxes**…

$$(N_{\mathrm{D}p} - \cancel{N_{\overline{\mathrm{D}p}}}) \overset{!}{=} 2^{p-5}(N_{\mathrm{O}p^-} - N_{\mathrm{O}p^+}) \qquad \text{(tadpole cancellation)}$$

The open string sector gauge groups are…

$$G_{\mathrm{YM}} = \left(\prod_a \mathrm{U}(N_a)\right) \times \left(\prod_b \mathrm{SO}(2N_b)\right) \times \left(\prod_c \mathrm{USp}(2N_c)\right)$$

The corresponding number of vector multiplets being

$$\boxed{\mathfrak{N} \equiv \sum_a N_a^2 + \sum_b N_b(2N_b - 1) + \sum_c N_c(2N_c + 1)}$$

Review of gauged N=4 supergravities in 4d

[Schoen, Weidner 2006]

Ungauged **global symmetry:**

$$\boxed{G_{\text{global}} = \mathrm{SL}(2,\mathbb{R}) \times \mathrm{SO}(6,6+\mathfrak{N})}$$

Extra VM's from open strings!

Consistent deformtions of the ungauged theory are encoded in the **embedding tensor**…

$$\boxed{\Theta \in (\mathbf{2}, \square) \oplus \left(\mathbf{2}, \begin{array}{|c|}\hline \\ \hline \\ \hline \\ \hline \end{array}\right)} \Longrightarrow$$

Irrep's of

$$G_{\text{global}} = \mathrm{SL}(2,\mathbb{R}) \times \mathrm{SO}(6,6+\mathfrak{N})$$

Set = 0 !

Subject to the following **quadratic constraints (QC)**

$$\boxed{f_{\alpha R[MN} f_{\beta PQ]}{}^{R} = 0\ , \qquad \varepsilon^{\alpha\beta} f_{\alpha MNR} f_{\beta PQ}{}^{R} = 0\ .}$$

Guarantee gauge invariance!

Induced scalar potentials…

The scalar fields span

$$\boxed{\mathcal{M}_{\text{scalar}} = \underbrace{\frac{\mathrm{SL}(2,\mathbb{R})}{\mathrm{SO}(2)}}_{M_{\alpha\beta}} \times \underbrace{\frac{\mathrm{SO}(6,6+\mathfrak{N})}{\mathrm{SO}(6)\times\mathrm{SO}(6+\mathfrak{N})}}_{M_{MN}}}$$

The **potential** reads

$$V = \frac{1}{64} f_{\alpha MNP} f_{\beta QRS} M^{\alpha\beta}\left[\frac{1}{3}M^{MQ}M^{NR}M^{PS} + \left(\frac{2}{3}\eta^{MQ} - M^{MQ}\right)\eta^{NR}\eta^{PS}\right]$$
$$- \frac{1}{144} f_{\alpha MNP} f_{\alpha QRS} \varepsilon^{\alpha\beta} M^{MNPQRS} \ .$$

Object to match!!

Swampland constraints on matter coupling

[Kim, Tarazi, Vafa 2020]

So far the number of VM's is **unspecified** in

$$\mathcal{M}_{\text{scalar}} = \underbrace{\frac{\mathrm{SL}(2,\mathbb{R})}{\mathrm{SO}(2)}}_{M_{\alpha\beta}} \times \underbrace{\frac{\mathrm{SO}(6,6\boxed{+\mathfrak{N}})}{\mathrm{SO}(\underset{10-d}{\boxed{6}}) \times \mathrm{SO}(\underset{r_G}{\boxed{6+\mathfrak{N}}})}}_{M_{MN}}$$

Even though **lower dimensional** theories are less constrained by **anomalies**…

$$\boxed{r_G \leq 26-d} \xrightarrow{\textbf{4d}} \boxed{\mathfrak{N} \leq 16}$$

Also expected to be **even**!

Non-Abelian brane actions & reductions…

[Myers 1999; Choi, Fernandez-Melgarejo, Sugimoto 2018]

Work in static gauge: $x^{\mathcal{M}} = (x^M, y^i)$

worldvolume **transverse**

Non-Abelian

$$\boxed{y^i = \lambda Y^i}$$

$$\{t_I\}_{I=1,\dots,\mathfrak{n}}$$

$$S^{\rm DBI}_{\rm D\mathit{p}} = -T_{\rm D\mathit{p}} \int d^{p+1}x \, {\rm Tr}\left(e^{-\hat{\Phi}} \sqrt{-\det(\mathbb{M}_{MN}) \det(\mathbb{Q}^i{}_j)} \right)$$

$$\lambda \equiv 2\pi \ell_s^2$$

$$\mathbb{M}_{MN} = {\rm P}\left[\hat{E}_{MN} + \hat{E}_{Mi}(\mathbb{Q}^{-1} - \delta)^{ij} \hat{E}_{jN} \right] + \lambda \mathcal{F}_{MN} \, ,$$

$$\mathbb{Q}^i{}_j = \delta^i{}_j + i\lambda [Y^i, Y^k] \hat{E}_{kj} \, .$$

$$S^{\rm WZ}_{\rm D\mathit{p}} = \mu_{\rm D\mathit{p}} \int_{{\rm WV(D}\mathit{p}{\rm)}} {\rm Tr}\left({\rm P}\left[e^{i\lambda \iota_Y \iota_Y} \hat{C} \wedge e^{\hat{B}_{(2)}} \wedge e^{\lambda \mathcal{F}} \right] \right)$$

… where all the objects needed in the previous transparency are

$\mathcal{F} = \mathrm{d}\mathcal{A} + i\mathcal{A} \wedge \mathcal{A}$ (YM non-Abelian field strength)

$$\boxed{\hat{E}_{\mathcal{M}\mathcal{N}} = \hat{G}_{\mathcal{M}\mathcal{N}} + \hat{B}_{\mathcal{M}\mathcal{N}}}$$

And each **hatted** quantity denotes the following expansion

$$\hat{\phi}(x^M, \lambda Y^i) \equiv \sum_{n=0}^{\infty} \frac{\lambda^n}{n!} Y^{i_1} \cdots Y^{i_n} \partial_{i_1} \cdots \partial_{i_n} \phi(x^M, y^i)\Big|_{y^i=0}$$

Finally, when pullback P acts,

$$\boxed{\partial_M Y^i} \xrightarrow{\mathrm{P}[\cdots]} \boxed{D_M Y^i \equiv \partial_M Y^i + i[A_M, Y^i]}$$

A complete example: mIIA with O6/D6

[Dall'Agata, Villadoro, Zwirner 2009]

$$\mathrm{O6}\ :\quad \underbrace{\times\ |\ \times\ \ \times\ \ \times}_{\text{4D spacetime}}\ \ \underbrace{\times\ \ \times\ \ \times}_{y^a}\ \ \underbrace{-\ \ -\ \ -}_{y^i}$$

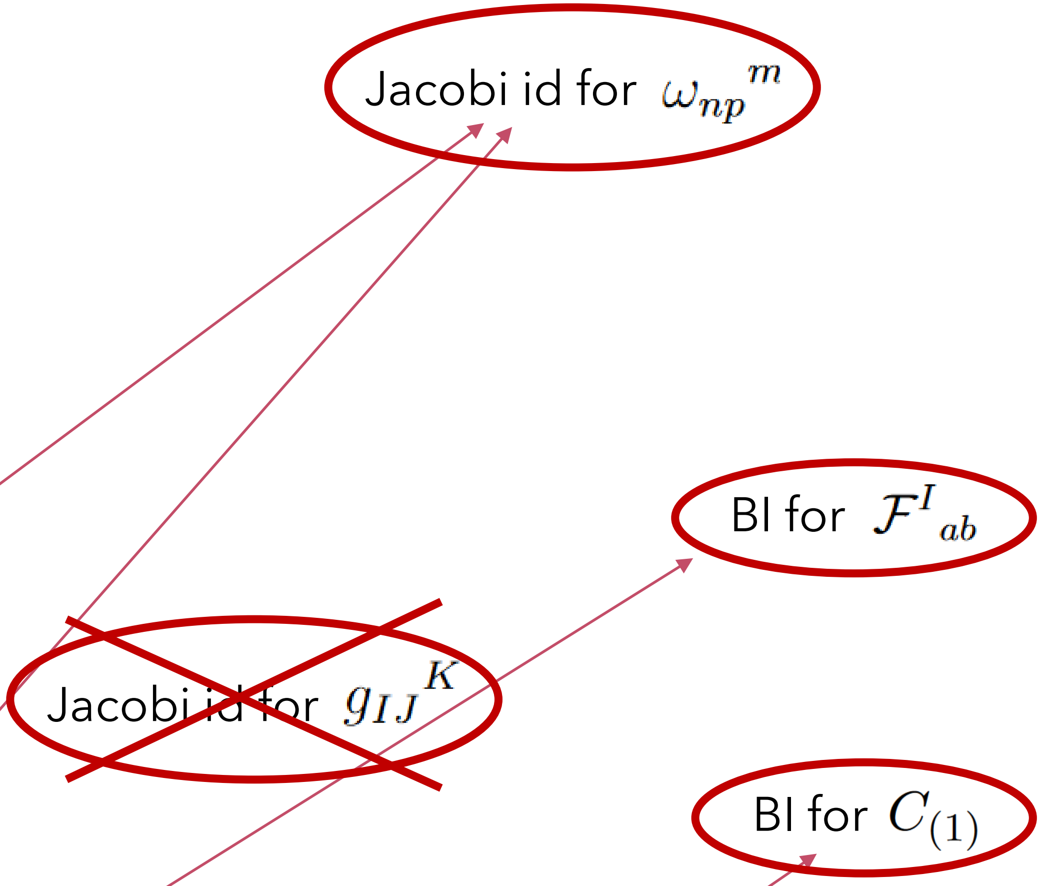
Type IIA Field	σ_{O6}	$(-1)^{F_L}\Omega$	physical dof's
Φ	$+$	$+$	1
B_{ai}	$-$	$-$	9
C_i	$-$	$-$	3
C_{abc}	$+$	$+$	1
C_{aij}	$+$	$+$	9
C_{abijk}	$-$	$-$	3
g_{ab}	$+$	$+$	6
g_{ij}	$+$	$+$	6
Y^{Ii}	$-$	$-$	$3\,\mathfrak{N}$
$A^I{}_a$	$+$	$+$	$3\,\mathfrak{N}$

Type IIA Flux	σ_{O6}	$(-)^{F_L}\Omega$
$\omega_{ab}{}^c$	$+$	$+$
$\omega_{ij}{}^c$	$+$	$+$
$\omega_{ai}{}^j$	$+$	$+$
H_{ijk}	$-$	$-$
H_{abi}	$-$	$-$
$F_{(0)}$	$+$	$+$
F_{ai}	$-$	$-$
F_{abij}	$+$	$+$
F_{abcijk}	$-$	$-$
$\mathcal{F}^I{}_{ab}$	$+$	$+$

Type IIA	Fluxes	$\mathrm{SO}(6,6+\mathfrak{N})$	$\mathrm{SO}(2,2+\mathfrak{N}/3)$
F_{aibjck}	a_0	$-f_{+\bar{a}\bar{b}\bar{c}}$	$-\Lambda_{+333}$
F_{aibj}	a_1	$f_{+\bar{a}\bar{b}\bar{k}}$	Λ_{+334}
F_{ai}	a_2	$-f_{+\bar{a}\bar{j}\bar{k}}$	$-\Lambda_{+344}$
$F_{(0)}$	a_3	$f_{+\bar{i}\bar{j}\bar{k}}$	Λ_{+444}
H_{ijk}	b_0	$-f_{-\bar{a}\bar{b}\bar{c}}$	$-\Lambda_{-333}$
H_{abk}	c_0	$f_{+\bar{a}\bar{b}k}$	Λ_{+233}
$\omega_{ij}{}^{c}$	b_1	$f_{-\bar{a}\bar{b}\bar{k}}$	Λ_{-334}
$\omega_{ka}{}^{j}=\omega_{bk}{}^{i}$	c_1	$f_{+\bar{a}\bar{j}k}=f_{+\bar{i}\bar{b}k}$	Λ_{+234}
$\omega_{bc}{}^{a}$	$\tilde{c}_1$	$f_{+a\bar{b}\bar{c}}$	Λ_{+133}
$\mathcal{F}^{K}{}_{ab}$	g_0	$f_{\alpha\bar{a}\bar{b}K}$	Λ_{+335}
$g_{IJ}{}^{K}$	g_1	$f_{\alpha IJK}$	Λ_{+555}

The **QC**'s imply...

$$c_1(c_1-\tilde{c}_1)=0\,,\quad b_1(c_1-\tilde{c}_1)=0\,,\quad a_3\,c_0+2\,a_2\,c_1-a_2\,\tilde{c}_1=0\,,$$
$$g_0\,g_1=0\,.$$



Jacobi id for $\omega_{np}{}^{m}$

BI for $\mathcal{F}^{I}{}_{ab}$

~~Jacobi id for $g_{IJ}{}^{K}$~~

BI for $C_{(1)}$

The reduction Ansatz & Matching

Unit volume!

$$ds^2_{(10)} = \tau^{-2}\, g_{\mu\nu}\, dx^\mu\, dx^\nu + \rho\left(\sigma^2\, M_{ab}\, e^a\, e^b + \sigma^{-2}\, M_{ij}\, e^i\, e^j\right)$$

$$\mathrm{d}e^m + \frac{1}{2}\,\omega_{np}{}^m\, e^n \wedge e^p = 0$$

twist

$$e^{2\Phi} = \tau^{-2}\rho^3$$

(4d Einstein frame!)

$$V_{\mathrm{Bulk}} = V_\omega + V_{H_3} + \sum_p V_{F_p}$$

Fixed by the WZ term!

$$+$$

$$V_{\mathrm{DBI}} = V^{(0)}_{\mathrm{DBI}} + \lambda^2 V^{(2)}_{\mathrm{DBI}}$$

Fixed by tadpole cancellation!

(neglect higher orders!)

$$\rightleftarrows$$

$$V_{\mathrm{Sugra}}$$

With appropriate choice of **embedding tensor** & **scalar** parametrization!

Modified field strengths for O6/D6

We get from the WZ reduction the following form for the **modified field strengths:**

$$\widetilde{F}_{(0)} = a_3 - g_1 Y^3$$

$$\tilde{f}_2 = a_2 + c_1 Y^2 + g_1 \mathcal{A} Y^2 - a_3 \chi_2 + g_1 Y^3 \chi_2$$

$$\Delta f_4 = \tilde{f}_4 - f_4 = -g_0 Y - g_1 \mathcal{A}^2 Y - \frac{c_0 Y^2}{2} - \frac{1}{2} \mathcal{A} Y (2c_1 + \bar{c}_1)$$

$$\Delta f_6 = \tilde{f}_6 - f_6 = \frac{3}{2} \bar{c}_1 \mathcal{A}^2 + 3 \mathcal{A} g_0 + \mathcal{A}^3 g_1 + \frac{3}{2} c_0 \mathcal{A} Y$$

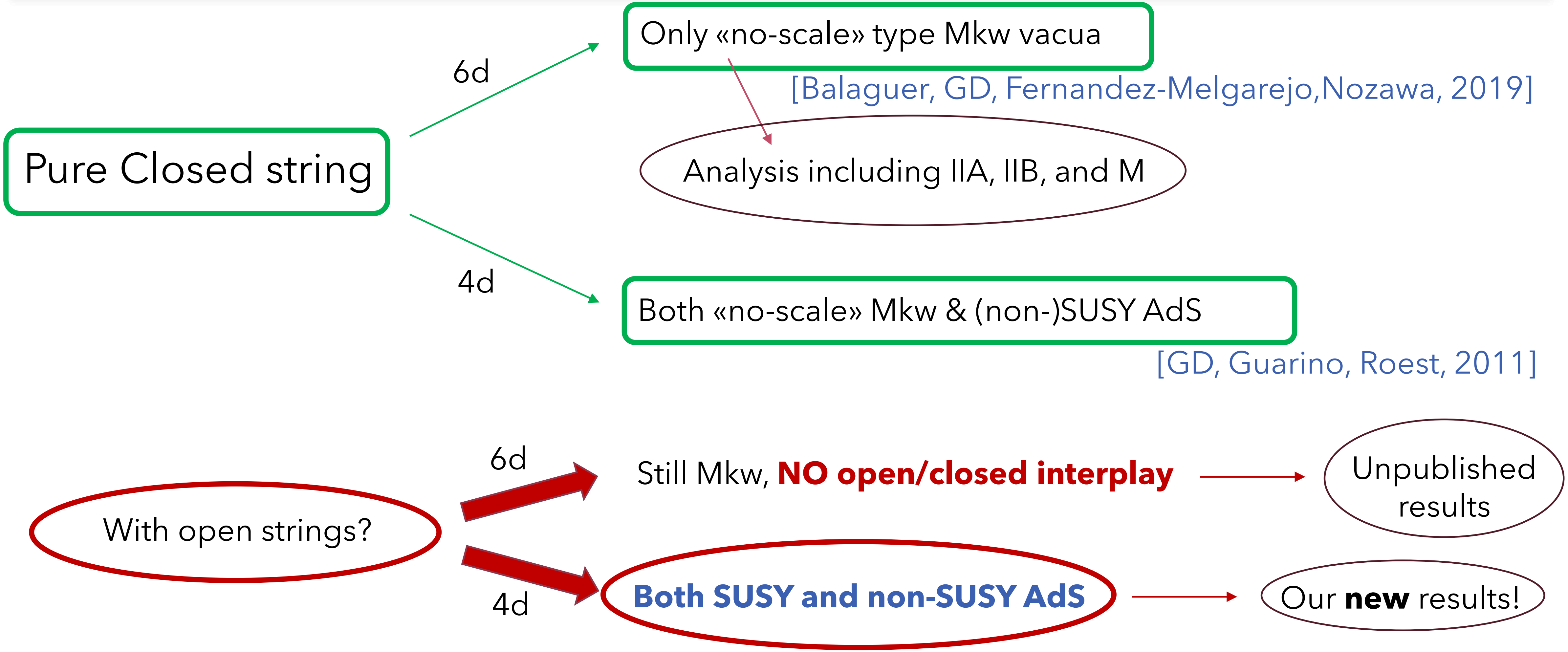
From modified BI!

From WZ!

⇨ Relation to **Green-Schwarz** via dualities…

Resulting in a **perfect matching**!

What about vacua?



Pure Closed string

6d

Only «no-scale» type Mkw vacua

[Balaguer, GD, Fernandez-Melgarejo,Nozawa, 2019]

Analysis including IIA, IIB, and M

4d

Both «no-scale» Mkw & (non-)SUSY AdS

[GD, Guarino, Roest, 2011]

With open strings?

6d

Still Mkw, **NO open/closed interplay**

Unpublished results

4d

Both SUSY and non-SUSY AdS

Our **new** results!

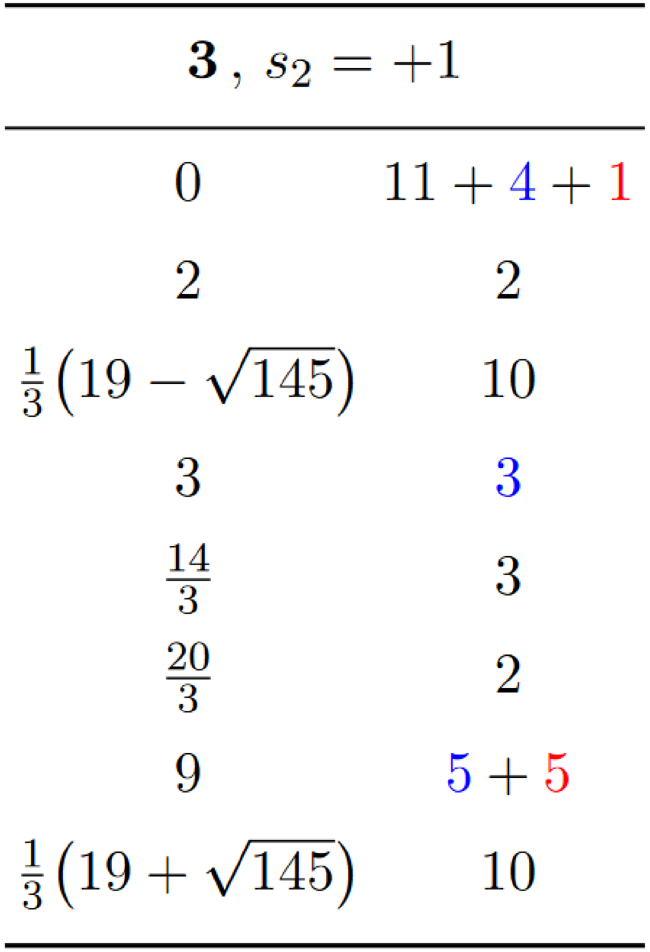
In the origin…

Solution	a_0	a_1	a_2	a_3	b_0	b_1	c_0	$c_1=\bar{c}_1$	g_0	g_1	**SUSY**	**Stability**
A	λ	0	0	$s_1\frac{\sqrt{5}+3\sqrt{13}}{14}\lambda$	0	$-\frac{11+\sqrt{65}}{14}\lambda$	0	$-\lambda$	$s_2\frac{5\sqrt{10}+\sqrt{26}}{14}\lambda$	0	✗	✗
B	λ	0	0	$s_1\frac{\sqrt{5}-3\sqrt{13}}{14}\lambda$	0	$\frac{-11+\sqrt{65}}{14}\lambda$	0	$-\lambda$	$s_2\frac{5\sqrt{10}-\sqrt{26}}{14}\lambda$	0	✗	✗

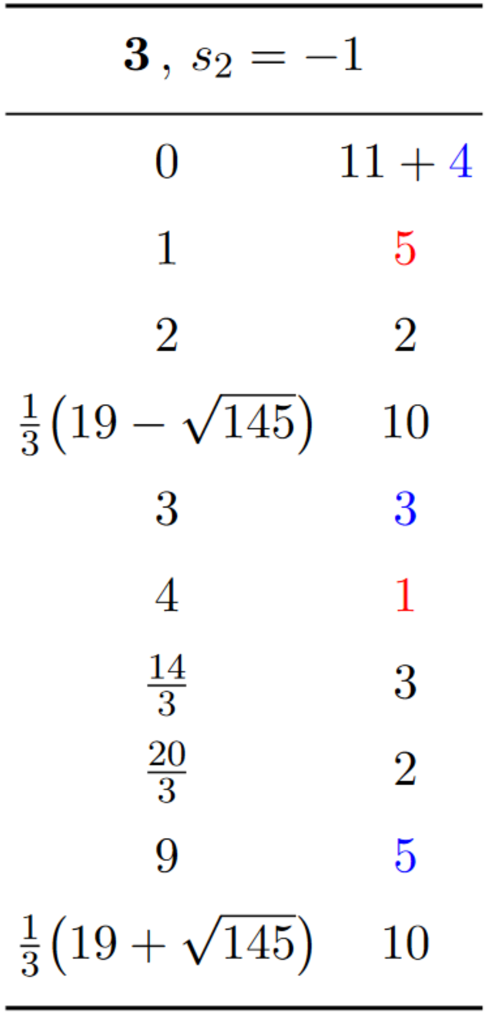
Moving out of the origin with A …

Solution	a_0	a_1	a_2	a_3	b_0	b_1	c_0	c_1 , $\bar{c}_1$	g_0	g_1		
1	$\left(s_2\frac{3}{2}-\frac{1}{2}\mathcal{A}^2\right)\lambda$	$s_1\frac{1}{2}\sqrt{\frac{3}{5}}\lambda$	$-s_2\frac{\lambda}{6}$	$s_1\frac{1}{2}\sqrt{\frac{5}{3}}\lambda$	$-s_1s_2\frac{\lambda}{\sqrt{15}}$	$\frac{\lambda}{3}$	$s_1s_2\frac{\lambda}{\sqrt{15}}$	λ	0	$-\frac{\lambda}{\mathcal{A}}$	✓	✓
2	$\left(s_2\frac{5}{3}-\frac{1}{2}\mathcal{A}^2\right)\lambda$	0	0	$s_1\frac{\sqrt{5}}{3}\lambda$	0	$\frac{\lambda}{3}$	0	λ	0	$-\frac{\lambda}{\mathcal{A}}$	✗	✗
3	$\left(s_2-\frac{1}{2}\mathcal{A}^2\right)\lambda$	$-s_1\frac{\lambda}{\sqrt{3}}$	$s_2\frac{\lambda}{3}$	$s_1\frac{\lambda}{\sqrt{3}}$	$s_1s_2\frac{\lambda}{\sqrt{3}}$	$\frac{\lambda}{3}$	$-s_1s_2\frac{\lambda}{\sqrt{3}}$	λ	0	$-\frac{\lambda}{\mathcal{A}}$	✗	✓
4	$\left(s_2\sqrt{5}-\frac{1}{2}\mathcal{A}^2\right)\lambda$	0	0	$s_1\lambda$	0	λ	0	λ	0	$-\frac{\lambda}{\mathcal{A}}$	✗	✓

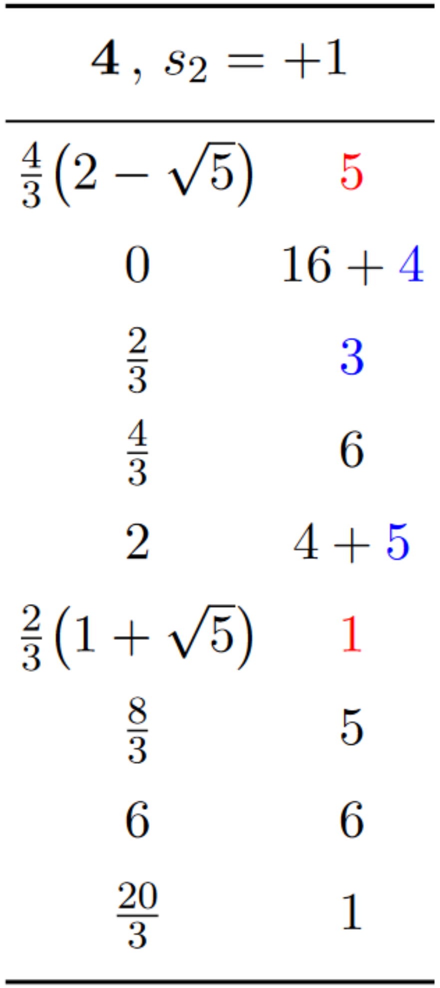
Our **non-SUSY** perturbatively **stable** AdS vacua…



$\mathbf{3}\,,\ s_2 = +1$	
0	$11 + 4 + 1$
2	2
$\frac{1}{3}(19 - \sqrt{145})$	10
3	3
$\frac{14}{3}$	3
$\frac{20}{3}$	2
9	$5 + 5$
$\frac{1}{3}(19 + \sqrt{145})$	10



$\mathbf{3}\,,\ s_2 = -1$	
0	$11 + 4$
1	5
2	2
$\frac{1}{3}(19 - \sqrt{145})$	10
3	3
4	1
$\frac{14}{3}$	3
$\frac{20}{3}$	2
9	5
$\frac{1}{3}(19 + \sqrt{145})$	10



$\mathbf{4}\,,\ s_2 = +1$	
$\frac{4}{3}(2 - \sqrt{5})$	5
0	$16 + 4$
$\frac{2}{3}$	3
$\frac{4}{3}$	6
2	$4 + 5$
$\frac{2}{3}(1 + \sqrt{5})$	1
$\frac{8}{3}$	5
6	6
$\frac{20}{3}$	1

Consider the following scaling limit…

$$\rho \sim \Omega^2 \ , \quad \tau \sim \Omega^6 \ , \quad \sigma \sim \Omega^0$$

Fluxes	$H_{(3)}$	$F_{(p)}$	ω	$\mathcal{F}^I$
Ω weights	Ω^2	Ω^{2+p}	Ω^0	Ω^4

In this limit flux numbers are HIGH and insensitive to flux quantization!

Scales	g_s	$\frac{Vol_6}{(2\pi\ell_s)^6}$	$\frac{\lvert\Lambda\rvert}{M_{\rm Pl}^4}$	$\frac{\ell_{\rm KK}}{\ell_{\rm AdS}}$
Ω weights	Ω^{-3}	Ω^6	Ω^{-14}	Ω^0

String loops

Higher derivatives

EFT validity

NO scale separation!

e.g.

$$\mathcal{R}^{(4)}_{10} \sim \Omega^{-20}$$

Conclusions & Outlook

- Studying the dynamics of open strings in flux compactifications is an important challenge for String Theory
- With many supercharges I can use lower d supergravities as a guideline for constructing this coupling
- This analysis is very crucial in the context of the Swampland and the SLP
- We derived generalized S-/T- dual versions of the GS modifications
- In our 4d setup we found interesting novel things, like new SUSY & non-SUSY AdS vacua…

→ Hopefully more to come, so stay tuned…

Thank you for your attention!