Instituto de Física Teórica presents:

Progress in AdS_4 Vacua

by Fernando Marchesano

In collaboration with Gonzalo F. Casas, Eran Palti, David Prieto, Alessandro Tomasiello, Joan Quirant & Matteo Zatti

Based on arXiv: 2003.13578,2110.11370,2204.11892 *& more*

Type IIA AdS_4 vacua

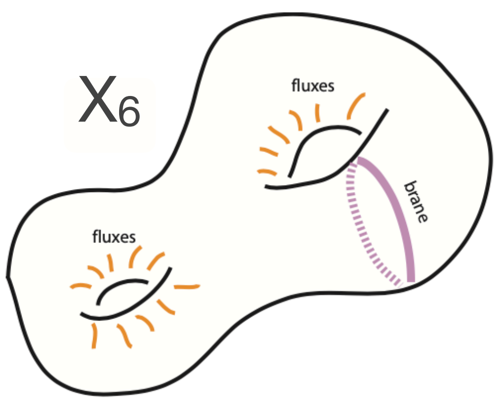
Simplest 10d solution:

Massive type IIA on a SU(3)-structure manifold with fluxes H_3, F_2, F_4, F_6. SUSY. No localised sources.

Lüst & Tsimpis '04

DGKT-CFI proposal:

Massive type IIA on a CY manifold with O6-planes, D6-branes and fluxes H_3, F_4. SUSY and non-SUSY.



- General CY *DeWolfe et al. '05*
- T^6, with also metric fluxes *Camara, Font, Ibanez '05*

see also Berhndt & Cvetic '04
Deredinger et al. '04
Villadoro & Zwirner '05

Not a 10d solution, but LT solution recovered if O6-planes/D6-branes are treated as smeared sources

Acharya, Benini, Valandro '06

Why do we care about DGKT vacua?

Main Features:

- 4d EFT analysis based on W and K

Grimm & Louis '04

- Infinite family of vacua indexed by internal 4-form flux: $e \sim \int_S F_4 \sim \text{Vol}(S)$

$$V_{\text{CY}} \sim e^{3/2}, \quad g_s \sim e^{-3/4}, \quad M_{\text{P}} R_{AdS} \sim e^{9/4}, \quad \frac{R_{\text{AdS}}}{R_{\text{KK}}} \sim e^{1/2}$$

- Other fluxes bounded by tadpole constraint: $mh + N_{\text{D6}} = 4$

F_0 (→ m) H (→ h) O6-plane (→ 4)

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Obtained without fluxes

- 4d EFT analysis based on W and K

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Scale separation

- Other fluxes bounded by tadpole constraint: $mh + N_{\mathrm{D6}} = 4$

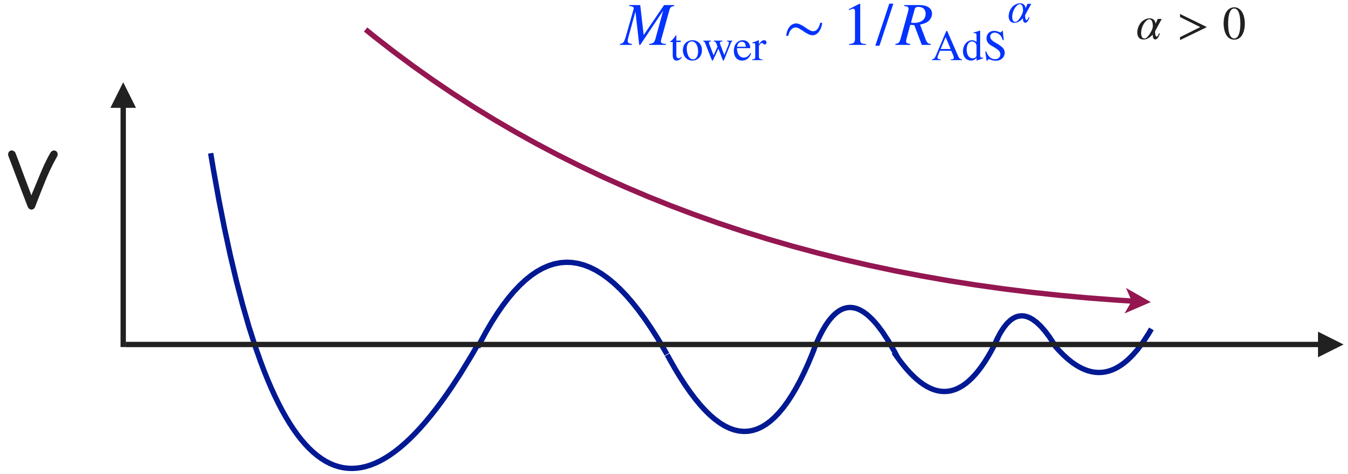
F_0 (m), H (h), O6-plane (4)

AdS Swampland conjectures

AdS Distance Conjecture

Lüst, Palti, Vafa '19

$M_{\text{tower}} \sim 1/R_{\text{AdS}}{}^{\alpha}$ $\alpha > 0$



strong ADC: $\alpha = 1$ for SUSY
Based on holographic intuition

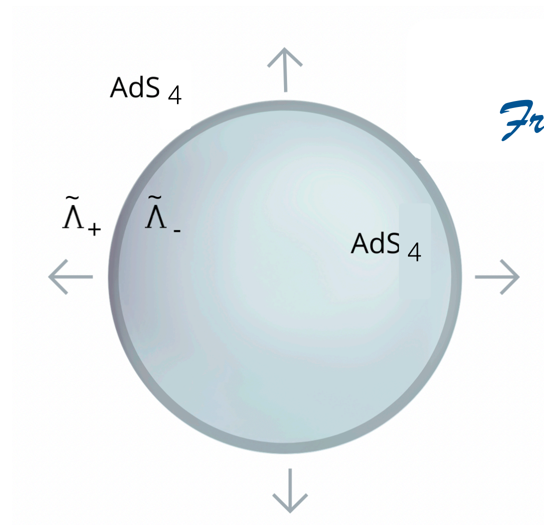
DGKT predicts $\alpha = 7/9$

(but holographic dual unknown)

AdS Instability Conjecture

Non-SUSY vacua unstable via membrane nucleation

Refined WGC: per each independent flux there must be a membrane with Q > T discharging it



Ooguri & Vafa '16
Freivogel & Kleban '16

Do DGKT-like vacua obey it?

Two viewpoints

Smearing of localised sources is natural below the KK scale

Kähler potential unaffected by fluxes due to weak coupling (even if they are not diluted)

$\Downarrow$

4d analysis should capture the relevant 10d physics

Scale separation is very unusual from the 10d eom viewpoint

In DGKT you mix ingredients that are only understood separately (Romans mass, O-planes)

Do not trust AdS vacua without known holographic duals

4d progress: Landscape of vacua

General flux potential for type IIA on large-volume CY with O6-planes.
Bilinear structure that factorises axions and saxion.

Herráez et al. '18

Allows for simple classification of CY vacua. Several branches.
Universal ones are of the form:

F.M. & Quirant'19

$$H = aF_0 g_s \,\mathrm{Re}\Omega_{\mathrm{CY}} \qquad F_2 = bF_0 J_{\mathrm{CY}} \qquad 1/R^2_{\mathrm{AdS}} = d\, g_s^2 F_0^2$$

$$F_4 = cF_0 J_{\mathrm{CY}} \wedge J_{\mathrm{CY}} \qquad F_6 = 0 \qquad M_{\mathrm{KK}} \sim 1/R_{\mathrm{AdS}}{}^{7/9}$$

Branch	a	b	c	d	SUSY	Pert. Stable	Zero modes
A+	2/5	0	3/10	1/25	Yes	Yes	N
A-	2/5	0	-3/10	1/25	No	Yes	N
B	1/2	±1/2	-1/4	1/24	No	Yes	2N

$F_4 \to -F_4$

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$F_4 \to -F_4$

Non-perturbative stability analysed for the case of $T^6/\mathbb{Z}_3 \times \mathbb{Z}_3$, Found only marginal decays, mediated by D4-branes on 2-cycles.

Narayan & Trivedi '10

10d progress: approximate solutions

Understand the 10d background as an expansion on g_s, $1/R_{\rm AdS}$ or $V_{\rm CY}^{-2/3}$

$$ds^2_{10d} = ds^2_{AdS_4} \times ds^2_{\rm CY} + g_s \left[ds^2_{10d}\right]_{(1)} + \ldots$$

Saracco & Tomasiello '04

$$F_{2p} = F^{(0)}_{2p} + g_s F^{(1)}_{2p} + \ldots$$

4d setup constrain the harmonic piece of the fluxes

- Applied to eom — *Junghans '20*
- Applied to SUSY eqs. — *F.M., Palti, Quirant, Tomasiello '20*

The results display scale separation and reproduce the set of 4d vacua

CY-ish compactifications

F.M., Palti, Quirant, Tomasiello '20

SU(3) x SU(3) deformation of a CY background: $ds^2 = e^{2A} ds^2_{\mathrm{AdS}_4} + ds^2_{X_6}$

$$J = J_{\mathrm{CY}} + \mathcal{O}(g_s^2) \qquad e^{-A} = 1 + g_s\varphi + \mathcal{O}(g_s^2)$$

$$\Omega = \Omega_{\mathrm{CY}} + g_s k + \mathcal{O}(g_s^2) \qquad e^{\phi} = g_s\left(1 - 3g_s\varphi\right) + \mathcal{O}(g_s^3)$$

Solution to F_2 Bianchi Identity:

$$\Delta_{\mathrm{CY}} K = \frac{2}{5} F_0^2 g_s \,\mathrm{Re}\Omega_{\mathrm{CY}} + (N_{D6} - 4)\,\delta_{\Pi_{O6}} \quad \longrightarrow \quad K = \varphi \mathrm{Re}\,\Omega_{\mathrm{CY}} + \mathrm{Re}\,k$$

$$\Delta_{\mathrm{CY}}\varphi \propto \left(\frac{V_{\Pi_{O6}}}{V_{\mathrm{CY}}} - \delta^{(3)}_{\Pi_{O6}}\right)$$

blows-up near the O6-planes

(2,1) primitive

CY-ish compactifications

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Background fluxes:

F.M., Quirant, Prieto '21
F.M., Quirant, Zatti

$$H = a F_0 g_s \left(\text{Re}\,\Omega_{\text{CY}} + m g_s K\right) - \frac{n}{2} g_s d \text{Re}\,\left(\bar{v} \cdot \Omega_{\text{CY}}\right) + \mathcal{O}(g_s^3)$$

$$F_2 = b F_0 J_{\text{CY}} + d^{\dagger}_{\text{CY}} K + \mathcal{O}(g_s)$$

$$F_4 = F_0 J_{\text{CY}} \wedge J_{\text{CY}} \left(c - \frac{4}{5} g_s \varphi\right) + n J_{\text{CY}} \wedge d \text{Im}\, v + \mathcal{O}(g_s^2)$$

$$v = \partial_{\text{CY}} f_\star \qquad \Delta_{\text{CY}} f_\star = - g_s 8 F_0 \varphi$$

	a	b	c	m	n
A+	2/5	0	3/10	1	1
A-	2/5	0	-3/10	-2	-1/5
B	1/2	±1/2	-1/4	-1	0

Questions

i) What about higher order terms in the expansion?

Technically involved: one does not know the solution for intersecting sources, even in the absence of fluxes. Also further corrections like closed string loops.

ii) Are the non-SUSY branches non-perturbatively stable?

Obvious thing to check: WGC for membranes

iii) What are the holographic duals of the SUSY branch?

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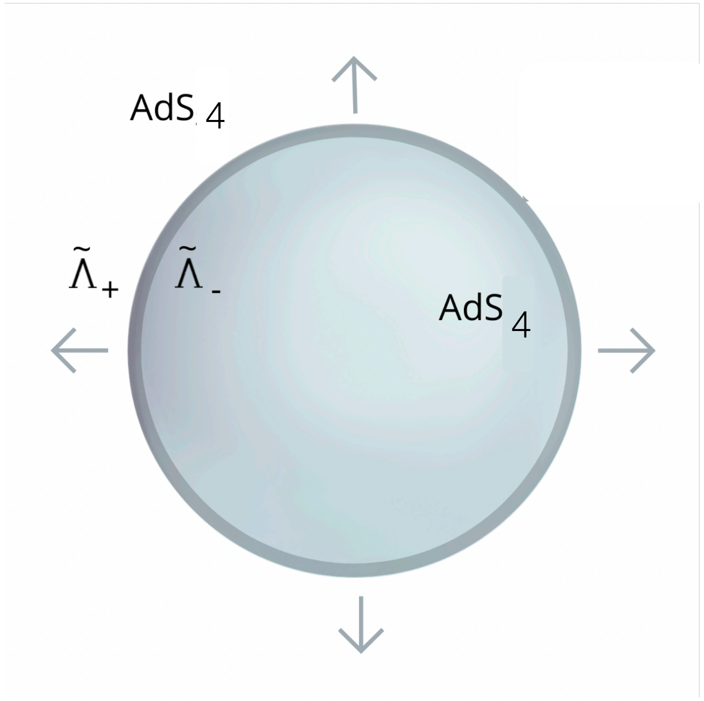
Membranes & non-perturbative stability

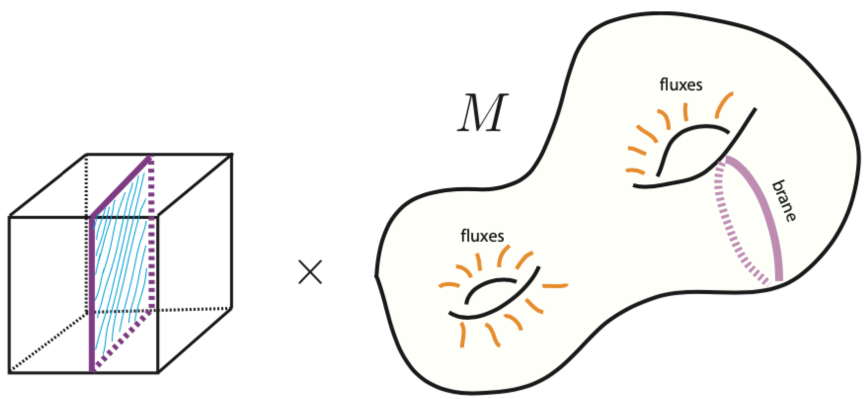


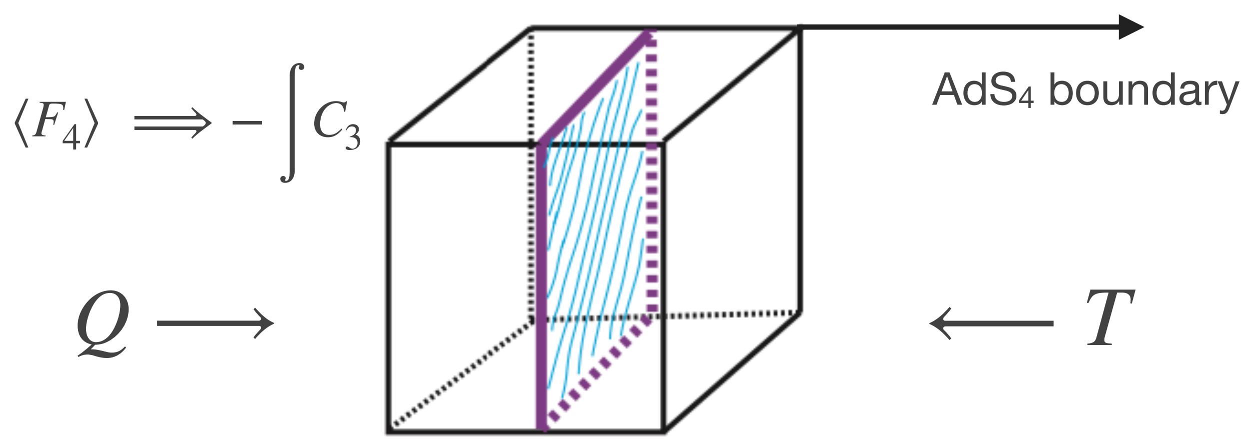
4d membranes in DGKT

Non-perturbative stability → analysis of 4d membranes

We consider probe membranes in the Poincaré patch of AdS_4:

Maldacena, Michelson, Strominger '98





$$Q \geq T$$

WGC for membranes

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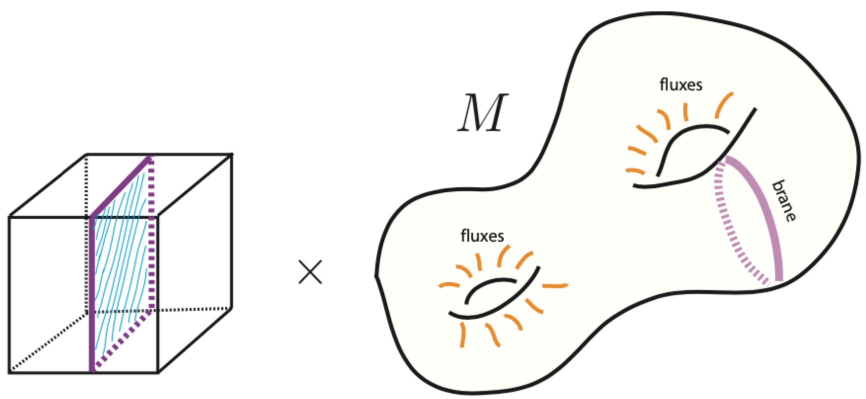

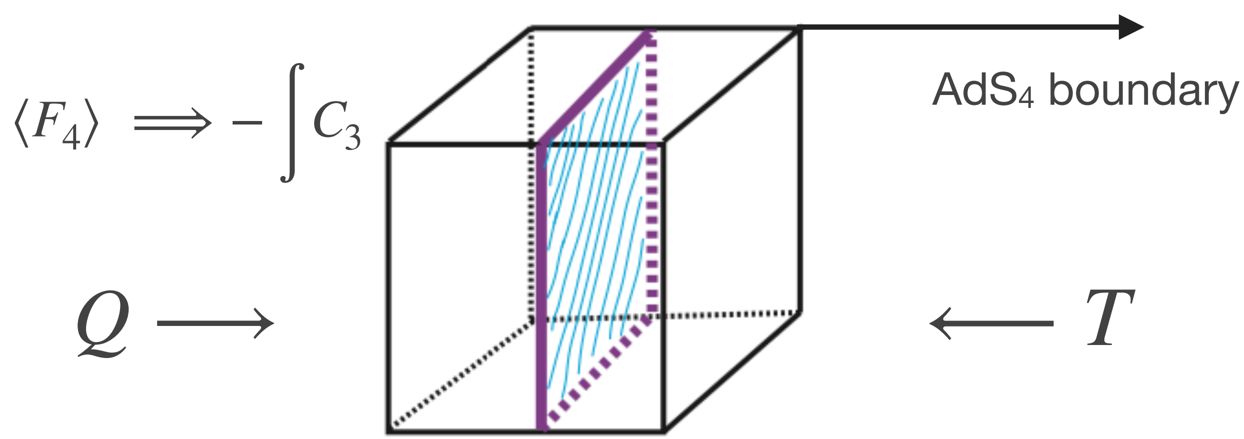

Ooguri & Vafa '16

$$Q > T$$

WGC for membranes

in N=0 vacua

4d membranes in A+

F.M., Quirant, Prieto '21

Let us look at EFT membranes: $\frac{T}{M_P^2} < \Lambda_{\rm EFT} \leq M_{\rm KK}$

Lanza et al. '19 & '20

N=1 vacua A+, smearing approx:

$$Q_{D2} = 0\,, \qquad Q_{D4} = e^{K/2}\int_\Sigma J_{\rm CY}\,, \qquad Q_{D6} = 0\,, \qquad Q_{D8} = -\frac{5}{3}e^{K/2}q_{\rm D8}V_{\rm CY}$$

Q_{D2}: cannot be BPS

Q_{D4}: BPS for Σ holom.

Q_{D6}: cannot be BPS

Q_{D8}: *recovers Narayan & Trivedi, '10; Aharony, Antebi, Berkooz '08*

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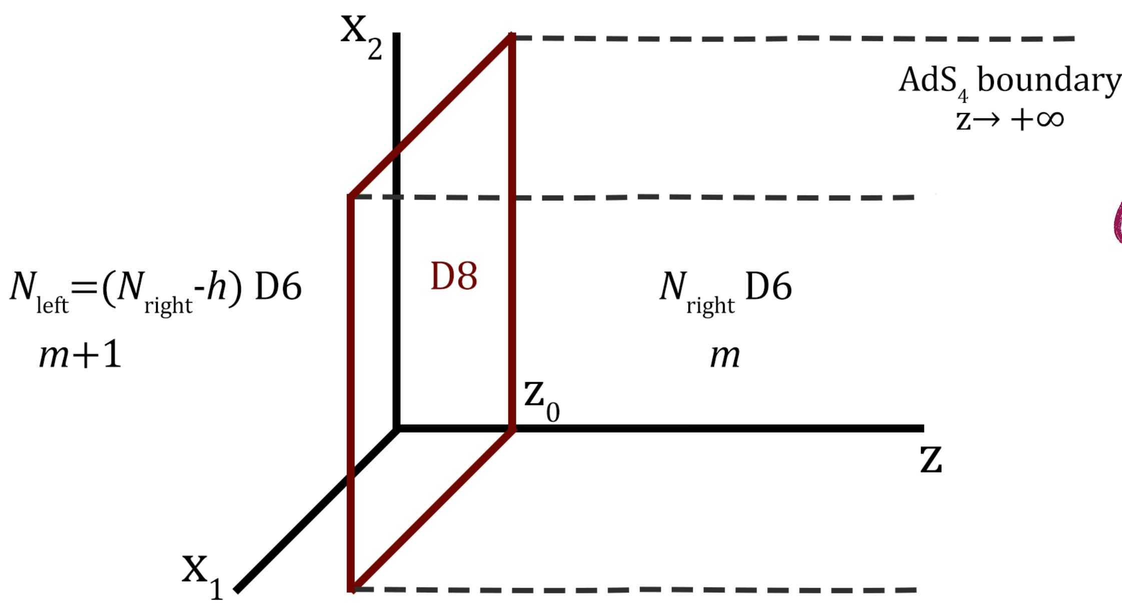

$$Q^{\rm eff}_{\rm D8} = e^{K/2}q_{\rm D8}V_{\rm CY}$$

BPS for $q_{\rm D8} = 1$

4d membranes in A-

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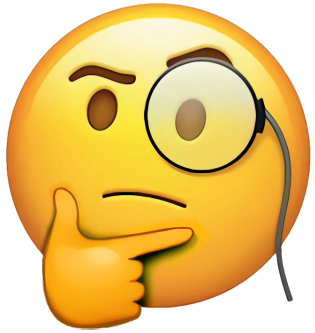
BPS for Σ antiholom.

BPS for $q_{\rm D8} = 1$

Refined WGC predicts that Q >T for D4 and D8-branes!



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Lanza et al. '19 & '20

N=0 vacua A-, smearing approx:

$$Q_{D2} = 0\,, \qquad Q_{D4} = -\,e^{K/2}\int_\Sigma J_{\mathrm{CY}}\,, \qquad Q_{D6} = 0\,, \qquad Q_{D8}^{\mathrm{eff}} = e^{K/2} q_{\mathrm{D8}} V_{\mathrm{CY}}$$

Way out: we may consider D8/D4 bound states:

$$K^F = \frac{1}{2}\int_{X_6} F \wedge F \wedge J_{\mathrm{CY}} > 0$$

$$T_{\mathrm{D8}}^{\mathrm{total}} = T_{\mathrm{D8}} + K^F - K^{(2)}$$

$$K^{(2)} = \frac{1}{24}\int_{X_6} c_2(X_6) \wedge J_{\mathrm{CY}}$$

$$Q_{\mathrm{D8}}^{\mathrm{total}} - T_{\mathrm{D8}}^{\mathrm{total}} = 2\left(K^{(2)} - K^F\right) > 0 \text{ when}$$

$$K^{(2)} > 0, \quad K^F = 0$$

→ *Instability!!*

Beyond smearing — D4's

F.M., Quirant, Prieto'21

N=1 vacua A+:

$$F_6 = -\,\mathrm{vol}_4 \wedge \left[J_{\mathrm{CY}} \frac{3}{g_s R_{\mathrm{AdS}}} + \frac{1}{2} d d^\dagger_{\mathrm{CY}} \left(f_\star J_{\mathrm{CY}} \right) \right] + \mathcal{O}(g_s^2) \longrightarrow Q_{D4} = e^{K/2} \int_\Sigma J_{\mathrm{CY}}$$

N=0 vacua A-:

$$F_6 = -\,\mathrm{vol}_4 \wedge \left[J_{\mathrm{CY}} \frac{3}{g_s R_{\mathrm{AdS}}} - \frac{1}{10} d d^\dagger_{\mathrm{CY}} \left(f_\star J_{\mathrm{CY}} \right) \right] + \mathcal{O}(g_s^2) \longrightarrow Q_{D4} = -\, e^{K/2} \int_\Sigma J_{\mathrm{CY}}$$

Still marginal at this order of approximation

Beyond smearing — D8's in A-

F.M., Quirant, Prieto '21

D8-brane worldvolume also hosts localised sources:

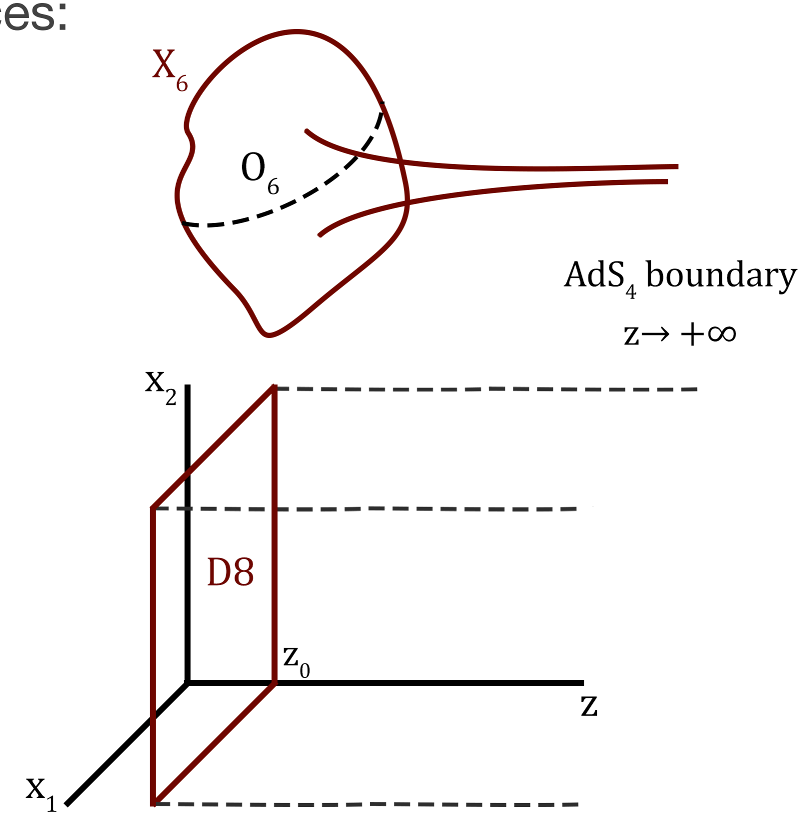
(2,0) comp.

$$d\mathcal{F} = H - h\delta_{\Pi_{O6}} \implies \mathcal{F} = \mathcal{F}_h + \mathcal{F}_{\rm BIon}$$

BIon-like solution!

$$T_{\rm D8}^{\rm total} = T_{\rm D8} + K^F - K^{(2)}$$

New contribution due to $\mathcal{F}_{\rm BIon}$



BIon excess charge:

$$2\Delta_{\rm D8}^{\rm Bion} = -\, e^{K/2}\int_{X_6} J_{\rm CY}\wedge\mathcal{F}_{\rm BIon}^2$$

comparable to $K^{(2)}$

can have both signs

Beyond smearing — D8's in A-

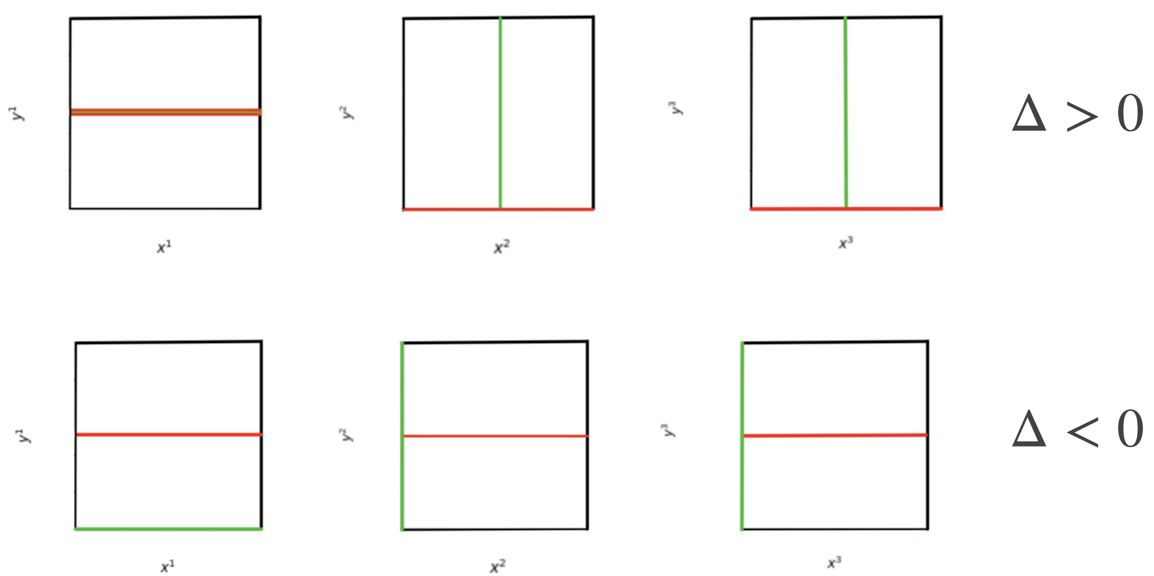
Casas, F.M., Prieto'22

One can compute the BIon excess charge in toroidal orbifolds:

$$\Delta_{\rm D8}^{\rm Bion} = \sum_{(\alpha,\beta)\in\mathcal{N}=2} \Delta_{\alpha,\beta}$$

Only D6-brane pairs at SU(2) angles contribute

The sign of Δ depends on their separation



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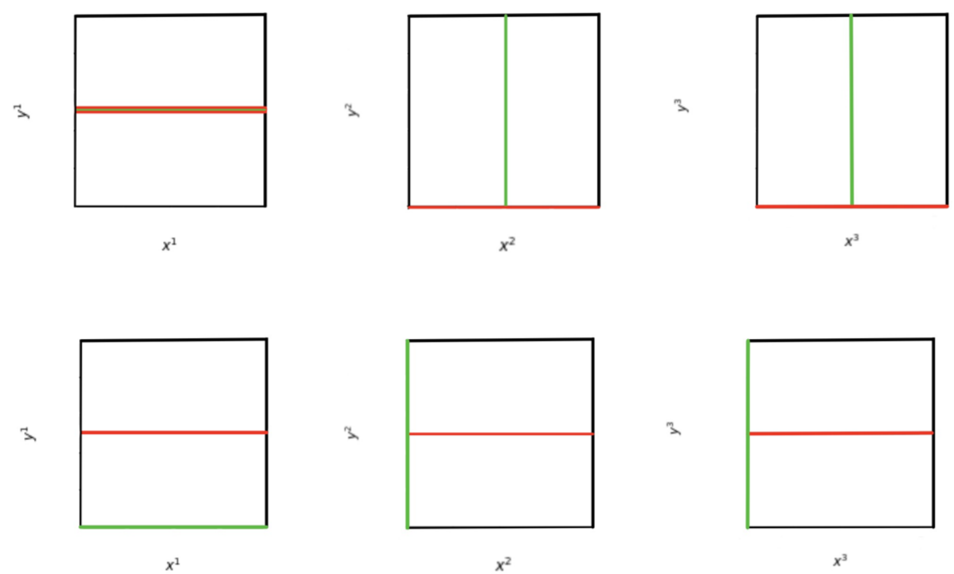
$$\Delta^{\rm Bion}_{\rm D8} = \sum_{(\alpha,\beta)\in\mathcal{N}=2} \Delta_{\alpha,\beta}$$

$$\Downarrow$$

Can build vacua for which
$Q^{\rm total}_{\rm D8} - T^{\rm total}_{\rm D8} < 0$

Only D6-brane pairs at SU(2) angles contribute

The sign of Δ depends on their separation



$\Delta > 0$

$\Delta < 0$

More exotic bound states

F.M., Quirant, Zatti

In N=1 vacua there are more exotic BPS bound states:

Anti-D8-brane with: $\mathscr{F} \wedge \mathscr{F} = 3J_{\rm CY} \wedge J_{\rm CY}$ D8/D6/D4/D2 bound state

D6-brane with: $\mathscr{F} \wedge \mathscr{F} = J_{\rm CY} \wedge J_{\rm CY}$ D6/D4/D2 bound state

In DGKT-like vacua, they exist thanks to the rational vevs that $b = \int B$ and $t = \int J_{\rm CY}$ take!

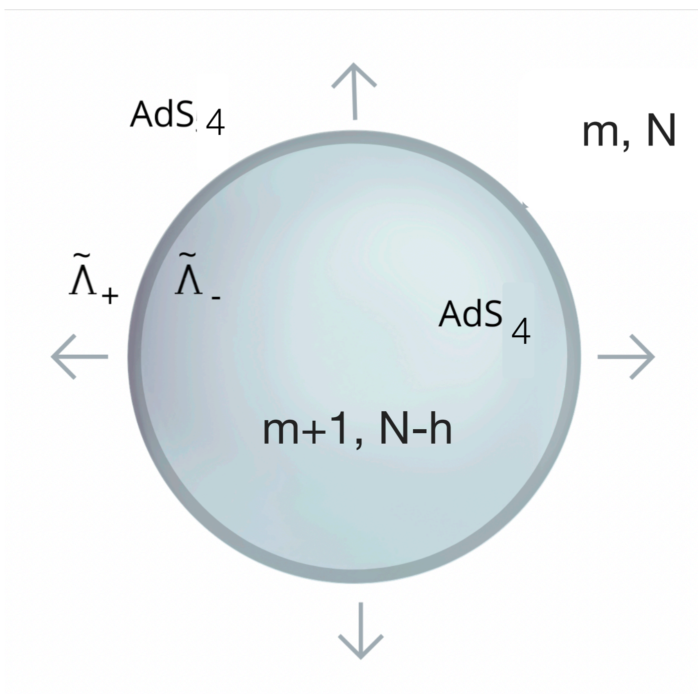
Considering these more exotic bound states, one finds membranes with Q>T in both branches of non-SUSY vacua

see J. Quirant's talk

Current WGC-membrane picture

F.M., Quirant, Zatti

Branch	SUSY	Pert. Stable	rWGC D4	rWGC D8	Np Stable
A+	Yes	Yes	✅	✅	Yes
A-	No	Yes	Marginal	✅	Unclear if no D6-branes
B	No	Yes	✅	✅	No

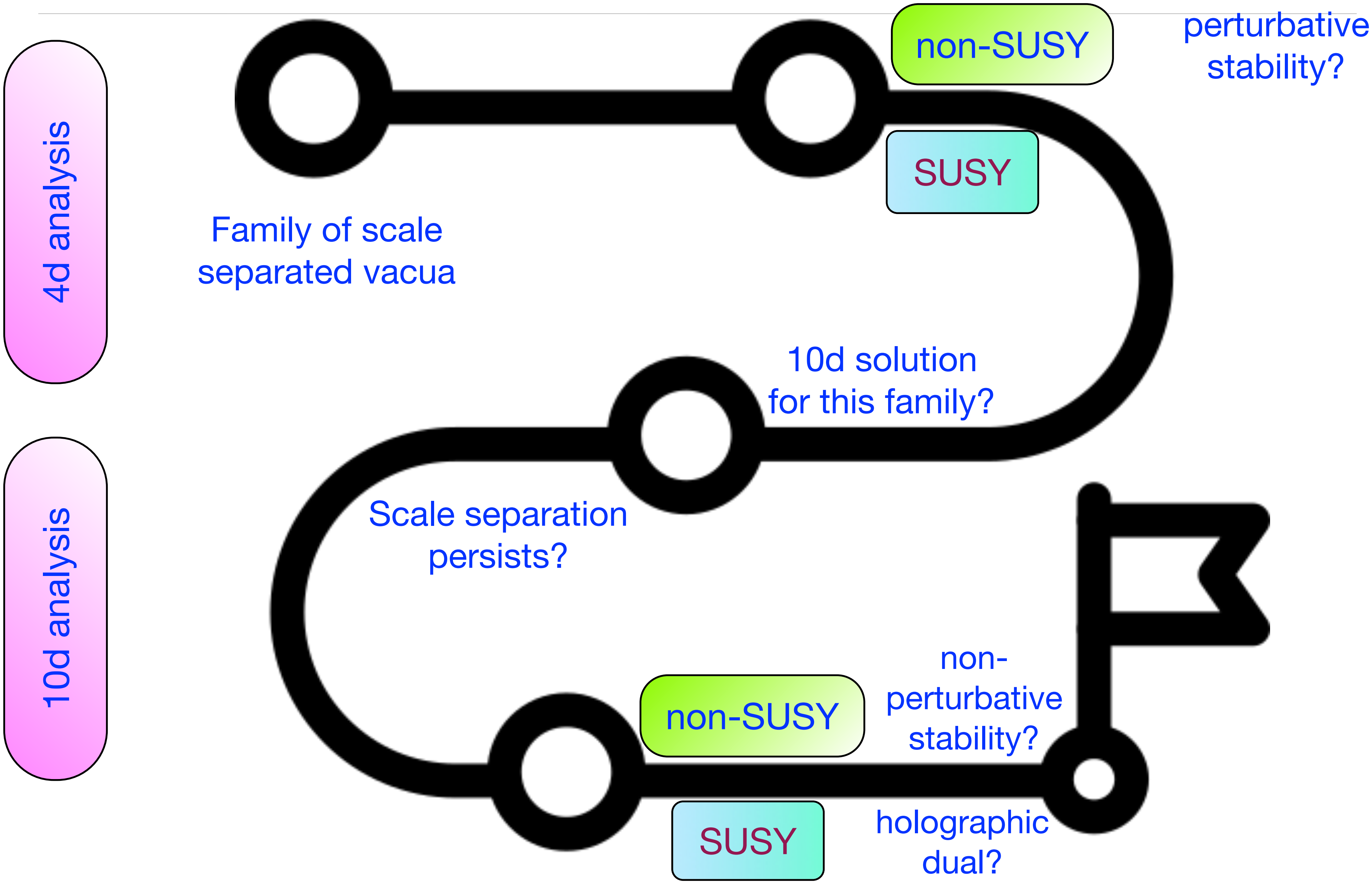


Nucleating bubble that increases F_0 and decreases N_{D6}

→ It stops when $N_{D6} = 0$

→ Suggests that models with gauge sectors are particularly unstable

AdS$_4$ road map



Further families

One can take a DGKT-like model on $T^6/(\mathbb{Z}_2 \times \mathbb{Z}_2)$ and perform two T-dualities

Banks & van den Broeck '06

Caviezel et al. '08

Cribiori et al. '21

$$H \to \text{metric fluxes} \qquad F_0, F_4 \to F_2, F_6$$

Standard type IIA compactification on a non-CY manifold

One can consider a particular non-homogeneous flux scaling, such that scale separation is achieved

Via a 4d analysis, one can generalise this construction to more general elliptically fibered manifolds

see D. Prieto's talk

Conclusions

- We have analysed the DKGT-CFI proposal from 4d and 10d perspectives
- From a 4d perspective we find one SUSY family and three infinite families of non-SUSY vacua for any CY, with similar scale separation properties
- From a 10d perspective obtain an approximate solution for all branches of solutions up to $\mathcal{O}(g_s^{4/3})$: the smearing approximation is the leading order term
- We have analysed 4d membranes for each branch of solutions, to see if they can trigger non-perturbative decays via nucleation.
- The refined WGC prediction Q > T is found in all non-SUSY cases, except for D4-branes in A- vacua, for which Q=T at this level of approximation
- In most cases, the membrane satisfying the refined WGC is quite exotic, as it involves non-diluted worldvolume fluxes
- Next step: holographic duals and other constructions with similar properties

Instituto de Física Teórica presents:

BACK TO THE SWAMP

Madrid, 26-28 *September* 2022