Progress in massive IIA holography

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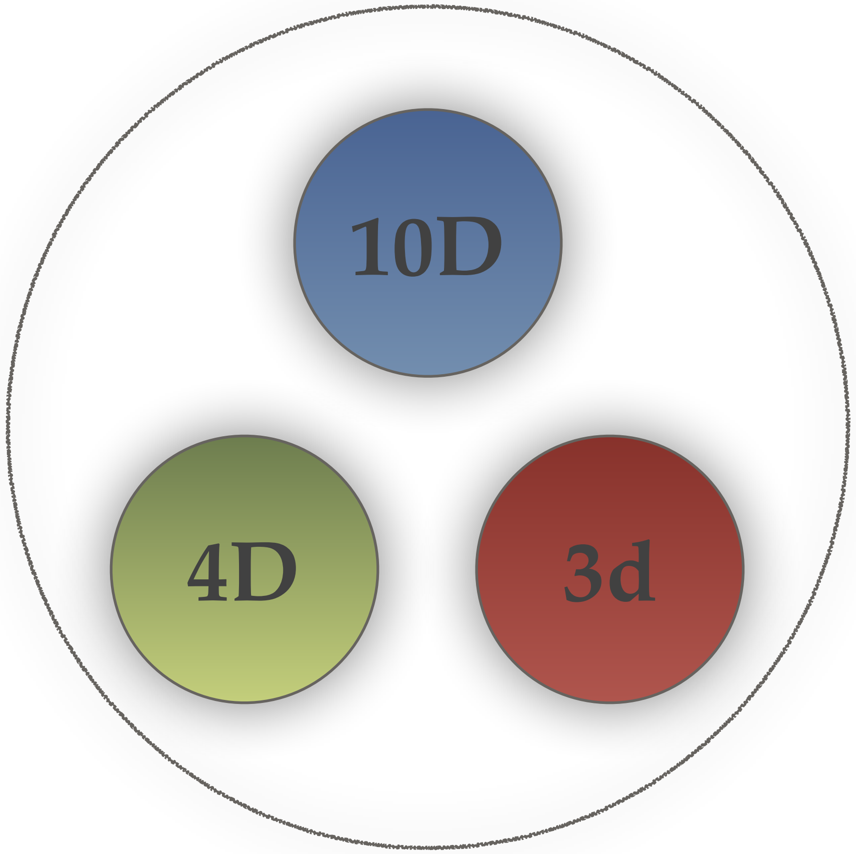


With D. Jafferis , J. Tarrío and O. Varela :

arXiv:1504.08009 , arXiv:1508.04432 , arXiv:1509.02526
arXiv:1605.09254 , arXiv:1703.10833 , arXiv:1706.01823
arXiv:1712.09549

Outlook

- Electric-magnetic duality in N=8 supergravity

- Massive IIA on S^6 / SYM-CS duality

- Holographic RG flows: domain-walls & black holes

Electric-magnetic duality in N=8 supergravity

N=8 supergravity in 4D

- SUGRA : metric + 8 gravitini + 28 vectors + 56 dilatini + 70 scalars

  (s = 2) (s = 3/2) (s = 1) (s = 1/2) (s = 0)

Ungauged (abelian) supergravity: Reduction of M-theory on a *torus* T^7 down to 4D produces $N = 8$ supergravity with $G = U(1)^{28}$ [Cremmer, Julia '79]

Gauged (non-abelian) supergravity:

- Reduction of M-theory on a *sphere* S^7 down to 4D produces $N = 8$ supergravity with $G = SO(8)$ [de Wit, Nicolai '82]
- Reduction of M-theory on $S^1 \times S^6$ down to 4D produces $N = 8$ supergravity with $G = ISO(7) = SO(7) \ltimes \mathbb{R}^7$ [Hull '84]

✱ These gauged supergravities believed to be unique for 30 years…

Electric-magnetic deformations

- Uniqueness historically inherited from the connection with NH geometries of branes and SCFT's

$AdS_4 \times S^7$ (M2-brane) , $AdS_7 \times S^4$ (M5-brane) , $AdS_5 \times S^5$ (D3-brane)

- N=8 supergravity in 4D admits a deformation parameter c yielding inequivalent theories. It is an electric/magnetic deformation

$$D = \partial - g\,(A^{\text{elec}} - c\,\tilde{A}_{\text{mag}})$$

g = 4D gauge coupling
c = deformation param.

[Dall'Agata, Inverso, Trigiante '12]

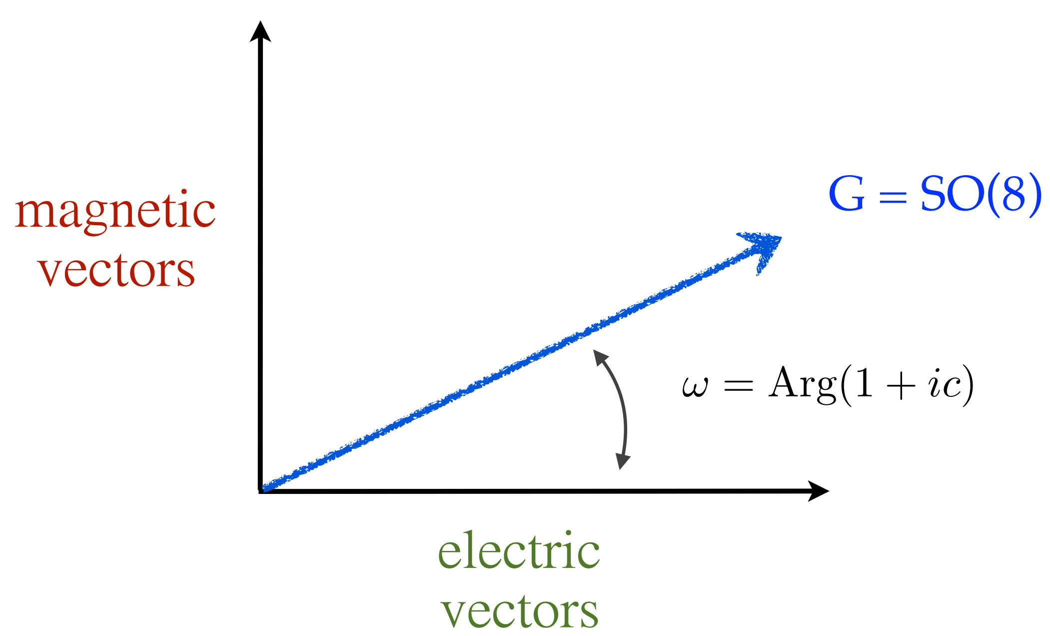
- There are two generic situations :

1) Family of $SO(8)_c$ theories : $c = [0, \sqrt{2} - 1]$ is a continuous param [similar for $SO(p,q)_c$]

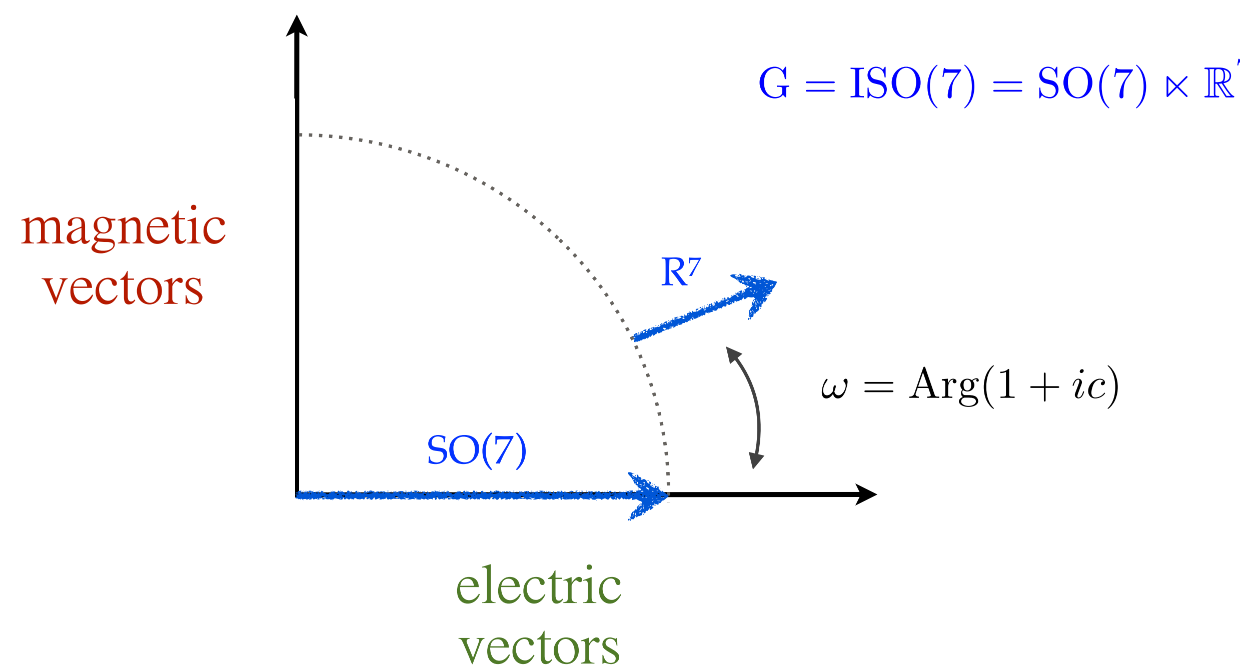
2) Family of $ISO(7)_c$ theories : $c = 0$ *or* 1 is an (on/off) param [same for $ISO(p,q)_c$]

[Dall'Agata, Inverso, Marrani '14]

$\mathrm{SO}(8)_c$ *vs* $\mathrm{ISO}(7)_c$



$$D = \partial - g\,(A^{\rm elec} - c\,\tilde{A}_{\rm mag})$$



$$D = \partial - g\,A^{\rm elec}_{\rm SO(7)} - g\,(A^{\rm elec}_{\mathbb{R}^7} - c\,\tilde{A}_{\mathbb{R}^7\,\rm mag})$$

Higher-dimensional origin?

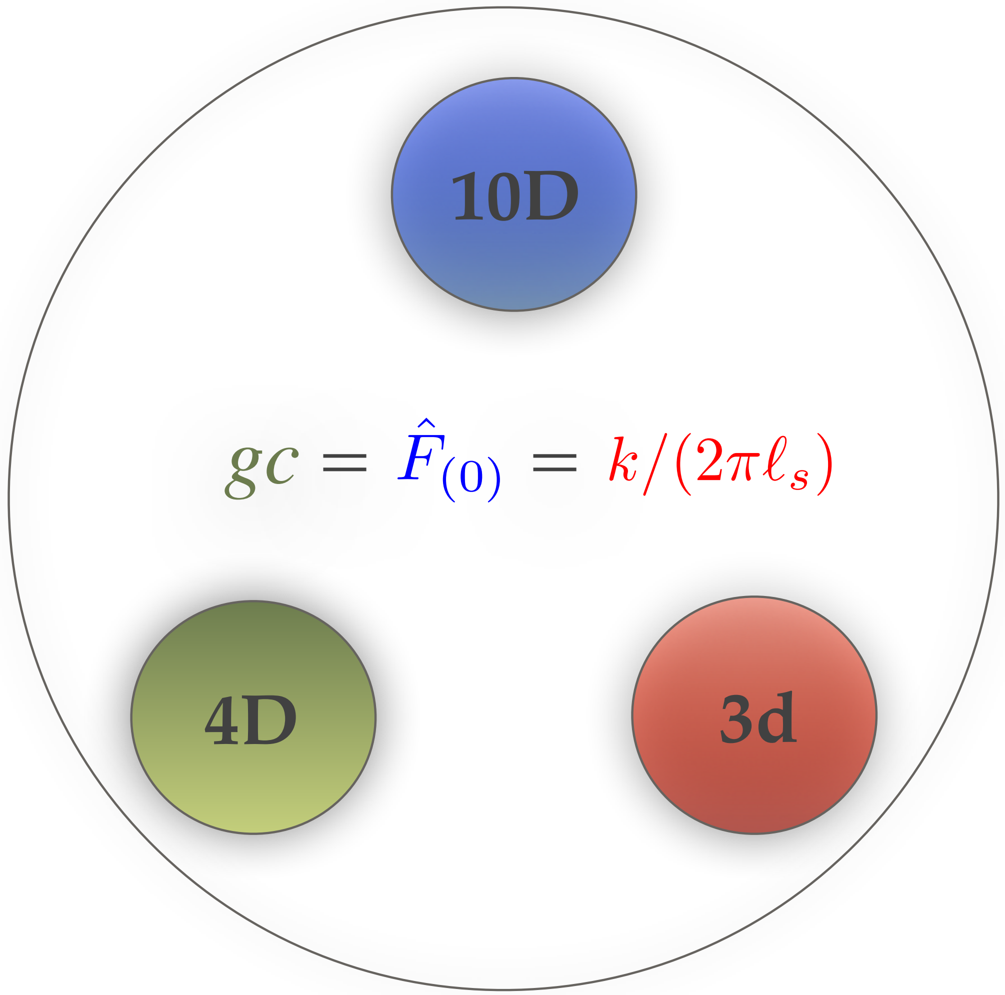
Obstruction for $\mathrm{SO}(8)_c$, *cf.* [de Wit, Nicolai ’13]

[Lee, Strickland-Constable, Waldram ’15]

Holographic dual?

A new 10D/4D/3d correspondence

massive IIA on S^6 « $ISO(7)_c$-gauged sugra » $SU(N)_k$ SYM-CS theory



gc = elec/mag deformation in 4D

$\hat{F}_{(0)}$ = Romans mass in 10D

k = Chern-Simons level in 3d

[AG, Jafferis, Varela '15]
[AG, Varela '15]

Well-established and independent dualities :

Type IIB on S^5 / N=4 SYM — M-theory on S^7 / ABJM — **mIIA on S^6/SYM-CS**

Massive IIA on S^6 / SYM-CS duality

$\color{red}{4D}$: ISO(7)$_c$ Lagrangian

$\mathbb{M} = 1, \ldots, 56$
$\Lambda = 1, \ldots, 28$
$I = 1, \ldots, 7$

$$\mathcal{L}_{\text{bos}} = (R - V)\,\text{vol}_4 - \tfrac{1}{48} D\mathcal{M}_{\mathbb{MN}} \wedge * D\mathcal{M}^{\mathbb{MN}} + \tfrac{1}{2}\,\mathcal{I}_{\Lambda\Sigma}\,\mathcal{H}^{\Lambda}_{(2)} \wedge * \mathcal{H}^{\Sigma}_{(2)} - \tfrac{1}{2}\,\mathcal{R}_{\Lambda\Sigma}\,\mathcal{H}^{\Lambda}_{(2)} \wedge \mathcal{H}^{\Sigma}_{(2)}$$
$$+ \, g\, c \left[\mathcal{B}^I \wedge \big(\tilde{\mathcal{H}}_{(2)I} - \tfrac{g}{2}\delta_{IJ}\mathcal{B}^J\big) - \tfrac{1}{4}\,\tilde{\mathcal{A}}_I \wedge \tilde{\mathcal{A}}_J \wedge \big(d\mathcal{A}^{IJ} + \tfrac{g}{2}\,\delta_{KL}\,\mathcal{A}^{IK} \wedge \mathcal{A}^{JL}\big)\right]$$

✦ Setting $c = 0$, all the magnetic pieces in the Lagrangian disappear.

✱ *Ingredients :*

- Electric vectors (21 + 7) : $\mathcal{A}^{IJ} = \mathcal{A}^{[IJ]}$ [SO(7)] and $\mathcal{A}^{I}$ [R⁷] with $\mathcal{H}^{\Lambda}_{(2)} = (\,\mathcal{H}^{IJ}_{(2)}\,,\,\mathcal{H}^{I}_{(2)}\,)$
- Auxiliary magnetic vectors (7) : $\tilde{\mathcal{A}}_I$ [R⁷] with $\tilde{\mathcal{H}}_{(2)I}$ field strength
- $E_7/SU(8)$ scalars : $\mathcal{M}_{\mathbb{MN}}$
- Auxiliary two-forms (7) : $\mathcal{B}^I$ [R⁷]
- Topological term : $g\,c\,[\,\ldots\,]$
- Scalar potential : $V(\mathcal{M}) = \dfrac{g^2}{672} X_{\mathbb{MN}}{}^{\mathbb{R}} X_{\mathbb{PQ}}{}^{\mathbb{S}} \mathcal{M}^{\mathbb{MP}} \big(\mathcal{M}^{\mathbb{NQ}} \mathcal{M}_{\mathbb{RS}} + 7\,\delta^{\mathbb{Q}}_{\mathbb{R}}\,\delta^{\mathbb{N}}_{\mathbb{S}}\big)$

AdS_4 solutions

[AG, Varela '15]

$\mathcal{N}$	G_0	$c^{-1/3}\,\chi$	$c^{-1/3}\,e^{-\varphi}$	$c^{-1/3}\,\rho$	$c^{-1/3}\,e^{-\phi}$	$\frac{1}{4}\,g^{-2}\,c^{1/3}\,V_0$	M^2L^2
$\mathcal{N}=1$	G_2	$-\frac{1}{2^{7/3}}$	$\frac{5^{1/2}\,3^{1/2}}{2^{7/3}}$	$-\frac{1}{2^{7/3}}$	$\frac{5^{1/2}\,3^{1/2}}{2^{7/3}}$	$-\frac{2^{22/3}\,3^{1/2}}{5^{5/2}}$	$4\pm\sqrt{6}\,,\ -\frac{1}{6}(11\pm\sqrt{6})$
$\mathcal{N}=2$	$U(3)$	$-\frac{1}{2}$	$\frac{3^{1/2}}{2}$	0	$\frac{1}{2^{1/2}}$	$-3^{3/2}$	$3\pm\sqrt{17}\,,\ 2\,,\ 2$
$\mathcal{N}=1$	$SU(3)$	$\frac{1}{2^2}$	$\frac{3^{1/2}\,5^{1/2}}{2^2}$	$-\frac{3^{1/2}}{2^2}$	$\frac{5^{1/2}}{2^2}$	$-\frac{2^6\,3^{3/2}}{5^{5/2}}$	$4\pm\sqrt{6}\,,\ 4\pm\sqrt{6}$
$\mathcal{N}=0$	$SO(6)_+$	0	$2^{1/6}$	0	$\frac{1}{2^{5/6}}$	$-3\,2^{5/6}$	$6\,,\ 6\,,\ -\frac{3}{4}\,,\ 0$
$\mathcal{N}=0$	$SO(7)_+$	0	$\frac{1}{5^{1/6}}$	0	$\frac{1}{5^{1/6}}$	$-\frac{3\,5^{7/6}}{2^2}$	$6\,,\ -\frac{12}{5}\,,\ -\frac{6}{5}\,,\ -\frac{6}{5}$
$\mathcal{N}=0$	G_2	$\frac{1}{2^{4/3}}$	$\frac{3^{1/2}}{2^{4/3}}$	$\frac{1}{2^{4/3}}$	$\frac{3^{1/2}}{2^{4/3}}$	$-\frac{2^{10/3}}{3^{1/2}}$	$6\,,\ 6\,,\ -1\,,\ -1$
$\mathcal{N}=0$	$SU(3)$	0.455	0.838	0.335	0.601	-5.864	$6.214\,,\ 5.925\,,\ 1.145\,,\ -1.284$
$\mathcal{N}=0$	$SU(3)$	0.270	0.733	0.491	0.662	-5.853	$6.230\,,\ 5.905\,,\ 1.130\,,\ -1.264$

- N = 2 solution will play a central role in holography !!

10D : ISO(7)$_c$ into type IIA supergravity

[AG, Varela '15]

$$d\hat{s}_{10}^2 = \Delta^{-1}\, ds_4^2 + g_{mn}\, Dy^m\, Dy^n \ ,$$

$$\begin{aligned}\hat{A}_{(3)} &= \mu_I \mu_J \left(\mathcal{C}^{IJ} + \mathcal{A}^I \wedge \mathcal{B}^J + \tfrac{1}{6}\mathcal{A}^{IK} \wedge \mathcal{A}^{JL} \wedge \tilde{\mathcal{A}}_{KL} + \tfrac{1}{6}\mathcal{A}^I \wedge \mathcal{A}^{JK} \wedge \tilde{\mathcal{A}}_K\right) \\ &\quad + g^{-1}\left(\mathcal{B}_J{}^I + \tfrac{1}{2}\mathcal{A}^{IK} \wedge \tilde{\mathcal{A}}_{KJ} + \tfrac{1}{2}\mathcal{A}^I \wedge \tilde{\mathcal{A}}_J\right) \wedge \mu_I D\mu^J + \tfrac{1}{2} g^{-2}\, \tilde{\mathcal{A}}_{IJ} \wedge D\mu^I \wedge D\mu^J \\ &\quad - \tfrac{1}{2}\, \mu_I\, B_{mn}\, \mathcal{A}^I \wedge Dy^m \wedge Dy^n + \tfrac{1}{6} A_{mnp}\, Dy^m \wedge Dy^n \wedge Dy^p \ ,\end{aligned}$$

$$\hat{B}_{(2)} = -\mu_I \left(\mathcal{B}^I + \tfrac{1}{2}\mathcal{A}^{IJ} \wedge \tilde{\mathcal{A}}_J\right) - g^{-1}\, \tilde{\mathcal{A}}_I \wedge D\mu^I + \tfrac{1}{2} B_{mn}\, Dy^m \wedge Dy^n \ ,$$

$$\hat{A}_{(1)} = -\mu_I\, \mathcal{A}^I + A_m\, Dy^m \ .$$

where we have defined : $\quad Dy^m \equiv dy^m + \tfrac{1}{2}\, g\, K^m_{IJ}\, \mathcal{A}^{IJ} \quad , \quad D\mu^I \equiv d\mu^I - g\, \mathcal{A}^{IJ} \mu_J$

The scalars are embedded as

$$\begin{aligned} g^{mn} &= \tfrac{1}{4}\, g^2\, \Delta\, \mathcal{M}^{IJ\,KL}\, K^m_{IJ}\, K^n_{KL} \quad , & B_{mn} &= -\tfrac{1}{2}\, \Delta\, g_{mp}\, K^p_{IJ}\, \partial_n \mu^K\, \mathcal{M}^{IJ}{}_{K8} \ , \\ A_m &= \tfrac{1}{2}\, g\, \Delta\, g_{mn}\, K^n_{IJ}\, \mu_K\, \mathcal{M}^{IJ\,K8} \quad , & A_{mnp} &= \tfrac{1}{8}\, g\, \Delta\, g_{mq}\, K^q_{IJ}\, K^{KL}_{np}\, \mathcal{M}^{IJ}{}_{KL} + A_m B_{np} \ .\end{aligned}$$

N=2 solution of massive type IIA

- N=2 & U(3) AdS_4 point of the $ISO(7)_c$ theory

$$d\hat{s}^2_{10} = L^2 \frac{\big(3+\cos 2\alpha\big)^{\frac{1}{2}}}{\big(5+\cos 2\alpha\big)^{-\frac{1}{8}}} \left[ds^2(\mathrm{AdS}_4) + \frac{3}{2}\, d\alpha^2 + \frac{6\sin^2\alpha}{3+\cos 2\alpha}\, ds^2(\mathbb{CP}^2) + \frac{9\sin^2\alpha}{5+\cos 2\alpha}\, \boldsymbol{\eta}^2 \right] ,$$

$$e^{\hat{\phi}} = e^{\phi_0}\, \frac{\big(5+\cos 2\alpha\big)^{3/4}}{3+\cos 2\alpha} \quad , \qquad \hat{H}_{(3)} = 24\sqrt{2}\; L^2\; e^{\frac{1}{2}\phi_0}\, \frac{\sin^3\alpha}{\big(3+\cos 2\alpha\big)^2}\, \boldsymbol{J}\wedge d\alpha \ ,$$

$$L^{-1}\, e^{\frac{3}{4}\phi_0}\, \hat{F}_{(2)} = -4\sqrt{6}\, \frac{\sin^2\alpha\cos\alpha}{\big(3+\cos 2\alpha\big)\big(5+\cos 2\alpha\big)}\, \boldsymbol{J} - 3\sqrt{6}\, \frac{\big(3-\cos 2\alpha\big)}{\big(5+\cos 2\alpha\big)^2}\, \sin\alpha\; d\alpha\wedge\boldsymbol{\eta} \ ,$$

$$L^{-3}\, e^{\frac{1}{4}\phi_0}\, \hat{F}_{(4)} = 6\,\mathrm{vol}_4 + 12\sqrt{3}\, \frac{7+3\cos 2\alpha}{\big(3+\cos 2\alpha\big)^2}\, \sin^4\alpha\ \mathrm{vol}_{\mathbb{CP}^2} + 18\sqrt{3}\, \frac{\big(9+\cos 2\alpha\big)\sin^3\alpha\cos\alpha}{\big(3+\cos 2\alpha\big)\big(5+\cos 2\alpha\big)}\, \boldsymbol{J}\wedge d\alpha\wedge\boldsymbol{\eta} \ ,$$

where we have introduced the quantities $L^2 \equiv 2^{-\frac{5}{8}}\, 3^{-1}\, g^{-2}\, c^{\frac{1}{12}}$ and $e^{\phi_0} \equiv 2^{\frac{1}{4}}\, c^{-\frac{5}{6}}$

✦ The angle $0 \leq \alpha \leq \pi$ locally foliates S_6 with S_5 regarded as Hopf fibrations over $\mathbb{CP}^2$

3D : CFT$_3$ dual & matching of free energies

[Schwarz '04]
[Gaiotto, Tomassiello '09]

- N=2 Chern-Simons-matter theory with simple gauge group SU(N), level k , three adjoint matter and cubic superpotential, as the CFT dual of the N=2 massive IIA solution.

- The 3d free energy F = -Log(Z), where Z is the partition function of the CFT on a Euclidean S$_3$, can be computed via localisation over supersymmetric configurations $N \gg k$

$$F = \frac{3^{13/6}\pi}{40}\left(\frac{32}{27}\right)^{2/3} k^{1/3} N^{5/3}$$

[Pestun '07] [Kapustin, Willett, Yaakov '09]
[Jafferis '10] [Jafferis, Klebanov, Pufu, Safdi '11]
[Closset, Dumitrescu, Festuccia, Komargodski '12 '13]

- The gravitational free energy can be computed from the warp factor in the N=2 massive IIA solution. Using the charge quantisation condition $N = -(2\pi\ell_s)^{-5}\int_{S^6} e^{\frac{1}{2}\phi}\hat{*}\hat{F}_{(4)} + \hat{B}_{(2)}\wedge d\hat{A}_{(3)} + \frac{1}{6}\hat{F}_{(0)}\,\hat{B}^3_{(2)}$ for the D2-brane, one finds

$$F = \frac{16\pi^3}{(2\pi\ell_s)^8}\int_{S^6} e^{8A}\,\mathrm{vol}_6 = \frac{\pi}{5}\,2^{1/3}\,3^{1/6}\,k^{1/3}\,N^{5/3}$$

provided

$$g\,c \;=\; \hat{F}_{(0)} \;=\; k/(2\pi\ell_s)$$

[Emparan, Johnson, Myers '99]

Holographic RG flows: domain-walls & black holes

Holographic RG flows on the D2-brane

[Boonstra, Skenderis, Townsend '98]

- RG flows are described holographically as non-AdS_4 solutions in gravity

- D2-brane :

$$d\hat{s}_{10}^2 = e^{\frac{3}{4}\phi}\left(-e^{2U}dt^2 + e^{-2U}dr^2 + e^{2(\psi-U)}ds^2_{\Sigma_2}\right) + g^{-2}e^{-\frac{1}{4}\phi}ds^2_{S^6}$$

$$e^{\hat{\Phi}} = e^{\frac{5}{2}\phi}$$

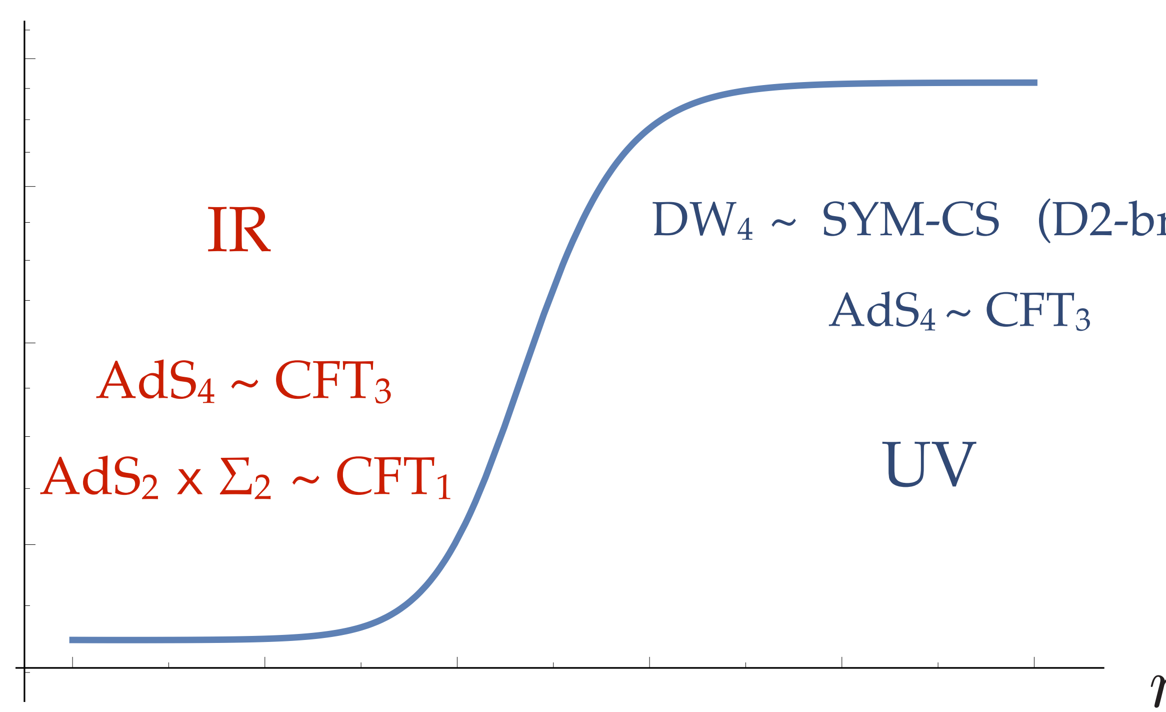
$$\hat{F}_{(4)} = 5\,g\,e^{\phi}\,e^{2(\psi-U)}\,dt\wedge dr\wedge d\Sigma_2$$

with $e^{2U} \sim r^{\frac{7}{4}}$, $e^{2(\psi-U)} \sim r^{\frac{7}{4}}$ and $e^{\phi} \sim r^{-\frac{1}{4}}$ ⇒ DW_4 domain-wall (SYM-CS)

- RG flows on D2-brane : ISO(7)-gauged sugra from type IIA on S^6

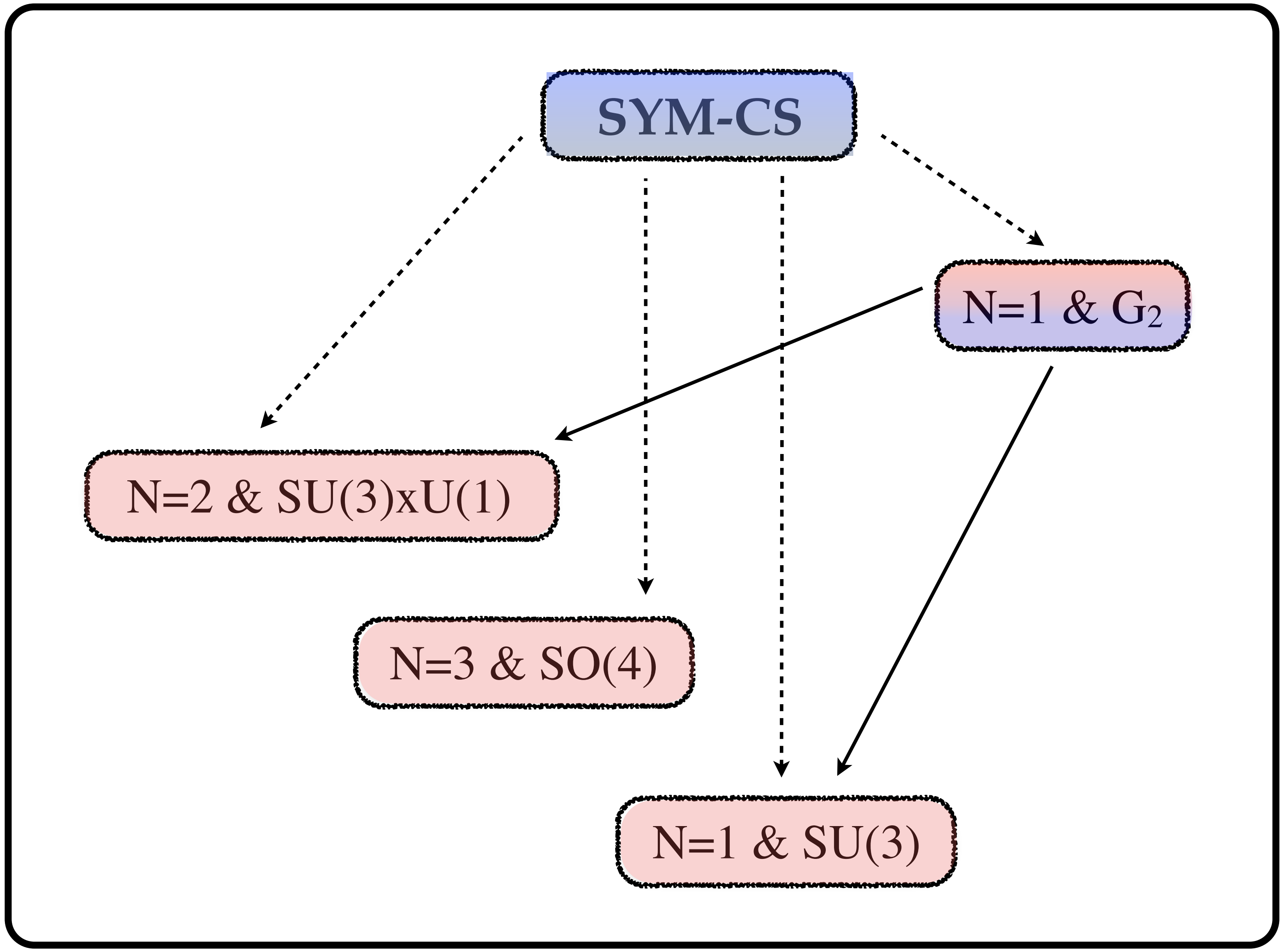
AdS_4 in IR : domain-wall

$AdS_2 \times \Sigma_2$ in IR : black hole



Domain-walls

[AG, Tarrío, Varela '16]



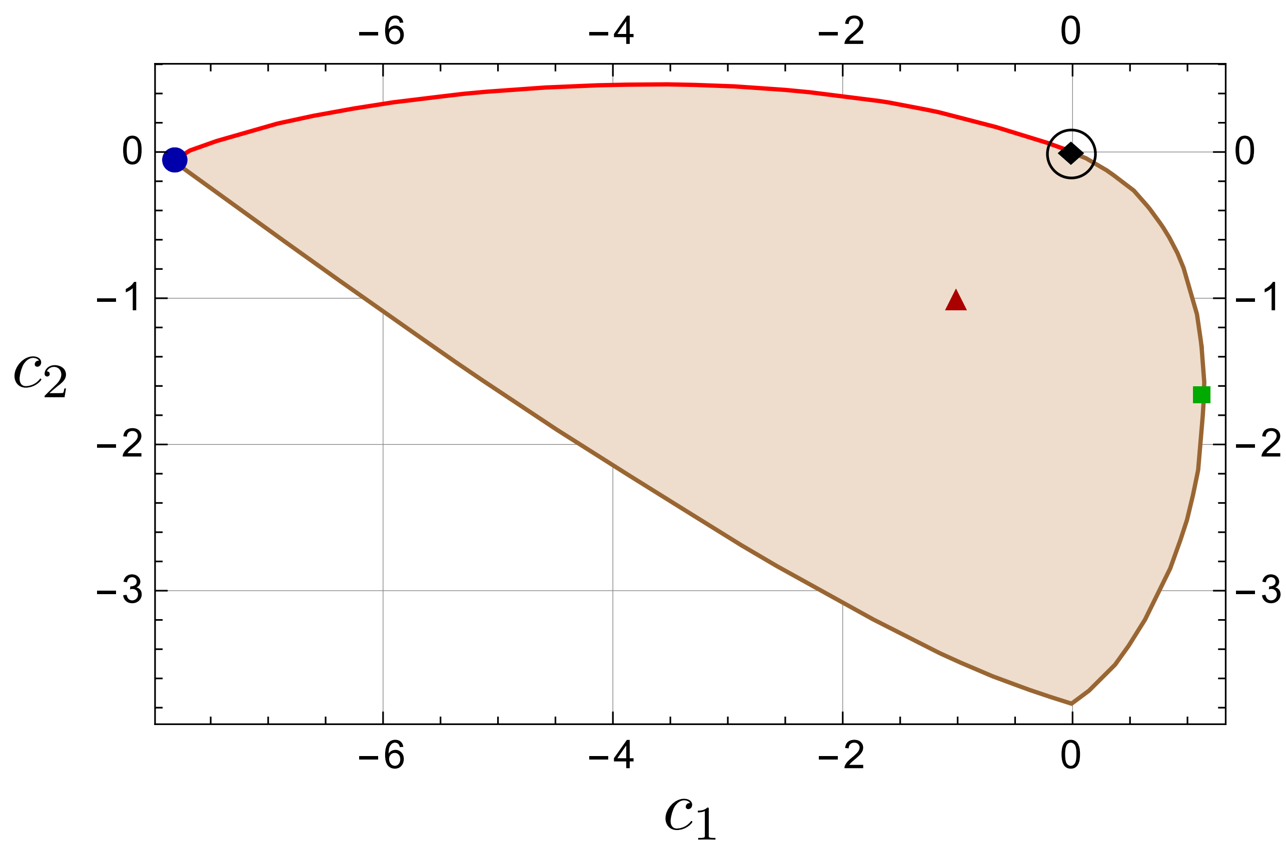
- RG flows from SYM-CS (dotted lines) and between CFT's (solid lines) dual to BPS domain-wall solutions of the dyonic ISO(7)-gauged supergravity

Black holes

[Dall'Agata, Gnecchi '10]
[Klemm, Petri, Rabbiosi '16]

- N=2 model with 1 vector + 1 hyper ▶ Unique $AdS_2 \times H^2$ horizon [attractor mechanism]

- Two irrelevant modes (c_1, c_2) when perturbing around the $AdS_2 \times H^2$ solution in the IR



▲ : $AdS_2 \times H^2$ to DW_4
◆ : $AdS_2 \times H^2$ to AdS_4
● : $AdS_2 \times H^2$ to Lifshitz (z=2)
■ : $AdS_2 \times H^2$ to conf-Lifshitz

[AG, Tarrío '17]

- RG flows across dimension from SYM-CS **or** CFT_3 **or** non-relativistic to CFT_1
- Universal (constant scalars) RG flow (◆) CFT_3 to CFT_1 [Caldarelli, Klemm '98]

- $AdS_2 \times \Sigma_g$ horizons for mIIA on $H^{(p,q)}$: STU-models with 3 vectors + 1 hyper

[AG '17]

Summary

- Dyonic N = 8 supergravity with $ISO(7)_c$ gauging connected to massive IIA reductions on S^6.

- Any 4D configuration (AdS, DW, BH) is embedded into 10D via the uplifting formulas.

  Example : $AdS_4 \times S^6$ solution of massive IIA based on an N = 2 & U(3) AdS_4 vacuum.

- CFT_3 dual for the N = 2 $AdS_4 \times S^6$ solution of mIIA based on the D2-brane field theory (SYM-CS).

- Holographic study of RG flows on D2-brane : DW solutions (CFT_3 / CFT_3 & SYM-CS / CFT_3)

  BH solutions (CFT_3 / CFT_1 & SYM-CS / CFT_1)

- Generalisation & further tests/conjectures on the duality (semiclassical observables, level-rank duality, …)

  [Fluder, Sparks '15]

  [Araujo, Nastase '16] [Araujo, Itsios, Nastase, Ó Colgáin '17]

- Recent progress in the holographic counting of BH microstates

  [Benini, Hristov, Zaffaroni '16]

  [Azzurli, Bobev, Crichigno, Min, Zaffaroni '17]

  [Hosseini, Hristov, Passias '17] [Benini, Khachatryan, Milan '17]

- $SO(8)_c$ theories?

¡ Muchas gracias !

Muito obrigado !