Cosmological and Holographical Applications of String Dualities

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Based on various collaborations with Borghese, Casas, Ciceri, Danielsson, de Carlos, Derendinger, Dibitetto, F-Melgarejo, Font, Inverso, Jafferis, Moreno, Roest, Tarrío, Varela & Weatherill

Linking strings to the real world

- String theory provides a framework where to describe General Relativity and Quantum Field Theory

- The fundamental building blocks are tiny vibrating strings with $l_s \sim 10^{-33}$ cm

String Theory

$g_s \ll 1$

low energies
$L \gg l_s$

10D Supergravity

- 10D space-time
- Supersymmetry

small
extra dimensions

4D Expanding Universe

$\Lambda_{c.c} > 0$

Six extra dimensions !!

The footprint of the extra dimensions

- Fluctuations of the extra dimensions (size and shape) translate into a set of massless 4D scalar fields known as “moduli fields”

$$\mathcal{L} = R - \frac{1}{2}\partial_\mu \phi_i \partial^\mu \phi^i$$

Deviations from GR !!

massless scalars = long range interactions (precision tests of GR)

- String phenomenology → Mechanisms for “moduli stabilisation”

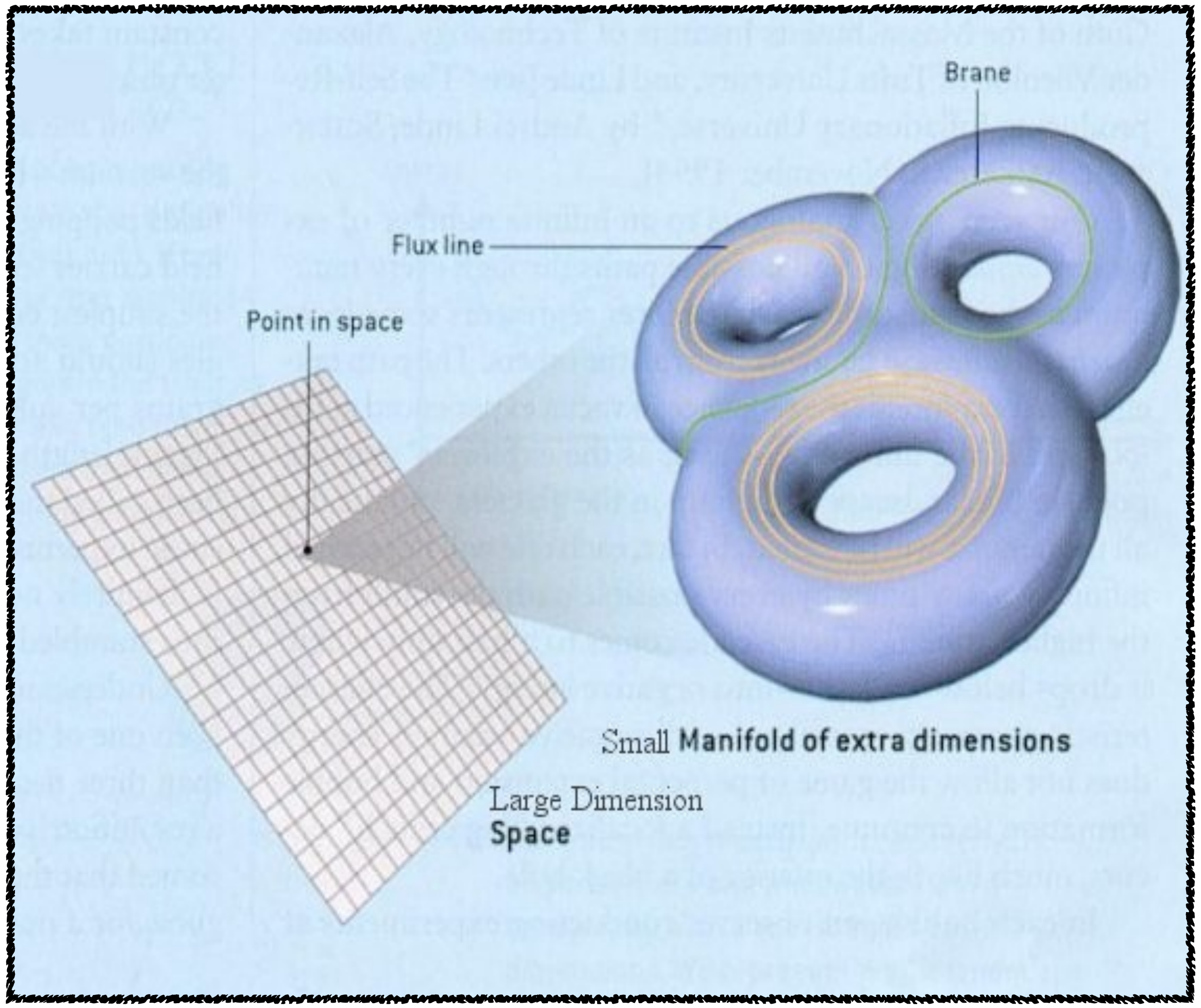
$$V(\phi) \;=\; m_{ij}^2\, \phi^i\, \phi^j \;+\; \ldots$$

- The moduli VEVs $\langle \phi^i \rangle = \phi_0^i$ determine the 4D cosmological constant !!

$$\Lambda_{c.c} \;\equiv\; V(\phi_0)$$

[sign = expansion (dS) vs collapse (AdS)]

Extra dimensions...

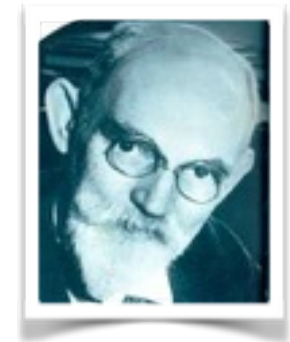


... will be non empty !!

- D-branes
- magnetic fluxes
- funny geometries
- ...

$$V(\phi) = V_{brane} + V_{flux} + V_{geom}$$

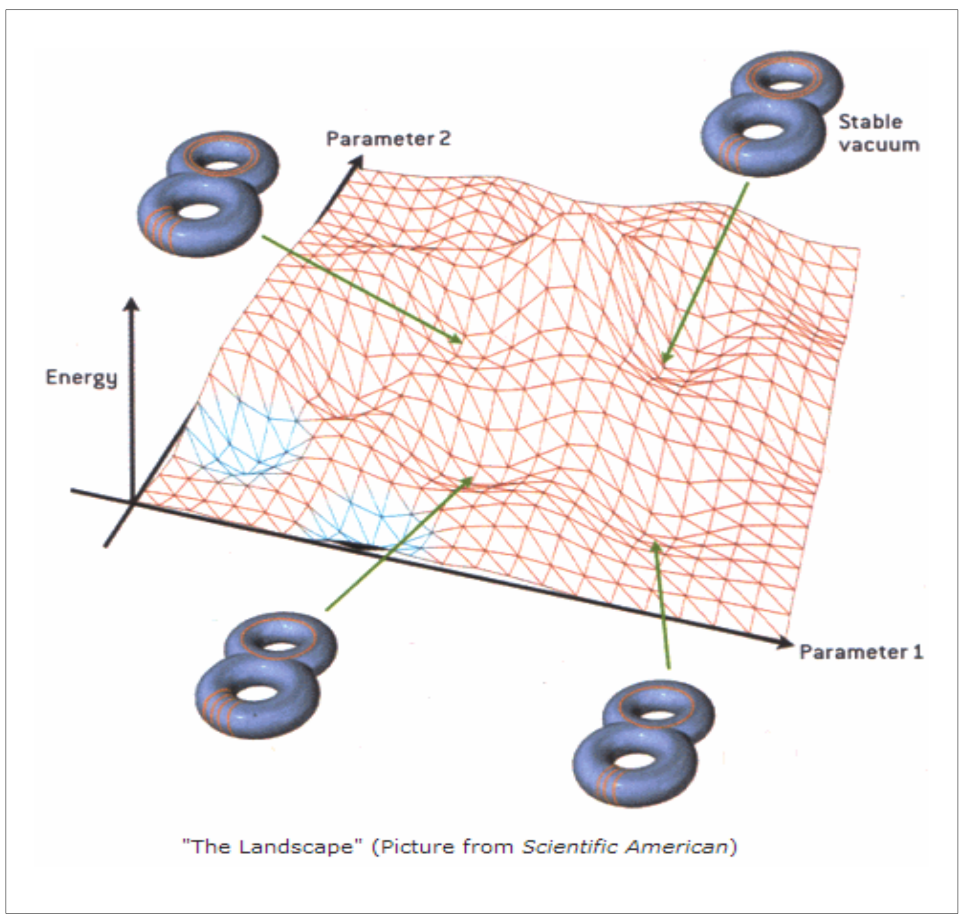
The problem = finding



Willem de Sitter
(1872 – 1934)

- Model building :

branes + fluxes + geometries + … = parameters



"The Landscape" (Picture from *Scientific American*)

[Giddings, Kachru, Polchinski '01]

[Blumemhagen, Cámara, de Carlos, Dall'Agata, Derendinger, DeWolfe, Giryavets, Graña, Ibáñez, Kachru, Kounnas, Kors, Lüst, Minasian, Petrini, Petropoulos, Reffert, Schulz, Schulgin, Stieberger, Taylor, Tomasiello, Trigiante, Tripathy, Trivedi , Villadoro, Zwirner, … 2002 - 2006]

$$\Lambda_{c.c} \equiv V(\phi_0) > 0$$

… but where is de Sitter
within the string landscape?

No-go theorems forbid perturbative dS vacua !!

[Hertzberg, Kachru, Taylor, Tegmark '07]

A way out:

To introduce ***mysterious*** non-geometric fluxes

[Dabholkar, Hull '05]

[Shelton, Taylor, Wecht '05, '06]

Motivation: what are non-geometric fluxes?

4D objects conjectured to exist based on string dualities (different regimes of strings)

[strong-weak coupling, winding-momentum states, ...]

[Hull, Townsend '94]

Questions to be addressed today :

- Are there stable dS vacua in these non-geometric 4D scenarios (useful at all)?
- Is there a 4D effective field theory where to describe such exotic fluxes systematically?
- Do they have a higher-dimensional (string) origin?

Challenges in string theory !!

From

non-geometric fluxes (2004-2006)

to

extended field theories (2014-2016)

(a personal trip)

(2004 - 2006)

[Dabholkar, Hull '05]
[Shelton, Taylor, Wecht '05, '06]

- Non-geometric fluxes were introduced for the first time in the context of effective N=1 supergravities in order to restore the *stringy* T-duality at the 4D level

- Starting from the field strength *H=dB* of the *B*-field (2-form gauge potential) of string theory and applying a chain of T-dualities , one finds

[Torus]	[Twisted torus]	[T-folds : Hull '04]	[??]
H_{mnp} $\rightarrow$	$\omega_{mn}{}^{p}$ $\rightarrow$	$Q_m{}^{np}$ $\rightarrow$	R^{mnp}
gauge flux	metric flux	??	??
GEOMETRIC		NON-GEOMETRIC	

[Kaloper, Myers '99]

- SO(6,6) T-duality symmetry of string theory becomes manifest at the 4D level !!

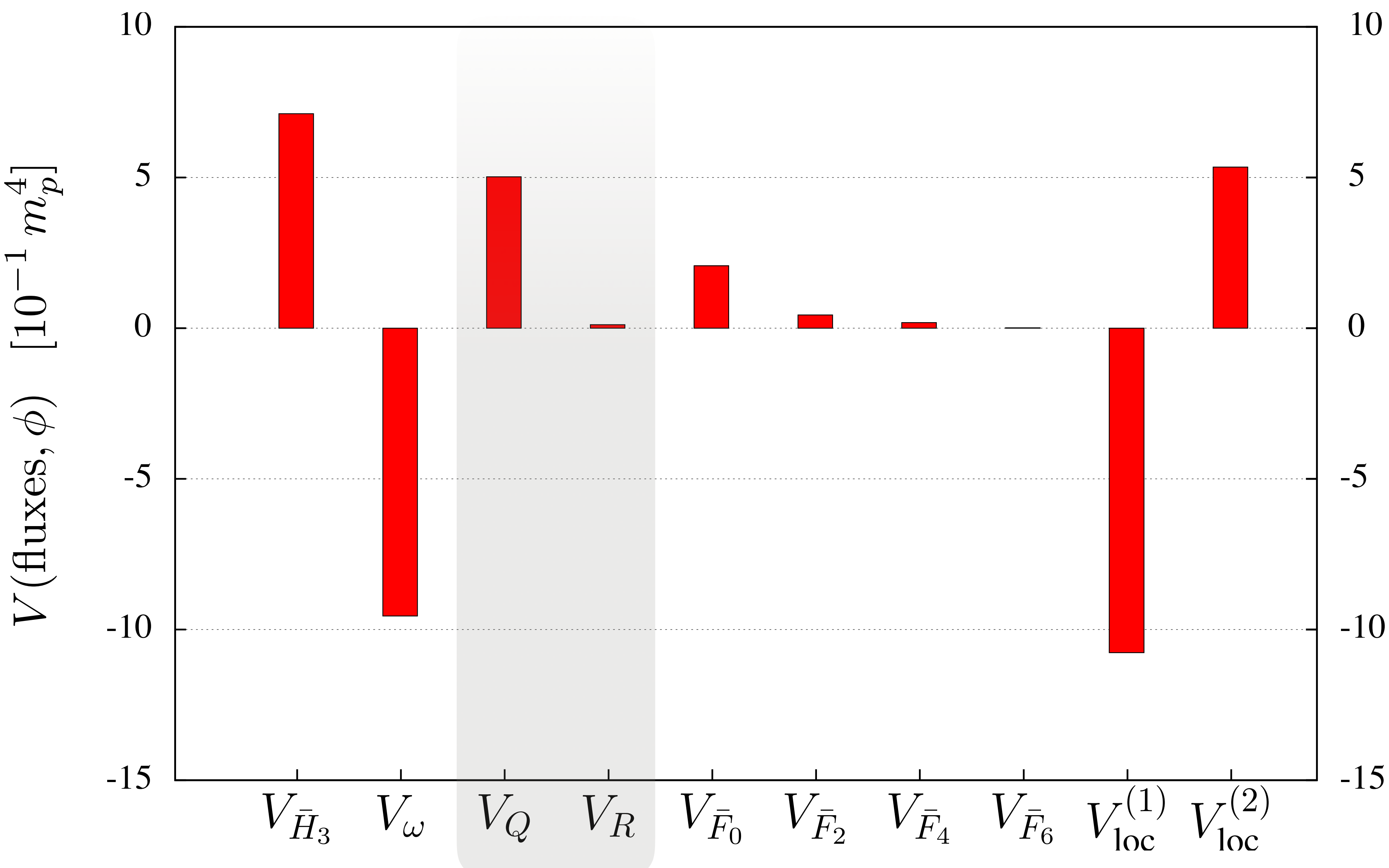
- Generalisation to other *stringy* SL(2) S-duality and E_7 U-duality : *P*-fluxes, etc…

[Aldazabal, Cámara, Font, Ibáñez '06]

(2007 - 2009)

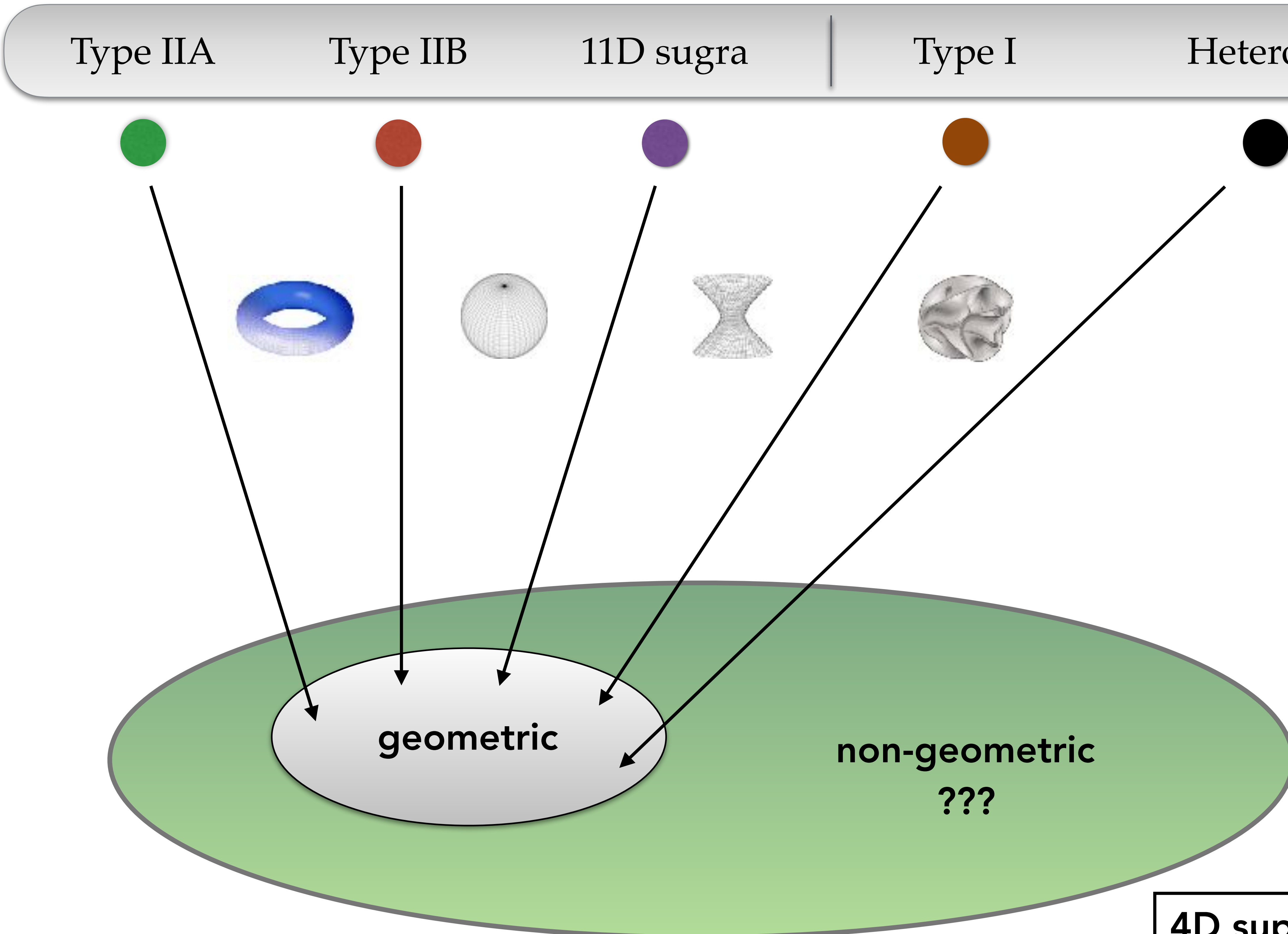
[Hull, Reid-Edwards '07] [Reid-Edwards '09]
[Dall'Agata, Prezas, Samtleben, Trigiante '07]
[Graña, Minasian, Petrini, Waldram '08]
[Font, AG, Moreno '08] [AG, Weatherill '08]

- Soon after their appearance, novel algebraic structures underlying the zoo of non-geometric fluxes started being uncovered. Making use of these algebraic structures, the first examples of *non-geometric stable dS vacua* were found!!



… although their higher-dimensional origin remained unclear [de Carlos, AG, Moreno '09]

Higher-dimensional supergravities



4D supergravities

(ET framework)

Embedding Tensor framework

[3D : Nicolai, Samtleben '00 '01]
[de Wit, Samtleben, Trigiante '05 '07]
[Schön, Weidner '06]

- Parallel to these developments, an effective field theory framework where to describe ***all*** the N=8 and N=4 supergravities irrespective of their origin enters the scene :

the *embedding tensor* framework

- The ET formalism implements all the stringy dualities in a 4D effective Lagrangian, namely, the interactions are determined by the symmetries of string theory

couplings in the potential (fluxes) $=$ *embedding tensor (reps. of duality group)*

Program : Precise correspondence between embedding tensor and fluxes (geometric and non-geometric) so that a systematic study of the latter can be achieved !!

Previous results :

[de Wit, Samtleben, Trigiante '03] [Angelantonj, Ferrara, Trigiante '03 '04]
[Derendinger, Kounnas, Petropoulos & Zwirner '04 '05 '06]
[Villadoro, Zwirner '05] [Aldazabal, Cámara, Font, Ibáñez '06]

Embedding Tensor / Flux correspondence

[Dall'Agata, Villadoro, Zwirner '09]
[Dibitetto, AG, Roest '11 '12 '14]

couplings	SO(6,6)
1	$-f_{+\bar{a}\bar{b}\bar{c}}$
U	$f_{+\bar{a}\bar{b}\bar{k}}$
U^2	$-f_{+\bar{a}\bar{j}\bar{k}}$
U^3	$f_{+\bar{i}\bar{j}\bar{k}}$
S	$-f_{-\bar{a}\bar{b}\bar{c}}$
$S\,U$	$f_{-\bar{a}\bar{b}\bar{k}}$
$S\,U^2$	$-f_{-\bar{a}\bar{j}\bar{k}}$
$S\,U^3$	$f_{-\bar{i}\bar{j}\bar{k}}$
T	$f_{+\bar{a}\bar{b}k}$
$T\,U$	$f_{+\bar{a}\bar{j}k} = f_{+\bar{i}\bar{b}k} \;,\; f_{+a\bar{b}\bar{c}}$
$T\,U^2$	$f_{+\bar{i}\bar{b}c} = f_{+\bar{a}\bar{j}c} \;,\; f_{+\bar{i}\bar{j}k}$
$T\,U^3$	$f_{+\bar{i}\bar{j}c}$
$S\,T$	$f_{-\bar{a}\bar{b}k}$
$S\,T\,U$	$f_{-\bar{a}\bar{j}k} = f_{-\bar{i}\bar{b}k} \;,\; f_{-a\bar{b}\bar{c}}$
$S\,T\,U^2$	$f_{-\bar{i}\bar{b}c} = f_{-\bar{a}\bar{j}c} \;,\; f_{-\bar{i}\bar{j}k}$
$S\,T\,U^3$	$f_{-\bar{i}\bar{j}c}$

Type IIB	Type IIA
F_{ijk}	F_{aibjck}
F_{ijc}	F_{aibj}
F_{ibc}	F_{ai}
F_{abc}	F_0
H_{ijk}	H_{ijk}
H_{ijc}	ω_{ij}^{c}
H_{ibc}	Q_i^{bc}
H_{abc}	R^{abc}
Q_k^{ab}	H_{abk}
$Q_k^{aj} = Q_k^{ib} \;,\; Q_a^{bc}$	$\omega_{ka}^{j} = \omega_{bk}^{i} \;,\; \omega_{bc}^{a}$
$Q_c^{ib} = Q_c^{aj} \;,\; Q_k^{ij}$	$Q_b^{ci} = Q_a^{jc} \;,\; Q_k^{ij}$
Q_c^{ij}	R^{ijc}
P_k^{ab}	
$P_k^{aj} = P_k^{ib} \;,\; P_a^{bc}$	
$P_c^{ib} = P_c^{aj} \;,\; P_k^{ij}$	
P_c^{ij}	

(2009 - 2016)

- New AdS and dS vacua (systematically) found using the ET / flux correspondence
- ET framework relevant for holography and cosmology [A biased choice of applications]

AdS vacua: applications in holography

- Dyonic gaugings and dual CFT_3

  [Dall'Agata, Inverso, Trigiante '12] [AG, Jafferis, Varela '15]

- New holographic RG flows from (M2)D2-branes and AdS_4/CFT_3

  [AG & Tarrío, Varela '13] [Pang, Rong '15] [AG, Tarrío, Varela '16]

- Consistent reductions of *massive* IIA /M-theory

  [Dall'Agata, Villadoro, Zwirner '09] [Godazgar's, Nicolai '13] [Derendinger, AG '14] [Danielsson, Dibitetto, AG '14] [Baron, Dall'Agata '14] [AG, Varela '15]

- Non-geometric superpotentials and BPS solutions

  [AG, '13 '15] [Danielsson, Dibitetto '15]

dS vacua: applications in cosmology

- dS in extended supergravity

  [Roest, Rosseel '09] [Borghese, Roest '10] [Dibitetto, AG, Roest '12]

- charting the landscape of flux vacua

  [Dall'Agata, Inverso '11] [Damian, Loaiza-Brito '13] [Danielsson, Haque, Shiu, van Riet & Koerber '10 '11] [Aldazabal, Marques, Nuñez, Rosabal '11] [Kodama, Nozawa '12] [Dibitetto, AG, Roest '11 '12 '14]

- inflationary models (slow-roll)

  [de Carlos, AG, Moreno '09] [Hassler, Lüst, Massi '14] [Kodama, Nozawa '15] [Blumenhagen et al '15]

- open/closed string interplay (alternative to anti-branes)

  [Blåbäk, Roest, Zavala & Danielsson, Dibitetto '13] [Kallosh, Linde, Vercnocke, Wrase '14] [AG, Inverso '15]

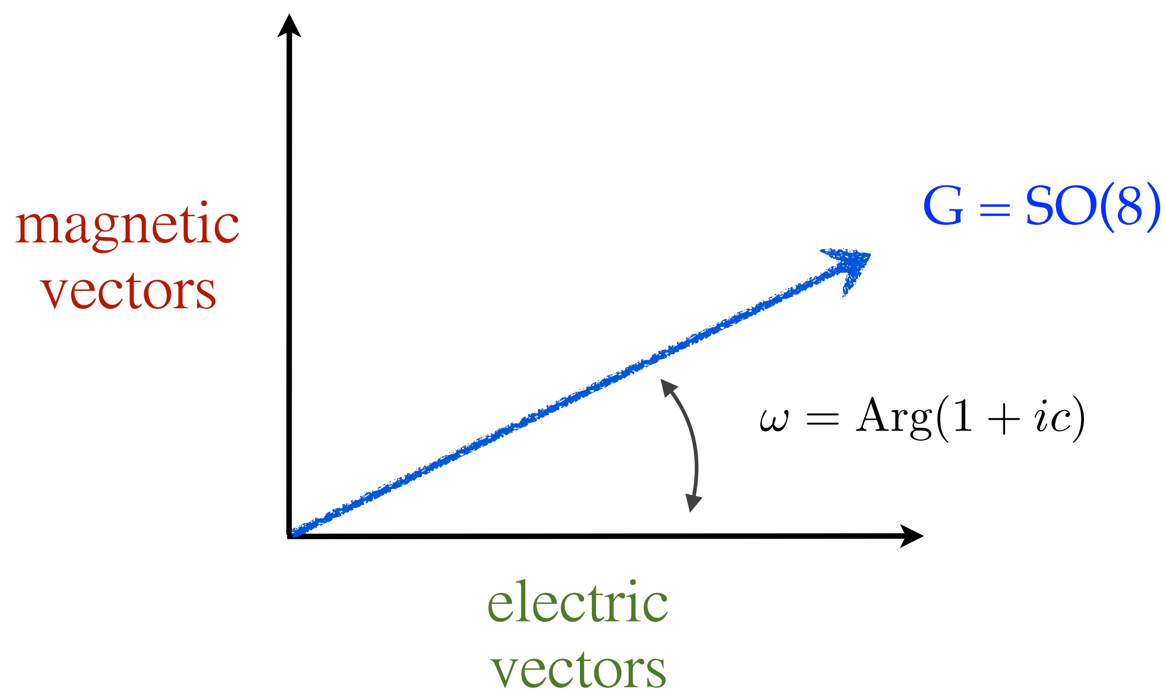
Holography : a new AdS_4/CFT_3 duality

- New *dyonic* maximal supergravities constructed using the ET framework

[Dall'Agata, Inverso, Trigiante & Marrani '12, '14] [Borghese, Dibitetto, AG, Roest, Varela '12] [Borghese, AG, Roest '12,'13]

Example : One-parameter family of SO(8)-gauged supergravities !!

[Dall'Agata, Inverso, Trigiante '12]



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

[de Wit, Nicolai '82]

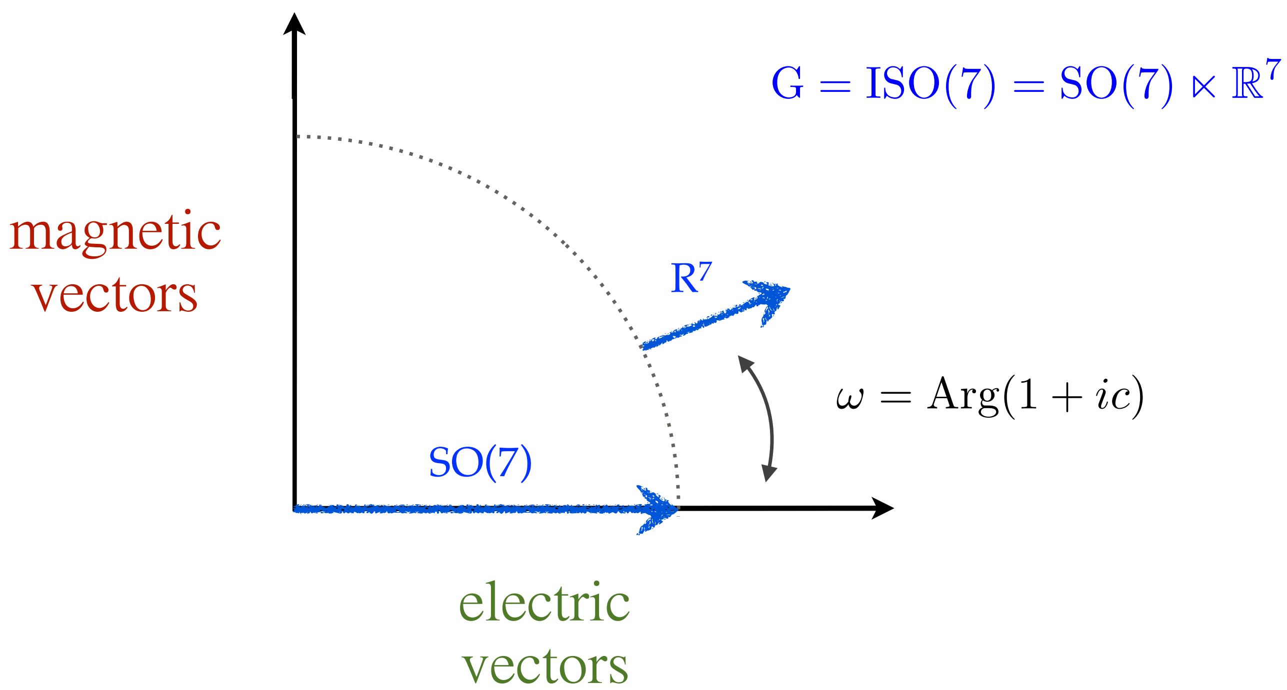
- $AdS_4 \times S^7$ backgrounds of 11D supergravity (M2-brane) ?
- AdS_4/CFT_3 duality (ABJM or ABJ) ?

... no conclusive answer yet

[Aharony, Bergman, Jafferis, Maldacena '08] [de Wit, Nicolai '13] [Lee, Strickland-Constable, Waldram '15]

Example : One-parameter family of ISO(7)-gauged supergravities

[Dall'Agata, Inverso, Marrani '14]



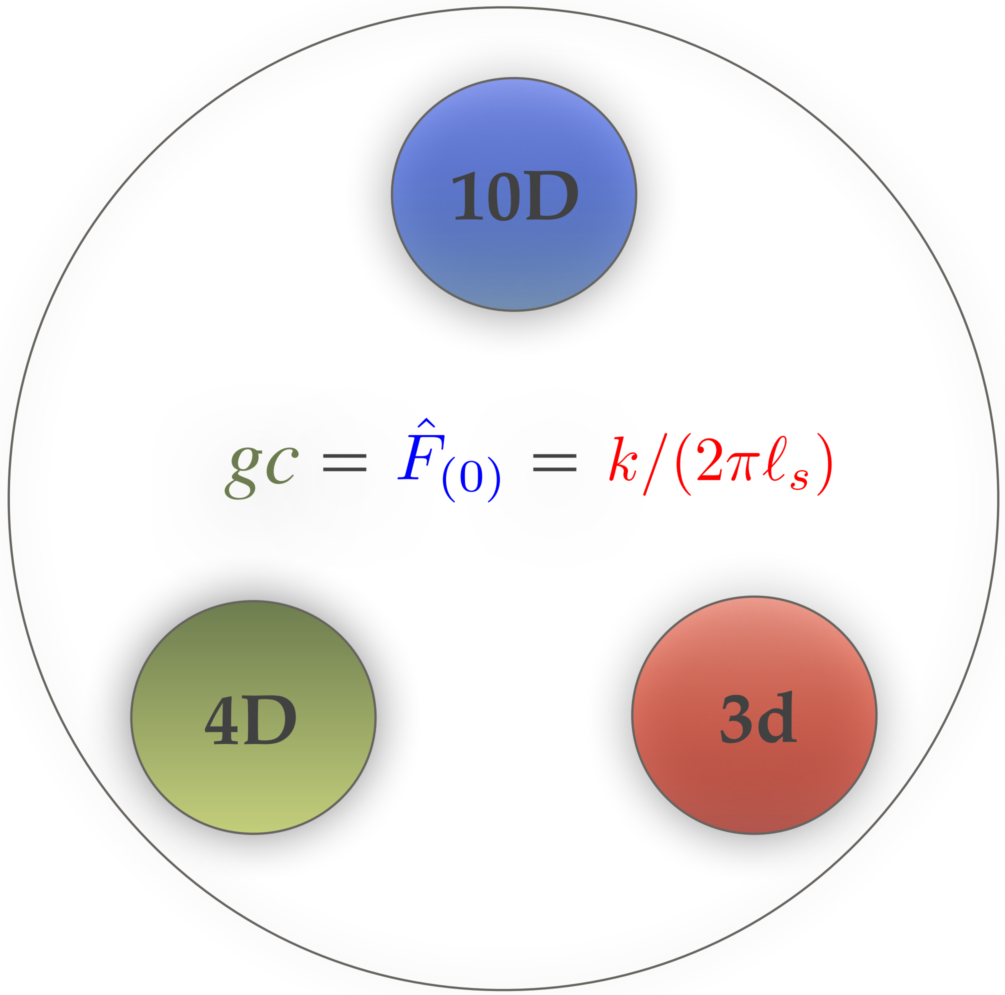
$$D = \partial - g\, A^{\mathrm{elec}}_{\mathrm{SO}(7)} - g\,(A^{\mathrm{elec}}_{\mathbb{R}^7} - c\,\tilde{A}_{\mathbb{R}^7\,\mathrm{mag}})$$

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

- $AdS_4 \times S^6$ background of massive IIA supergravity (D2-brane)
- AdS_4/CFT_3 duality : Chern-Simons-SYM theories with simple gauge group SU(N) and level k given by Romans mass
  [Schwarz '04]
- Matching of the free energies in supergravity and field theory sides (localisation)
- Further checks of the duality have been performed afterwords [Araujo, Nastase '16]

A new 10D/4D/3d correspondence

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



gc = elec/mag deformation in 4D

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

k = Chern-Simons level in 3d

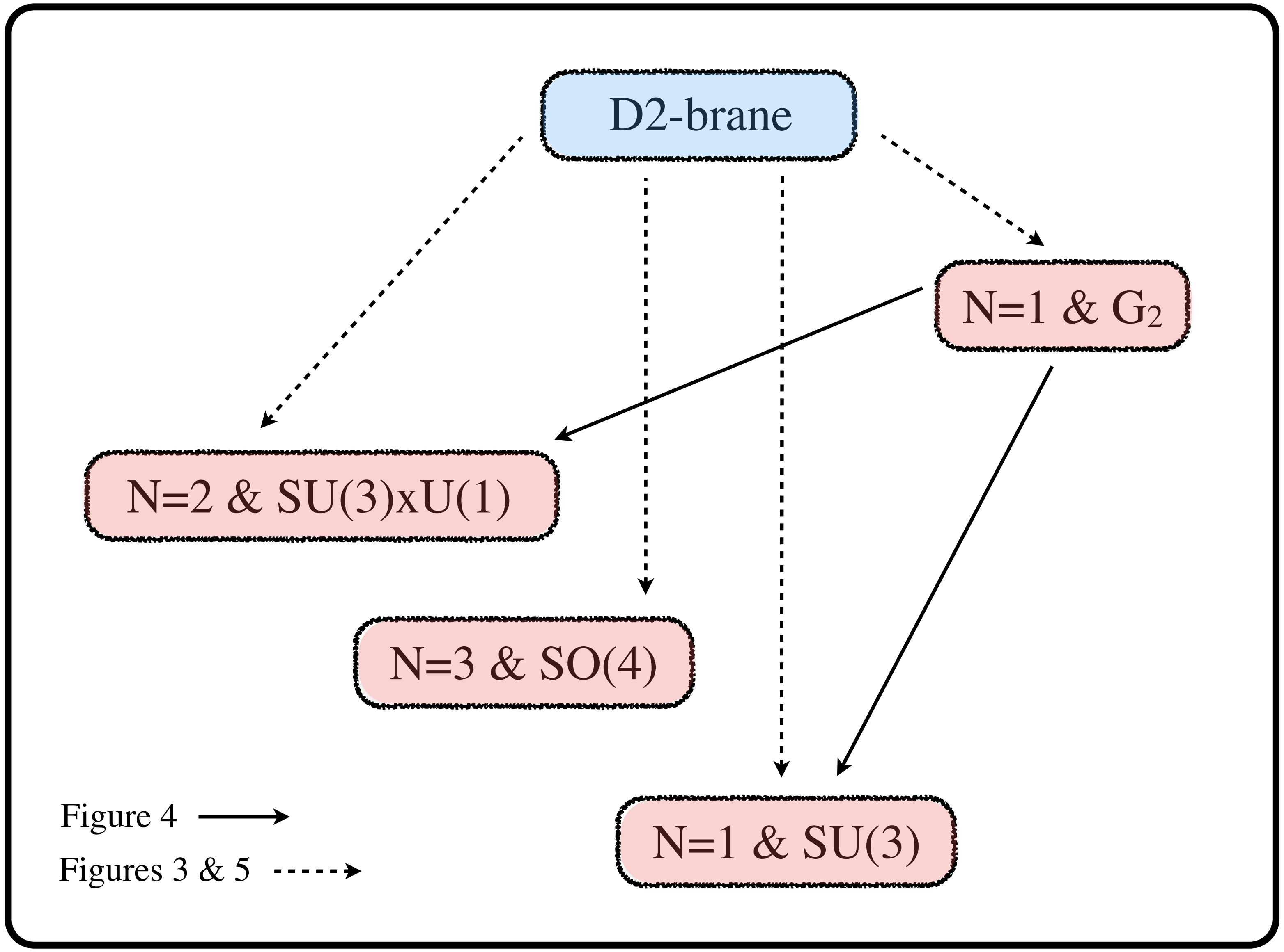
[AG, Jafferis, Varela '15]
[AG, Varela '15]

Well-established and independent dualities :

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

mIIA on S^6/CS-SYM correspondence & holographic RG flows

[AG, Tarrío, Varela '16]



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

Back to a long-standing question

What is the higher-dimensional origin of non-geometric fluxes and, more generally, of the various supergravities obtained using the lower-dimensional and duality covariant ET framework ?

(2013 - 2016) : string dualities in higher-dimensions

- Different strings related by dualities: IIA / IIB T-duality, IIB S-duality, …

- *String dualities* realised as global symmetries in lower-dimensional SUGRA

lower-dimensional phenomenon vs **higher-dimensional** phenomenon

embedding tensor, non-geometric fluxes… ß-supergravity , γ-supergravity…

[Andriot, Betz '13] [Lee, Rey, Sakatani '16]

New approach : **Extended Field Theories** [extend internal coords to transform under duality]

- Double Field Theory (DFT) ➡ Orthogonal groups $O(d,d)$ [half-max SUGRA (T-duality)]
- Exceptional Field Theory (EFT) ➡ Exceptional groups $E_{d+1(d+1)}$ [max SUGRA (U-duality)]

[Siegel '93] [Hull, Zwiebach & Hohm '09 '10] [Hohm, Samtleben '13]

Double Field Theory (DFT)

[Siegel '93]
[Hull, Zwiebach & Hohm '09 '10]

- T-duality covariant framework to describe momentum + winding modes

- The theory lives in D (external) + $2d$ (internal) coordinates y^M, with $D + d = 10$, and has an $R^+ \times O(d, d)$ symmetry linearly realised

$$
\begin{aligned}
S_{\rm DFT} \; &= \; \int d^4x\, d^{12}y\, e\, e^{-2\phi} \Big[\hat{R}(e) + 4\, \mathcal{D}^{\mu}\phi\, \mathcal{D}_{\mu}\phi + \tfrac{1}{8}\, \mathcal{D}^{\mu} M^{MN}\, \mathcal{D}_{\mu} M_{MN} \\
&- \; \tfrac{1}{12}\, H_{\mu\nu\rho}\, H^{\mu\nu\rho} - \tfrac{1}{4}\, M_{MN}\, \mathcal{F}_{\mu\nu}{}^{M} \mathcal{F}^{\mu\nu\, N} - V_{\rm DFT}(\phi, M_{MN}, g) \Big]
\end{aligned}
$$

Example : $D = 4$, $d = 6$ & $M = 1, \ldots, 12$

- Consistency requires a section constraint : $\eta^{MN}\, \partial_M \otimes \partial_N = 0$ → **N=1 sugra in 10D**

- $M_{MN} \in O(6,6)/O(6)^2$ generalised metric : metric + B-field

- Generalised geometries (beyond Riemann) & non-geometry (T-folds)

[Coimbra, Strickland-Constable, Waldram '11]

[asymmetric orbifolds]
[Dabholkar, Hull '03] [Hull '04 '06]

Exceptional Field Theory (EFT)

[Hohm, Samtleben '13]

- U-duality covariant framework to describe momentum + winding + brane modes

- The theory lives in D (external) + R[$E_{d(d)}$] (internal) coordinates $y^{\mathcal{M}}$, with $D + d = 11$, and has an $E_{d(d)}$ symmetry linearly realised

$$S_{\mathrm{E}_{7(7)}\text{-EFT}} = \int d^4x\, d^{56}y\, e\, \Big[\, \hat{R} + \tfrac{1}{48}\, g^{\mu\nu}\, \mathcal{D}_\mu M^{\mathcal{MN}}\, \mathcal{D}_\nu M_{\mathcal{MN}} - \tfrac{1}{8}\, M_{\mathcal{MN}}\, \mathcal{F}^{\mu\nu\mathcal{M}} \mathcal{F}_{\mu\nu}{}^{\mathcal{N}} + e^{-1}\, \mathcal{L}_{\text{top}} - V_{\mathrm{E}_{7(7)}\text{-EFT}}(M_{\mathcal{MN}}, g) \,\Big]$$

Example : $D = 4$, $d = 7$ & $\mathcal{M} = 1, \ldots, 56$

[Massive IIA : Ciceri, AG, Inverso '16]

- Consistency requires a section constraint : $Y^{MN}{}_{PQ}\, \partial_M \otimes \partial_N = 0 \longrightarrow$ **Type IIB or 11D supergravity**

- $M_{\mathcal{MN}} \in \mathrm{E}_{7(7)}/\mathrm{SU}(8)$ generalised metric : metric + type IIB *or* $A_{(3)}$ potentials

- Exceptional generalised geometries (beyond Riemann) & non-geometry (U-folds)

[Coimbra, Strickland-Constable, Waldram '11 '12]

Dualities in SUGRA and Extended Field Theory

D	Maximal sugra / EFT	Half-maximal sugra	DFT
9	$\mathbb{R}^+ \times \mathrm{SL}(2)$	$\mathbb{R}^+ \times \mathrm{O}(1, 1+n)$	$\mathbb{R}^+ \times \mathrm{O}(1, 1+n)$
8	$\mathrm{SL}(2) \times \mathrm{SL}(3)$	$\mathbb{R}^+ \times \mathrm{O}(2, 2+n)$	$\mathbb{R}^+ \times \mathrm{O}(2, 2+n)$
7	$\mathrm{SL}(5)$	$\mathbb{R}^+ \times \mathrm{O}(3, 3+n)$	$\mathbb{R}^+ \times \mathrm{O}(3, 3+n)$
6	$\mathrm{SO}(5, 5)$	$\mathbb{R}^+ \times \mathrm{O}(4, 4+n)$	$\mathbb{R}^+ \times \mathrm{O}(4, 4+n)$
5	$\mathrm{E}_{6(6)}$	$\mathbb{R}^+ \times \mathrm{O}(5, 5+n)$	$\mathbb{R}^+ \times \mathrm{O}(5, 5+n)$
4	$\mathrm{E}_{7(7)}$	$\mathrm{SL}(2) \times \mathrm{O}(6, 6+n)$	$\mathbb{R}^+ \times \mathrm{O}(6, 6+n)$
3	$\mathrm{E}_{8(8)}$	$\mathrm{O}(8, 8+n)$	$\mathbb{R}^+ \times \mathrm{O}(7, 7+n)$

Duality groups of half-maximal SUGRA and DFT differ for $\mathbf{D \leq 4}$

* n = additional vector multiplets

… so there is a theory in between EFT and DFT in D = 4

EFT with $E_{7(7)}$ duality group

[Hohm, Samtleben ’13]

↓

[Ciceri, Dibitetto, F-Melgarejo, AG, Inverso ‘16]

SL(2)-DFT with SL(2) x O(6,6+n) duality group

↓

DFT with R^+ x O(6,6+n) duality group

[Siegel ’93]
[Hull, Zwiebach ’09]
[Hohm, Hull, Zwiebach ’10]
[Hohm, Kwak ’11]

SL(2) -Double Field Theory

- SL(2) x O(6, 6) covariant framework [$n = 0$] [Ciceri, Dibitetto, F-Melgarejo, AG, Inverso '16]

- The theory lives in D (external) + 2 x 12 (internal) coordinates $y^{\alpha M} = (y^{+M}, y^{-M})$, and has an SL(2) x O(6, 6) symmetry linearly realised

$$S_{\text{SL(2)-DFT}} = \int d^4x\, d^{24}y\, e\, \Big[\, \hat{R} + \tfrac{1}{4}\, g^{\mu\nu}\, \mathcal{D}_\mu M^{\alpha\beta}\, \mathcal{D}_\nu M_{\alpha\beta} + \tfrac{1}{8}\, g^{\mu\nu}\, \mathcal{D}_\mu M^{MN}\, \mathcal{D}_\nu M_{MN} - \tfrac{1}{8}\, M_{\alpha\beta}\, M_{MN}\, \mathcal{F}^{\mu\nu\,\alpha M}\, \mathcal{F}_{\mu\nu}{}^{\beta N} + e^{-1}\, \mathcal{L}_{\text{top}} - V_{\text{SL(2)-DFT}}(M, g) \,\Big]$$

Example : $D = 4$, $d = 6$ & $\alpha = +, -$, $M = 1, \ldots, 12$

- Consistency section constraints : $\eta^{MN}\, \partial_{\alpha M} \otimes \partial_{\beta N} = 0$, $\epsilon^{\alpha\beta}\, \partial_{\alpha[M|} \otimes \partial_{\beta|N]} = 0$ → **N=1 sugra in 10D** ***or*** **(2,0) sugra in 6D**

- $M_{\alpha\beta} \in \mathrm{SL}(2)/\mathrm{SO}(2)$ generalised dilaton : dilaton + axion

- $M_{MN} \in \mathrm{SO}(6,6)/\mathrm{SO}(6)^2$ generalised metric : metric + B-field

- DFT corresponds to $\mathrm{SL}(2)_+$ -DFT

… but what for ?

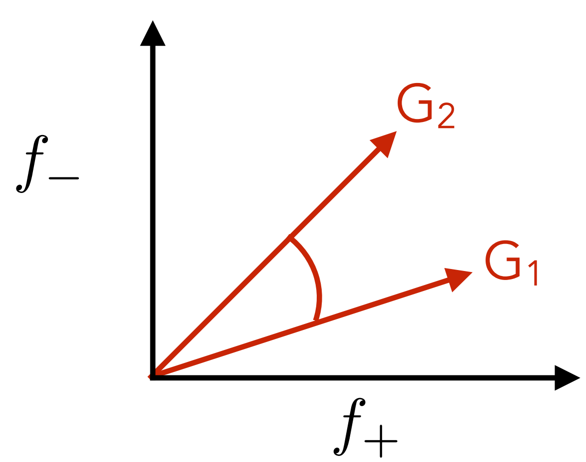
SL(2) angles and moduli stabilisation

- Scherk-Schwarz (SS) reductions with SL(2) x O(6,6) twist matrices $U_{\alpha M}{}^{\beta N} = e^{\lambda}\, e_{\alpha}{}^{\beta}\, U_M{}^N$ yield N = 4 , D = 4 gaugings [Schön, Weidner '06]

$$
\begin{aligned}
f_{\alpha MNP} &= -3\, e^{-\lambda}\, e_{\alpha}{}^{\beta}\, \eta_{Q[M}\, U_N{}^R\, U_{P]}{}^S\; \partial_{\beta R} U_S{}^Q \\
\xi_{\alpha M} &= 2\, U_M{}^N \partial_{\beta N} (e^{-\lambda} e_{\alpha}{}^{\beta})
\end{aligned}
$$

[de Roo, Wagemans '85]

- Moduli stabilisation **requires** gaugings $G = G_1 \times G_2$ at **relative** SL(2) angles



(sec. constraint violated)

$$
\epsilon^{\alpha\beta}\, \partial_{\alpha[M|} \otimes \partial_{\beta|N]} \neq 0
$$

- Dependence on **both** type + & type - coordinates [**not** possible in DFT]

Example : SO(4) x SO(4)-gauged sugra and non-geometry

- SS with $U(y^{\alpha M}) \in \mathrm{O}(6,6)$: Half of the coords of type + & half of type -

- SL(2)-superposition of **two chains** of **non-geometric** fluxes $(H \,,\, \omega \,,\, Q \,,\, R)_{\pm}$

f_{+}	$f_{+mnp} = H^{+}{}_{mnp}$, $f_{+mn\bar{p}} = \omega^{+}{}_{mn}{}^{p}$, $f_{+\bar{m}\bar{n}p} = Q^{+mn}{}_{p}$, $f_{+\bar{m}\bar{n}\bar{p}} = R^{+mnp}$
f_{-}	$f_{-mnp} = H^{-}{}_{mnp}$, $f_{-mn\bar{p}} = \omega^{-}{}_{mn}{}^{p}$, $f_{-\bar{m}\bar{n}p} = Q^{-mn}{}_{p}$, $f_{-\bar{m}\bar{n}\bar{p}} = R^{-mnp}$

Most general family (8 params) of SO(4) x SO(4)-gauged N=4 sugra

- SO(4) x SO(4) SUGRA : **AdS$_4$** & **dS$_4$** vacua (sphere / hyperboloid reductions)

[de Roo, Westra, Panda, Trigiante '03] [Dibitetto, AG, Roest '12]

- ``Hybrid ±" sources to cancel flux-induced tadpoles : **SL(2)-dual NS-NS branes ??**

[exotic branes : de Boer, Shigemori '10]

Summary & Future directions (2017 - …)

- Understanding the string dynamics beyond the standard 10D / 11D supergravity regime is a key step towards linking strings to cosmological data, *e.g.* de Sitter from strings

- String dualities connect different regimes of the string dynamics, thus motivating the search for duality covariant frameworks :

  - Lower-dimensional (Embed. Tensor)
    - Cosmology : non-geometry & de Sitter vacua charting the string landscape
    - Holography : new AdS_4 / CFT_3 duality **mIIA on S^6/CS-SYM**

  - Higher-dimensional (Ext. Field Theories)
    - Unification of 10D / 11D supergravities
    - Generalised geometries (T / S / U-folds)
    - Consistent reductions ($AdS_5 \times S^5$, …)
    - Non-geometry *vs* section constraint
    - …

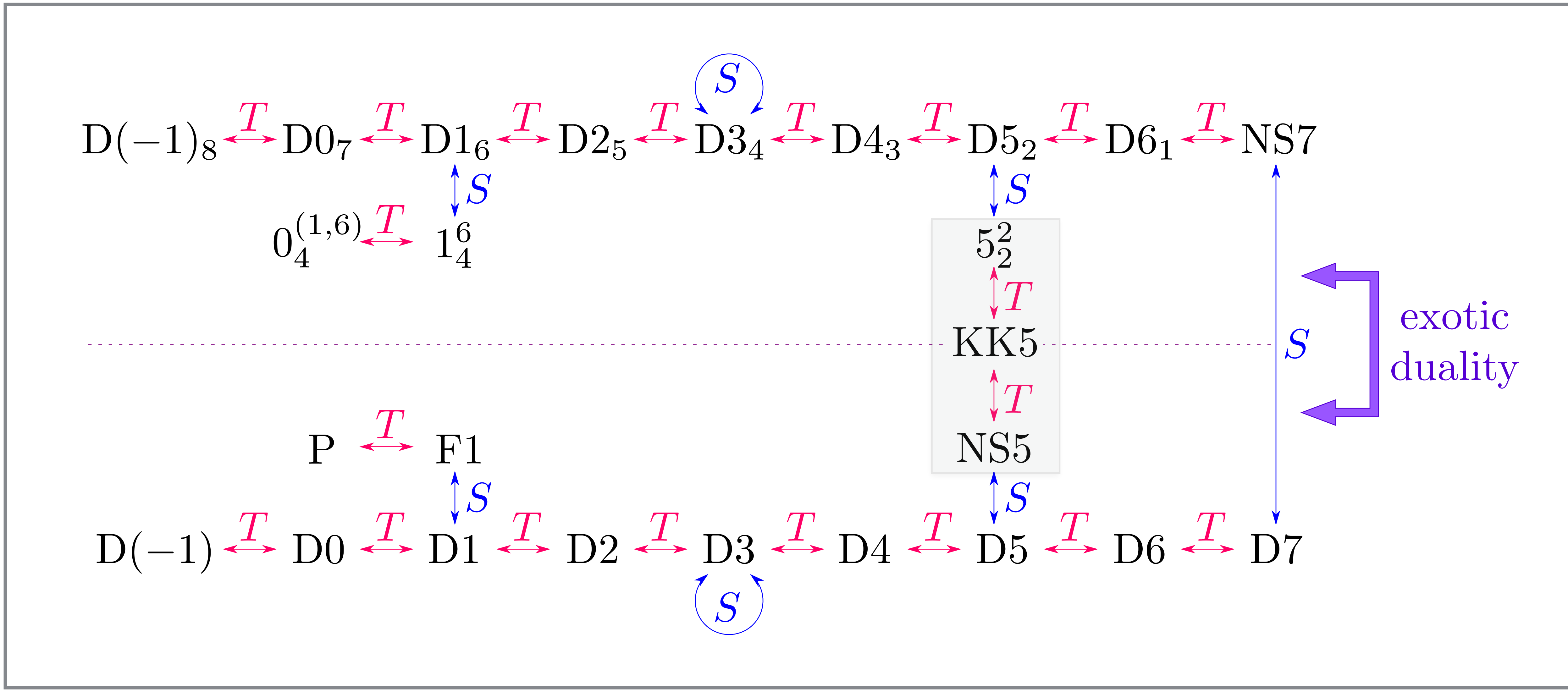
- Exotic branes & BH microstates counting

New generalised *stringy* geometries, exotic dual branes , black hole microstates , inflationary models , new de sitter vacua , AdS_4/CFT_3 , holographic RG flows and much more to be explored in the near future!!

Thanks

Extra material

A family of exotic branes



[Sakatani '15]

Deformations of EFT (XFT)

- Generalised Lie derivative

[no density term]

$$\mathbb{L}_\Lambda U^{\mathcal{M}} \quad = \quad \Lambda^{\mathcal{N}}\partial_{\mathcal{N}}U^{\mathcal{M}} - U^{\mathcal{N}}\partial_{\mathcal{N}}\Lambda^{\mathcal{M}} + Y^{\mathcal{M}\mathcal{N}}{}_{\mathcal{P}\mathcal{Q}}\,\partial_{\mathcal{N}}\Lambda^{\mathcal{P}}\,U^{\mathcal{Q}}$$

in terms of an $E_{n(n)}$-invariant structure Y-tensor. Closure requires **sec. constraint**

- **Deformed** generalised Lie derivative

$$\widetilde{\mathbb{L}}_\Lambda U^{\mathcal{M}} \quad = \quad \Lambda^{\mathcal{N}}\partial_{\mathcal{N}}U^{\mathcal{M}} - U^{\mathcal{N}}\partial_{\mathcal{N}}\Lambda^{\mathcal{M}} + Y^{\mathcal{M}\mathcal{N}}{}_{\mathcal{P}\mathcal{Q}}\,\partial_{\mathcal{N}}\Lambda^{\mathcal{P}}\,U^{\mathcal{Q}} - \underbrace{X_{\mathcal{N}\mathcal{P}}{}^{\mathcal{M}}\,\Lambda^{N}\,U^{\mathcal{P}}}_{\text{non-derivative}}$$

in terms of an X deformation which is $E_{n(n)}$-algebra valued

- Closure & triviality of the Jacobiator require (*together with* ***sec. constraint***)

$$X_{\mathcal{M}\mathcal{N}}{}^{\mathcal{P}}\,\partial_{\mathcal{P}} = 0$$

X constraint

$$X_{\mathcal{M}\mathcal{P}}{}^{\mathcal{Q}}\,X_{\mathcal{N}\mathcal{Q}}{}^{\mathcal{R}} - X_{\mathcal{N}\mathcal{P}}{}^{\mathcal{Q}}\,X_{\mathcal{M}\mathcal{Q}}{}^{\mathcal{R}} + X_{\mathcal{M}\mathcal{N}}{}^{\mathcal{Q}}\,X_{\mathcal{Q}\mathcal{P}}{}^{\mathcal{R}} = 0$$

Quadratic constraint (gauged max. supergravity)

[*X* deformation *vs* embedding tensor]

X deformation : background fluxes & Romans mass

$$Y^{\mathcal{PQ}}{}_{\mathcal{MN}}\ \partial_{\mathcal{P}} \otimes \partial_{\mathcal{Q}} = 0$$

section constraint

$$X_{\mathcal{MN}}{}^{\mathcal{P}}\ \partial_{\mathcal{P}} = 0$$

X constraint

[algebraic system]

M-theory (**n** coords)

- SL(n) orbit
- Freund-Rubin param. (n = 4 and n = 7)
- *massless* IIA (subcase)

Type IIB (**n-1** coords)

- SL(n-1) orbit
- *p*-form fluxes compatible with SL(n-1)
- **SL(2)-triplet of 1-form flux** (includes compact SO(2))

+

New massive Type IIA (**n-1** coords)

- SL(n-1) orbit
- *p*-form fluxes compatible with SL(n-1)
- dilaton flux
- **Romans mass parameter** (*kills the M-theory coord*)

Massive Type IIA described in a purely geometric manner !!

[QC = flux-induced tadpoles]

$E_{7(7)}$-XFT action

- $E_{7(7)}$-XFT action $[\ \mathcal{D}_\mu = \partial_\mu - \widetilde{\mathbb{L}}_{A_\mu}\ ]$ [$y^{\mathcal{M}}$ coords in the **56** of $E_{7(7)}$]

$$S_{\rm XFT} = \int d^4x\, d^{56}y\, e\, \Big[\, \hat{R} + \tfrac{1}{48}\, g^{\mu\nu}\, \mathcal{D}_\mu \mathcal{M}^{\mathcal{M}\mathcal{N}}\, \mathcal{D}_\nu \mathcal{M}_{\mathcal{M}\mathcal{N}} - \tfrac{1}{8}\, \mathcal{M}_{\mathcal{M}\mathcal{N}}\, \mathcal{F}^{\mu\nu\mathcal{M}} \mathcal{F}_{\mu\nu}{}^{\mathcal{N}} + e^{-1}\, \mathcal{L}_{\rm top} - V_{\rm XFT}(\mathcal{M}, g) \,\Big]$$

with *field strengths* & *potential* given by

(deformed tensor hierarchy)

$$\mathcal{F}_{\mu\nu}{}^{\mathcal{M}} = 2\, \partial_{[\mu} A_{\nu]}{}^{\mathcal{M}} + X_{[\mathcal{P}\mathcal{Q}]}{}^{\mathcal{M}}\, A_\mu{}^{\mathcal{P}} A_\nu{}^{\mathcal{Q}} - \big[A_\mu, A_\nu\big]_{\rm E}^{\mathcal{M}} + \text{two-form terms}$$

$$V_{\rm XFT}(\mathcal{M}, g, X) = V_{\rm EFT}(\mathcal{M}, g) + \underbrace{\tfrac{1}{12}\, \mathcal{M}^{MN} \mathcal{M}^{KL} X_{MK}{}^{P}\, \partial_N \mathcal{M}_{PL}}_{\text{cross term}} + \underbrace{V_{\rm SUGRA}(\mathcal{M}, X)}_{\text{gauged max. sugra}}$$

- Two-One-**Zero**-derivative potential : **gauged** 4D max. sugra when $\Phi(x,y) = \Phi(x)$

Extended (super) Poincaré superalgebra

- Central charges (internal symmetries) $\mathcal{Z}_{IJ} = (a^a_{IJ})\ T^a$

- The algebra :

$$[P_\mu, P_\nu] = 0 \qquad [M_{\mu\nu}, M_{\rho\sigma}] = i\,(\eta_{\nu\rho}\, M_{\mu\sigma} - \eta_{\nu\sigma}\, M_{\mu\rho} - \eta_{\mu\rho}\, M_{\nu\sigma} + \eta_{\mu\sigma}\, M_{\nu\rho})$$

$$[P_\mu, M_{\rho\sigma}] = i\,(\eta_{\mu\rho}\, P_\sigma - \eta_{\mu\sigma}\, P_\rho)$$

$$\left[T^a, T^b\right] = if^{ab}_{\ \ c}\ T^c \qquad [T^a, P_\mu] = [T^a, M_{\mu\nu}] = 0$$

$$\left[\mathcal{Q}^I_\alpha, P_\mu\right] = \left[\bar{\mathcal{Q}}^I_{\dot\alpha}, P_\mu\right] = 0 \qquad \left[\mathcal{Q}^I_\alpha, T^a\right] = (b_a)^I{}_J\ \mathcal{Q}^J_\alpha \qquad \left[\bar{\mathcal{Q}}^I_{\dot\alpha}, T^a\right] = -\bar{\mathcal{Q}}^J_{\dot\alpha}\ (b_a)_J{}^I$$

$$\left[\mathcal{Q}^I_\alpha, M_{\mu\nu}\right] = \frac{1}{2}(\sigma_{\mu\nu})_\alpha^{\ \beta}\ \mathcal{Q}^I_\beta \qquad \left[\bar{\mathcal{Q}}^I_{\dot\alpha}, M_{\mu\nu}\right] = -\frac{1}{2}\bar{\mathcal{Q}}^I_{\dot\beta}\ (\bar\sigma_{\mu\nu})^{\dot\beta}{}_{\dot\alpha}$$

$$\left\{\bar{\mathcal{Q}}^I_{\dot\alpha}, \bar{\mathcal{Q}}^J_{\dot\beta}\right\} = -2\,\epsilon_{\dot\alpha\dot\beta}\ \mathcal{Z}^{IJ\,\dagger} \qquad \left\{\mathcal{Q}^I_\alpha, \mathcal{Q}^J_\beta\right\} = 2\,\epsilon_{\alpha\beta}\ \mathcal{Z}^{IJ} \qquad \left\{\mathcal{Q}^I_\alpha, \bar{\mathcal{Q}}^J_{\dot\beta}\right\} = 2\ \delta^{IJ}\ (\sigma^\mu)_{\alpha\dot\beta}\ P_\mu$$