The landscape of 4d (anti-) de Sitter and Minkowski solutions of 10d supergravities

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arXiv:2201.04152, 2204.05327 (with L. Horer, P. Marconnet)

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Introduction

String theory backgrounds with **maximally symmetric spacetimes**: dS, Mink, AdS

Ubiquitous in string pheno.: cosmology, particle physics

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⟶ Instability of non-supersymmetric backgrounds:

- dS D. Andriot [arXiv:1806.10999], S. K. Garg et al [arXiv:1807.05193], H. Ooguri et al [arXiv:1810.05506], …
- Mink B. S. Acharya [arXiv:1906.06886], B. S. Acharya et al [arXiv:2010.02933]
- AdS H. Ooguri, C. Vafa [arXiv:1610.01533]

⟶ Scale separation F. F. Gautason et al [arXiv:1810.08518], D. Lust et al [arXiv:1906.05225], …
D. Andriot et al [arXiv:2006.01848]

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Classification of 10d type IIA/B supergravity solutions with dS_4, $Mink_4$, AdS_4

(candidates for classical string backgrounds)

⟶ identify general properties?

⟶ new, previously unexplored classes of solutions exhibiting new physics?

(Common) **ansatz** for solutions:

- 6d group manifold
- constant flux components
- smeared D_p/O_p sources

⟶ consistent truncation to a 4d gauged supergravity

⟶ solutions still with a variety of properties: (non)-susy, (un)stable, (non)-scale separated (see examples)

+ always include O_p (key)
+ solutions have a possibly non-vanishing tadpole (e.g. O_3 with D_7 or D_5 not included)

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⟶ classification

⟶ look for new solutions in unexplored classes, with *MaxSymSolSearch.nb* (*MSSS*)

⟶ study **properties** of solutions: existence (dS), stability (Mink), scale separation (AdS)…

Classification and (new) solutions

Classification: 3 steps:

- Pick some (space-filling) O_p wrapping some internal dimensions

Example: O_5 along 12, O_5 along 34

class s_{55} (or m_{55})

Set I	Sources	Space dimensions								
		4d			1	2	3	4	5	6
1	O_5	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$				
2	O_5	$\otimes$	$\otimes$	$\otimes$			$\otimes$	$\otimes$		

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- Apply O_p projection: get list of compatible fields

  Example:

$$F_1 : \quad F_{1\ 5}\,, \quad F_{1\ 6}\,,$$

$$F_3 : \quad F_{3\ 315}\,, \quad F_{3\ 316}\,, \quad F_{3\ 325}\,, \quad F_{3\ 326}\,, \quad F_{3\ 415}\,, \quad F_{3\ 416}\,, \quad F_{3\ 425}\,, \quad F_{3\ 426}\,,$$

$$F_5 : \quad F_{5\ 34125}\,, \quad F_{5\ 34126}\,,$$

$$H : \quad H_{125}\,, \quad H_{126}\,, \quad H_{345}\,, \quad H_{346}\,,$$

$$f^a{}_{bc} : \quad f^3{}_{15}\,,\ f^3{}_{16}\,,\ f^3{}_{25}\,,\ f^3{}_{26}\,,\ f^4{}_{15}\,,\ f^4{}_{16}\,,\ f^4{}_{25}\,,\ f^4{}_{26}\,,\ f^1{}_{53}\,,\ f^1{}_{63}\,,\ f^1{}_{54}\,,\ f^1{}_{64}\,,$$

$$f^2{}_{53}\,,\ f^2{}_{63}\,,\ f^2{}_{54}\,,\ f^2{}_{64}\,,\ f^5{}_{13}\,,\ f^5{}_{23}\,,\ f^5{}_{14}\,,\ f^5{}_{24}\,,\ f^6{}_{13}\,,\ f^6{}_{23}\,,\ f^6{}_{14}\,,\ f^6{}_{24}$$

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- Apply O_p projection: get list of compatible fields

Example:

$$\begin{aligned} F_1 &: \quad F_{1\ 5}\,, \quad F_{1\ 6}\,, \\ F_3 &: \quad F_{3\ 315}\,, \quad F_{3\ 316}\,, \quad F_{3\ 325}\,, \quad F_{3\ 326}\,, \quad F_{3\ 415}\,, \quad F_{3\ 416}\,, \quad F_{3\ 425}\,, \quad F_{3\ 426}\,, \\ F_5 &: \quad F_{5\ 34125}\,, \quad F_{5\ 34126}\,, \\ H &: \quad H_{125}\,, \quad H_{126}\,, \quad H_{345}\,, \quad H_{346}\,, \\ f^a{}_{bc} &: \quad f^3{}_{15}\,, f^3{}_{16}\,, f^3{}_{25}\,, f^3{}_{26}\,, f^4{}_{15}\,, f^4{}_{16}\,, f^4{}_{25}\,, f^4{}_{26}\,, f^1{}_{53}\,, f^1{}_{63}\,, f^1{}_{54}\,, f^1{}_{64}\,, \\ & \quad f^2{}_{53}\,, f^2{}_{63}\,, f^2{}_{54}\,, f^2{}_{64}\,, f^5{}_{13}\,, f^5{}_{23}\,, f^5{}_{14}\,, f^5{}_{24}\,, f^6{}_{13}\,, f^6{}_{23}\,, f^6{}_{14}\,, f^6{}_{24} \end{aligned}$$

- Determine non-zero components of sourced Bianchi identities $\longrightarrow$ read allowed D_p/O_p class:

Example: $\mathrm{d}F_3 - H \wedge F_1 = \sum_I \frac{T_{10}^I}{6}\, \mathrm{vol}_{\perp_I}$

$\sim f^a{}_{[bc} F_{3\, de]a} + H_{[bcd} F_{1\, e]}$ $\longrightarrow$ D_5 along 12, 34, 56 $\longrightarrow$ s_{55}

(D_7 along 2456, 2356, 1456, 1356) $\longrightarrow$ m_{55}

Solution class	Source directions	Field content	dS sol.	Mink. sol.	AdS sol.
s_3	(2.7)	(2.6)	×	[27]	
s_4	(2.10)	(2.9)		[28]	
s_5	(2.13)	(2.12)		[28]	
s_{55}	(2.15)	(2.14)	[9, 24], ✓	[29]	✓
s_{555}	(2.17)	(2.16)	×	✓	×
s_6	(2.20)	(2.19)		[28]	
s_{66}	(2.22)	(2.21)	✓	[29]	
s_{6666}	(2.24)	(2.23)	[25], ✓	[30]	[30–32]
s_7	(2.27)	(2.26)	×	[28]	
s_{77}	(2.29)	(2.28)	×		
m_4	(2.36)	(2.9)			
m_{46}	(2.33)	(2.32)	✓	✓	✓
m_{466}	(2.35)	(2.34)	×	✓	×
m_6	(2.30)	(2.19)			
m_{66}	(2.31)	(2.21)			
m_5	(2.37)	(2.12)			
m_{55}	(2.38)	(2.14)	✓		
m_{57}	(2.40)	(2.39)			
m_{5577}	(2.43)	(2.41)	[26], ✓		[32, 33]
m_7	(2.44)	(2.26)			
m_{77}	(2.45)	(2.28)			

Known solutions: [..]

New solutions: ✓

No-go: ×

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s_{55}	(2.15)	(2.14)	[9, 24], ✓	[29]	✓
s_{555}	(2.17)	(2.16)	×	✓	×
s_6	(2.20)	(2.19)		[28]	
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s_{77}	(2.29)	(2.28)	×		
m_4	(2.36)	(2.9)			
m_{46}	(2.33)	(2.32)	✓	✓	✓
m_{466}	(2.35)	(2.34)	×	✓	×
m_6	(2.30)	(2.19)			
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m_5	(2.37)	(2.12)			
m_{55}	(2.38)	(2.14)	✓		
m_{57}	(2.40)	(2.39)			
m_{5577}	(2.43)	(2.41)	[26], ✓		[32, 33]
m_7	(2.44)	(2.26)			
m_{77}	(2.45)	(2.28)			

Known solutions: [..]

New solutions: ✓

No-go: ×

4 main classes: s_{6666}
m_{5577}

s_{55}
m_{46}

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s_4	(2.10)	(2.9)		[28]	
s_5	(2.13)	(2.12)		[28]	
s_{55}	(2.15)	(2.14)	[9, 24], $\checkmark$	[29]	$\checkmark$
s_{555}	(2.17)	(2.16)	$\times$	$\checkmark$	$\times$
s_6	(2.20)	(2.19)		[28]	
s_{66}	(2.22)	(2.21)	$\checkmark$	[29]	
s_{6666}	(2.24)	(2.23)	[25], $\checkmark$	[30]	[30–32]
s_7	(2.27)	(2.26)	$\times$	[28]	
s_{77}	(2.29)	(2.28)	$\times$		
m_4	(2.36)	(2.9)			
m_{46}	(2.33)	(2.32)	$\checkmark$	$\checkmark$	$\checkmark$
m_{466}	(2.35)	(2.34)	$\times$	$\checkmark$	$\times$
m_6	(2.30)	(2.19)			
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m_{77}	(2.45)	(2.28)			

s_{6666}

Set I	Sources	Space dimensions								
		4d			1	2	3	4	5	6
1	$O_6, (D_6)$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$			
2	$O_6, (D_6)$	$\otimes$	$\otimes$	$\otimes$	$\otimes$			$\otimes$	$\otimes$	
3	$O_6, (D_6)$	$\otimes$	$\otimes$	$\otimes$		$\otimes$			$\otimes$	$\otimes$
4	$O_6, (D_6)$	$\otimes$	$\otimes$	$\otimes$			$\otimes$	$\otimes$		$\otimes$

- dS C. Caviezel et al [arXiv:0812.3551], U. H. Danielsson et al [arXiv:1103.4858], …
  + new solutions
- Mink P. G. Camara et al [hep-th/0506066], F. Marchesano et al [arXiv:1908.11386]
- AdS P. G. Camara et al [hep-th/0506066], O. DeWolfe et al[hep-th/0505160], C. Caviezel et al [arXiv:0806.3458], ...

Solution class	Source directions	Field content	dS sol.	Mink. sol.	AdS sol.
s_3	(2.7)	(2.6)	$\times$	[27]	
s_4	(2.10)	(2.9)		[28]	
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s_{6666}	(2.24)	(2.23)	[25], $\checkmark$	[30]	[30–32]
s_7	(2.27)	(2.26)	$\times$	[28]	
s_{77}	(2.29)	(2.28)	$\times$		
m_4	(2.36)	(2.9)			
m_{46}	(2.33)	(2.32)	$\checkmark$	$\checkmark$	$\checkmark$
m_{466}	(2.35)	(2.34)	$\times$	$\checkmark$	$\times$
m_6	(2.30)	(2.19)			
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m_7	(2.44)	(2.26)			
m_{77}	(2.45)	(2.28)			

m_{5577}

Set I	Sources	Space dimensions								
		4d			1	2	3	4	5	6
1	$O_5, (D_5)$	$\otimes$	$\otimes$	$\otimes$	$\otimes$	$\otimes$				
2	$O_5, (D_5)$	$\otimes$	$\otimes$	$\otimes$			$\otimes$	$\otimes$		
3	$O_7, (D_7)$	$\otimes$	$\otimes$	$\otimes$		$\otimes$		$\otimes$	$\otimes$	$\otimes$
4	$O_7, (D_7)$	$\otimes$	$\otimes$	$\otimes$	$\otimes$		$\otimes$		$\otimes$	$\otimes$

T-dual D_p/O_p to s_{6666} (but not nec. for fields)

- dS — C. Caviezel et al [arXiv:0912.3287]

  + new solutions

- AdS — C. Caviezel et al [arXiv:0806.3458], M. Petrini et al [arXiv:1308.1265], ...

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s_{55}

Set I	Sources	Space dimensions						
		4d			1	2	3	4	5	6
1	$O_5, (D_5)$	⊗	⊗	⊗	⊗	⊗				
2	$O_5, (D_5)$	⊗	⊗	⊗			⊗	⊗		
3	(D_5)	⊗	⊗	⊗					⊗	⊗

- dS — D. Andriot et al [arXiv:2005.12930], D. Andriot [arXiv:2101.06251]

  \+ new solutions

- Mink — M. Grana et al [hep-th/0609124], D. Andriot et al [arXiv:2005.12930]

- AdS: new solutions

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m_{46}

Set I	Sources	Space dimensions								
		4d			1	2	3	4	5	6
1	$O_4, (D_4)$	⊗	⊗	⊗				⊗		
2	$O_6, (D_6)$	⊗	⊗	⊗	⊗	⊗	⊗			
3	(D_6)	⊗	⊗	⊗	⊗				⊗	⊗
...	(D_6)	⊗	⊗	⊗	...					

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m_{46}	(2.33)	(2.32)	✓	✓	✓
m_{466}	(2.35)	(2.34)	×	✓	×
m_6	(2.30)	(2.19)			
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2 peculiar classes: s_{555} and m_{466}

We prove no-gos for dS and AdS

⟶ only Mink. solutions!

⟶ we find examples.

De Sitter solutions and $\mathcal{N} = 1$

All de Sitter solutions only found with at least 3 (intersecting) sets of D_p/O_p.

Examples: s_{6666} : O_6 along 123, 145, 256, (346)

s_{55} : O_5 along 12, 34, D_5 along 56

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Previously: **Conjecture 1**: *no de Sitter solution with 1 set (i.e. parallel D_p/O_p).*

D. Andriot [arXiv:1902.10093]

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Here: **Conjecture 4**: *no de Sitter solution with 2 (intersecting) sets of D_p/O_p.*

+ T-duality argument: classes with 2 sets ``T-dual'' to a class with a no-go

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Implication: *A 4d effective theory of a classical string compactification, with a de Sitter critical point, is at most $\mathcal{N}=1$ supersymmetric.*

in agreement with gauged supergravities de Sitter solutions

(see also N. Cribiori et al [arXiv:2011.06597], G. Dall'Agata et al [arXiv:2108.04254])

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(see also N. Cribiori et al [arXiv:2011.06597], G. Dall'Agata et al [arXiv:2108.04254])

Great news for phenomenology! $\mathcal{N} \leq 1$ better for particle physics (chirality).
Here a common stringy framework for (viable) cosmology and particle physics *naturally* appears.

Solutions stability

We study the **stability** of the solutions with a 4d effective action:

$$\mathcal{S} = \int \mathrm{d}^4x \sqrt{|g_4|} \left(\frac{M_p^2}{2} \mathcal{R}_4 - \frac{1}{2} g_{ij} \partial_\mu \phi^i \partial^\mu \phi^j - V \right)$$

Restricted set of fields (but enough for our purposes): $(\rho,\, \tau,\, \sigma_I)$

6d volume   4d dilaton   ~ volume of cycle wrapped by set *I*

Determination of g_{ij}, V + spectrum fully automatized in *`MaxSymSolSpec.nb`* (*`MSSSp`*)

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Results:

- **Mink**.: most interesting!

- **dS**: always tachyonic, as in proposal U. H. Danielsson et al [arXiv:1212.5178]
$\eta_V \sim -1$ as in refined dS conjecture, with few (interesting) exceptions
Requires more dedicated solution searches D. Andriot [arXiv:2101.06251]

- **AdS**: few (non-susy?) solutions are ``perturbatively stable'' ⟶ to be investigated
H. Ooguri et al [arXiv:1610.01533]

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$$\mathcal{R}_4 = 0\,, \quad \mathcal{R}_6 = -1.0206\,,$$
$$\text{masses}^2 = (3.6377, 1.5406, 0.33559, 0)\,.$$

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⟶ systematic massless mode in Mink solutions?

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$\longrightarrow$ systematic massless mode in Mink solutions?

Many examples in the literature, starting with CY + no-scale potential

Proof of systematic flat direction in IIA D_6/O_6 $\mathcal{N}=1$ Mink solutions

A. Micu et al [hep-th/0701173], M. Ihl et al [arXiv:0705.3410]

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2 important (new) points in claim:

- independent of $\mathcal{N}$ susy of theory or solution
- specification of field sector ⟶ useful for proof
  ⟶ relation to dS tachyon?

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4d version, with potential V from 10d supergravity compactification:

If there exists a Mink critical point, $M_p\, \nabla V = V = 0$ *, then the mass matrix* $\nabla \partial V$ *admits a vanishing eigenvalue.*

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Strong version:

Such a critical point admits no tachyon:

$$0 = \min\ \nabla\partial V = \frac{|\nabla V|}{M_p} = \frac{V}{{M_p}^2}$$

The inequalities of all refined de Sitter conjectures are saturated!

In a quantum gravity effective theory, any correction beyond (10d) supergravity could alter massless property…
Still interesting for phenomenology!

Scale separation for AdS

Scale separation in AdS solutions: only with compact manifold being **Ricci flat** or a **nilmanifold**?

⟶ the case for solutions in s_{6666} and m_{5577}

(see also N. Cribiori et al [arXiv:2107.00019])

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Arguments in favor of this: - group manifolds, not nilmanifold, can have curvature scales > KK scale

⟶ no scale separation with such solution

D. Andriot [arXiv:1806.10999]

- Ricci flat and nilmanifolds: gap between curvature $\mathcal{R}_6$ and eigenmode Laplacian Δ_6

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Can we find AdS solutions in new classes s_{55} and m_{46} on a Ricci flat or nilmanifold?

⟶ no ! Prove no-gos about it ⟶ probably no scale-separation in our new solutions

Related to having only D_p along some internal dimensions…

⟶ Is s_{6666} only class for (classical) scale sep.?

Summary

- **Classification** of 10d type IIA/B supergravity solutions with dS_4, $Mink_4$, AdS_4
- Found **new solutions** in previously unexplored classes (e.g. m_{46} with O_4, O_6, D_6)
- Developed **tools**: *MaxSymSolSearch.nb*

  MaxSymSolSpec.nb

  AlgId.nb, *AlgIso.nb* (algebra/group identification)

- De Sitter: in 4d theory with $\mathcal{N} \leq 1$ (**Conjecture 4**)
- Minkowski: always a 4d massless scalar, among (ρ, τ, σ_I) (**Massless Minkowski Conjecture**)
- Scale separated AdS: only on Ricci flat or nilmanifolds?

  ⟶ scale separated classical AdS only in s_{6666} ?

Thank you for your attention!