Accelerated expansion and scalar potentials from string theory

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arXiv:2201.04152, 2204.05327 (with L. Horer, P. Marconnet)
2208.14462 (with L. Horer)
2209.08015 (with P. Marconnet, M. Rajaguru, T. Wrase)
2212.04517 (with L. Horer, G. Tringas)

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Introduction

Dark energy: energy responsible for accelerated expansion observed: today

early universe (inflation)

Today: well-described by cosmological constant $\Lambda > 0$

Inflation: scalar potential $V > 0$, very flat $\frac{|V'|}{V} \ll 1$, single scalar field slowly rolling-down Planck '18

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Both described by 4d theory: $\int \mathrm{d}^4x \sqrt{|g_4|} \left(\frac{M_p^2}{2} \mathcal{R}_4 - \frac{1}{2} g_{ij} \partial_\mu \varphi^i \partial^\mu \varphi^j - V \right)$

minimally coupled scalar fields φ^i

(most of the talk: $M_p = 1, \varphi^i \to \varphi$)

$\hookrightarrow$ Reproduce dark energy as solutions

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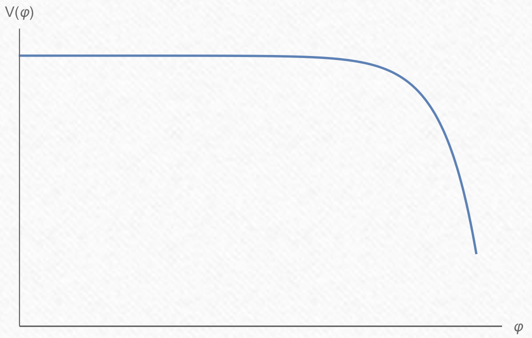
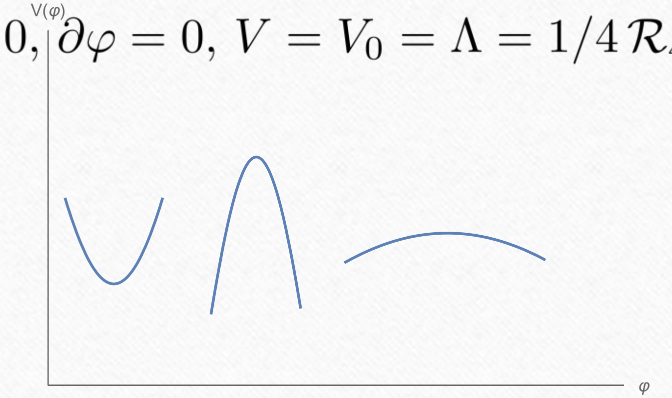
$\hookrightarrow$ Reproduce dark energy as solutions:

Slow-roll single-field inflation: plateau V:



Λ: de Sitter solution: critical point of V:

$$\partial_\varphi V = 0, \partial\varphi = 0, V = V_0 = \Lambda = 1/4\, \mathcal{R}_4 > 0$$



Dark energy from string theory?

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+ V > 0 + right shape of V ?

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+ allow to distinguish among various V that are ok with observations (e.g. inflation)

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Answers:

Yes, natural from string compactification
V is due to extra dimensions and physical content

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(in a controlled way)

Very challenging!

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- **Potential slopes**

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⟶ Massless Minkowski Conjecture: always a massless mode

⟶ Mass bound in (susy) AdS: always a mode $m^2 l^2 \leq -2$

I. Classical dS solutions

Classical de Sitter string backgrounds: why classical? Andriot ’19

⟶ tree-level, low energy: ``easy” to control: $g_s \ll 1,\ r \gg l_s,\ \ldots$

KKLT, LVS: include (non)-perturbative contributions Kachru, Kallosh, Linde, Trivedi ’03, Conlon, Quevedo ’05

⟶ debate on validity of approximations/regimes/control

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$dS_4 \times$ 6d group manifold

obtained in 10d type IIA supergravity, with F_0 , with 4 sets of intersecting O_6/D_6 ($\mathcal{N}=1$ in 4d)

Why group manifold? Show that require $\mathcal{R}_6 < 0$

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Why group manifold? Show that require $\mathcal{R}_6 < 0$

First difficulty: tough to find dS solutions! Require 6d curvature, fluxes, O_p/D_p

⟶ many no-go theorems: if $\mathcal{R}_6 \geq 0$, if $F_k = 0$, etc., then no dS.

⟶ progress in identifying the required ingredients/where to find dS solutions ⟶ new/all solutions

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

Andriot, Horer, Marconnet ’22

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Ansatz: 6d group manifold, smeared O_p/D_p, etc.
+ always include O_p (key)

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]
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Known solutions: [..]

New solutions: ✓

No-go: ×

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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	$O_6, (D_6)$	$\otimes$	$\otimes$	$\otimes$			$\otimes$	$\otimes$		$\otimes$

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- dS Caviezel, Koerber, Kors, Lüst, Wrase, Zagermann '08
  Danielsson, Haque, Koerber, Shiu, Van Riet, Wrase '11
+ new solutions

- Mink Camara, Font, Ibanez '05
  Marchesano, Quirant '19

- AdS Camara, Font, Ibanez '05
  DeWolfe, Giryavets, Kachru, Taylor '05
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s_{55} ⟶ **new** dS solutions with $2\,O_5,\ 1\,D_5$

s_{6666} ⟶ **old** (< 2020) dS solutions with $4\,O_6$

m_{46} ⟶ **new** dS solutions with $1\,O_4,\ 1\,O_6,\ 1\,D_6$

m_{5577} ⟶ **new** dS solutions with $2\,O_5,\ 2\,O_7$

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

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

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

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with a de Sitter critical point, is at most $\mathcal{N}=1$ *supersymmetric*.

in agreement with gauged supergravities de Sitter solutions

(see also Cribiori, Dall'Agata, Farakos '20, Dall'Agata, Emelin, Farakos, Morittu '21)

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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.

+ important role for dS_d , $d > 4$ ($\longrightarrow$ no solution?)

Do solutions with dS_d, $3 \leq d \leq 10$, exist (in 10d type II supergravities)? Andriot, Horer ’22

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⟶ extend no-go theorems to *d*-dim., against dS_d

Results: ⟶ **No dS_d solution for** $d \geq 8$ Van Riet '11

⟶ **No dS_d solution for** $d = 7$ **in IIB**

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\+ supersymmetry-preserving O_p/D_p

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⟶ **very constrained/unlikely dS_d solution for** $d = 6, 5$

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⟶ **very constrained/unlikely dS_d solution for $d = 6, 5$**

Only O_p/D_p configuration with 1 or 2 sets: e.g.

⟶ conjectures 1 and 4: no dS_d !

(susy in $d > 4$ requires > 4 supercharges)

Sources	$d = 6$ spacetime	1	2	3	4
O_6, (D_6)	$\otimes$	$\otimes$			
(O_8, D_8)	$\otimes$		$\otimes$	$\otimes$	$\otimes$

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⟶ **very constrained/unlikely dS_d solution for** $d = 6, 5$

Only O_p/D_p configuration with 1 or 2 sets: e.g.

⟶ conjectures 1 and 4: no dS_d !

(susy in $d > 4$ requires > 4 supercharges)

Sources	$d = 6$ spacetime	1	2	3	4
O_6, (D_6)	$\otimes$	$\otimes$			
(O_8, D_8)	$\otimes$		$\otimes$	$\otimes$	$\otimes$

Summary: we know where to find dS solutions:

$d = 4$, need 3 or more sets of intersecting O_p/D_p ($\mathcal{N} = 1$ in 4d), fluxes, 6d curvature

Second difficulty: (in)stability

All dS solutions found are perturbatively unstable:
at least one tachyonic field/maximum in 4d V

$\longrightarrow \eta_V < 0$ with $\eta_V = M_p^2 \, \frac{\mathrm{Min}\left(g^{ik} \nabla_k \partial_j V\right)}{V}$

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Key: no parametric control on classicality for dS $\longrightarrow$ solutions: isolated points in field space (bulk)
$\longrightarrow$ Numerically very challenging!

Side result 1:
Massless Minkowski Conjecture

If we allow for many fluxes, 6d curvature, O_p/D_p ,
can all fields be stabilized for a Minkowski solution?

Classification of Minkowski solutions

$\longrightarrow$ diversity of solutions w.r.t. fluxes, 6d manifold, O_p/D_p

Spectrum computed thanks to V and mass matrix $(g^{ik}\nabla_k \partial_j V)$
first for $(\rho,\, \tau,\, \sigma_I)$, then for full consistent truncation

Andriot, Horer, Marconnet '22, Andriot, Marconnet, Rajaguru, Wrase '22

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$$\mathcal{R}_4 = 0\,, \quad \mathcal{R}_6 = -1.0206\,,$$
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(reminiscent of the Tadpole Conjecture Bena, Blaback, Grana, Lust '20)

Beyond supergravity compactif.? Becker, Gonzalo, Walcher, Wrase '22

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

II. Potential slopes

We consider as string EFT: $\int \mathrm{d}^4x \sqrt{|g_4|} \left(\frac{M_p^2}{2} \mathcal{R}_4 - \frac{1}{2} g_{ij} \partial_\mu \varphi^i \partial^\mu \varphi^j - V \right)$

If no de Sitter critical point: $V > 0,\ V' \neq 0,\ \frac{|V'|}{V} > 0$

Cosmology with potential slopes and rolling fields: inflation, quintessence

Can we get $\frac{|V'|}{V} \ll 1$: quasi de Sitter / almost flat V ? $\longrightarrow$ Very unlikely!

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Discussions, refinements: this cannot be true everywhere in field space

⟶ only true in the **asymptotics** of field space: $\varphi \to \infty$

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$$\varphi \to \infty,\ \frac{|V'|}{V} \geq \sqrt{\frac{2}{3}} \approx 0.82$$

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$$V \sim V_0\, e^{-\lambda \varphi}\,, \quad |V'|/V = \lambda$$

Bulk of field space:
dS solution or
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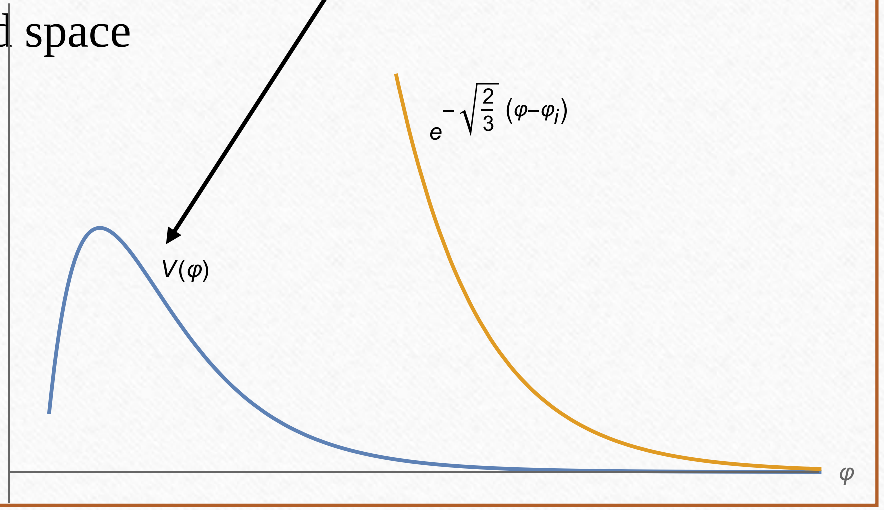

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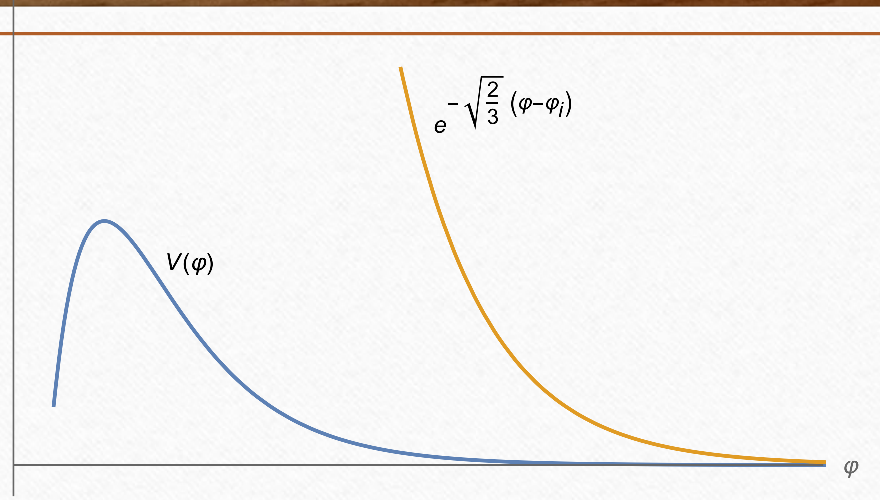

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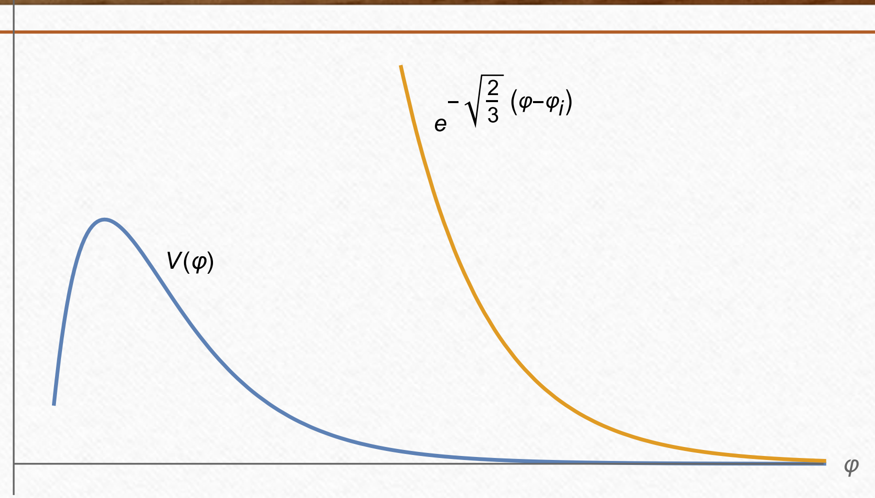

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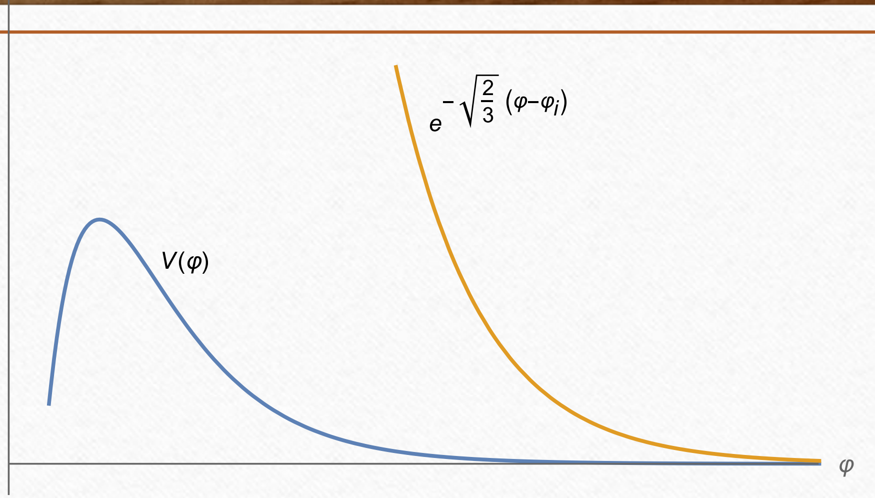

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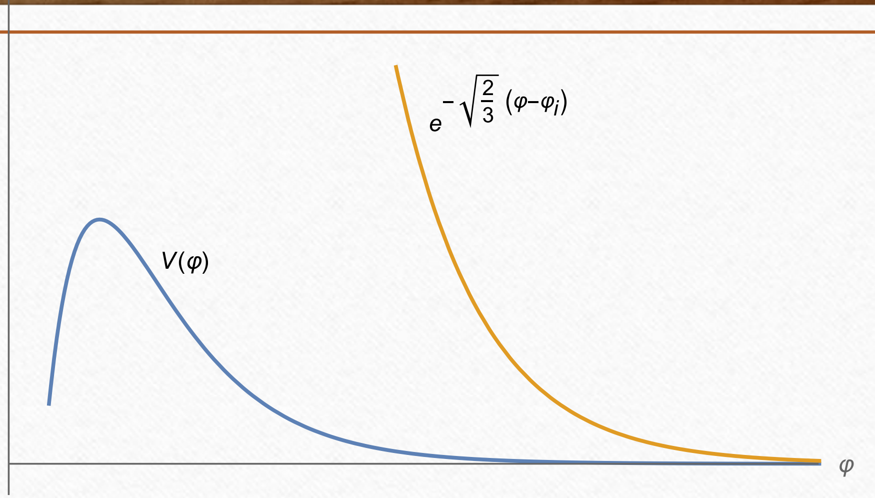

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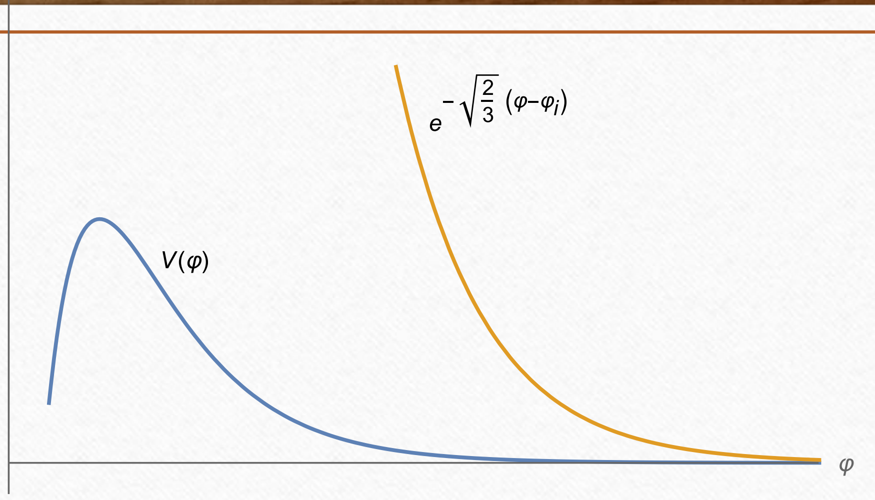

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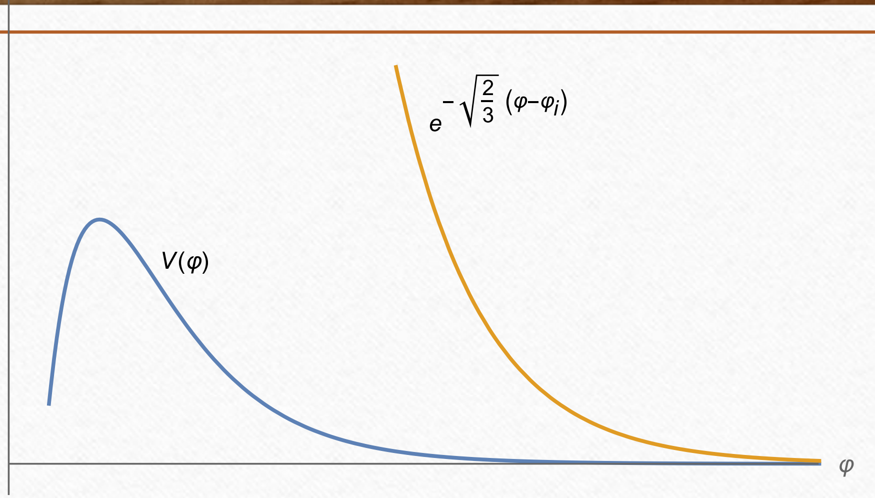

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Many supergravity compactification potentials obey TCC asymptotic bound

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⟶ Cosmology in the asymptotics of field space?

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(Possible exception: $\frac{|V'|}{V} \geq \sqrt{\frac{2}{7}} \approx 0.53$ Calderon-Infante, Ruiz, Valenzuela '22)

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Asymptotic accelerated expansion: bound: $\lambda \leq \sqrt{2}$ Halliwell '86, Copeland, Liddle, Wands '97

$\longrightarrow$ Tight!

$\longrightarrow$ More examples or more exotic scenarios…

Negative scalar potentials from string theory: $V < 0$: characterisation?

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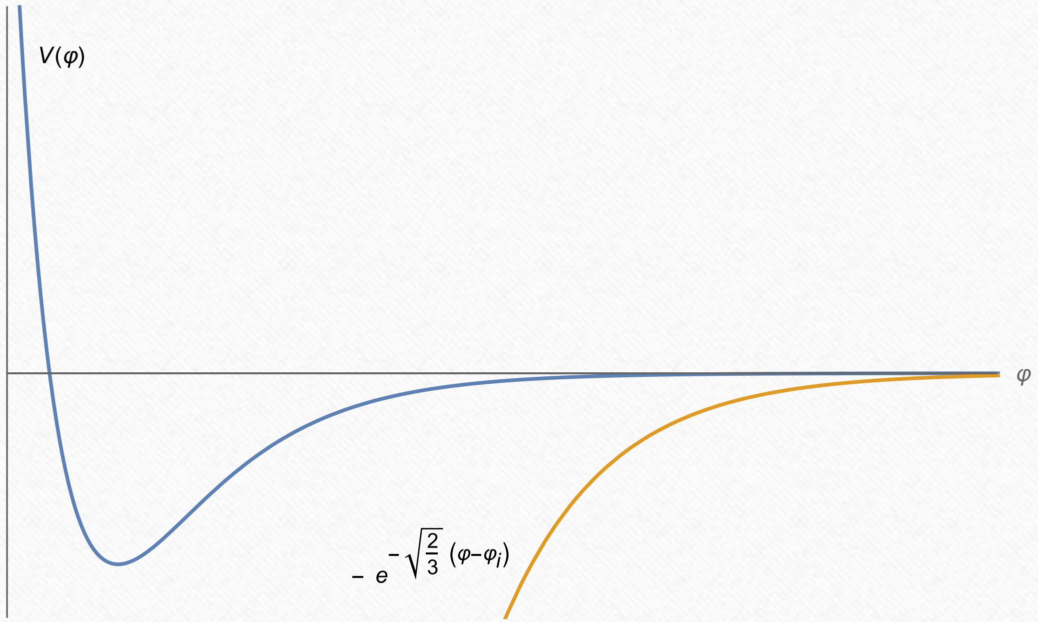
Proposed an Anti- Trans-Planckian Censorship Conjecture (**ATCC**) Andriot, Horer, Tringas '22

Bottom-up argument on contracting universe, Trans-Planckian modes, validity of EFT, etc.

⟶ bound $(V < 0, V' > 0):\quad d \geq 4:\ \varphi \to \infty,\ -\frac{V'}{V} \geq \frac{2}{\sqrt{(d-1)(d-2)}}$



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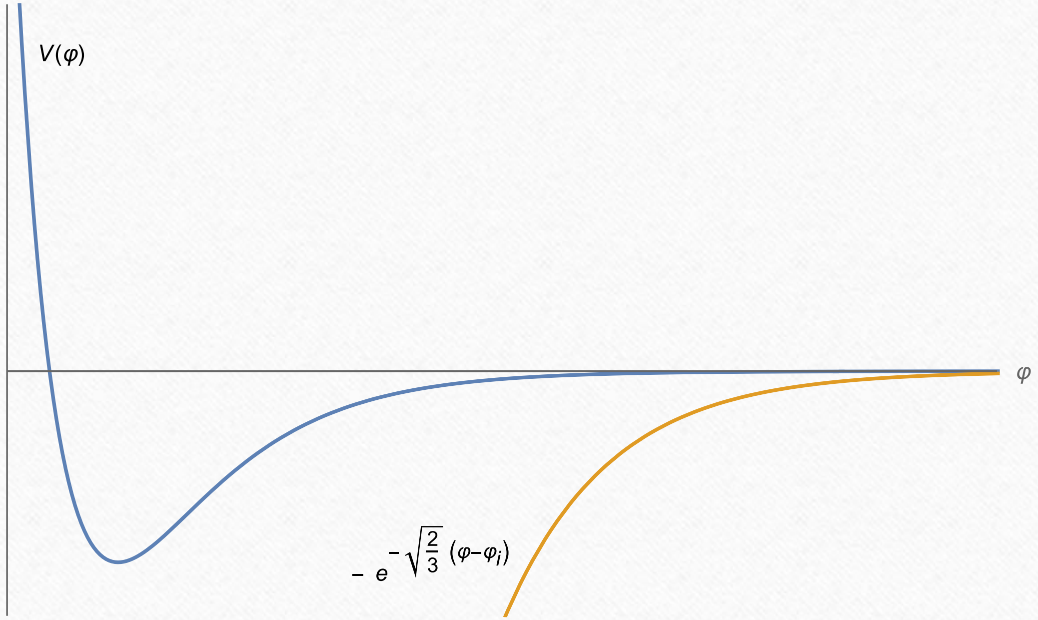
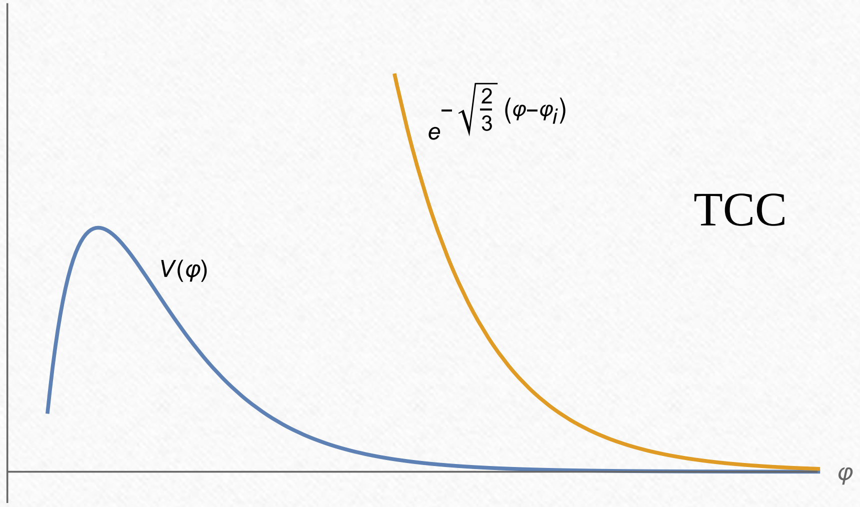
Well-tested in compactification examples:

- $V(\rho, \tau, \sigma)$,
- AdS no-go theorems,
- DGKT 4d



Side result 2:
AdS mass bound



$$-\frac{V'}{V} \geq c_0$$
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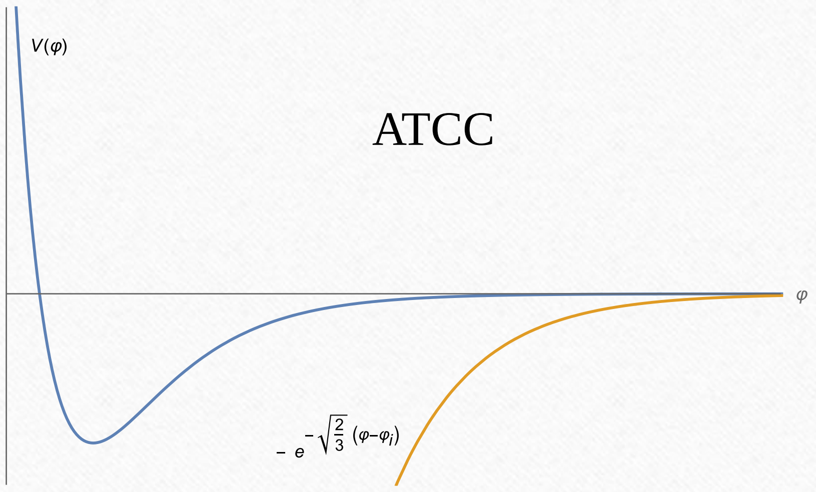
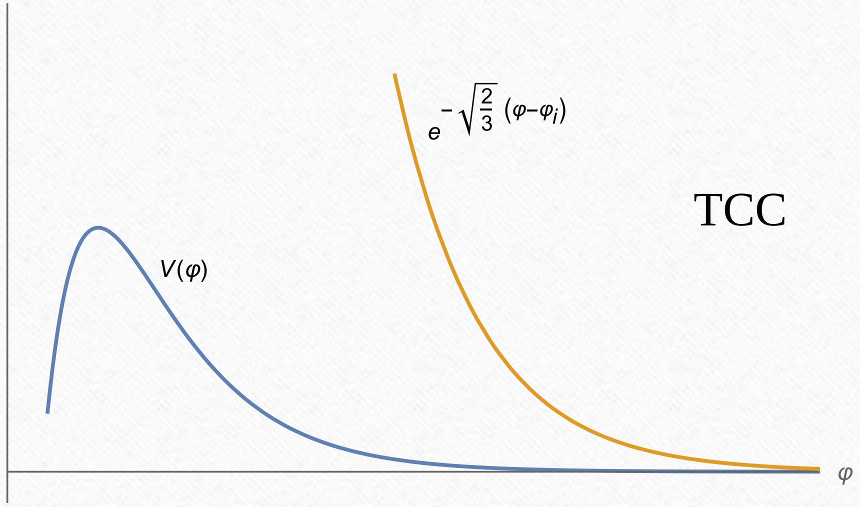


$\longrightarrow$ New asymptotic bound on V'': $\frac{V''}{V} \geq c_0^2 \qquad (d \geq 4)$ Andriot, Horer, Tringas ’22



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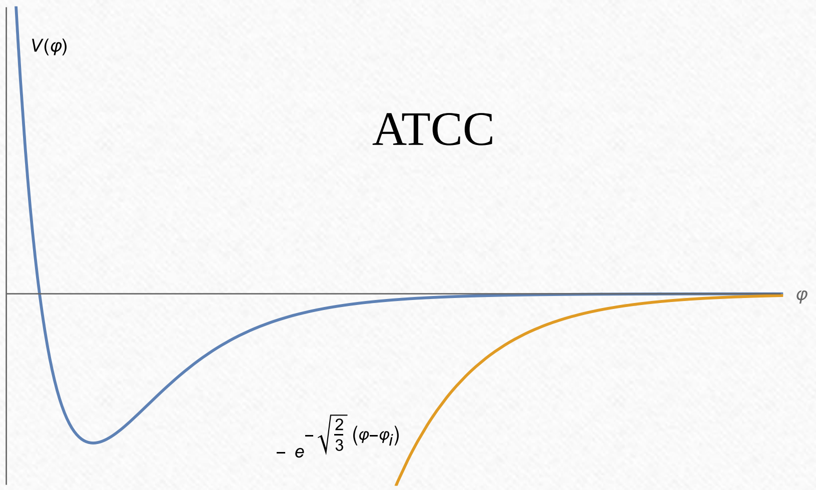

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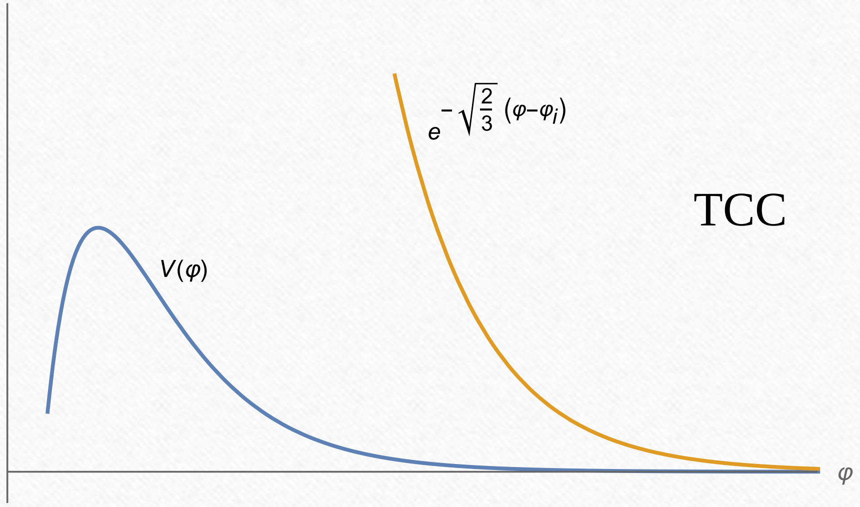
Extrapolate it to AdS solution (radius l): $m^2 = V'' \leq \frac{4}{(d-1)(d-2)} V = -\frac{2}{l^2}$

⟶ **Mass bound**: in AdS$_d$, $(d \geq 4)$, one scalar with mass: $m^2 l^2 \lesssim -2$



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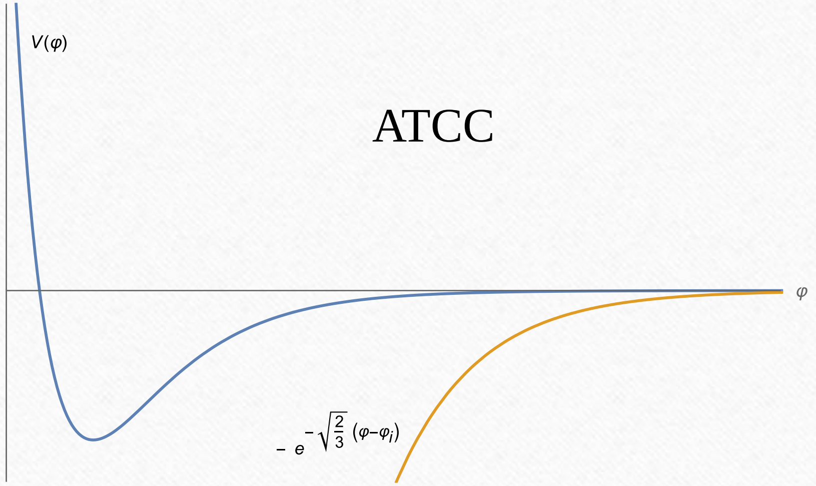

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BF bound: $d = 4: \; m^2 l^2 \geq -2.25$
$d = 5: \; m^2 l^2 \geq -4$ ⟶ Perturbatively unstable AdS ✓ with our bound
$d = 6: \; m^2 l^2 \geq -6.25$
$d = 7: \; m^2 l^2 \geq -9$

AdS_d	$\mathcal{N}$	Specification	Spectrum reference	Scalar lowest $m^2 l^2$
$d=4$		AdS_4, M-th., with:		
	8	$SO(8)$	[39, Tab. 4]	$-9/4$
	2	$SU(3)\times U(1)$		-2.222
	1	G_2		-2.242
	1	$U(1)\times U(1)$	[40]	-2.25
	1	$SO(3)$		-2.245
		$AdS_4\times S^6$, IIA, with:		
	1	G_2		-2.24158
	2	$SU(3)\times U(1)$		$-20/9$
	3	$SO(3)\times SO(3)$	[41, App. B]	$-9/4$
	1	$SU(3)$	[42, App. A]	$-20/9$
	1	$U(1)$		-2.23969
	1	$\varnothing$		-2.24943
	1	$U(1)$		-2.24908
	1	DGKT, IIA	[29, 43]	>0
	1	DGKT-like Branch A1-S1, IIA	[44, Tab. 2]	-2
	1	KKLT, IIB	[27, 45]	≥ 0
	1	LVS, IIB	[46, Sec. 2]	≥ 0
		S-fold, IIB, with:		
	1	$U(1)^2$	[47]	-2
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$d=5$		$AdS_5\times S^5$, IIB, with:		
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	2	$SU(2)\times U(1)$	[49, Tab. D.4]	-4
$d=7$	1	$AdS_7\times S^3$, IIA	[50]	-8

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Here the same with ATCC: drop the debate on scale separation

Lust, Palti, Vafa ’19

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Perturbatively stable non-susy AdS_d : most examples: $m^2 l^2 \leq -1$
Spectrum less preserved when moving in field space?
+ non-perturbative instabilities…

Summary

Can we obtain (observed) **dark energy** from string theory?

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

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- **Potential slopes and rolling fields**

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Thank you for your attention!

Backup slides

Further solution classes

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]	
s_5	(2.13)	(2.12)		[28]	
s_{55}	(2.15)	(2.14)	[9, 24], ✓	[29]	✓
s_{555}	(2.17)	(2.16)	$\times$	✓	$\times$
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)	$\times$	[28]	
s_{77}	(2.29)	(2.28)	$\times$		
m_4	(2.36)	(2.9)			
m_{46}	(2.33)	(2.32)	✓	✓	✓
m_{466}	(2.35)	(2.34)	$\times$	✓	$\times$
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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)			

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 — Caviezel, Wrase, Zagermann ’09

  + new solutions

- AdS

  Caviezel, Koerber, Kors, Lüst, Tsimpis, Zagermann ’08

  Petrini, Solard, Van Riet ’13

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s_3	(2.7)	(2.6)	×	[27]	
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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 — Andriot, Marconnet, Wrase ’20; Andriot ’21

  + new solutions

- Mink — Graña, Minasian, Petrini, Tomasiello ’06; Andriot, Marconnet, Wrase ’20

- AdS: new solutions

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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)			

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)	⊗	⊗	⊗	...					

T-dual D_p/O_p to s_{55} (but not nec. for fields)

- dS: new solutions
- Mink: new solutions
- AdS: new solutions

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]	
s_5	(2.13)	(2.12)		[28]	
s_{55}	(2.15)	(2.14)	[9, 24], ✓	[29]	✓
s_{555}	(2.17)	(2.16)	$\times$	✓	$\times$
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)	$\times$	[28]	
s_{77}	(2.29)	(2.28)	$\times$		
m_4	(2.36)	(2.9)			
m_{46}	(2.33)	(2.32)	✓	✓	✓
m_{466}	(2.35)	(2.34)	$\times$	✓	$\times$
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)			

2 peculiar classes: s_{555} and m_{466}

We prove no-gos for dS and AdS

$\longrightarrow$ only Mink. solutions!

$\longrightarrow$ we find examples.

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 Cribiori, Junghans, Van Hemelryck, Van Riet, Wrase ’21)

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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

Andriot ’18

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

Andriot, Tsimpis ’18
Andriot ’19

⟶ circumvent constraints on scale separation

Gautason, Schillo, Van Riet, Williams ’15

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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.?

No-go theorem and TCC

No-go: compactification with O_p/D_p, with $p = 7, 8, 9$, or $p = 4, 5, 6$ with $F_{6-p} = 0$

$$\frac{2(p-3)}{d}\mathcal{R}_d = -|H|^2 + (4-p)|H_7|^2 + \frac{1}{2}g_s^2 \sum_{q=0}^{7}(8-p-q)|F_q|^2 \ \leq 0$$

No-go: compactification with O_p/D_p, with $p=7,8,9$, or $p=4,5,6$ with $F_{6-p}=0$

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Reproduce it in *d*-dim. effective theory with $V(\rho,\tau)$

$$\frac{2}{M_p^2}\left(\frac{2(p-3)}{d-2}V - \frac{d+4-2p}{2(d-2)}\tau\partial_\tau V + \rho\partial_\rho V\right)$$

$$= -\tau^{-2}\rho^{-3}|H|^2 + (4-p)\tau^{2-2d}\rho^{3-d}|H_7|^2 + \tau^{-d}\frac{1}{2}g_s^2\sum_{q=0}^{10-d}\rho^{\frac{10-d-2q}{2}}\,(8-p-q)\,|F_q|^2 \ \leq 0$$

Valid at critical point: $\partial_\varphi V=0,\ \rho=\tau=1$, but also beyond

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Valid at critical point: $\partial_\varphi V = 0,\ \rho = \tau = 1$, but also beyond

⟶ swampland format: $M_p \frac{|\nabla V|}{V} \geq \frac{2(p-3)}{\sqrt{(d-2)(5d-1-4p-pd+p^2)}}$

No-go: compactification with O_p/D_p, with $p = 7, 8, 9$, or $p = 4, 5, 6$ with $F_{6-p} = 0$

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⟶ obey and saturate the **TCC bound** on c

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Valid at critical point: $\partial_\varphi V = 0,\ \rho=\tau=1$, but also beyond

⟶ swampland format: $M_p\frac{|\nabla V|}{V} \geq \frac{2(p-3)}{\sqrt{(d-2)(5d-1-4p-pd+p^2)}} \geq \frac{2}{\sqrt{(d-1)(d-2)}} \quad (p=4)$

⟶ obey and saturate the **TCC bound** on c

All other supergravity no-go theorems where tested with $d\geq 4$: **true!!**

$(d=4)$ Andriot, Cribiori, Erkinger ’20