# Do classical de Sitter string backgrounds exist?

**David ANDRIOT**

ITP, TU Wien, Austria

Based on arXiv:1902.10093
arXiv:2004.00030 (with N. Cribiori, D. Erkinger)
arXiv:2005.12930, 2006.01848 (with P. Marconnet, T. Wrase)

13/10/2020
Seminar Series on String Phenomenology

# Introduction

**De Sitter solutions**: 4d de Sitter space-time, $\mathcal{R}_4 = 4\,\Lambda > 0$.

# Introduction

**De Sitter solutions**: 4d de Sitter space-time, $\mathcal{R}_4 = 4\,\Lambda > 0$.
(Quasi) de Sitter solutions in cosmological models, ✓ observ.
Appear in periods of accelerated expansion, where
dark energy: (approx.) $\Lambda$
Late universe $\Lambda$CDM, early univ. (slow roll single field) inflation

# Introduction

**De Sitter solutions**: 4d de Sitter space-time, $\mathcal{R}_4 = 4\,\Lambda > 0$.
(Quasi) de Sitter solutions in cosmological models, ✓ observ.
Appear in periods of accelerated expansion, where dark energy: (approx.) $\Lambda$
Late universe $\Lambda$CDM, early univ. (slow roll single field) inflation

$\hookrightarrow$ de Sitter solutions in fundamental theory/quantum gravity?
In string theory: difficult to get well-controlled de Sitter solutions

U. H. Danielsson, T. Van Riet [arXiv:1804.01120]

# Introduction

**De Sitter solutions**: 4d de Sitter space-time, $\mathcal{R}_4 = 4\,\Lambda > 0$.
(Quasi) de Sitter solutions in cosmological models, ✓ observ.
Appear in periods of accelerated expansion, where
dark energy: (approx.) $\Lambda$
Late universe $\Lambda$CDM, early univ. (slow roll single field) inflation

$\hookrightarrow$ de Sitter solutions in fundamental theory/quantum gravity?
In string theory: difficult to get well-controlled de Sitter solutions

U. H. Danielsson, T. Van Riet [arXiv:1804.01120]

Various approaches, perturbative or not

S. Kachru, R. Kallosh, A. D. Linde, S. P. Trivedi [hep-th/0301240],

V. Balasubramanian, P. Berglund, J. P. Conlon, F. Quevedo [hep-th/0502058]

Here: focus on classical regime,
i.e. **classical de Sitter string backgrounds**.

D. A. [arXiv:1902.10093]

## Classical de Sitter string backgrounds

Motivation: “simple” well-defined framework, good chances to control approximations.

## Classical de Sitter string backgrounds

Motivation: "simple" well-defined framework, good chances to control approximations.

In practice: 10d = 4d de Sitter × 6d compact space $\mathcal{M}$
+ fluxes + $D_p$-branes, orientifold $O_p$-planes
10d description ($\sim$ type II supergravity) or 4d effective description with a scalar potential $V$
$\Rightarrow$ (classical) de Sitter solutions? **Well-posed question**.

## Classical de Sitter string backgrounds

Motivation: “simple” well-defined framework, good chances to control approximations.

In practice: 10d = 4d de Sitter $\times$ 6d compact space $\mathcal{M}$
+ fluxes + $D_p$-branes, orientifold $O_p$-planes
10d description ($\sim$ type II supergravity) or 4d effective description with a scalar potential $V$
$\Rightarrow$ (classical) de Sitter solutions? **Well-posed question**.

Cost to simplicity: not many ingredients at hand,
very constrained framework, many no-go theorems.
$\rightarrow$ very difficult to find such solutions, none is known up-to-date, but not excluded

## Classical de Sitter string backgrounds

Motivation: "simple" well-defined framework, good chances to control approximations.

In practice: 10d = 4d de Sitter $\times$ 6d compact space $\mathcal{M}$
+ fluxes + $D_p$-branes, orientifold $O_p$-planes
10d description ($\sim$ type II supergravity) or 4d effective description with a scalar potential $V$
$\Rightarrow$ (classical) de Sitter solutions? **Well-posed question**.

Cost to simplicity: not many ingredients at hand,
very constrained framework, many no-go theorems.
$\rightarrow$ very difficult to find such solutions, none is known up-to-date, but not excluded

**Do classical de Sitter string backgrounds exist?**

Go through attempts to find some, or to constrain more.

Conjectured answer: **no**

**Swampland program**: characterizing what can be obtained from string theory

E. Palti [arXiv:1903.06239]

T. D. Brennan, F. Carta, C. Vafa [arXiv:1711.00864]

$\hookrightarrow$ no de Sitter solution, in asymptotic regime, e.g. classical...

Conjectured answer: **no**

**Swampland program**: characterizing what can be obtained from string theory

E. Palti [arXiv:1903.06239]

T. D. Brennan, F. Carta, C. Vafa [arXiv:1711.00864]

$\hookrightarrow$ no de Sitter solution, in asymptotic regime, e.g. classical...

Can one trust these swampland de Sitter conjectures? $\rightarrow$ Test them (accurately)! Comparison to no-go theorems

Conjectured answer: **no**
**Swampland program**: characterizing what can be obtained from string theory

E. Palti [arXiv:1903.06239]

T. D. Brennan, F. Carta, C. Vafa [arXiv:1711.00864]

$\hookrightarrow$ no de Sitter solution, in asymptotic regime, e.g. classical...

Can one trust these swampland de Sitter conjectures? $\rightarrow$ Test them (accurately)! Comparison to no-go theorems

Deeper physical reason?
Through relations between swampland conjectures, web of conjectures?
$\Rightarrow$ hints at a more fundamental principle...

Conjectured answer: **no**

**Swampland program**: characterizing what can be obtained from string theory

E. Palti [arXiv:1903.06239]

T. D. Brennan, F. Carta, C. Vafa [arXiv:1711.00864]

$\hookrightarrow$ no de Sitter solution, in asymptotic regime, e.g. classical...

Can one trust these swampland de Sitter conjectures? $\rightarrow$ Test them (accurately)! Comparison to no-go theorems

Deeper physical reason?
Through relations between swampland conjectures, web of conjectures?
$\Rightarrow$ hints at a more fundamental principle...

**Plan**:

- Search for classical de Sitter string backgrounds and discuss difficulties faced
- Swampland de Sitter conjectures and no-go theorems: a surprising quantitative match
- (Deeper into the web: relation to the (generalized) swampland distance conjecture and bounds)

# Classical de Sitter solutions

Classical (perturb.) string background: sol. of 10d supergravity

**4d de Sitter** $\times$ 6d compact manifold

+ fluxes, intersecting $O_p/D_p$ sources, curvature ($\mathcal{R}_6 < 0$)
Typically: 6d compact group manifold, constant fluxes, "smeared" sources

(Ansatz different than in

C. Cordova, G. Bruno De Luca, A. Tomasiello [arXiv:1812.04147],

N. Cribiori, D. Junghans [arXiv:1902.08209],

C. Cordova, G. Bruno De Luca, A. Tomasiello [arXiv:1911.04498],

N. Kim [arXiv:2004.05885]

$\rightarrow$ not considered further)

**Two steps**:

**1.**

**2.**

**Two steps**:

**1.** find 10d (type II) supergravity de Sitter solution
Very constrained, no-go theorems
Find some:

C. Caviezel, P. Koerber, S. Kors, D. Lüst, T. Wrase, M. Zagermann [arXiv:0812.3551],
R. Flauger, S. Paban, D. Robbins, T. Wrase [arXiv:0812.3886],
C. Caviezel, T. Wrase, M. Zagermann [arXiv:0912.3287],
U. H. Danielsson, P. Koerber, T. Van Riet [arXiv:1003.3590],
U. H. Danielsson, S. S. Haque, P. Koerber, G. Shiu, T. Van Riet, T. Wrase [arXiv:1103.4858],
C. Roupec, T. Wrase [arXiv:1807.09538],
D. A., P. Marconnet, T. Wrase [arXiv:2005.12930]

with intersecting $O_6/D_6$, or $O_5 \,\&\, O_7$, or $O_5/D_5$ (new).

**2.**

**Two steps**:

**1.** find 10d (type II) supergravity de Sitter solution
Very constrained, no-go theorems
Find some:

C. Caviezel, P. Koerber, S. Kors, D. Lüst, T. Wrase, M. Zagermann [arXiv:0812.3551],
R. Flauger, S. Paban, D. Robbins, T. Wrase [arXiv:0812.3886],
C. Caviezel, T. Wrase, M. Zagermann [arXiv:0912.3287],
U. H. Danielsson, P. Koerber, T. Van Riet [arXiv:1003.3590],
U. H. Danielsson, S. S. Haque, P. Koerber, G. Shiu, T. Van Riet, T. Wrase [arXiv:1103.4858],
C. Roupec, T. Wrase [arXiv:1807.09538],
D. A., P. Marconnet, T. Wrase [arXiv:2005.12930]

with intersecting $O_6/D_6$, or $O_5 \,\&\, O_7$, or $O_5/D_5$ (new).

**2.** verify that in classical string regime: small $g_s$, large volume...

C. Roupec, T. Wrase [arXiv:1807.09538],
D. Junghans [arXiv:1811.06990],
A. Banlaki, A. Chowdhury, C. Roupec, T. Wrase [arXiv:1811.07880],
D. A. [arXiv:1902.10093],
T. W. Grimm, C. Li, I. Valenzuela [arXiv:1910.09549],
D. A., P. Marconnet, T. Wrase [arXiv:2006.01848]

$\hookrightarrow$ **no solution left!**

## No-go theorems and parameter space

Existence of de Sitter solutions
5 supergravity equations (e.o.m., BI) $\rightarrow$ constraints:

T. Wrase, M. Zagermann [arXiv:1003.0029], G. Shiu, Y. Sumitomo [arXiv:1107.2925]

D. A., J. Blåbäck, [arXiv:1609.00385], D. A. [arXiv:1710.08886]

D. A. [arXiv:1807.09698], [arXiv:1902.10093]

| $p$ | A de Sitter solution requires $T_{10} > 0$ and $\mathcal{R}_6 \geqslant 0$ | $\mathcal{R}_6 < 0$ |
|---|---|---|
| 3 | $\times$ | $\times$ |
| 4 | $\times$ | ?? |
| 5 | $\times$ | ?? |
| 6 | $\times$ | ?? |
| 7 | $\times$ | $\times$ |
| 8 | $\times$ | $\times$ |
| 9 | $\times$ | $\times$ |

Excluded in many cases. Small corner of parameter space left:
$O_p$ $(T_{10} > 0)$, $\mathcal{R}_6 < 0$, $p = 4, 5, 6$, $F_{6-p} \neq 0$, + more restrictions.

# No-go theorems and parameter space

Existence of de Sitter solutions
5 supergravity equations (e.o.m., BI) → constraints:

T. Wrase, M. Zagermann [arXiv:1003.0029], G. Shiu, Y. Sumitomo [arXiv:1107.2925]

D. A., J. Blåbäck, [arXiv:1609.00385], D. A. [arXiv:1710.08886]

D. A. [arXiv:1807.09698], [arXiv:1902.10093]

| $p$ | A de Sitter solution requires $T_{10} > 0$ and $\mathcal{R}_6 \geqslant 0$ | $\mathcal{R}_6 < 0$ |
|---|---|---|
| 3 | $\times$ | $\times$ |
| 4 | $\times$ | ?? |
| 5 | $\times$ | ?? |
| 6 | $\times$ | ?? |
| 7 | $\times$ | $\times$ |
| 8 | $\times$ | $\times$ |
| 9 | $\times$ | $\times$ |

Excluded in many cases. Small corner of parameter space left:
$O_p$ ($T_{10} > 0$), $\mathcal{R}_6 < 0$, $p = 4, 5, 6$, $F_{6-p} \neq 0$, + more restrictions.
+ having $N > 1$ sets of intersecting sources $O_p/D_p$ helps,
i.e. wrap different internal directions.
Example: known sol. with intersecting $O_6/D_6$, $\mathcal{R}_6 < 0$, $F_0 \neq 0$.

# No-go theorems and parameter space

Existence of de Sitter solutions
5 supergravity equations (e.o.m., BI) → constraints:

T. Wrase, M. Zagermann [arXiv:1003.0029], G. Shiu, Y. Sumitomo [arXiv:1107.2925]

D. A., J. Blåbäck, [arXiv:1609.00385], D. A. [arXiv:1710.08886]

D. A. [arXiv:1807.09698], [arXiv:1902.10093]

| | A de Sitter solution requires $T_{10} > 0$ and | |
|---|---|---|
| $p$ | $\mathcal{R}_6 \geqslant 0$ | $\mathcal{R}_6 < 0$ |
| 3 | × | × |
| 4 | × | ?? |
| 5 | × | ?? |
| 6 | × | ?? |
| 7 | × | × |
| 8 | × | × |
| 9 | × | × |

Excluded in many cases. Small corner of parameter space left: $O_p$ ($T_{10} > 0$), $\mathcal{R}_6 < 0$, $p = 4, 5, 6$, $F_{6-p} \neq 0$, + more restrictions.
+ having $N > 1$ sets of intersecting sources $O_p/D_p$ helps, i.e. wrap different internal directions.
Example: known sol. with intersecting $O_6/D_6$, $\mathcal{R}_6 < 0$, $F_0 \neq 0$.
↪ very constrained, but also ✓ indicates **where to look** to find new solutions.

## Looking for de Sitter solutions

$\hookrightarrow$ Look for IIB de Sitter solutions with intersecting $O_5/D_5$

D. A., P. Marconnet, T. Wrase [arXiv:2005.12930]

Motivation + placement of sources: strong analogy between $p = 5$ and $p = 6$

D. A. [arXiv:1710.08886]

## Looking for de Sitter solutions

$\hookrightarrow$ Look for IIB de Sitter solutions with intersecting $O_5/D_5$

D. A., P. Marconnet, T. Wrase [arXiv:2005.12930]

Motivation + placement of sources: strong analogy between $p=5$ and $p=6$

D. A. [arXiv:1710.08886]

$\hookrightarrow$ $N=3$ sets $(I=1,2,3)$ of $O_5/D_5$

| Space dimensions | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| $I=1$: $O_5, D_5$ | $\otimes$ | $\otimes$ | $\otimes$ | $\otimes$ | $\otimes$ | | | | |
| $I=2$: $(O_5), D_5$ | $\otimes$ | $\otimes$ | $\otimes$ | | | $\otimes$ | $\otimes$ | | |
| $I=3$: $(D_5)$ | $\otimes$ | $\otimes$ | $\otimes$ | | | | | $\otimes$ | $\otimes$ |

Search on group manifolds, defined by Lie algebra $\{f^a{}_{bc}\}$

We find (numerically) **17 new de Sitter solutions** in type IIB supergravity with intersecting $O_5/D_5$, on group manifolds.

One example: ${f^a}_{bc}, F_1, F_3, H, T_{10}^I$ (units of $2\pi l_s$)

$$
\begin{gathered}
{f^2}_{35} = -0.35847, \quad {f^2}_{45} = 0.95728, \quad {f^2}_{46} = -0.59118, \\
{f^3}_{15} = 0.21904, \quad {f^3}_{16} = 0.18899, \quad {f^4}_{15} = 0.11460, \\
{f^6}_{14} = -0.045686, \quad {f^3}_{25} = -{f^4}_{15}, \quad {f^1}_{45} = -{f^2}_{35}, \\
g_s F_{1\ 5} = -0.38308, \quad g_s F_{3\ 136} = 0.35228, \quad g_s F_{3\ 235} = 0.50883, \\
g_s F_{3\ 236} = 1.0454, \quad F_{3\ 246} = F_{3\ 136}, \quad H_{125} = 0.039232, \\
H_{126} = -0.093956, \quad H_{345} = -0.012542, \quad H_{346} = 0.29391, \\
g_s T_{10}^1 = 10, \quad g_s T_{10}^2 = 1.0654, \quad g_s T_{10}^3 = -0.28655.
\end{gathered}
$$

For this solution, we have $\mathcal{R}_4 = 0.049845$ .

We find (numerically) **17 new de Sitter solutions** in type IIB supergravity with intersecting $O_5/D_5$, on group manifolds.

One example: $f^a{}_{bc}, F_1, F_3, H, T_{10}^I$ (units of $2\pi l_s$)

$$\begin{gathered}
f^2{}_{35} = -0.35847, \quad f^2{}_{45} = 0.95728, \quad f^2{}_{46} = -0.59118, \\
f^3{}_{15} = 0.21904, \quad f^3{}_{16} = 0.18899, \quad f^4{}_{15} = 0.11460, \\
f^6{}_{14} = -0.045686, \quad f^3{}_{25} = -f^4{}_{15}, \quad f^1{}_{45} = -f^2{}_{35}, \\
g_s F_{1\ 5} = -0.38308, \quad g_s F_{3\ 136} = 0.35228, \quad g_s F_{3\ 235} = 0.50883, \\
g_s F_{3\ 236} = 1.0454, \quad F_{3\ 246} = F_{3\ 136}, \quad H_{125} = 0.039232, \\
H_{126} = -0.093956, \quad H_{345} = -0.012542, \quad H_{346} = 0.29391, \\
g_s T_{10}^1 = 10, \quad g_s T_{10}^2 = 1.0654, \quad g_s T_{10}^3 = -0.28655.
\end{gathered}$$

For this solution, we have $\mathcal{R}_4 = 0.049845$ .

**Compactness** of group manifold: existence of a lattice (constraints on structure constants): proven for 4 solutions.

We find (numerically) **17 new de Sitter solutions** in type IIB supergravity with intersecting $O_5/D_5$, on group manifolds.

One example: ${f^a}_{bc}, F_1, F_3, H, T_{10}^I$ (units of $2\pi l_s$)

$$
\begin{gathered}
{f^2}_{35} = -0.35847, \quad {f^2}_{45} = 0.95728, \quad {f^2}_{46} = -0.59118, \\
{f^3}_{15} = 0.21904, \quad {f^3}_{16} = 0.18899, \quad {f^4}_{15} = 0.11460, \\
{f^6}_{14} = -0.045686, \quad {f^3}_{25} = -{f^4}_{15}, \quad {f^1}_{45} = -{f^2}_{35}, \\
g_s F_{1\ 5} = -0.38308, \quad g_s F_{3\ 136} = 0.35228, \quad g_s F_{3\ 235} = 0.50883, \\
g_s F_{3\ 236} = 1.0454, \quad F_{3\ 246} = F_{3\ 136}, \quad H_{125} = 0.039232, \\
H_{126} = -0.093956, \quad H_{345} = -0.012542, \quad H_{346} = 0.29391, \\
g_s T_{10}^1 = 10, \quad g_s T_{10}^2 = 1.0654, \quad g_s T_{10}^3 = -0.28655.
\end{gathered}
$$

For this solution, we have $\mathcal{R}_4 = 0.049845$ .

**Compactness** of group manifold: existence of a lattice (constraints on structure constants): proven for 4 solutions.

**Stability**: all solutions are pert. unstable. Tools developed...

## Classical regime of string theory

D. A., P. Marconnet, T. Wrase [arXiv:2006.01848]

A 10d supergravity solution: a classical string background?

## Classical regime of string theory

D. A., P. Marconnet, T. Wrase [arXiv:2006.01848]

A 10d supergravity solution: a classical string background?
$\hookrightarrow$ **5** (sufficient) **requirements**:

- Small $g_s$
- "Large volume"

## Classical regime of string theory

D. A., P. Marconnet, T. Wrase [arXiv:2006.01848]

A 10d supergravity solution: a classical string background?
$\hookrightarrow$ **5** (sufficient) **requirements**:

- Small $g_s$: $g_s \ll 1 \Rightarrow 0 < g_s \leqslant 10^{-1}$
- "Large volume"

## Classical regime of string theory

D. A., P. Marconnet, T. Wrase [arXiv:2006.01848]

A 10d supergravity solution: a classical string background?
$\hookrightarrow$ **5** (sufficient) **requirements**:

- Small $g_s$: $g_s \ll 1 \Rightarrow 0 < g_s \leqslant 10^{-1}$
- "Large volume": large 6d **radii** $r^{a\,=\,1,\,\ldots,\,6} \gg 1$ (units of $l_s$) $\Rightarrow r^a \geqslant 10$

## Classical regime of string theory

D. A., P. Marconnet, T. Wrase [arXiv:2006.01848]

A 10d supergravity solution: a classical string background?
$\hookrightarrow$ **5** (sufficient) **requirements**:

- Small $g_s$: $g_s \ll 1 \Rightarrow 0 < g_s \leqslant 10^{-1}$
- "Large volume": large 6d **radii** $r^{a=1,\dots,6} \gg 1$ (units of $l_s$) $\Rightarrow r^a \geqslant 10$
- Quantization of (harmonic components of) **fluxes**: $F_{q\,a_1\dots a_q} = \frac{N_{q\,a_1\dots a_q}}{r^{a_1}\dots r^{a_q}}$ (units of $2\pi l_s$) $\Rightarrow N_{q\,a_1\dots a_q} \in \mathbb{Z}$

## Classical regime of string theory

D. A., P. Marconnet, T. Wrase [arXiv:2006.01848]

A 10d supergravity solution: a classical string background?
$\hookrightarrow$ **5** (sufficient) **requirements**:

- Small $g_s$: $g_s \ll 1 \Rightarrow 0 < g_s \leqslant 10^{-1}$
- "Large volume": large 6d **radii** $r^{a=1,\dots,6} \gg 1$ (units of $l_s$) $\Rightarrow r^a \geqslant 10$
- Quantization of (harmonic components of) **fluxes**: $F_{q\, a_1 \dots a_q} = \frac{N_{q\, a_1 \dots a_q}}{r^{a_1} \dots r^{a_q}}$ (units of $2\pi l_s$) $\Rightarrow N_{q\, a_1 \dots a_q} \in \mathbb{Z}$
- Number of orientifolds $N^I_{O_5}$ finite, fixed by geometry $\Rightarrow$ number of **sources** $N^I_s = N^I_{O_5} - N^I_{D_5}$ bounded. $T^I_{10} = \frac{6\, N^I_s}{r^{a_{1\perp}} \dots r^{a_{4\perp}}}$ (units of $2\pi l_s$) $\Rightarrow N^I_s \in \mathbb{Z}\ ,\ \ N^I_s \leqslant N^I_{O_5}$

## Classical regime of string theory

D. A., P. Marconnet, T. Wrase [arXiv:2006.01848]

A 10d supergravity solution: a classical string background?
$\hookrightarrow$ **5** (sufficient) **requirements**:

- Small $g_s$: $g_s \ll 1 \Rightarrow 0 < g_s \leqslant 10^{-1}$
- "Large volume": large 6d **radii** $r^{a\,=\,1,\,\dots,\,6} \gg 1$ (units of $l_s$) $\Rightarrow r^a \geqslant 10$
- Quantization of (harmonic components of) **fluxes**: $F_{q\, a_1 \dots a_q} = \frac{N_{q\, a_1 \dots a_q}}{r^{a_1} \dots r^{a_q}}$ (units of $2\pi l_s$) $\Rightarrow N_{q\, a_1 \dots a_q} \in \mathbb{Z}$
- Number of orientifolds $N^I_{O_5}$ finite, fixed by geometry $\Rightarrow$ number of **sources** $N^I_s = N^I_{O_5} - N^I_{D_5}$ bounded. $T^I_{10} = \frac{6\, N^I_s}{r^{a_{1\perp}} \dots r^{a_{4\perp}}}$ (units of $2\pi l_s$) $\Rightarrow N^I_s \in \mathbb{Z}\ ,\ \ N^I_s \leqslant N^I_{O_5}$
- **Lattice** quantization conditions: ${f^a}_{bc} = \frac{r^a\, N_a}{r^b r^c}$ (units $2\pi l_s$) $\Rightarrow N_a$ quantization conditions

## Classical regime of string theory

D. A., P. Marconnet, T. Wrase [arXiv:2006.01848]

A 10d supergravity solution: a classical string background?
$\hookrightarrow$ **5** (sufficient) **requirements**:

- Small $g_s$: $g_s \ll 1 \Rightarrow 0 < g_s \leqslant 10^{-1}$
- "Large volume": large 6d **radii** $r^{a=1,\dots,6} \gg 1$ (units of $l_s$) $\Rightarrow r^a \geqslant 10$
- Quantization of (harmonic components of) **fluxes**: $F_{q\, a_1\dots a_q} = \frac{N_{q\, a_1\dots a_q}}{r^{a_1}\dots r^{a_q}}$ (units of $2\pi l_s$) $\Rightarrow N_{q\, a_1\dots a_q} \in \mathbb{Z}$
- Number of orientifolds $N^I_{O_5}$ finite, fixed by geometry $\Rightarrow$ number of **sources** $N^I_s = N^I_{O_5} - N^I_{D_5}$ bounded. $T^I_{10} = \frac{6\, N^I_s}{r^{a_{1\perp}}\dots r^{a_{4\perp}}}$ (units of $2\pi l_s$) $\Rightarrow N^I_s \in \mathbb{Z}\ ,\quad N^I_s \leqslant N^I_{O_5}$
- **Lattice** quantization conditions: ${f^a}_{bc} = \frac{r^a\, N_a}{r^b r^c}$ (units $2\pi l_s$) $\Rightarrow N_a$ quantization conditions

Last 3 conditions: need a detailed knowledge of 6d geometry...

Full program only carried out for 2 solutions:
$\Rightarrow$ **not classical de Sitter backgrounds!**

Full program only carried out for 2 solutions:
$\Rightarrow$ **not classical de Sitter backgrounds!**
Other solutions: partial checks of requirements: successful for 2 other solutions.

Full program only carried out for 2 solutions:
⇒ **not classical de Sitter backgrounds!**
Other solutions: partial checks of requirements: successful for 2 other solutions.

Example: solution 14:

- $g_s = 0.068818$ ✓
- $r^1 = 86.658\ ,\ r^2 = 272.28\ ,\ r^3 = 10.834\ ,$
  $r^4 = 18.142\ ,\ r^5 = 198.25\ ,\ r^6 = 10.562$ ✓
- Fluxes: $N_{1\,5} = -1\ ,\ N_{3\,\omega_1} = 38\ ,\ N_{3\,\omega_2} = 135$ ✓
- Sources: $N_{O_5} = 16,\ N_s^1 = 16\ ,\ N_s^2 = -17\ ,\ N_s^3 = -14$ ✓
- Lattice: $\sqrt{N_2 N_3} \in \mathbb{N}^*$, $\sqrt{N_1 N_6} \in \mathbb{N}^*$: ×
  $N_3 = 0.084801 = (0.015659)^2/N_2$
  $N_6 = 0.077905 = (0.012107)^2/N_1$

Full program only carried out for 2 solutions:
$\Rightarrow$ **not classical de Sitter backgrounds!**
Other solutions: partial checks of requirements: successful for 2 other solutions.

Example: solution 14:

- $g_s = 0.068818$ ✓
- $r^1 = 86.658\ ,\ r^2 = 272.28\ ,\ r^3 = 10.834\ ,$
  $r^4 = 18.142\ ,\ r^5 = 198.25\ ,\ r^6 = 10.562$ ✓
- Fluxes: $N_{1\,5} = -1\ ,\ N_{3\,\omega_1} = 38\ ,\ N_{3\,\omega_2} = 135$ ✓
- Sources: $N_{O_5} = 16,\ N_s^1 = 16\ ,\ N_s^2 = -17\ ,\ N_s^3 = -14$ ✓
- Lattice: $\sqrt{N_2 N_3} \in \mathbb{N}^*$, $\sqrt{N_1 N_6} \in \mathbb{N}^*$: ×
  $N_3 = 0.084801 = (0.015659)^2/N_2$
  $N_6 = 0.077905 = (0.012107)^2/N_1$

Similarly, can satisfy all requirements except the orientifold bound: $N_s^1 = 50960$.
Or satisfy first conditions on fluxes, sources, lattices, then study $g_s$ and $r^a$: get small $g_s$, not large radius (substringy).

Comments:

- Analysis very complete.
  Goes beyond what has been done before in literature.

Comments:

- Analysis very complete.
  Goes beyond what has been done before in literature.
- Almost working: satisfy 4 out of 5 requirements.
  Why not working? A general property of string theory?

Comments:

- Analysis very complete.
  Goes beyond what has been done before in literature.
- Almost working: satisfy 4 out of 5 requirements.
  Why not working? A general property of string theory?
- A very constrained problem.
  Move/**deform** in one direction in parameter/moduli space
  $\rightarrow$ hit a bound.
  $\hookrightarrow$ classical de Sitter sol. live *at best* in **bounded region** of parameter space. Probably not in asymptotics (see swampland conjectures).

Comments:

- Analysis very complete.
  Goes beyond what has been done before in literature.
- Almost working: satisfy 4 out of 5 requirements.
  Why not working? A general property of string theory?
- A very constrained problem.
  Move/**deform** in one direction in parameter/moduli space
  $\rightarrow$ hit a bound.
  $\hookrightarrow$ classical de Sitter sol. live *at best* in **bounded region** of parameter space. Probably not in asymptotics (see swampland conjectures).
- Relation to **scale separation** and (DGKT) anti-de Sitter solution

  O. DeWolfe, A. Giryavets, S. Kachru, W. Taylor [hep-th/0505160]

  In that solution, no lattice constraint (flat torus)

Comments:

- Analysis very complete.
  Goes beyond what has been done before in literature.
- Almost working: satisfy 4 out of 5 requirements.
  Why not working? A general property of string theory?
- A very constrained problem.
  Move/**deform** in one direction in parameter/moduli space
  $\rightarrow$ hit a bound.
  $\hookrightarrow$ classical de Sitter sol. live *at best* in **bounded region** of parameter space. Probably not in asymptotics (see swampland conjectures).
- Relation to **scale separation** and (DGKT) anti-de Sitter solution

  O. DeWolfe, A. Giryavets, S. Kachru, W. Taylor [hep-th/0505160]

  In that solution, no lattice constraint (flat torus)

Summary:

- No-gos
- Remaining region $\rightarrow$ find de Sitter supergravity solutions
- Classical regime analysis

# Testing swampland de Sitter conjectures

Several swampland conjectures that forbid (classical) de Sitter solutions.

**De Sitter swampland conjecture:** (initial version)

G. Obied, H. Ooguri, L. Spodyneiko, C. Vafa, [arXiv:1806.08362]

# Testing swampland de Sitter conjectures

Several swampland conjectures that forbid (classical) de Sitter solutions.

**De Sitter swampland conjecture:** (initial version)

G. Obied, H. Ooguri, L. Spodyneiko, C. Vafa, [arXiv:1806.08362]

Consider a 4d theory of minimally coupled scalars $\phi^i$

$$\mathcal{S} = \int \mathrm{d}^4x \sqrt{|G_4|} \left( \frac{M_p^2}{2} \mathcal{R}_4 - \frac{1}{2} g_{ij}(\phi) \partial_\mu \phi^i \partial^\mu \phi^j - V(\phi) \right)$$

**Criterion**: if NOT in the swampland, one has:

- $|\nabla V| \geqslant \frac{c}{M_p} V$ with $|\nabla V| = \sqrt{g^{ij} \partial_{\phi^i} V \partial_{\phi^j} V}$
- $c \sim O(1)$

$\Rightarrow$ no de Sitter solution (extremum) from string theory.

## Refined de Sitter conjectures

Various criticisms:
- example based (e.g. no-go theorems)/deeper physical reason?
- what is $c$ ?
- allow for maxima!

## Refined de Sitter conjectures

Various criticisms:
- example based (e.g. no-go theorems)/deeper physical reason?
- what is $c$ ?
- allow for maxima!

$\hookrightarrow$ refinements:

- To include the notion of stability, i.e. $V''$ or $\eta_V$...

  D. A. [arXiv:1806.10999],
  S. K. Garg, C. Krishnan [arXiv:1807.05193],
  H. Ooguri, E. Palti, G. Shiu, C. Vafa [arXiv:1810.05506],
  D. A., C. Roupec [arXiv:1811.08889],
  T. Rudelius [arXiv:1905.05198]

- No de Sitter solution in asymptotics of moduli space, e.g. classical regime(?)

  H. Ooguri, E. Palti, G. Shiu, C. Vafa [arXiv:1810.05506]

  Reminiscent/generalization of Dine-Seiberg argument.

  M. Dine, N. Seiberg *Phys. Lett.* **B 162** (1985) 299

  $\frac{|\nabla V|}{V} \geqslant \frac{c}{M_p}$ for $\varphi \to \infty$.

**TCC**: Trans-Planckian Censorship Conjecture

A. Bedroya, C. Vafa [arXiv:1909.11063]

Conjectured physical argument on trans-Planckian modes
$\hookrightarrow$ scalar field $\varphi$ and potential, in 4d (with $M_p = 1$):

$$0 < V(\varphi) < A\, e^{-c_0\, \varphi} \quad \Rightarrow \quad \left\langle \frac{|V'|}{V} \right\rangle_{\varphi \to \infty} \geqslant c_0 = \sqrt{\frac{2}{3}}$$

## **TCC**: Trans-Planckian Censorship Conjecture

A. Bedroya, C. Vafa [arXiv:1909.11063]

Conjectured physical argument on trans-Planckian modes

$\hookrightarrow$ scalar field $\varphi$ and potential, in 4d (with $M_p = 1$):

$$0 < V(\varphi) < A\, e^{-c_0\, \varphi} \quad \Rightarrow \quad \left\langle \frac{|V'|}{V} \right\rangle_{\varphi\to\infty} \geqslant c_0 = \sqrt{\frac{2}{3}}$$

Compare to $\frac{|\nabla V|}{V} \geqslant c$ :

$\Rightarrow$ gives a **physical motivation** for such an inequality

$\Rightarrow$ gives a **number**!

$\Rightarrow$ **asymptotic limit** is crucial

$$\text{TCC bound:} \quad c \geqslant c_0 = \sqrt{\frac{2}{3}} \quad \text{in 4d}$$

## Testing conjectures with no-go theorems

"Parameter space" for classical de Sitter solutions:

| $p$ | A de Sitter solution requires $T_{10} > 0$ and $\mathcal{R}_6 \geqslant 0$ | $\mathcal{R}_6 < 0$ |
|---|---|---|
| 3 | $\times$ | $\times$ |
| 4 | $\times$ | ?? |
| 5 | $\times$ | ?? |
| 6 | $\times$ | ?? |
| 7 | $\times$ | $\times$ |
| 8 | $\times$ | $\times$ |
| 9 | $\times$ | $\times$ |

In remaining corner, reason preventing us from accessing classical regime?
No clear no-go theorem formulation of this...
$\hookrightarrow$ focus on all other no-go theorems

## 9 no-go theorems (for parallel $D_p/O_p$)

| $p$ | A de Sitter solution requires $T_{10} > 0$ (**1.**) and $\mathcal{R}_6 \geqslant 0$ | $\mathcal{R}_6 < 0$ |
|---|---|---|
| 3 | (**4.**) | |
| 4 | (**3.**) | $F_{6-p}$ (**2.**), |
| 5 | | ${f^{\vert\vert}}_{\perp\perp}$ (**5.**), (**6.**), (**9.**), ${f^{\perp}}_{\perp\vert\vert}$ (**7.**), (**8.**), |
| 6 | | linear combi (**5.**), (**6.**) |
| 7 | (**2.**), (**3.**) | (**2.**) |
| 8 | | |
| 9 | | |

(**number.**) = no-go theorem;
entry = necessary ingredient

$\Rightarrow$ put them in swampland conjecture format!

## **No-go theorem (2.)**: for $p = 7, 8$, or $p = 4, 5, 6$ & $F_{6-p} = 0$

**No-go theorem (2.)**: for $p = 7, 8$, or $p = 4, 5, 6$ & $F_{6-p} = 0$

**10d** type II supergravities e.o.m.:

$$(p-3)\ \mathcal{R}_4 = -2|H|^2 - g_s^2 \sum_{q=0}^{6} (q+p-8)|F_q|^2$$

**No-go theorem (2.)**: for $p = 7, 8$, or $p = 4, 5, 6$ & $F_{6-p} = 0$

**10d** type II supergravities e.o.m.:

$$(p-3)\ \mathcal{R}_4 = -2|H|^2 - g_s^2 \sum_{q=0}^{6} (q+p-8)|F_q|^2 \leqslant \mathbf{0}$$

**No-go theorem (2.)**: for $p = 7, 8$, or $p = 4, 5, 6$ & $F_{6-p} = 0$

**10d** type II supergravities e.o.m.:

$$(p-3)\ \mathcal{R}_4 = -2|H|^2 - g_s^2 \sum_{q=0}^{6} (q+p-8)|F_q|^2 \leqslant \mathbf{0}$$

**4d** corresponding equations with $V(\rho, \tau)$:

$$4(p-3)\ \mathbf{V} + 2(p-4)\ \tau\partial_\tau \mathbf{V} + 4\ \rho\partial_\rho \mathbf{V}$$

$$= -\tau^{-2}\rho^{-3}\, 2|H|^2 - g_s^2 \sum_{q=0}^{6} \tau^{-4}\rho^{3-q}\, (q+p-8)|F_q|^2 \leqslant \mathbf{0}$$

**No-go theorem (2.)**: for $p = 7, 8$, or $p = 4, 5, 6$ & $F_{6-p} = 0$

**10d** type II supergravities e.o.m.:

$$(p-3)\ \mathcal{R}_4 = -2|H|^2 - g_s^2 \sum_{q=0}^{6} (q+p-8)|F_q|^2 \leqslant \mathbf{0}$$

**4d** corresponding equations with $V(\rho, \tau)$:

$$4(p-3)\ \mathbf{V} + 2(p-4)\ \tau\partial_\tau \mathbf{V} + 4\ \rho\partial_\rho \mathbf{V}$$
$$= \ -\tau^{-2}\rho^{-3}\, 2|H|^2 - g_s^2 \sum_{q=0}^{6} \tau^{-4}\rho^{3-q}\,(q+p-8)|F_q|^2 \leqslant \mathbf{0}$$

Swampland format:

$$\Rightarrow \frac{|\nabla V|}{V} \geqslant \mathbf{c} = \sqrt{\frac{2(p-3)^2}{3+(p-4)^2}}$$

**No-go theorem (2.)**: for $p = 7, 8$, or $p = 4, 5, 6$ & $F_{6-p} = 0$

**10d** type II supergravities e.o.m.:

$$(p-3)\ \mathcal{R}_4 = -2|H|^2 - g_s^2 \sum_{q=0}^{6} (q+p-8)|F_q|^2 \leqslant \mathbf{0}$$

**4d** corresponding equations with $V(\rho, \tau)$:

$$4(p-3)\ \mathbf{V} + 2(p-4)\ \tau\partial_\tau \mathbf{V} + 4\ \rho\partial_\rho \mathbf{V}$$

$$= \ -\tau^{-2}\rho^{-3}\, 2|H|^2 - g_s^2 \sum_{q=0}^{6} \tau^{-4}\rho^{3-q}\,(q+p-8)|F_q|^2 \leqslant \mathbf{0}$$

Swampland format:

$$\Rightarrow \frac{|\nabla V|}{V} \geqslant \mathbf{c} = \sqrt{\frac{2(p-3)^2}{3+(p-4)^2}} \geqslant \sqrt{\frac{\mathbf{2}}{\mathbf{3}}}\ (\text{for } \mathbf{p} = \mathbf{4})$$

**No-go theorem (2.)**: for $p = 7, 8$, or $p = 4, 5, 6$ & $F_{6-p} = 0$

**10d** type II supergravities e.o.m.:

$$(p-3)\ \mathcal{R}_4 = -2|H|^2 - g_s^2 \sum_{q=0}^{6} (q+p-8)|F_q|^2 \leqslant \mathbf{0}$$

**4d** corresponding equations with $V(\rho,\tau)$:

$$\begin{aligned} &4(p-3)\ \mathbf{V} + 2(p-4)\ \tau\partial_\tau \mathbf{V} + 4\ \rho\partial_\rho \mathbf{V} \\ = &-\tau^{-2}\rho^{-3}\, 2|H|^2 - g_s^2 \sum_{q=0}^{6} \tau^{-4}\rho^{3-q}\,(q+p-8)|F_q|^2 \leqslant \mathbf{0} \end{aligned}$$

Swampland format:

$$\Rightarrow \frac{|\nabla V|}{V} \geqslant \mathbf{c} = \sqrt{\frac{2(p-3)^2}{3+(p-4)^2}} \geqslant \sqrt{\frac{\mathbf{2}}{\mathbf{3}}}\ (\text{for } \mathbf{p=4})$$

$\hookrightarrow$ **TCC bound**?!
(no quantum gravity argument, no limit, no average... except in a swampland perspective...)

**No-go theorem (2.)**: for $p = 7, 8$, or $p = 4, 5, 6$ & $F_{6-p} = 0$

**10d** type II supergravities e.o.m.:

$$(p-3)\ \mathcal{R}_4 = -2|H|^2 - g_s^2 \sum_{q=0}^{6} (q+p-8)|F_q|^2 \leqslant \mathbf{0}$$

**4d** corresponding equations with $V(\rho, \tau)$:

$$4(p-3)\ \mathbf{V} + 2(p-4)\ \tau\partial_\tau \mathbf{V} + 4\ \rho\partial_\rho \mathbf{V}$$
$$= \ -\tau^{-2}\rho^{-3}\, 2|H|^2 - g_s^2 \sum_{q=0}^{6} \tau^{-4}\rho^{3-q}\,(q+p-8)|F_q|^2 \leqslant \mathbf{0}$$

Swampland format:

$$\Rightarrow \frac{|\nabla V|}{V} \geqslant \mathbf{c} = \sqrt{\frac{2(p-3)^2}{3+(p-4)^2}} \geqslant \sqrt{\frac{\mathbf{2}}{\mathbf{3}}}\ (\text{for } \mathbf{p} = \mathbf{4})$$

$\hookrightarrow$ **TCC bound**?!
(no quantum gravity argument, no limit, no average... except in a swampland perspective...)
$\rightarrow$ all 9 no-go theorems...

Done in D. A., N. Cribiori, D. Erkinger [arXiv:2004.00030]

| No-go number | Condition for the no-go | $c$ |
|---|---|---|
| **(1.)** | $T_{10} \leqslant 0$ | $\sqrt{2}$ |
| **(2.)** | $p = 7, 8,$ or $p = 4, 5, 6$ & $F_{6-p} = 0$ | $\sqrt{\frac{2(p-3)^2}{3+(p-4)^2}} \geqslant \sqrt{\frac{2}{3}}$ |
| **(3.)** | $\mathcal{R}_6 \geqslant 0,\ p \geqslant 4$ | $\sqrt{\frac{2(p+3)^2}{3+p^2}} > 1$ |
| **(4.)** | $p = 3$ | $2\sqrt{\frac{2}{3}}$ |
| **(5.)** | $\mathcal{R}_{\vert\vert} + \mathcal{R}_{\vert\vert}^{\perp} + \frac{\sigma^{-12}}{2} \vert f^{\vert\vert}{}_{\perp\perp}\vert^2 \leqslant 0,\ p \geqslant 4$ | $\sqrt{\frac{2(p-3)}{p-1}} \geqslant \sqrt{\frac{2}{3}}$ |
| **(6.)** | $-2\rho^2\sigma^{2(p-6)}(\mathcal{R}_{\vert\vert} + \mathcal{R}_{\vert\vert}^{\perp}) + \vert H^{(2)}\vert^2 \leqslant 0$ | $2\sqrt{\frac{2}{3}}$ |
| **(7.)** | $\lambda \leqslant 0,\ p \geqslant 4$ | $\sqrt{\frac{2}{3}}$ |
| **(9.)** | $\exists\, a_{\vert\vert}$ s.t. $f^{a_{\vert\vert}}{}_{ij} = 0\ \ \forall i, j \neq a_{\vert\vert},\ p \geqslant 4$ | $\sqrt{\frac{2}{3}}$ |

**TCC bound** always satisfied! Sometimes with saturation.

**Surprising quantitative verification** of de Sitter swampland conjectures (in this part of parameter space).

**Surprising quantitative verification** of de Sitter swampland conjectures (in this part of parameter space).

In remaining corner of parameter space: failure to find classical de Sitter backgrounds, less clear why.

**Surprising quantitative verification** of de Sitter swampland conjectures (in this part of parameter space).

In remaining corner of parameter space: failure to find classical de Sitter backgrounds, less clear why.

Confidence in swampland conjectures: hint at a deeper reason?

**Surprising quantitative verification** of de Sitter swampland conjectures (in this part of parameter space).

In remaining corner of parameter space: failure to find classical de Sitter backgrounds, less clear why.

Confidence in swampland conjectures: hint at a deeper reason?
All swampland conjectures are related: a **web of conjectures**.
Translate the impossibility of getting classical de Sitter to another conjecture?
$\hookrightarrow$ the **distance conjecture**: also involves large field distances, and a parameter $\lambda \sim \mathcal{O}(1)$...

**Surprising quantitative verification** of de Sitter swampland conjectures (in this part of parameter space).

In remaining corner of parameter space: failure to find classical de Sitter backgrounds, less clear why.

Confidence in swampland conjectures: hint at a deeper reason?
All swampland conjectures are related: a **web of conjectures**.
Translate the impossibility of getting classical de Sitter to another conjecture?
$\hookrightarrow$ the **distance conjecture**: also involves large field distances, and a parameter $\lambda \sim \mathcal{O}(1)$...

Inspired by examples in literature + new quantitative tests of conj., **we proposed a bound**

$$\text{4d}: \quad \lambda \geqslant \lambda_0 = \frac{1}{2}\sqrt{\frac{2}{3}}\ , \quad \lambda_0 = \frac{1}{2} c_0$$

To justify bound on $\lambda$: **generalization** of distance conj.
To justify relation to $c_0$: **relation** between conj. $\frac{m}{m_i} \simeq \left|\frac{V}{V_i}\right|^{\frac{1}{2}}$.
$\hookrightarrow$ translates the "no de Sitter" into asymptotic bound on $m$.
**A new perspective.**

# Conclusion

- Connection to cosmology → (quasi) **de Sitter string backgrounds**? → **classical** ones (simplicity, well-controlled)
- Constrained by **no-go theorems** → **a corner** of parameter space remains → we look there and find new de Sitter solutions of 10d supergravity
- Thorough analysis of classical regime for these solutions → failure, but close.
- Intuition of a **bounded region** of parameter space for classical de Sitter backgrounds, not asymptotics.

# Conclusion

- Connection to cosmology → (quasi) **de Sitter string backgrounds**? → **classical** ones (simplicity, well-controlled)
- Constrained by **no-go theorems** → **a corner** of parameter space remains → we look there and find new de Sitter solutions of 10d supergravity
- Thorough analysis of classical regime for these solutions → failure, but close.
- Intuition of a **bounded region** of parameter space for classical de Sitter backgrounds, not asymptotics.

- Answer from **de Sitter swampland conjectures**: $\sim$ no de Sitter solution in asymptotic limit, $c \geqslant c_0$.
- A surprisingly good quantitative check with no-go theorems → confidence in swampland conjectures?

# Conclusion

- Connection to cosmology → (quasi) **de Sitter string backgrounds**? → **classical** ones (simplicity, well-controlled)
- Constrained by **no-go theorems** → **a corner** of parameter space remains → we look there and find new de Sitter solutions of 10d supergravity
- Thorough analysis of classical regime for these solutions → failure, but close.
- Intuition of a **bounded region** of parameter space for classical de Sitter backgrounds, not asymptotics.

- Answer from **de Sitter swampland conjectures**: $\sim$ no de Sitter solution in asymptotic limit, $c \geqslant c_0$.
- A surprisingly good quantitative check with no-go theorems → confidence in swampland conjectures?

- Connection to the distance conjecture? First observe/**propose a bound** $\lambda \geqslant \lambda_0 = \frac{1}{2} c_0$.
- To justify it: **generalize** swampland distance conjecture, and propose a map/**relation to de Sitter conjecture** → translation of the obstruction

## Do classical de Sitter string backgrounds exist?

Tendency towards “no”, but not established.
Reason is not clear.
Highlighted many directions where to make progress on this important matter.

## Do classical de Sitter string backgrounds exist?

Tendency towards “no”, but not established.
Reason is not clear.
Highlighted many directions where to make progress on this important matter.

**Thank you for your attention!**