Classical de Sitter solutions and the swampland

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Based on arXiv:1609.00385 (with J. Blåbäck), 1710.08886
arXiv:1806.10999, 1807.09698, 1811.08889 (with C. Roupec)

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Introduction

- **Landscape**

- **Swampland**

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  $\hookrightarrow$ criticism of string theory as non-predictive
  More troublesome: is any matching our world? In which corner?
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  $\hookrightarrow$ change of strategy / "paradigm shift"
  More useful to distinguish different cosmological or BSM models
  Joins the idea of EFT and U.V. completion

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  $\hookrightarrow$ change of strategy / "paradigm shift"
  More useful to distinguish different cosmological or BSM models
  Joins the idea of EFT and U.V. completion
- **"Swampland program"**: give a list of properties / criteria for a model to be or not in swampland
  List given e.g. in T. D. Brennan, F. Carta, C. Vafa [arXiv:1711.00864]

List:

- No continuous global symmetry
- ...
- ...
- ...
- ...
- Weak Gravity conjecture (several versions)

N. Arkani-Hamed, L. Motl, A. Nicolis, C. Vafa [hep-th/0601001]

- Distance conjecture

H. Ooguri, C. Vafa [hep-th/0605264], D. Klaewer, E. Palti [arXiv:1610.00010]

- Non-SUSY AdS conjecture

H. Ooguri, C. Vafa [arXiv:1610.01533], B. Freivogel, M. Kleban [arXiv:1610.04564]

- de Sitter conjecture/criterion

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

- ...

Here: focus on de Sitter conjecture
+ good illustration of the swampland idea

De Sitter conjecture:

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

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Consider a 4d theory of minimally coupled scalars ϕ_i ($M_4 = 1$)

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

solutions as extrema of potential: $\partial_{\phi^i} V|_0 = 0$, $\mathcal{R}_4 = 2V|_0$
$\Rightarrow$ de Sitter solutions: $\Lambda_4 = \frac{1}{2} V|_0 > 0$.

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Criterion: if NOT in the swampland, one has:

- $|\nabla V| \geqslant c\, V$ at any point in field space with $c > 0$, $|\nabla V| = \sqrt{g^{ij} \partial_{\phi^i} V \partial_{\phi^j} V}$
- $c \sim O(1)$

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$\Rightarrow$ extremum: $|\nabla V|_0 = 0 \Rightarrow V|_0 \leqslant 0$
$\hookrightarrow$ no de Sitter solution for a theory coming from string theory.

$\Rightarrow$ Why? Motivations?

$\Rightarrow$ Consequences?

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1. Difficult to obtain de Sitter solutions / vacua from string theory in a controlled manner.

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2. Consequences and refined versions of conjecture
3. Constraints on classical de Sitter solutions

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   - Connection to other swampland conjecture: distance conjecture H. Ooguri, E. Palti, G. Shiu, C. Vafa [arXiv:1810.05506]

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   - Line of thoughts from non-SUSY AdS conjecture: non-SUSY AdS solutions (with finite number of fields) is unstable / not a trustable solution (✓ with holographic attempts)
   ↪ only SUSY solutions are ✓? See [arXiv:1711.00864]
   - Difficult to build holographic duals to de Sitter
   - Difficult to have well-defined QFT on de Sitter, so what about quantum gravity?

De Sitter solutions in string theory

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Three main stringy constructions to get de Sitter:

1. Classical solutions (10d)
2. KKLT, (LVS), ... (10d/4d)
3. Non-geometric fluxes (4d)

Other approaches, e.g. world-sheet, heterotic, asymmetric orbifolds...

1. **Classical 10d solutions**

The simplest option / best controlled setting:
classical (perturbative) string background: 10d supergravity sol.

4d de Sitter × 6d compact manifold

+ fluxes, orientifold O_p-planes, D_p-branes, curvature ($\mathcal{R}_6 < 0$)

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Intrinsically difficult: parallel D_6/O_6: D.A., J.Blåbäck [arXiv:1609.00385]

$$\begin{aligned}
\Lambda_4 \ = \ & -\frac{e^{2A}}{8}\left(*_\perp H|_\perp + e^\phi F_0\right)^2 - \frac{e^{2A}}{4}\left(e^{4A} *_\perp \mathrm{d}e^{-4A} - e^\phi F_2^{(0)}\right)^2 \\
& -\frac{e^{2A}}{8}\sum_{a_{||}}\left(*_\perp \mathrm{d}e^{a_{||}}|_\perp - e^\phi(\iota_{a_{||}} F_2^{(1)})\right)^2 \\
& -\frac{e^{2A+2\phi}}{8}\left(2\left(F_4^{(0)}\right)^2 + 2\left(F_4^{(1)}\right)^2 + \left(F_4^{(2)}\right)^2 + \left(F_6\right)^2\right) \\
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Still, **few solutions have been found**... but some criticism...

What else can be done? Away from class. perturbative regime
$\hookrightarrow$ non-perturbative contributions, quantum corr. (α', g_s)...
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- Problem with SUSY breaking: loose control on quantum corrections S. Sethi [arXiv:1709.03554]
- 10d realisation of non-perturbative contrib. as D_7 gaugino condensate, with $\overline{D}_3$ to uplift to de Sitter: $\mathcal{R}_4 < 0$, contrary to 4d analysis J.Moritz,A.Retolaza,A.Westphal [arXiv:1707.08678]
- Singularities due to (backreaction of) $\overline{D}_3$ in 10d

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3. **Non-geometric fluxes**

Find (stable) de Sitter solution in 4d $\mathcal{N} = 1$ gauged supergravity ⇒ 10d realisation as a stringy non-geometry?
Problem: many different non-geometric fluxes
+ NS Bianchi identities not satisfied: exotic sources?

Rough **conclusion of de Sitter conjecture**:

- 10d/4d or 4d approaches (de Sitter solutions ✓) are not obtainable from string theory / are in the swampland

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But we have not tried everything...
More precise checks / progress in unexplored corners, e.g. classical solutions

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$\exists$ 10d classical de Sitter sol. of type IIA/B supergravities

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Criticism on these solutions (smeared O-planes, Romans mass, flux quantization/large volume/small coupling, etc.)

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+ all known solutions: **unstable**/tachyonic/at maximum
$\Rightarrow$ no known classical de Sitter vacuum
$\hookrightarrow$ refine de Sitter swampland criterion D. Andriot [arXiv:1806.10999]

$\exists\ b_i \in \mathbb{R}, c_i \in \mathbb{R}_+$ such that

$$V + \sum_i b_i\ \phi^i \partial_{\phi^i} V + \sum_i c_i\ {\phi^i}^2 \partial^2_{\phi^i} V \leqslant 0$$

$\Rightarrow$ **no stable de Sitter solution**, tachyonic de Sitter sol. ✓

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Possible to rewrite the above in a covariant manner
Single field and $V > 0$: refined criterion becomes:

$$\sqrt{\epsilon} - a\ \eta \geqslant c\ , \qquad \text{with } a \geqslant 0\ ,\ c > 0$$

D. Andriot [arXiv:1806.10999]

where $\epsilon = \frac{1}{2}\left(\frac{\nabla V}{V}\right)^2\ ,\ \eta = \frac{\nabla^2 V}{V}$.

$\Rightarrow$ checks? Cosmological implications?

Consequences: cosmology:

P. Agrawal, G. Obied, P. J. Steinhardt, C. Vafa [arXiv:1806.09718]

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- **Inflation**: difficulties with single-field inflation
  Slow-roll inflation: $\sqrt{2\epsilon} \ll 1$ while here $\sqrt{2\epsilon} \geqslant c \sim 1$.

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  Combination with **distance conjecture**: $\Delta\phi \leqslant d \sim O(1)$.
  Under some assumptions, one has $\Delta\phi = N_e \sqrt{2\epsilon}$
  $\Rightarrow \sqrt{\epsilon} \leqslant \frac{d}{N_e \sqrt{2}} \sim 10^{-2}$...

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David ANDRIOT

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  With other coupling to SM, more contributions to $V(\phi)$
  $\Rightarrow$ obs. bounds give $c \lesssim 10^{-1}$.
  But neutral Pion π_0: cos potential: get $c \lesssim 10^{-2} - 10^{-5}$.

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- $\min(\nabla_{\phi^i}\partial_{\phi^j} V) \leqslant -c'\, V$
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Get $\quad V(\phi) \simeq \left(n(\phi)\, e^{d\phi}\right)^{-k} \;, \quad d, k > 0 \qquad \Rightarrow |\nabla V| \geqslant c\, V$

Reactions:

- Tests/consequences on various phenomenological models:

S.-J. Wang [arXiv:1810.06445]
H. Fukuda, R. Saito, S. Shirai, M. Yamazaki [arXiv:1810.06532]
C.-M. Lin [arXiv:1810.11992]
P. Agrawal, G. Obied [arXiv:1811.00554]
C.-I. Chiang, J. M. Leedom, H. Murayama [arXiv:1811.01987]
D. Y. Cheong, S. M. Lee, S. C. Park [arXiv:1811.03622]
W. H. Kinney [arXiv:1811.11698]

- Relations to stringy constructions:

Y. Olguin-Trejo, S. L. Parameswaran, G. Tasinato, I. Zavala [arXiv:1810.08634]
S. K. Garg, C. Krishnan, M. Zaid [arXiv:1810.09406]
J. Blåbäck, U. Danielsson, G. Dibitetto [arXiv:1810.11365]
J. J. Heckman, C. Lawrie, L. Lin, G. Zoccarato [arXiv:1811.01959]
J. J. Blanco-Pillado, M. A. Urkiola, J. Wachter [arXiv:1811.05463]
D. Junghans [arXiv:1811.06990]
M. Emelin, R. Tatar [arXiv:1811.07378]
A. Banlaki, A. Chowdhury, C. Roupec, T. Wrase [arXiv:1811.07880]
B. S. Acharya, A. Maharana, F. Muia [arXiv:1811.10633]
Q. Bonnefoy, E. Dudas, S. Lüst [arXiv:1811.11199]

- Comments in a more general swampland context:

A. Hebecker, T. Wrase [arXiv:1810.08182]
G. Dvali, C. Gomez, S. Zell [arXiv:1810.11002]
R. Schimmrigk [arXiv:1810.11699]
M. Ibe, M. Yamazaki, T. T. Yanagida [arXiv:1811.04664]

Alternative refined de Sitter conj. D. A., C. Roupec [arXiv:1811.08889]

A low energy effective theory of a quantum gravity should verify, at any point in field space where $V > 0$*,*

$$\left(M_p \, \frac{|\nabla V|}{V} \right)^q - a \, {M_p}^2 \, \frac{\min \nabla\partial V}{V} \geqslant b \ , \quad a + b = 1 \ , \ a, b > 0 \ , \ q > 2$$

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Properties:
- For $M_p \to \infty$, it becomes $(|\nabla V|/V)^q \geqslant 0$, i.e. trivial.
- At an extremum: $(\min \nabla \partial V|_0)/(V|_0) < 0$, i.e. only tachyonic de Sitter solutions ✓.

$\hookrightarrow$ similar to previous refined version, difference is in parameters.

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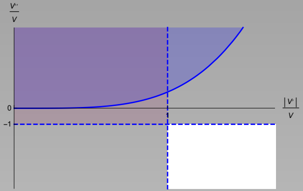
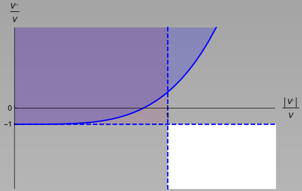


(a) $a \simeq 1$



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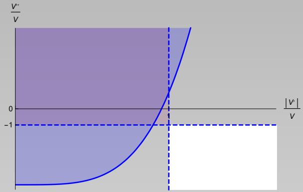

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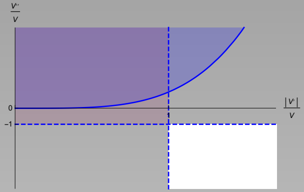

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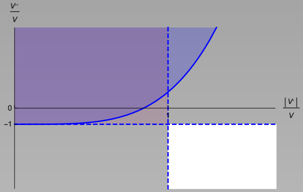

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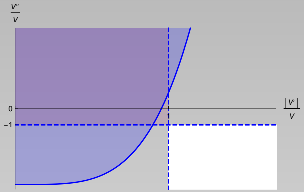

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- Derivation in weak coupling semi-classical regime: compute V'' and compare it to V': top right corner, new conjecture is stronger/further refinement.
- Case (a): allows for (concave!) slow-roll single field inflation

Constraints on 10d classical de Sitter solutions

D. Andriot [arXiv:1807.09698]

Reasoning and known results

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M. P. Hertzberg, S. Kachru, W. Taylor, M. Tegmark [arXiv:0711.2512],

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$$\left.\begin{array}{r} \mathcal{R}_4 = \cdots > 0 \\ \partial_\rho V|_0 = 0 \\ \partial_\tau V|_0 = 0 \end{array}\right| \qquad \left.\right|$$

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Combine 3 equations, get constraints

Existence of sol.: necessary ingredients (parallel D_p/O_p)

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

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Considering on top the 10d sourced Bianchi identity

$$\mathrm{d}F_{8-p} - H \wedge F_{6-p} = \varepsilon_p \, \frac{T_{10}}{p+1} \mathrm{vol}_{\perp}$$

$\Rightarrow$ more constraints, more ingredients needed

J. Blåbäck, U. H. Danielsson, D. Junghans, T. Van Riet, T. Wrase, M. Zagermann [arXiv:1009.1877], D. Andriot, J. Blåbäck, [arXiv:1609.00385]

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Analogous results derived for intersecting D_p/O_p:
sligthly less constraining $\leftrightarrow$ solutions known.

G. Shiu, Y. Sumitomo [arXiv:1107.2925], D. Andriot [arXiv:1710.08886]

New results

D. Andriot [arXiv:1807.09698]

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Introduce **new scalar** field σ: distinguishes $||, \perp$ dir. of D_p/O_p

U. H. Danielsson, G. Shiu, T. Van Riet, T. Wrase [arXiv:1212.5178]

Gives new constraints through

$$\partial_\sigma V|_0 = 0 \quad \Big| \qquad \Big|$$

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Introduce **new scalar** field σ: distinguishes $||, \perp$ dir. of D_p/O_p

U. H. Danielsson, G. Shiu, T. Van Riet, T. Wrase [arXiv:1212.5178]

Gives new constraints through

$$\partial_\sigma V|_0 = 0 \;\Big|\; \longleftrightarrow \;\Big|\; \text{trace Einstein eq. internal } || \text{ directions}$$

Reproduces constraints obtained in 10d + new ones

D. Andriot, J. Blåbäck [arXiv:1609.00385]

New results

D. Andriot [arXiv:1807.09698]

3 equations + sourced Bianchi identity

	A de Sitter solution requires $T_{10} > 0$ and	
$p = \dots$	$\mathcal{R}_6 \geqslant 0$	$\mathcal{R}_6 < 0$
3		
4		F_2, $f^{\|\|}{}_{\perp\perp}$, combi, $f^{\perp}{}_{\perp\|\|}$
5		F_1, $f^{\|\|}{}_{\perp\perp}$, combi, $f^{\perp}{}_{\perp\|\|}$
6		F_0, $f^{\|\|}{}_{\perp\perp}$, combi, $f^{\perp}{}_{\perp\|\|}$
7		
8		
9		

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$$
\begin{aligned}
V(\rho,\tau,\sigma) = &-\tau^{-2}\left(\rho^{-1}\mathcal{R}_6(\sigma) - \frac{1}{2}\rho^{-3}\sum_n \sigma^{-An-B(3-n)}|H^{(n)}|^2\right)\\
&- g_s \tau^{-3}\rho^{\frac{p-6}{2}}\sigma^{B\frac{p-9}{2}}\frac{T_{10}}{p+1}\\
&+\frac{1}{2}g_s^2\Bigg(\tau^{-4}\sum_{q=0}^{4}\rho^{3-q}\sum_n \sigma^{-An-B(q-n)}|F_q^{(n)}|^2 - \tau^4\rho^3|F_6|^2\\
&+\frac{1}{2}\sum_n(\tau^{-4}\rho^{-2}\sigma^{-An-B(5-n)}|F_5^{(n)}|^2\\
&-\tau^4\rho^2\sigma^{-An-B(1-n)}|(*_6F_5)^{(n)}|^2)\Bigg)
\end{aligned}
$$

$$
\begin{aligned}
\text{with } \mathcal{R}_6(\sigma) = &\ \sigma^{-B}\left(\mathcal{R}_\perp + \delta^{ab}\partial_{a_\perp} f^{c_\perp}{}_{c_\perp b_\perp} + \mathcal{R}_\perp^{||} + |f^{||}{}_{\perp\perp}|^2\right)\\
&+\sigma^{-A}\left(\mathcal{R}_{||} + \delta^{ab}\partial_{a_{||}} f^{c_{||}}{}_{c_{||} b_{||}} + \mathcal{R}_{||}^{\perp} + |f^{\perp}{}_{||||}|^2\right)\\
&-\frac{1}{2}\sigma^{-2A+B}|f^{\perp}{}_{||||}|^2 - \frac{1}{2}\sigma^{-2B+A}|f^{||}{}_{\perp\perp}|^2
\end{aligned}
$$

and $A = p-9,\ B = p-3$

On **group manifolds** (with constant fluxes): constraints in terms of $\lambda = -\frac{\delta^{cd} f^{b_\perp}{}_{a_{||} c_\perp} f^{a_{||}}{}_{b_\perp d_\perp}}{\frac{1}{2}\delta^{ab}\delta^{cd}\delta_{ij} f^{i_{||}}{}_{a_\perp c_\perp} f^{j_{||}}{}_{b_\perp d_\perp}}$:

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$$\mathcal{R}_4 + \frac{3}{2}\ \tau\partial_\tau V|_0 + \frac{A+B}{A-B}\ \rho\partial_\rho V|_0 + \frac{2}{B-A}\ \sigma\partial_\sigma V|_0$$
$$+ 2\left|*_\perp H^{(0)} + \varepsilon_p g_s F^{(0)}_{k-2}\right|^2 + 2\sum_{a_{||}}\left|*_\perp(\mathrm{d}e^{a_{||}})|_\perp - \varepsilon_p g_s\, \iota_{a_{||}} F^{(1)}_k\right|^2$$
$$= -\,2g_s^2\left(|F_{k+2}|^2 + |F_{k+4}|^2\right) + 2\,\lambda |f^{||}{}_{\perp\perp}|^2\ ,$$

$$\mathcal{R}_4 + \frac{1}{2}\frac{A-5B}{A-3B}\ \tau\partial_\tau V|_0 + \frac{1}{3}\ \rho\partial_\rho V|_0 + \frac{2}{3(A-3B)}\ \sigma\partial_\sigma V|_0$$
$$= -\,\frac{2}{p}(\lambda-1)|f^{||}{}_{\perp\perp}|^2 - \frac{2}{p}|H^{(2)}|^2 - \frac{2}{p}\, g_s^2 \frac{1}{2}\sum_{q=6-p}^{p}(q-(6-p))\ |F_q|^2\ .$$

David ANDRIOT

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\end{aligned}$$

$\hookrightarrow$ no de Sitter solution on nilmanifold, semi-simple group manifold, some solvmanifolds (in standard basis).

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Not conclusive for $0 < \lambda < 1 \Rightarrow$ possibilities left.

Stability island:

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a de Sitter solution would have $\partial_\rho^2 V|_0 > 0$, $\partial_\tau^2 V|_0 > 0$, $\partial_\sigma^2 V|_0 > 0$ for

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We show e.g. for τ:

$$\begin{aligned} &\frac{1-10\lambda}{2}\ \mathcal{R}_4 + \frac{3-32\lambda}{4}\ \tau\partial_\tau V|_0 + \frac{6-p}{6}\ \rho\partial_\rho V|_0 + \frac{1}{6}\ \sigma\partial_\sigma V|_0 \\ &+ (1-\lambda)\left(\left| *_\perp H^{(0)} + \varepsilon_p g_s F^{(0)}_{k-2} \right|^2 + \sum_{a_{||}} \left| *_\perp (\mathrm{d}e^{a_{||}})|_\perp - \varepsilon_p g_s\ \iota_{a_{||}} F^{(1)}_k \right|^2 \right) \\ &- \lambda\ \tau^2 \partial_\tau^2 V|_0 \\ = &- \lambda |H^{(0)}|^2 - (1-\lambda+8\lambda(p-6)) g_s^2 |F^{(2)}_{10-p}|^2 - (1-17\lambda) g_s^2 |F^{(3)}_{12-p}|^2\ , \end{aligned}$$

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i.e. $\partial_\tau^2 V|_0 > 0$ for a de Sitter solution.

$\Rightarrow$ Tiny region of parameter space where **possible stable de Sitter solutions** (with parallel D_p/O_p)
$\hookrightarrow$ explore!

Summary

- (Refined) de Sitter conjecture / swampland criterion
- Positive aspect: focus on connection of string theory and cosmology
- Get, in a controlled manner, de Sitter vacua from string theory? $\Rightarrow$ Progress...

- Precise checks with constraints on classical 10d de Sitter solutions
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- Explore more intersecting D_p/O_p

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Thank you for your attention!