Classical string backgrounds with a de Sitter spacetime and swampland conjectures

David ANDRIOT

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Based on arXiv:2101.06251
arXiv:2004.00030 (with N. Cribiori, D. Erkinger)
arXiv:2005.12930, 2006.01848 (with P. Marconnet, T. Wrase)
+ work in progress

Théorie, Univers et Gravitation
14/12/2021, IHP, Paris, France

Introduction

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Future (ΛCDM): completely dominated by dark energy
$\hookrightarrow$ 4d **de Sitter spacetime**: $\mathcal{R}_4 = 4\Lambda > 0$.
Gravitational description:

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Accelerated expansion in **early universe**: inflation models
Scalar field(s) ϕ^i coupled to gravity:

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

Models in agreement with observations: single-field slow-roll inflation, plateau $V(\phi)$: $\partial_\phi V \approx 0$, $V \sim$ constant.
$\hookrightarrow$ **de Sitter spacetime**: $\partial_\phi V|_0 = 0$, $\mathcal{R}_4 = 4\Lambda = \frac{4}{M_p^2} V|_0 > 0$.

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$V(\phi)$ can mimick Λ (for some duration) $\Rightarrow$ the case today?
$\hookrightarrow$ **quintessence models**.

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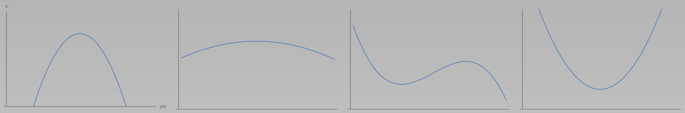
Important aspect for cosmological models: duration
$\rightarrow$ **stability** of $V(\phi)$ around de Sitter point



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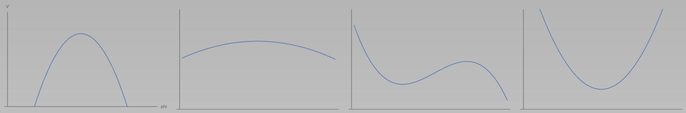

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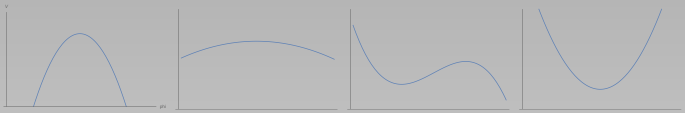

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Stability captured by $\partial_\phi^2 V|_0$, or more precisely (single field)

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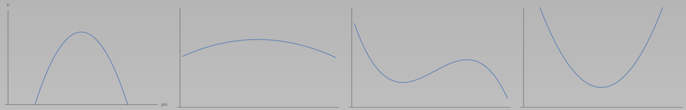

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Obs. slow-roll single field inflation: $\eta_V \sim -0.01$, $\epsilon_V \sim 0.001$.

Planck Collaboration [arXiv:1807.06211]

Multi-field inflation: different values possible, ✓ obs. Difficult to realise in supergravity?

V. Aragam, R. Chiovoloni, S. Paban, R. Rosati, I. Zavala [arXiv:2110.05516]

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Various approaches: KKLT, LVS (non-pert.)...
Here: focus on classical perturbative regime,
i.e. **classical de Sitter string backgrounds**.

D. A. [arXiv:1902.10093]

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

Effective theory: 10d supergravity
Look for solutions: 10d = 4d de Sitter $\times$ 6d compact space $\mathcal{M}$ + curvature ($\mathcal{R}_6$), fluxes, sources (D_p-branes, O_p-planes)

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- **Existence**: Few 10d supergravity de Sitter solutions: "candidate" solutions, despite no-go theorems.
  But no proper classical string background known.
- **Stability**: before 2021: observe on "candidate" de Sitter solutions: $\eta_V \leqslant -1 \rightarrow$ **very unstable**
  $\hookrightarrow$ Prove that always true? Stability no-go theorem?

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- **Existence**: no de Sitter solution in the asymptotics

  TCC bound: $M_p \; \frac{|\partial_\phi V|}{V}_{\phi\rightarrow\infty} \geqslant c \geqslant \sqrt{\frac{2}{3}}$

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

  (see however multifield proposal T. Rudelius [arXiv:2101.11617])
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Existence constraints (TCC bound) on **solid grounds** thanks to no-go theorems D. Andriot, N. Cribiori, D. Erkinger [arXiv:2004.00030]

(in a large region of parameter space)

→ **no-go theorems for stability?**
↪ clarify / check swampland proposals?
↪ characterise cosmological models?

Existence of classical de Sitter solutions

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Parameter space and no-go theorems

(A standard ansatz: intersecting O_p/D_p sources, 6d compact group manifold, constant fluxes)
Parameter space: p size of D_p/O_p sources, $\mathcal{R}_6$ 6d curvature

p	$\mathcal{R}_6 \geqslant 0$	$\mathcal{R}_6 < 0$
3	$\times$	$\times$
4	$\times$	??
5	$\times$	??
6	$\times$	??
7	$\times$	$\times$
8	$\times$	$\times$
9	$\times$	$\times$

$\times$: no-go theorem! ??: possible, constrained.
Constraints obtained with 5 supergravity equations (e.o.m., BI)

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]

$\hookrightarrow$ **excluded in many cases**.
Remaining region: $\mathcal{R}_6 < 0$, $p = 4, 5, 6$, $F_{6-p} \neq 0$, ... $\rightarrow$ **sol.?**

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

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Relate supergravity constraints to **swampland conjectures**?
$\Rightarrow$ put them in swampland conjecture format!

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

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

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$\rightarrow$ 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.)	$\mathcal{R}_{\|\|} + \mathcal{R}_{\|\|}^{\perp} + \frac{\sigma^{-12}}{2}\|f^{\|\|}{}_{\perp\perp}\|^2 \leqslant 0,\ p \geqslant 4$	$\sqrt{\frac{2(p-3)}{p-1}} \geqslant \sqrt{\frac{2}{3}}$
(6.)	$-2\rho^2\sigma^{2(p-6)}(\mathcal{R}_{\|\|} + \mathcal{R}_{\|\|}^{\perp}) + \|H^{(2)}\|^2 \leqslant 0$	$2\sqrt{\frac{2}{3}}$
(7.)	$\lambda \leqslant 0,\ p \geqslant 4$	$\sqrt{\frac{2}{3}}$
(9.)	$\exists\, a_{\|\|}$ s.t. $f^{a_{\|\|}}{}_{ij} = 0\ \ \forall i, j \neq a_{\|\|},\ p \geqslant 4$	$\sqrt{\frac{2}{3}}$

TCC bound always satisfied! Sometimes with saturation.

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

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Aparte: **web of swampland conjectures** $\rightarrow$ translate the obstruction on classical de Sitter to another conjecture?
$\hookrightarrow$ the **distance conjecture** $\rightarrow$ bound on parameter λ

$$\text{4d}: \quad \lambda \geqslant \lambda_0 = \frac{1}{2}\sqrt{\frac{2}{3}} = \frac{1}{\sqrt{6}} \ , \quad \lambda_0 = \frac{1}{2} c_0$$

$$\text{asymptotic claims:} \quad m \sim V^{\frac{1}{2}}$$

Verified in all examples!

T. W. Grimm, E. Palti, I. Valenzuela [1802.08264]
...
A. Ashmore, F. Ruehle [2103.07472]

Looking for classical de Sitter solutions

Remaining region of par. space: $p = 4, 5, 6$. Or multiple sizes.
Two steps:

1.

2.

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Two steps:

1. find 10d supergravity de Sitter solution ("candidate"):

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

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Two steps:

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C. Caviezel, P. Koerber, S. Kors, D. Lüst, T. Wrase, M. Zagermann [arXiv:0812.3551],
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C. Caviezel, T. Wrase, M. Zagermann [arXiv:0912.3287],
U. H. Danielsson, P. Koerber, T. Van Riet [arXiv:1003.3590],
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D. Andriot [arXiv:2101.06251]

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

Teaser: D. Andriot, L. Horer, P. Marconnet, work in progess
More general and systematic search for de Sitter solutions:
Solutions with 1 O_4, 1 O_6, 1 D_6...

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2. verify that in classical string regime: small g_s, large vol$_6$...

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!**

Classical regime of string theory

Comments:

- Why not working? A general property of string theory?

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  - KKLT: “The tadpole problem”
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Summary on existence:

- No-gos, match swampland conjectures
- Remaining region → find de Sitter supergravity solutions
- Classical regime analysis

Stability of classical de Sitter solutions

D. Andriot [arXiv:2101.06251]

10d supergravity de Sitter solutions (< 2021) are all pert. **unstable**: 4d tachyon, maximum of V, $\eta_V < -1$.
$\hookrightarrow$ **Always the case?** (cosmology, swampland conjectures...)

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Multifield: mass matrix $\hat{M}^i{}_j = \delta^{ik} \partial_{\hat{\phi}^k} \partial_{\hat{\phi}^j} V$

$$\eta_V = M_p^2 \ \frac{\text{Min}\nabla\partial V}{V}$$

where $\text{Min}\nabla\partial V =$ **minimal eigenvalue** of $\hat{M}$.

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Proving $\eta_V < 0, -1$:

Get sign/upper bound on eigenvalue(s) of $\hat{M}$

Problem: 4×4 matrix $\rightarrow$ simple information on eigenvalues? Use mathematical results...

Interesting proposal of U. H. Danielsson, G. Shiu, T. Van Riet, T. Wrase [arXiv:1212.5178] , further studied in D. Junghans [arXiv:1603.08939]:

The tachyon lies among $(\rho, \tau, \sigma_{I=1\ldots N})$.

Claim verified in many examples.
Proof of **systematic tachyon**? Sufficient to study $V(\rho, \tau, \sigma_I)$

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Use mathematical results and prove: for any real $(\hat{c}_{\hat{\rho}}, \hat{c}_{\hat{\tau}}, \hat{c}_{\hat{\sigma}_1}, \hat{c}_{\hat{\sigma}_2})$

$$\left(\hat{c}_{\hat{\rho}}\partial_{\hat{\rho}} + \hat{c}_{\hat{\tau}}\partial_{\hat{\tau}} + \hat{c}_{\hat{\sigma}_1}\partial_{\hat{\sigma}_1} + \hat{c}_{\hat{\sigma}_2}\partial_{\hat{\sigma}_2}\right)^2 V < 0 \ \Rightarrow \ \eta_V < 0, \ \textbf{instability}$$

In addition, if

$$V + \left(\hat{c}_{\hat{\rho}}\partial_{\hat{\rho}} + \hat{c}_{\hat{\tau}}\partial_{\hat{\tau}} + \hat{c}_{\hat{\sigma}_1}\partial_{\hat{\sigma}_1} + \hat{c}_{\hat{\sigma}_2}\partial_{\hat{\sigma}_2}\right)^2 V < 0 \ \Rightarrow \ \eta_V < -\frac{1}{\hat{c}_{\hat{\rho}}^2 + \hat{c}_{\hat{\tau}}^2 + \hat{c}_{\hat{\sigma}_1}^2 + \hat{c}_{\hat{\sigma}_2}^2}$$

$\rightarrow$ get a **bound** on η_V.
Single field interpretation of $\hat{c}_{\hat{\phi}^i}\partial_{\hat{\phi}^i}$ as **tachyonic direction**

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$$\partial_{\hat{t}_c}^2 V < 0$$

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Is there a **universal tachyon**, i.e. a fixed combination $\hat{t}_c$?

Study in IIB framework with O_5/D_5, where 17 solutions found

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

$$\frac{2}{M_p^2} V(\rho,\tau,\sigma_1,\sigma_2) = -\tau^{-2}\rho^{-1}\mathcal{R}_6(\sigma_1,\sigma_2)$$

$$+ \frac{1}{2}\tau^{-2}\rho^{-3}\left(\sigma_2^6\sigma_1^{12}\,|H^{(0)_1}|^2 + \sigma_1^6\sigma_2^{12}\,|H^{(2)_1}|^2\right)$$

$$- g_s\,\tau^{-3}\,\rho^{-\frac{1}{2}}\left(\sigma_1^{-4}\sigma_2^2\,\frac{T_{10}^1}{6} + \sigma_1^2\sigma_2^{-4}\,\frac{T_{10}^2}{6} + \sigma_1^2\sigma_2^2\,\frac{T_{10}^3}{6}\right)$$

$$+ \frac{1}{2}g_s^2\,\tau^{-4}\left(\rho^2(\sigma_1\sigma_2)^{-2}|F_1|^2 + |F_3|^2 + \rho^{-2}(\sigma_1\sigma_2)^2|F_5|^2\right)$$

$$\mathcal{R}_6(\sigma_1,\sigma_2) = R_1\,\sigma_1^{-8}\sigma_2^4 + R_2\,\sigma_1^4\sigma_2^{-8} + R_3\,\sigma_1^4\sigma_2^4 + \dots$$

$\rightarrow$ go to canonical basis $\phi^i \rightarrow \hat{\phi}^i$

$$\mathcal{S} = \int \mathrm{d}^4x\sqrt{|g_4|}\left(\frac{M_p^2}{2}\mathcal{R}_4 - \frac{M_p^2}{2}\left((\partial\hat{\rho})^2 + (\partial\hat{\tau})^2 + (\partial\hat{\sigma}_1)^2 + (\partial\hat{\sigma}_2)^2\right) - V\right)$$

with $V(\hat{\rho},\hat{\tau},\hat{\sigma}_1,\hat{\sigma}_2)$

David ANDRIOT

Introduction

Existence

Stability

Conclusion

Result: **no universal tachyon** (for all 17 solutions)
Rather: several different

Similar to existence no-gos: here, parameter space (partially) covered by different assumptions capturing different stability no-go theorems and corresponding tachyons.

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We find 13 (interesting) sufficient **conditions $C1 - C13$ for tachyons**. For example: $C7$

$$\frac{439}{4} g_s^2 |F_1|^2 + \frac{421}{4} g_s^2 |F_3|^2 + \frac{439}{4} g_s^2 |F_5|^2 - 72 R_3 - \frac{1675}{96} g_s T_{10} + \frac{3}{2} g_s T_{10}^3 \leqslant 0$$

$\leftrightarrow$ sufficient condition for a tachyon on dS extremum with

$$c_{\sigma_1} = c_{\sigma_2} = 1 \ , \ c_\rho = \frac{7}{2} \ , \ c_\tau = \frac{9}{2}$$

Obeyed by **14 of the 17 solutions** with O_5/D_5. No universal condition obeyed by all known solutions.

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$$\eta_V \leqslant -\frac{8}{567} \approx -0.0141093$$

Bounds range: $[-\frac{4}{3}, -\frac{25}{3422}] \approx [-1.33333, -0.00730567]$
$\hookrightarrow$ **not conclusive** for phenomenology nor swampland...

$\Rightarrow$ different parts of a parameter space!

$\hookrightarrow$ Solutions **counter-examples?** Violate assumptions...

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Condition $C11$, obeyed by 16 solutions on 17 with O_5/D_5

$$-2R_3(g_s^2|F_1|^2 - \mathcal{R}_4) - g_s^2|F_1|^2\mathcal{R}_4 < 0$$

$\hookrightarrow$ search for solutions violating this condition

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$\hookrightarrow$ we obtain **10 new de Sitter solutions, new physics**

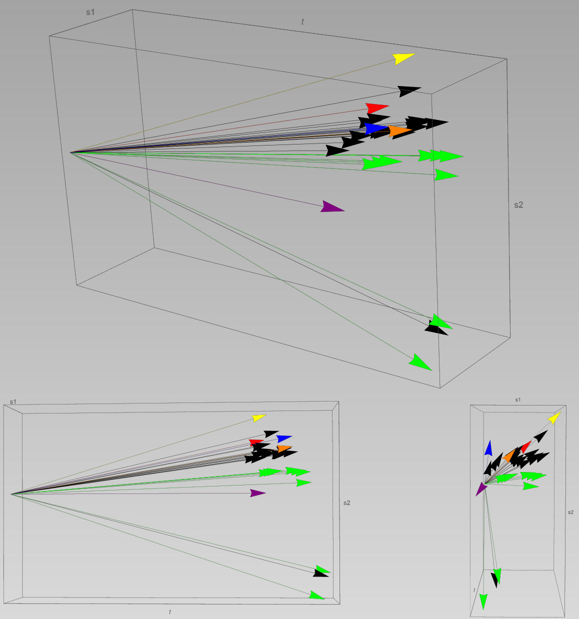
- New solutions on compact $\mathcal{M}$ with η_V up to -0.90691.
- One solution with $\eta_V = -0.12141$! Compact $\mathcal{M}$!

D. Andriot, L. Horer, P. Marconnet, work in progess

- One solution with $\eta_V = 3.7926$! But $\mathcal{M}$ non-compact. Still, first "stable" (geometric) solution of this kind $\Rightarrow$ compactness plays a role in proof...

$\hookrightarrow$ look in the **remaining regions** to find new interesting examples...

Tachyonic directions of solutions and no-gos



black: 17 old sol.; green + blue: 10 new sol.; others: no-gos

Conclusion

Existence, stability of classical dS string backgrounds?

For both existence and stability: formalism and methods to get formal constraints
Several no-go theorems that cover partially parameter space: $\rightarrow$ no de Sitter solution, instability.

For both: **remaining regions** to explore: to find (classical?) de Sitter solutions, (stable?)

Difference between existence and stability: **bounds**:

$$\epsilon_V \geqslant \frac{1}{3} \ , \qquad \eta_V <?$$

$\hookrightarrow$ good for TCC? Good for phenomenology?

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Thank you for your attention!