# Scalar potentials from (classical) string theory

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2208.14462 (with L. Horer)
2209.08015 (with P. Marconnet, M. Rajaguru, T. Wrase)
2212.04517 (with L. Horer, G. Tringas)
2305.07480 and more…

String Pheno 2023 - 03/07/23 IBS, Daejeon, South Korea


JET LAG
WARNING JET LAG

# Introduction

Consider 4d theory of scalar fields $\varphi^i$ with scalar potential $V$ :

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

minimally coupled to gravity.

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Properties: $V > 0,\ V < 0$

$\partial_\varphi V = 0\ ,\ \partial_\varphi V \neq 0\ ,\ \nabla V$ Critical points (dS, AdS), slope (steep/flat), single/multi-field

$V''\ ,\ g^{ij} \nabla_j \partial_k V\ ,\ m^2$ Stability, mass spectrum

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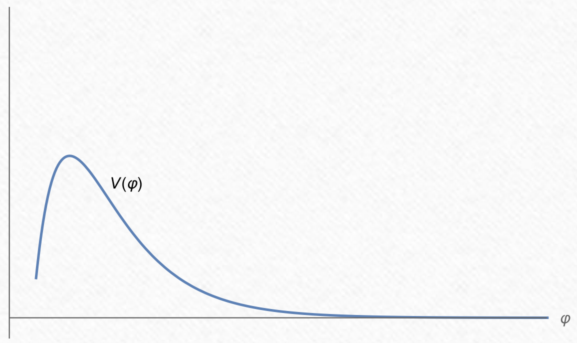
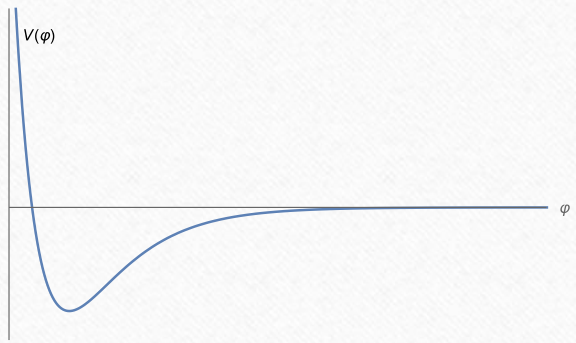
2 motivations:

- Swampland program (characterisation of Q.G. EFTs)
- String Pheno $\longrightarrow$ cosmology (accelerated expansion phases, dark energy).

dS solution $\longleftrightarrow$ cosmo. constant $\Lambda = V > 0$ , single-field flat $V$ $\longleftrightarrow$ inflation

Consider $V > 0, \; V < 0$ with shape: (typical shape?)



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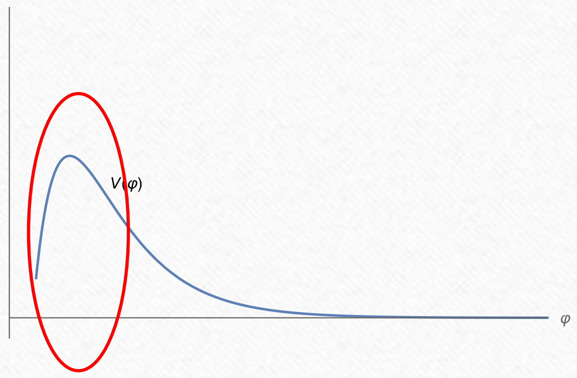


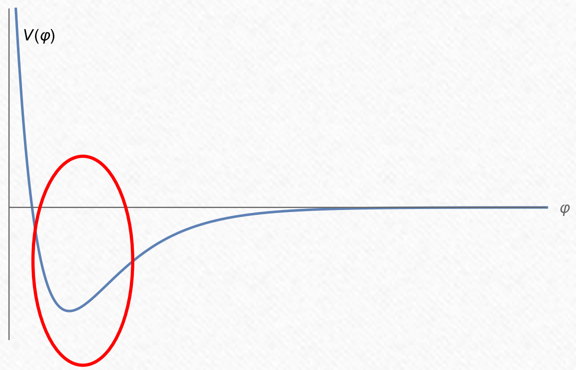


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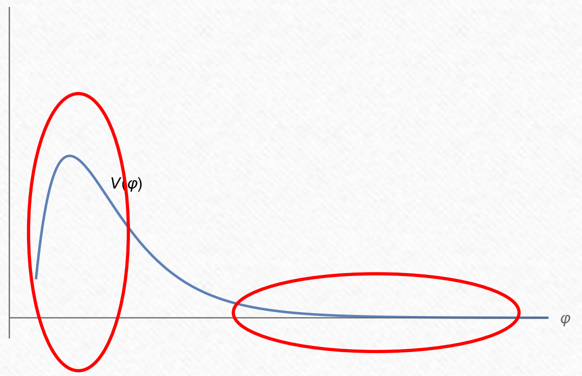


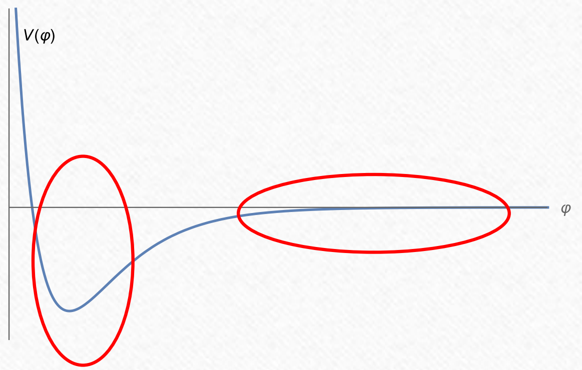


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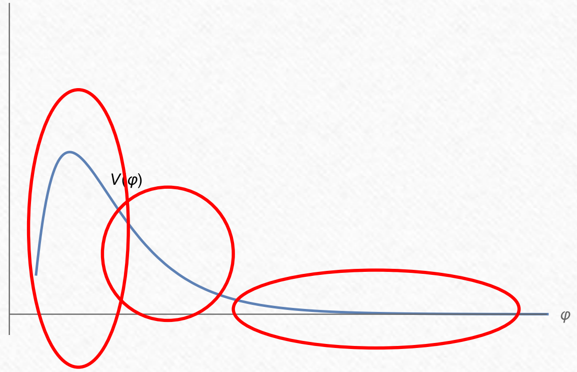


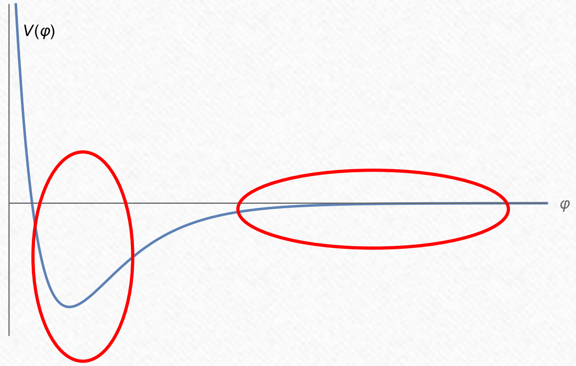


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**III. In between** – interesting, transcient physics? (species scale, bump, multifield inflation?)

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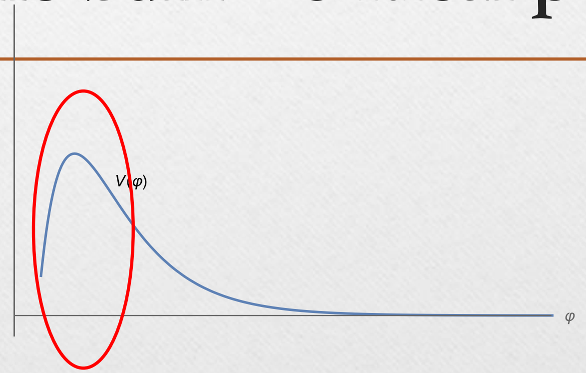

For $\varphi \sim e^{-\phi}, r/l_s$ , **bulk** of field space: strong coupling, stringy regime

**asymptotics**: weak coupling, low energy $\longrightarrow$ classical

But **classical regime** starts away from asymptotics / grey zone in the bulk at $e^{\phi} \lesssim 1,\ r/l_s \gtrsim 1$

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**KKLT, LVS**: include (non)-perturbative contributions ⟶ in the bulk

Kachru, Kallosh, Linde, Trivedi ’03, Conlon, Quevedo ’05

⟶ debate on validity of approximations/regimes/control

Recent LVS example in grey zone: C. Crinò, F. Quevedo, R. Valandro ’20 (see also Junghans ’22 Bento et al ’23)

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**1.** find solution in 10d supergravity: candidate solution

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**2.** verify that solution obeys $e^{\phi} < 1,\ r > l_s,\ ...$ Difficult to check

typically not well realised / boundary of validity /grey zone ⟶ in the bulk

(no parametric control)

From 10d supergravity solution (database IIA/B) $dS_4 \times$ 6d group manifold

$\longrightarrow$ dimensional reduction / consistent truncation to 4d theory with $V$

Automatized into code `MSSV.nb` : 10d solutions $\longrightarrow g_{ij}(\varphi^k),\ V(\varphi^k)$

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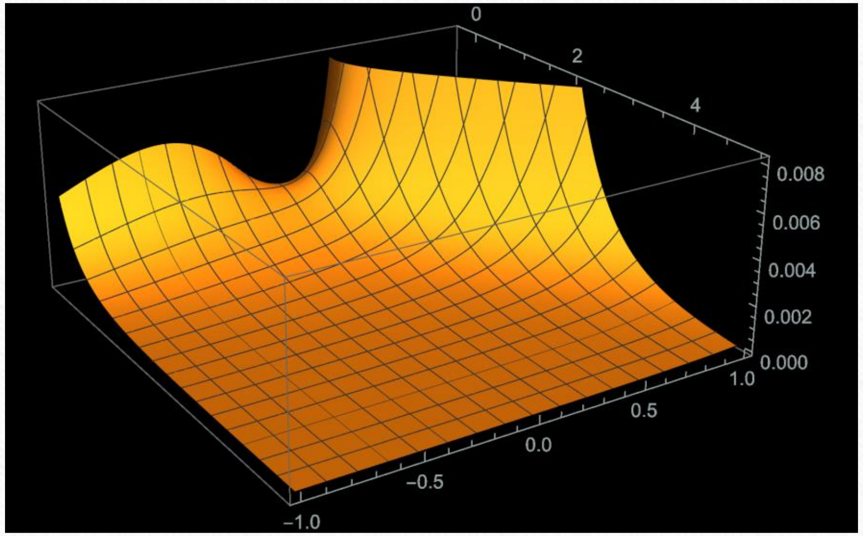

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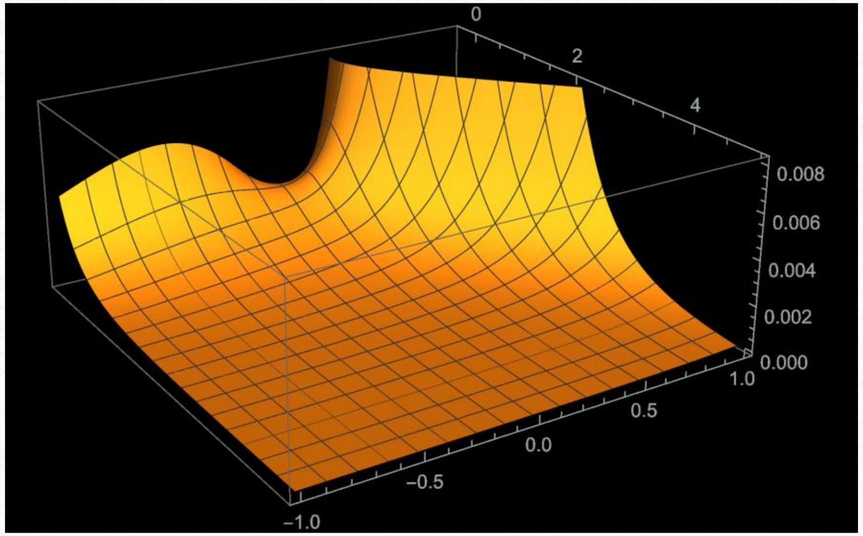

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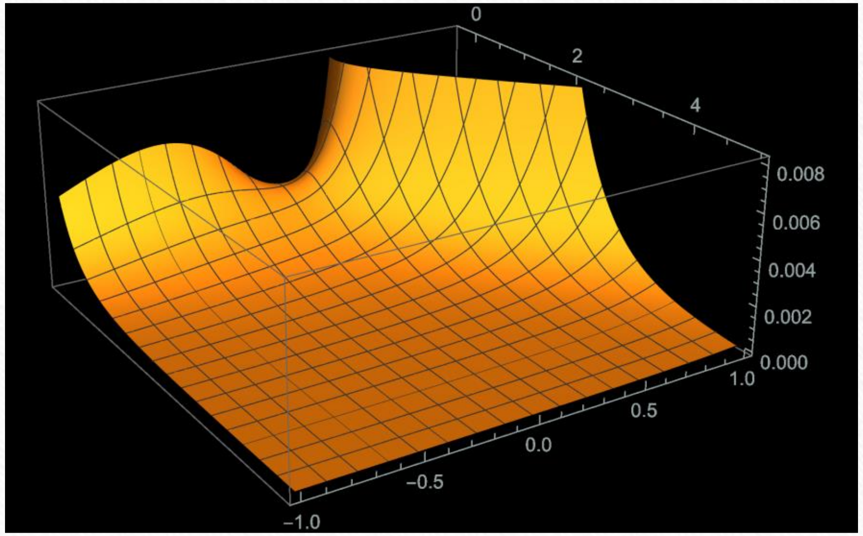


$$V^{\rm IIB}(\varphi^i) = \frac{M_p^2}{2}\frac{e^{2\phi}}{vol_6}\Bigg( - R_6 + \frac{1}{2}|H_3|^2_{\rm int} - e^{\phi} \sum_{p=3,5,7,9} \frac{T_{10}^{(p)}}{p+1} + \frac{e^{2\phi}}{2}\Big[ |F_1|^2_{\rm int} + \big|F_3 - C_0 \wedge H_3 + F_1 \wedge B_2\big|^2_{\rm int} + \Big|F_5 - C_2 \wedge H_3 + F_3 \wedge B_2 - C_0 \wedge H_3 \wedge B_2 + \frac{1}{2} F_1 \wedge B_2 \wedge B_2\Big|^2_{\rm int} \Big]\Bigg)$$

(also for Mink., AdS sol.)

⟶ check (in)stability

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


Very unstable: $\eta_V < -1$

⟶ not ok for single-field slow-roll inflation

multi-field, non-geodesic inflation?
(tuned) quintessence?

More dedicated searches of specific solutions? Andriot '21

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**Summary**: « classical » dS solutions: in the bulk, grey zone; unstable
At hand many examples of $g_{ij}(\varphi^k),\ V(\varphi^k)$ away from dS critical point.

Probably no dS$_d$ solution with $d > 4$ (related to susy) Andriot, Horer '22

**AdS solutions?** Many.
Critical points of $V<0$ in consistent truncations

Study of $V''$ , and mass spectrum (+ may involve KK modes)
$\longrightarrow$ claim: Andriot, Horer, Tringas ’22

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

Some justification from asymptotics of $V, V''$ (ATCC) ⟶ See talk Ludwig Horer

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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
$d = 6 : \; m^2 l^2 \geq -6.25$
$d = 7 : \; m^2 l^2 \geq -9$

**Susy** $\mathrm{AdS}_d$ (stable): $m^2l^2 \leq -2$ in most examples

| $\mathrm{AdS}_d$ | $\mathcal{N}$ | Specification | Spectrum reference | Scalar lowest $m^2 l^2$ |
|---|---|---|---|---|
| | | $\mathrm{AdS}_4$, M-th., with: | | |
| | 8 | $SO(8)$ | [47, Tab. 4] | $-9/4$ |
| | 2 | $SU(3)\times U(1)$ | | $-2.222$ |
| | 1 | $G_2$ | [48] | $-2.242$ |
| | 1 | $U(1)\times U(1)$ | | $-2.25$ |
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| | | $\mathrm{AdS}_4\times S^6$, IIA, with: | | |
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| | 2 | $SU(3)\times U(1)$ | | $-20/9$ |
| | 3 | $SO(3)\times SO(3)$ | [49, App. B] | $-9/4$ |
| $d=4$ | 1 | $SU(3)$ | [50, App. A] | $-20/9$ |
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| | 1 | DGKT, IIA | [37, 51] | $>0$ |
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| | 1 | KKLT, IIB | [35, 53] | $\geq 0$ |
| | 1 | LVS, IIB | [54, Sec. 2] | $\geq 0$ |
| | | S-fold, IIB, with: | | |
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Junghans '20, Marchesano, Palti, Quirant, Tomasiello '20

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Perturbatively stable **non-susy** $AdS_d$ : most examples: $m^2 l^2 \leq -1$

Non-perturbative instabilities…

Ooguri, Vafa '16

# II. The asymptotics – tail: slope

$V > 0$ : **de Sitter swampland conjecture**: $\frac{|V'|}{V} \geq c$ Obied, Ooguri, Spodyneiko, Vafa '18

Refinements $\longrightarrow$ only true in the **asymptotics** of field space

Trans-Planckian Censorship Conjecture (**TCC**): $\varphi \to \infty, \; \frac{|V'|}{V} \geq \sqrt{\frac{2}{3}} \approx 0.82$ Bedroya, Vafa '19

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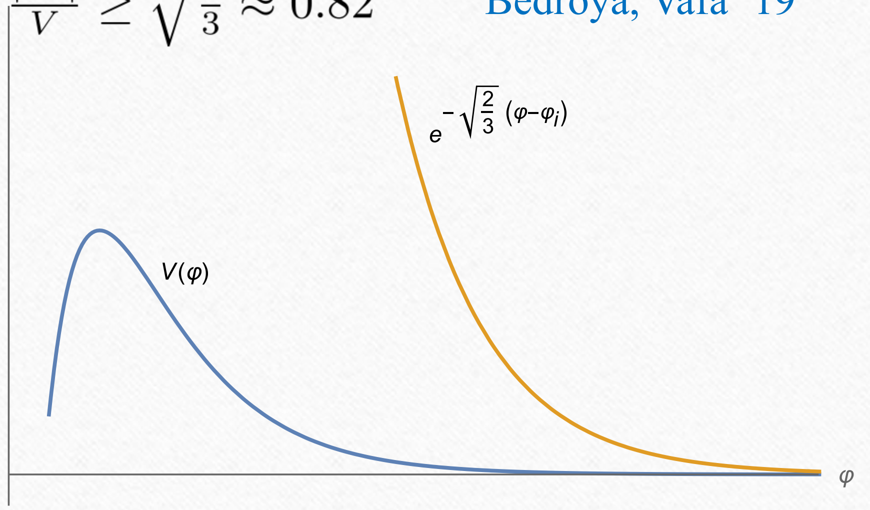

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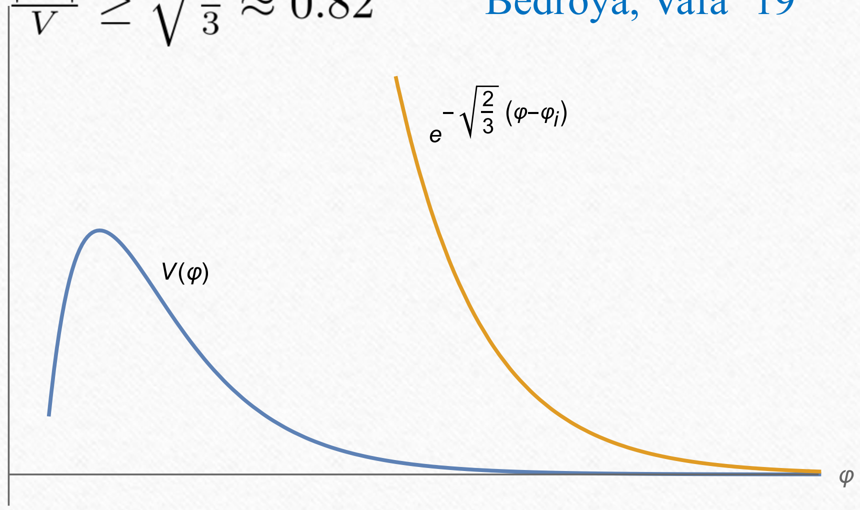


Asymptotics of field space ~ string classical regime

Obstruction to dS in the asymptotics $\longleftrightarrow$ difficulties with classical dS

Link made precise with **supergravity no-go theorems**:

no-gos against $dS_d$ reformulated in the form $\frac{|V'|}{V} \geq c$ $\quad c \geq \frac{2}{\sqrt{(d-1)(d-2)}}$ Andriot, Horer '22

**Many supergravity compactif. potentials obey TCC bound** Andriot, Cribiori, Erkinger '20

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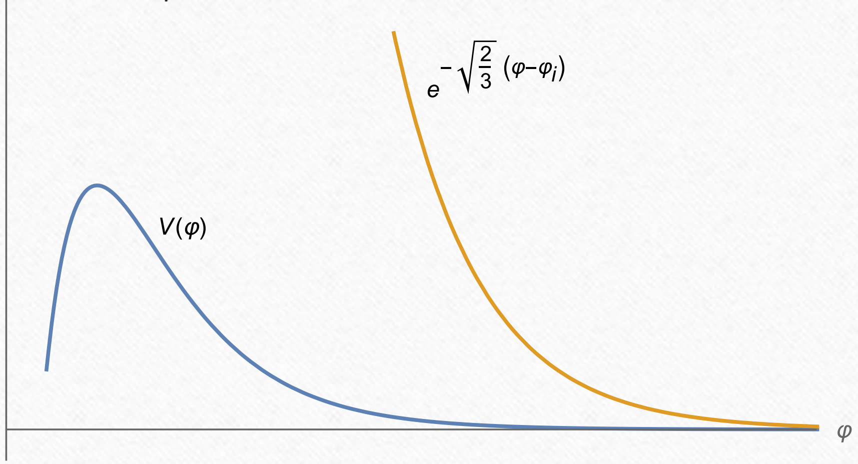


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(Possible exception: $\frac{|V'|}{V} \geq \sqrt{\frac{2}{7}} \approx 0.53$ Calderon-Infante, Ruiz, Valenzuela '22 )

(Multifield: Strong de Sitter conjecture: $\frac{\nabla V}{V} \geq \sqrt{2}, \frac{2}{\sqrt{d-2}}$ Rudelius '21, '22 )

→ **Cosmology in the asymptotics of field space?** Very difficult

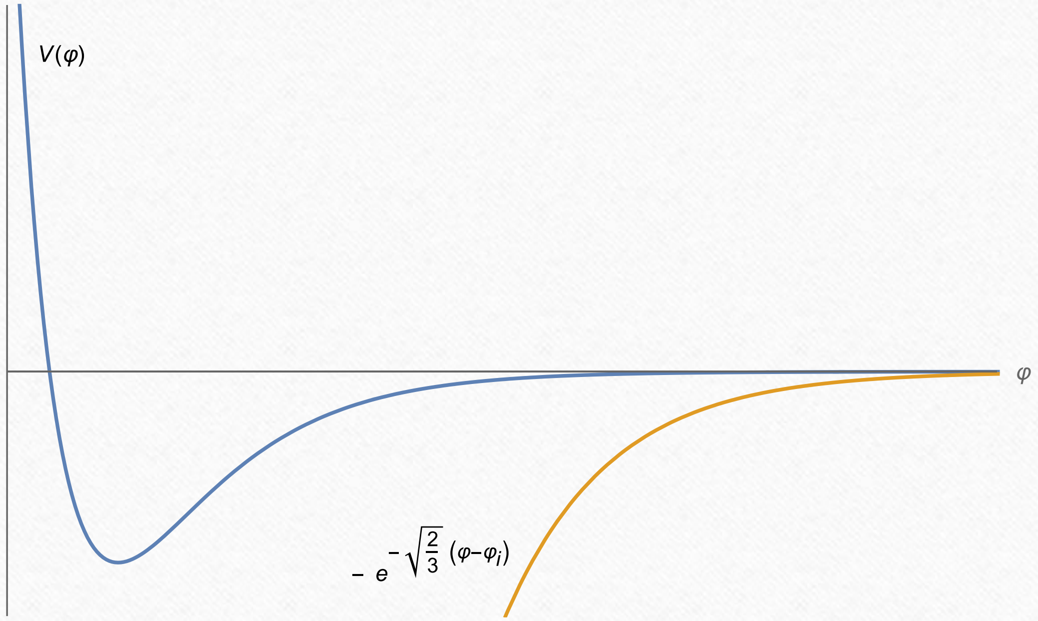
No slow-roll single-field inflation
Multi-field non-geodesic inflation?
Quintessence: very tight/boundary of possibility

…, Rudelius ’21, ’22, Andriot, Horer ’22, Calderon-Infante, Ruiz, Valenzuela ’22, Shiu, Tonioni, Tran ’23, Cremonini, Gonzalo, Rajaguru, Tang, Wrase ’23, ...

$V < 0$ : proposed Anti- Trans-Planckian Censorship Conjecture (**ATCC**) Andriot, Horer, Tringas '22

→ See talk Ludwig Horer

⟶ 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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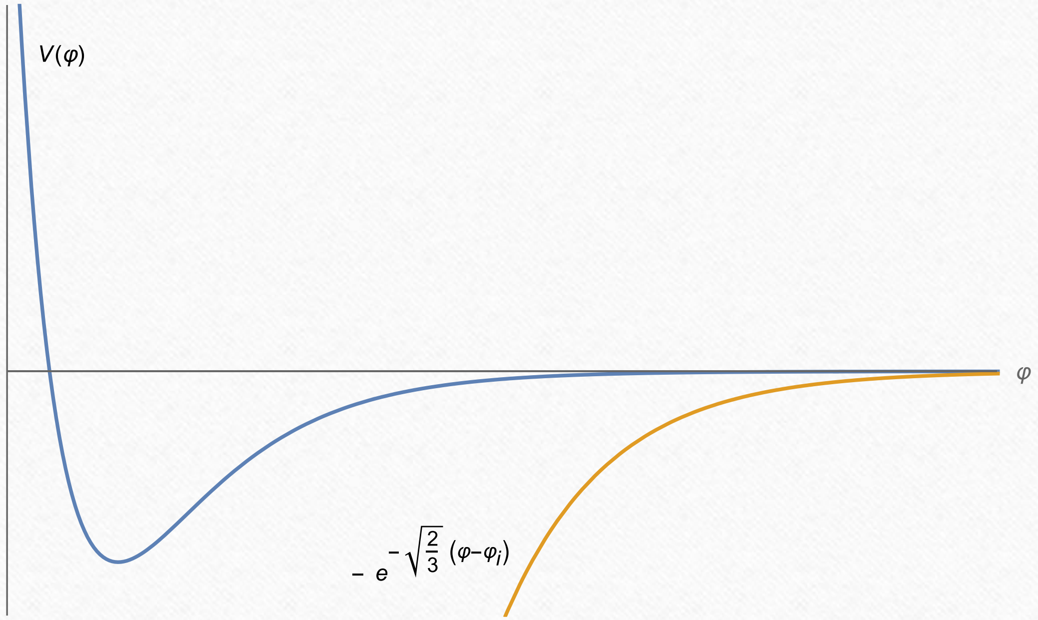
Well-tested in compactification examples:

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

One exception in stringy example?
Cremonini, Gonzalo, Rajaguru, Tang, Wrase '23



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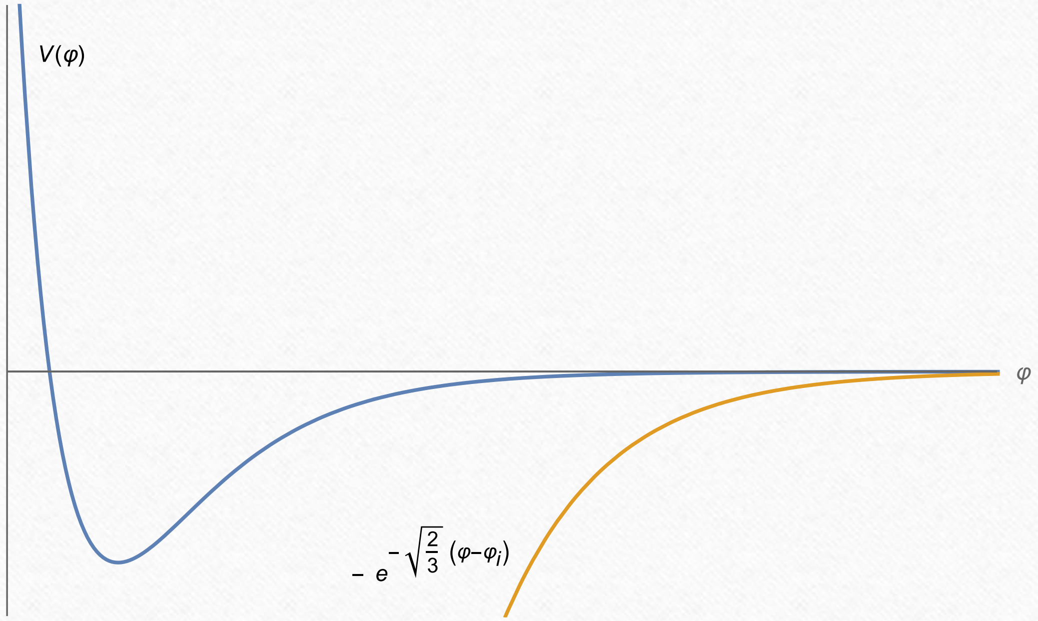
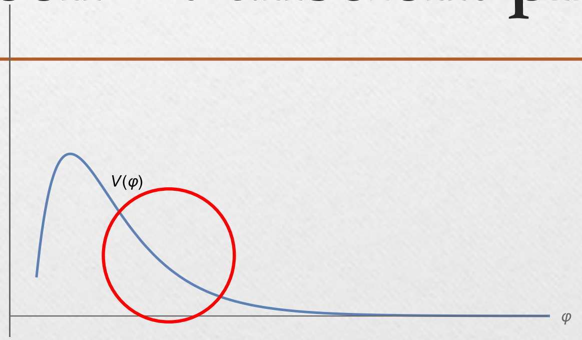
New asymptotic constraint on $V''$
→ AdS mass bound



# III. In between – transcient physics?



One motivation: comparison of $V$ to **species scale** $\Lambda_s$

Species scale: energy scale at which quantum gravity effects become relevant: $\Lambda_s < M_p$

Dvali, Gomez, Lüst, Redi '07-'10

Castellano, Herraez, Ibanez '21, '22, Long, Montero, Vafa, Valenzuela '21

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Typical EFT energy scale: $\frac{\sqrt{V}}{M_p}$

$\longrightarrow \Lambda_s \geq \frac{\sqrt{V}}{M_p}$ (see Hebecker, T. Wrase '18, M. Scalisi, I. Valenzuela '18)

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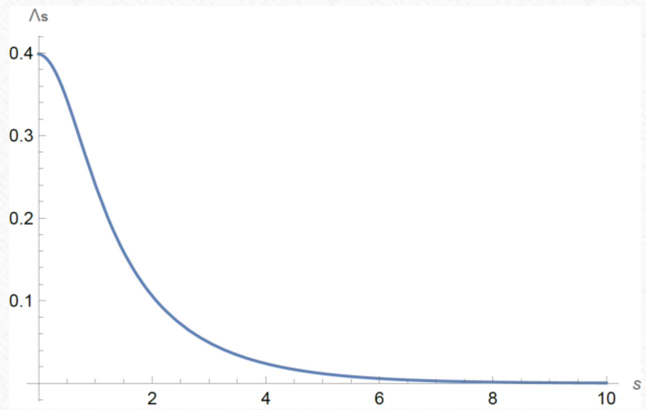
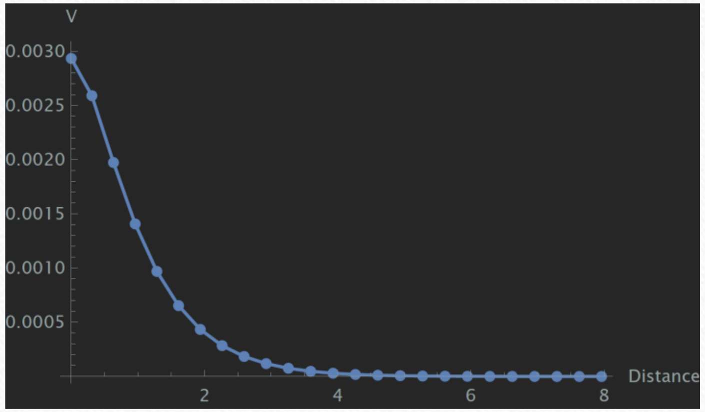
In addition: moduli dependence $\Lambda_s(\varphi)$ $\longrightarrow$ Compare to such a $V$ (dS max. in bulk, asympt. to 0) not so easy to find!

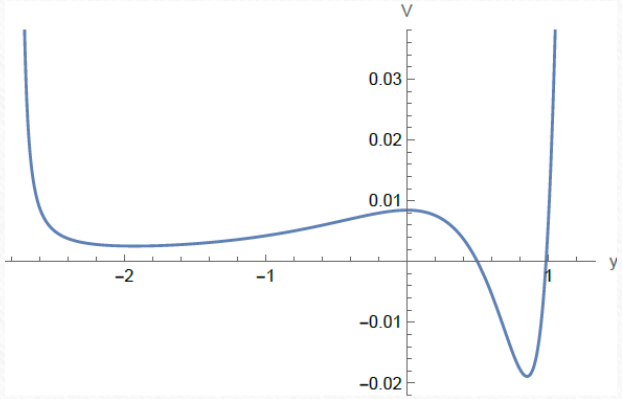
Behaviour:

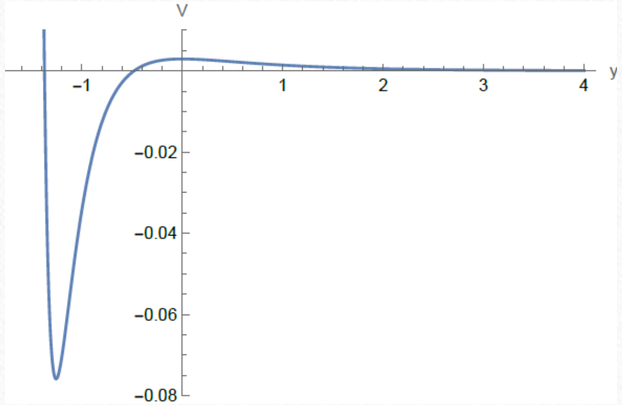


Use 10d supergravity dS solutions found + scalar potentials

Look at tachyonic direction (in classical regime direction): asymptotic behaviour?



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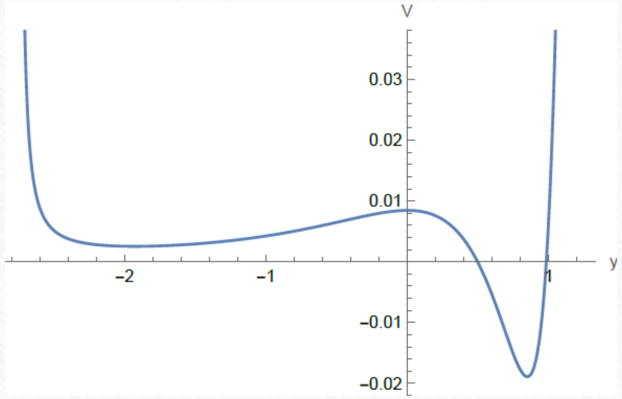
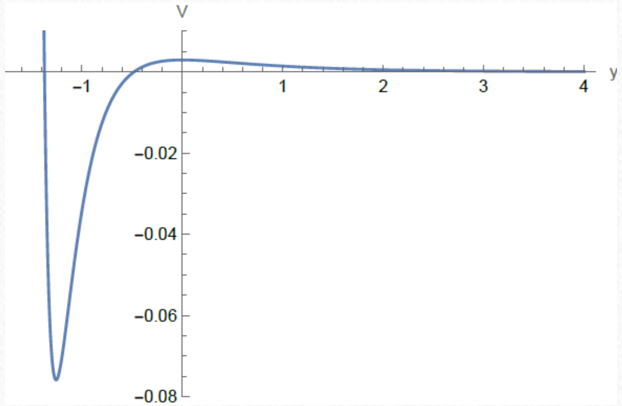


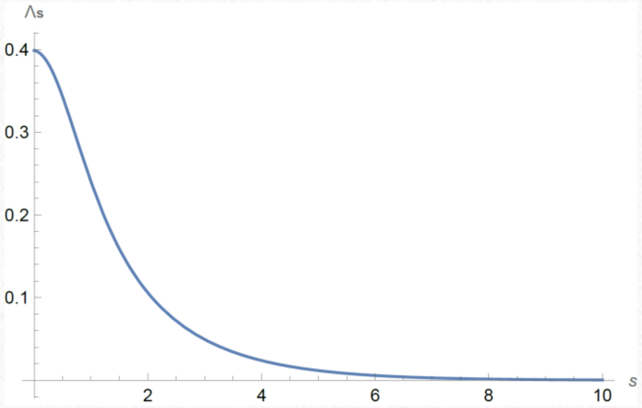



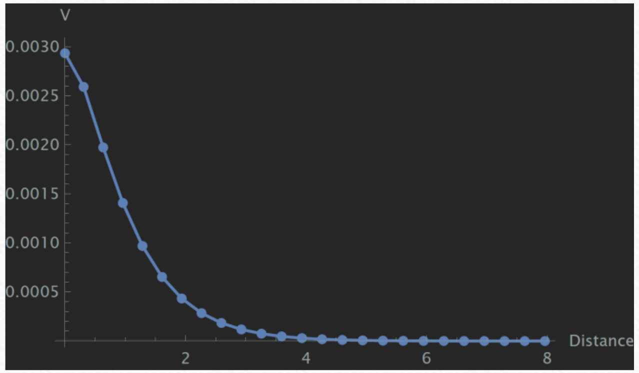

Use solution $m^{+}_{5577}4$

$V$ : 14 fields $\longrightarrow$ choose field trajectory

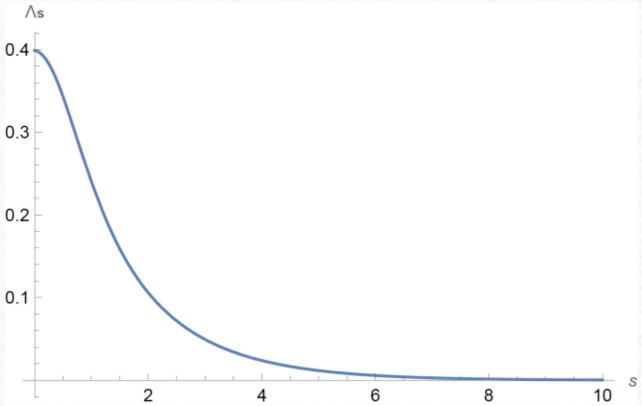
$\longrightarrow$ steepest descent path: starts with tachyonic direction, then deviates

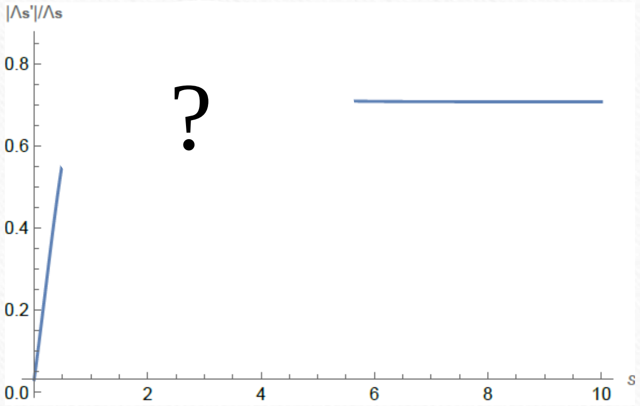
Compare $V$ and $\Lambda_s$


Λs
0.4
0.3
0.2
0.1
2
4
6
8
10
s

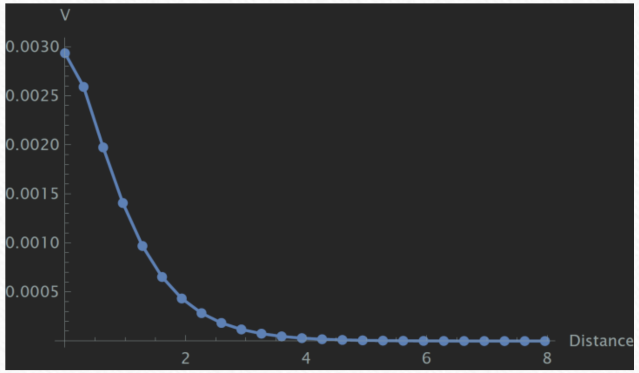

V
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
2
4
6
8
Distance

Interested in the rate $\frac{|\nabla\Lambda_s|}{\Lambda_s}$ van de Heisteeg, Vafa, Wiesner '23




**In between** region



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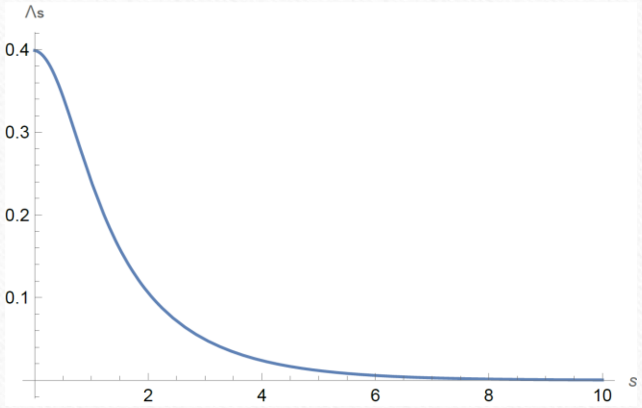
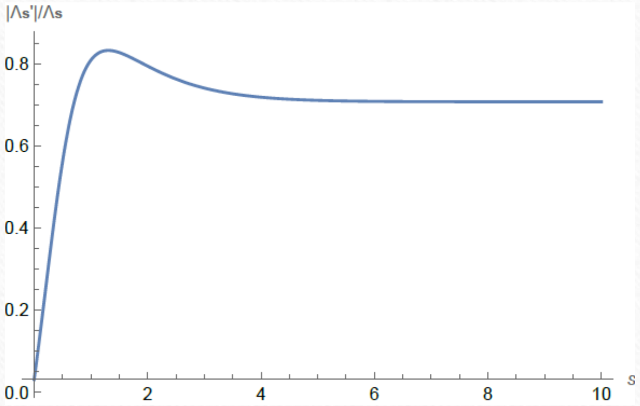
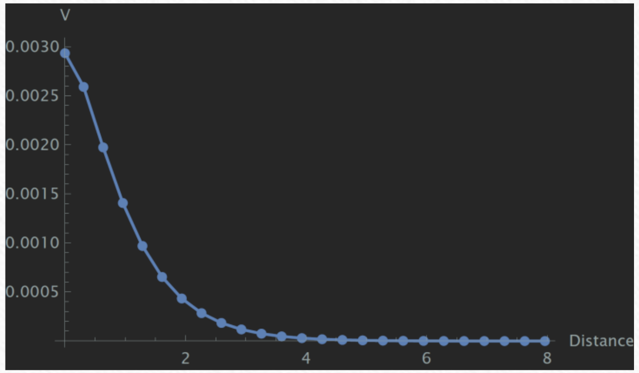



**In between** region : a bump in the rate!

$$\Lambda_s \propto e^{-\frac{c}{2}\hat{s}} + \frac{1}{2}\frac{\beta c}{\alpha}\, e^{-\frac{3c}{2}\hat{s}}\ \hat{s}$$

Bump due to linear dependence



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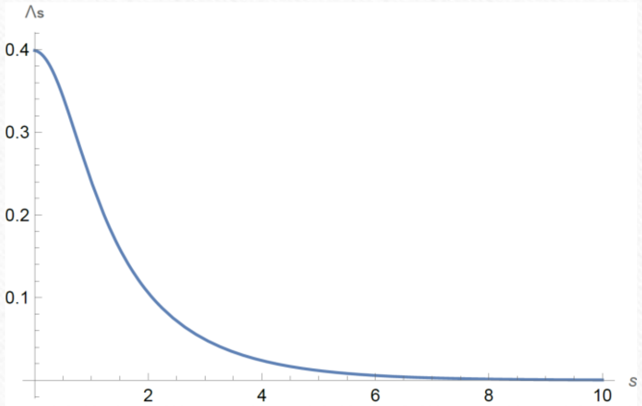


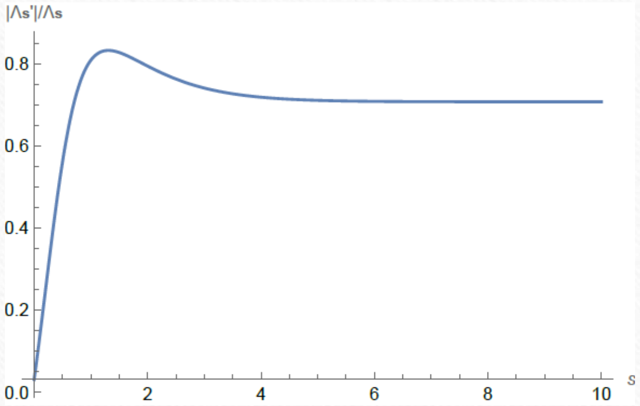


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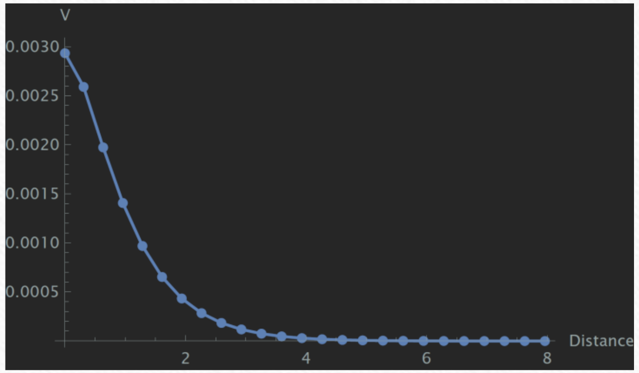
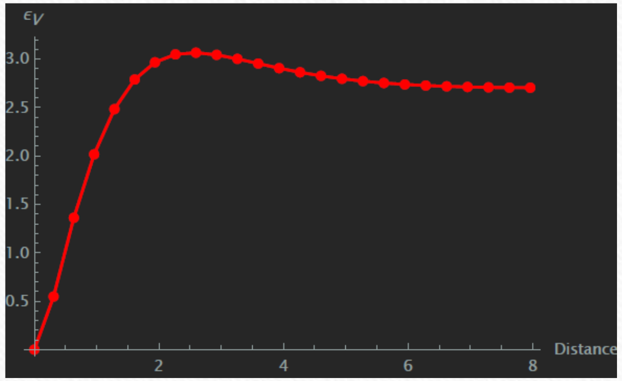
Now considering $V, \frac{|\nabla V|}{V}$ :




Origin of the bump?

Comparison:

$$\frac{|\nabla \Lambda_s|}{\Lambda_s} \leq \frac{|\nabla V|}{V}$$

Same origin?

14 fields + steepest descent trajectory:
difficult to identify relevant field direction / origin of bump

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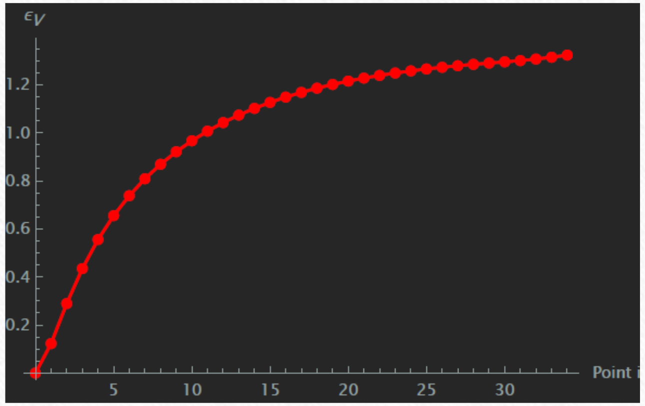
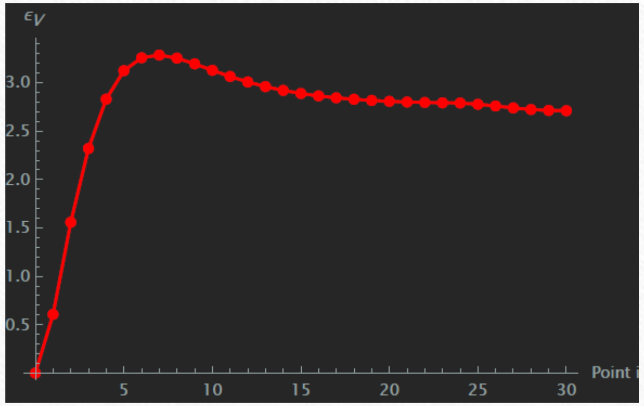
Show that not due to axion (linear dependence) but purely saxions (dilaton, radii, exponentials)



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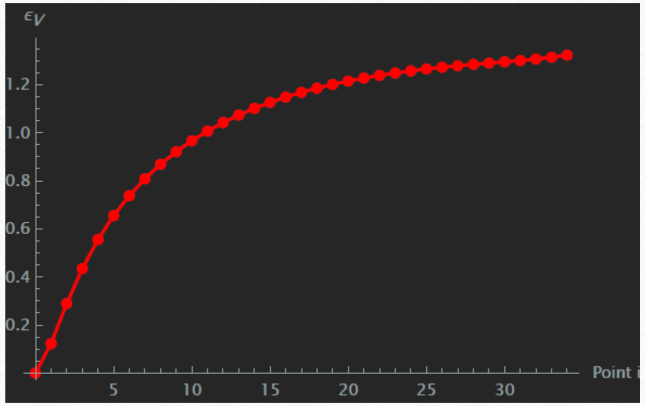
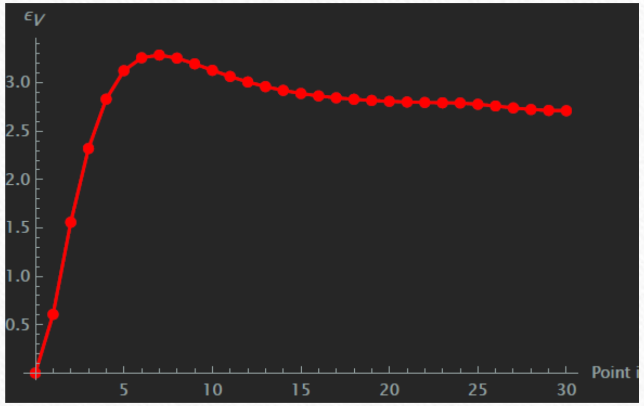
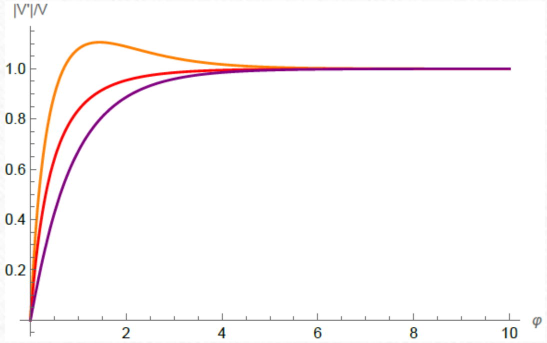



Show that purely exponential potential can generate bump:

$$V(\hat{\varphi}) = \sum_{i=1}^{n} A_i \; e^{a_i \hat{\varphi}} \; , \; a_1 < \cdots < a_n < 0 \; , \; A_n > 0$$

a bump in $|V'|/V$ if $A_{n-1} > 0$



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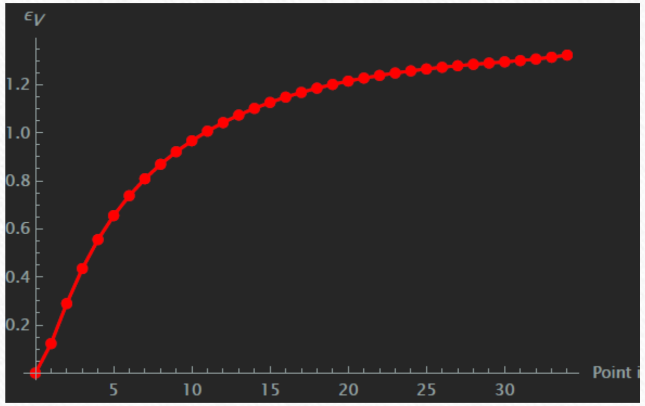


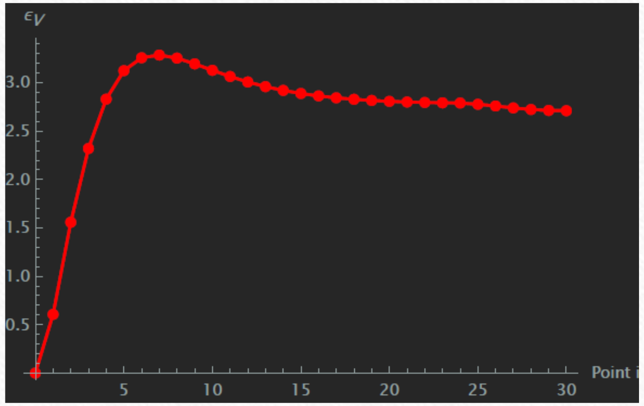


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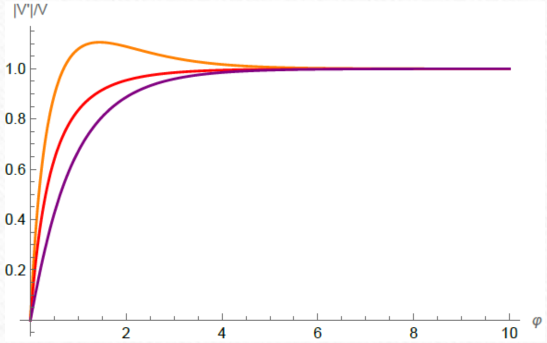
$\longrightarrow$ different origin




But… different compactification… Species scale on group manifold?

**In between** region and cosmology: realise valid **transcient** cosmological scenarios?

Transcient: see e.g. Marconnet, Tsimpis '22

Enough e-folds?

Slow-roll inflation points? Difficult: IIA: $\epsilon_V = 0.38306$ , $\eta_V = -0.16264$

Blaback, Danielsson, Dibitetto '13

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Blaback, Danielsson, Dibitetto ’13

Transcient, multi-field non-geodesic scenarios? $\longrightarrow$ Work in progress with Paul Marconnet

$\longrightarrow$ accelerated expansion is doomed to stop?!

# Summary

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

⟶ properties of $V$ ?

⟶ suited for realistic cosmology?

**I. The bulk**

- dS critical points typically in the bulk ⟶ difficult to trust
- Database of dS solutions with $V$ extending to classical regime
- Susy AdS$_d$ , $(d \geq 4)$: one scalar with mass: $m^2 l^2 \leq -2$

**II. The asymptotics** – tail

- TCC slope bound: well verified in supergravity compactif. $(d \geq 4)$
- Cosmology difficult in asymptotics
- ATCC: slope bound for $V < 0$

**III. In between**

- Comparison of $V, \ \Lambda_s$ , rates $\frac{|\nabla \Lambda_s|}{\Lambda_s}, \ \frac{|\nabla V|}{V}$ and bumps
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**Thank you for your attention!**

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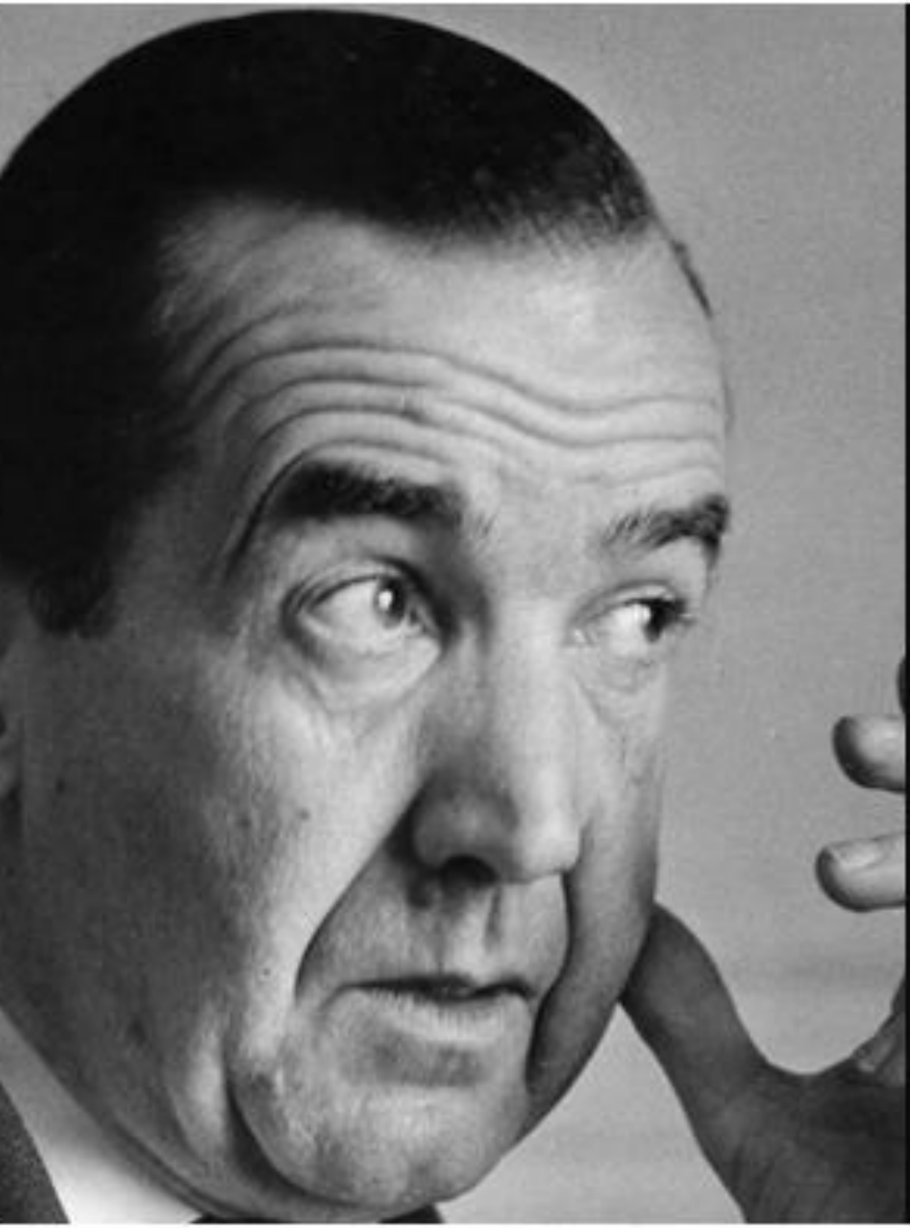

Good night, and good luck.

— Edward R. Murrow —

AZ QUOTES