Challenges of an accelerating universe in string theory

I. Antoniadis

LPTHE, Sorbonne Université, CNRS, Paris

and

Department of Mathematical Sciences, University of Liverpool

21st STRING PHENOMENOLOGY

Conference LIVERPOOL | 4 - 8 JULY 2022

Costas Kounnas 1952-2021

Costas Kounnas 1952-2021

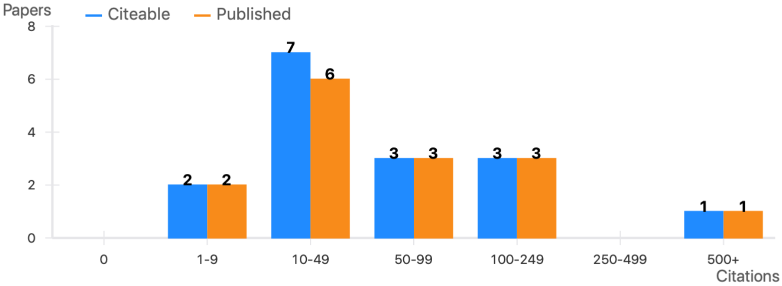
Costas 60th anniversary, Cyprus 2012

summary of joint publications

Citation Summary

☐ Exclude self-citations ?

	Citeable ?	Published ?
Papers	**16**	**15**
Citations	**1,801**	**1,786**
h-index ?	**14**	**13**
Citations/paper (avg)	**112.6**	**119.1**



construction of 4d strings

FOUR-DIMENSIONAL SUPERSTRINGS

I. ANTONIADIS*

CERN, Genève, Switzerland

C.P. BACHAS

Centre de Physique Théorique, Ecole Polytechnique, 91128 Palaiseau Cedex, France

C. KOUNNAS**

Lawrence Berkeley Laboratory, Berkeley, California 94720, USA

Received 30 December 1986

Nuclear Physics B 289 (1987) 87-108

We solve completely the constraints of factorization and multiloop modular invariance for closed string theories in which all internal quantum numbers of the string are carried by free periodic and antiperiodic world-sheet fermions. We derive a simple set of necessary and sufficient rules, and illustrate how they can be used to find the spectrum, one-loop amplitudes and low-energy lagrangian of many realistic four-dimensional chiral models. We prove that modular invariance and factorization ensure the presence of a massless graviton and the correct connection between spin and statistics. We also prove that the existence of a massless spin-$\frac{3}{2}$ state ensures the absence of tachyons and the vanishing of the one-loop cosmological constant.

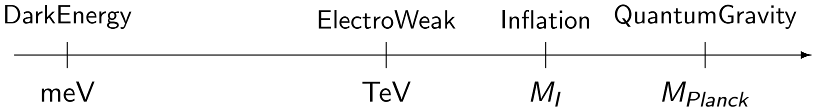
Universe evolution:
based on positive cosmological constant

- Dark Energy

  simplest case: infinitesimal (tuneable) +ve cosmological constant

- Inflation (approximate de Sitter)

  describe possible accelerated expanding phase of our universe



Swampland de Sitter conjecture

String theory: vacuum energy and inflation models

related to the moduli stabilisation problem

Difficulties to find dS vacua led to a conjecture:

$$\frac{|\nabla V|}{V} \geq c \quad \text{or} \quad \min(\nabla_i \nabla_j V) \leq -c' \quad \text{in Planck units}$$

with c, c' positive order 1 constants — Ooguri-Palti-Shiu-Vafa '18

Dark energy: forbid dS minima but allow maxima

Inflation: forbid standard slow-roll conditions

ongoing debate on the validity of the assumptions and on KKLT

here: explicit construction based on quantum corrections

with Y. Chen, O. Lacombe, G. Leontaris '18-'21

Moduli stabilisation in type IIB

Compactification on a Calabi-Yau manifold $\Rightarrow$ $N = 2$ SUSY in 4 dims

Moduli: Complex structure in vector multiplets

Kähler class & dilaton in hypermultiplets

$\Rightarrow$ decoupled kinetic terms

turn on appropriate 3-form fluxes (primitive self-dual) $\Rightarrow$ $N = 1$ SUSY

$\uparrow$ field-strengths of 2-index antisymmetric gauge potentials

$+$ orientifolds and D3/D7-branes

vectors and RR companions of geometric moduli are projected away $\Rightarrow$

all moduli in $N = 1$ chiral multiplets $+$ superpotential for the

complex structure & dilaton $\rightarrow$ fixed in a SUSY way Frey-Polchinski '02

Kähler moduli: no scale structure, vanishing potential (classical level)

Stabilisation of Kähler moduli

Non perturbative superpotential from gaugino condensation on D-branes

$\Rightarrow$ stabilisation in an AdS vacuum Derendinger-Ibanez-Nilles '85

Uplifting using anti-D3 branes Kachru-Kallosh-Linde-Trivedi '03

or D-terms and perturbative string corrections to the Kähler potential

Large Volume Scenario (LVS) Conlon-Quevedo et al '05

Ongoing debate on the validity of these ingredients in full string theory

While perturbative stabilisation has the old Dine-Seiberg problem

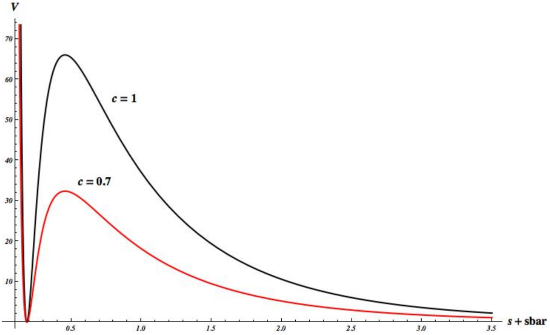
put together 2 orders of perturbation theory violating the expansion

possible exception known from field theory:

logarithmic corrections $\rightarrow$ Coleman-Weinberg mechanism [11]

The Dine-Seiberg problem

Runaway potential towards vanishing string coupling or large volume



$\Rightarrow$ if there is perturbative minimum, it is likely to be at strong coupling

or string size volume

Analogy with Coleman-Weinberg symmetry breaking

Effective potential in massless $\lambda\Phi^4$

$$V = \left\{ \sum_{N>1} c_N \lambda^N(\Phi) \right\} \Phi^4 \;\Rightarrow\; \text{minimum at } \lambda = 0 \text{ or } \mathcal{O}(1)$$

C-W perturbative symmetry breaking needs 2 couplings + logs: [16]

$$V_{\rm C-W} = \left(\lambda + c_1 e^4 \ln \frac{|\Phi|^2}{\mu^2} \right) |\Phi|^4 \;\Rightarrow\; |\Phi|^2_{\rm min} \propto \mu^2 e^{-\frac{\lambda}{c_1 e^4}}$$

both λ and e are weak < 1

realising this proposal in string theory:

- replace gaugino condensation by log corrections in the F-part potential
- use D-term uplifting as in LVS

Log corrections in string theory:

localised couplings + closed string propagation in $d \leq 2$

Effective propagation of massless bulk states in $d \leq 2 \Rightarrow$ IR divergences [16]

$d = 1$: linear, $d = 2$: logarithmic

$\Rightarrow$ corrections to (brane) localised couplings

depending on the size of the bulk due to local closed string tadpoles

I.A.-Bachas '98

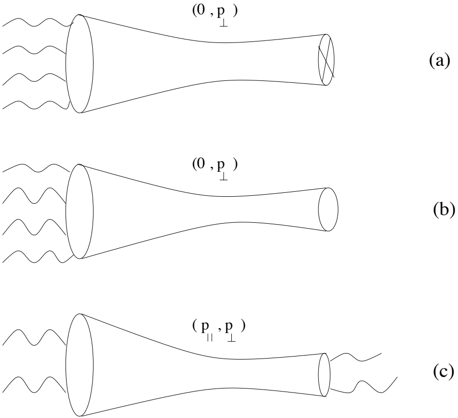
e.g. threshold corrections to 4d gauge coupling

linear dilaton dependence on the 11th dim of M-theory

Type II strings: correction to the Kähler potential $\leftrightarrow$ Planck mass [14]

I.A.-Ferrara-Minasian-Narain '97

decompactification limit in the presence of branes



$$\mathcal{A} \sim \frac{1}{V_\perp} \sum_{|p_\perp|<M_s} \frac{1}{p_\perp^2} F(\vec{p}_\perp)$$

$$V_\perp = R^d \quad \vec{p}_\perp = \vec{n}/R$$

$$R >> l_s \Rightarrow$$

$$\mathcal{A} \sim \begin{cases} \mathcal{O}(R) & \text{for } d{=}1 \\ \mathcal{O}(\log R) & \text{for } d{=}2 \\ \text{finite} & \text{for } d > 2 \end{cases}$$

local tadpoles: $F(\vec{p}_\perp) \sim \left(2^{5-d} \prod_{i=1}^{d} (1 + (-)^{n_i}) - 2 \sum_{a=1}^{16} \cos(\vec{p}_\perp \vec{y}_a)\right)$

Localised gravity kinetic terms

Corrections to the 4d Planck mass in type II strings

Large volume limit: localised Einstein-Hilbert term in the 6d internal space

I.A.-Minasian-Vanhove '02 [16]

10d: $R \wedge R \wedge R \wedge R \quad \rightarrow \quad$ in 4d: $\chi \mathcal{R}_{(4)}$

$\nwarrow$ Euler number $= 4(n_H - n_V)$ [19]

$$S_{\rm grav}^{IIB} = \frac{1}{(2\pi)^7 \alpha'^4} \int_{M_4 \times \mathcal{X}_6} e^{-2\phi} \mathcal{R}_{(10)} + \frac{\chi}{(2\pi)^4 \alpha'} \int_{M_4} \left(2\zeta(3) e^{-2\phi} + \frac{2\pi^2}{3} \right) \mathcal{R}_{(4)}$$

4-loop σ-model $\nearrow$ vanishes for orbifolds

localisation width $w \sim |\chi| l_s = l_p^{(4)}$

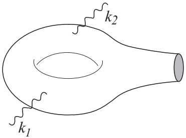
in agreement with general arguments of localised gravity

Dvali-Gabadadze-Porrati '00

perturbative moduli stabilisation I.A.-Chen-Leontaris '18, '19

localised vertices from $\mathcal{R}_{(4)}$ can emit massless closed strings

$\Rightarrow$ local tadpoles in the presence of distinct 7-brane sources

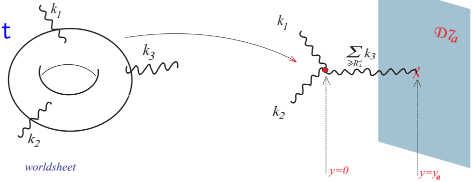


propagation in 2d transverse bulk $\rightarrow$ $\log R_\perp$ corrections

exact computation: difficult either in CY or in orbifolds - genus 3/2

computation in the degeneration limit

for Z_N orbifold ($\chi \sim N$)



$$\sim -\sum_{q_\perp \neq 0} g_s^2 T N e^{-w^2 q_\perp^2/2} \frac{1}{q_\perp^2 R_\perp^2} = -N g_s^2 T \log(R_\perp/w) + \cdots$$

$T = T_0/g_s$: brane tension

Kähler potential:

$$\mathcal{K} = -2\ln\left(\mathcal{V} + \xi + \eta\ln\frac{\mathcal{V}_\perp}{w^2} + \mathcal{O}(\frac{1}{\mathcal{V}})\right) = -2\ln\left(\mathcal{V} + \eta\ln\mu^2\mathcal{V}_\perp\right)$$ [19]

$$\xi = -\tfrac{1}{4}\chi f(g_s)\,; \quad f(g_s) = \begin{cases} \zeta(3) \simeq 1.2 & \text{smooth CY} \\ \frac{\pi^2}{3} g_s^2 & \text{orbifolds} \end{cases} \qquad \eta = -\tfrac{1}{2} g_s T_0 \xi$$ [14]

Using 3 mutual orthogonal 7-brane stacks with D-terms (magnetic fluxes)

and minimising with respect to transverse volume ratios [11]

$$\Rightarrow\; V \simeq \frac{3\eta\mathcal{W}_0^2}{\mathcal{V}^3}\left(\ln\mu^6\mathcal{V} - 4\right) + 3\frac{d}{\mathcal{V}^2}$$ $\mathcal{W}_0$: constant superpotential, d: D-term

dS minimum: $-0.007242 < \dfrac{d}{\eta\mathcal{W}_0^2\mu^6} \equiv \rho < -0.006738$ with $\mathcal{V} \simeq e^5/\mu^6$ [18]

FI D-terms

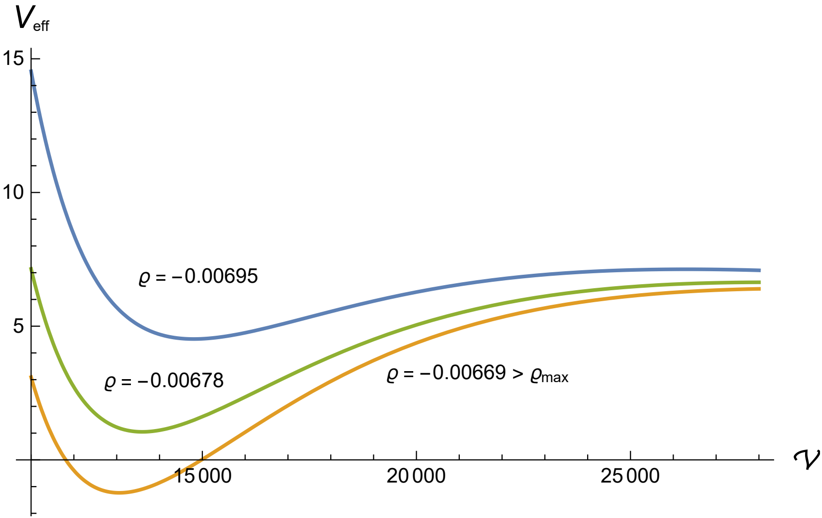
$$V_{D_i} = \frac{d_i}{\tau_i}\left(\frac{\partial K}{\partial_{\tau_i}}\right)^2 = \frac{d_i}{\tau_i^3} + \mathcal{O}(\eta_j)$$

τ_i: world-volume modulus of D7_i-brane stack with $\mathcal{V} = (\tau_1\tau_2\tau_3)^{1/2}$

$$\eta_i \equiv \eta \;\Rightarrow\quad V_{tot} = \frac{3\eta\mathcal{W}_0^2}{\mathcal{V}^3}\left(\ln(\mathcal{V}\mu^6) - 4\right) + \frac{d_1}{\tau_1^3} + \frac{d_2}{\tau_2^3} + \frac{d_3\tau_1^3\tau_2^3}{\mathcal{V}^6}$$

minimising with respect to τ_1 and $\tau_2 \Rightarrow \frac{\tau_i}{\tau_j} = \left(\frac{d_i}{d_j}\right)^{1/3} \Rightarrow$

$$V_D = 3\frac{d}{\mathcal{V}^2} \quad \text{with} \quad d = (d_1 d_2 d_3)^{1/3}$$



2 extrema min+max $\rightarrow -0.007242 < \rho < -0.006738 \leftarrow$ +ve energy [16] [22]

perturbative moduli stabilisation I.A.-Chen-Leontaris '18, '19

$$\xi = -\frac{1}{4}\chi f(g_s)\,; \quad f(g_s) = \begin{cases} \zeta(3) \simeq 1.2 & \text{smooth CY} \\ \frac{\pi^2}{3} g_s^2 & \text{orbifolds} \end{cases} \qquad \eta = -\frac{1}{2} g_s T_0 \xi$$

dS minimum: $-0.007242 < \dfrac{d}{\eta \mathcal{W}_0^2 \mu^6} \equiv \rho < -0.006738$ with $\mathcal{V} \simeq e^5/\mu^6$

exponentially large volume:

$$\mu = \frac{e^{\xi/6\eta}}{w} = \sqrt{|\chi|}\, e^{-\frac{1}{3 g_s T_0}} \to 0 \quad \Rightarrow$$ [16]

weak coupling and

large χ or/and $\mathcal{W}_0$ from 3-form flux to keep ρ fixed

requirement: negative χ $(\eta < 0)$ [14] and surplus of D7-branes $(T_0 > 0)$

Inflation possibilities

I.A.-Lacombe-Leontaris '20

- Inflaton: canonically normalised $\phi = \sqrt{2/3}\ln\mathcal{V}$ (in Planck units)
- one relevant parameter: ρ or $x = -\ln(-4\rho/3) - 16/3$

$0 < x < 0.072$ for dS minimum

- extrema $V'(\phi_\pm) = 0$

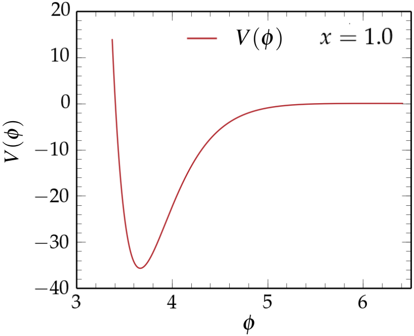
$$\phi_+ - \phi_- = \sqrt{2/3}\left(W_0(-e^{-x-1}) - W_{-1}(-e^{-x-1})\right)$$

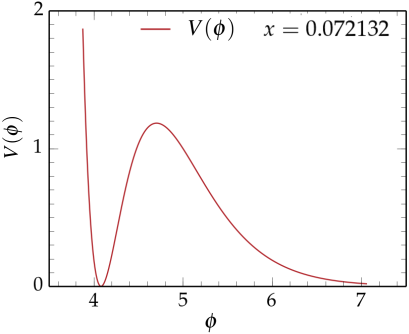
$W_{0/-1}$: Lambert functions satisfying $W(xe^x) = x$

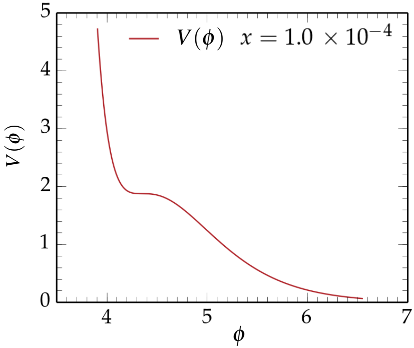
$$\frac{V(\phi_+)}{V(\phi_-)} = \frac{\left(W_0(-e^{-x-1})\right)^3\left(2+3W_{-1}(-e^{-x-1})\right)}{(W_{-1}(-e^{-x-1}))^3(2+3W_0(-e^{-x-1}))}$$

- slow roll parameter $\eta(\phi_{-/+}) = \frac{V''(\phi_{-/+})}{V(\phi_{-/+})} = -9\frac{1+W_{0/-1}(-e^{-x-1})}{\frac{2}{3}+W_{0/-1}(-e^{-x-1})}$ [23]

successful inflation possible around the minimum from the inflection point


$V(\phi)$ $x = 1.0$
$V(\phi)$
ϕ
20
10
0
−10
−20
−30
−40
3
4
5
6


$V(\phi)$ $x = 0.072132$
$V(\phi)$
ϕ
2
1
0
4
5
6
7


$V(\phi)$ $x = 1.0 \times 10^{-4}$
$V(\phi)$
ϕ
5
4
3
2
1
0
4
5
6
7

[24] [25]

Inflation possibilities

- Friedmann equations with time replaced by the inflaton $\Rightarrow$

  Hubble parameter $\rightarrow$ $H'(\phi) = \mp\frac{1}{\sqrt{2}}\sqrt{3H^2(\phi) - V(\phi)}$

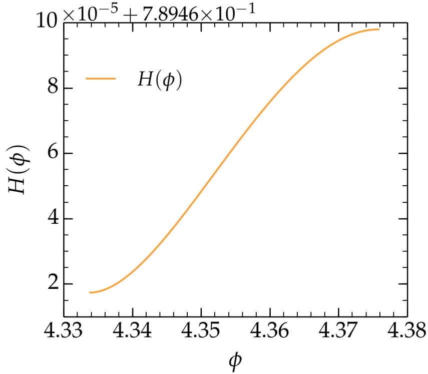
- slow-roll parameters: $\eta(\phi) = \frac{V''(\phi)}{V(\phi)}, \quad \epsilon(\phi) = \frac{1}{2}\left(\frac{V'(\phi)}{V(\phi)}\right)^2$

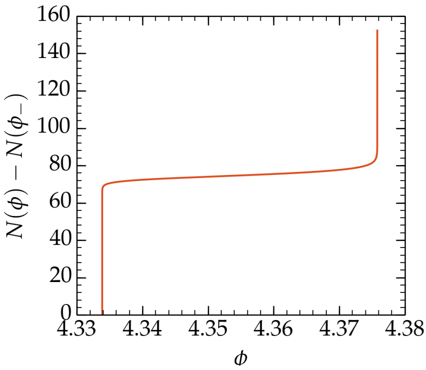
- number of e-folds by the end of inflation: $N(\phi) = \int_{\phi_{end}}^{\phi} \frac{d\phi}{\sqrt{2\epsilon}}$

Observational constraints at the horizon exit $\phi = \phi_*$:

1. $N_* \simeq 50 - 60$
2. spectral index of power spectrum $n_S - 1 = 2\eta_* - 6\epsilon_* \simeq -0.04$
3. amplitude of scalar perturbations $\mathcal{A}_S = \frac{V_*}{24\pi^2\epsilon_*} \simeq 2.2 \times 10^{-9}$

$\Rightarrow$ inflation possible around the minimum from the inflection point [18]





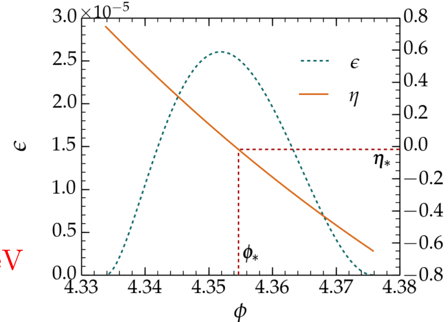
$x = 3.3 \times 10^{-4}\,; \quad \eta(\phi_*) = -0.02$

ϕ_* near the inflection point

$\Delta\phi \simeq 0.02$: small field

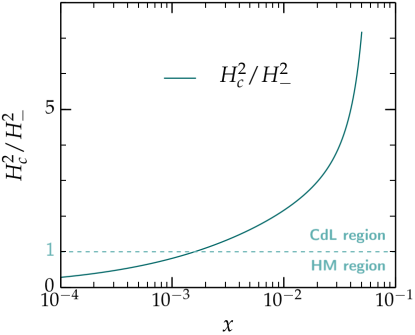
$\Rightarrow r \simeq 4 \times 10^{-4}$

$H_* \simeq 5 \times 10^{12}\,\mathrm{GeV}$



dS vacuum metastability [21]

- through tunnelling $H_c > H_-$ Coleman - de Luccia instanton
- over the barrier $H_c < H_-$ Hawking - Moss transition



$$\frac{H_c^2}{H_-^2} \equiv -\frac{3V''(\phi_+)}{4V(\phi_-)}$$

HM region: $\Gamma \sim e^{-B}$; $B \simeq \frac{24\pi^2}{V}\frac{\Delta V}{V}$

$$\frac{\Delta V}{V} \simeq 24\sqrt{2}x^{3/2} \Rightarrow$$

$B \simeq 3 \times 10^9$ for $x \simeq 3 \times 10^{-4}$

End of inflation with waterfall field

Hybrid scenario

$$V(\phi, S) = V(\phi) + \frac{1}{2} m_S^2(\phi) S^2 + \frac{\lambda}{4} S^4$$

$$\phi > \phi_c \quad : \quad m_S^2 > 0 \Rightarrow \langle S \rangle = 0, \qquad V(\phi, 0) = V(\phi)$$

$$\phi < \phi_c \quad : \quad m_S^2 < 0 \Rightarrow \langle S \rangle = \pm \frac{|m_S|}{\sqrt{\lambda}}, \quad V(\phi, \langle S \rangle) = V(\phi) - \frac{m_S^4(\phi)}{4\lambda}$$

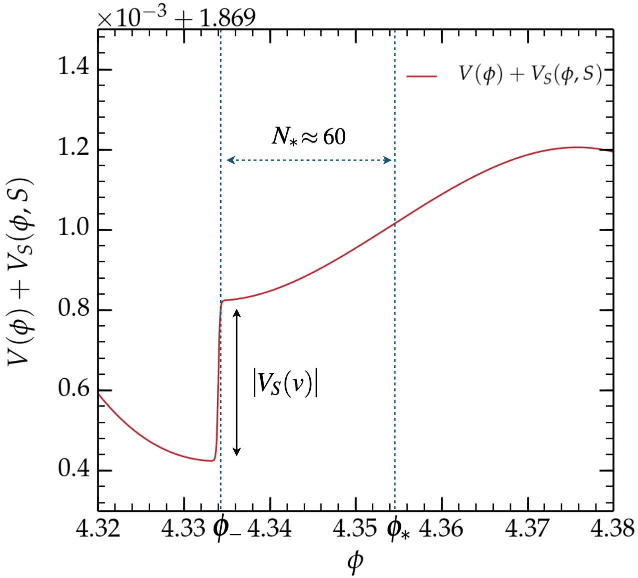
ϕ_c: near the minimum of $V(\phi)$

waterfall field S: open string state on D7-branes

negative contribution to m_S^2: from internal magnetic fluxes along the world-volumes [27]

I.A.-Lacombe-Leontaris '21

End of inflation with waterfall field



Conclusions

New mechanism of moduli stabilisation is string theory (type IIB)

- perturbative: weak coupling, large volume
- based on log corrections in the transverse volume of 7-branes

  due to local tadpoles induced by localised gravity kinetic terms

  arising only in 4 dimensions!
- can lead to de Sitter vacua in string theory

  explicit counter-example to dS swampland conjecture
- inflation possible around the minimum from the inflection point
- realisation of hybrid inflation to lower the vacuum energy