PERTURBATIVE DE SITTER AND BRANE INFLATION

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Image: (Scientific American, February 2017)

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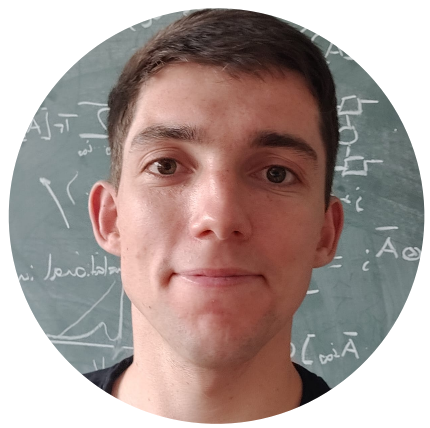

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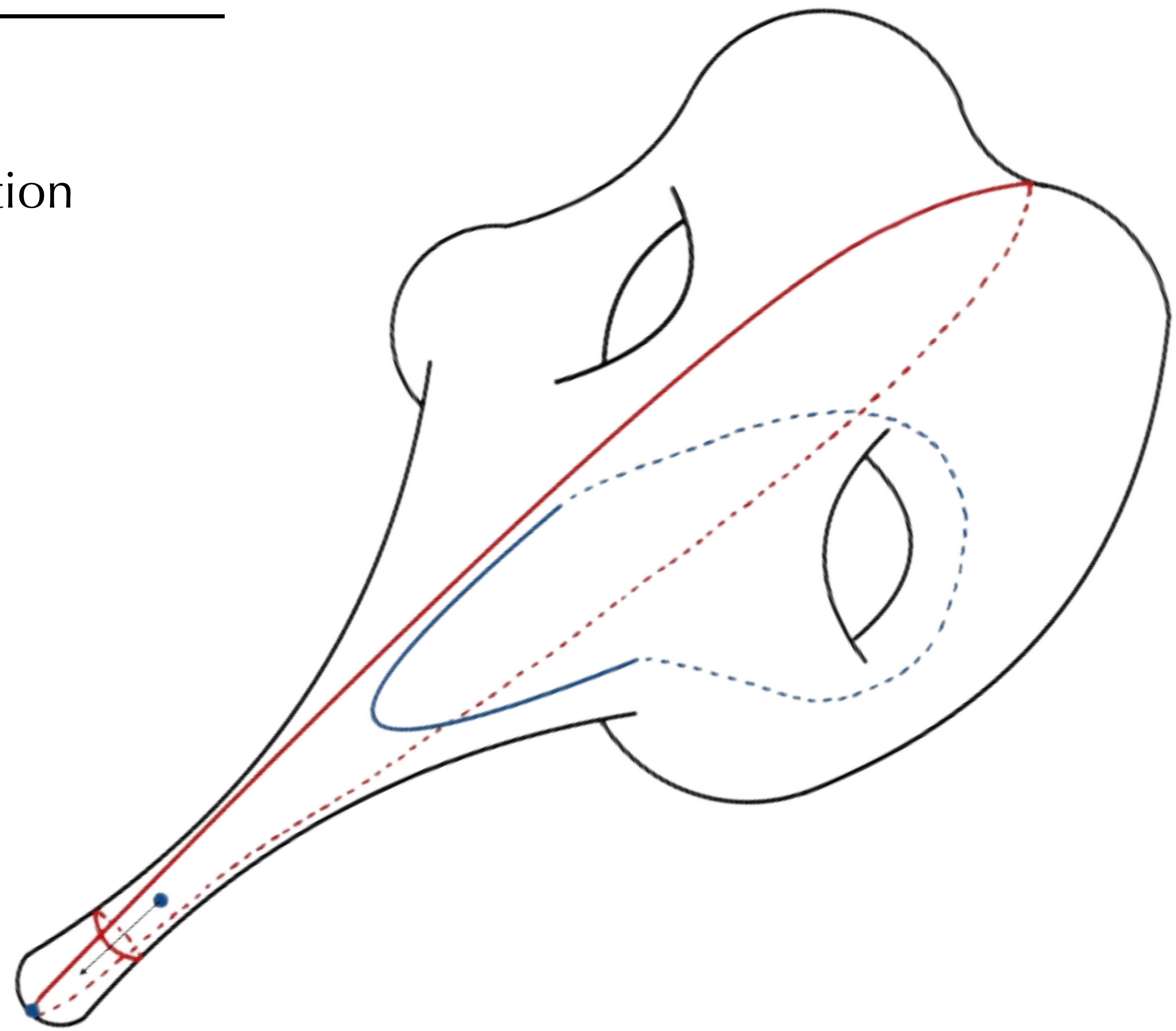
OUTLINE

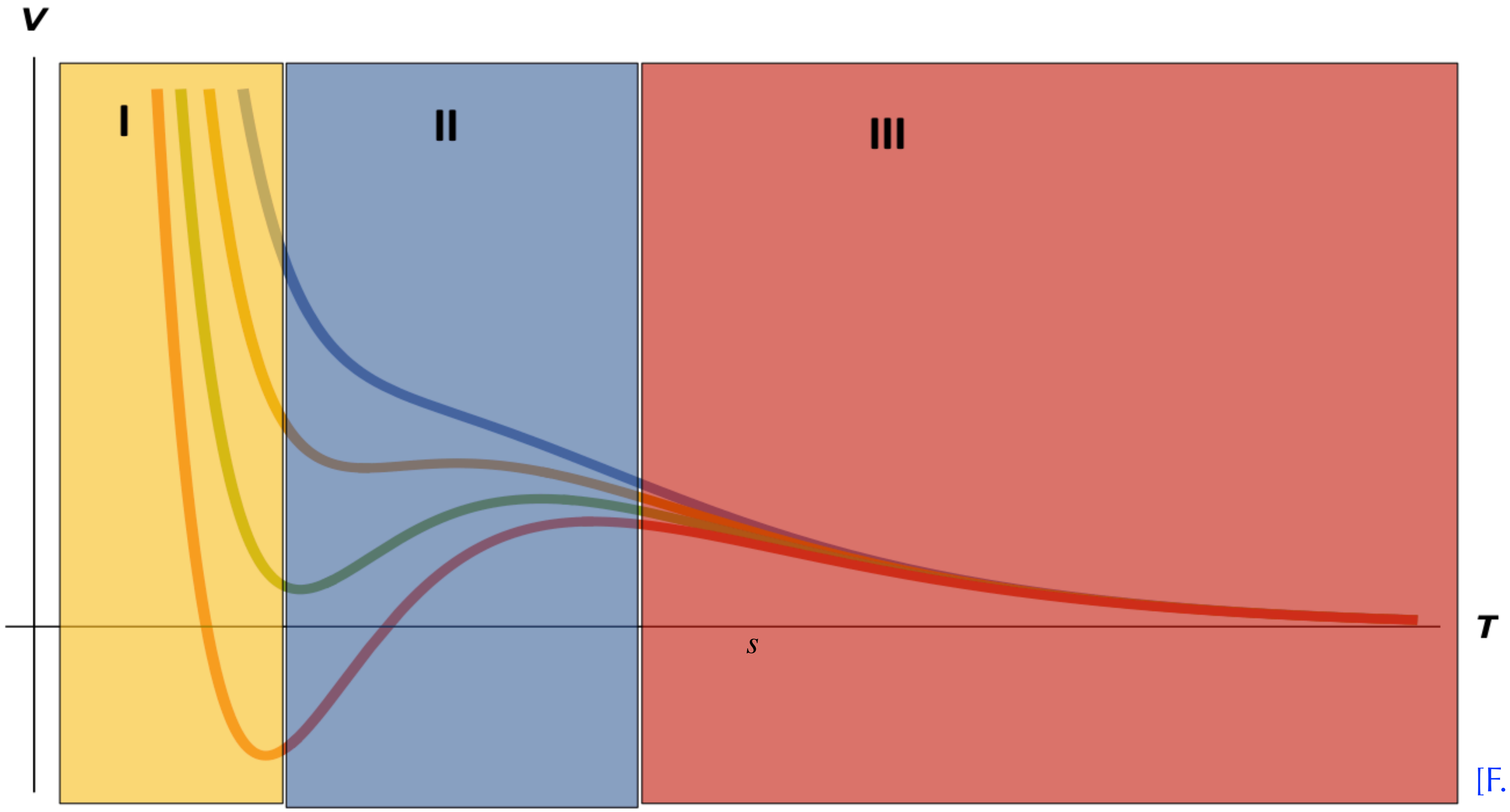
- RG-Induced modulus stabilisation
- Brane-anti-brane inflation
- EFT analysis
- Conclusions



RG-INDUCED MODULUS STABILISATION

DINE-SEIBERG PROBLEM

[M. Dine. N. Seiberg, 1985]



[F. Quevedo, 2022]

- Region I: out of the domain of parametric control of the EFT (small $\mathscr{V}$/strong g_s).
- Region II: requires extra ingredients in the compactification to get a minimum.
- Region III: runaway region which is the only one fully trustable in the EFT.

If the scalar potential has a minimum, it is generically at $s \sim \tau \sim \mathcal{O}(1)$.
(Two accidental approximate scale symmetries with s and τ as pseudo Goldstone bosons)

RG-INDUCED MODULI STABILISATION

[C. Burguess and F. Quevedo 2022]

Consider IIB string theory compactified in a CY three-fold with the complex structure moduli stabilised as in GKP with $W = \omega_0$ independent of $T = \frac{1}{2}(\tau + i\mathfrak{a})$.

Two accidental symmetries broken by α' and loop corrections to the EFT action:

- α' expansion becomes an expansion in inverse powers of $\mathscr{V} := \tau^{2/3}$.
- String loop corrections become an expansion in powers of $\mathrm{Re}(\mathscr{S})^{-1} = e^{\phi}$.

In the regime where $\tau \gg 1$ the following expansion is valid:

$$e^{-K/3} = \tau - k + \frac{h}{\tau} + \dots \qquad \Rightarrow K(T,\bar{T}) = -3\ln\mathscr{P}, \quad \text{with} \quad \mathscr{P} = \tau\left[1 - \frac{k}{\tau} + \frac{h}{\tau^{3/2}} + \dots\right]$$

and where $k = k(\ln\tau)$ and $h = h(\ln\tau)$, more explicitly, for $\alpha_g \sim \epsilon \ll 1$:

[Conlon and Palti., 2009]
[Grimm et al., 2015]
[Weigand et al., 2019]

$$\Rightarrow \quad k \simeq k_0 + k_1\alpha_g + \frac{k_2}{2}\alpha_g^2 + \dots \quad \text{and} \quad \tau\frac{d\alpha_g}{d\tau} = \beta(\alpha_g) = b_1\alpha_g^2 + b_2\alpha_g^3 + \dots$$

$$\therefore \quad \boxed{\alpha_g(\tau) = \frac{\alpha_{g0}}{1 - b_1\alpha_{g0}\ln\tau}}$$ for some integration constant $\alpha_{g0} = \alpha_g(\tau = 1)$.

RG-INDUCED MODULI STABILISATION

The corresponding dominant term in the scalar potential is given by

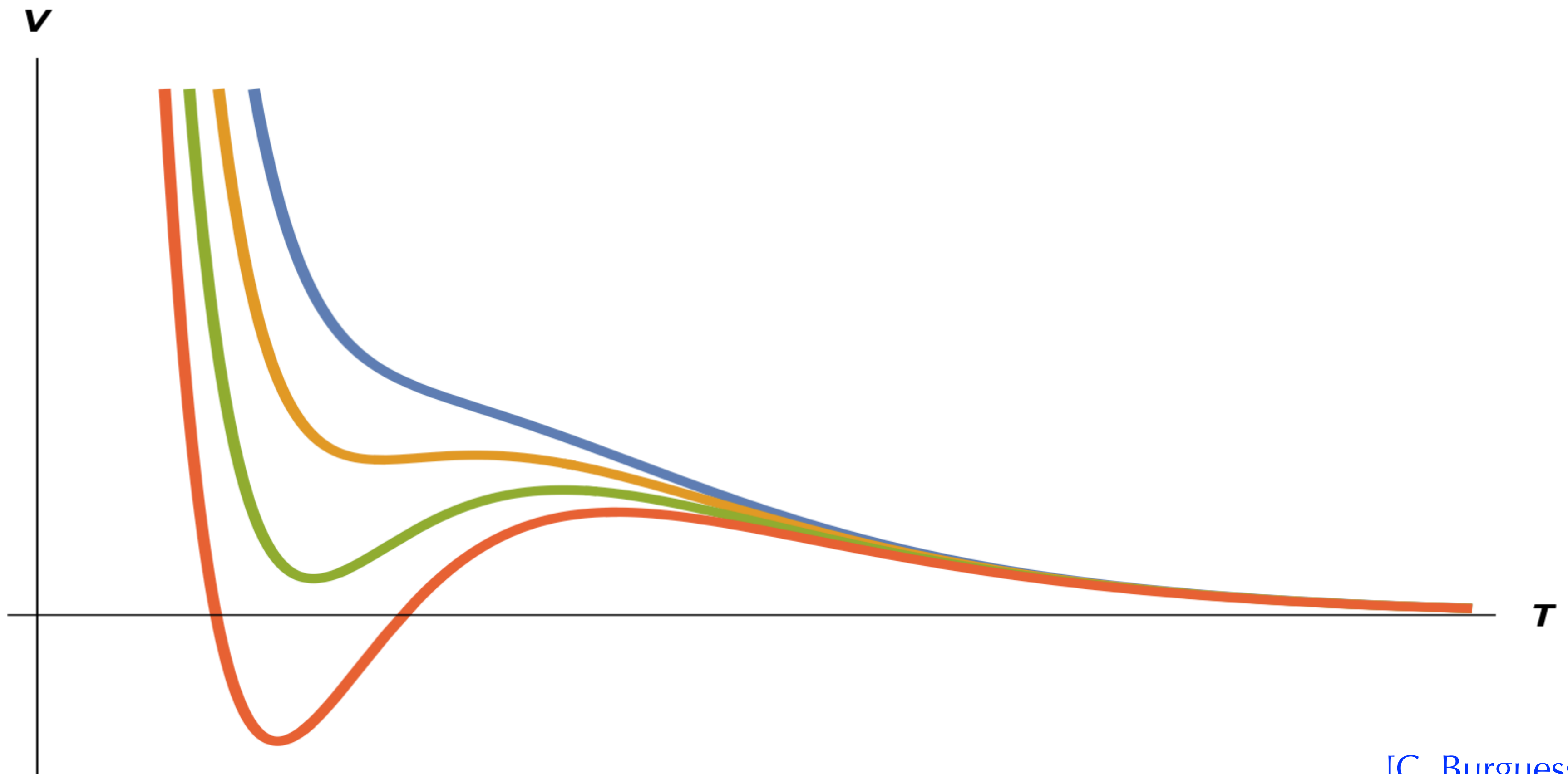
$$V \simeq -\frac{3(k' - k'')}{\tau^4} \simeq \frac{U(\ln \tau)}{\tau^4} \quad \text{where} \quad U \simeq U_1 \alpha_g^2 - U_2 \alpha_g^3 + U_3 \alpha_g^4 + \dots$$

$$\Rightarrow \quad \alpha_{g0} \ln(\tau_0) \simeq \mathcal{O}(1).$$

Dine-Seiberg argument implies a minimum at exponentially large volume:

$$\tau_0 \sim e^{\frac{1}{\epsilon}} \gg 1.$$

Moreover, by tuning U_i we can obtain AdS or dS without requiring an uplift:



[C. Burguess and F. Quevedo 2022]

BRANE -ANTIBRANE INFLATION

NON-LINEAR SUSY

We can describe the brane-antibrane scenario by implementing non-linear SUSY:

[See talk by Casagrande last Tuesday]

- Chiral superfield T related to the Kähler modulus.
- Nilpotent non-chiral superfield $X^2 = 0$ (SUSY breaking sector).
- Chiral superfield Φ involving the inflaton field ϕ (distance separation).

To incorporate these fields into a supersymmetric framework with accidental approximate scale invariance:

$$e^{-K/3} = \tau - k + \frac{h}{\tau} + \ldots,$$

but now, $k = \kappa(\overline{\Phi}, \Phi, \ln\tau) + (X + \overline{X})\, \kappa_X(\overline{\Phi}, \Phi, \ln\tau) + \overline{X}X\, \kappa_{\overline{X}X}(\overline{\Phi}, \Phi, \ln\tau)$.

The most general superpotential is given by

$$W \simeq w_0(\Phi) + X w_X(\Phi, \overline{\Phi}).$$

SCALAR POTENTIAL

The corresponding scalar potential is given by

$$V = \frac{A|w_x|}{\mathscr{P}^2} - \frac{2\mathrm{Re}(B\overline{w_X}w_0)}{\mathscr{P}^3} + \frac{C|w_0|^2}{\mathscr{P}^4},$$

where $A \simeq \frac{1}{3}\kappa^{\overline{X}X}, \frac{B}{\mathscr{P}} \simeq \kappa^{\overline{X}X}\kappa_{X\overline{T}}$ and $\frac{C}{\mathscr{P}^2} \simeq -3(\kappa_{\overline{T}T} - \kappa^{\overline{X}X}\kappa_{T\overline{X}}\kappa_{X\overline{T}})$ and $\mathscr{P} \sim \mathscr{V}^{2/3}$.

A local positive minimum can be found at:

$$\frac{1}{\mathscr{P}} = \frac{|\omega_X|}{|\omega_0|}D := \delta D, \quad \text{if} \quad \frac{8}{9}AC < B^2 < AC,$$

where

$$D \equiv \frac{3B}{4C} + \sqrt{\frac{9B^2}{16C^2} - \frac{A}{2C}} \quad \text{and} \quad \delta \equiv \frac{|\omega_X|}{|\omega_0|}.$$

To stay in the parametric supergravity regime: $\mathscr{P} \sim \frac{\epsilon^2}{\delta} \gg 1$ and therefore $\delta \ll \epsilon^2$.

In addition, $\epsilon_\tau \sim \left(\frac{V_\chi}{V}\right)^2 \sim \left(\tau\frac{V_\tau}{V}^2\right) \sim \mathcal{O}(1)$ and $m_\tau^2 = \left(\frac{\partial^2 V}{\partial\chi^2}\right)_{\tau_0} \sim \tau^2\frac{\partial^2 V}{\partial\tau^2} \sim H_I^2.$ (Single field analysis valid)

EFT ANALYSIS

INFLATIONARY REQUIREMENTS

To capture the antibrane tension and the separation-dependent Coulomb interaction we use the following superpotential:

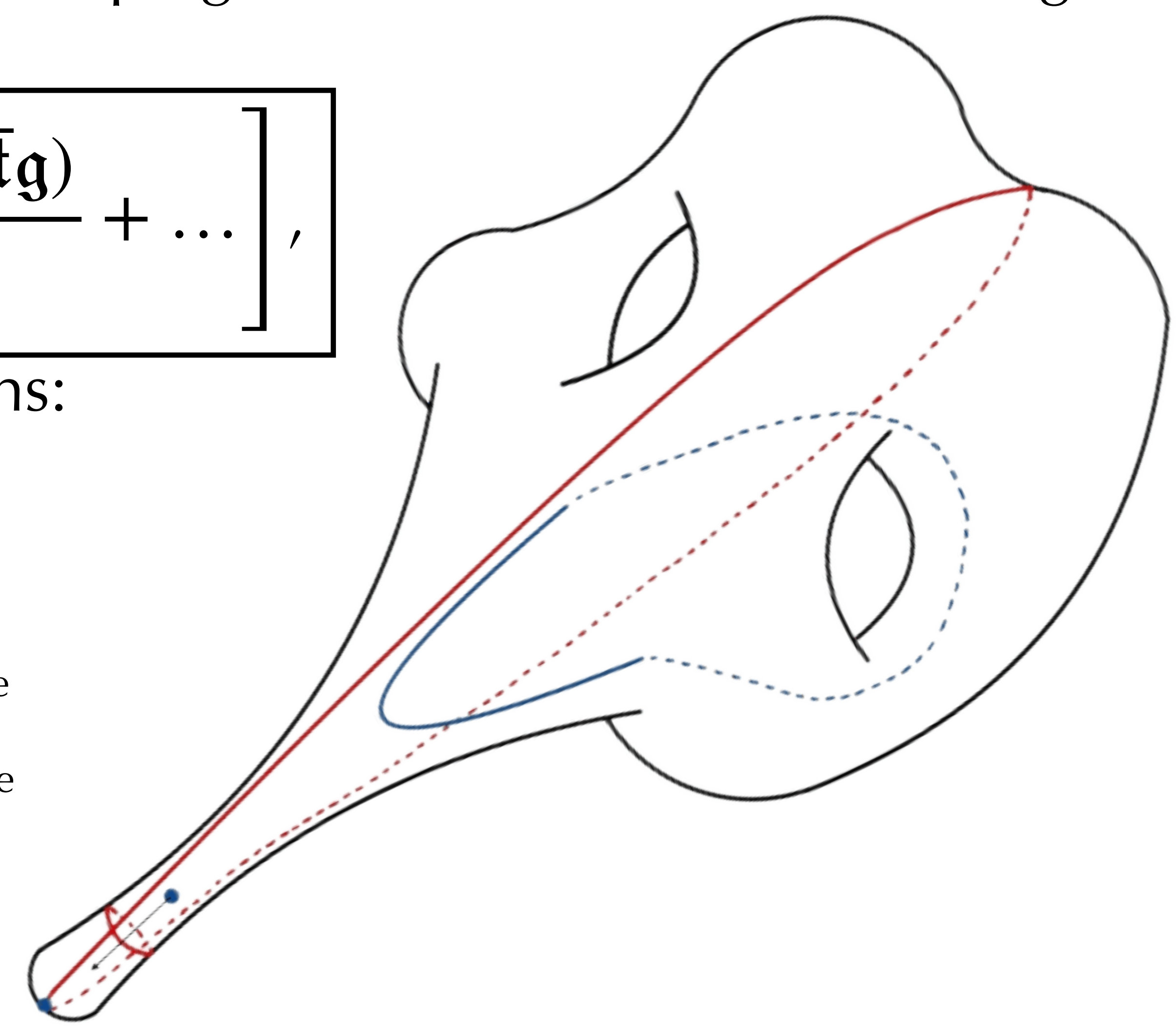
$$W \simeq w_0(\Phi) + X\, w_X(\Phi, \overline{\Phi}) \quad \text{with} \quad \omega_X(\phi) = \mathfrak{t} - \frac{\mathfrak{g}}{\phi^4}\,,$$

with $\mathfrak{t}^3 \sim \mathfrak{g} \sim e^{-6\rho}$ with ρ parameterising the warping. With this choice the leading term in the scalar potential then is

$$V = \frac{\kappa^{\overline{X}X}\,|w_X|^2}{3\mathscr{P}^2} = \frac{\kappa^{\overline{X}X}}{3\mathscr{P}^2}\left[\mathfrak{t}^2 - \frac{2\mathrm{Re}(\bar{\mathfrak{t}}\mathfrak{g})}{\phi^4} + \ldots\right],$$

with the following EFT and slow-roll conditions:

$\delta \ll \epsilon^2$	Supergravity regime
$e^{\rho} \lesssim \mathscr{P}$	Warped string scale < KK scale
$\phi < \mathscr{P}^{-1/2}$	Inter-brane distance < extra dim size
$\phi > \mathscr{P}^{-3/4}$	Inter-brane separation > string scale
$\mathscr{P} \ll e^{4\rho}$	Slow-roll inflation ($\epsilon \ll \lvert\eta\rvert \ll 1$)
$m_{3/2} \lesssim M_{KK}$	Gravitino mass $\lesssim$ KK mass scale



SUMMARY AND CONCLUSIONS

CONCLUSIONS

- RG-induced modulus stabilisation is a novel alternative to KKLT and LVS motivated by the Dine-Seiberg argument and logarithmic corrections.
- In this scheme, inflation does not suffer the η-problem, which is present in other brane-antibrane inflation models (e.g. with KKLT stabilisation).
- Inflation seems to take place in the domain of validity of the EFT and therefore in the region of parametric control.
- We still need to study carefully if the end of inflation can be realised within the regime of control of the EFT.

EXTRA CREDITS

One more option to choose:

[A. Rakin, 2023 (Twitter)]

감사합니다

"The invisible and the non-existent look very much alike."

-S. Weinberg.

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BACKUP SLIDES

TYPE IIB REALISATION

Bosonic action in IIB 10D supergravity:

$$S_{bulk} = \int d^{10}x\sqrt{-\tilde{g}}\left\{\tilde{R} - \frac{|\partial\mathcal{S}|^2}{(\mathrm{Re}\mathcal{S})^2} - \frac{|G_{(3)}|^2}{\mathrm{Re}\mathcal{S}} - \tilde{F}^2_{(5)}\right\} + \int \frac{1}{\mathrm{Re}\mathcal{S}} C_{(4)} \wedge G_{(3)} \wedge \bar{G}_{(3)}.$$

Two symmetries are present:

- $SL(2,\mathbb{R})$ **symmetry**

$$\mathcal{S} \to \frac{a\mathcal{S} - ib}{ic\mathcal{S} + d} \quad \text{and} \quad G_{(3)} \to \frac{G_{(3)}}{ic\mathcal{S} + d} \quad \text{for } \; ad - bc = 1.$$

When $b = c = 0$ and $a = 1/d$:

$$\tilde{g}_{MN} \to \tilde{g}_{MN}, \quad \mathcal{S} \to a^2\mathcal{S}, \quad G_{(3)} \to aG_{(3)}, \quad \text{and} \quad \tilde{F}_{(5)} \to \tilde{F}_{(5)}.$$

- **Approximate accidental scale invariance**

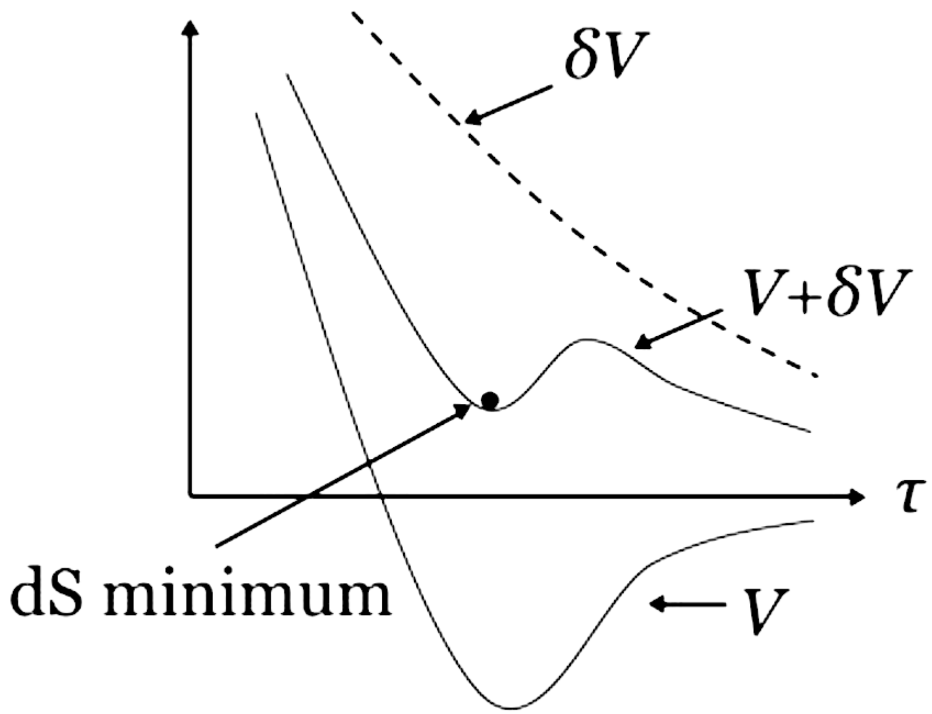
$$\tilde{g}_{MN} \to \lambda\tilde{g}_{MN}, \quad \mathcal{S} \to \mathcal{S}, \quad B_{(2)} \to \lambda B_{(2)}, \quad C_{(2)} \to \lambda C_{(2)}, \quad \text{and} \quad \tilde{C}_{(4)} \to \lambda^2\tilde{C}_{(4)},$$

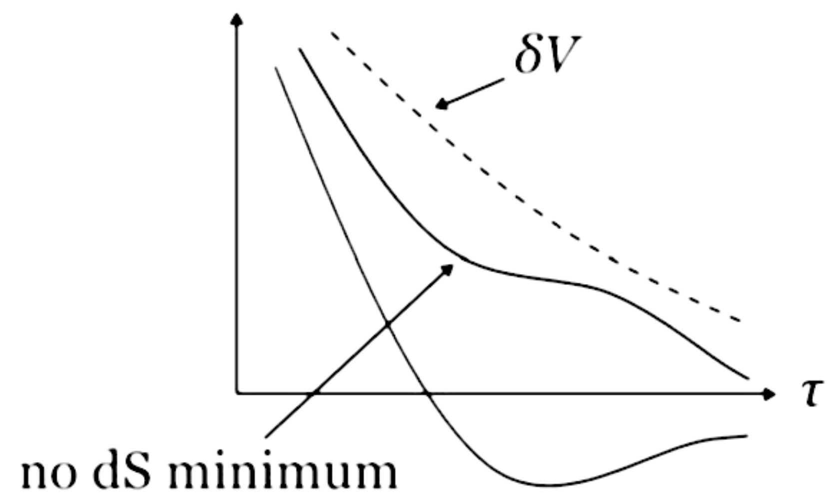
With the tree-level action $S_{bulk} \to \lambda^4 S_{bulk}$. Upon compactification: $\mathcal{V} \to \lambda^3\mathcal{V}$.

IIB MODULI STABILISATION

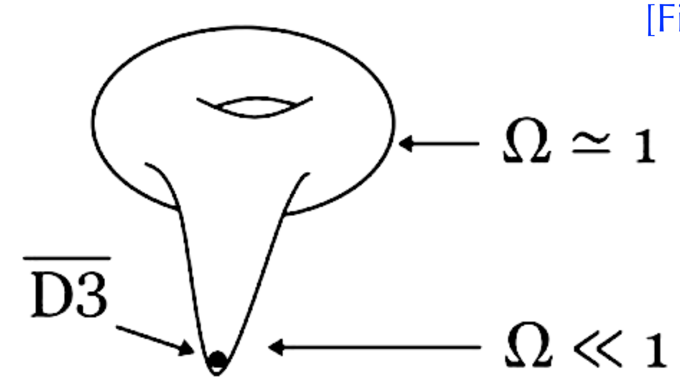
Non-Kähler moduli stabilised a là GKP with fluxes: $V_F = e^K (K^{-1}_{a\bar{b}} D_a W D_{\bar{b}} W) \geq 0.$

Quantum corrections alter the scalar potential: $\delta V \sim W_0^2 \delta K + W_0 \delta W.$





[Figures: A. Hebecker, 2020]



- KKLT: non-perturbative corrections $\delta W \sim e^{-a\tau} \sim W_0 \ll 1.$ [KKLT, 2003]
- LVS: competition of corrections $\delta K \sim 1/\mathcal{V} \sim W_0\, \delta W.$ [BBQC, 2005]

η-PROBLEM

The Kähler potential very generally depends on both τ and ϕ:

$$K = -3\ln[\tau - k(\phi,\overline{\phi}) + \ldots] \quad \text{where} \quad k(\phi,\overline{\phi}) \simeq \overline{\phi}\phi + \ldots$$ (Kinetic term of ϕ)

Once τ is fixed by adding $W_{np}(T)$:

$$V = e^K \hat{V}_0 \simeq \frac{\hat{V}_0}{(\tau - \overline{\phi}\phi + \ldots)^3} \simeq \frac{\hat{V}_0}{\tau^3}\left[1 + \frac{3\overline{\phi}\phi}{\tau} + \ldots\right] \simeq \frac{\hat{V}_0}{\tau^3}\left[1 + \overline{\varphi}\varphi + \ldots\right],$$

where $\hat{V}_0$ contains small warp factors and depends so weakly on ϕ that inflation can be possible. Moreover, when the energy density is dominated by V:

$$H_I^2 \simeq \frac{V}{M_p^2} \simeq \frac{\hat{V}_0^2}{\tau^3 M_p^2}\text{, and therefore } m_\phi^2 \sim \frac{\hat{V}_0}{\tau^3 M_p^2} \sim H_I^2.$$

$$\Rightarrow \eta = \frac{M_p^2 V_{\phi\phi}}{V} \simeq \frac{m_\phi^2}{H_I^2}$$

A lot of fine-tuning required to get slow-roll!

PARAMETERISATION

Experimentally, $n_s \sim 0.96$ and $\delta_H \sim 1.9 \times 10^{-5}$. Parameterising the coefficients as

$$A = \frac{1}{3}, \quad B \simeq b\epsilon^2 \quad \text{and} \quad C \simeq a\frac{\epsilon^2\alpha_g^2}{\mathscr{P}^2} \quad \text{with} \quad \alpha_g \sim \epsilon$$

$$\Rightarrow \frac{1}{\mathscr{P}} = \frac{\delta}{\epsilon^2}\left(\frac{3b}{12(b^2-a)} + \sqrt{\frac{9b^2}{144(b^2-a)^2} - \frac{1}{18(b^2-a)}}\right).$$

For a positive minimum: $-\dfrac{b^2}{8} < a < 0 \quad \Rightarrow \quad a = -\dfrac{b^2}{10} \quad \text{and} \quad b = \dfrac{1}{3}.$

- **Free parameters**: $\epsilon, \quad \delta \quad$ and $\quad w_0$.
- $g_s = \epsilon \ll 1$: string coupling constant plays the role of α_g in the RG-stabilisation.
- We impose $(\mathscr{P}g_s)^{3/2} \gg 1$ (no α'-corrections)
- We can finally parameterise:

$$\delta = 10^{-x}\epsilon^3, \; x > 0 \;\text{ and }\; w_0 = 13 \times 10^{-y+x/2}, \; y > 0.$$

INFLATIONARY REGIME

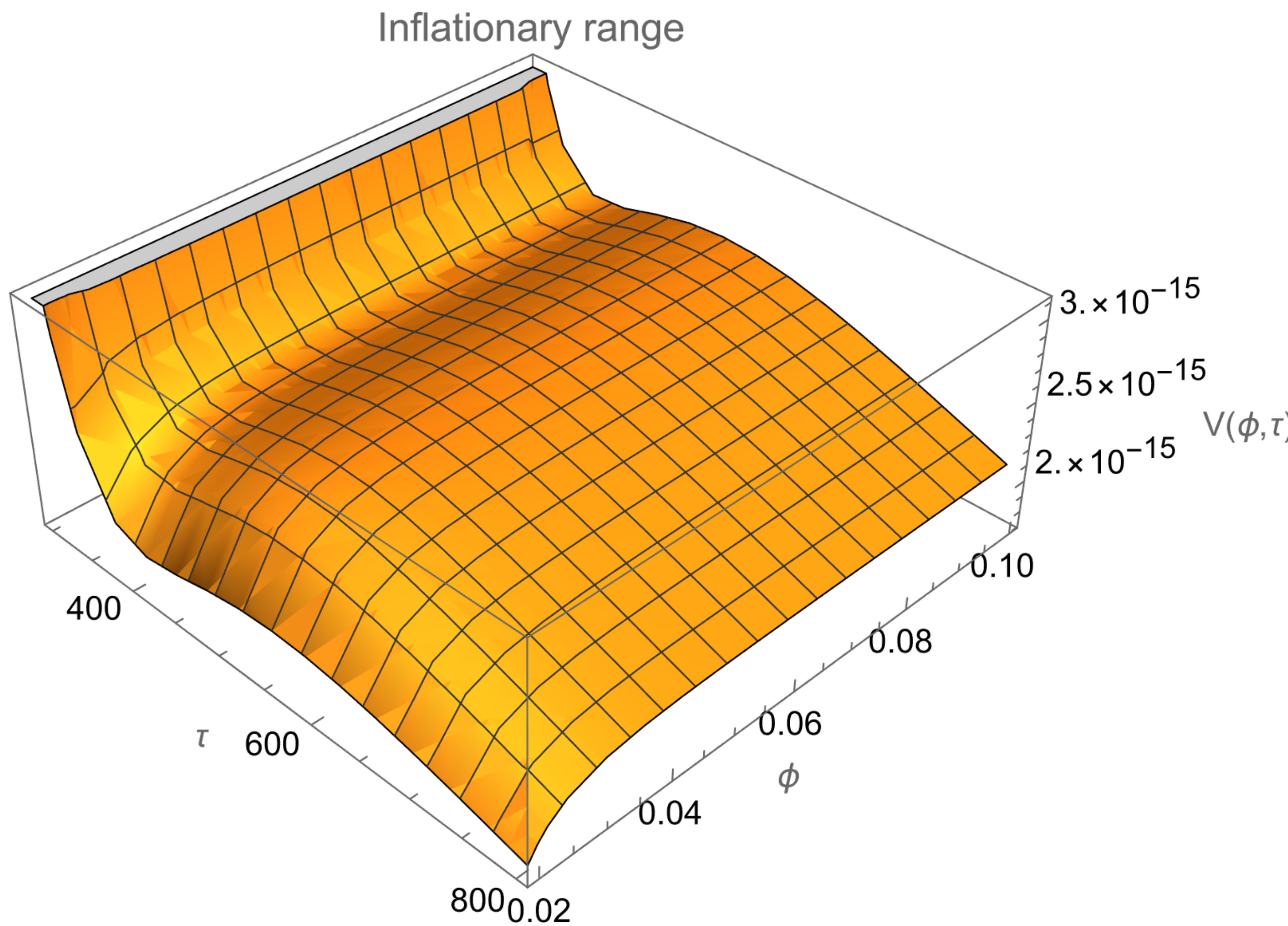


Figure: 3D potential in the inflationary regime. The field rolls down towards small ϕ and inflation eventually stops as the potential becomes steeper. This was calculated for 100 efolds.