Loop Blowup Inflation

Arthur Hebecker (Heidelberg)

based on work with: Sukṛti Bansal, Luca Brunelli, Michele Cicoli, Ruben Küspert

Outline:

- The Large Volume Scenario
- Blowup Inflation and Loop corrections
- Loop Blowup Inflation
- Inflationary phenomenology / Cosmo phenomenology

The Large Volume Scenario

- Consider type IIB on CY orientifold with O3/O7 planes
- F_3/H_3 flux $\Rightarrow$ C.S. moduli stabilized

  $\Rightarrow$ Minkowski vacuum ("no-scale")

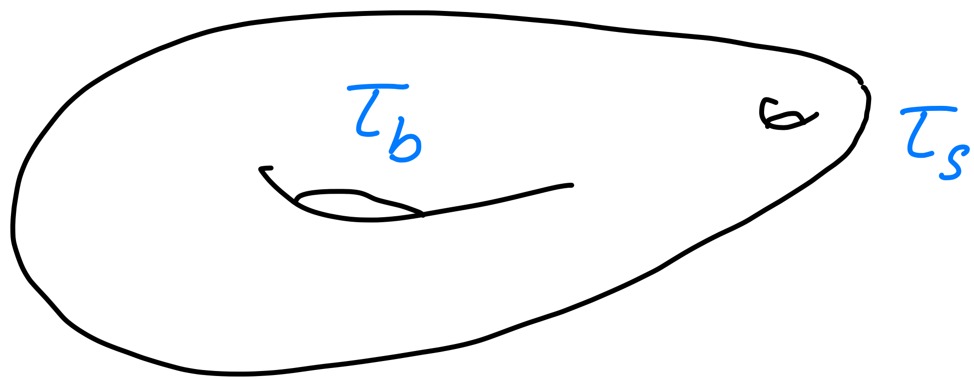
- Kahler moduli stabilization:

$$W = W_0 \quad ; \quad K = -2\ln\mathcal{V} \quad ; \quad \mathcal{V} = \mathcal{V}(T_i, \bar{T}_{\bar{i}})$$

$$\left(\tau_i = \mathrm{Re}(T_i) \equiv \text{4-cycle volumes}\right)$$

"LVS": $\quad \mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2}$

LVS:



At leading order: $W = W_0 \quad ; \quad K = -2\ln\mathcal{V}$

$$\Rightarrow \quad V = e^K\left(|DW|^2 - 3|W|^2\right) \equiv 0$$

With corrections:

$$W = W_0 + e^{-\tau_s} \quad ; \quad K = -2\ln\left(\mathcal{V} + \xi/g_s^{3/2}\right)$$

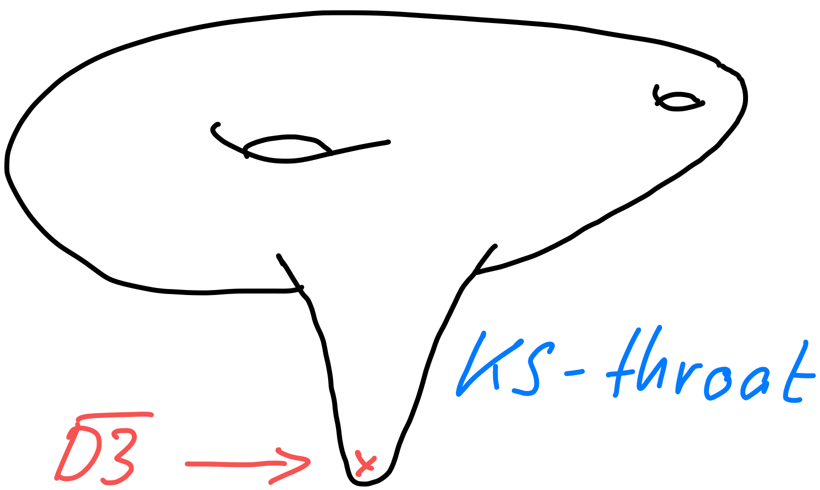
$$\Rightarrow \quad \boxed{V \sim |W_0|^2\left(\frac{\sqrt{\tau_s}\, e^{-2\tau_s}}{\mathcal{V}} - \frac{\tau_s e^{-\tau_s}}{\mathcal{V}^2} + \frac{\xi}{\mathcal{V}^3 g_s^{3/2}}\right)}$$

$\Rightarrow$ τ_s and $\mathcal{V}$ are stabilized in AdS at

$$\tau_s \sim \xi^{2/3}/g_s \quad \& \quad \mathcal{V} \sim \exp(\tau_s)$$

$\Rightarrow$ Volume can be exponentially large by a mild tuning of g_s.

Uplift: "old" anti-D3-idea:



$$\Rightarrow \quad V_{up} \sim \frac{\exp(-K/g_s M)}{\mathcal{V}^{4/3}}$$

It is known that creating metastable dS vacua in this way has issues. In particular:

$$V_{AdS} \sim \frac{1}{\mathcal{V}^3} \; ; \qquad V_{up} \sim \frac{\exp\left(-K/g_s M\right)}{\mathcal{V}^{4/3}}$$

must be comparable

$$\Rightarrow \exp\left(K/g_s M\right) \sim \mathcal{V}^{5/3}$$

flux numbers defining KS throat ;

at the same time: $K \cdot M \equiv N_{throat} < N_{tadpole}$

($N_{tadpole} \lesssim 250$ in known CY-orientifolds)

- Recent work has shown that there are serious "control issues"

[Junghans '22
Gao / AH / Schreyer / Venken '22
AH / Schreyer / Venken '22
Schreyer / Venken '22 ; Schreyer '24]

⇒ "Parametric Tadpole Constraint"

⇒ Higher curvature corrections in throat limiting $g_s M^2$ (enforcing large $K \cdot M$)

Nevertheless:

- let us assume some form of Uplift can be realized

- Just as an example, the F-term-uplift may be promising [Saltman/Silverstein '04
  Gallego/Marsh/Vercnocke/Wrase '17
  AH/Leonhardt '20
  Krippendorf/Schachner '23]

- Also: "T-brane uplift" [Cicoli/Quevedo/Valandro '15, ...]

We base our work on a stabilized, uplifted LVS

- Realizing inflation is a serious additional challenge
- However, the LVS has a good "built-in" starting point:

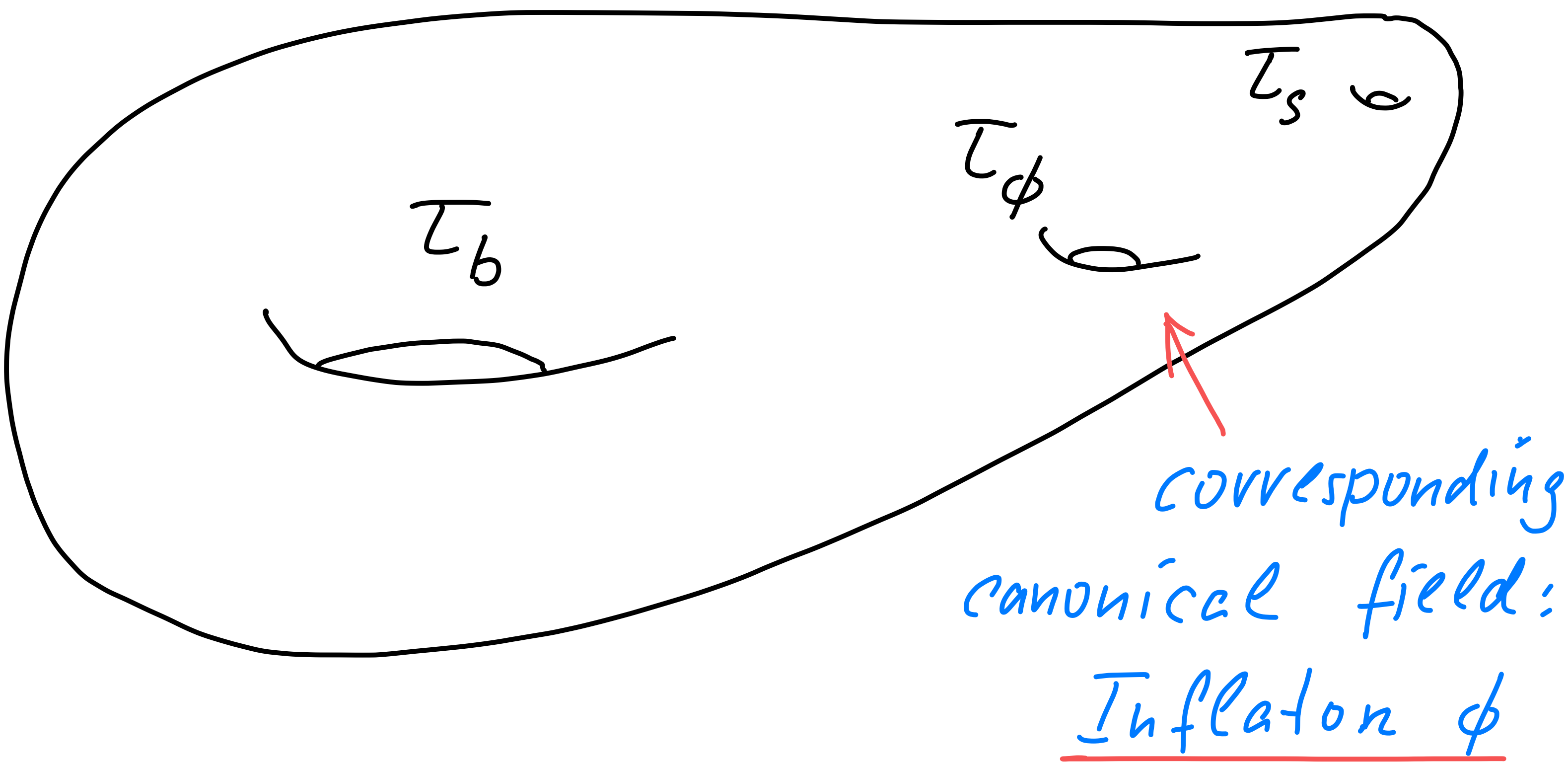
"LVS flat directions":

include more "big-cycle-type" Kahler moduli:

$$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2} \longrightarrow \mathcal{V} = \tilde{\mathcal{V}}(\tau_i) - \tau_s^{3/2}$$

The LVS potential stabilizes only $\tilde{\mathcal{V}} \simeq \mathcal{V}$ & τ_s. The ratios τ_i/τ_j of of additional "big" cycles remain unfixed.

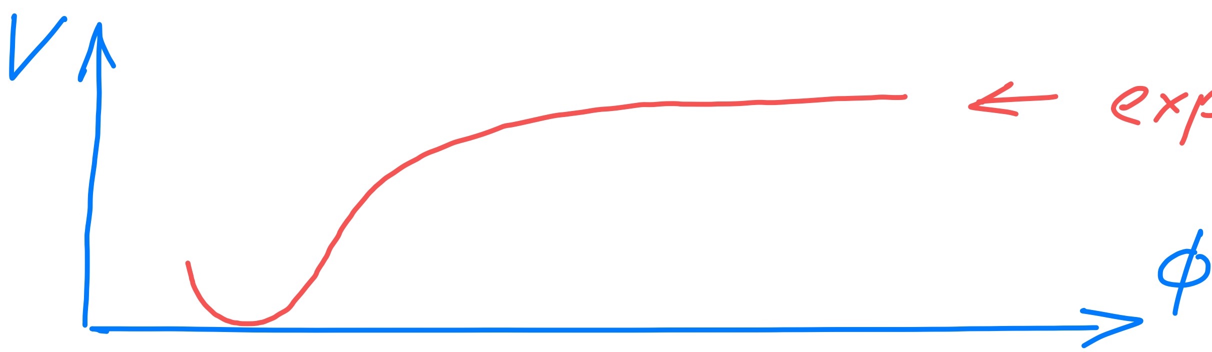
- This observation underlies many inflationary models
  [Conlon/Quevedo '05 ; Bond/Kofman/... '06
  Cicoli/Burgess/Quevedo '08 ; Cicoli/Ciupke/...'16 ; ...]
- Simplest version: Blowup Inflation



$$\mathcal{V} = \underbrace{\tau_b^{3/2} - \tau_\phi^{3/2}}_{\tilde{\mathcal{V}}(\tau_i)} - \tau_s^{3/2}$$

- τ_ϕ large $\Rightarrow$ flat potential
- τ_ϕ small $\Rightarrow$ stabilized non-perturbatively, just like τ_s

$$V = V_{LVS,\,up}(\mathcal{V}, \tau_s) + \left[\frac{\sqrt{\tau_\phi}\, e^{-2\tau_\phi}}{\mathcal{V}} - \frac{\tau_\phi\, e^{-\tau_\phi}}{\mathcal{V}^2} \right]$$



← exponential flatness

- It is well-known that loop corrections endanger Blowup Inflation [Conlon/Quevedo ; Cicoli/Burgess/Quevedo]
- Let us discuss this in detail :

Loop corrections

- Can be viewed as 10d field theory loops on CY [von Gersdorff/AH '05]
- Can be calculated explicitly for torus orbifolds [Berg/Haack/Körs '05]
- More discussion & comparative analysis : [Berg/Haack/Pajer ; Cicoli/Conlon/Quevedo ; Gao/AH/Schreyer/Venken]

- We want to work on a CY and hence need the field-theoretic approach [recent comprehensive study: Gao/AH/Schreyer/Venken '22]

- Classically, all geometric moduli acquire logarithmic kinetic terms in 4d:

$$\mathcal{L} \supset \frac{1}{\tau^2}(\partial\tau)^2$$

- The loop-corrected form is then

$$\mathcal{L} \supset \left(1 + M_{KK}^2/M_4^2\right)(\partial\tau)^2/\tau^2$$

UV cutoff (implied by 10d SUSY)

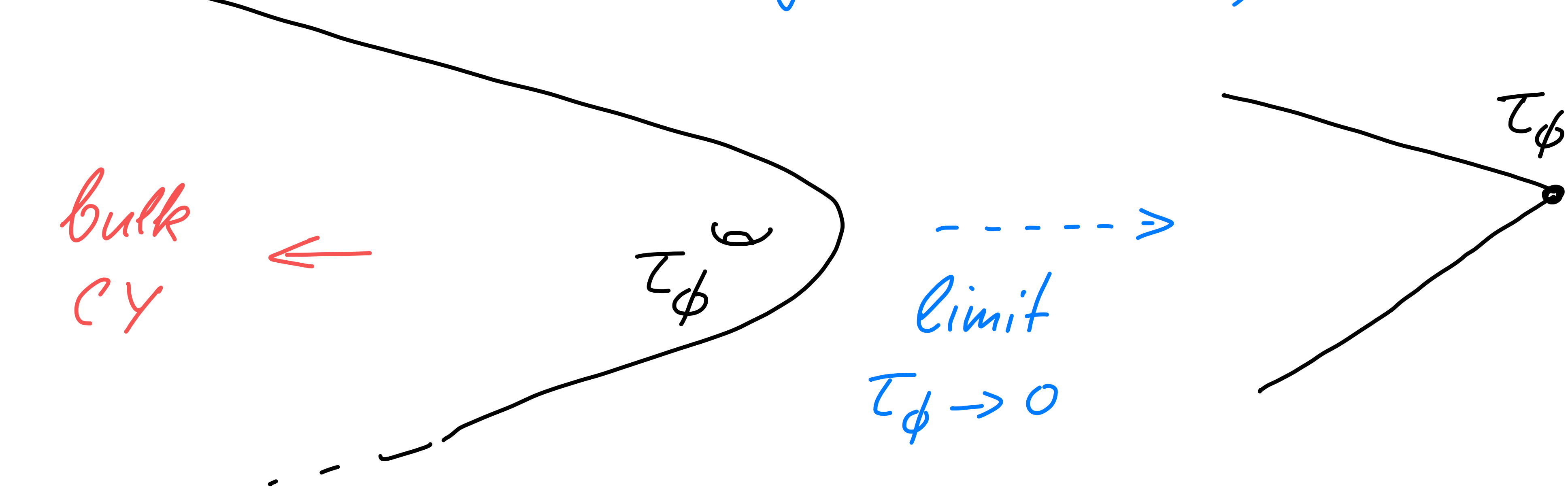
coupling suppression

- It follows that loop corrections to a modulus kinetic term enjoy a <u>relative</u> suppression by <u>$1/R^8$</u>

  ($R \equiv$ generic radius scale)

- Now focus specifically on the blowup modulus τ_ϕ

  (For simplicity, we ignore τ_s, treating it as fixed)



- The specific blowup structure implies that, before Weyl rescaling to the 4d Einstein frame, τ_ϕ should be part of "sequestered sector":

$$\mathcal{L}_{4d,\,\text{Brans-Dicke}} \supset k(\tau_\phi)\,(\partial\tau_\phi)^2$$

- After Weyl rescaling:

$$\mathcal{L}_{4d,\,E} \supset k(\tau_\phi)/\mathcal{V} \cdot (\partial\tau_\phi)^2$$

$$= (\partial\tau_\phi)^2/\sqrt{\tau_\phi}\,\mathcal{V}$$

(from known Kahler potential)

- With loop corrections:

$$\mathcal{L}_{4d,E} \supset \left(1 + \underline{\underline{1/\tau_\phi^2}}\right)(\partial\tau_\phi)^2/\sqrt{\tau_\phi}\,\mathcal{V}$$

(Recall: $1/R^8$)

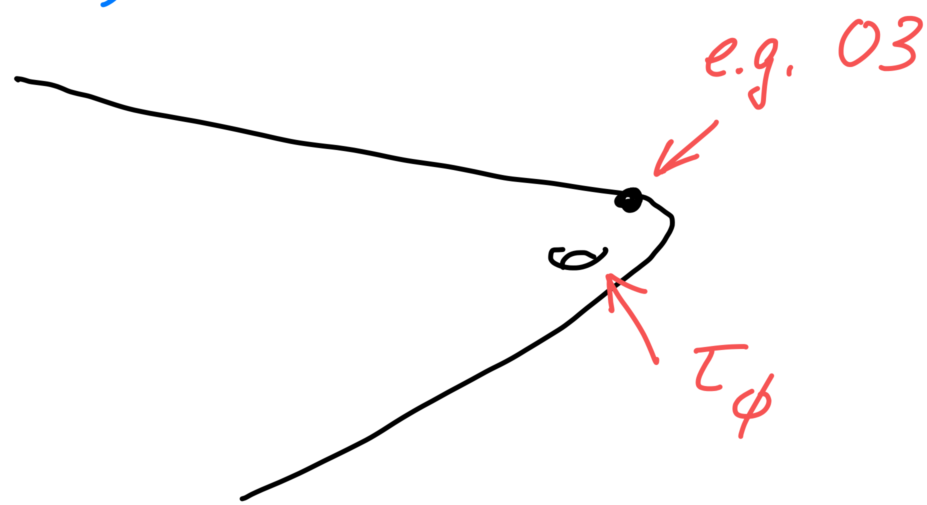
- This integrates to a Kahler potential correction

$$\delta K \sim \frac{1}{\mathcal{V}\sqrt{\tau_\phi}}$$

(Consistent with what BHK/BHP call a "winding mode correction". But, crucially, we claim it arises in any $\mathcal{N}=1$ situation, also without local D7 branes.)

- More precise picture:

(must avoid $\mathcal{N}=2$ cancellation)



Important question: Can we avoid such a correction by insisting on a "local" $\mathcal{N}=2$ situation?

(i.e. no nearby O-planes)

Answer: No, since this would also forbid the crucial $e^{-\tau\phi}$ - term

(creating the minimum in which we reheat)

Comment: Even fluxes can not induce the $e^{-\tau\phi}$ term in $\mathcal{N}=2$ geometries due to V-scaling & holomorphicity

- Thus, we finally arrive at

$$V_{inf} \sim \frac{1}{\mathcal{V}^3}\left\{\mathcal{V}^2\sqrt{\tau_\phi}\,e^{-2\tau_\phi} - \mathcal{V}\tau_\phi e^{-\tau_\phi} - \frac{c_{loop}}{\sqrt{\tau_\phi}}\right\}$$

$$c_{loop} \in \left\{\sim \frac{1}{(2\pi)^4} \;\cdots\; \frac{1}{16\pi^2}\right\}$$

Gao et al., using BHK   4d EFT logic

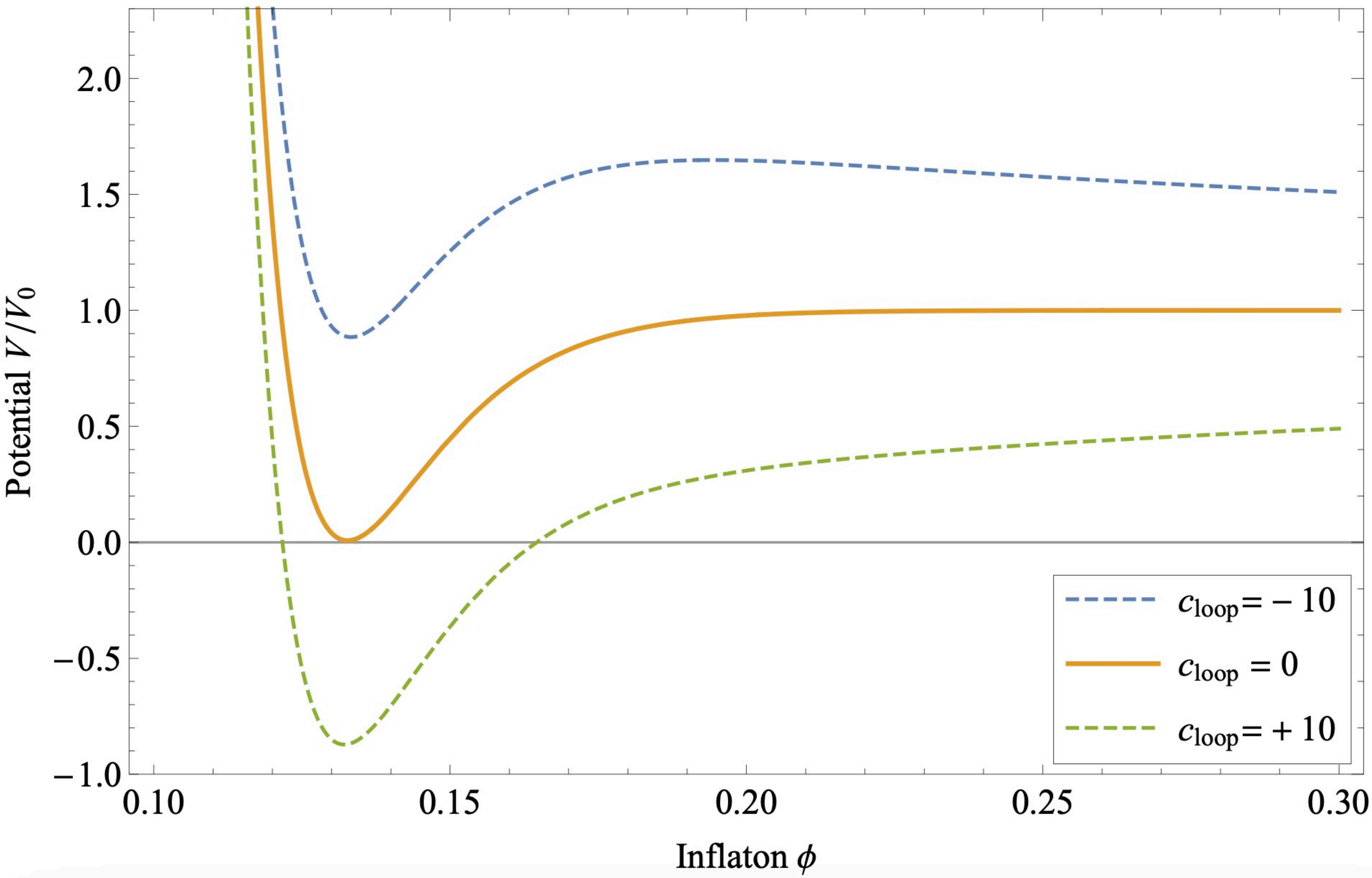
- Blowup inflation in trouble!
- Potential way out: Go to much larger τ_ϕ.

(was mentioned but not analysed by Cicoli/Quevedo '11)

Illustration of resulting potential

(c_{loop} chosen much too large for better visibility.)

$c_{loop} > 0$ is a necessity!



- From now on: Use canonical field $\phi \sim \tau_\phi^{3/4}/\sqrt{\mathcal{V}}$

- Note: • $\phi \sim 1$ is the largest allowed value since it implies $\tau_\phi \sim \tau_b$.

  • $\phi \sim 1/\sqrt{\mathcal{V}}$ is the "small-ϕ" regime, where non-pert. effects create a minimum.

- Potential relevant for inflation:

$$\boxed{V(\phi) \sim \frac{W_0^2}{\mathcal{V}^3}\left(1 - \frac{\delta}{\phi^{2/3}}\right)} \quad \text{with} \quad \boxed{\delta \equiv \frac{c_{loop}}{\mathcal{V}^{1/3}}}$$

(with $O(1)$ factors & log-factors suppressed)

- Deriving the inflationary parameters is straightforward:

$$\epsilon = \frac{1}{2}\frac{V'^2}{V^2} \sim \frac{\delta^2}{\phi^{10/3}} \quad ; \quad \eta = \frac{V''}{V} \sim \frac{\delta}{\phi^{8/3}}$$

$$n_s - 1 \sim \frac{\delta}{\phi^{8/3}} \quad ; \quad N_e \sim \frac{\phi^{8/3}}{\delta}$$

number of e-foldings from ϕ to ϕ_{reheat}

$$A_s \sim \frac{W_0^2}{\mathcal{V}^3} \cdot \frac{\phi^{10/3}}{\delta^2}$$

Non-trivial: Need $\phi = \phi^*$ & $\mathcal{V}$ to match all data & theory constraints.

Issues:

- slow-roll needs large V
- but large V makes A_s too small
- this can be counteracted by large W_0, but this is limited by the $N_{tadpole} \lesssim 250$.

Trading W_0 for $N_{tadpole}$, one derives:

$$\phi_* \sim \left[A_s N_e^7 C_{loop}^9 / N_{tadp.}\right]^{1/22} \; ; \quad V \sim \left[N_e^5 N_{tadp.}^4 / A_s^4 C_{loop}^3\right]^{1/11}$$

(for $O(1)$ factors see paper)

Based on this, explicit numerical solutions satisfying all constraints are easily found:

e.g.: $c_{loop} \sim \frac{1}{16\pi^2}$; $N_{tadp.} \sim 50$

$$\Rightarrow \quad \phi_* = 0.06 \cdot N_e^{7/22} \sim 0.2$$

$$V = 1700 \cdot N_e^{3/11} \sim 10^4$$

(with $N_e \sim 50$)

$\Rightarrow$ (most critical parameter) $n_s \simeq 1 - \frac{5/4}{N_e} \simeq 0.975$

(CMB-data: $n_s = 0.967 \pm 0.004$ at 1σ)

- at an approximate level, this is excellent:

  Only a 2σ-deviation in the most critical parameter!

- However, let us explore more details:

  - The prediction $n_s \simeq 1 - \frac{5/4}{N_e}$ depends only on the functional form $V \sim 1 - \frac{\delta}{\phi^{2/3}}$.

  - But this form may be compromised by terms of higher order in $\tau_\phi / \mathcal{V}^{2/3}$:

$$\Rightarrow \quad V \sim 1 - \delta \cdot \left[\frac{1}{\phi^{2/3}} + a + b\phi^{2/3} + \cdots \right]$$

- Here we assumed analyticity in 2-cycle variables

  (Is this justified?)

- The sign and size of the crucial coefficient "b" are not known.

- Much more could be done here in principle, but it involves further research in loop effects ...

Second line of thought concerning a possible, more precise prediction of n_s:

- assume that our result $n_s = 1 - \frac{5}{4N_e}$ holds w/o corrections
- Note that A) We can be more precise about N_e by studying reheating

  B) The CMB result $n_s = 0.967$ changes if dark radiation is present (cf. A))

Different scenarios have to be distinguished

SM on D7s

- Inflaton-cycle wrapped by (other) D7's (I)
- Inflaton-cycle not wrapped by D7's (II)

SM on fractional D3s

- Inflaton-cycle wrapped by D7's (III a)
- Inflaton-cycle not wrapped by D7's (III b)

Key players in analysis:

- Dark radiation contribution ΔN_{eff} from $\mathcal{V}$-axion and (potentially) τ_{SM}-axion

- $N_e = 57 + \frac{1}{4} \ln r - \frac{1}{4} N_\phi - \frac{1}{4} N_\mathcal{V}$

e-foldings with early DM domination by inflaton ϕ or by volume modulus $\mathcal{V}$.

Non-trivial aspects of analysis:

- Determine decay rates between:

  τ_ϕ & its axion ; τ_{SM} & its axion ; $\mathcal{V}$ & its axion

  D7-gauginos (SM & hidden) ; SM-Higgses

- Determine who dominates energy density ρ for how long.

[Helpful in some scenarios:

Fast $\mathcal{V}$-decay to SM-Higgs through loops helps avoiding too much Dark Radiation

→ Cicoli/AH/Jaeckel/Wittner '22]

as an example, consider scenario (IIIa)

SM on D3s ; inflaton-cycle wrapped by D7's

- inflaton decays quickly to hidden sector gauge bosons
- $\Rightarrow$ no significant N_ϕ
- ρ is dominated for a long time by $\mathcal{V}$

  ($N_{\mathcal{V}} \sim 10$)

- finally, $\mathcal{V}$ decays to its own axion and to SM-Higgs

$\Rightarrow$ significant amount of DR ; $\Delta N_{eff} \simeq 0.36$

(near max. allowed value)

Results for this scenario:

- $N_e = 51.5$; $n_s(\mathrm{CMB};\ \Delta N_{eff} = 0.36) = 0.983 \pm 0.006$

[recall: $n_s(\mathrm{CMB},\ \Delta N_{eff} = 0) = 0.967$]

- $n_s(\text{Loop Blowup},\ \underline{\mathrm{III}}a) = 0.976$

$\Rightarrow$ This $1.2\,\sigma$ off in opposite direction!

Thus, it is clear that intermediate scenarious (e.g. ($\underline{\mathrm{II}}$) with $\Delta N_{eff} = 0.14$) fit even better.

Unfortunately, Planck does not provide n_s for all ΔN_{eff}....

Conclusions

- LVS Kahler moduli sector has (relatively) flat directions
- Concretely, an additional blowup cycle provides an excellent inflaton candidate
- However, loop corrections spoil slow-roll
- Slow-roll is regained in a new regime (at much larger τ_ϕ) with a power-like potential.
- Quite non-trivially, one can find regimes with both calculational control & almost perfect pheno.