Loop Blow-up Inflation

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based on work with **Michele Cicoli, Sukruti Bansal, Luca Brunelli, Ruben Küspert**

Outline

- Introduction: The LVS and its flat directions.
- Blow-up Inflation and loop corrections.
- Our proposal: Loop Blow-up Inflation.
- Inflationary and Reheating Phenomenology.

The LVS

Balasubramanian/Berglund/Conlon/Quevedo '05

- Start with flux-stabilized type-IIB CY orientifold with O3/O7

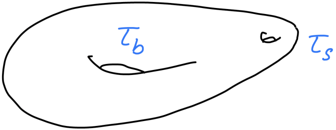
  $\Rightarrow$ No-scale Minkowski vacuum ('GKP').

- Stabilization of Kahler moduli $T_j = \tau_j + ic_j$ based on:

$$W = W_0 + e^{-T_s}$$

and

$$K = -\ln\left(\mathcal{V} + \xi/g_s^{3/2}\right) \qquad \text{with} \qquad \mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2}$$



The LVS (continued)

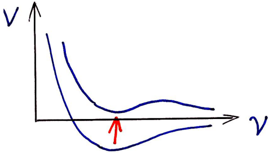
- The standard supergravity formula $V = e^K(|DW|^2 - 3|W|^2)$ then gives

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

stabilizing τ_s and $\mathcal{V}$ according to

$$\tau_s \sim \xi^{2/3}/g_s \qquad \text{and} \qquad \mathcal{V} \sim \exp(\tau_s) \,.$$

- Finally, this needs to be 'uplifted' to (near) Minkowski or dS:



$$V \;\rightarrow\; V + \frac{(\text{small } \#)}{\mathcal{V}^k}$$

An Aside on Uplifts

- It is well-known that getting a small uplift is hard.
- This causes severe problems for KKLT ....

  Carta/Moritz/Westphal '19, Gao/AH/Junghans '20
- ... but also the LVS is has related control problems...

  Junghans, AH/Schreyer/Venken '22
- especially in view of the curvature corrections in the KS-throat

  AH/Schreyer/Venken, Schreyer/Venken '22, Schreyer '24

> Nevertheless, for the purpose of this talk,
> I willl assume some form of uplift can be realized.

- For example, one may think of the
  - complex-structure F-term term uplift

    Saltman/Silverstein '04, ... , Gallego/Marsh/Vercknocke/Wrase '17, AH/Leonhardt '20, Krippendorf/Schachner '23
  - T-brane uplift, ... etc. Cicoli/Quevedo/Valandro '15
  - Controlling small cycles McAllister/Moritz/Nally/Schachner '24

Inflation

- Given an uplifted flux vacuum, slow-roll inflation represents a significant additional challenge.

- The LVS has a good 'built-in' starting point in the form of 'flat Kahler directions'.

- Indeed, including more 'big-cycle-type' Kahler moduli gives:

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

- The LVS-potential stabilizes only τ_s and $\tilde{\mathcal{V}} \simeq \tau_b^{3/2}$.

Ratios τ_i / τ_j of additional 'big' cycles remain unfixed.

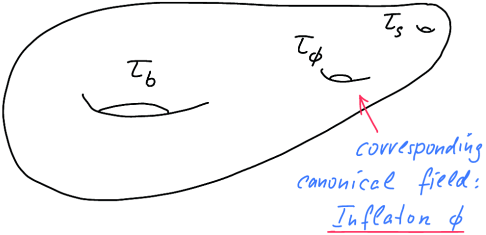
- This observation underlies many models of inflation...

  Conlon/Quevedo '05, Bond/Kofman/... '06,
  Cicoli/Burgess/Quevedo '08, Cicoli/Ciupke/de Alwis/Muia '16, ...
  ..., Bera/Chakraborty/Leontaris/Shukla'24

Simplest version:

Blow-up Inflation

Conlon/Quevedo '05

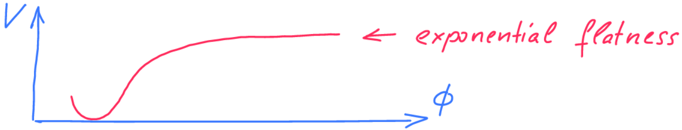


$$\mathcal{V} = \underbrace{\tau_b^{3/2} - \tau_\phi^{3/2}}_{\tilde{\mathcal{V}}(\tau_i)} - \tau_s^{3/2}$$

- Large τ_ϕ $\Rightarrow$ flat potential
- Small τ_ϕ $\Rightarrow$ non-perturbative stabilization (just like τ_s)

Blow-up Inflation: Potential

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



- Well-known: Loop corrections endanger Blow-up Inflation.

Conlon/Quevedo, Cicoli/Burgess/Quevedo

- Need to consider loop corrections in detail!

Loop Corrections

- Can be estimated as 10d field theory loops on CY.

  Gersdorff/AH '05

- Can be calculated explicitly for torus orbifolds.

  Berg/Haack/Körs '05

  More discussions and comparative analysis:

  Berg/Haack/Pajer, Cicoli/Conlon/Quevedo, Gao/AH/Schreyer/Venken

- We want to work on CY. $\Rightarrow$ Need field-theoretic approach.

  Let τ be generic Kahler modulus:

$$\mathcal{L}_{tree} \sim \frac{(\partial\tau)^2}{\tau^2} \quad \rightarrow \quad \mathcal{L}_{tree+loop} \sim \left(1 + \frac{M_{KK}^2}{M_4^2}\right)\frac{(\partial\tau)^2}{\tau^2}$$

Here: M_{KK} – UV-cutoff implied by 10d SUSY.

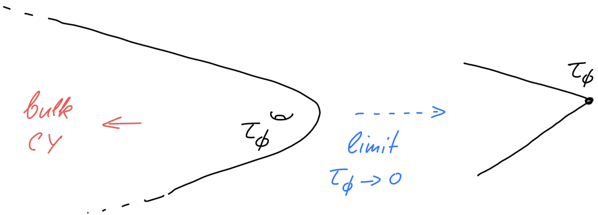
$1/M_4$ – Coupling constant of KK-mode theory.

Loop Corrections (continued)

- With R a generic CY length scale, it follow that loop corrections enjoy a relative suppression by $1/R^8$.

- Now focus specifically on the blowup modulus τ_ϕ.

  (We ignore τ_s, treating it as fixed.)



- The specific blow-up geometry implies that, before Weyl rescaling to 4d Einstein-frame, τ_ϕ appears as part of a 'sequestered sector':

$$\mathcal{L}_{Brans-Dicke} \sim k(\tau_\phi)\,(\partial\tau_\phi)^2\,.$$

- A volume dependence arises only after Weyl rescaling:

$$\mathcal{L}_{Einstein} \sim k(\tau_\phi)\,(\partial\tau_\phi)^2/\mathcal{V}\,.$$

- The known tree-level kinetic term and the $1/R^8$ suppression discussed above fix $k(\tau_\phi)$:

$$\mathcal{L}_{Einstein} \sim \frac{1}{\sqrt{\tau_\phi}}\left(1+\frac{1}{\tau_\phi^2}\right)(\partial\tau_\phi)^2/\mathcal{V}\,.$$

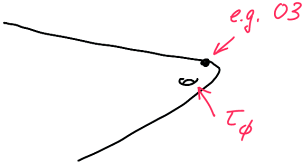
- This integrates to a Kahler potential correction:

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

Gao/AH/Schreyer/Venken '22

(This is consistent with what BHP call a 'winding mode correction'. But we claim it arises in any $\mathcal{N}=1$ situation, also in the absence of D7-branes.)

- More precisely: We do need at least a local O3, such that SUSY is locally recuded to $\mathcal{N} = 1$:



- <u>Important question:</u>

  Can we avoid this loop correction by insisting on a local $\mathcal{N} = 2$ geometry, i.e. no nearby O3's ?

- <u>Answer:</u>

  No, since then the crucial $\exp(-\tau_\phi)$ terms would not arise (we need this term for the minimum which we reheat in).

<u>Comment:</u> Fluxes can not create the required $\exp(-\tau_\phi)$ terms in $\mathcal{N} = 2$ geometries due to $\mathcal{V}$-scaling and holomorphicity constraints.

cf. e.g. Conlon/Quevedo '05

Result:

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

- The numerical coefficient can be estimated using the torus calculations of BHK (cf. Gao et al.) or simply using 4d 1-loop logic:

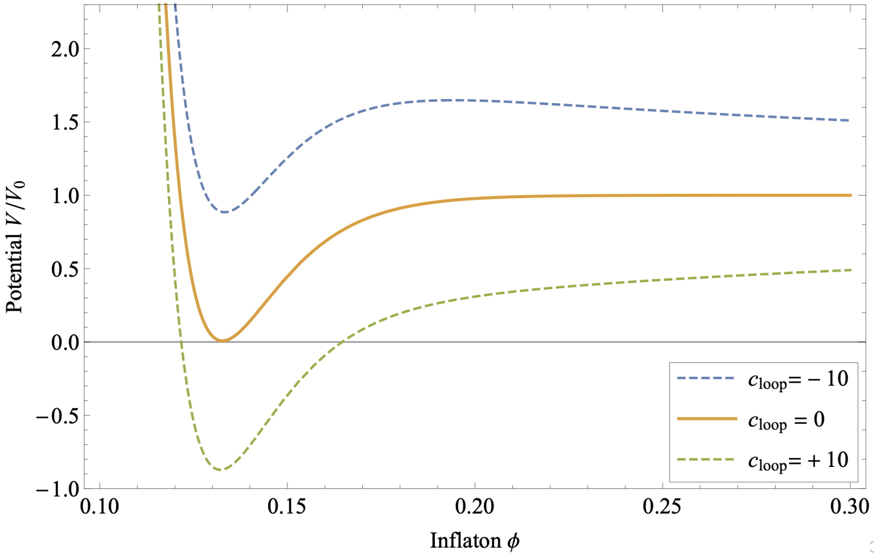
$$c_{loop} \in \left\{\sim \frac{1}{(2\pi)^2} \cdots \frac{1}{16\pi^2}\right\}$$

- With these numbers, Blow-up inflation is in trouble!
- Potential way out: Go to much larger τ_ϕ.

  (This was mentioned but not analysed in Cicoli/Quevedo '11.)

Illustration of the resulting potential

(c_{loop} chosen much too large for better visibility;
the condition $c_{loop} > 0$ must be fulfilled.)



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-perturbative effects create a minimum.

The potential relevant for inflation reads:

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

(Here all $\mathcal{O}(1)$ factors have been suppressed.)

The inflationary parameters are derived straigthforwardly:

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

$$n_s - 1 \sim \frac{\delta}{\phi^{8/3}} \quad , \quad A_s \sim \frac{W_0^2}{\mathcal{V}^3} \cdot \frac{\phi^{10/3}}{\delta^2} \quad .$$

- They come together with a known number of e-foldings between the field-value ϕ and the (much smaller) ϕ_{reheat}:

$$N \sim \frac{\phi^{8/3}}{\delta} \quad .$$

- Non-trivial: Need to find 'CMB-value' of $\phi = \phi_*$ and $\mathcal{V}$ matching all data and theory constraints.

Competing requirements:

- Slow-roll needs large $\mathcal{V}$
- But large $\mathcal{V}$ makes A_s too small.
- One may countract this by taking W_0 to its maximal value, prescribed by $N_{tadpole}$

Thus, trading W_0 for $N_{tadpole} \leq 252$, we find:

$$\phi \sim \left[A_s N_e^7 c_{loop}^9 / N_{tadpole}\right]^{1/22} \quad , \quad \mathcal{V} \sim \left[N_e^5 N_{tadpole}^4 / A_s^4 c_{loop}^3\right]^{1/11} \; .$$

(For $\mathcal{O}(1)$ factors see paper.)

- Based on this analytical understanding, explicit solutions satisfying all constraints are easily found:

- For example, taking $c_{loop} \sim 1/16\pi^2$ and $N_{tadpole} \sim 50$ gives:

$$\phi_* \sim 0.02\, N_e^{7/22} \sim 0.2 \qquad , \qquad \mathcal{V} \sim 1700\, N_e^{5/11} \sim 10^4 \,.$$

(Here we used the a posteriori reasonable value $N_e \simeq 50$.)

- It turns out that the most critical parameter is the spectral index:

$$\boxed{n_s \simeq 1 - \frac{5/4}{N_e} \simeq 0.975\,.}$$

- At the 2σ-level, this agrees with the CMB-result:

$$\boxed{n_s = 0.967 \pm 0.004}$$

- This is excellent! But can we be more precise? ....

(1) – Possible theory improvements:

- 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 modified by terms of higher order in $\tau_\phi/\mathcal{V}^{2/3}$:

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

- Here we assumed analyticity in 2-cycle variables. But is this justified?
- The sign and size of b need to be determined.

$\Rightarrow$ Much more could be achieved at the price of further research on loop effects.

(2) – Possible improvements from reheating / phenomenology:

→ cf. parallel talk by Luca Brunelli

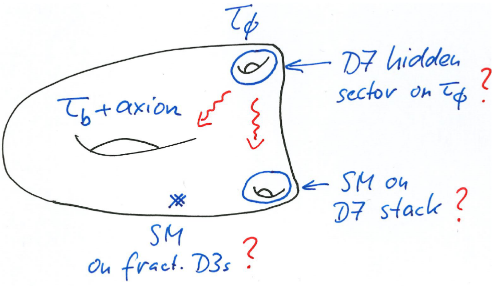
(2.A) – **Number of e-foldings**

- We can be more precise about N_e by studying reheating.
- Require assumptions about detailed brane setup (e.g. SM)
- The number $N_e = 50$ used above turns out to be fairly robust.

(2.B) – **Dark radiation can help**

- Crucial observation: $n_s(CMB, \Delta N_{eff} = 0.36) = 0.983 \pm 0.006$ deviates from our prediction by $1.2\,\sigma$ in the opposite direction.
- Some of the most natural settings produce the right amount of dark radiation to match CMB data perfectly.

Reheating after Loop Blow-up Inflation



- We studied reheating and dark radiation production in various settings, following in particular

  Cicoli/Mazumdar '10, Cicoli/Licheri/Piantadosi/Quevedo/Shukla '23

- Crucial in some scenarios: Fast $\mathcal{V}$-decay to SM through loops helps avoiding dark-radiation overproduction.

  Cicoli/AH/Jaeckel/Wittner '22

Summary / Conclusions

- LVS Kahler moduli sector has (relatively) flat directions.
- Specifically, an additional blowup modulus is an excellent inflaton candidate
- However, loop corrections spoil slow-roll.
- Slow roll is regained in a new regime, at much larger τ_ϕ and with a power-like potential.
- Quite non-trivially, one finds regions in parameter space with calculational control and almost perfect pheno.

For more cf. talk by Luca Brunelli