Loop Blow-Up Inflation

A novel way to inflate with the Kähler moduli

Luca Brunelli
University of Bologna and INFN
String Phenomenology 2024, Padova

Istituto Nazionale di Fisica Nucleare

Based on:
S. Bansal, LB, M. Cicoli, A. Hebecker, R. Kuespert: 2403.04831

See Hebecker's talk

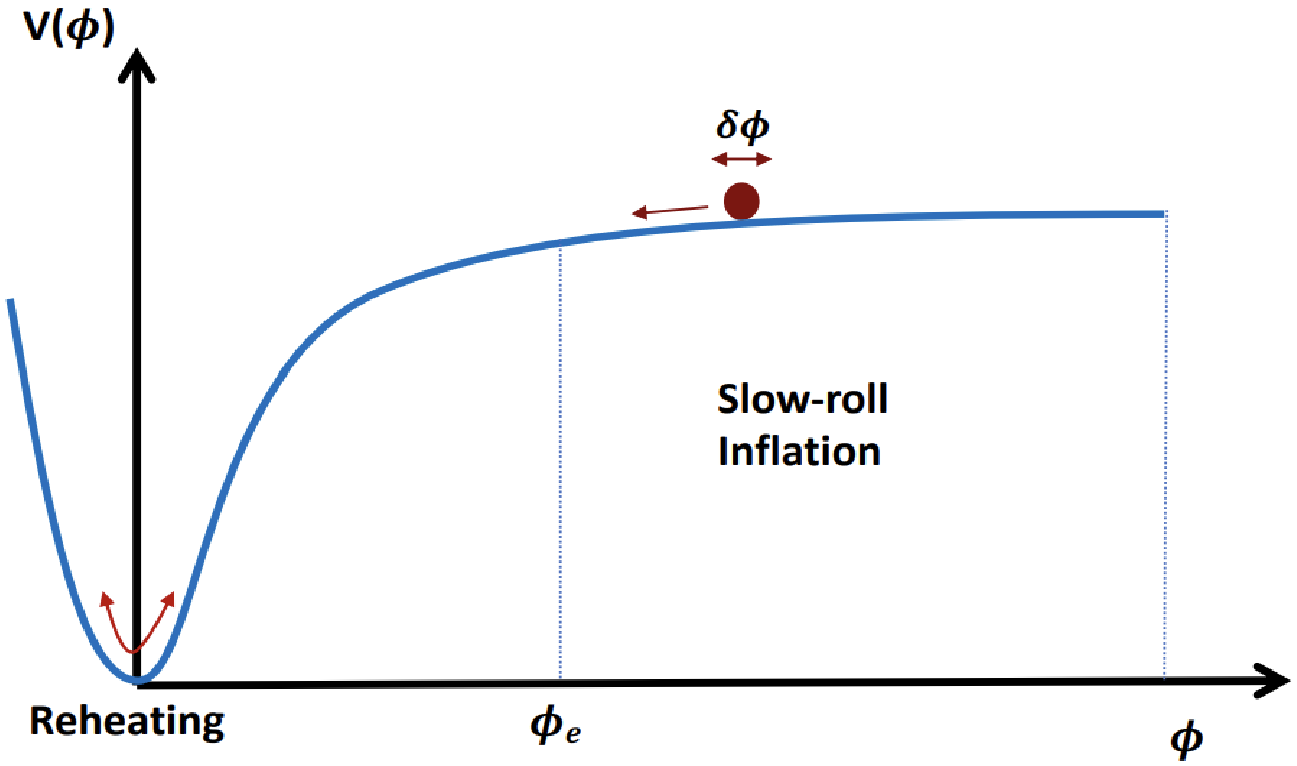
Slow-Roll Inflation

- Standard Slow-Roll: Scalar field with almost-flat direction in the potential

- Possible form of the potential:

$$V(\varphi) = V_0[1 - f(\varphi)]$$

with $f(\varphi) \to 0$ as $\varphi \to +\infty$.



Credits: String Cosmology: from the Early Universe to Today [Cicoli, Conlon, Maharana, Parameswaran, Quevedo, Zavala: 2023]

Kähler Moduli Inflation

- Type IIB String Compactifications $\Longrightarrow$ Moduli with leading-order flat potential

- Kähler moduli: Tree level no-scale + 1-loop extended no-scale [Cicoli, Conlon, Quevedo: 2008]

- Volume $\mathcal{V}$: lifted by leading-order corrections:

  - BBHL: $V_{\alpha'^3}(\mathcal{V})$ [Becker, Becker, Haack, Louis: 2002]
  - Uplifting: $V_{\rm up}(\mathcal{V})$ (anti-D3, T-branes, …)

- Other Kähler moduli: LO flat directions $\Longrightarrow$ good inflaton candidates τ_φ!

- Need: Subleading quantum corrections (loops, non-perturbative effects)

Classification of Inflationary Models

- Classification of inflationary models with Kähler moduli based on:

  a) Topology (bulk/local): determines the canonical normalization $\tau_\varphi(\varphi)$
  b) Lifting Effects (perturbative/non-perturbative): determine the shape of the potential

- All models give a potential of the form:

$$V(\varphi) = V_0[1 - f(\varphi)]$$

with $f(\varphi)$ depending on topology + lifting effects and such that $f(\varphi) \ll 1$ for $\varphi \gg 1$.

Lifting Effect / Topology	**Non-Perturbative:** $V(\tau) \sim e^{-a\tau} \quad (a > 0)$	**Perturbative:** $V(\tau) \sim \frac{1}{\tau^{\beta}} \quad (\beta > 0)$
Bulk (fibre) $\tau(\varphi) = e^{k\varphi}$	**Non-Perturbative Fibre Inflation**: $f(\varphi) \propto e^{-ae^{k\varphi}}$ [Cicoli, Pedro, Tasinato: 2011] [Lüst, Zhang: 2013]	**Loop Fibre Inflation** $f(\varphi) \propto e^{-\beta k\varphi}$ [Cicoli, Burgess, Quevedo: 2008] [Broy, Ciupke, Pedro Westphal: 2015] [Cicoli, Ciupke, de Alwis, Muia: 2016]
Local (Blow-up) $\tau(\varphi) = \gamma\, \mathcal{V}^{2/3}\varphi^{4/3}$	**Non-Perturbative Blow-Up Inflation** $f(\varphi) \propto e^{-a\gamma\mathcal{V}^{2/3}\varphi^{4/3}}$ [Conlon, Quevedo: 2006] [Bond, Kofman, Prokushkin, Vaudrevange: 2006]	**Loop Blow-Up Inflation** $f(\varphi) \propto \frac{1}{\mathcal{V}^{2\beta/3}\varphi^{4\beta/3}}$ [Bansal, LB, Cicoli, Hebecker, Kuespert: 2024] **New!**

Non-Perturbative Blow-Up Inflation

- Calabi-Yau volume:

$$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2} - \tau_\phi^{3/2} \simeq \tau_b^{3/2} \qquad \text{with} \qquad T_i = \tau_i + i\vartheta_i$$

- LVS stabilisation: $\mathcal{O}(\alpha'^3)$ correction to Kähler potential and non-perturbative correction to W:

$$K = -2\ln\left(\mathcal{V} - \frac{\xi}{2g_s^{3/2}}\right) \qquad W = W_0 + A_s\, e^{-a_s T_s} + A_\varphi e^{-a_\varphi T_\varphi}$$

- Scalar Potential: $V = V_{LVS} + V_\varphi$

$$V_{LVS}(\mathcal{V},\tau_s) = \tilde{V}\left(B_s \frac{\sqrt{\tau_s}\, e^{-2a_s\tau_s}}{\mathcal{V}} - C_s \frac{\tau_s e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{3\,\xi}{4g_s^{3/2}\mathcal{V}^3} + \frac{D}{\mathcal{V}^2}\right)$$

$$V_\varphi(\mathcal{V},\tau_\varphi) = \tilde{V}\left(B_\varphi \frac{\sqrt{\tau_\varphi}\, e^{-2a_\varphi\tau_\varphi}}{\mathcal{V}} - C_\varphi \frac{\tau_\varphi e^{-a_\varphi\tau_\varphi}}{\mathcal{V}^2}\right) \qquad \text{with } a_\varphi^{3/2} \gg a_s^{3/2}$$

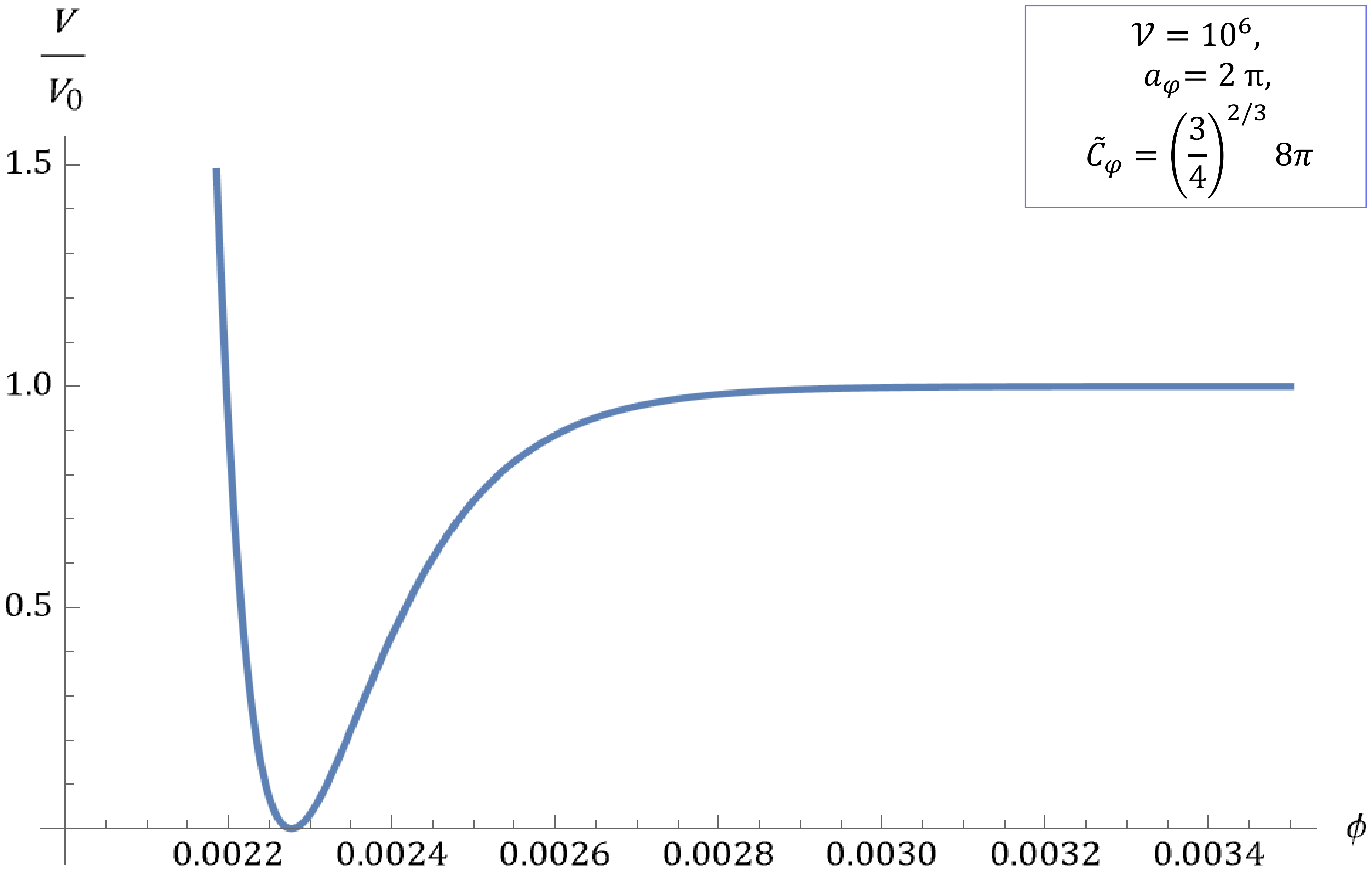
$$\Longrightarrow \quad <\tau_{s,\varphi}> \sim \xi^{2/3} g_s^{-1} \qquad \text{and} \qquad <\mathcal{V}> \sim e^{a_s\tau_s} \sim e^{a_\varphi\tau_\varphi}$$

- Inflationary potential [Conlon, Quevedo: 2006] :

$$V(\tau_\varphi) \simeq V_0[1 - C_\varphi \mathcal{V}\,\tau_\varphi e^{-a_\varphi\tau_\varphi}] \xrightarrow{\tau = \left(\frac{3\mathcal{V}}{4}\right)^{2/3}\varphi^{4/3}} V(\varphi) = V_0\,[1 - \tilde{C}_\varphi \mathcal{V}^{5/3}\varphi^{4/3} e^{-a_\varphi \mathcal{V}^{2/3}\varphi^{4/3}}]$$

with $V_0 = \tilde{V}\frac{\beta}{\mathcal{V}^3}$

Exponentially Flat Plateau!


$\frac{V}{V_0}$
1.5
1.0
0.5
0.0022
0.0024
0.0026
0.0028
0.0030
0.0032
0.0034
ϕ
$\mathcal{V} = 10^6$,
$a_\varphi = 2\pi$,
$\tilde{C}_\varphi = \left(\frac{3}{4}\right)^{2/3} 8\pi$

Loop Corrections

- No exact computation of loop corrections on CY background
- 1-loop corrections computed on toroidal orientifolds [Berg, Haack, Körs: 2005]
- Conjectured generalization to CY orientifold [Berg, Haack, Pajer: 2007]
- Two kinds of corrections to K:
  1. Kaluza-Klein (KK): $\delta K^{(KK)} = g_s \sum_i \frac{c_i^{(KK)} t_i}{\mathcal{V}}$ ⟹ Extended no-scale in V [Cicoli, Conlon, Quevedo: 2008]
  2. Winding (W): $\delta K^{(W)} = \sum_i \frac{c_i^{(W)}}{\mathcal{V} t_i}$

- For a Blow-Up mode τ:

$$\delta K(\tau) \simeq \frac{c_{loop}}{\mathcal{V}\sqrt{\tau}} \Longrightarrow \delta V(\tau) \simeq \frac{c_{loop}}{\mathcal{V}^3\sqrt{\tau}}$$

See Hebecker's talk for details

- EFT understanding from 1-loop corrections to 2-point functions and V

[Von Gersdorff, Hebecker: 2005] [Cicoli, Conlon, Quevedo: 2008] [Gao, Hebecker, Schreyer, Venken:2022]

Loop Blow-Up Inflation

- Potential for τ_φ including loop corrections:

$$V = \tilde{V}\left[\frac{\beta}{\mathcal{V}^3} + B_\varphi \frac{\sqrt{\tau_\varphi}\, e^{-2a_\varphi \tau_\varphi}}{\mathcal{V}} - C_\varphi \frac{\tau_\varphi e^{-a_\varphi \tau_\varphi}}{\mathcal{V}^2} - \frac{c_{loop}}{\mathcal{V}^3 \sqrt{\tau_\varphi}}\right]$$

- Non-perturbative Blow-Up inflation if:

$$c_{loop} \ll 10^{-6}$$

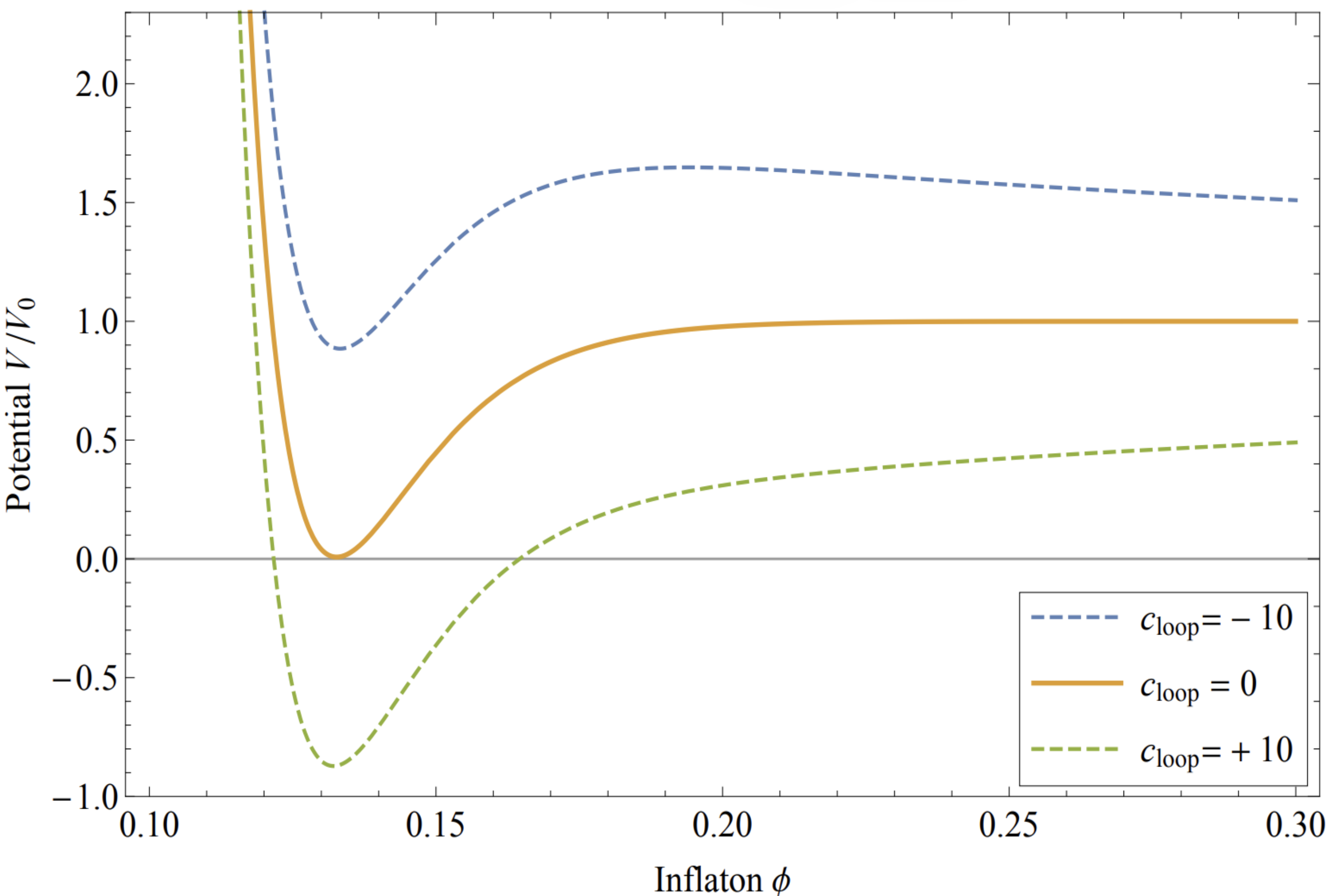
- If $c_{loop} \gtrsim 10^{-6}$ ⟹ Loops dominate

- Inflationary potential:

$$V \simeq V_0\left(1 - \frac{c_{loop}}{\beta\sqrt{\tau_\varphi}}\right) = V_0\left(1 - \frac{b\, c_{loop}}{\mathcal{V}^{1/3}\varphi^{2/3}}\right)$$

with $b = \frac{1}{\beta}\left(\frac{4}{3}\right)^{1/3}$.

Fixed parameters: $\mathcal{V} = 1000$, $C_\varphi = B_\varphi = a_\varphi = \beta = 1$



Inflationary Parameters

- Slow-roll parameters:

$$V = V_0\left(1 - \frac{b\, c_{loop}}{\mathcal{V}^{1/3}\varphi^{2/3}}\right)$$

$$\begin{cases} \epsilon = \frac{1}{2}\left(\frac{V_{,\varphi}}{V}\right)^2 \simeq \frac{2}{9}\frac{(bc_{loop})^2}{\mathcal{V}^{2/3}\varphi^{10/3}} \\ \eta = \frac{V_{,\varphi\varphi}}{V} \simeq -\frac{10}{9}\frac{bc_{loop}}{\mathcal{V}^{1/3}\varphi^{8/3}} \end{cases}$$

- Cosmological parameters:

$$N_e = \int_{\varphi_e}^{\varphi_*} \frac{1}{\sqrt{2\epsilon}}\, d\varphi \simeq \frac{2}{9}\frac{\mathcal{V}^{1/3}\varphi_*^{8/3}}{bc_{loop}}$$

$$\hat{A}_s = \frac{V^3}{V_{,\varphi}^2} = \frac{9V_0}{4}\frac{\mathcal{V}^{2/3}\varphi_*^{10/3}}{(bc_{loop})^2} \equiv 2.5 \times 10^{-7}$$

$c_{loop} = 1/(16\,\pi^2)$

$$\begin{cases} \varphi_* = 0.06\, N_e^{7/22} \\ \mathcal{V} = 1743\, N_e^{5/11} \end{cases}$$

- $r - n_s$ relation:

$$n_s = 1 + 2\eta_* - 6\epsilon_* \simeq 1 - \frac{20}{9}\frac{bc_{loop}}{\mathcal{V}^{1/3}\,\varphi_*^{8/3}}$$

$$r \simeq 16\epsilon_* \simeq \frac{32}{9}\frac{(bc_{loop})^2}{\mathcal{V}^{2/3}\varphi_*^{10/3}}$$

$$r = 0.003(1 - n_s)^{11/15}$$

Post-Inflationary Evolution

- N_e from post-inflationary dynamics [Dutta, Maharana: 2015]:

$$N_e \simeq 57 + \frac{1}{4}\ln r - \frac{1}{4}\left(N_\varphi + N_\chi\right) + \frac{1}{4}\ln\left(\frac{\rho_*}{\rho_{end}}\right)$$

- N_φ, N_χ : e-folds of inflaton and volume domination ⟹ depend on SM realization

- Decay of last dominant modulus ψ drives reheating:

$\Delta N_{\rm eff} \lesssim 0.2 - 0.5$ 95% CL
[Planck: 2018]

ψ → SM fields (Higgs, gauge bosons)

ψ → big cycle axions ϑ_b: Dark Radiation ⟹

$$\Delta N_{\rm eff} = \frac{43}{7}\left(\frac{10.75}{g_*(T_{rh})}\right)^{1/3} \frac{\Gamma_{\psi\to\vartheta\vartheta}}{\Gamma_{\psi\to SMSM}}$$

[Higaki, Takahashi: 2012]
[Cicoli, Conlon, Quevedo: 2013]

SM Realization and Scenarios

- SM D7-branes cannot wrap τ_s [Blumehagen, Moster, Plauschinn: 2007] nor τ_φ (FI terms would make it too heavy)
  ⟹ introduce τ_{SM} and τ_{int}

$$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2} - \tau_\varphi^{3/2} - \tau_{SM}^{3/2} - \lambda(\tau_{int} - \tau_{SM})^{3/2}$$

- D-term stabilization ($\xi_{FI} = 0$):

$$\tau_{SM} = \lambda^2(\tau_{int} - \tau_{SM})$$

  - $\lambda = 0$ ⟹ $\tau_{SM} \to 0$: SM on D3-branes at singularity
  - $\lambda \neq 0$ ⟹ τ_{int} fixed in terms of τ_{SM}, still flat. Fixed by loop potential [Cicoli, Mayrhofer, Valandro: 2011]:

$$V_{loop}(\tau_{SM}) = \frac{W_0^2}{\mathcal{V}^3}\left(\frac{\gamma}{\sqrt{\tau_{SM}}} - \frac{\delta}{\sqrt{\tau_{SM}} - \sqrt{\tau_s}}\right)$$ ⟹ SM on D7-branes

- 3 Scenarios:
  i. Scenario I: SM on D7, τ_φ wrapped by hidden-sector D7s
  ii. Scenario II: SM on D7, τ_φ *not* wrapped
  iii. Scenario III: SM on D3

Scenario I

$$\Gamma(\varphi \to \gamma_h \gamma_h) \simeq \frac{\mathcal{V}}{64\,\pi}\,\frac{m_\varphi^3}{M_p^2}$$

$$N_\varphi \simeq \frac{2}{3}\, ln\left(\frac{H_{inf}}{\Gamma_{\varphi\to\gamma_h\gamma_h}}\right) \simeq 1$$

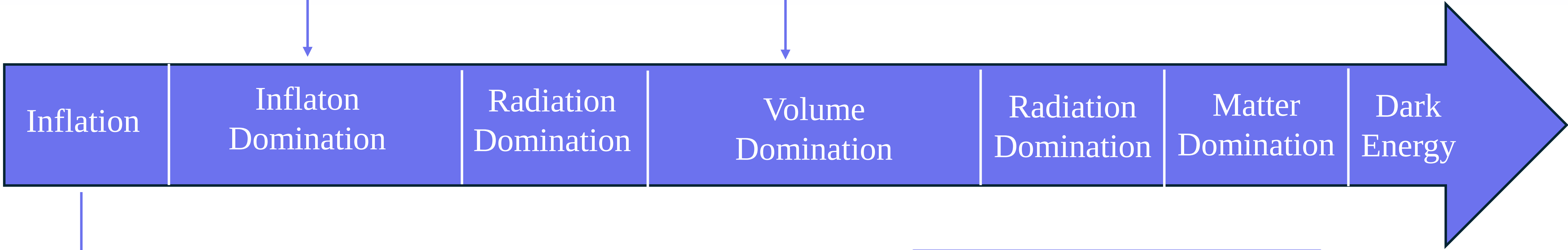
$$\Gamma(\chi \to hh) \simeq \left(\frac{c^2 W_0^3 \sqrt{ln\,\mathcal{V}}}{32\,\pi}\right)\frac{M_p}{\mathcal{V}^{5/2}}$$

[Cicoli, Hebecker, Jaeckel, Wittner: 2022]

$$N_\chi \simeq \frac{2}{3}\, ln\left(\frac{H(t_{eq})}{\Gamma_\chi}\right) \simeq 3$$

$$\frac{\Gamma(\chi \to \vartheta_b \vartheta_b)}{\Gamma(\chi \to hh)} \ll 1$$

$\Delta N_{\rm eff} \simeq 0$



$N_e \simeq 53$

$\varphi_* \simeq 0.2$
$\mathcal{V} \simeq 10616$

$n_s \simeq 0.9765$
$r \simeq 1.7 \times 10^{-5}$
$T_{rh} \simeq 4 \times 10^{10}\,\mathrm{GeV}$

Scenario II

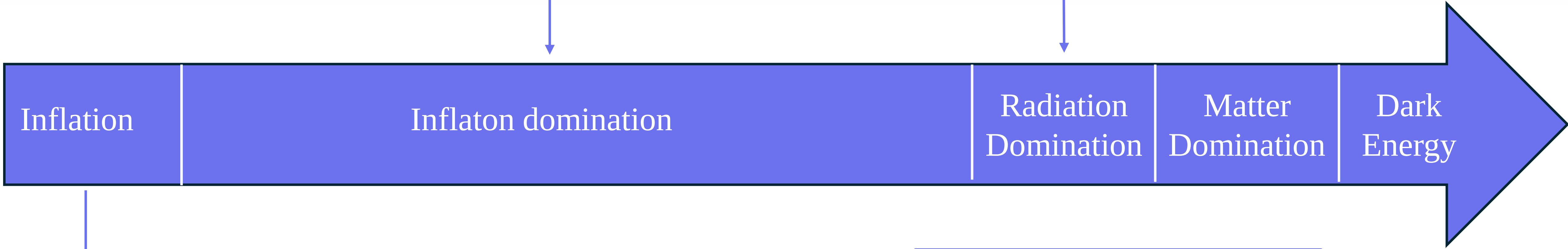
$$\Gamma(\varphi \rightarrow AA) = \left(\frac{N_g W_0^3 (\ln \mathcal{V})^{9/2}}{8\,\pi}\right)\frac{M_p}{\mathcal{V}^4}$$

$$N_\varphi \simeq \frac{2}{3} \ln\left(\frac{H_{inf}}{\Gamma_{\varphi\rightarrow A\,A}}\right) \simeq 8$$

$$\Delta N_{eff} \simeq 0.14$$

$$\frac{H(t_{eq})}{\Gamma(\chi \rightarrow hh)} \ll 1$$

$$N_\chi = 0$$



$N_e \simeq 52$ → $\varphi_* \simeq 0.2$, $\mathcal{V} \simeq 10525$ →

$$n_s \simeq 0.9761$$
$$r \simeq 1.7 \times 10^{-5}$$
$$T_{rh} \simeq 3 \times 10^{12}\,\text{GeV}$$

Scenario IIIa

$$\Gamma(\varphi \to \gamma_h \gamma_h) \simeq \frac{\mathcal{V}}{64\,\pi} \frac{m_\varphi^3}{M_p^2}$$

$$N_\varphi \simeq \frac{2}{3} ln\left(\frac{H_{inf}}{\Gamma_{\varphi\to\gamma_h\gamma_h}}\right) \simeq 1$$

$$\Gamma(\chi \to H_u H_d) = \frac{Z^2}{24\,\pi} \frac{m_\chi^3}{M_p^2}$$

$$N_\chi \simeq \frac{2}{3} ln\left(\frac{H(t_{eq})}{\Gamma_{\chi\to HH}}\right) \simeq 10.5$$

$$\frac{\Gamma(\chi \to \vartheta_b \vartheta_b)}{\Gamma(\chi \to H_u H_d)} \simeq 2Z^2$$

$Z \simeq 2$

$$\Delta N_{eff} \simeq \frac{1.43}{Z^2} \simeq 0.36$$

Inflation | Inflaton Domination | Radiation Domination | Volume Domination | Radiation Domination | Matter Domination | Dark Energy

$N_e \simeq 51.5$ → $\varphi_* \simeq 0.2$, $\mathcal{V} \simeq 10447$ →

$n_s \simeq 0.9757$
$r \simeq 1.8 \times 10^{-5}$
$T_{rh} \simeq 10^8$GeV

Scenario IIIb

$$\Gamma(\varphi \to \vartheta_b\vartheta_b) \simeq \left(\frac{W_0^3(\ln \mathcal{V})^{9/2}}{64\,\pi}\right)\frac{M_p}{\mathcal{V}^4}$$

$$N_\varphi \simeq \frac{2}{3}\ln\left(\frac{H_{inf}}{\Gamma_{\varphi\to\vartheta\vartheta}}\right) \simeq 11$$

$$\Gamma(\chi \to H_u H_d) = \frac{Z^2}{24\,\pi}\frac{m_\chi^3}{M_p^2}$$

$$N_\chi \simeq \frac{2}{3}\ln\left(\frac{H(t_{eq})}{\Gamma_{\chi\to HH}}\right) \simeq 0.5$$

$$\frac{\Gamma(\chi \to \vartheta_b\vartheta_b)}{\Gamma(\chi \to H_u H_d)} \simeq 2Z^2$$

$Z \simeq 2$

$$\Delta N_{eff} \simeq \frac{1.43}{Z^2} \simeq 0.36$$

Inflation → Inflaton Domination → Radiation Domination → Volume Domination → Radiation Domination → Matter Domination → Dark Energy

$N_e \simeq 51.5$ → $\varphi_* \simeq 0.2$, $\mathcal{V} \simeq 10447$ →

$n_s \simeq 0.9757$
$r \simeq 1.8 \times 10^{-5}$
$T_{rh} \simeq 10^8\,\text{GeV}$

Same predictions as in Scenario IIIa!

Conclusions

- New inflationary model: Loop Blow-up Inflation
- Inflaton: blow-up mode with potential from 1-loop corrections
- Loop corrections from BHP conjecture and low-energy EFT considerations
- Inflationary potential:

$$V(\varphi) \simeq V_0 \left(1 - \frac{c_{loop}}{\mathcal{V}^{1/3}\varphi^{2/3}}\right)$$

- Interesting predictions:

1. Microscopic parameters: $\mathcal{V} \sim \mathcal{O}(10^4)$, $\varphi_* \simeq 0.2$ with EFT under control
2. Number of e-foldings: $51.5 \lesssim N_e \lesssim 53$
3. Cosmological Parameters: $n_s \simeq 0.976$, $r \simeq 2 \times 10^{-5}$, $0 \lesssim \Delta N_{eff} \lesssim 0.36$

Thank you for your attention!

Control over EFT

- EFT always under control: τ_φ is within Kähler cone throughout inflation.
- For $51.5 \lesssim N_e \lesssim 53$: $\mathcal{V} \sim \mathcal{O}(10^4)$, $\varphi_* \simeq 0.2$ ⟹ Need to check!

- Explicit CY example [Cicoli, Krippendorf, Mayrhofer, Quevedo, Valandro: 2012]:

$$\mathcal{V} = \frac{1}{9}\sqrt{\frac{2}{3}}\left(\tau_b^{3/2} - \sqrt{3}\tau_s^{3/2} - \sqrt{3}\tau_\varphi^{3/2}\right) \quad \text{with} \quad \tau_b = \frac{27}{2}t_b^2,\ \ \tau_s = \frac{9}{2}t_s^2,\ \ \tau_\varphi = \frac{9}{2}t_\varphi^2$$

- Kähler cone conditions:

$$t_b + t_s > 0, \qquad t_b + t_\varphi > 0, \qquad t_s < 0, \qquad t_\varphi < 0$$

- Canonical normalization:

$$\tau_\varphi = \left(\frac{\sqrt{3}}{2}\right)^{2/3} \mathcal{V}^{2/3}\varphi^{4/3} \simeq \left(\frac{1}{18\sqrt{2}}\right)^{2/3} \tau_b\, \varphi^{4/3}$$

- At horizon exit:

$$\frac{|t_\varphi|}{t_b} = \left(\frac{1}{2\sqrt{6}}\right)^{1/3} {\varphi_*}^{2/3} \simeq 0.6\, {\varphi_*}^{2/3} \simeq 0.2$$ ⟹ Inside the Kähler cone!

Comments on Spectral Index

- Scenario I:

$n_s \simeq 0.9765,\ \Delta N_{\text{eff}} \simeq 0$ ⟷ (~ 2σ) $n_s = 0.9665 \pm 0.0038$ 68% CL

[Planck: 2018]

- Scenario II:

$n_s \simeq 0.9761,\ \Delta N_{\text{eff}} \simeq 0.14$ ⟷ (~ 2σ) $n_s = 0.9589 \pm 0.0084$ 68% CL

$N_{\text{eff}} = 2.89^{+0.36}_{-0.38}$

[Planck: 2018]

- Scenario III:

$n_s \simeq 0.9757,\ \Delta N_{\text{eff}} \simeq 0.36$ ⟷ (~ 1.2σ) $n_s = 0.983 \pm 0.006$ 68% CL

$\Delta N_{\text{eff}} = 0.39$

[Planck: 2015]

- Possible improvements: include additional corrections
  - ➢ F^4 corrections [Cicoli, Licheri, Piantadosi, Quevedo, Shukla: 2023]
  - ➢ Subleading loop corrections