Loop Blow-Up Inflation

A novel way to inflate with the Kähler moduli

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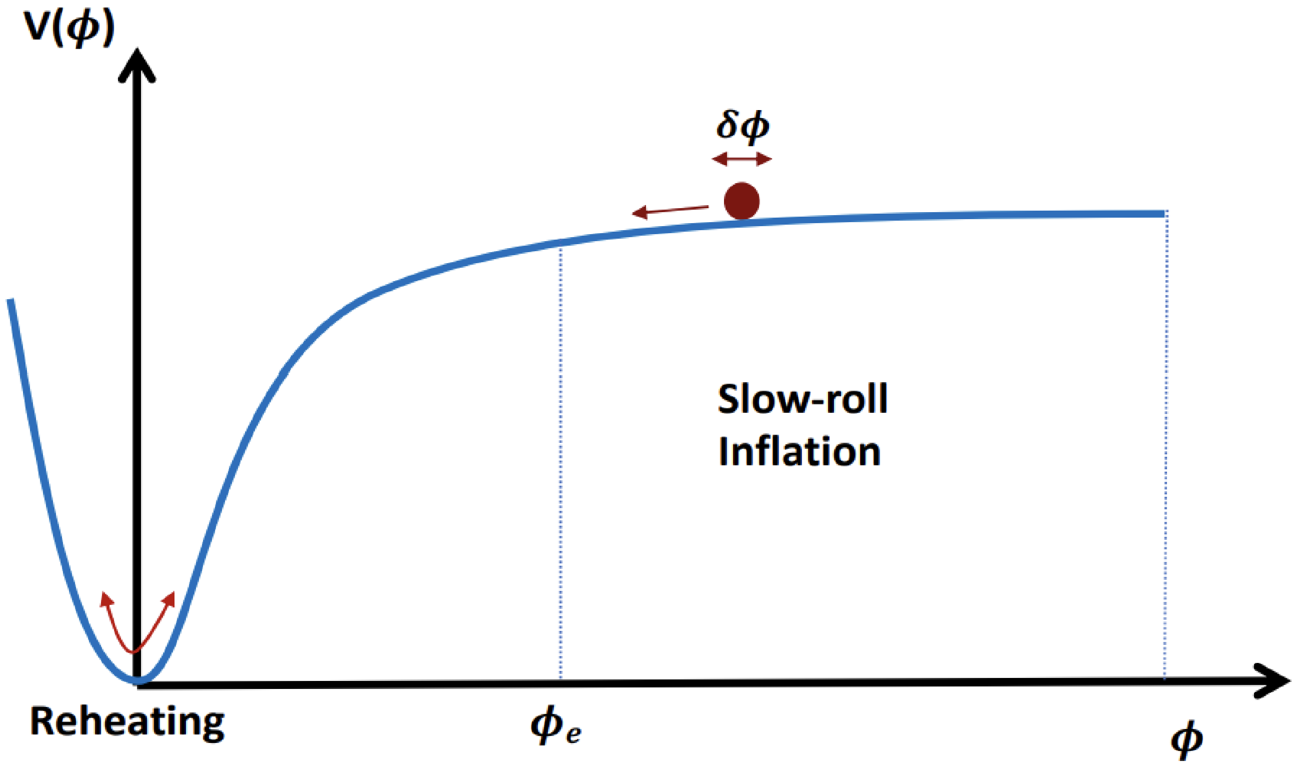
COSMIC WISPers Geneal Meeting 2024, Istanbul

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

Slow-Roll Inflation

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



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

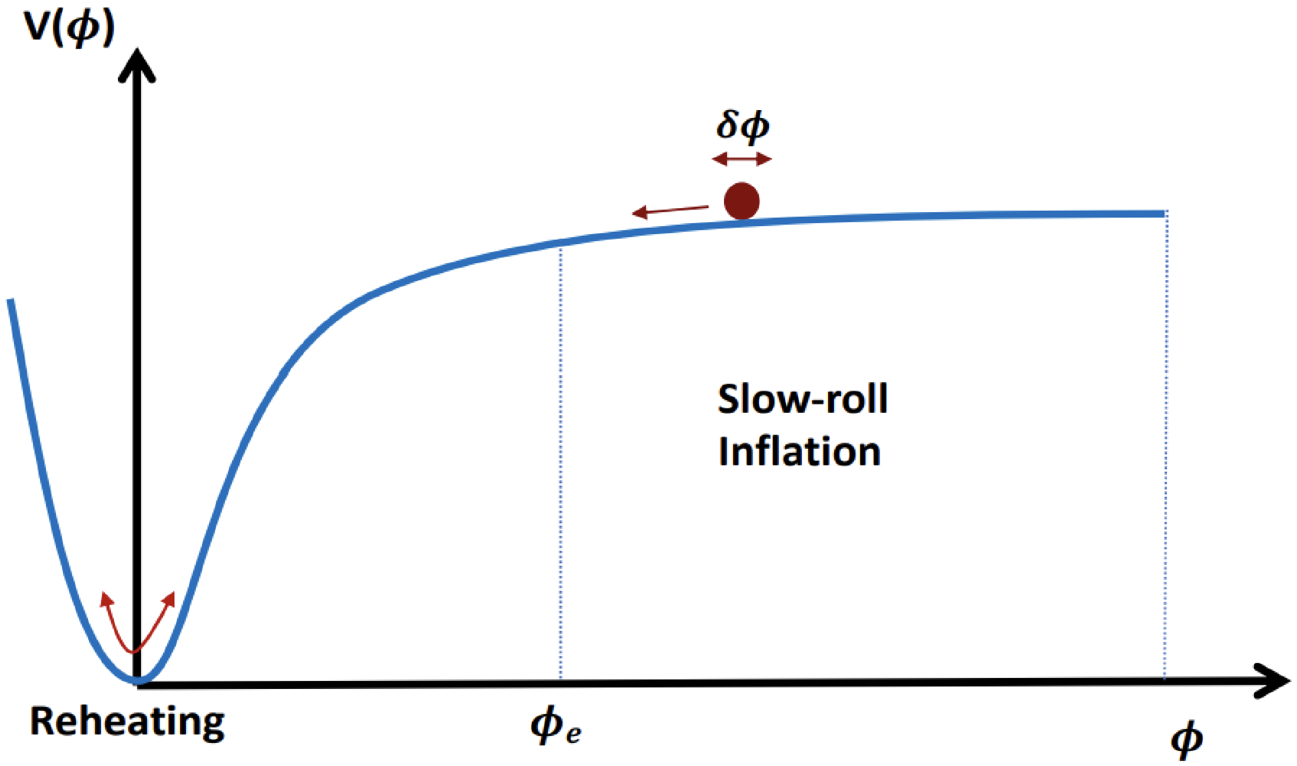
Slow-Roll Inflation

- 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 $\varphi \to \infty$.



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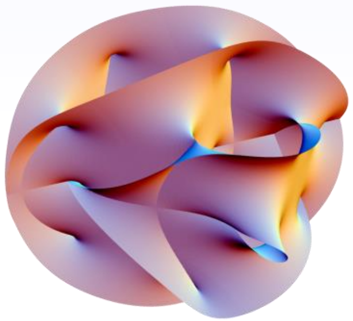
Kähler Moduli in Type IIB

D = 10 TYPE IIB
STRING THEORY

⇓



Calabi-Yau

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D=4 $\mathcal{N}$=1
SUGRA EFT

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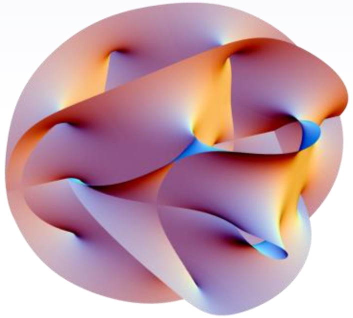

Calabi-Yau

Moduli

Scalars with flat potential

D=4 $\mathcal{N}$=1 SUGRA EFT

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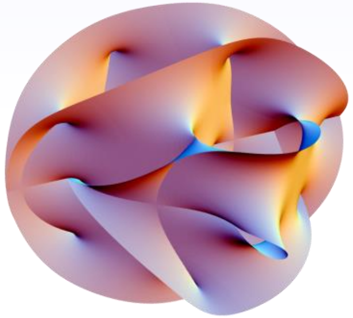

Calabi-Yau

D=4 $\mathcal{N}$=1 SUGRA EFT

Moduli
Scalars with flat potential

Complex Structure Moduli:
- Shape or Extra Dimensions
- Fixed Semiclassically by Fluxes

Kähler Moduli:
- Size of 4-cycles on Extra Dimensions
- Fixed by Quantum Corrections

Kähler Moduli as Flat Directions

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

- Volume: lifted by leading-order corrections:

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

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

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

Non-Perturbative Blow-Up Inflation

[Conlon, Quevedo: 2006]

SWISS CHEESE
CY VOLUME

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

LVS
STABILISATION

$\mathcal{O}(\alpha'^3)$ correction to K:

$$K = -2\ln\left(\mathcal{V} - \frac{\xi}{2g_s^{3/2}}\right)$$

non-perturbative correction to W:

$$W = W_0 + A_s e^{-a_s T_s} + A_\varphi e^{-a_\varphi T_\varphi}$$

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SCALAR POTENTIAL

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

$$V_\varphi(\mathcal{V},\tau_\varphi) = \tilde{V}\left(B_\varphi \frac{\sqrt{\tau_\varphi}\, e^{-2a_\varphi\tau_\varphi}}{\mathcal{V}} - C_\varphi \frac{\tau_\varphi e^{-a_\varphi\tau_\varphi}}{\mathcal{V}^2}\right)$$

$\Longrightarrow$ $\langle a_i\tau_i\rangle \sim \xi^{2/3} g_s$ and $\langle \mathcal{V}\rangle \sim e^{a_s\tau_s} \sim e^{a_\varphi\tau_\varphi}$

Non-Perturbative Blow-Up Inflation

[Conlon, Quevedo: 2006]

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$$V_\varphi(\mathcal{V},\tau_\varphi) = \tilde{V}\left(B_\varphi \frac{\sqrt{\tau_\varphi}\, e^{-2a_\varphi\tau_\varphi}}{\mathcal{V}} - C_\varphi \frac{\tau_\varphi e^{-a_\varphi\tau_\varphi}}{\mathcal{V}^2}\right)$$

$$\Longrightarrow \quad \langle a_i\tau_i\rangle \sim \xi^{2/3} g_s \quad \text{and} \quad \langle\mathcal{V}\rangle \sim e^{a_s\tau_s} \sim e^{a_\varphi\tau_\varphi}$$

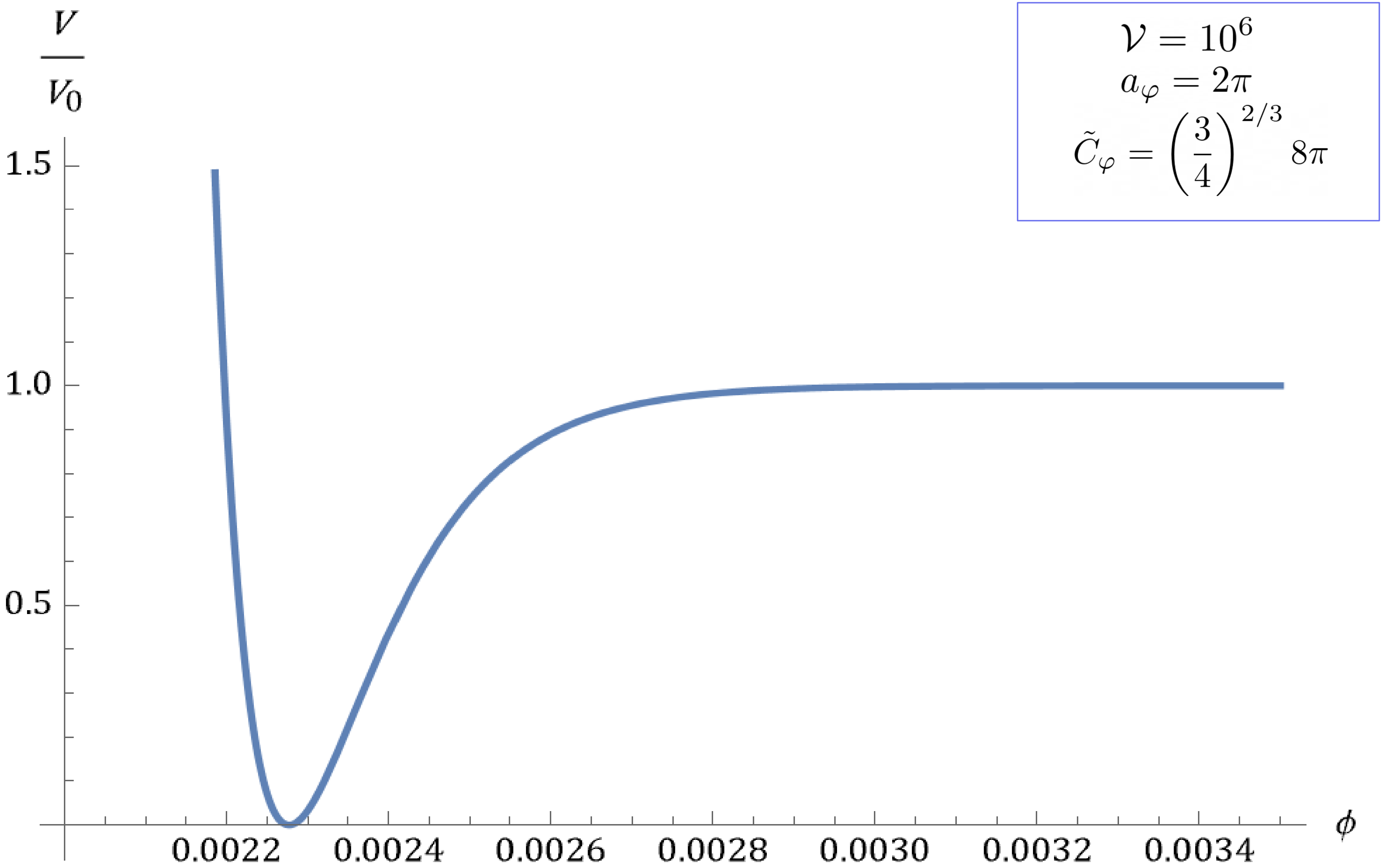
INFLATIONARY POTENTIAL

$$\tau_\varphi = \left(\frac{3\mathcal{V}}{4}\right)^{2/3} \varphi^{4/3}$$

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

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

Exponentially Flat Plateau!



V / V0
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): $\delta K_{g_s}^{(KK)} = g_s \sum_i \frac{C_i^{(KK)} t_i}{\mathcal{V}}$ ⟹ Extended no-scale in V [Cicoli, Conlon, Quevedo: 2008]
2. Winding (W): $\delta K_{g_s}^{(W)} = \sum_i \frac{C_i^{(W)}}{\mathcal{V} t_i}$

- For a Blow-Up mode τ:

$$\delta K_{g_s}(\tau) \simeq \frac{c_{\text{loop}}}{\mathcal{V}\sqrt{\tau}} \quad \Longrightarrow \quad \delta V_{g_s}(\tau) \simeq \frac{c_{\text{loop}}}{\mathcal{V}^3\sqrt{\tau}}$$

- 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

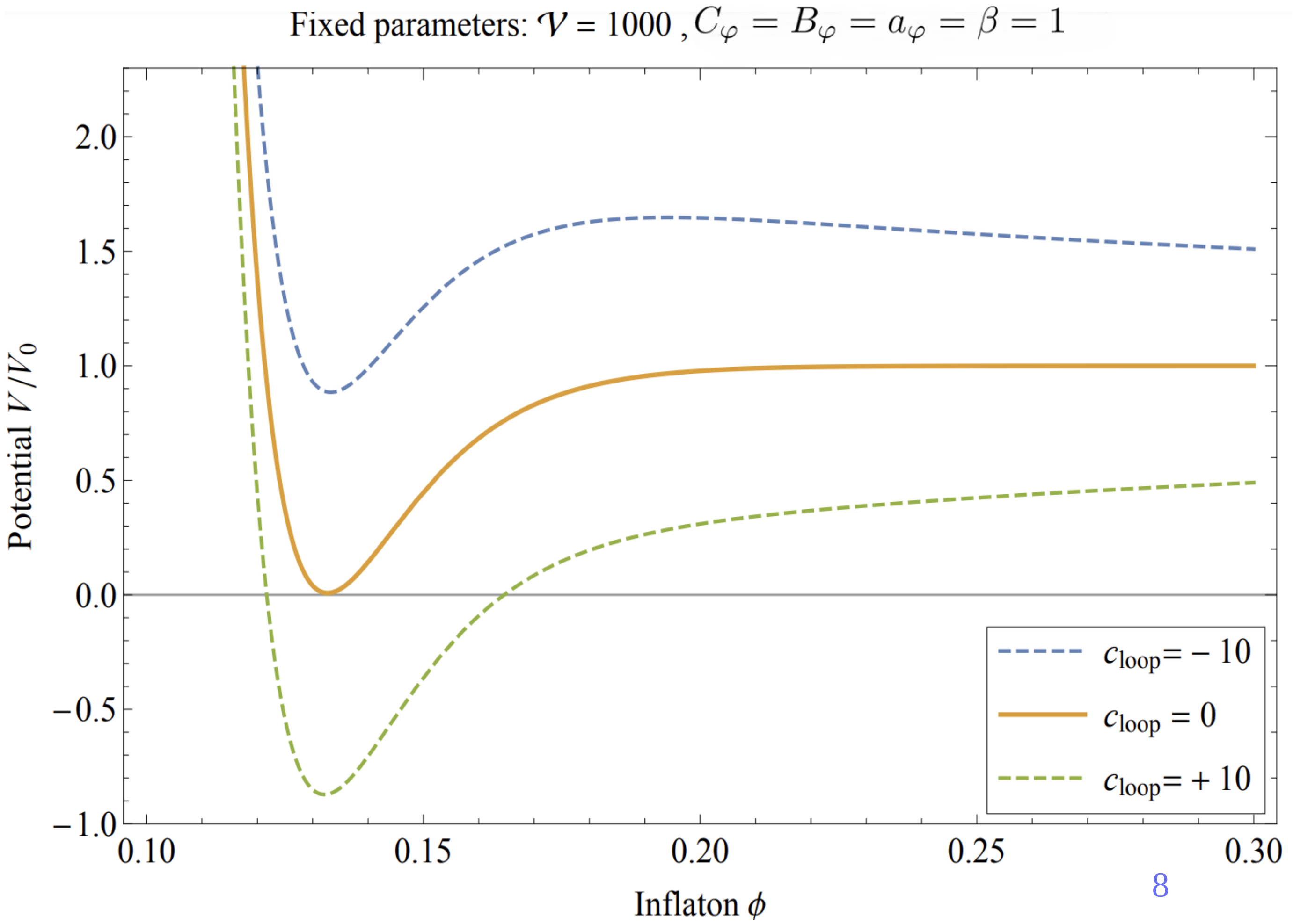
- Potential

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

Loop Blow-Up Inflation

- Potential including loop corrections:

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



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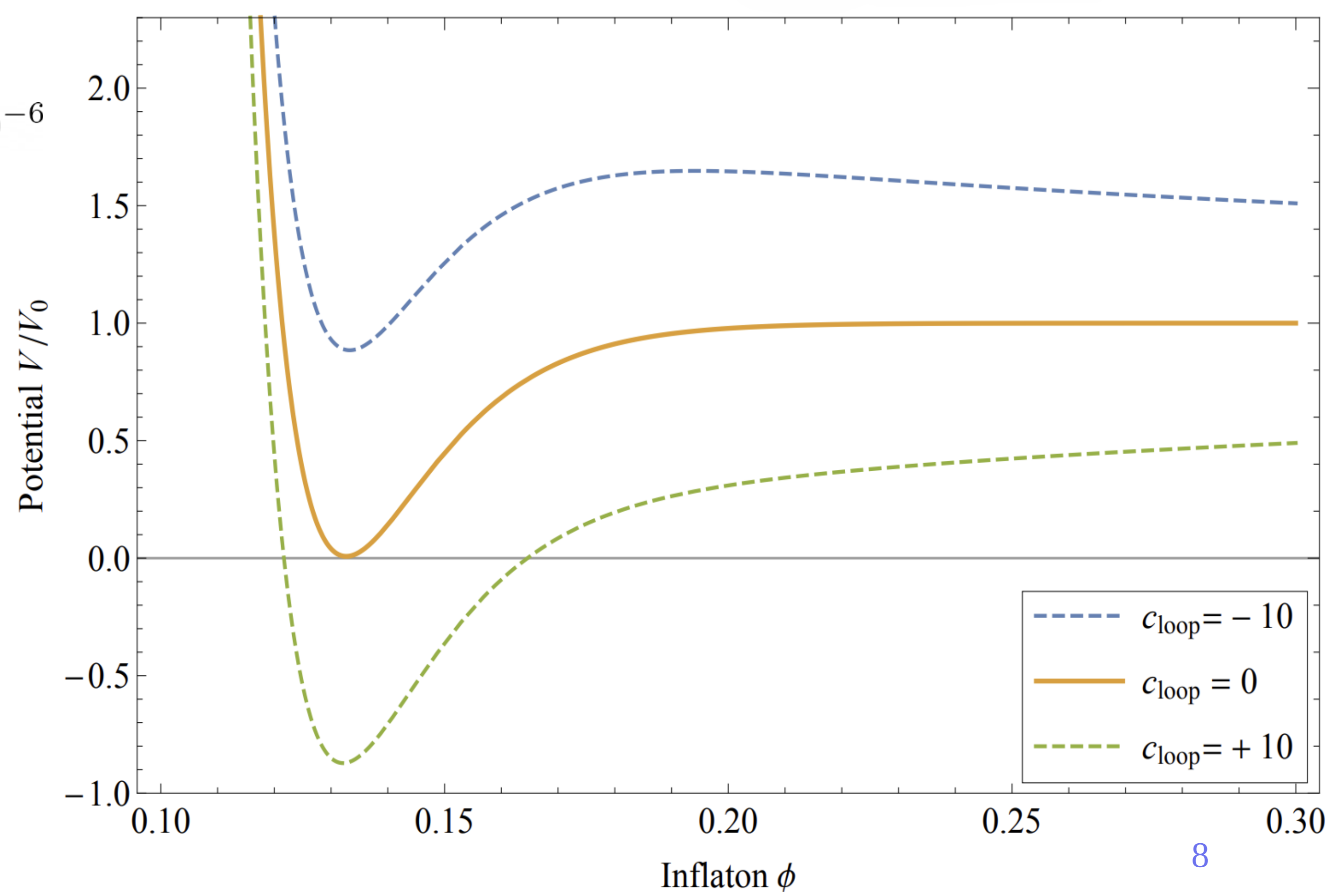
- Runaway for $c_{\text{loop}} < 0$
- Non-perturbative Blow-Up inflation if $c_{\text{loop}} \ll 10^{-6}$
- If $c_{\text{loop}} \gtrsim 10^{-6}$ loops dominate
- Inflationary potential:

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

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:

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

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

- Cosmological parameters:

$$N_e = \int_{\varphi_{\rm end}}^{\varphi_*} \frac{V}{V_{,\varphi}}\, {\rm d}\varphi \simeq \frac{9}{16}\,\frac{\mathcal{V}^{1/3}\varphi_*^{8/3}}{b\, c_{\rm loop}}$$

$$\hat{A}_s = \left.\frac{V^3}{V_{,\varphi}^2}\right|_{\varphi=\varphi_*} = \frac{9V_0}{4}\,\frac{\mathcal{V}^{2/3}\varphi_*^{10/3}}{(b\, c_{\rm loop})^2} \equiv 2.5\times 10^{-7}$$

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

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

- $r - n_s$ relation:

$$\begin{cases} n_s &= 1 + 2\,\eta - 6\,\epsilon \simeq 1 - \frac{20}{9}\,\frac{b\, c_{\rm loop}}{\mathcal{V}^{1/3}\varphi_*^{8/3}} \\ r &= 16\,\epsilon \simeq \frac{32}{9}\,\frac{(b\, c_{\rm loop})^2}{\mathcal{V}^{2/3}\varphi_*^{10/3}} \end{cases}$$

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

Post-Inflationary Evolution

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

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

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

- Decay of last dominant modulus ψ drives reheating:

ψ → SM fields (Higgs, gauge bosons)

ψ → big cycle axions ϑ_b: Dark Radiation ⇒ $$\Delta N_{\rm eff} = \frac{43}{7}\left(\frac{10.75}{g_*(T_{\rm rh})}\right)^{1/3}\frac{\Gamma_{\psi\to\vartheta\vartheta}}{\Gamma_{\psi\to SM\,SM}}$$

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

$$\Delta N_{\rm eff} \leq 0.2 - 0.5 \quad 95\%{\rm CL}$$

[Planck: 2018]

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 $\tau_{\rm SM}$ and $\tau_{\rm int}$

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

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

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

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

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

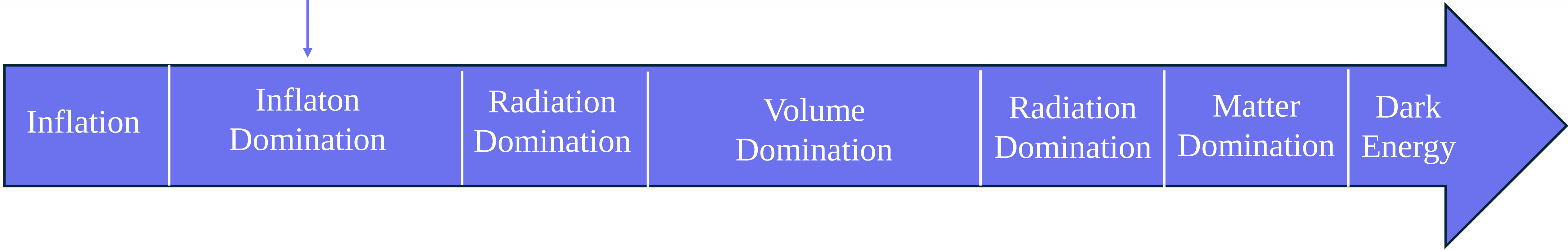
IIIa: τ_φ wrapped

IIIb: τ_φ *not* wrapped

Scenario I

$$\Gamma_{\varphi\to\gamma_h\gamma_h} \simeq \frac{\mathcal{V}}{64\pi}\frac{m_\varphi^3}{M_p^2}$$

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



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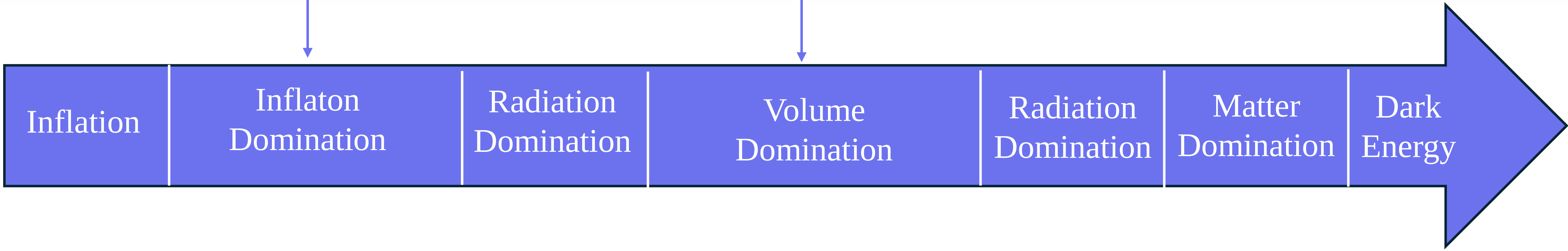
$$\Gamma_{\chi\to hh} \simeq \left(\frac{c^2 W_0^3\sqrt{\ln\mathcal{V}}}{32\pi}\right)\frac{M_p}{\mathcal{V}^{5/2}}$$

[Cicoli, Hebecker, Jaeckel, Wittner: 2022]

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

$$\frac{\Gamma_{\chi\to\vartheta_b\vartheta_b}}{\Gamma_{\chi\to hh}} \ll 1 \quad\Longrightarrow\quad \Delta N_{\rm eff} \simeq 0$$



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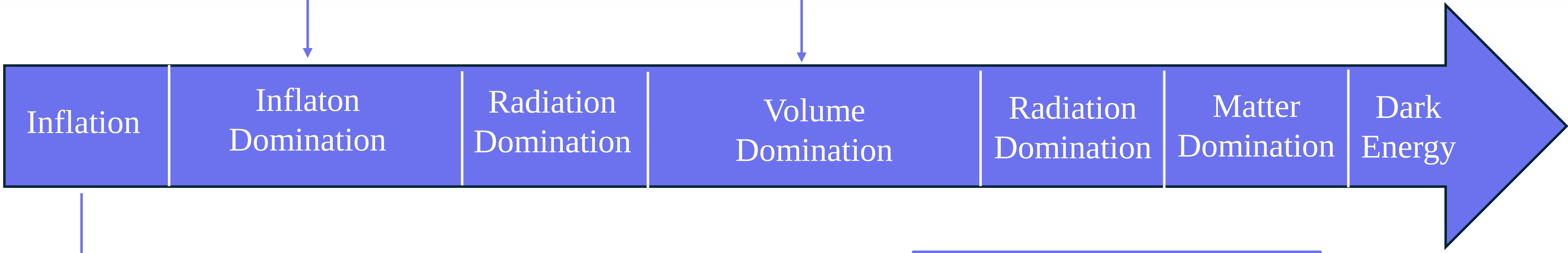
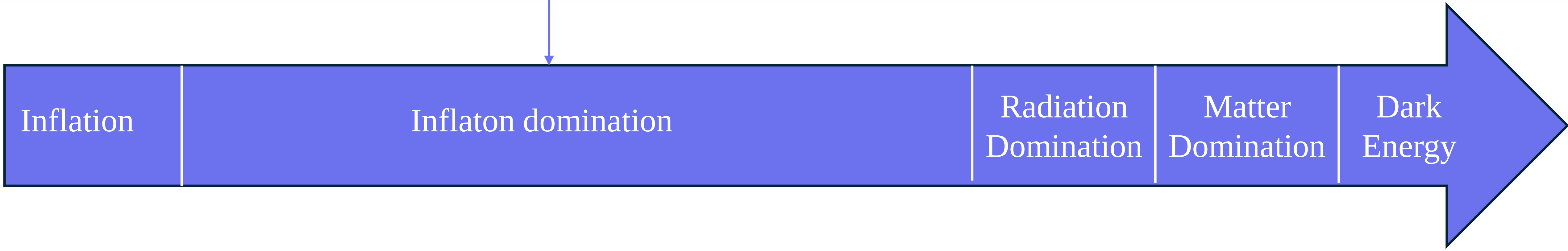


$$N_e \simeq 53 \quad \Rightarrow \quad \begin{cases} \varphi_* \simeq 0.2 \\ \mathcal{V} \simeq 10616 \end{cases} \quad \Rightarrow \quad \begin{array}{c} n_s \simeq 0.9765 \\ r \simeq 1.7\times 10^{-5} \\ T_{\rm rh} \simeq 4\times 10^{10}\,{\rm GeV} \end{array}$$

Scenario II

$$\Gamma_{\varphi \to AA} \simeq \left(\frac{N_g W_0^3 (\ln \mathcal{V})^{9/2}}{8\pi} \right) \frac{M_p}{\mathcal{V}^4}$$

$$N_\varphi \simeq \frac{2}{3} \ln \left(\frac{H_{\rm inf}}{\Gamma_{\varphi \to AA}} \right) \simeq 8$$



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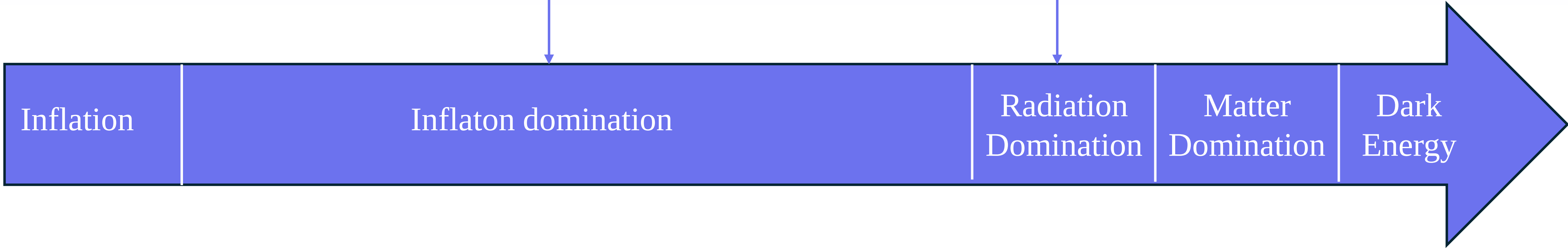
$$\frac{H(t_{\rm eq})}{\Gamma_{\chi\to hh}} \ll 1$$

$$N_\chi = 0$$



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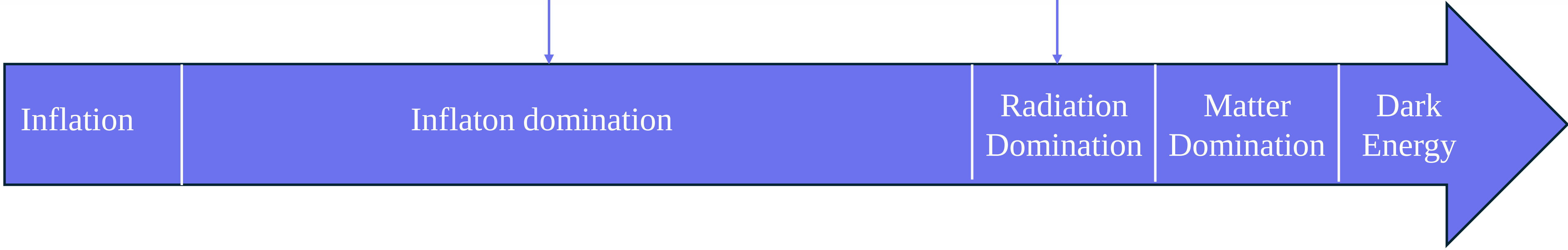

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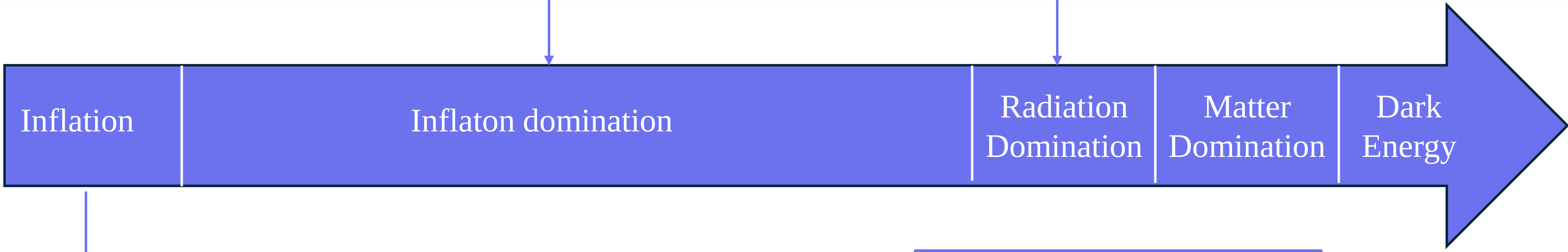

$$N_e \simeq 52$$

$$\begin{cases} \varphi_* \simeq 0.2 \\ \mathcal{V} \simeq 10525 \end{cases}$$

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

Scenario IIIa

$$\Gamma_{\varphi\to\gamma_h\gamma_h} \simeq \frac{\mathcal{V}}{64\pi}\frac{m_\varphi^3}{M_p^2}$$

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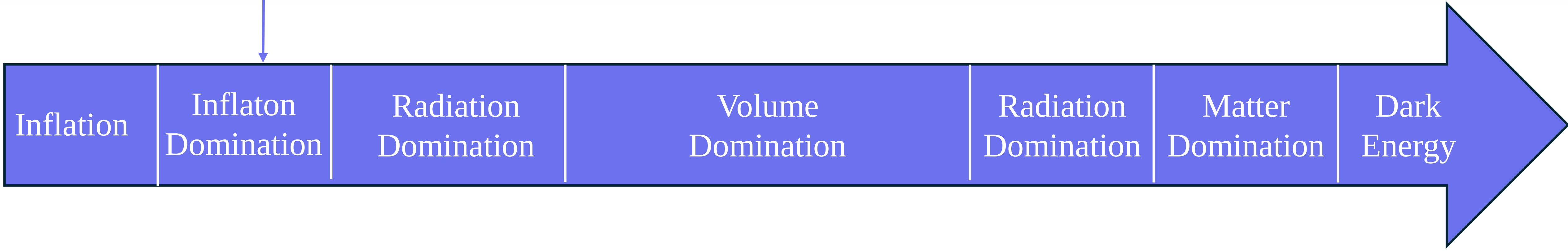

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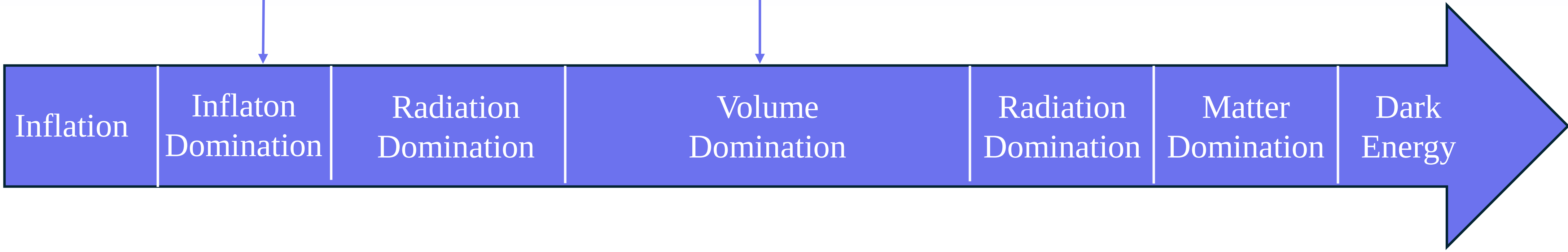
$$\Gamma_{\chi\to H_u H_d} = \frac{Z^2}{24\pi}\frac{m_\chi^3}{M_p^2}$$

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

$$\frac{\Gamma_{\chi\to\vartheta_b\vartheta_b}}{\Gamma_{\chi\to H_u H_d}} \simeq 2Z^2$$

$$Z \simeq 2$$

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



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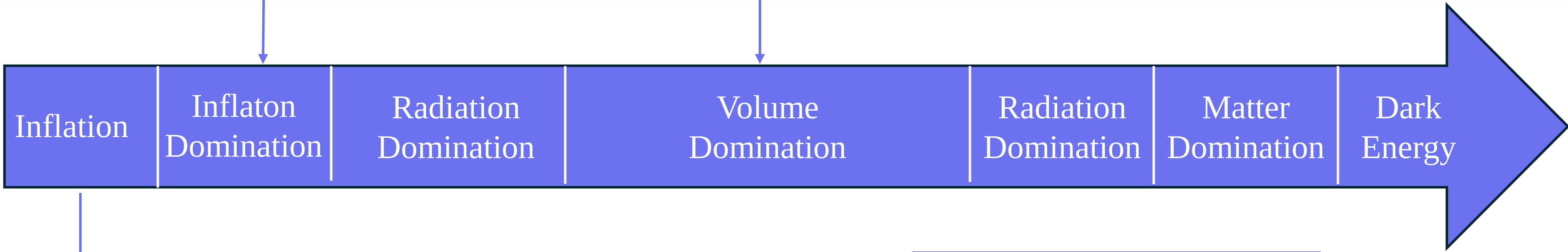
$$\frac{\Gamma_{\chi\to\vartheta_b\vartheta_b}}{\Gamma_{\chi\to H_u H_d}} \simeq 2Z^2$$

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



$$N_e \simeq 51.5 \quad \Longrightarrow \quad \begin{cases} \varphi_* \simeq 0.2 \\ \mathcal{V} \simeq 10477 \end{cases} \quad \Longrightarrow \quad \begin{array}{c} n_s \simeq 0.9757 \\ r \simeq 1.8\times 10^{-5} \\ T_{\rm rh} \simeq 10^8\ {\rm GeV} \end{array}$$

Scenario IIIb

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

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

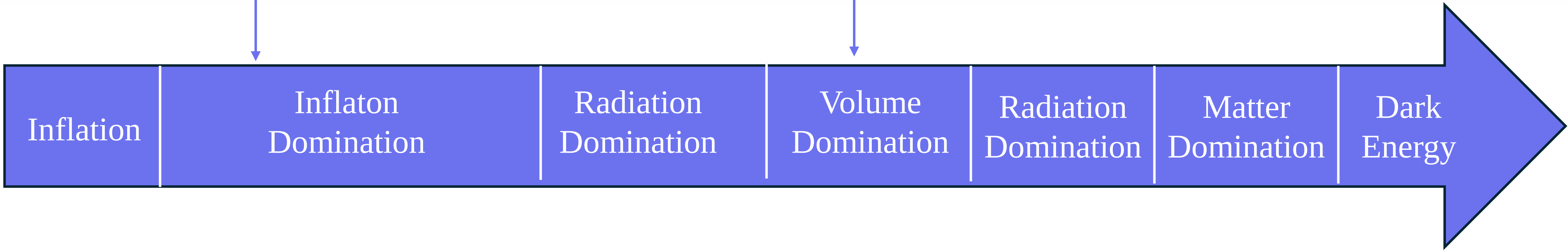
$$\Gamma_{\chi\to H_u H_d} = \frac{Z^2}{24\pi}\frac{m_\chi^3}{M_p^2}$$

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

$$\frac{\Gamma_{\chi\to\vartheta_b\vartheta_b}}{\Gamma_{\chi\to H_u H_d}} \simeq 2Z^2$$

$$Z \simeq 2$$

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



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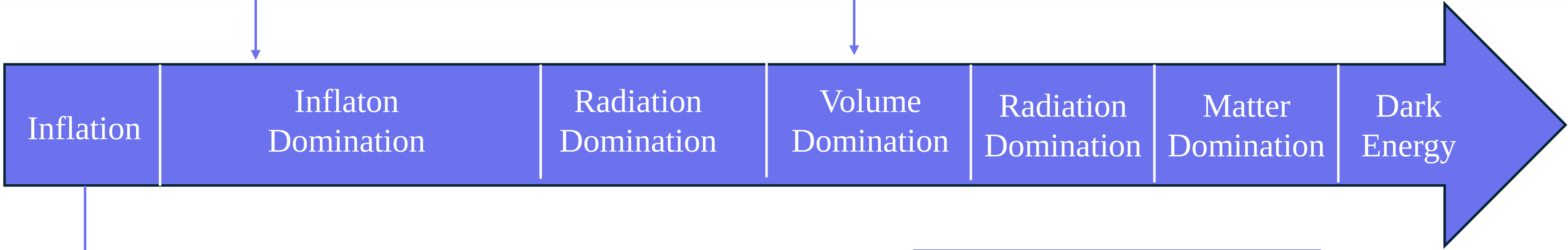
$Z \simeq 2$ → $$\Delta N_{\rm eff} \simeq \frac{1.43}{Z^2} \simeq 0.36$$



$N_e \simeq 51.5$ → $\begin{cases}\varphi_* \simeq 0.2 \\ \mathcal{V} \simeq 10477\end{cases}$ →

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

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:

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

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

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]:

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

- 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:

$$n_s \simeq 0.9765,\ \Delta N_{\text{eff}} \simeq 0 \quad \overset{\sim 2\sigma}{\Longleftrightarrow} \quad n_s = 0.9665 \pm 0.0038 \quad 68\%\ \text{CL}$$

[Planck: 2018]

- Scenario II:

$$n_s \simeq 0.9761,\ \Delta N_{\text{eff}} \simeq 0.14 \quad \overset{\sim 2\sigma}{\Longleftrightarrow} \quad n_s = 0.9589 \pm 0.0084 \quad 68\%\ \text{CL}$$

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

[Planck: 2018]

- Scenario III:

$$n_s \simeq 0.9757,\ \Delta N_{\text{eff}} \simeq 0.36 \quad \overset{\sim 1.2\sigma}{\Longleftrightarrow} \quad n_s = 0.983 \pm 0.006 \quad 68\%\ \text{CL}$$

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

[Planck: 2015]

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