Recent progress on inflation and dark energy from string theory

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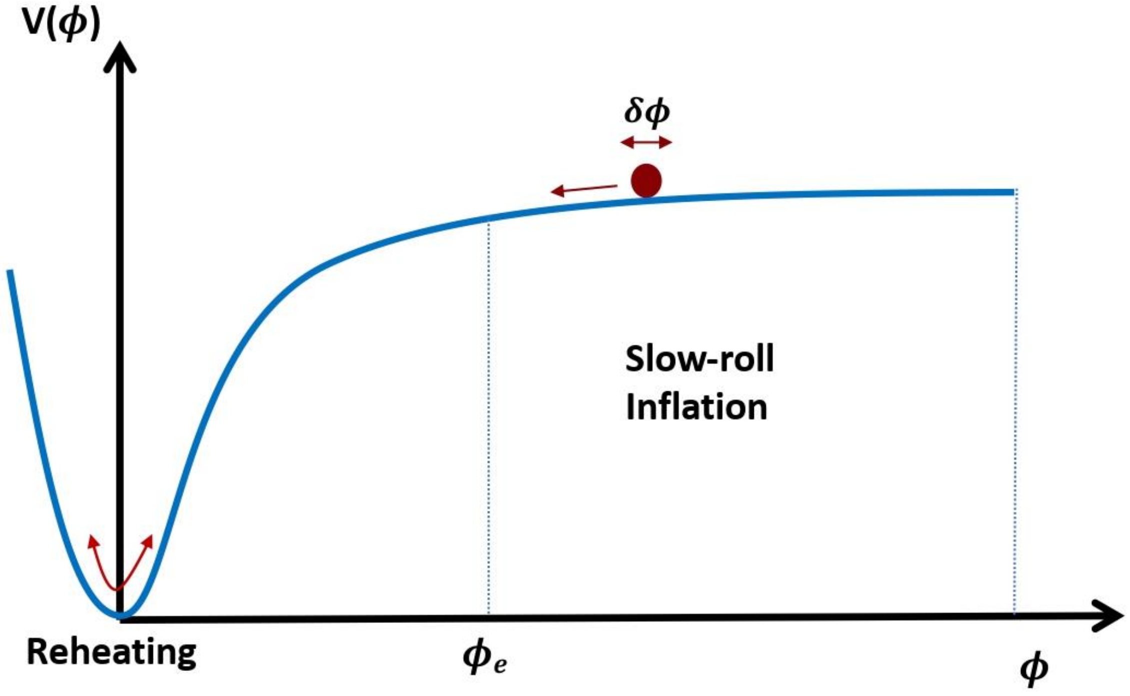
Based on recent work in collaboration with:
Bansal, Brunelli, Cunillera, Hebecker, Kuespert, Padilla, Pedro

See also: ‘String cosmology: from the early universe to today’
MC, Conlon, Maharana, Parameswaran, Quevedo, Zavala

Inflation

Standard slow-roll



$$V(\phi) = V_0[1 - g(\phi)] \simeq V_0$$

since $g(\phi) \ll 1$ for $\phi \gg 1$

Inflating with string moduli

- Slow-roll picture with inflaton ϕ reproduced with type IIB Kaehler moduli
- Volume mode $\mathcal{V}$ couples to all sources of energy due to $\mathrm{e}^{K} = \mathcal{V}^{-2}$

  → cannot have a ϕ-independent plateau if $\phi \equiv \mathcal{V}$

  → ϕ should be a direction $\perp$ $\mathcal{V}$: $\phi \equiv \tau_\phi$

- Since each term in V depends on $\mathcal{V}$, $V(\phi) \simeq V_0$ only if leading dynamics fixes $\mathcal{V}$ but not τ_ϕ

  → $\phi \equiv \tau_\phi$ is a leading order flat direction with an approximate shift symmetry

  [Burgess,MC,Quevedo,Williams][Burgess,MC,deAlwis,Quevedo]

- Type IIB Kaehler sector: tree-level no-scale cancellation
  + 1-loop extended no-scale [MC,Conlon,Quevedo]

- Leading no-scale breaking effects: $O(\alpha'^3)$ corrections which lift only $\mathcal{V}$
- ϕ lifted by subdominant quantum effects

Leading dynamics

- Total potential:

$$V_{\rm tot}(\mathcal{V},\tau_\phi) = V_{\rm lead}(\mathcal{V}) - V_{\rm sub}(\mathcal{V},\tau_\phi) \qquad V_{\rm sub}(\mathcal{V},\tau_\phi) \ll V_{\rm lead}(\mathcal{V})$$

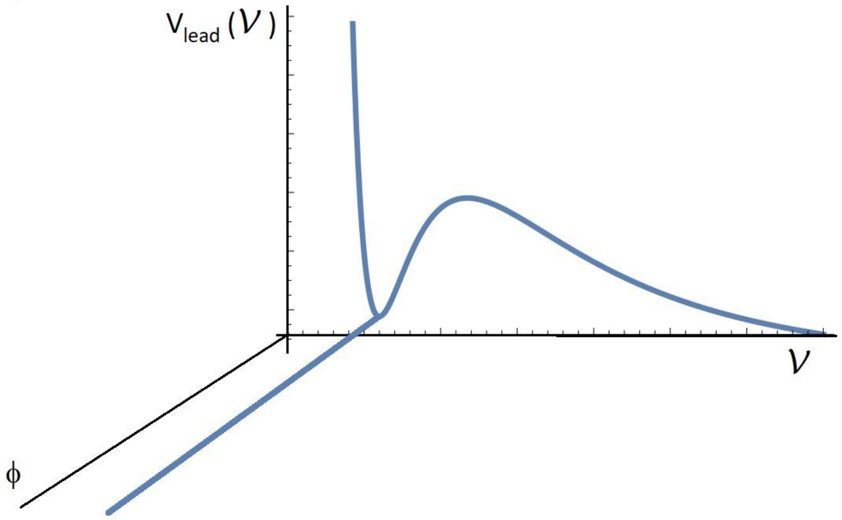
- Stabilisation:

$$\frac{\partial V_{\rm lead}}{\partial \mathcal{V}}(\langle\mathcal{V}\rangle) = 0 \quad \text{and} \quad \frac{\partial V_{\rm sub}}{\partial \tau_\phi}(\langle\mathcal{V}\rangle,\langle\tau_\phi\rangle) = 0$$

with:

$$V_{\rm lead}(\langle\mathcal{V}\rangle) = V_{\rm sub}(\langle\mathcal{V}\rangle,\langle\tau_\phi\rangle)$$

$$\longrightarrow \quad V_{\rm tot}(\langle\mathcal{V}\rangle,\langle\tau_\phi\rangle) = 0$$



Subleading dynamics

- Setting $\mathcal{V} = \langle\mathcal{V}\rangle$, $V_{tot}(\langle\mathcal{V}\rangle, \tau_\phi)$ becomes:

$$V(\phi) = V_0[1 - g(\phi)]$$

with:

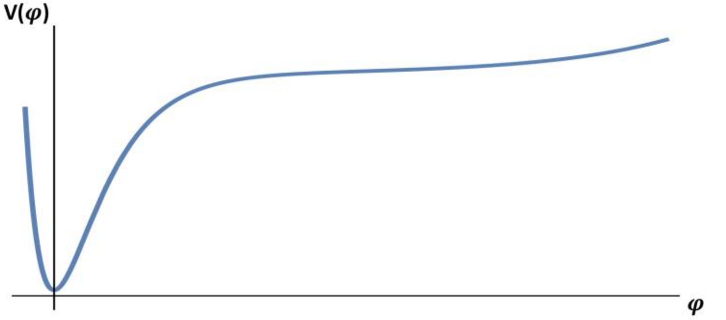
$$V_0 \equiv V_{sub}(\langle\mathcal{V}\rangle, \langle\tau_\phi\rangle) \qquad \text{and} \qquad g(\phi) \equiv \frac{V_{sub}\left(\langle\mathcal{V}\rangle, \tau_\phi(\phi)\right)}{V_{sub}(\langle\mathcal{V}\rangle, \langle\tau_\phi\rangle)}$$

with $\tau_\phi(\phi)$ determined by canonical normalisation

- Since τ_ϕ is a leading order flat direction

$$V_{sub}(\langle\mathcal{V}\rangle, \tau_\phi) \ll V_{sub}(\langle\mathcal{V}\rangle, \langle\tau_\phi\rangle) \qquad \text{for} \qquad \tau_\phi > \langle\tau_\phi\rangle$$

$$\longrightarrow \quad g(\phi) \ll 1 \quad \text{and} \quad V(\phi) \simeq V_0 \quad \text{for} \quad \phi \gg 1$$



String inflation potentials

Function $g(\phi)$ depends on 2 features:

1. Origin of effects which generate $V_{\rm sub}(\langle\mathcal{V}\rangle, \tau_\phi)$:

- Perturbative effects:

$$V_{\rm sub}(\langle\mathcal{V}\rangle, \tau_\phi) \propto \frac{1}{\tau_\phi^p} \longrightarrow 0 \quad \text{for} \quad \tau_\phi \to \infty \;\; \text{if} \;\; p > 0$$

- Non-perturbative effects:

$$V_{\rm sub}(\langle\mathcal{V}\rangle, \tau_\phi) \propto {\rm e}^{-{\rm k}\tau_\phi} \longrightarrow 0 \quad \text{for} \quad \tau_\phi \to \infty \;\; \text{if} \;\; {\rm k} > 0$$

2. Topology of τ_ϕ which determines $\tau_\phi(\phi)$ (canonical normalisation):

- Bulk (fibre) modulus:

$$\tau_\phi = e^{\lambda\phi} \qquad \text{with} \qquad \lambda \sim \mathcal{O}(1)$$

- Local (blow-up) modulus:

$$\tau_\phi = \mu\,\mathcal{V}^{2/3}\,\phi^{4/3} \qquad \text{with} \qquad \mu \sim \mathcal{O}(1)$$

String inflation potentials

$$V(\phi) = V_0[1 - g(\phi)]$$

- Non-perturbative Blow-up Inflation: [Conlon,Quevedo][Bond,Kofman,Prokushkin,Vaudrevange]

$$g(\phi) \propto e^{-k\mu \mathcal{V}^{2/3} \phi^{4/3}} \ll 1 \qquad \text{for} \qquad \phi > 0$$

- Non-perturbative Fibre Inflation: [MC,Pedro,Tasinato][Luest,Zhang]

$$g(\phi) \propto e^{-k\, e^{\lambda\phi}} \ll 1 \qquad \text{for} \qquad \phi > 0$$

- Loop Fibre Inflation: [MC,Burgess,Quevedo][Broy,Ciupke,Pedro,Westphal][MC,Ciupke,deAlwis,Muia]

$$g(\phi) \propto e^{-p\lambda\phi} \ll 1 \qquad \text{for} \qquad \phi > 0$$

α-attractor realisation
see Linde's talk

- Loop Blow-up Inflation: [Bansal,Brunelli,MC,Hebecker,Kuespert]

$$g(\phi) \propto \frac{1}{\mathcal{V}^{2p/3}\, \phi^{4p/3}} \ll 1 \qquad \text{for} \qquad \phi \lesssim 1$$

$$p = 1/2 \longrightarrow \boxed{V = V_0\left(1 - \frac{c}{\mathcal{V}^{1/3}\phi^{2/3}}\right)}$$

The model

- Type IIB compactification on CY with volume:

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

- Kaehler potential (tree-level + α'^3) and superpotential (tree-level + non-pert.):

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

- Scalar potential:

$$V = V_{\text{lead}}(\mathcal{V}, \tau_s) + V_{\text{sub}}(\mathcal{V}, \tau_\phi)$$

$$V_{\text{lead}}(\mathcal{V}, \tau_s) = \frac{C_{up}}{\mathcal{V}^2} + C_s \frac{\sqrt{\tau_s}\, e^{-2a_s\tau_s}}{\mathcal{V}} - D_s \frac{\tau_s\, e^{-a_s\tau_s}}{\mathcal{V}^2} + \frac{C_{\alpha'}}{g_s^{3/2}\mathcal{V}^3}$$

$$V_{\text{sub}}(\mathcal{V}, \tau_\phi) = C_\phi \frac{\sqrt{\tau_\phi}\, e^{-2a_\phi\tau_\phi}}{\mathcal{V}} - D_\phi \frac{\tau_\phi\, e^{-a_\phi\tau_\phi}}{\mathcal{V}^2} \qquad a_\phi \gg a_s$$

- LVS Minkowski mininum at:

$$\tau_s \sim g_s^{-1} \qquad \mathcal{V} \sim e^{a_s\tau_s} \sim e^{a_\phi\tau_\phi}$$

Loop corrections

- 1-loop K computed only in toroidal orientifolds: [Berg,Haack,Koers]

$$\mathcal{V} = \sqrt{\tau_1 \tau_2 \tau_3} \qquad \delta K_{(g_s)} = \delta K_{(g_s)}^{KK} + \delta K_{(g_s)}^{W}$$

i) tree-level exchange of KK closed strings between parallel D7/O7s:

$$\delta K_{(g_s)}^{KK} = g_s \left(\frac{C_1^{KK}(U,\bar{U})}{\tau_1} + \frac{C_2^{KK}(U,\bar{U})}{\tau_2} + \frac{C_3^{KK}(U,\bar{U})}{\tau_3} \right)$$

ii) tree-level exchange of winding closed strings at D7 intersection:

$$\delta K_{(g_s)}^{W} = \frac{C_1^{W}(U,\bar{U})}{\tau_2 \tau_3} + \frac{C_2^{W}(U,\bar{U})}{\tau_1 \tau_3} + \frac{C_3^{W}(U,\bar{U})}{\tau_1 \tau_2}$$

- Conjecture for 1-loop K for CYs: [Berg,Haack,Pajer]

$$\delta K_{(g_s)}^{KK} = \frac{g_s}{\mathcal{V}} \sum_i C_i^{KK}(U,\bar{U})\, M_{KK,i}^{-2}$$

→ Extended no-scale cancellation in V [MC,Conlon,Quevedo]

$$\delta K_{(g_s)}^{W} = \frac{1}{\mathcal{V}} \sum_i C_i^{W}(U,\bar{U})\, M_{W,i}^{-2}$$

Loop corrections from EFT

- 1-loop K yields corrections to kinetic terms and V

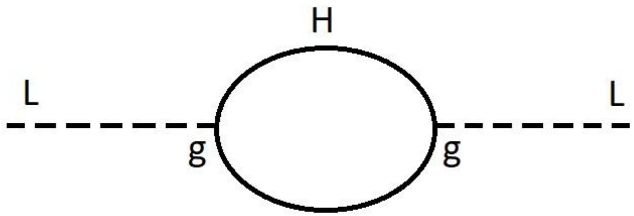
  → EFT interpretation [von Gersdorff,Hebecker][MC,Conlon,Quevedo][Gao,Hebecker,Schreyer,Venken]

- Heavy mode H coupled to a light mode L

$$\mathcal{L} \supset M^2 H^2 + g\, L\, H^2$$

- 2-point function 1-loop renormalisation:

$$\mathcal{L}_{kin} = \left[1 + \frac{1}{16\pi^2}\left(\frac{g}{M}\right)^2\right] \partial_\mu L \partial^\mu L$$



- Coupling g when L is a Kaehler modulus:

$$g \simeq \frac{M^2}{M_p}$$

- 1-loop correction to K:

$$\delta K \simeq \frac{1}{16\pi^2}\left(\frac{M}{M_p}\right)^2$$

Loop corrections from 4D

$$\delta K \simeq c_{\rm loop}\left(\frac{M}{M_p}\right)^2$$

- If H = massive string state:

$$M \equiv M_s \simeq \frac{M_p}{\sqrt{\mathcal{V}}} \quad \Rightarrow \quad \delta K \simeq \frac{c_{\rm loop}}{\mathcal{V}}$$

matches $\delta K_{\alpha'^3}$ [Becker,Becker,Haack,Louis]

- If H = winding mode:

$$M \equiv M_W \simeq \frac{M_p}{\sqrt{\mathcal{V}}}\tau^{1/4} \Rightarrow \delta K \simeq c_{\rm loop}\frac{\sqrt{\tau}}{\mathcal{V}}$$

matches $\delta K_{(g_s)}^{KK}$ [Berg,Haack,Pajer]

→ $\delta K_{(g_s)}^{KK}$ = tree-level KK closed strings = 1-loop winding open strings

extended no-scale cancellation in V [MC,Conlon,Quevedo]

- If H = Kaluza-Klein mode:

$$M \equiv M_{KK} \simeq \frac{M_p}{\sqrt{\mathcal{V}}\,\tau^{1/4}} \quad \Rightarrow \delta K \simeq \frac{c_{\rm loop}}{\mathcal{V}\sqrt{\tau}}$$

matches $\delta K_{(g_s)}^{W}$ [Berg,Haack,Pajer]

→ $\delta K_{(g_s)}^{W}$ = tree-level winding closed strings = 1-loop KK open strings

if $\tau = \tau_\phi \quad \delta K \simeq \frac{c_{\rm loop}}{\mathcal{V}\sqrt{\tau_\phi}} \quad \Rightarrow$ $\boxed{\delta V \simeq \frac{c_{\rm loop}}{\mathcal{V}^3\sqrt{\tau_\phi}}}$ leading correction to V → crucial for inflation

Loop corrections from 4D

- 1-loop K from KK modes in loop should match 1-loop Coleman-Weinberg potential:

$$V^{CW}_{1-\text{loop}} \simeq \frac{1}{16\pi^2}\Lambda^2\,\text{Str}\,M^2$$

[MC,Conlon,Quevedo]

- Supertrace in supergravity:

$$\text{Str}\,M^2 \simeq m^2_{3/2} \simeq \frac{M_p^2}{\mathcal{V}^2}$$

- Cut-off Λ given by KK mass of open strings on D7s

i) D7s on τ_b: $\Lambda \simeq \frac{M_p}{\mathcal{V}^{2/3}}$

$$\delta V_{(g_s)} \simeq \frac{c_{\text{loop}}}{\mathcal{V}^{10/3}}$$

ii) D7s on τ_ϕ: $\Lambda \simeq \frac{M_p}{\tau_\phi^{1/4}\sqrt{\mathcal{V}}}$

$$\boxed{\delta V_{(g_s)} \simeq \frac{c_{\text{loop}}}{\mathcal{V}^3\sqrt{\tau_\phi}}}$$

same as from 1-loop 2-pt function

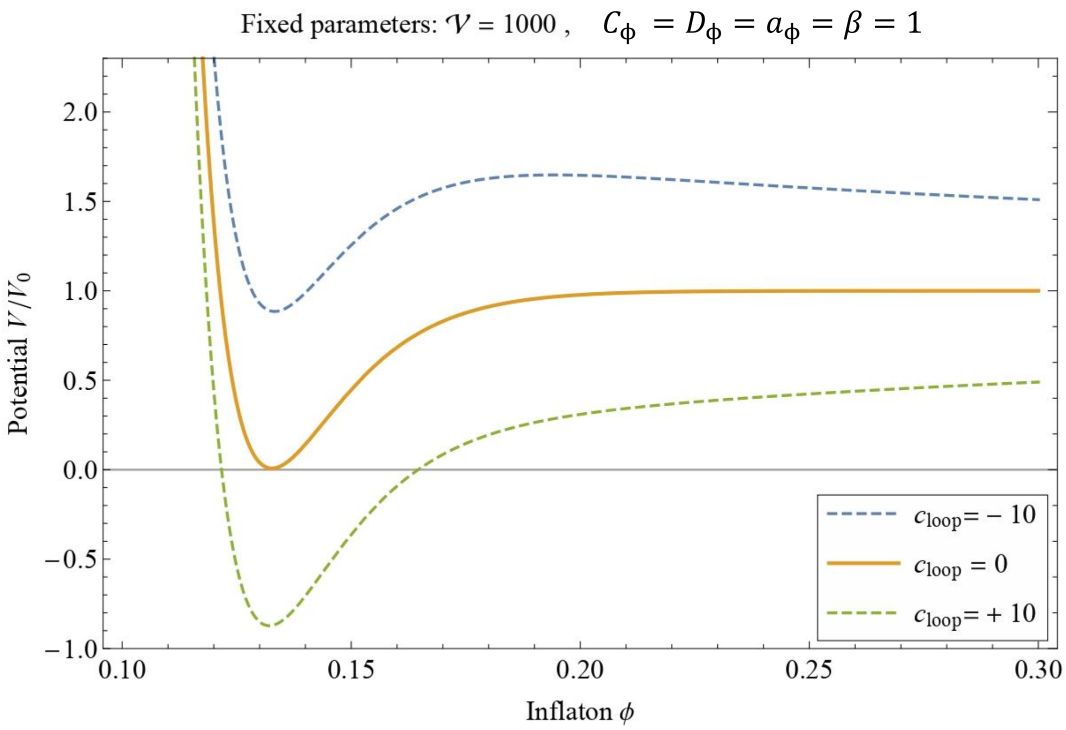
- If there is no D7 on τ_ϕ, can still have KK modes of τ_ϕ (closed strings) in loop

⟶ $\Lambda \simeq \frac{M_p}{\tau_\phi^{1/4}\sqrt{\mathcal{V}}}$ ⟶ τ_ϕ-dependent loop corrections to V are unavoidable

Inflaton potential

- Potential with loops: [Bansal,Brunelli,MC,Hebecker,Kuespert]

$$V(\tau_\phi) = \frac{\beta}{\mathcal{V}^3} + C_\phi \frac{\sqrt{\tau_\phi}\, e^{-2a_\phi \tau_\phi}}{\mathcal{V}} - D_\phi \frac{\tau_\phi\, e^{-a_\phi \tau_\phi}}{\mathcal{V}^2} - \frac{c_{\rm loop}}{\mathcal{V}^3 \sqrt{\tau_\phi}} \qquad \phi = \sqrt{\frac{4}{3\mathcal{V}}}\, \tau_\phi^{3/4}$$



- Non-perturbative blow-up inflation [Conlon,Quevedo] requires $c_{\rm loop} \ll 10^{-6}$
- For $c_{\rm loop} \gtrsim 10^{-6}$ potential in inflationary region is

$$V \simeq V_0 \left(1 - \frac{c_{\rm loop}}{\mathcal{V}^{1/3} \phi^{2/3}}\right) \qquad V_0 \equiv \frac{\beta}{\mathcal{V}^3}$$

Inflationary dynamics

- Slow-roll parameters:

$$\epsilon = \frac{1}{2}\left(\frac{V_\phi}{V}\right)^2 \simeq \frac{2}{9}\frac{c_{\rm loop}^2}{\mathcal{V}^{2/3}\phi^{10/3}}$$

$$\eta = \frac{V_{\phi\phi}}{V} \simeq -\frac{10}{9}\frac{c_{\rm loop}}{\mathcal{V}^{1/3}\phi^{8/3}}$$

- Cosmological observables:

$$N_{\rm e} = \int_{\phi_{\rm end}}^{\phi_*} \frac{\rm V}{{\rm V}_\phi}\, d\phi \simeq \frac{9}{16}\frac{\mathcal{V}^{1/3}\phi_*^{8/3}}{c_{\rm loop}}$$

$$\hat{A}_s = \frac{9V_0}{4}\frac{\mathcal{V}^{2/3}\phi_*^{10/3}}{c_{\rm loop}^2} \simeq 2.5\times 10^{-7}$$

$$\phi_* = 0.06\, N_e^{7/22}$$

$$\mathcal{V} = 1743\, N_e^{5/11}$$

$$c_{\rm loop} \simeq \frac{1}{16\pi^2}$$

$$n_s = 1 + 2\eta - 6\epsilon \simeq 1 - \frac{20}{9}\frac{c_{\rm loop}}{\mathcal{V}^{1/3}\phi_*^{8/3}}$$

$$r = 16\,\epsilon \simeq \frac{32}{9}\frac{c_{\rm loop}^2}{\mathcal{V}^{2/3}\phi_*^{10/3}}$$

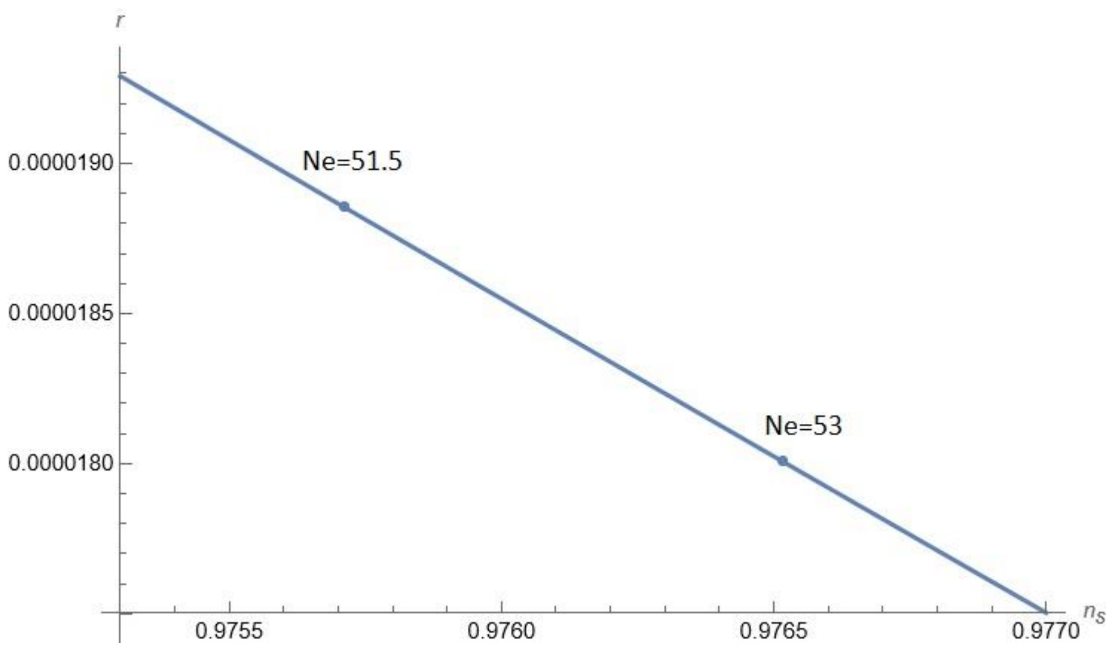
$$n_s \simeq 1 - \frac{1.25}{N_e} \qquad r \simeq \frac{0.004}{N_e^{15/11}}$$

→

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

Cosmological predictions

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



for $51.5 \lesssim N_{\rm e} \lesssim 53$ $\quad$ n_s in agreement with CMB data $\quad$ $r \simeq 2 \times 10^{-5}$

determined by post-inflationary evolution

Control over EFT

- Values of UV parameters:

$$\text{for } 51.5 \lesssim N_e \lesssim 53 \qquad \mathcal{V} = 1743\, N_e^{5/11} \sim \mathcal{O}(10^4) \qquad \phi_* = 0.06\, N_e^{7/22} \sim \mathcal{O}(0.2)$$

- Canonical normalisation: $\phi \simeq \tau_\phi^{3/4}/\sqrt{\mathcal{V}} \simeq (\tau_\phi/\tau_b)^{3/4}$

  $\phi \sim \mathcal{O}(0.2)$ implies $\tau_\phi \lesssim \tau_b$ ⟶ can have inflation within Kaehler cone?

- Check in an explicit CY example from [MC,Krippendorf,Mayrhofer,Quevedo,Valandro]:

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

- Kaehler cone conditions:

$$t_b + t_s > 0 \qquad t_b + t_\phi > 0 \qquad t_s < 0 \qquad t_\phi < 0$$

- Canonical normalisation:

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

- At horizon exit:

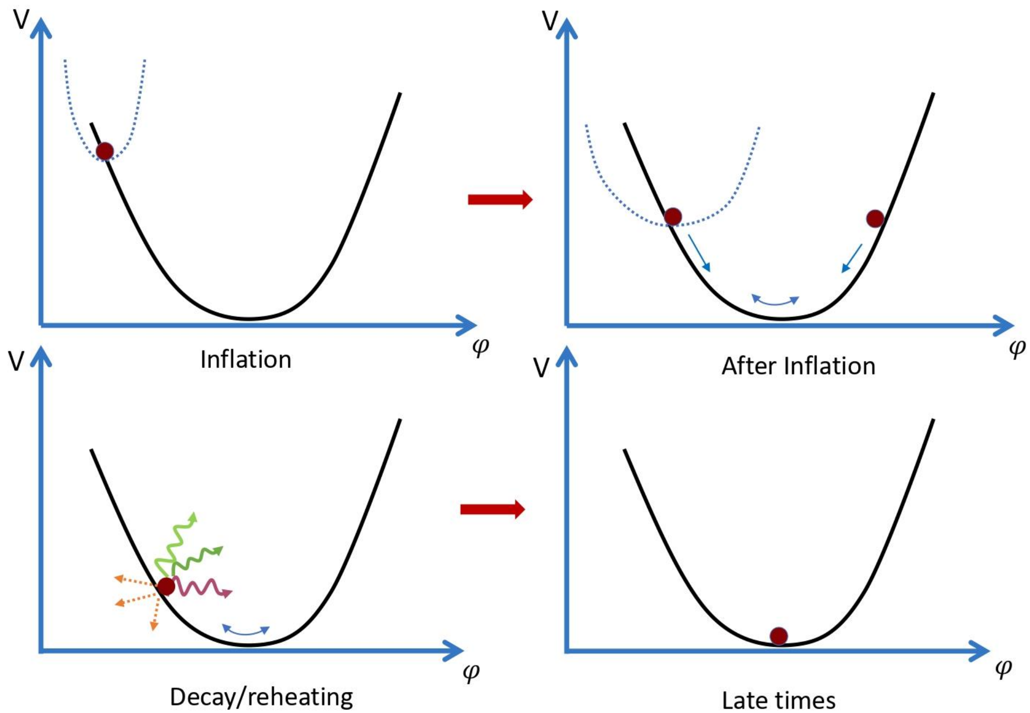
$$\frac{|t_\phi|}{t_b} = \left(\frac{1}{2\sqrt{6}}\right)^{1/3} \phi^{2/3} \simeq 0.6\,\phi^{2/3} \simeq 0.2 \quad \text{for} \quad \phi \simeq 0.2$$

well inside Kaehler cone!

N_e from post-inflation

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

τ_ϕ domin. $\quad$ $\mathcal{V}$ domin.



$\varphi \equiv \tau_\phi$ or $\mathcal{V}$

φ

$\Gamma_{\varphi\to SM}$ → SM dof

$\Gamma_{\varphi\to\vartheta_b\vartheta_b}$ → τ_b axions → $\Delta N_{eff} \neq 0$

$\Delta N_{eff} \lesssim 0.2 - 0.5$ at 95% CL

SM realisation

- SM D7s cannot wrap τ_s due to tension between non-pert effects and chirality [Blumenhagen,Moster,Plauschinn]
- SM D7s cannot wrap τ_ϕ since τ_ϕ-dependent FI-term would make τ_ϕ too heavy

→ need to introduce 2 additional intersecting blow-ups τ_{SM} and τ_{int}

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

- D-term stabilisation:

$$\xi_{FI} = 0 \qquad \Leftrightarrow \qquad \tau_{\rm SM} = \lambda^2\left(\tau_{\rm int} - \tau_{\rm SM}\right)$$

i) if $\lambda = 0$, $\tau_{SM} \to 0$ → SM on D3-branes at a CY singularity

ii) if $\lambda \neq 0$, $\xi_{FI} = 0$ fixes τ_{int} in terms of τ_{SM} and τ_{SM} remains as a flat direction fixed by loops

$$V(\tau_{\rm SM}) = \left(\frac{d_{\rm loop}}{\sqrt{\tau_{\rm SM}}} - \frac{g_{\rm loop}}{\sqrt{\tau_{\rm SM}} - \sqrt{\tau_s}}\right)\frac{W_0^2}{\mathcal{V}^3}$$ [MC,Mayrhofer,Valandro]

→ $$\tau_s = \left(1 + \sqrt{\frac{g_{\rm loop}}{d_{\rm loop}}}\right)^2 \tau_{\rm SM} \sim \tau_{\rm SM} \sim \mathcal{O}(10) \simeq g_{\rm SM}^{-2}$$

→ SM on D7-branes wrapped around τ_{SM}

Volume decay rates

- Masses of canonically normalised moduli: τ_ϕ becomes ϕ and $\mathcal{V}$ becomes χ

$$m_\phi \simeq \frac{W_0 \ln \mathcal{V}}{\mathcal{V}} M_p \qquad \text{and} \qquad m_\chi \simeq \frac{W_0}{\mathcal{V}^{3/2}\sqrt{\ln \mathcal{V}}} M_p$$

- Decays of volume χ:

i) closed string axions ϑ_b

$$\Gamma_{\chi\to\vartheta_b\vartheta_b} = \frac{1}{48\pi}\frac{m_\chi^3}{M_p^2}$$

ii) MSSM Higgses H_u and H_d

$$\Gamma_{\chi\to H_u H_d} = 2Z^2\,\Gamma_{\chi\to\vartheta_b\vartheta_b}$$

iii) SM Higgses h

$$\Gamma_{\chi\to hh} = \frac{c_{\text{loop}}^2}{32\pi}\left(\frac{m_0}{m_\chi}\right)^4 \frac{m_\chi^3}{M_p^2}$$

$\longrightarrow$ $$\frac{\Gamma_{\chi\to hh}}{\Gamma_{\chi\to\vartheta_b\vartheta_b}} \simeq c_{\text{loop}}^2\left(\frac{m_0}{m_\chi}\right)^4$$

SM on D7s: $m_0 \simeq \frac{M_p}{\mathcal{V}} \gg m_\chi$ $\qquad$ $\frac{\Gamma_{\chi\to hh}}{\Gamma_{\chi\to\vartheta_b\vartheta_b}} \simeq \left(c_{\text{loop}}\mathcal{V}\right)^2 \gg 1$

$\longrightarrow$ χ decays into SM Higgses h

SM on D3s: $m_0 \lesssim m_\chi$ $\qquad$ $\frac{\Gamma_{\chi\to hh}}{\Gamma_{\chi\to\vartheta_b\vartheta_b}} \lesssim c_{\text{loop}}^2 \ll 1$

$\longrightarrow$ χ decays into ϑ_b axions, H_u and H_d

Inflaton decay rates

- Inflaton wrapped by hidden D7s:

decay into hidden gauge bosons γ_h

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

- Inflaton not wrapped by any D7:

i) decay into volume moduli χ and ϑ_b axions

$$\Gamma_{\phi\to\chi\chi} \simeq \Gamma_{\phi\to\vartheta_b\vartheta_b} \simeq \frac{(\ln\mathcal{V})^{3/2}}{64\pi\,\mathcal{V}}\frac{m_\phi^3}{M_p^2}$$

SM on D7s: χ then decays istantaneously into h h

SM on D3s: χ then decays later on into H_u and H_d, and ϑ_b ϑ_b

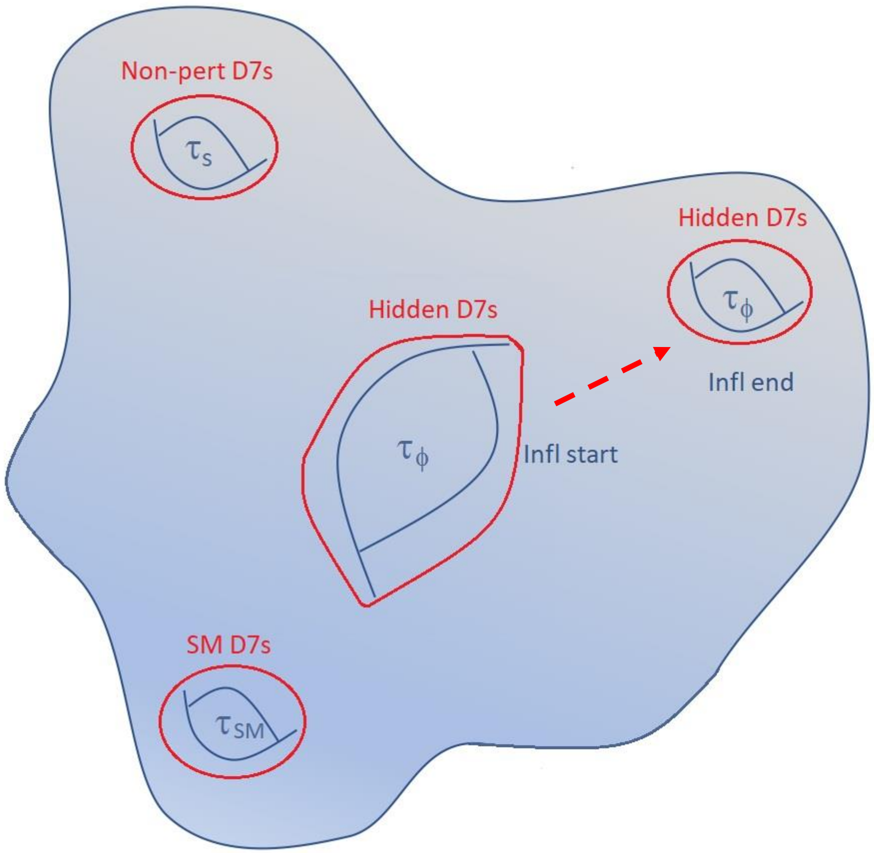
ii) for SM on D7s, extra decays into SM gauge bosons γ, τ_{SM} moduli and ϑ_{SM} (QCD) axions

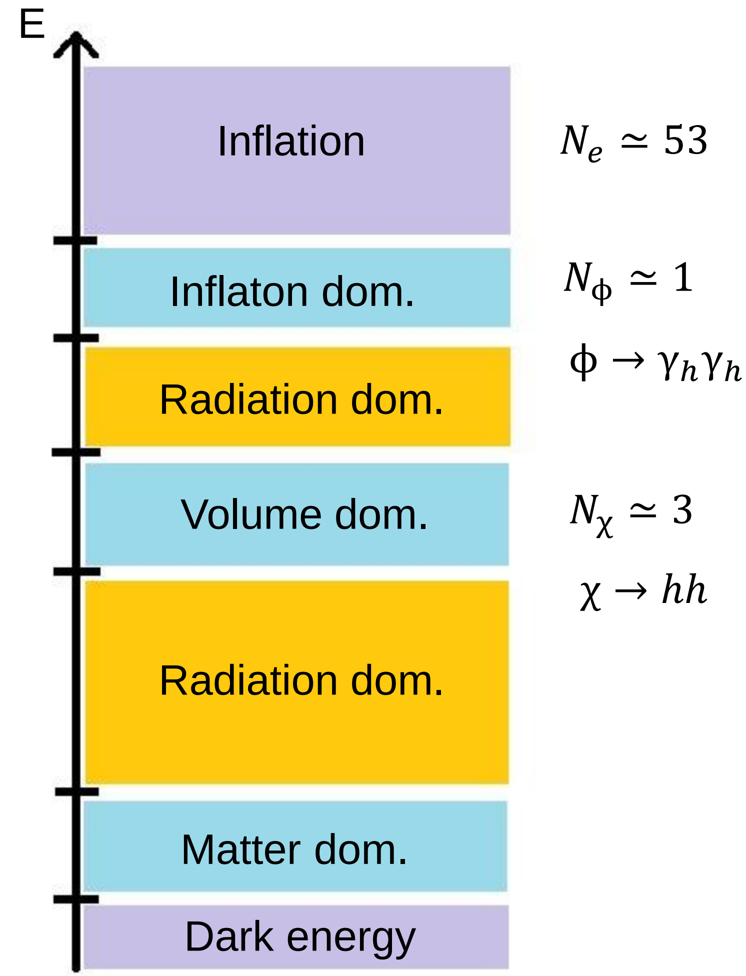
$$\Gamma_{\phi\to\tau_{SM}\tau_{SM}} \simeq \Gamma_{\phi\to\vartheta_{SM}\vartheta_{SM}} \simeq \Gamma_{\phi\to\chi\chi} \qquad \Gamma_{\phi\to\gamma\gamma} \simeq N_g\,\Gamma_{\phi\to\chi\chi} \simeq 12\,\Gamma_{\phi\to\chi\chi}$$

τ_{SM} then decays istantaneosuly into γ γ, and ϑ_{SM} ϑ_{SM} with [MC,Hebecker,Jaeckel,Wittner]

$$\frac{\Gamma_{\tau_{SM}\to\gamma\gamma}}{\Gamma_{\tau_{SM}\to\vartheta_{SM}\vartheta_{SM}}} = 8\,N_g \geq 96 \gg 1$$

SM on D7s and inflaton wrapped by D7s

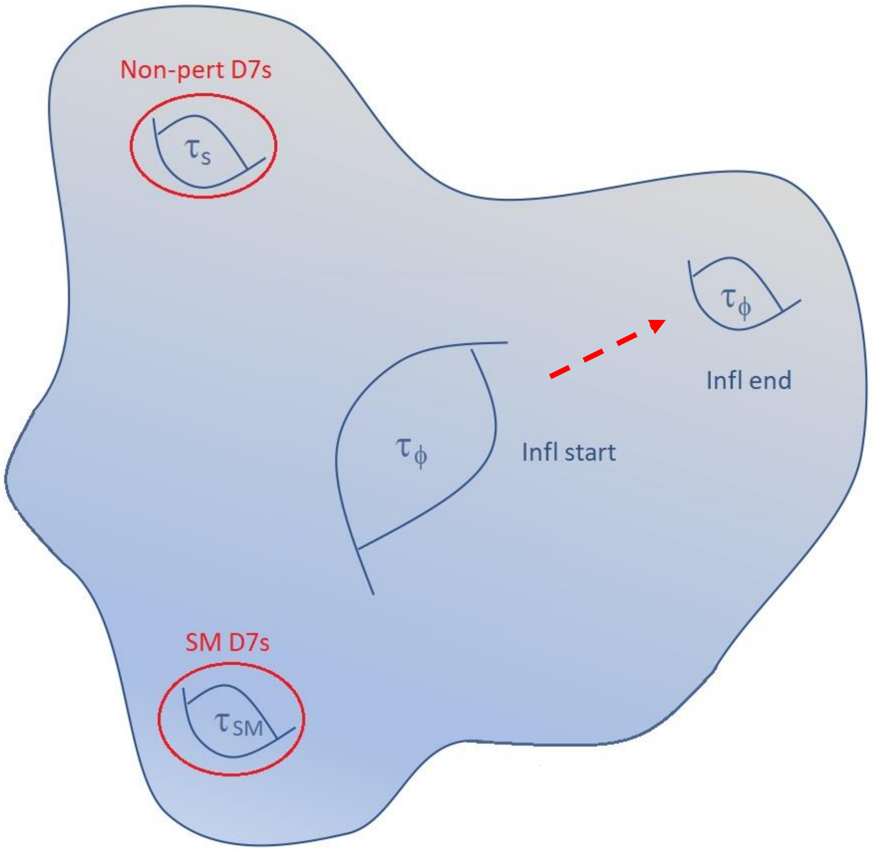


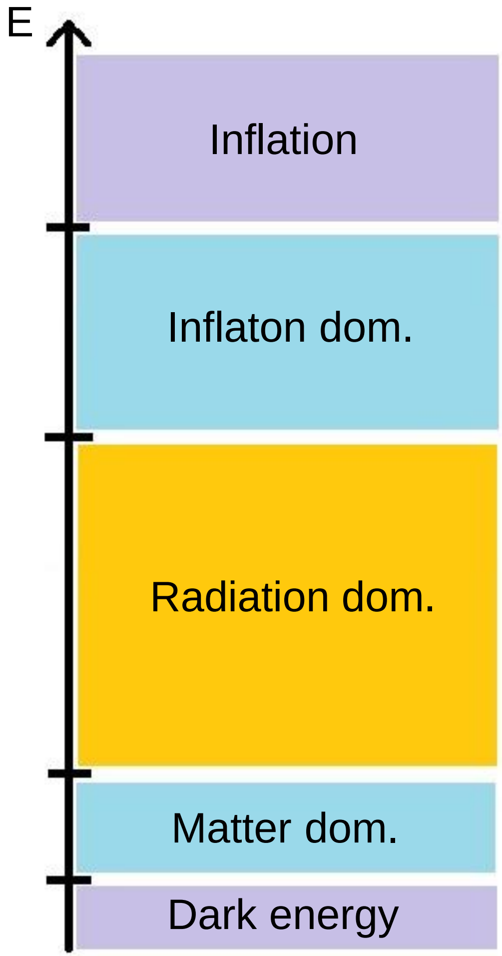


Predictions:

$n_s \simeq 0.9765$ $\quad r \simeq 1.7 \times 10^{-5}$ $\quad T_{\rm rh} \simeq 4 \times 10^{10}\,\text{GeV}$ $\quad \Delta N_{\rm eff} \simeq 0$

SM on D7s and unwrapped inflaton





$N_e \simeq 52$

$N_\phi \simeq 8$

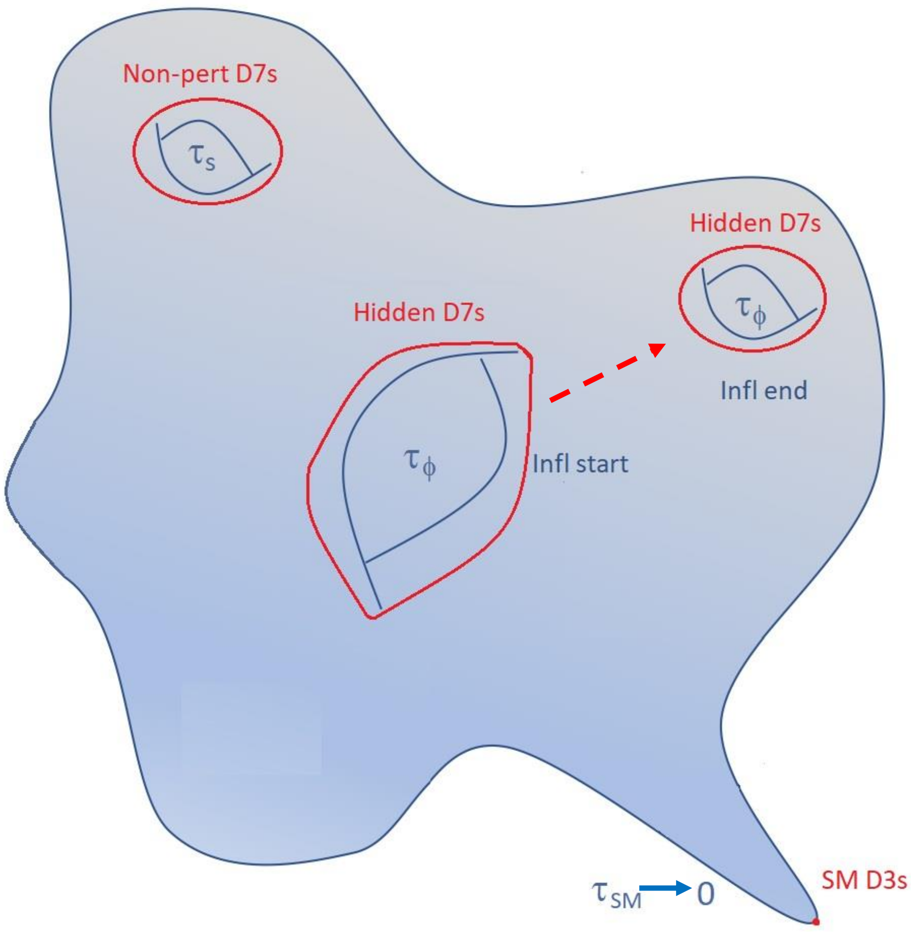
$\phi \to \gamma\gamma, \vartheta_b \vartheta_b$

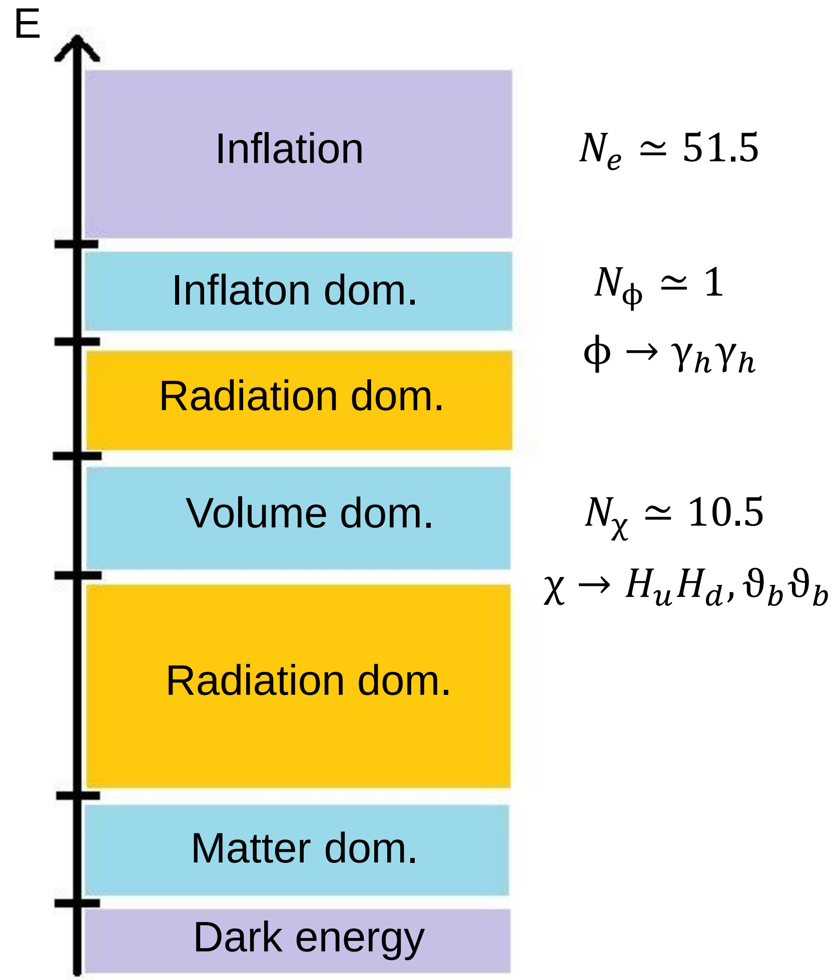
$N_\chi = 0$

Predictions:

$n_s \simeq 0.9761$ $\quad r \simeq 1.7 \times 10^{-5}$ $\quad T_{\rm rh} \simeq 3 \times 10^{12}\,\text{GeV}$ $\quad \Delta N_{\rm eff} \simeq 0.14$

SM on D3s and inflaton wrapped by D7s

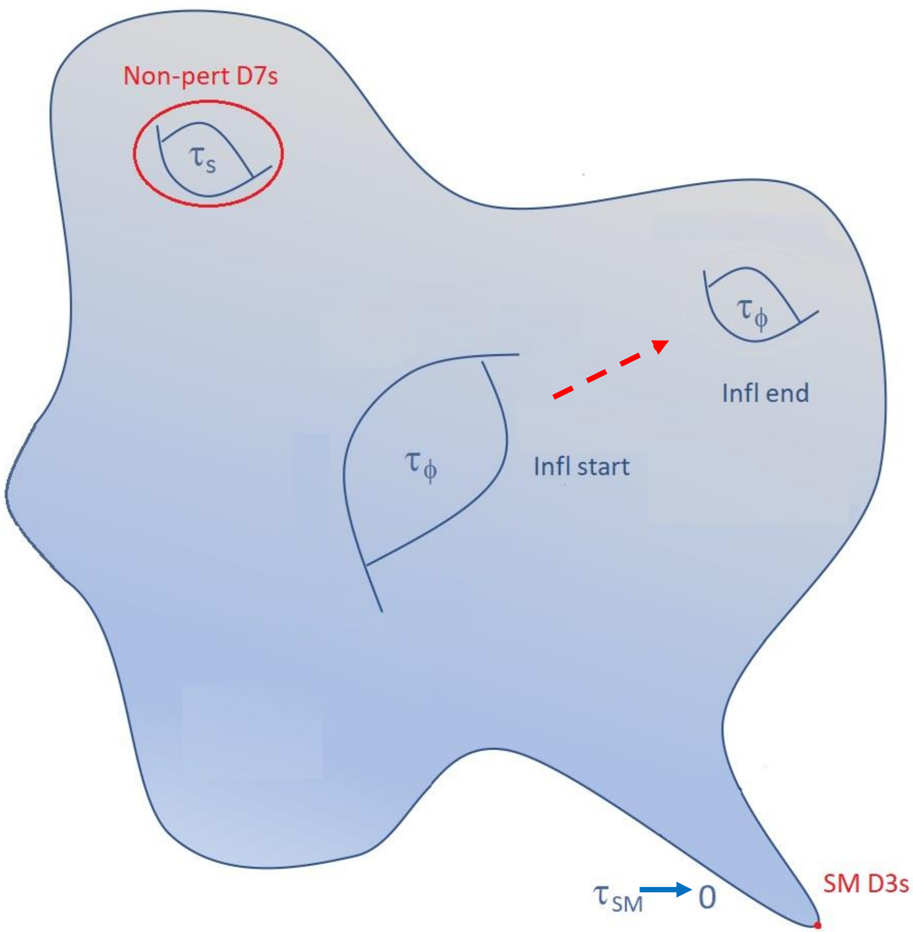


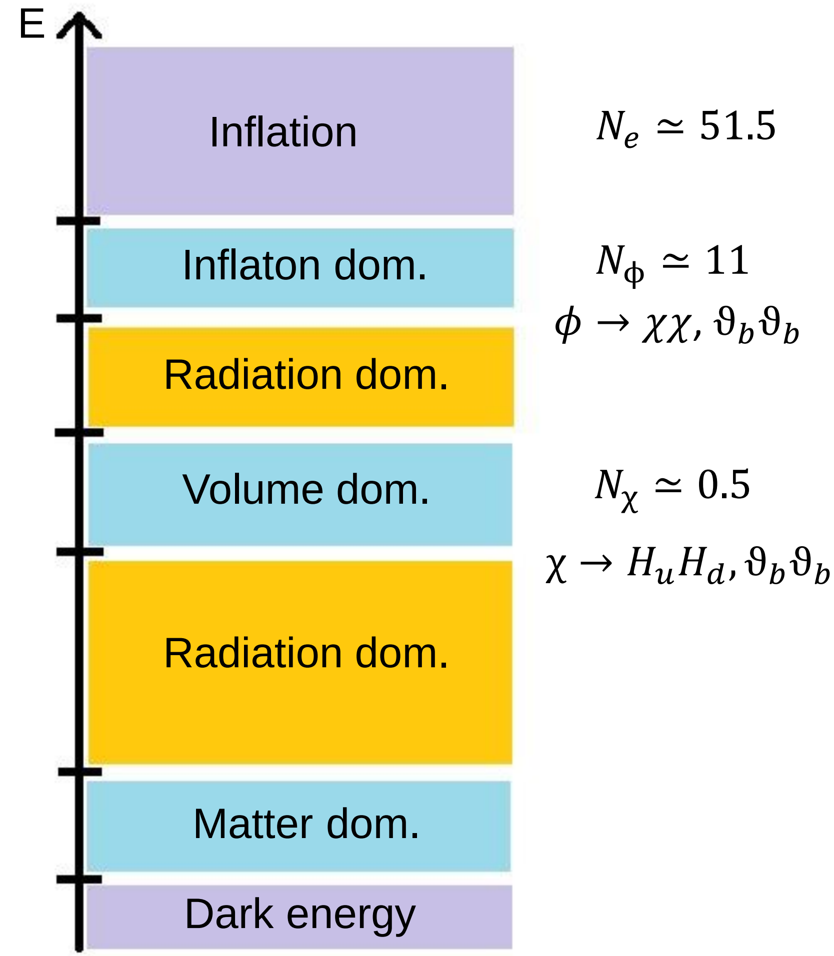


Predictions:

$n_s \simeq 0.9757$ $r \simeq 1.8 \times 10^{-5}$ $T_{\rm rh} \simeq 1 \times 10^8$ GeV $\Delta N_{\rm eff} \simeq \frac{1.43}{Z^2} \simeq 0.36$ $Z = 2$

SM on D3s and unwrapped inflaton





$N_\phi + N_\chi \simeq 11.5$ as before → same predictions:

$n_s \simeq 0.9757$ $\quad r \simeq 1.8 \times 10^{-5}$ $\quad T_{rh} \simeq 1 \times 10^8\ \text{GeV}$ $\quad \Delta N_{eff} \simeq \frac{1.43}{Z^2} \simeq 0.36 \quad Z = 2$

Conclusions on inflation

- Type IIB Kaehler moduli $\perp \mathcal{V}$ are good inflatons ϕ due to approximate shift symmetries
- $V(\phi)$ determined by nature of breaking effects (pert/non-pert.) and topology (bulk/local cycle)

  → can have several scenarios
- New model: Loop Blow-up Inflation [Bansal,Brunelli,MC,Hebecker,Kuespert]
- Inflation driven by a blow-up mode with $V(\phi)$ generated by 1-loop corrections to K
- 1-loop K: conjecture from toroidal computation
  + EFT matching with 1-loop 2-point function and Coleman-Weinberg potential
- Inflaton potential:

$$V(\phi) = V_0 \left(1 - \frac{c}{\mathcal{V}^{1/3}\phi^{2/3}}\right)$$

- EFT under control with inflation inside Kaehler cone
- Microscopic parameters: $\mathcal{V} \sim \mathcal{O}(10^4)$ and $\phi_* \sim \mathcal{O}(0.2)$
- Predictions: $0.9757 \lesssim n_s \lesssim 0.9765$ and $r \simeq 2 \times 10^{-5}$
- Post-inflation with moduli domination and reheating from moduli decay
- Depending on SM realisation: $51.5 \lesssim N_{\rm e} \lesssim 53$ and $0 \lesssim \Delta N_{\rm eff} \lesssim 0.36$

Dark energy

dS from string theory?

- Stable dS does not exist
- Difficulty to get dS with EFT under control
- Extreme point of view: metastable dS may also be incompatible with QG

  → No dS conjectures see Ooguri's talk

  → DE has to be quintessence

- Conservative point of view: no dS conjecture applies only at boundary of moduli space

  → can have metastable dS in interior of moduli space

- No dS with parametric control but dS with numerical control is OK due to small parameters [MC,de Alwis,Maharana,Muia,Quevedo]

  $W_0 \ll 1$ in KKLT and $\mathcal{V}^{-1} \sim e^{-1/g_s} \ll 1$ in LVS

- Several uplifting mechanisms:
  anti-D3s, D-terms, T-branes, α' effects, $F^{cx\ str} \neq 0$, non-pert. effects at singularities

- Progress in classifying α' and g_s corrections using 10D symmetries [Burgess,MC,Ciupke,Krippendorf,Quevedo]

- Global CY models with SM on D3s and dS from T-branes [MC,Garcia Extebarria,Quevedo,Schacher,Shukla,Valandro]

- Metastable dS may exist but its lifetime is upper-bounded see talks by Dvali and Vafa

Quintessence from string theory?

- Take no metastable dS point of view

  → implications for quintessence?

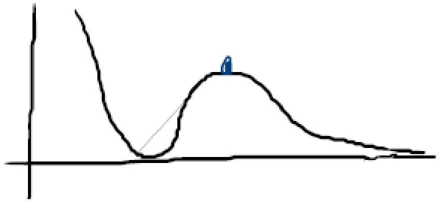
- Models that would be ruled out:

  i) Saxion quintessence slow-roll down a shallow potential (due to no dS conjecture)

  ii) Axion quintessence with $f \gtrsim M_p$ (due to WGC)

- Models that would be OK:

  i) Saxion/axion hilltop for a Minkowski/AdS vacuum



  ii) Saxion runaway

No quintessence at boundary of moduli space

- Focus on type IIB volume mode (similar results for type IIA and heteretic)

[MC,Cunillera,Padilla,Pedro]

$$K = -3\ln\tau \quad \Rightarrow \quad \mathcal{L}_{kin} = \frac{3}{4\tau^2}\partial_\mu\tau\partial^\mu\tau = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi \qquad \tau = e^{\sqrt{2/3}\phi}$$

- Potential for $\partial_\tau W = 0$ and $\tau \to \infty$ (α' expansion under control)

$$V = e^K(|D_U W|^2 + |D_S W|^2) = \frac{V_0}{\tau^3}$$

- If $|D_U W| = |D_S W| = 0$, quantum corrections give a larger suppression for $\tau \to \infty$

$$V = \frac{V_0}{\tau^{3+p}} = V_0\, e^{-\lambda\phi} \qquad \lambda = \sqrt{6}\,(1+p) \qquad p > 0$$

$$\longrightarrow \quad \epsilon = \frac{1}{2}\left(\frac{V_\phi}{V}\right)^2 = \frac{\lambda^2}{2} = 3\,(1+p)^2 > 1$$

No acceleration

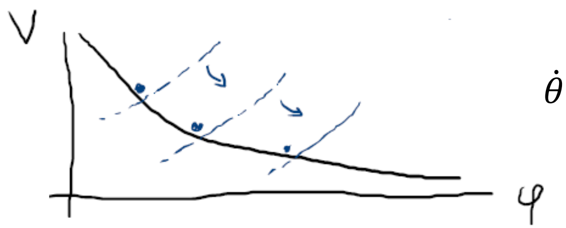
- Similar results for dilaton $s \to \infty$ (g_s expansion under control)

Multifield quintessence?

- Quintessence could still work due to kinetic coupling with axion
  → non-geodesic motion in curved field space gives acceleration [MC,Dibitetto,Pedro]
- Idea: $T = \tau + i\theta \quad \Rightarrow \quad \mathcal{L}_{kin} \supset \frac{3}{4\tau^2}\partial_\mu\theta\partial^\mu\theta = \frac{3}{4}e^{-2\sqrt{\frac{2}{3}}\phi}\dot{\theta}^2$

  gives effective time-dependent contribution to $V(\phi)$ if $\dot{\theta} \neq 0$

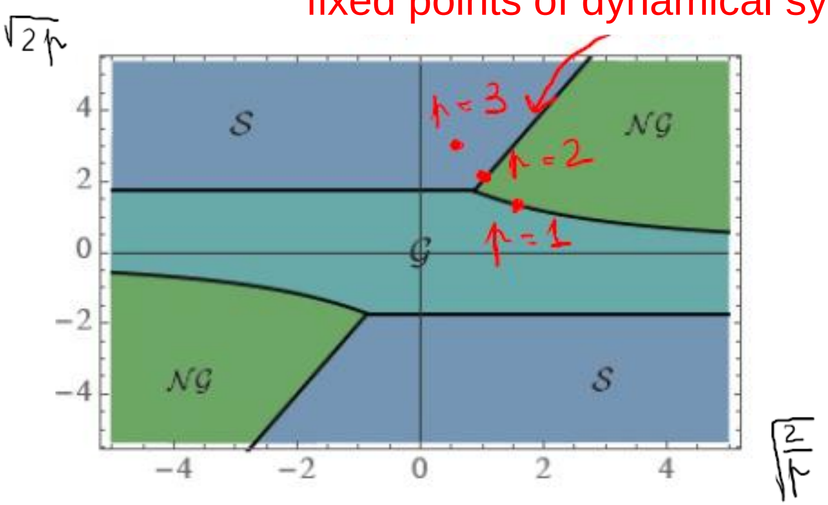
  → $V_{\text{eff}} = V_0\, e^{-\lambda\phi} - \frac{3}{4}e^{-2\sqrt{\frac{2}{3}}\phi}\dot{\theta}^2$



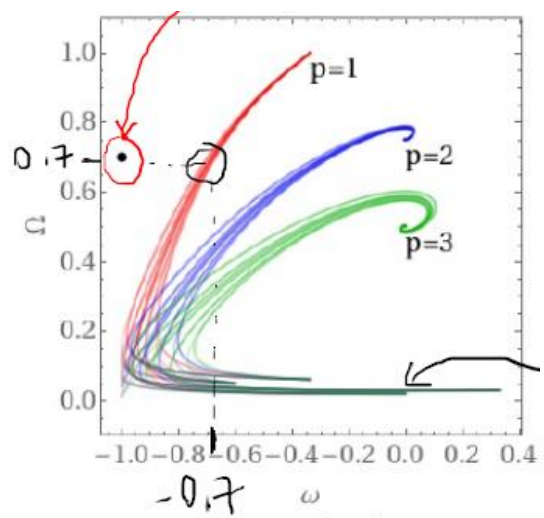
$\dot{\theta}^2 \propto \frac{1}{a^6} \qquad m_\theta \simeq 0$

- However it does not work in string theory: $K = -p\,\ln(X + \bar{X}) \qquad V = V_0\, e^{-\sqrt{2p}\,\phi} - \frac{p}{4}e^{-2\sqrt{\frac{2}{p}}\phi}\dot{\theta}^2$

fixed points of dynamical system



today



matter dom. initial cond.

[Brinkmann,MC, Dibitetto,Pedro]

Challenges for quintessence

- Quintessence, as dS, has to be in bulk of moduli space

- Same control issue as dS + extra challenges:

  i) Ultra-light quintessence field

  $$m_\phi \lesssim H_0 \sim 10^{-60}\, M_p \qquad from \qquad \eta = \frac{V_{\phi\phi}}{V} \lesssim 1$$

  radiatively stable?
  fifth-forces?

  ii) String and SUSY scale above 1 TeV

  $$M_s \simeq \frac{M_p}{\sqrt{\mathcal{V}}} \gtrsim 1\, TeV \qquad \Leftrightarrow \qquad \mathcal{V} \lesssim 10^{30}$$

  iii) Heavy volume mode

  $m_{\mathcal{V}} \gtrsim 1\, meV \simeq 10^{-30}\, M_p$ from fifth-forces (screening/sequestering hard to work)

  $$\Rightarrow \qquad m_{\mathcal{V}} \gg m_\phi$$

- Leading order: $\mathcal{V}$ is lifted while ϕ is flat: $V = \mathrm{V}_{\mathrm{lead}}(\mathcal{V}) + \mathrm{V}_{\mathrm{sub}}(\mathcal{V}, \phi)$

  $$\frac{\mathrm{V}_{\mathrm{lead}}}{\mathrm{V}_{\mathrm{sub}}} \sim \left(\frac{m_\phi}{m_{\mathcal{V}}}\right)^2 \lesssim 10^{-60}$$

  cannot be obtained with perturbative corrections

  since $$\frac{\mathrm{V}_{\mathrm{loop}}}{V_{\alpha'^3}} \sim \frac{1}{\mathcal{V}^{1/3}} \lesssim 10^{-60} \qquad \Leftrightarrow \qquad \mathcal{V} \gtrsim 10^{180} \qquad \Rightarrow \qquad M_s \ll 1\, TeV$$

Quintessence model building

- Quintessence as challenging as dS + extra challenges (fifth forces, right scales, stability)
- Metastable dS seems easier to build [MC,Cunillera,Padilla,Pedro]
- But what if quintessence is preferred by data? (DESI?)
- Best candidate: axion quintessence
- $V_{\rm lead}(\mathcal{V})$ has a SUSY breaking Minkowski vacuum and axion ϕ is flat
- $V_{\rm sub}(\phi,\mathcal{V})$ generated by non-perturbative effects

  i) Right hierarchy: $V_{\rm sub}(\phi,\mathcal{V}) \ll V_{\rm lead}(\mathcal{V})$

  $$V_{\rm sub} \sim e^{-a\tau} \sim e^{-a\mathcal{V}^{2/3}} \longrightarrow \frac{V_{\rm lead}}{V_{\rm sub}} \sim \frac{e^{a\mathcal{V}^{2/3}}}{\mathcal{V}^3} \gtrsim 10^{60} \quad \text{for} \quad \mathcal{V} \lesssim 10^{30} \quad and \quad M_s \gtrsim 1\, TeV$$

  ii) Radiative stability due to perturbative shift symmetry

  iii) No fifth-force problem
- But axion potential yields acceleration only for $f \gtrsim M_p$

  $$V_{\rm sub}(\phi,\mathcal{V}) = \Lambda(\mathcal{V})\left[1-\cos\left(\frac{\phi}{f}\right)\right]$$
- Never obtained in EFT + forbidden by WGC
- For $f < M_p$ can have quintessence from axion hilltop

Axion hilltop

[MC,Cunillera,Padilla,Pedro]

- Focus on axions in LVS

$$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2} \qquad K = -2\ln\left(\mathcal{V} + \frac{\xi}{g_s^{3/2}}\right) \qquad W = W_0 + e^{-a_s T_s} + e^{-a_b T_b}$$

- Leading order stabilisation: SUSY breaking Minkowski vacuum at

$$\theta_s = 0 \qquad \tau_s \sim g_s^{-1} \gg 1$$

$$\mathcal{V} \sim e^{a_s \tau_s} \sim e^{a_s/g_s} \gg 1 \qquad \theta_b \ \ is\ flat$$

$$V_{\text{lead}}(\mathcal{V}_{max}) \sim m_{\mathcal{V}}$$

- Subleading order:

$$V_{\text{sub}}(\phi, \mathcal{V}) \sim e^{-\sqrt{\frac{3}{2}}\frac{M_p}{f}} M_p^4 \left[1 - \cos\left(\frac{\phi}{f}\right)\right] \qquad f = \sqrt{\frac{3}{2}}\frac{M_p}{a_b \tau_b}$$

$$10^{-120} \quad for \quad f \sim 0.003\, M_p \quad \Leftrightarrow \quad \mathcal{V} \simeq \tau_b^{3/2} \sim 10^3$$

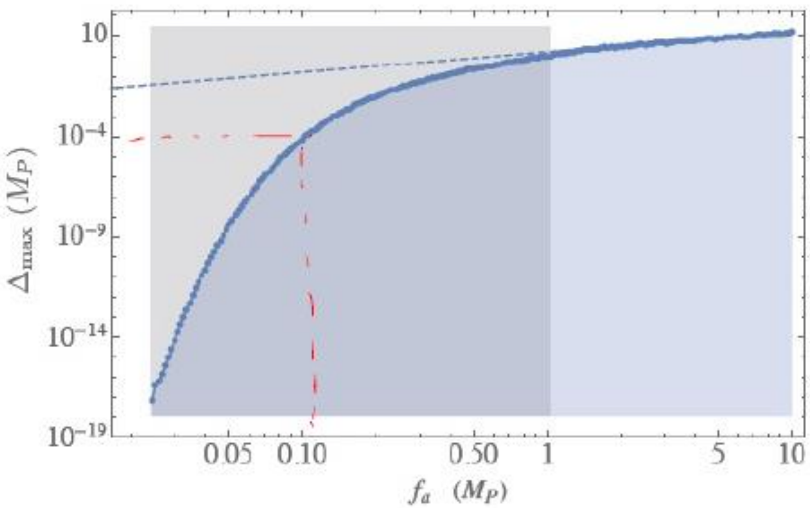
natural + EFT under control

$$m_{\mathcal{V}} \sim 10^{13}\ \text{GeV}$$

Hilltop and initial conditions

- How close should ϕ be to the maximum to get acceleration with $\omega_\phi \simeq -1$ and $\Omega_\phi \simeq 0.7$?

[MC,Cunillera,Padilla,Pedro]



- Quantum diffusion during inflation causes fluctuations $\Delta\phi \sim H_{inf}$
- Need to require $H_{inf} \lesssim \Delta_{max}$

i) $f \simeq 0.1\ M_p$ ⟶ $H_{inf} \lesssim 10^{-4}\ \mathrm{M_p} \sim 10^{14}\ GeV$ but can get DE scale for $f \simeq 0.1\ M_p$?

ii) $f \simeq 0.02\ M_p$ ⟶ $H_{inf} \lesssim 10^{-18}\ \mathrm{M_p} \sim 1\ GeV$ tiny and even lower for $f \simeq 0.003\ M_p$

- In (i) use poly-instantons to generate axion potential with right DE scale
- In (ii) use axion alignment to get an effective $f \simeq 0.1\ M_p$

Quintessence from poly-instantons

- LVS in fibred CYs: $\mathcal{V} = \sqrt{\tau_f}\tau_b - \tau_s^{3/2}$ [MC,Padilla,Pedro]
- Potential:

$$V = V_{lead}(\mathcal{V}, \tau_s, \vartheta_s) + V_{inf}(\tau_f) + V_{sub}(\vartheta_b, \vartheta_f)$$

- Loop Fibre Inflation: [MC,Burgess,Quevedo]

$$V_{inf} \simeq V_0(1 - \frac{4}{3} e^{-\phi/\sqrt{3}}) \qquad \text{and} \qquad H_{inf} \simeq 10^{-5} M_p$$

- 2 light bulk axions: ϑ_b = spectator (0.2% of DM) and ϑ_f = DE via poly-instantons

$$W = W_{LVS} + e^{-a_b T_b + e^{-a_f T_f}}$$

[Blumenhagen,Schmidt-Sommerfeld;Luest,Zhang]

- Axion potential:

$$V_{sub} \sim e^{-a_b \tau_b}\left[1 - \cos\left(\frac{\phi_b}{f_b}\right)\right] + e^{-a_b \tau_b - a_f \tau_f}\left[1 - \cos\left(\frac{\phi_b}{f_b} + \frac{\phi_f}{f_f}\right)\right]$$

$$\longrightarrow \quad V_{DE} \sim e^{-f_f^{-1} - f_b^{-1}}\left[1 - \cos\left(\frac{\phi_f}{f_f}\right)\right] \quad \text{after fixing} \quad \phi_b = 0$$

$$f_f = \frac{N_f}{2\sqrt{2}\pi\tau_f} M_p \simeq 0.1\, M_p \qquad \text{and} \qquad f_b = \frac{N_b}{2\pi\tau_b} M_p \simeq 0.005\, M_p$$

- Numerical results:

$$\tau_f \sim O(5) \qquad \tau_b \sim O(500) \qquad N_1 \sim O(5) \qquad N_2 \sim O(10)$$

$$m_b \simeq 10^{-29}\, eV \qquad m_f \simeq 10^{-32}\, eV$$

Conclusions on dark energy

- No quintessence at boundary of moduli space where α' and g_s expansions are under control
- Multifield string models can give late time acceleration but without $\omega_\phi \simeq -1$ and $\Omega_\phi \simeq 0.7$
- Quintessence as challenging as dS + extra challenges (fifth forces, right scales, stability)
- dS models seem easier to build
- If quintessence is preferred by data (DESI?), axions are the best candidates to drive DE
- But simplest axion potential does not yield acceleration
- Need to rely on axion hilltop:

  i) $f \simeq 0.1\, M_p$ ⟶ $H_{inf} \lesssim 10^{-4}\, \mathrm{M_p} \sim 10^{14}\, GeV$

  ii) $f \simeq 0.02\, M_p$ ⟶ $H_{inf} \lesssim 10^{-18}\, \mathrm{M_p} \sim 1\, GeV$

- In (i) do not get right DE scale for a single axion

  ⟶ poly-instantons, not tuned but need an explicit CY example

- In (ii) need alignment to get an effective $f \simeq 0.1\, M_p$ but contrived and tuned