α' Inflation

Moduli stabilisation and large tensors from higher derivatives

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Ioannina, 22 June 2016

Based on:

MC, Ciupke, de Alwis, Muia, arXiv:1606.xxxxx

Outline

- Higher derivative $(\alpha')^3$ terms
- Applications to moduli stabilisation: General LVS models
- Application to cosmology: α' Inflation with $r \simeq 0.01$

Standard LARGE Volume Scenario

- Kahler potential and superpotential

$$K = -2\ln\mathcal{V} - \frac{\xi}{g_s^{3/2}\mathcal{V}} \qquad W = W_0 + \sum_{s=1}^{N_{small}} A_s\, e^{-a_s T_s}$$

- Strong Swiss-cheese CY

$$\mathcal{V} = \tau_b^{3/2} - \sum_{s=1}^{N_{small}} \tau_s^{3/2}$$

- Scalar potential

$$V = \sum_{s=1}^{N_{small}} \left[K_{ss}^{-1} (a_s A_s)^2 \frac{e^{-2a_s\tau_s}}{\mathcal{V}^2} - 4a_s A_s W_0 \tau_s \frac{e^{-a_s\tau_s}}{\mathcal{V}^2} \right] + \frac{3\xi W_0^2}{4 g_s^{3/2}\mathcal{V}^3}$$

where $K_{ij}^{-1} = 4\left(\tau_i\tau_j - \mathcal{V} k_{ijk} t_k\right)$ $\longrightarrow$ $K_{ss}^{-1} = 4\left(\tau_s^2 + \frac{2}{3}\mathcal{V}\sqrt{\tau_s}\right) \approx \frac{8}{3}\mathcal{V}\sqrt{\tau_s}$

- Minimising with respect to τ_s $\quad \mathcal{V} \approx \frac{3\sqrt{\tau_s}}{4a_s A_s} W_0\, e^{a_s\tau_s} \quad \forall\, s = 1,\ldots, N_{small}$

- Substitute back in V:

$$V = \left(-2 \sum_{s=1}^{N_{small}} \tau_s^{3/2} + \xi\, g_s^{-3/2} \right) \frac{3W_0^2}{4\mathcal{V}^3} \qquad \text{with} \quad \tau_s \approx \frac{\ln\mathcal{V}}{a_s}$$

- AdS minimum at

$$\tau_s \approx (\xi/2)^{2/3}\, g_s^{-1} \approx g_s^{-1} \approx O(10) \quad \text{for } g_s \approx 0.1$$

$$\mathcal{V} \approx W_0\, e^{a_s\tau_s} \approx e^{1/g_s} >> 1$$

Advantages of LVS models

Several nice properties of LVS models:

- Fix moduli without tuning flux superpotential
- Each τ_s is a diagonal blow-up mode ⟶ good since:
  i) τ_s is a local effect: $\tau_s << \tau_b$
  ii) τ_s is a rigid cycle: W_{np} gets generated!
- Trust approximations for $\mathcal{V}$ >> 1
- Generate hierarchies naturally with exponentials

$$m_{3/2} \approx \frac{W_0 M_p}{\mathcal{V}} \approx M_p e^{-a_s g_s^{-1}} << M_p$$

TeV-scale SUSY naturally

- Spontaneous SUSY breaking within 4D EFT

$$F^{T_b} \approx \frac{M_p^2}{\mathcal{V}^{1/3}} \neq 0 \qquad F^{T_s} \approx \frac{M_p^2}{\mathcal{V}} \approx m_{3/2} M_p \neq 0$$

- AdS minimum can be turned into dS with:
  i) anti-branes
  ii) non-zero hidden matter F-terms induced by D-terms (T-branes in flux background)
  iii) non-perturbative effects at singularities

[MC,Quevedo,Valandro]

What about more general CY cases?

General LVS models

- General conditions to get LVS vacua [MC, Conlon, Quevedo]

  i) $h^{1,2} > h^{1,1} \Rightarrow \hat{\xi} > 0$

  ii) Existence of at least 1 diagonal blow-up mode τ_s

  ⇒ General weak Swiss-cheese form of the volume

$$\mathcal{V} = \frac{1}{6}\sum_{i,j,k=1}^{N_{\rm large}} k_{ijk} t_i t_j t_k - \frac{1}{6}\sum_{s=1}^{N_{\rm small}} k_{sss} t_s^3$$

- Moduli stabilisation:

  i) at leading order fix $\mathcal{V}$ mode and all N_{small} moduli by α' and non-perturbative effects

  ⇒ $N_{flat} = h^{1,1} - N_{small} - 1$ flat directions

  ii) flat directions lifted by perturbative corrections to K since non-perturbative corrections to W are either exponentially suppressed if $\tau_{flat} >> \tau_s$ or cannot give a minimum if $\tau_{flat} \sim \tau_s$

  iii) flat directions should be lifted by string loop corrections to K since they depend on all moduli and $\mathcal{V}$ is fixed at leading order

  ⇒ Good inflaton candidates [Fibre Inflation]

  1) Inflaton naturally lighter than H
  2) Flatness protected by an approximate rescaling shift symmetry [Burgess, MC, Williams, Quevedo]

  But loop corrections only conjectured for an arbitrary CY [Berg,Haack, Pajer]

  Are there other important perturbative effects?

Higher derivative corrections

- 10D supergravity bulk action

$$S_{IIB} = S_0 + \alpha'^3 S_3 + \alpha'^4 S_4 + \ldots$$

where for weak warping and large volume

$$S_3 \approx \frac{1}{\alpha'^4}\int d^{10}x\sqrt{-g}\left(R^4 + R^3 G_3^2 + R^2 G_3^4 + R G_3^6 + G_3^8\right)$$

- Only the tensor structure of R^4 term is known
- Dimensional reduction of R^4 term gives 4D corrections to kinetic terms

  $\Rightarrow \alpha'$ corrections to the scalar potential via supersymmetry

1) Leading order $\alpha'\, F^2$ correction [Becker, Becker, Haack, Louis]

$$V_{\alpha'} = \left(\frac{g_s}{8\pi}\right)\frac{3\xi W_0^2}{4 g_s^{3/2}\mathcal{V}^3} \qquad \xi = -\chi\zeta(3)/2(2\pi)^3$$

comes from 10D $R^3 G_3^2$ term

2) Subleading $\alpha'\, F^4$ correction [Ciupke, Louis, Westphal]

$$V_{F^4} = -T_{\bar{i}\bar{j}kl}\bar{F}^{\bar{i}}\bar{F}^{\bar{j}}F^k F^l \qquad F^i = e^{K/2}K^{i\bar{j}}D_{\bar{j}}\bar{W}$$

comes from 10D $R^2 G_3^4$ term

where

$$T_{\bar{i}\bar{j}kl} = \frac{\lambda}{g_s^{3/2}}\Pi_m t_m K_{\bar{i}} K_{\bar{j}} K_k K_l \qquad \Pi_m = \int_X c_2 \wedge \hat{D}_m > 0 \qquad t_i > 0\ \forall i = 1, \cdots, h^{1,1}$$

$$V_{F^4} = -\left(\frac{g_s}{8\pi}\right)^2 \frac{3^4 \lambda W_0^4}{g_s^{3/2}\mathcal{V}^4}\Pi_i t_i$$

simple dependence on all Kahler moduli!

Can explicitly fix all LVS flat directions for an arbitrary CY

Lifting flat directions

- Volume form

$$\mathcal{V} = \frac{1}{6}\sum_{i,j,k=1}^{N_{\rm large}} k_{ijk} t_i t_j t_k - \frac{1}{6}\sum_{s=1}^{N_{\rm small}} k_{sss} t_s^3$$

- Total scalar potential $V = V_{\rm LVS}(\mathcal{V}, t_s) + V_{F^4}(t_i, t_s) + V_{\rm up}(\mathcal{V})$

- Integrate out small blow-ups and get

$$V = \left(\frac{g_s}{8\pi}\right)\frac{3W_0^2}{2\mathcal{V}^3}\left(\frac{\hat{\xi}}{2} - \tau_s(\mathcal{V})^{3/2}\right) - \left(\frac{g_s}{8\pi}\right)^2 \frac{\hat{\lambda} W_0^4}{\mathcal{V}^4}\sum_{i=1}^{N_{\rm large}} \Pi_i t_i + \frac{\kappa}{\mathcal{V}^\alpha} \qquad \tau_s(\mathcal{V}) \simeq \frac{1}{a_s}\ln\left(\frac{\mathcal{V}}{W_0}\right)$$

- Minimise with respect to 2-cycle moduli with $\hat{V} = V_{LVS} + V_{up}$

$$\frac{\partial V}{\partial t_i} = \frac{\partial \hat{V}}{\partial \mathcal{V}}\tau_i + \frac{\partial V_{F^4}}{\partial t_i} = 0 \qquad (\boxtimes)$$

where

$$\frac{\partial \hat{V}}{\partial \mathcal{V}} = -\frac{9cW_0^2}{2\mathcal{V}^4}\left(\frac{\hat{\xi}}{2} - \tau_s(\mathcal{V})^{3/2}(1-2\epsilon_s)\right) - \frac{\alpha\kappa}{\mathcal{V}^{\alpha+1}} \qquad \frac{\partial V_{F^4}}{\partial t_i} = \frac{c^2\hat{\lambda} W_0^4}{\mathcal{V}^4}\left(\frac{\Pi_k t_k}{\mathcal{V}} 4\tau_i - \Pi_i\right)$$

- Using $3V = t_i\tau_i$ $\quad \frac{\partial \hat{V}}{\partial \mathcal{V}} = -\frac{c^2\hat{\lambda} W_0^4}{3\mathcal{V}^5}\left(\frac{\Pi_k t_k}{\mathcal{V}} 4t_i\tau_i - \Pi_i t_i\right) = -\frac{11c^2\hat{\lambda} W_0^4}{3\mathcal{V}^5}\Pi_k t_k$

- Thus $(*)$ becomes

$$\frac{\Pi_k t_k}{\mathcal{V}} 4\tau_i - \Pi_i = \frac{11}{3}\frac{\Pi_k t_k}{\mathcal{V}}\tau_i \quad \Leftrightarrow \quad \tau_i = \frac{3\mathcal{V}}{\Pi_k t_k}\Pi_i$$

Lifting flat directions

- Solution for flat directions

$$\tau_\alpha = \frac{\Pi_\alpha}{\Pi_*}\,\tau_*(\mathcal{V}) \qquad\qquad \forall\,\alpha = 1, \cdots, N_{\rm flat} = N_{\rm large} - 1$$

where

$$\tau_*(\mathcal{V}) = h(k_{ijk}, \Pi_i)\,\mathcal{V}^{2/3}$$

- Volume fixed by

$$\frac{\partial \hat{V}}{\partial \mathcal{V}} = -\frac{11 c^2 \hat{\lambda}\, W_0^4 \Pi_*}{h\,\mathcal{V}^{14/3}} \qquad (\boxtimes)$$

- EFT under control when $V_{F^4} \ll \hat{V} \Rightarrow (*)$ gives a small shift of $\mathcal{V}$ minimum for $\frac{\partial \hat{V}}{\partial \mathcal{V}} = 0$
- Solution to $(*)$ is

$$\frac{\hat{\xi}}{2} = \tau_s(\mathcal{V})^{3/2}\,(1 - 2\epsilon_s) \; - \frac{2\alpha\kappa}{9cW_0^2}\mathcal{V}^{3-\alpha} + \frac{22 c\hat{\lambda}\, W_0^2 \Pi_*}{9\mathcal{V}^{2/3}} \simeq \tau_s(\mathcal{V})^{3/2} - \frac{2\alpha\kappa}{9cW_0^2}\mathcal{V}^{3-\alpha} \qquad \mathcal{V} \gg 1$$

- Vacuum energy becomes

$$\langle V \rangle = -\frac{3cW_0^2}{\mathcal{V}^3}\epsilon_s \tau_s(\mathcal{V})^{3/2} + \frac{2c^2\hat{\lambda}\, W_0^4 \Pi_*}{3h\,\mathcal{V}^{11/3}} + \frac{\kappa(3-\alpha)}{3\mathcal{V}^\alpha}$$

- To set $\langle V \rangle = 0$ need to tune κ and $0 < \alpha < 3$
- Substitute vacuum energy tuning in solution for $\mathcal{V}$ and get

$$\frac{\hat{\xi}}{2} = \tau_s(\mathcal{V})^{3/2}\left[1 - 2\epsilon_s\left(1 + \frac{\alpha}{(3-\alpha)}\right)\right] + 2c\hat{\lambda}\, W_0^2 \frac{\Pi_*}{h\,\mathcal{V}^{2/3}}\left(1 + \frac{2}{3(3-\alpha)}\right) \simeq \tau_s(\mathcal{V})^{3/2} \qquad \Rightarrow \xi > 0$$

Global minimum

- Hessian

$$\frac{\partial^2 V}{\partial t_i \partial t_j} = \frac{\partial^2 \hat{V}}{\partial \mathcal{V}^2}\,\tau_i \tau_j + \frac{\partial \hat{V}}{\partial \mathcal{V}}\,A_{ij} + \frac{\partial^2 V_{F^4}}{\partial t_i \partial t_j}$$

where

$$\frac{\partial^2 \hat{V}}{\partial \mathcal{V}^2} = \frac{18 c W_0^2}{\mathcal{V}^5}\left(\frac{\hat{\xi}}{2} - \tau_s(\mathcal{V})^{3/2}\,(1 - 7\epsilon_s)\right) + \frac{\alpha(\alpha+1)\,\kappa}{\mathcal{V}^{\alpha+2}}$$

and

$$\frac{\partial^2 V_{F^4}}{\partial t_i \partial t_j} = \frac{4 c^2 \hat{\lambda}\, W_0^4}{\mathcal{V}^5}\left[\Pi_k t_k \left(A_{ij} - \frac{5}{\mathcal{V}}\tau_i \tau_j\right) + (\Pi_i \tau_j + \Pi_j \tau_i)\right]$$

- At the minimum the Hessian becomes (with $A_{ij} = \partial \tau_i / \partial t_j$)

$$\frac{\partial^2 V}{\partial t_i \partial t_j} = \frac{\partial^2 \hat{V}}{\partial \mathcal{V}^2}\,\tau_i \tau_j + \frac{c^2 \hat{\lambda}\, W_0^4 \Pi_*}{h\,\mathcal{V}^{17/3}}\,(\mathcal{V} A_{ij} - 52 \tau_i \tau_j)$$

- Since $K_{ij}^{-1} = 4\left(\tau_i \tau_j - \mathcal{V} A_{ij}\right)$

$$\frac{\partial^2 V}{\partial t_i \partial t_j} = c_1\, K_{ij}^{-1} + c_2\, \tau_i \tau_j$$

with

$$c_1 = -\frac{c^2 \hat{\lambda}\, W_0^4 \Pi_*}{h\,\mathcal{V}^{17/3}} \qquad c_2 = \frac{\partial^2 \hat{V}}{\partial \mathcal{V}^2} - \frac{51 c^2 \hat{\lambda}\, W_0^4 \Pi_*}{h\,\mathcal{V}^{17/3}}$$

- K_{ij}^{-1} is positive definite $\Rightarrow\ c_1 > 0 \Leftrightarrow \hat{\lambda} < 0$
- Also $M_{ij} = \tau_i \tau_j$ is positive definite since $\langle \vec{t}, M\vec{t} \rangle = t_i \tau_i t_j \tau_j = 9\mathcal{V}^2 > 0 \quad \Rightarrow\ c_2 > 0$

Global minimum

- Value of c_2 at the minimum

$$c_2 = \frac{cW_0^2}{\mathcal{V}^5}\left[9(10-\alpha)\epsilon_s\tau_s(\mathcal{V})^{3/2} - (7-2\alpha)\frac{c\hat{\lambda}\,W_0^2\Pi_*}{h\,\mathcal{V}^{2/3}}\right] \simeq 9(10-\alpha)cW_0^2\frac{\epsilon_s\tau_s(\mathcal{V})^{3/2}}{\mathcal{V}^5} > 0$$

⇒ All flat directions can be lifted by F^4 terms for an arbitrary CY with at least 1 blow-up mode

- Stabilisation of flat directions similar to [Ciupke,Louis,Westphal] but $\mathcal{V}$ fixing is different
- In [Ciupke,Louis,Westphal] $\mathcal{V}$ fixed by F^2 against F^4 α' terms ⇒ EFT under control? $m_{3/2} \backsim M_{KK}$
- Here $\mathcal{V}$ fixed by F^2 α' terms against non-perturbative effects and $F^4 << F^2$ ⇒ control EFT
- To clearly see that flat moduli are fixed by F^4 terms trade t_i for $(t_\alpha, \mathcal{V})$ $\alpha = 1, \ldots, N_{large} - 1$

$$\frac{\partial V}{\partial t_\alpha} = \frac{\partial V_{F^4}}{\partial t_\alpha} - \frac{\tau_\alpha}{\tau_*}\frac{\partial V_{F^4}}{\partial t_*} = \frac{c^2\hat{\lambda}\,W_0^4}{\mathcal{V}^4}\left(\Pi_*\frac{\tau_\alpha}{\tau_*} - \Pi_\alpha\right) = 0 \qquad (✉)$$

and

$$\frac{\partial V}{\partial \mathcal{V}} = \frac{\partial \hat{V}}{\partial \mathcal{V}} + \frac{1}{\tau_*}\frac{\partial V_{F^4}}{\partial t_*} = \frac{\partial \hat{V}}{\partial \mathcal{V}} + \frac{c^2\hat{\lambda}\,W_0^4}{\mathcal{V}^4\tau_*}\left(\frac{\Pi_k t_k}{\mathcal{V}}\,4\tau_* - \Pi_*\right) = 0 \qquad (✉✉)$$

- Solution to $(*)$ is $\tau_\alpha = \frac{\Pi_\alpha}{\Pi_*}\tau_* = \frac{\Pi_\alpha}{\Pi_*}h\mathcal{V}^{2/3}$ showing that flat moduli are fixed by F^4 terms
- $\mathcal{V}$ fixed by $(**)$ which can be rewritten as $\frac{\partial \hat{V}}{\partial \mathcal{V}} = -\frac{11c^2\hat{\lambda}\,W_0^4\Pi_*}{h\,\mathcal{V}^{14/3}}$
- Without non-perturbative effects, $\hat{V}$ has just a maximum since

$$\frac{\partial \hat{V}}{\partial \mathcal{V}} = -\frac{9cW_0^2}{2\mathcal{V}^4}\frac{\hat{\xi}}{2} - \frac{\alpha\,\kappa}{\mathcal{V}^{\alpha+1}} = 0 \qquad \frac{\partial^2 \hat{V}}{\partial \mathcal{V}^2} = \frac{18cW_0^2}{\mathcal{V}^5}\frac{\hat{\xi}}{2} + \frac{\alpha(\alpha+1)\,\kappa}{\mathcal{V}^{\alpha+2}} = -\frac{\alpha\,\kappa}{\mathcal{V}^{\alpha+2}}(3-\alpha) < 0$$

⇒ to find a minimum need to include F^4 terms and $\xi < 0$ [Ciupke,Louis,Westphal]

String loops

- String loop corrections to K for arbitrary CY [Berg,Haack,Kors]

$$K_{g_s}^{\rm KK} = g_s \sum_i \frac{C_i\, t_i^{\perp}}{\mathcal{V}} \qquad\qquad K_{g_s}^{\rm W} = \sum_i \frac{D_i}{\mathcal{V}\, t_i^{\cap}}$$

- Leading 1-loop winding correction to V [MC,Conlon,Quevedo]

$$V_{g_s}^{\rm W} = -2\left(\frac{g_s}{8\pi}\right)\frac{W_0^2}{\mathcal{V}^2} K_{g_s}^{\rm W}$$

- Extended no-scale: leading 1-loop KK correction vanishes (match Coleman-Weinberg potential)
- First non-vanishing contribution by expanding $K_{g_s}^{KK}$ to second order [MC,Conlon,Quevedo]

$$V_{g_s}^{\rm KK} = g_s^2\left(\frac{g_s}{8\pi}\right)\frac{W_0^2}{\mathcal{V}^2}\sum_{ij} C_i C_j K_{ij}$$ effectively of 2-loop order

$\Rightarrow$ need to include 2-loop effects to linear order in $K_{g_s}^{KK}$ which are poorly understood

- In isotropic limit $K_{ij} \backsim \mathcal{V}^{-4/3}$ string loops scale as

$$V_{g_s}^{\rm KK} \sim g_s^3 \frac{W_0^2}{\mathcal{V}^{10/3}} \ll V_{g_s}^{\rm W} \sim g_s \frac{W_0^2}{\mathcal{V}^{10/3}} \qquad g_s \ll 1$$

- Higher derivative terms behave as $V_{F^4} \sim g_s^{1/2}\frac{W_0^4}{\mathcal{V}^{11/3}} \sim g_s^{-1/2}\frac{W_0^2}{\mathcal{V}^{1/3}} V_{g_s}^{\rm W}$

$\Rightarrow \alpha' F^4$ terms dominate over loops if $\mathcal{V} \ll g_s^{-3/2} W_0^6$

String loops might also be absent by construction due to the brane setup

Inflation with Kahler moduli

- 3 conditions to trust inflation:
  i) Inflaton is a pseudo Nambu-Goldstone boson
  ii) Get a flat potential (over trans-Planckian distance for large r)
  iii) Make all other fields heavy and trust EFT

- Kahler moduli: non-compact shift symmetry from no-scale [Burgess,MC,Williams,Quevedo]

$$\Phi \to e^{\alpha}\Phi \qquad \Phi = \varrho e^{i\vartheta} \qquad \varrho \to e^{\alpha}\varrho$$

- Canonical normalisation: $\varrho = e^{\phi/f} \quad \Rightarrow \quad \phi \to \phi + \alpha f$ non-periodic
- EFT under control when $\varrho \gg 1 \quad \Leftrightarrow \quad \phi \gg f \quad \Leftrightarrow \quad \phi \gg M_p$ for $f \backsim M_p$
- $N_{flat} = h^{1,1} - N_{small} - 1$ flat directions naturally lighter than other moduli and H
- Breaking of non-compact shift symmetry: $V_0\, e^{\pm\,\phi/f} \quad \Rightarrow \quad V = V_0\left(1 - e^{-\phi/f} + \delta\, e^{+\,\phi/f}\right) \quad \delta \ll 1$
- General implications for plateau [Burgess,MC,de Alwis,Quevedo]

$$\epsilon \simeq \frac{1}{2}\left(\frac{f}{M_p}\right)^2 \eta^2 \qquad \eta \simeq -\left(\frac{M_p}{f}\right)^2 e^{-\frac{\phi}{f}} < 0 \quad \Rightarrow \quad \epsilon \ll |\eta| \ll 1$$

$$\boxed{r \simeq 2\left(\frac{f}{M_p}\right)^2 (n_s - 1)^2} \quad \Rightarrow \quad n_s \simeq 0.97 \qquad r \simeq 0.002\left(\frac{f}{M_p}\right)^2$$

1) Fibre Inflation: KK +winding loops [MC, Burgess,Quevedo] $\quad f_{FI} = \sqrt{3}M_p \quad \Rightarrow \quad r \simeq 0.006$
2) F^4 + KK loops [Broy,Ciupke,Pedro,Westphal] $\quad f = f_{FI}$ or $f = f_{FI}/2 \quad \Rightarrow \quad r \lesssim 0.006$
3) Poly-instantons [MC,Pedro,Tasinato] $\quad f \simeq M_p/ln\mathcal{V} \quad \Rightarrow \quad r \simeq 10^{-5}$
4) Instantons for blow-ups [Conlon,Quevedo] $\quad f \simeq M_p/\sqrt{\mathcal{V}} \quad \Rightarrow \quad r \simeq 10^{-10}$

α' Inflation

- $K3$ or T^4-fibration of size τ_1 over a $\mathbb{P}^1$ base of volume t_1 plus an exceptional divisor τ_s

$$\mathcal{V} = t_1\tau_1 - \tau_s^{3/2}$$

- Leading 1-loop winding contribution (neglecting subleading KK loops)

$$V_{g_s} = -\left(\frac{g_s}{8\pi}\right)\frac{BW_0^2}{\mathcal{V}^3\sqrt{\tau_1}}$$

- Higher derivative terms

$$V_{F^4} = \left(\frac{g_s}{8\pi}\right)^2 \frac{|\lambda|W_0^4}{g_s^{3/2}\mathcal{V}^4}\left(\Pi_1\frac{\mathcal{V}}{\tau_1} + \Pi_2\sqrt{\tau_1}\right)$$

- Total potential

$$V = V_{g_s} + V_{F^4} = \left(\frac{g_s}{8\pi}\right)\frac{W_0^2}{\mathcal{V}^3}\left[\frac{C_1}{\tau_1} - \frac{B}{\sqrt{\tau_1}} + C_2\frac{\sqrt{\tau_1}}{\mathcal{V}}\right]$$

where

$$C_1 = \left(\frac{g_s}{8\pi}\right)\frac{|\lambda|W_0^2\Pi_1}{g_s^{3/2}} > 0 \qquad C_2 = \left(\frac{g_s}{8\pi}\right)\frac{|\lambda|W_0^2\Pi_2}{g_s^{3/2}} > 0$$

- For $B > 0$, minimum at $\langle\tau_1\rangle = (4C_1/B)^2$
- Canonically normalised inflaton ϕ shifted from the minimum: $\phi = \langle\phi\rangle + \hat{\phi}$

$$\tau_1 = e^{\kappa\phi} \quad \Rightarrow \quad \tau_1 = \langle\tau_1\rangle\, e^{\kappa\hat{\phi}} \quad \text{for} \quad \kappa = \frac{2}{\sqrt{3}}$$

⇒ Inflationary potential becomes $V = V_0\left(1 - R + e^{-\kappa\hat{\phi}} - 2\,e^{-\kappa\hat{\phi}/2} + R\,e^{\kappa\hat{\phi}/2}\right)$

$$V_0 \equiv \left(\frac{g_s}{8\pi}\right)\frac{W_0^2}{\mathcal{V}^3}\frac{B^2}{4C_1} \qquad R \equiv \frac{8C_2C_1^2}{B^3\mathcal{V}} = \frac{\Pi_2}{\Pi_1}\frac{\langle\tau_1\rangle^{3/2}}{\mathcal{V}} \ll 1 \qquad \text{for} \quad \Pi_2 \ll \Pi_1 \quad \text{and} \quad \langle\tau_1\rangle \ll \mathcal{V}^{2/3}$$

Cosmological observables

- Slow-roll parameters

$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 = \frac{\left(2e^{-\frac{\hat{\phi}}{\sqrt{3}}} - 2e^{-\frac{2\hat{\phi}}{\sqrt{3}}} + Re^{\frac{\hat{\phi}}{\sqrt{3}}}\right)^2}{6\left(1 - R + e^{-\frac{2\hat{\phi}}{\sqrt{3}}} - 2e^{-\frac{\hat{\phi}}{\sqrt{3}}} + Re^{\frac{\hat{\phi}}{\sqrt{3}}}\right)^2}$$

$$\eta = \frac{V''}{V} = \frac{4e^{-\frac{2\hat{\phi}}{\sqrt{3}}} - 2e^{-\frac{\hat{\phi}}{\sqrt{3}}} + Re^{\frac{\hat{\phi}}{\sqrt{3}}}}{3\left(1 - R + e^{-\frac{2\hat{\phi}}{\sqrt{3}}} - 2e^{-\frac{\hat{\phi}}{\sqrt{3}}} + Re^{\frac{\hat{\phi}}{\sqrt{3}}}\right)}$$

- η vanishes at two inflection points

$$\hat{\phi}_{\rm ip}^{(1)} \simeq \sqrt{3}\ln 2 \simeq 1.2 \qquad \hat{\phi}_{\rm ip}^{(2)} = \tfrac{1}{2}\hat{\phi}_{\rm ip}^{(1)} - \tfrac{\sqrt{3}}{2}\ln R \gg \hat{\phi}_{\rm ip}^{(1)}$$

- At first inflection point ϵ becomes $\epsilon_{ip}^{(1)} \simeq 2/3$ ⇒ inflation ends close to $\hat{\phi}_{ip}^{(1)}$
- $\epsilon \simeq 1$ around $\hat{\phi}_{end} \simeq 1$ independently of microscopic parameters
- Plateau to the right of $\hat{\phi}_{ip}^{(1)}$ and inflation for $\hat{\phi}_{ip}^{(1)} < \hat{\phi} < \hat{\phi}_{ip}^{(2)}$ ($n_s \gtrsim 1$ for $\hat{\phi} > \hat{\phi}_{ip}^{(2)}$)
- Number of efoldings

$$N_e = \int_1^{\hat{\phi}_*} \frac{1}{\sqrt{2\epsilon(\hat{\phi})}}\, d\hat{\phi}$$

- Amplitude of density perturbations

$$A_{\rm COBE} = \left(\frac{V^{3/2}}{V'}\right)^2\Bigg|_{\hat{\phi}_*} = 2.7 \cdot 10^{-7}$$

- Spectral index and tensor-to-scalar-ratio $\quad n_s = 1 + 2\eta_* - 6\epsilon_* \qquad r = 16\epsilon_*$

Cosmological observables

- At large $\hat{\phi}$ close to horizon exit

$$\epsilon \simeq \frac{1}{6}\left(2e^{-\frac{\hat{\phi}}{\sqrt{3}}} + R\, e^{\frac{\hat{\phi}}{\sqrt{3}}}\right)^2 \qquad \eta \simeq -\frac{1}{3}\left(2e^{-\frac{\hat{\phi}}{\sqrt{3}}} - R\, e^{\frac{\hat{\phi}}{\sqrt{3}}}\right)$$

$$\Rightarrow \qquad \epsilon \simeq \frac{3}{2}\eta^2 + \frac{4}{3}R$$

- For $\eta \ll 1$ this implies

$$n_s \simeq 1 + 2\eta - 8R \qquad r \simeq 6\,(n_s - 1)^2 + \frac{64}{3}R$$

- For $R \to 0$ reobtain predictions of Fibre Inflation: $n_s \simeq 0.97$ and $r \simeq 0.006$
- For $R = b\eta^2$ the prediction for r changes (but not the one for n_s)

$$n_s \simeq 1 + 2\eta \qquad r \simeq \left(6 + \frac{16}{3}\,b\right)(n_s - 1)^2$$

⇒ can get larger tensors with the same spectral index

- Single field approximation requires

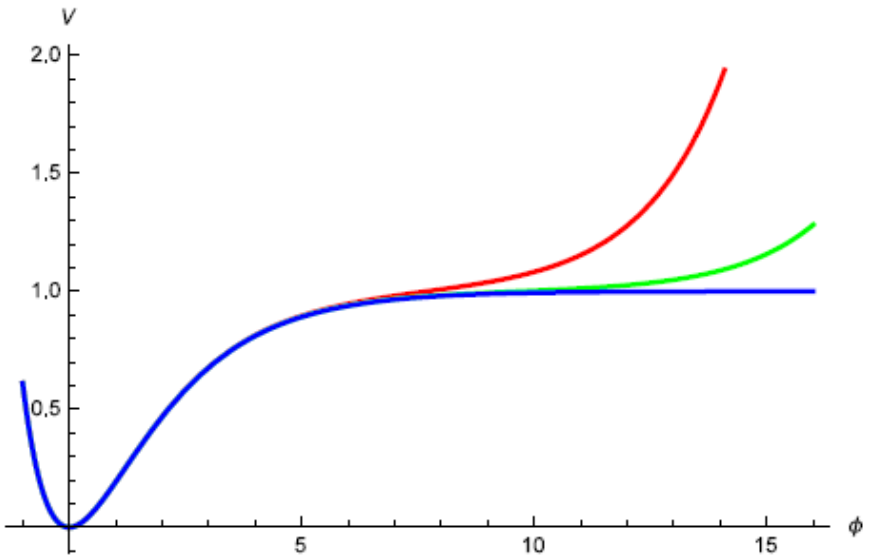
$$\mathcal{R} \equiv \left.\frac{H}{m_{\mathcal{V}}^2}\right|_{\hat{\phi}} \simeq \frac{V_0}{V_{\alpha'}} = \frac{4C_1 g_s^{3/2}}{3\xi\langle\tau_1\rangle} \ll 1$$

- Can trust expansion of leading α' term if

$$\epsilon_\xi \equiv \frac{\xi}{2g_s^{3/2}\mathcal{V}} \ll 1$$

Predictions

- Shape of the potential: $R = 2.74 \cdot 10^{-4}$ (red), $R = 2.74 \cdot 10^{-5}$ (green), $R = 0$ (blue)



- Illustrative parameter choices

1) $\Pi_2 = 0 \quad \Rightarrow \quad C_2 = R = 0 \quad \Rightarrow$ Fibre Inflation-like case

$g_s = 0.1 \quad W_0 = 10 \quad \xi = 1 \quad B = 5.248 \quad \Pi_1 = 100 \quad \lambda = 0.01 \quad \mathcal{V} = 10^3$

$\langle \tau_1 \rangle = 23 \quad \langle \tau_2 \rangle = 417 \quad N_e = 56.5 \quad \hat{\phi}_* = 6.5 \quad \boxed{n_s = 0.966 \quad r = 0.006}$

$\mathcal{R} = 0.022 \quad$ and $\quad \epsilon_\xi = 0.016$

2) $g_s = 0.1 \quad W_0 = 10 \quad \xi = 1 \quad B = 3.4 \quad \Pi_1 = 26 \quad \Pi_2 = 1 \quad \lambda = 0.01 \quad \mathcal{V} = 10^3 \quad \Rightarrow \quad R = 2.74 \cdot 10^{-4}$

$\langle \tau_1 \rangle = 3.7 \quad \langle \tau_2 \rangle = 1039 \quad N_e = 50 \quad \hat{\phi}_* = 6.425 \quad \boxed{n_s = 0.972 \quad r = 0.01}$

$\mathcal{R} = 0.037 \quad$ and $\quad \epsilon_\xi = 0.016$

Energy scales

- High inflationary scale

$$M_{\rm inf}^4 = V(\hat{\phi}) = \frac{r}{0.12}\left(1.94\cdot 10^{16}\,{\rm GeV}\right)^4 \simeq \left(1\cdot 10^{16}\,{\rm GeV}\right)^4 \qquad \text{for} \quad r\simeq 0.01$$

- Needs to be below KK scale
- For $\ell_s = 2\pi\sqrt{\alpha'}$ dimensional reduction gives

$$M_s = 2\pi\ell_s^{-1} = \frac{g_s^{1/4}\sqrt{\pi}}{\sqrt{\mathcal{V}}}\,M_p \qquad M_{\rm KK} = \frac{M_s}{\mathcal{V}_s^{1/6}} = \sqrt{\pi}\,\frac{M_p}{\mathcal{V}^{2/3}} \qquad \mathcal{V}_s = g_s^{-3/2}\mathcal{V}$$

⇒ we get the bounds

$$M_{\rm inf}^4 \ll M_{\rm KK}^4 \ll M_s^4 \qquad \Leftrightarrow \qquad g_s^{-3/2} \ll \mathcal{V} \ll 1390\, r^{-3/8}$$

- For $g_s = 0.1$ we find $\mathcal{V} \gg 30$

1) For $\mathcal{V}\simeq 10^3$ ⇒ $r \ll 2.4$ ⇒ the prediction $r\simeq 0.01$ can be trusted

2) For $\mathcal{V}\simeq 10^4$ ⇒ $r \ll 0.005$ ⇒ the prediction $r\simeq 0.01$ cannot be trusted

- For $R = 2.74\cdot 10^{-4}$ we have

$$M_{\rm KK} \simeq 4.35\cdot 10^{16}\ {\rm GeV} \qquad \Rightarrow \qquad (M_{\rm inf}/M_{\rm KK})^4 \simeq 0.0034$$

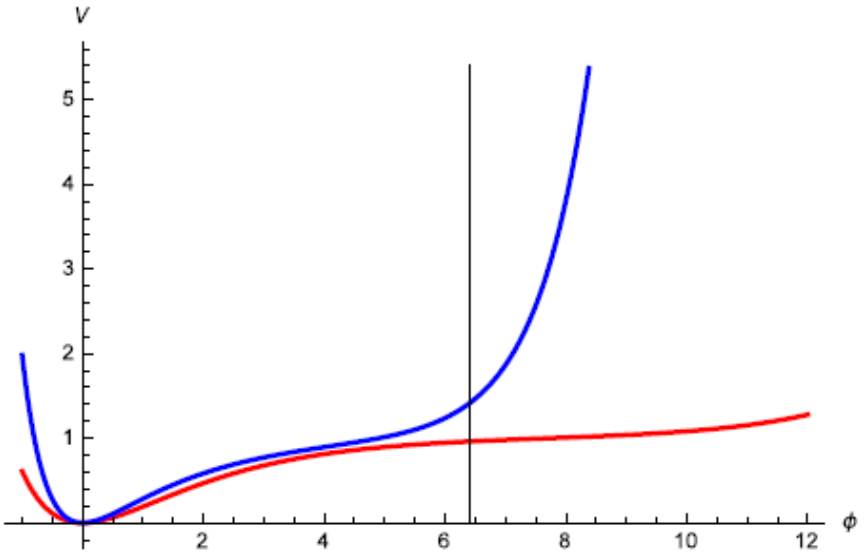
This general analysis shows that $r\simeq 0.01$ is probably the largest possible to trust the EFT!

Comparison with Fibre Inflation

- Potential for α' Inflation (red) and Fibre Inflation (blue)

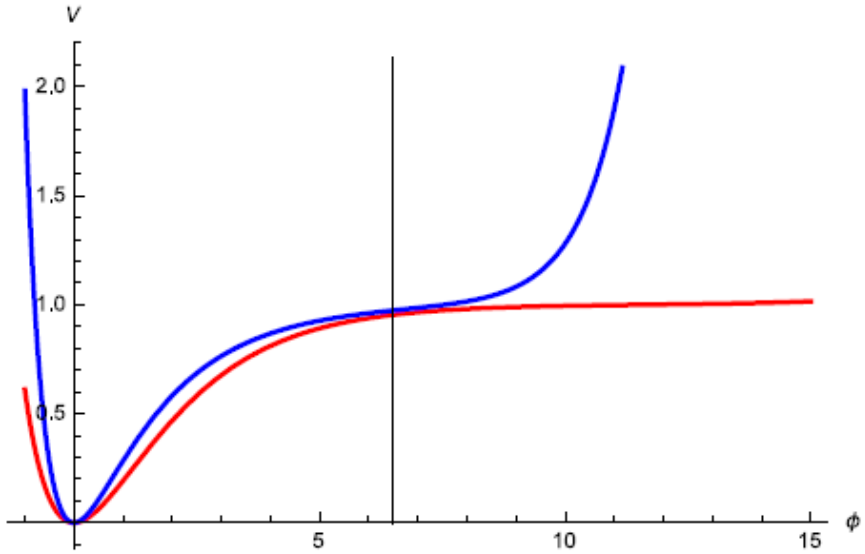
$$V = V_0\left(1 - R + e^{-\kappa\hat{\phi}} - 2\,e^{-\kappa\hat{\phi}/2} + R\,e^{\kappa\hat{\phi}/2}\right) \qquad V_{\rm FI} = V_0\left(1 + \frac{1}{3}e^{-2\kappa\hat{\phi}} - \frac{4}{3}\,e^{-\kappa\hat{\phi}/2} + R\,e^{\kappa\hat{\phi}}\right) \qquad R \ll 1$$

- Milder steepening for α' Inflation $\Rightarrow$ longer plateau



$R = 2.74 \cdot 10^{-4}$

potential of Fibre Inflation is too steep



$R = 2.74 \cdot 10^{-5}$

Similar predictions

- In α' Inflation horizon exit is naturally close to the second inflection point $\Rightarrow$ larger r
- In Fibre Inflation horizon exit is in the plateau otherwise n_s is too blue $\Rightarrow$ smaller r

Conclusions

- Leading LVS: α' and non-perturbative effects fix volume and all blow-ups
- Remaining flat directions lifted by higher derivative α' effects for arbitrary CY
- Simple fibred cases with 1 flat direction: inflation from F^4 terms and winding loops
- Natural parameters give $n_s = 0.97$ and $r=0.01$
- Flatness protected by approximate non-compact shift symmetry
- EFT marginally under control