Type IIB inflation models

Veronica Guidetti

Università di Bologna, INFN

TFI 2019

[1709.01518], [1801.05434], [1807.03818], [1903.01497] in collaboration with: M. Cicoli, F. G. Pedro, G. P. Vacca, D. Ciupke, V. Diaz, F. Muia and P. Shukla

Aim of the BIG Project

- Embed Fibre Inflation into consistent Calabi Yau orientifolds with D-branes and fluxes compatible with tadpole cancellations
- Presence of a chiral visible sector with GUT or MSSM-like gauge group whose degrees of freedom can be excited at reheating after the end of inflation
- Get full moduli stabilisation
- Match the correct amplitude of density perturbations
- Stable inflationary dynamics: inflation is not spoiled by orthogonal directions in field space
- Effective field theory under control: energy scale hierarchies, dynamics inside Kähler cone

Toric Data: [Polytope ID # 1206 Altman et al. '15] [Blumenhagen et al. '10 , '11]

- $h_{1,1} = 4$, Volume form $\mathcal{V} = \alpha_1\sqrt{\tau_1\tau_2\tau_3} - \alpha_2\tau_s^{3/2}$ [Cicoli,Muia,Shukla]

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
4	0	0	0	1	1	0	0	2
4	0	0	1	0	0	1	0	2
4	0	1	0	0	0	0	1	2
8	1	0	0	1	0	1	1	4
	dP_7	NdP_{11}	NdP_{11}	K3	NdP_{11}	K3	K3	SD

- SR1 $= \{x_1x_4,\, x_1x_6,\, x_1x_7,\, x_2x_7,\, x_3x_6,\, x_4x_5x_8,\, x_2x_3x_5x_8\}$
- Intersection polynomial : $I_3 = 2D_4D_6D_7 - 2D_1^3$
- Volume form: $\mathcal{V} = 2t_4t_6t_7 + \frac{t_1^3}{3} = \frac{\sqrt{\tau_4\tau_6\tau_7}}{\sqrt{2}} - \frac{\tau_1^{3/2}}{3}$
- Kähler cone: $t_1 < 0\,;\quad t_1 + t_7 > 0\,;\quad t_1 + t_4 > 0\,;\quad t_1 + t_6 > 0$
- Second Chern class: $c_2(X) = D_4D_5 + 4D_5^2 + 12D_5D_6 + 12D_5D_7 + 12D_6D_7$
- Topological quantities: $\Pi_i = \int_X c_2 \wedge \hat{D}_i$

Intersection curves and volumes:

	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8
D_1	$\mathcal{C}_3$	$\mathbb{T}^2$	$\mathbb{T}^2$	$\emptyset$	$\mathbb{T}^2$	$\emptyset$	$\emptyset$	$\mathcal{C}_3$
D_2	$\mathbb{T}^2$	$\mathbb{P}^1 \sqcup \mathbb{P}^1$	$\mathbb{P}^1 \sqcup \mathbb{P}^1$	$\mathbb{T}^2$	$\mathbb{P}^1 \sqcup \mathbb{P}^1$	$\mathbb{T}^2$	$\emptyset$	$\mathcal{C}_3$
D_3	$\mathbb{T}^2$	$\mathbb{P}^1 \sqcup \mathbb{P}^1$	$\mathbb{P}^1 \sqcup \mathbb{P}^1$	$\mathbb{T}^2$	$\mathbb{P}^1 \sqcup \mathbb{P}^1$	$\emptyset$	$\mathbb{T}^2$	$\mathcal{C}_3$
D_4	$\emptyset$	$\mathbb{T}^2$	$\mathbb{T}^2$	$\emptyset$	$\emptyset$	$\mathbb{T}^2$	$\mathbb{T}^2$	$\mathcal{C}_9$
D_5	$\mathbb{T}^2$	$\mathbb{P}^1 \sqcup \mathbb{P}^1$	$\mathbb{P}^1 \sqcup \mathbb{P}^1$	$\emptyset$	$\mathbb{P}^1 \sqcup \mathbb{P}^1$	$\mathbb{T}^2$	$\mathbb{T}^2$	$\mathcal{C}_3$
D_6	$\emptyset$	$\mathbb{T}^2$	$\emptyset$	$\mathbb{T}^2$	$\mathbb{T}^2$	$\emptyset$	$\mathbb{T}^2$	$\mathcal{C}_9$
D_7	$\emptyset$	$\emptyset$	$\mathbb{T}^2$	$\mathbb{T}^2$	$\mathbb{T}^2$	$\mathbb{T}^2$	$\emptyset$	$\mathcal{C}_9$
D_8	$\mathcal{C}_3$	$\mathcal{C}_3$	$\mathcal{C}_3$	$\mathcal{C}_9$	$\mathcal{C}_3$	$\mathcal{C}_9$	$\mathcal{C}_9$	$\mathcal{C}_{81}$

	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8
D_1	$2\,t_1$	$-2\,t_1$	$-2\,t_1$	0	$-2\,t_1$	0	0	$-4\,t_1$
D_2	$-2\,t_1$	$2\,t_1$	$2(t_1+t_4)$	$2\,t_6$	$2(t_1+t_6)$	$2\,t_4$	0	$4(t_1+t_4+t_6)$
D_3	$-2\,t_1$	$2(t_1+t_4)$	$2\,t_1$	$2\,t_7$	$2(t_1+t_7)$	0	$2\,t_4$	$4(t_1+t_4+t_7)$
D_4	0	$2\,t_6$	$2\,t_7$	0	0	$2\,t_7$	$2\,t_6$	$4(t_6+t_7)$
D_5	$-2\,t_1$	$2(t_1+t_6)$	$4(t_1+t_7)$	0	$2\,t_1$	$2\,t_7$	$2\,t_6$	$4(t_1+t_6+t_7)$
D_6	0	$2\,t_4$	0	$2\,t_7$	$2\,t_7$	0	$2\,t_4$	$4(t_4+t_7)$
D_7	0	0	$2\,t_4$	$2\,t_6$	$2\,t_6$	$2\,t_4$	0	$4(t_4+t_6)$
D_8	$-4\,t_1$	$4(t_1+t_4+t_6)$	$4(t_1+t_4+t_7)$	$4(t_6+t_7)$	$4(t_1+t_6+t_7)$	$4(t_4+t_7)$	$4(t_4+t_6)$	$8(t_1+2(t_4+t_6+t_7))$

Orientifold involution:

σ	O7	O3	N_{O3}	$\chi(O7)$	$\chi_{\rm eff}$
$x_1 \to -x_1$	D_1	$\{D_2D_3D_4, D_2D_4D_6, D_2D_5D_6, D_3D_4D_7, D_3D_5D_7, D_4D_6D_7, D_5D_6D_7\}$	14	10	-184
$x_2 \to -x_2$	$D_2 \sqcup D_7$	$D_1D_3D_5$	2	38	-192
$x_2 \to -x_3$	$D_3 \sqcup D_6$	$D_1D_2D_5$	2	38	-192
$x_4 \to -x_4$	$D_4 \sqcup D_5$	$D_1D_2D_3$	2	38	-192
$x_5 \to -x_5$	$D_4 \sqcup D_5$	$D_1D_2D_3$	2	38	-192
$x_6 \to -x_6$	$D_3 \sqcup D_6$	$D_1D_2D_5$	2	38	-192
$x_7 \to -x_7$	$D_2 \sqcup D_7$	$D_1D_3D_5$	2	38	-192
$x_8 \to -x_8$	D_8	$\emptyset$	0	208	-28

- Focus on: $x_8 \to -x_8 \implies$ no $O3$-plane, 1 $O7$-plane in D_8
- $\chi_{eff} = \chi(X) + 2\int_X [O7] \wedge [O7] \wedge [O7]$ [Minasian, Pugh, Savelli]

Brane setup:

- Focus on brane setup which gives rise to **winding corrections**
- Stacks of $D7$**-branes** around D_4, D_6 and $D_2 = D_7 - D_1$
- $D7$ **tadpole cancellation**: $8[O7] \equiv 8([D_8]) = 16([D_2] + [D_4] + [D_6])$
- $D3$ **tadpole cancellation**:

$$N_{D_3} + \frac{N_{flux}}{2} + N_{gauge} = \frac{N_{O3}}{4} + \frac{\chi(O7)}{12} + \sum_a \frac{N_a(\chi(D_a) + \chi(D_a^{'})}{48} = 38$$

$\rightarrow$ Room for gauge and background three-form fluxes

- $D3$**-brane instanton** on D_1
- **Worldvolume Gauge Fluxes**: $\mathcal{F}_i = \sum_{j=1}^{h_{1,1}} f_{i,j} \hat{D}_j - \frac{1}{2} c_1(D_i) - \iota^*_{D_j} B \qquad f_{1j} \in \mathbb{Z}$

$$B = \frac{1}{2}\hat{D}_1 + \frac{1}{2}\hat{D}_2 \qquad \Longrightarrow \qquad \mathcal{F}_1 = \mathcal{F}_4 = \mathcal{F}_6 = 0; \qquad \mathcal{F}_2 = \sum_{j=1}^{h_{1,1}} f_{2,j} \hat{D}_j \neq 0$$

Brane setup:

- $\mathcal{F}_2 \neq 0$

$$\left[\begin{array}{l} Sp(16) \to U(8) = SU(8) \times U(1) \\ q_{i2} = \int_X \hat{D}_i \wedge \hat{D}_2 \wedge \mathcal{F}_2; \qquad q_{12} = -2f_{21}; \quad q_{42} = 2f_{26}; \quad q_{62} = 2f_{24}; \quad q_{72} = 0 \\ Re(f_2) = \frac{4\pi}{g_2^2} = \tau_2 - Re(S)h(\mathcal{F}_2) \qquad h(\mathcal{F}_2) = \frac{1}{2}(f_{21}q_{12} + f_{24}q_{42} + f_{26}q_{62}) \\ \xi = \frac{1}{4\pi\mathcal{V}} \sum_{j=1}^{h_{1,1}} q_{j2}t_j = \frac{1}{4\pi\mathcal{V}}(q_{12}t_1 + q_{42}t_4 + q_{62}t_6) \end{array}\right.$$

- **No chiral intersection** between $D7$ on D_2 and the instanton on D_1: $q_{12} = 0$

Moduli stabilisation and Inflationary potential:

- D-term supersymmetric stabilisation (vanishing open string VEV): $\xi = 0; \qquad t_4 = \alpha\, t_6$
- Reduced moduli field space $\mathcal{V} = \frac{1}{\sqrt{2\alpha}}\sqrt{\tau_7}\tau_6 - \frac{1}{3}\tau_1^{3/2}$
- LVS stabilisation: $K = -2\ln\left(\mathcal{V} + \frac{\hat{\xi}}{2}\right); \qquad W = W_0 + A_1 e^{-a_1 T1}$

$$\langle\mathcal{V}\rangle = \frac{W_0}{4a_1 A_1}\sqrt{\langle\tau_1\rangle}\, e^{a_1\langle\tau_1\rangle} \qquad \langle\tau_1\rangle = \left(\frac{3\hat{\xi}}{2}\right)^{2/3}$$

- Winding 1-loop: $V_{g_s}^W = -2\kappa\frac{W_0^2}{\mathcal{V}^3}\sum_i \frac{C_i^W}{t_i^{\cap}}$ [Berg, Haack, Kors], [Berg, Haack, Pajer] [Cicoli, Conlon, Quevedo]
- HD $\alpha'^{\,3}F^4$: $V_{F^4} = -\kappa^2\frac{\lambda W_0^4}{g_s^{3/2}\mathcal{V}^4}\sum_{i=1}^{h_{1,1}}\Pi_i t_i; \quad \kappa = \frac{e^{K_{cs}}g_s}{8\pi}$ [Ciupke, Louis, Westphal]

$$V_{inf} = V_{g_s}^W + V_{F^4} = \kappa\,\frac{W_0^2}{\mathcal{V}^3}\left(\frac{A_1}{\tau_7} - \frac{A_2}{\sqrt{\tau_7}} + \frac{B_1\sqrt{\tau_7}}{\mathcal{V}} + \frac{B_2\,\tau_7}{\mathcal{V}}\right)$$

- Assume de Sitter uplifting term

Single-field inflation - Requirements:

- $Vol_S^{1/4} \gg \sqrt{\alpha'} \qquad \rightarrow \qquad \epsilon_{\tau_i} = \frac{1}{(2\pi)^4 g_s \tau_i} \ll 1$
- Dynamics inside KC: $\begin{cases} 2\alpha\langle\tau_1\rangle < \tau_7 < \frac{\mathcal{V}}{\sqrt{\langle\tau_1\rangle}} & \alpha \geq 1 \\ \frac{2}{\alpha}\langle\tau_1\rangle < \tau_7 < \frac{\mathcal{V}}{\sqrt{\langle\tau_1\rangle}} & \alpha \leq 1 \end{cases}$
- Number of e-folds: $N_e \simeq 57 + \frac{1}{4}\ln(r_* V_*) - \frac{1}{3}\ln\left(\frac{V_{end}}{T_{rh}}\right)$

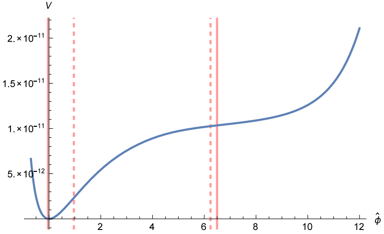
  $T_{rh} \simeq 0.1 m_\phi \sqrt{\frac{m_\phi}{M_P}}$ [Cicoli, Piovano]
- Amplitude of density perturbation matches COBE: $\frac{V_*^3}{V_*'^2} \simeq 2.6 \times 10^{-7}$
- Check α' expansion: $\frac{\hat{\xi}}{2\mathcal{V}} \ll 1$
- EFT under control: $m_{inf} < H < m_{3/2} < M_{KK}^i < M_s < M_P; \qquad M_{KK}^i = \frac{\sqrt{\pi} M_P}{\tau_i^{1/4}\sqrt{\mathcal{V}}}$
- Single field approximation: $\delta = \frac{H}{m_{\mathcal{V}}} \sim \sqrt{\frac{V_*}{3V_{\alpha'}}} \lesssim 1$

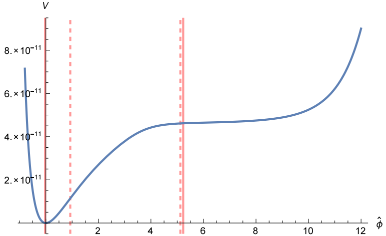
Single-field inflation - Parameters:

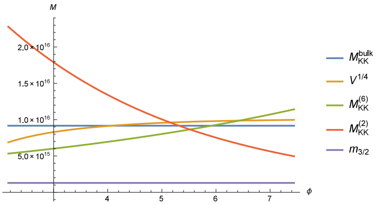
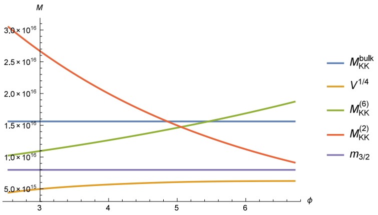
$$V = \kappa \frac{A_2 W_0^2}{\mathcal{V}^3 \sqrt{\langle \tau_7 \rangle}} \left(C_{dS} + c\, e^{-k\hat{\phi}} - e^{-\frac{k\hat{\phi}}{2}} + \mathcal{R}_1\, e^{\frac{k\hat{\phi}}{2}} + \mathcal{R}_2\, e^{k\hat{\phi}} \right)$$

[Grimm, Mayer, Weissenbacher]

Case 1: $\lvert\lambda\rvert = 10^{-3}, \quad \chi_{eff}(X)$	**Case 2:** $\lvert\lambda\rvert = 10^{-7}, \quad \chi(X)$
$\alpha = 1, \quad g_s = 0.114, \quad \mathcal{V} = 10^4, \quad W_0 = 80,$ $\langle\tau_1\rangle = 1.91, \quad \xi = 0.067$	$\alpha = 1, \quad g_s = 0.25, \quad \mathcal{V} = 4500, \quad W_0 = 150,$ $\langle\tau_1\rangle = 3.10, \quad \xi = 0.456$ ......





Case 1: $\lvert\lambda\rvert = 10^{-3}, \quad \chi_{eff}(X)$	**Case 2:** $\lvert\lambda\rvert = 10^{-7}, \quad \chi(X)$
	
$r \sim 10^{-3}, \quad n_s = 0.983, \quad \Delta N_{eff} = 0.39,$	$r \sim 0.0014, \quad n_s = 0.963, \quad \Delta N_{eff} = 0$
$N_{max} \simeq 60, \quad m_\phi \simeq 4 \cdot 10^{13}\, GeV,$	$N_{max} \simeq 58, \quad m_\phi \simeq 1.8 \cdot 10^{13}\, GeV,$
$T_{rh} \simeq 1.8 \cdot 10^{10}\, GeV, \quad N_e = 52, \quad \delta \simeq 1.6$	$T_{rh} \simeq 5.2 \cdot 10^{9}\, GeV, \quad N_e = 51, \quad \delta \simeq 0.05$

Explicit computation of swampland distance conjecture (similar coefficients for $M_{KK}^{(6)}$)

$$\frac{m_{3/2}}{M_{KK}^{(2)}} = \alpha_1 e^{\alpha_2 \phi} \qquad \alpha_2 = \frac{1}{2\sqrt{3}}; \qquad \alpha_1 = 10^{-2 \div -1}$$

$$\Delta\phi = 4 \div 6 \qquad \textbf{allowed!}$$

Multi-field inflation - Equations of motion:

- Kintetic Lagrangian:

$$\mathcal{L}_{kin} = \frac{1}{2}\left(-\frac{\mathcal{V}'^{\,2}}{\mathcal{V}^2} + \frac{\mathcal{V}'\tau_7'}{\mathcal{V}\tau_7} - \frac{3\tau_7'^{\,2}}{4\tau_7^2} + \frac{\sqrt{\tau_1}\tau_7'\tau_1'}{2\mathcal{V}\tau_7} - \frac{\tau_1'^{\,2}}{4\mathcal{V}\sqrt{\tau_1}}\right)$$

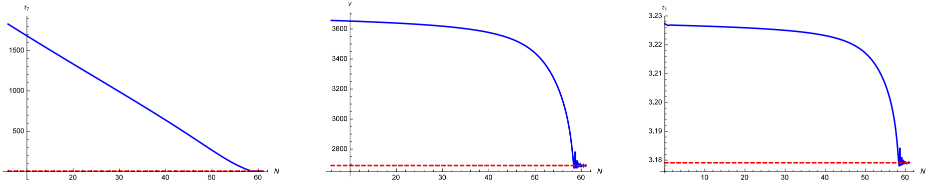
- Potential:

$$\begin{aligned} V = \quad & \kappa\left[32A_s^2\pi^2\,\frac{\sqrt{\tau_1}}{\mathcal{V}}\,e^{-4\pi\tau_1} - 8\pi A_s\,\frac{W_0\tau_1}{\mathcal{V}^2}\,e^{-2\pi\tau_1} + \frac{3\xi}{4g_s^{3/2}}\,\frac{W_0^2}{\mathcal{V}^3} + \right. \\ & \left. + \frac{W_0^2}{\mathcal{V}^3}\,\left(\frac{A_1}{\tau_7} - \frac{A_2}{\sqrt{\tau_7}} + \frac{B_1\sqrt{\tau_7}}{\mathcal{V}} + \frac{B_2\,\tau_7}{\mathcal{V}}\right) + \frac{\delta_{up}}{\mathcal{V}^{4/3}}\right] \end{aligned}$$

- EOM:

$$\begin{cases} \phi''^{\,i} + \Gamma^i_{jk}\phi'^{\,j}\phi'^{\,k} + (3+\mathcal{L}_{kin})\left[g^{ij}\,\frac{\partial_j V}{V} + \phi'^{\,i}\right] = 0 \\ H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{V}{3+\mathcal{L}_{kin}} \end{cases}$$

Multi-field inflation - Parameters and Results:



Case 1: $\lvert\lambda\rvert = 10^{-3}, \quad \chi_{eff}(X)$	**Case 2:** $\lvert\lambda\rvert = 10^{-6}, \quad \chi(X)$
Min: $\mathcal{V} \simeq 3221, \quad \tau_7 \simeq 6.4, \quad \tau_1 = 3.18$	Min: $\mathcal{V} \simeq 2690, \quad \tau_7 \simeq 6.5, \quad \tau_1 = 3.18$
IC: $\mathcal{V} \simeq 4436, \quad \tau_7 \simeq 2456, \quad \tau_1 = 3.23$	IC: $\mathcal{V} \simeq 3670, \quad \tau_7 \simeq 2036, \quad \tau_1 = 3.22$
$n_s \simeq 0.967, \quad r \simeq 0.002, \quad N_{max} \simeq 58$ $\sqrt{P} \simeq 2 \cdot 10^{-7}$ vs $\sqrt{P_{\text{COBE}}} \simeq 2 \cdot 10^{-5}$	$n_s \simeq 0.97, \quad r \simeq 0.002, \quad N_{max} \simeq 69$ $\sqrt{P} \simeq 1 \cdot 10^{-5}$ vs $\sqrt{P_{\text{COBE}}} \simeq 2 \cdot 10^{-5}$

Effective field theory still under control

What have we learned

- First explicit realisation of FI in concrete type IIB CY
- Inflationary parameters in good accordance with Planck results
- Observable tensor modes
- Kähler cone conditions strongly constrain the dynamics $\rightarrow$ hard to match COBE

Further investigations were needed:

- Compute χ_{eff} and λ in full detail
- Determination of the actual CY Kähler cone
- Find a mechanism to realise dS vacuum
- Generate density perturbations through curvaton mechanism?

Geometrical bound on inflaton range [1801.05434]

Motivation:

- Previous work: we used approximated KC conditions
- Interested in LVS scenario reduced moduli space: $\mathcal{M}_r$
- Want to have a better estimate of $Vol(\mathcal{M}_r)$

What has been done:

- Study of Kähler moduli space in type IIB CY orientifold compactifications with BG fluxes
- Classification of LVS vacua using KS list of CY 3-folds with $h_{1,1} = 2, 3, 4$
- $Vol(\mathcal{M}_r)$ computed for all CY in the list having $h_{1,1} = 3$
- Explicit bound on $Vol(\mathcal{M}_r)$ for $h_{1,1} = 3$, conjecture in case of $dim(\mathcal{M}_r) > 1$

Requirements for LVS stabilisation

4D SUGRA from type IIB orentifold compactification + D3/D7- branes + O3/O7 planes + BG fluxes

$$K = -2\ln\left(\mathcal{V} + \frac{\hat{\xi}}{2}\right); \qquad \hat{\xi} = -\frac{\chi(X)\zeta(3)}{2(2\pi)^3 g_s^{3/2}}$$

$$W = W_0 + \sum_i A_i e^{-a_1 T_i}; \qquad T_i = \tau_i + i\int_{D_i} C_4$$

Knowing that $J = t^i \hat{D}_i;$ $\mathcal{V} = \frac{1}{3!}\int_X J\wedge J\wedge J;$ $\tau_i = \frac{1}{2!}\int_X \hat{D}_i \wedge J \wedge J$

F-term scalar potential

$$V_F = \sum_{i,j} a_i a_j A_i A_j K^{i\bar{j}} \frac{e^{-(a_i\tau_i + a_j\tau_j)}}{\mathcal{V}} - \sum_i 4A_i W_0 a_i \tau_i \frac{e^{-a_i\tau_i}}{\mathcal{V}^2} + \frac{3\hat{\xi}W_0^2}{4\mathcal{V}^3}$$

If the following conditions are satisfied:

- $\chi(X) < 0$
- D_s with n.p. effects such that $\mathcal{V}(\tau_s \to 0) > 0$
- $K^{s\bar{s}} = \lambda\sqrt{\tau_s}\mathcal{V}$

$$\mathcal{V}_0 \simeq \frac{W_0\sqrt{\tau_{i0}}}{4a_i A_i} e^{a_i \tau_{i0}}$$

$$\hat{\xi} \simeq \sum_i \lambda_i \tau_{i0}^{3/2}$$

Scan of LVS vacua for $h_{1,1} = 2, 3, 4$

$h^{1,1}$	$n_{\rm CY}$	$n_{\rm LVS}$	%	$n_{\rm ddP}=1$	$n_{\rm ddP}=2$	$n_{\rm ddP}=3$
2	39	22	56.4%	22	–	–
3	305	132	43.3%	93	39	–
4	1997	749	37.5%	464	261	24

Case $h_{1,1} = 3$: different geometries

- Strong Swiss Cheese (SSC) $\mathcal{V} = \alpha\tau_b^{3/2} - \beta_1\tau_{s1}^{3/2} - \beta_2\tau_{s2}^{3/2}$
- K3 fibration over P^1 base (K3f) $\mathcal{V} = \alpha\tau_b\sqrt{\tau_f} - \beta\tau_s^{3/2}$
- Structurless $\mathcal{V} = f_{3/2}(\tau_1, \tau_2) - \beta\tau_s^{3/2}$
- Strong Swiss Cheese like (SSC-like) $\mathcal{V} = \alpha\tau_b^{3/2} - \beta_1\tau_s^{3/2} - \beta_2(\gamma_1\tau_s + \gamma_2\tau_*)^{3/2}$

$h^{1,1}$	$n_{\rm CY}$	$n_{\rm LVS}$	SSC	K3 fibred	SSC-like	structureless
3	305	132	39	43	36	14

Estimate of $Vol(\mathcal{M}_r)$ for $h_{1,1} = 3$

M_A = intersecting all the Mori cones of the ambient varieties which are connected by "irrelevant" flop transformations

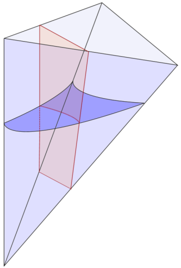
$M_\cap$ = intersecting all toric surfaces of the ambient varieties with CY surface

$$M_A \supseteq M_X \supseteq M_\cap$$

$$\mathcal{K}_A \subseteq \mathcal{K}_X \subseteq \mathcal{K}_\cap$$

Imposing hypersurfaces $\quad \mathcal{V}(\tau_i) = \mathcal{V}_0; \qquad \tau_s = \tau_0$

$$Vol(\mathcal{M}_{A,r}) \leq Vol(\mathcal{M}_r) \leq Vol(\mathcal{M}_{\cap,r})$$



Estimate of $Vol(\mathcal{M}_r)$ for $h_{1,1} = 3$

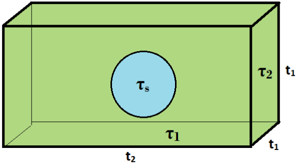
Analitical estimate taking into account various geometries for $h_{1,1} = 3$

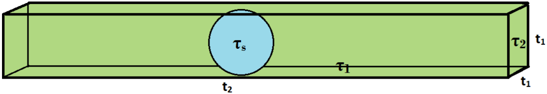
$$\frac{\Delta\phi}{M_P} \leq c \ln(\mathcal{V})$$

Conjecture for $h_{1,1} > 3$

$$Vol(\mathcal{M}_r) \leq \left[\ln\left(\frac{M_P}{\Lambda}\right)\right]^{dim(\mathcal{M}_r)}$$

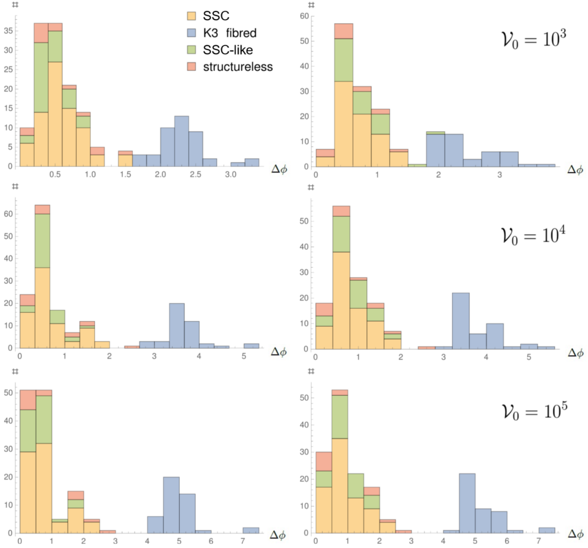
Λ = cut-off scale of EFT (KK scale of bulk or wrapped internal 4-cycle)





Numerical results for $h_{1,1} = 3$

Only CY geometries with K3 fibrations show transplanckian $Vol(\mathcal{M}_r)$



Summing up the results

- Finite volume of reduced moduli space (g_s and $\mathcal{V}_0$ dependence)
- Transplanckian inflaton range allowed only in presence of K3 fibration
- Boundary in agreement with swampland distance conjecture (despite different origin)

Open problems

- Extend the explicit scan of reduced moduli space to $h_{1,1} > 3$
- Strict bound on $\Delta\phi$ $\rightarrow$ tension between $Vol(\mathcal{M}_r)$ and COBE normalisation
- Need of other ways to produce primordial density perturbations

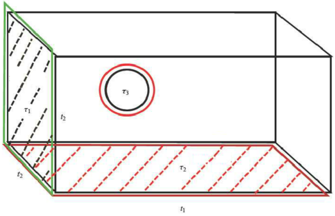
Viable curvaton mechanism?

- Curvature perturbations are not produced by the inflaton field
- Need of a light spectator field σ (plethora of light axions in string theory)
- Curvature perturbations $\mathcal{R}$ depend on post-inflationary dynamics

Mechanism

- Energy density of σ negligible during inflation $V(\sigma) \ll V_{inf}$
- After inflation curvaton unfreezes when $m_\sigma \sim H$ and oscillates around its VEV
- Curvaton energy density dominates the Universe imposing its curvature perturbations
- σ decays into the thermal bath

Case of Fibre Inflation: *[Cicoli, Quevedo, Burgess '09]*



Fibred CY volume: $\mathcal{V} = \alpha\left(\sqrt{\tau_1}\tau_2 - \lambda_3\tau_3^{3/2}\right)$

Superpotential: $W = W_0 + A_3\, e^{-a_3 T_3}$

Large Volume Scenario $\rightarrow$ expansion of V_F in inverse powers of $\mathcal{V}$

$$V_{\rm LVS} = \frac{8a_3^2 A_3^2\sqrt{\tau_3}}{3\alpha\lambda_3\mathcal{V}}e^{-2a_3\tau_3} + \frac{4a_3 A_3\tau_3 W_0\cos(a_3\theta_3)}{\mathcal{V}^2}e^{-a_3\tau_3} + \frac{3\xi W_0^2}{4g_s^{3/2}\mathcal{V}^3}$$

$$V_{\rm inf} \propto \frac{W_0^2}{\mathcal{V}^{10/3}} \qquad \Longrightarrow \qquad V_{\rm LVS} \gg V_{\rm inf}$$

Stabilisation of heavy fields:

$$a_3\langle\theta_3\rangle = \pi\,, \qquad a_3\langle\tau_3\rangle \sim \frac{1}{g_s}\,, \qquad \langle\mathcal{V}\rangle \sim W_0\sqrt{\langle\tau_3\rangle}\,e^{a_3\langle\tau_3\rangle}$$

$$m_{\theta_3}^2 \simeq m_{\tau_3}^2 \simeq \frac{W_0^2}{\mathcal{V}^2} \gg m_{\tau_2}^2 \simeq \frac{W_0^2}{\mathcal{V}^3} \gg H^2 \simeq \frac{W_0^2}{\mathcal{V}^{10/3}}$$

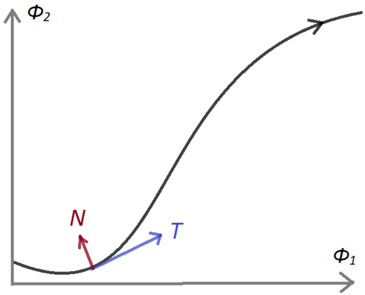
Light fields: $\underbrace{\tau_1}_{\rm inflaton}\quad \underbrace{\theta_1\,,\ \theta_2}_{\rm massless\ axions}$

Geometrical destabilisation: general setup

Multifield inflation in curved field space:

$$\mathcal{L} = \frac{1}{2} G_{ij}(\phi^i)\partial_\mu \phi^i \partial^\mu \phi^j - V(\phi)$$

Split the background trajectory in tangent and normal directions



$$T^i = \frac{\dot{\phi}^i}{\dot{\phi}_0}$$

$$(N_a)_i T^i = 0 \qquad a = 1 \dots d-1$$

$$(N_a)_i (N_a)^i = T_i T^i = 1$$

$$\dot{\phi}_0 = \sqrt{G_{ij}\dot{\phi}^i \dot{\phi}^j}$$

$$\ddot{\phi}^i + 3H\dot{\phi}^i + \Gamma^i_{jk}\dot{\phi}^j\dot{\phi}^k + G^{ij}V_j = 0$$

What do we look at?

Superhorizon behaviour of isocurvature modes *[Sasaki et al. '96] [Di Marco et al. '03] [Achucarro et al. '11] [Petel et al. '15]*

$$\delta Q^a = \delta\phi^a + \psi\frac{\dot{\phi}^a}{H} \qquad \rightarrow \qquad \mathcal{R} = \frac{H}{\dot{\phi}_0}Q^T \qquad \mathcal{S} = \frac{H}{\dot{\phi}_0}Q^N$$

$$m^2_{\mathrm{NN\,eff}} \equiv N^i N^j \left(V_{ij} - \Gamma^k_{ij}V_k\right) + \left(\epsilon\mathbb{R} + 3\eta_\perp^2\right) H^2$$

where

$$\eta_\perp = \frac{N^i V_i}{(H\dot{\phi}_0)}$$

Tachyonic effective mass $\Longrightarrow$ Exponential growth

Negative contributions can come from:

- **Negative field space curvature**
- **Metric connection**

Two field subspaces - Light fields

Massless axions:

$$\begin{cases} \gamma_{ij}(\phi) \sim \begin{pmatrix} 1 & 0 \\ 0 & f^2(\phi_1) \end{pmatrix} \\ \mathbb{R} = -2\frac{f_{11}}{f} \leq 0 \quad \text{const} \end{cases} \implies \begin{array}{l} f(\phi_1) \in \{A_+ e^{\lambda\phi_1}\,;\, A_- e^{-\lambda\phi_1}\} \\ \lambda = \sqrt{|\mathbb{R}|/2} \end{array}$$

Define $\alpha_1 = \frac{\phi_1'}{\phi_0'}$ $\quad \alpha_2 = \frac{f\phi_2'}{\phi_0'}$; $\quad \alpha_1^2 + \alpha_2^2 = 1$

Equation of motion and effective mass

$$\left(f\theta_i'\right)(N) = \left(f\theta_i'\right)(0)\, e^{-g(N)} \qquad \text{where} \qquad g(N) \simeq 3N \pm \lambda\left(\hat{\phi}_1(N) - \hat{\phi}_1(0)\right)$$

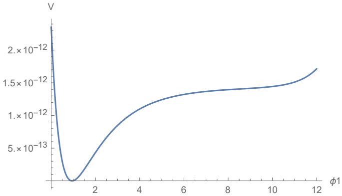
If the inflationary trajectory is not able to overcome Hubble friction $\alpha_2 \sim 0$

$$m^2_{\perp,\,\mathrm{eff}} \simeq \lambda\left(\pm V_1 - \lambda\dot{\phi}_0^2\right) > 0 \qquad\qquad \frac{\lambda\dot{\phi}_0^2}{|V_1|} \sim \frac{\lambda\sqrt{2\epsilon}}{3}$$

Axions with different exponential couplings $\implies$ **Potential geometrical destabilisation!**

Results for massless axions

	θ_1	θ_2
γ_{ij}	$\begin{pmatrix} 1 & 0 \\ 0 & A_-^2\, e^{-\frac{4}{\sqrt{3}}\phi_1} \end{pmatrix}$	$\begin{pmatrix} 1 & 0 \\ 0 & A_+^2\, e^{+\frac{2}{\sqrt{3}}\phi_1} \end{pmatrix}$
$\mathbb{R}$	$-8/3$	$-2/3$



Inflationary potential from g_s-loop corrections:

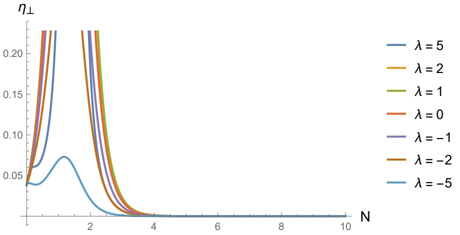
$$V = V_0 \left(3 - 4\, e^{-\frac{\hat\phi_1}{\sqrt{3}}} + e^{-\frac{4\hat\phi_1}{\sqrt{3}}}\right) \qquad \text{where} \qquad V_0 \sim \frac{W_0^2}{\mathcal{V}^{10/3}}$$

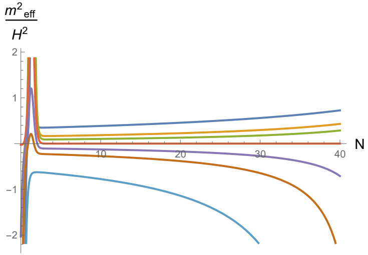
$$\hat\phi_1(N) - \hat\phi_1(0) \simeq \tfrac{1}{k_2} \ln\left(1 - \tfrac{4N}{9}\, e^{-k_2 \hat\phi_1(0)}\right) \qquad k_2 = 1/\sqrt{3}$$

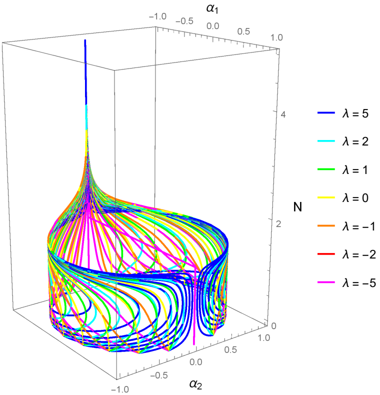
$$g(N) = 3N \pm \tfrac{\lambda}{k_2} \ln\left(1 - \tfrac{4N}{9}\, e^{-k_2 \hat\phi_1(0)}\right) > 0 \qquad \forall\, \lambda_i\,; \quad i = 1, 2 \qquad \alpha_2 \to 0!$$

Since $V_1 > 0$ we have $m^2_{\theta_1,\,\text{eff}} < 0$, $m^2_{\theta_2,\,\text{eff}} > 0$ $\Longrightarrow$ **GD of θ_1!**

Numerics:







$$\epsilon_i = \{0, 0.5, 1, 2, 3\}$$

Giving a mass to axions

Axions can receive a mass through

$$W = W_0 + A_3\, e^{-a_3 T_3} + A_i\, e^{-a_i T_i}\,, \qquad i = 1, 2$$

New terms in the potential:

$$V(\theta_i, \hat{\phi}_1) = \Lambda_i^{(0)}\, e^{-g_i(\hat{\phi}_1)} \cos(a_i \theta_i)\,, \qquad \text{with} \quad \Lambda_i^{(0)} = \frac{4 a_i A_i W_0 \langle \tau_i \rangle}{\mathcal{V}^2} \quad \forall i = 1, 2$$

$$g_1(\hat{\phi}_1) = -2k_2 \hat{\phi}_1 + a_1 \langle \tau_1 \rangle\, e^{2k_2 \hat{\phi}_1}$$

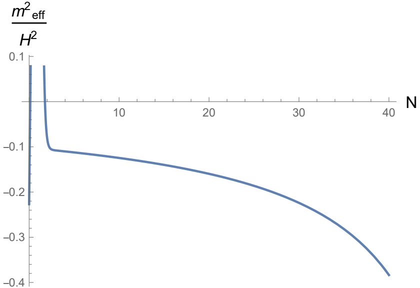
Effective mass:

$$m^2_{\theta_i,\,\mathrm{eff}} = \left(\frac{V_{\theta_i \theta_i}}{f^2} + \frac{f_{\hat{\phi}_1}}{f} V_{\hat{\phi}_1} + 3 \frac{V^2_{\theta_i}}{\dot{\phi}_0^2 f^2} \right) - \dot{\phi}_0^2 \frac{f_{\hat{\phi}_1 \hat{\phi}_1}}{f}$$

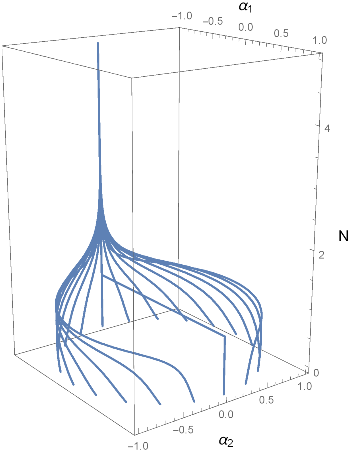
Corrections proportional to:

$$\delta_1 \equiv \frac{V(\theta_i, \hat{\phi}_1)}{V(\hat{\phi}_1)} \propto \exp\left\{ -a_1 \langle \tau_1 \rangle\, e^{2k_2 \hat{\phi}_1} \right\}$$

Numerics:



$\frac{m^2_{eff}}{H^2}$
0.1
−0.1
−0.2
−0.3
−0.4
10
20
30
40
N



α_1
−1.0
−0.5
0.0
0.5
1.0
N
4
2
0
α_2
−1.0
−0.5
0.0
0.5
1.0

Summing up the results:

- Presence of **many light fields** is common in string setup (Axiverse)
- **Massless axions** can lead to geometrical destabilisation of inflation
- Giving a **mass** to axions does not ensure absence of problems

What to do:

- ~~Check the presence of the instability without projecting 1 orthogonal dimension at time~~
- Beyond perturbation theory: Numerical GR or stochastic inflation
- Perturbation theory valid until the end of inflation? (nearly massless field, no DM)
- End of inflation? Backreaction of perturbations?
- New phenomenological features: non-gaussianities, gravity waves, PBH?

Grazie per l'attenzione

Phenomenomenological implications

Bound on tensor modes

- Full dynamics inside KC (also post- inflationary)
- Simplified FI potential: $V(\phi) = V_0 \left(1 - c_1 e^{-c_2 \phi}\right)$
- largest $Vol(\mathcal{M}_r)$ for $g_s = 0.3$
- Slow-roll conditions and $N_e \sim 50$

$$\begin{cases} r(\phi_*) = 16\epsilon(\phi_*) \\ \epsilon(\phi_{end}) = 1 \end{cases} \quad \rightarrow \quad \frac{\Delta\phi}{M_P} \sim \frac{N_e}{2}\sqrt{\frac{r(\phi_*)}{2}} \ln\left(\frac{4}{\sqrt{r(\phi_*)}}\right)$$