Chiral Global Embedding of Fibre Inflation

Veronica Guidetti

Dipartimento di Fisica e Astronomia, Università di Bologna,
via Irnerio 46, 40126 Bologna, Italy

INFN, Sezione di Bologna, viale Berti Pichat 6/2, 40127 Bologna, Italy

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[1709.01518] in collaboration with: M. Cicoli, D. Ciupke, V. Diaz, F. Muia and P. Shukla

Aim of the project

- Embed FI into consistent Calabi Yau orientifolds with D-branes and fluxes
- Get full moduli stabilisation
- Realise a chiral visible sector

Requirements:

- $h_{1,1} = 4$, Volume form $\mathcal{V} = \alpha_1 \sqrt{\tau_1 \tau_2 \tau_3} - \alpha_2 \tau_s^{3/2}$ [Cicoli,Muia,Shukla]
- **Orientifold involution** + $D3/D7$-**brane setup** + tadpole cancellation
- World volume fluxes turned on, **chiral matter** on $D7$
- Freed-Witten anomaly cancellation + just one FI term
- No chiral intersection between visible sector and del Pezzo divisor
- **Moduli stabilisation** and inflation inside the Kähler cone
- **EFT** under control (Hierarchy of scales)

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

	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}	$\chi(\mathrm{O7})$	χ_{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: $x_8 \to -x_8 \quad \Longrightarrow \quad$ 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 branes around D_4, D_6 and $D_2 = D_7 - D_1$
- $D7$ tadpole cancellation: $\quad 8[O7] \equiv 8([D_8]) = 16([D_2] + [D_4] + [D_6])$
- $D3$ 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
- Fluxes: $F_i = \sum_{j=1}^{h_{1,1}} f_{i,j}\hat{D}_j - \frac{1}{2}c_1(D_i) - \iota_{D_j}^* B \qquad f_{1j} \in \mathbb{Z}$

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

Brane setup:

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

$$\left[\begin{array}{l} Sp(16) \to U(8) = SU(8) \times U(1) \\ q_{i2} = \int_X \hat{D}_i \wedge \hat{D}_2 \wedge \mathcal{F}_2; \qquad q_{12} = -2f_{21}; \quad q_{42} = 2f_{26}; \quad q_{62} = 2f_{24}; \quad q_{72} = 0 \\ Re(f_2) = \frac{4\pi}{g_2^2} = \tau_2 - Re(S)h(\mathcal{F}_2) \qquad h(\mathcal{F}_2) = \frac{1}{2}(f_{21}q_{12} + f_{24}q_{42} + f_{26}q_{62}) \\ \xi = \frac{1}{4\pi\mathcal{V}} \sum_{j=1}^{h_{1,1}} q_{j2}t_j = \frac{1}{4\pi\mathcal{V}}(q_{12}t_1 + q_{42}t_4 + q_{62}t_6) \\ I_2^S = 2q_{12} - q_{42} - q_{62} \qquad I_2^A = q_{42} + q_{62} \end{array}\right.$$

- No chiral intersection between $D7$ on D_2 and the instanton on D_1: $\quad I_{21} = q_{12} = 0$
- D-term constraint: $\quad t_4 = \alpha\, t_6; \qquad \alpha = -\frac{q_{62}}{q_{42}}$

Inflationary potential:

- D-term constraint: $t_4 = \alpha\, t_6;$ $\mathcal{V} = \frac{1}{\sqrt{2\alpha}}\sqrt{\tau_7}\tau_6 - \frac{1}{3}\tau_1^{3/2}$
- LVS stabilisation: $\langle\mathcal{V}\rangle = \frac{W_0}{4a_1 A_1}\sqrt{\langle\tau_1\rangle}\, e^{a_1\langle\tau_1\rangle}$ $\langle\tau_1\rangle = \left(\frac{3\hat{\xi}}{2}\right)^{2/3}$
- 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 $\alpha'^3 F^4$: $V_{F^4} = -\kappa^2\frac{\lambda W_0^4}{g_s^{3/2}\mathcal{V}^4}\sum_{i=1}^{h_{1,1}}\Pi_i t_i;$ $\kappa = \frac{e^{K_{cs}}g_s}{8\pi}$ [Ciupke, Louis, Westphal]

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

$$A_1 = \frac{3}{\pi}\frac{|\lambda|W_0^2}{\sqrt{g_s}}; \quad A_2 = C_W - \tilde{C}_W(\tau_7); \quad B_1 = \frac{(\alpha+1)}{\sqrt{2}\,\alpha}A_1; \quad B_2 = |C_3^W| - \hat{C}_W(\tau_7)$$

$$C_W = \sqrt{2\alpha}\left(C_1^W + \frac{C_2^W}{\alpha}\right); \quad \tilde{C}_W(\tau_7) = \frac{|C_4^W|}{(\alpha+1)}\sqrt{\frac{\alpha}{2}}\left(1 - \frac{\sqrt{2\alpha}}{(\alpha+1)}\sqrt{\frac{\langle\tau_1\rangle}{\tau_7}}\right)^{-1}$$

$$\hat{C}_W(\tau_7) = \frac{C_5^W}{2}\left(1 + \frac{1}{\sqrt{2}\,\alpha}\frac{\tau_7^{3/2}}{\mathcal{V}}\right)^{-1} + \frac{C_6^W}{2}\left(1 + \sqrt{\frac{\alpha}{2}}\frac{\tau_7^{3/2}}{\mathcal{V}}\right)^{-1}$$

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:

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

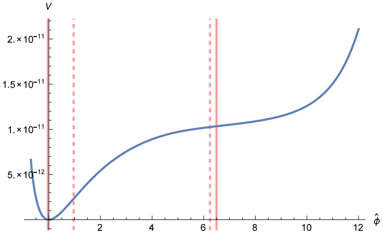
$$\mathcal{R}_1 = \frac{(\alpha+1)c}{\sqrt{2}\,\alpha} \frac{\langle \tau_7 \rangle^{\frac{3}{2}}}{\mathcal{V}} \ll 1; \quad \mathcal{R}_2 = \frac{\left(|C_3^W| - \hat{C}_W(\tau_7)\right)}{\left(C_W - \tilde{C}_W(\tau_7)\right)} \frac{\langle \tau_7 \rangle^{\frac{3}{2}}}{\mathcal{V}} \ll 1$$

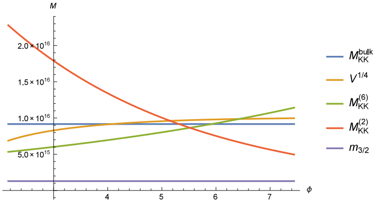
$$c = \frac{3}{\pi(C_W - \tilde{C}_W(\tau_7))} \frac{|\lambda| W_0^2}{\sqrt{g_s} \langle \tau_7 \rangle} \sim \mathcal{O}(1);$$

[Grimm, Mayer, Weissenbacher]

Case 1: $\lvert\lambda\rvert = 10^{-3}, \quad \chi_{eff}(X)$	**Case 2:** $\lvert\lambda\rvert = 10^{-7}, \quad \chi(X)$
$\alpha = 1, \quad g_s = 0.114, \quad \mathcal{V} = 10^4, \quad W_0 = 80,$ $\langle \tau_1 \rangle = 1.91, \quad \xi = 0.067$ $C_1^W = C_2^W = 15, \quad \lvert C_3^W \rvert = 0.013,$ $\lvert C_4^W \rvert = 18, \quad C_5^W = C_6^W = -5$	$\alpha = 1, \quad g_s = 0.25, \quad \mathcal{V} = 4500, \quad W_0 = 150,$ $\langle \tau_1 \rangle = 3.10, \quad \xi = 0.456$ $C_1^W = C_2^W = 0.034, \quad \lvert C_3^W \rvert = 10^{-5},$ $\lvert C_4^W \rvert = 0.068, \quad C_5^W = C_6^W = -0.048$

Case 1: $|\lambda| = 10^{-3}, \quad \chi_{eff}(X)$



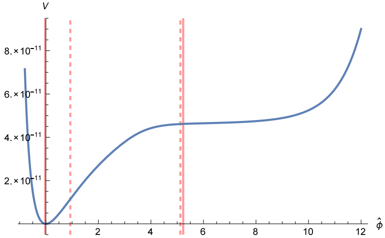


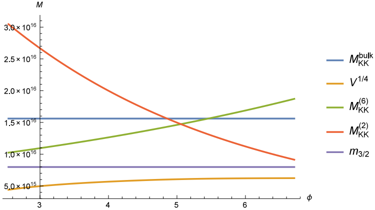
$$r \sim 10^{-3}, \quad n_s = 0.983, \quad \Delta N_{eff} = 0.39,$$

$$N_{max} \simeq 60, \quad m_\phi \simeq 4 \cdot 10^{13}\, GeV,$$

$$T_{rh} \simeq 1.8 \cdot 10^{10}\, GeV, \quad N_e = 52, \quad \delta \simeq 1.6$$

Case 2: $|\lambda| = 10^{-7}, \quad \chi(X)$





$$r \sim 0.0014, \quad n_s = 0.963, \quad \Delta N_{eff} = 0$$

$$N_{max} \simeq 58, \quad m_\phi \simeq 1.8 \cdot 10^{13}\, GeV,$$

$$T_{rh} \simeq 5.2 \cdot 10^{9}\, GeV, \quad N_e = 51, \quad \delta \simeq 0.05$$

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:

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

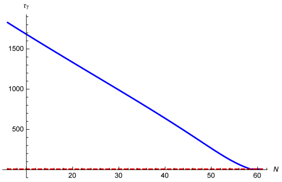
- EOM:

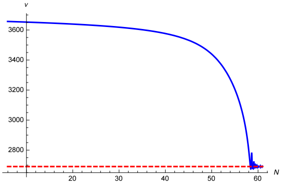
$$\begin{cases} \phi''^{\,i} + \Gamma^i_{jk}\phi'^{\,j}\phi'^{\,k} + (3+\mathcal{L}_{kin})\left[g^{ij}\,\frac{\partial_j V}{V} + \phi'^{\,i}\right] = 0 \\ H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{V}{3+\mathcal{L}_{kin}} \end{cases}$$

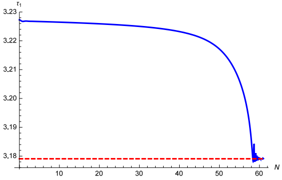
Multi-field inflation - Parameters and Results:

Case 1: $\lvert\lambda\rvert = 10^{-3}, \quad \chi(X)$	**Case 2:** $\lvert\lambda\rvert = 10^{-6}, \quad \chi(X)$
$\alpha = 1, \quad g_s = 0.25, \quad W_0 = 1,$ $\xi = 0.456, \quad A_s = 1 \cdot 10^4,$ $C_1^W = C_2^W = 0.05, \quad \lvert C_3^W\rvert = 10^{-4},$ $\lvert C_4^W\rvert = 0.1, \quad C_5^W = C_6^W = -0.05$	$\alpha = 1, \quad g_s = 0.25, \quad W_0 = 50,$ $\xi = 0.456, \quad A_s = 6 \cdot 10^5,$ $C_1^W = C_2^W = 0.05, \quad \lvert C_3^W\rvert = 10^{-4},$ $\lvert C_4^W\rvert = 0.1, \quad C_5^W = C_6^W = -0.05$
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 $\sqrt{P_{\rm COBE}} \simeq 2 \cdot 10^{-5}$	$n_s \simeq 0.97, \quad r \simeq 0.002, \quad N_{max} \simeq 69$ $\sqrt{P} \simeq 1 \cdot 10^{-5}$ vs $\sqrt{P_{\rm COBE}} \simeq 2 \cdot 10^{-5}$

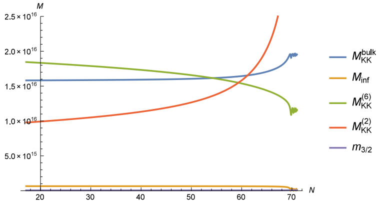
Multi-field inflation - Plots:



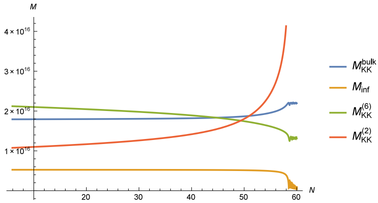




Case 1: $\lvert\lambda\rvert = 10^{-3}, \quad \chi(X)$



Case 2: $\lvert\lambda\rvert = 10^{-6}, \quad \chi(X)$



Conclusions:

- 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 are needed:

- Compute χ_{eff} and λ in full detail
- Determination of the actual CY Kähler cone $\rightarrow$ **Shukla's Talk!**
- Find a mechanism to realise dS vacuum
- Generate density perturbations through curvaton mechanism? $\rightarrow$ **Pedro's Talk!**

Thank you for your attention