Reheating and geometrical destabilisation in String Inflation

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Based on:
MC, Guidetti, Pedro, Vacca, 1807.03818
MC, Piovano, 1809.01159
MC, Guidetti, Pedro, 1903.01497

Challenges for string inflation

- Conditions for string inflation:

  (i) inflaton is a pseudo NG boson to control quantum corrections

  (ii) moduli stabilisation to control all directions and fix energy scales

  (iii) CY embedding to check theoretical consistency

  (iv) understand post-inflationary cosmology to make trustable predictions

- n_s and r depend on:

  i) N_e which depends on post-inflation:

  reheating: T_{re}? w_{re}?

  moduli domination: N_{mod}?

$$N_e + \frac{1}{4}N_{\rm mod} + \frac{1}{4}(1-3w_{\rm re})N_{\rm re} \approx 57 + \frac{1}{4}\ln r + \frac{1}{4}\ln\left(\frac{\rho_*}{\rho_{\rm end}}\right)$$

  ii) fix n_s by matching observations and then predict r

  BUT Planck value of n_s depends on priors:

  $\Delta N_{eff} = 0$ $\longrightarrow$ $n_s = 0.965 \pm 0.004$ [Planck coll. 2018]

  $\Delta N_{eff} = 0.39$ $\longrightarrow$ $n_s = 0.983 \pm 0.006$ [Planck coll. 2015]

  can get different r! $\longrightarrow$ compute dark radiation ΔN_{eff} ultra-light axions?

Moduli stabilisation

- Swiss-cheese CY volume

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

- EFT coordinates: Kahler moduli

$$T_i = \tau_i + \mathrm{i}\,\vartheta_i \qquad \tau_i = \frac{\partial \mathcal{V}}{\partial t_i}$$

- Leading order: α' + non-perturbative effects

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

- LVS models: fix $\mathcal{V}$ + $N_{\rm small}$ del Pezzo moduli [MC, Conlon, Quevedo]

$$\mathcal{V} \simeq e^{a_s \tau_s} \gg 1 \qquad \tau_s \simeq g_s^{-1} > 1 \quad \forall s = 1, \ldots, N_{\rm small}$$

⟶ $N_{\rm flat} = h^{1,1} - N_{\rm small} - 1$ flat directions!
$+\, N_{\rm flat} + 1$ massless axions!

- Flat directions lifted by perturbative corrections
  - g_s loops
  - higher derivative α' effects

⟶ Good inflaton candidates:

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

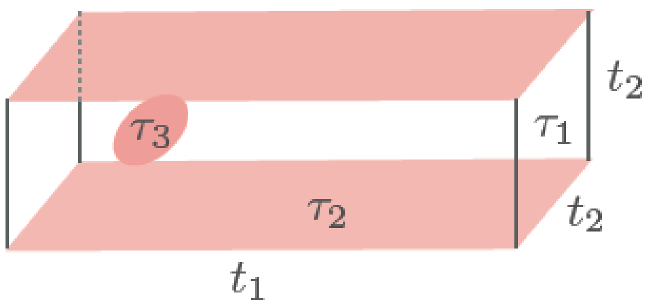
Explicit CY models

- Need CY 3-folds with (from Kreuzer-Skarke list):

$$N_{\rm small} \geq 1 \qquad N_{\rm flat} = h^{1,1} - N_{\rm small} - 1 \geq 1 \qquad h^{1,1} \geq N_{\rm small} + 2 \geq 3$$

- $h^{1,1} = 3$: brane set-up + moduli stabilisation + inflation + no chirality [MC,Muia,Shukla]
- CY volume with 2 large moduli (K3 fibre over a P^1 base):

$$\mathcal{V} = t_1 t_2^2 + t_3^3 = \sqrt{\tau_1}\tau_2 - \tau_3^{3/2}$$



- τ_1 is the inflaton with $\mathcal{V}$ constant

$\longrightarrow$ 2 ultra-light axions ϑ_1 and ϑ_2

- $h^{1,1} = 4$: brane set-up + moduli stabilisation + inflation + chirality [MC,Ciupke,Diaz,Guidetti,Muia,Shukla]
- CY volume with 3 large moduli (3 K3 fibrations):

$$\mathcal{V} = t_1 t_2 \tilde{t}_2 + t_3^3 = \sqrt{\tau_1 \tau_2 \tilde{\tau}_2} - \tau_3^{3/2}$$

- Visible sector on D7s wrapping τ_1, τ_2 and $\tilde{\tau}_2$
- Turn on gauge fluxes $\longrightarrow$ FI-term = 0 fixes $\tau_2 \sim \tilde{\tau}_2$ $\longrightarrow$ reduce to $h^{1,1} = 3$ case
- dS from hidden sector F-terms: background fluxes + gauge fluxes (T-branes)

$$V_{\rm up} = m^2 |\phi|^2$$

[MC,Quevedo,Valandro]

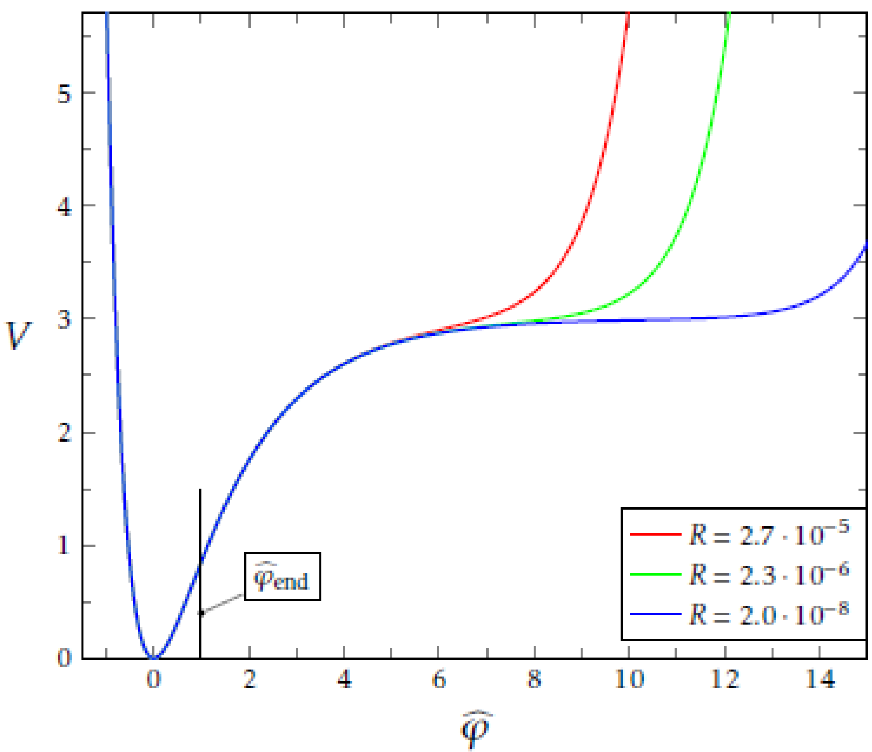
Fibre Inflation

- Potential for canonical inflaton shifted from minimum:

$$V_{\rm inf} = V_0 \left(3 - R - 4\, e^{-\varphi/\sqrt{3}} + e^{-4\varphi/\sqrt{3}} + R\, e^{2\varphi/\sqrt{3}}\right)$$

[MC, Burgess, Quevedo]
[MC,Ciupke, de Alwis, Muia]

$$V_0 \simeq \frac{M_p^4}{\mathcal{V}^{10/3}} \qquad R \simeq \left(\frac{C_1 C_2}{C_3}\right)^2 \frac{g_s^4}{18} \leq 10^{-5} \qquad g_s \leq 0.1 \qquad C_i \sim O(1)$$



Assume no instability of ultra-light axions

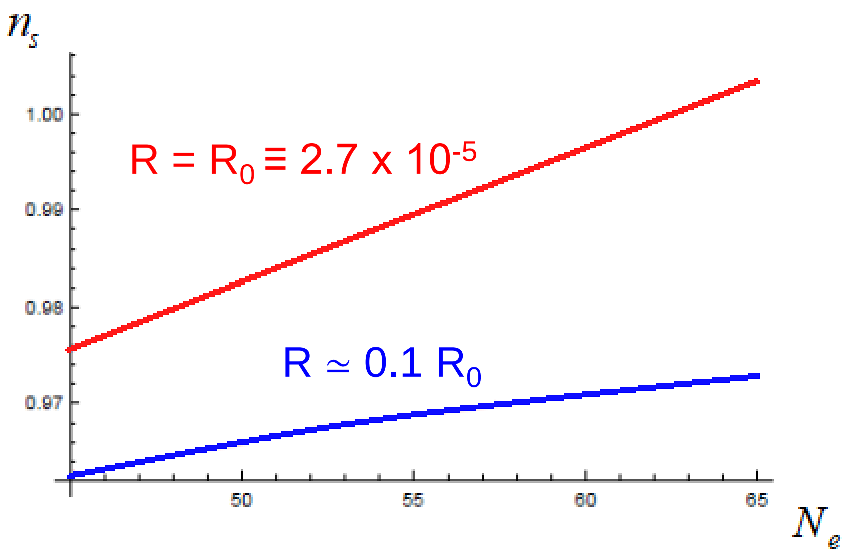
α-attractor (E-model) with $\boxed{\Delta\varphi \simeq 5 M_p}$

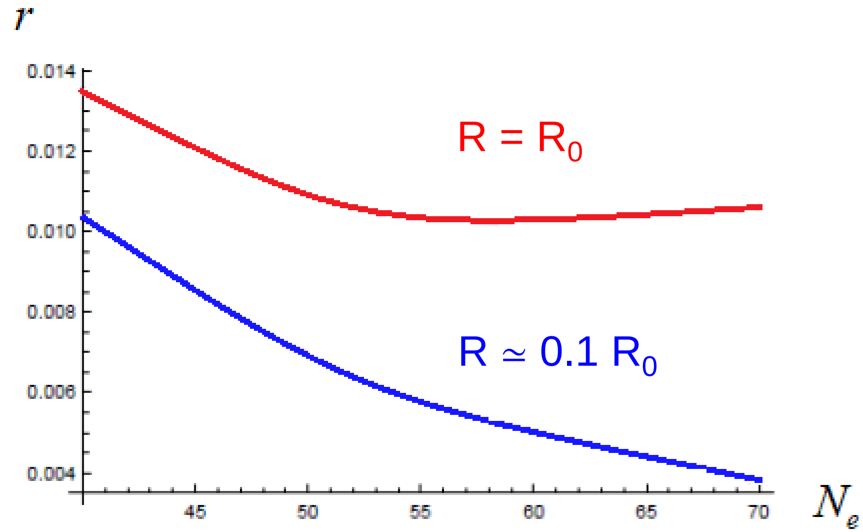
BUT predictions depend on reheating

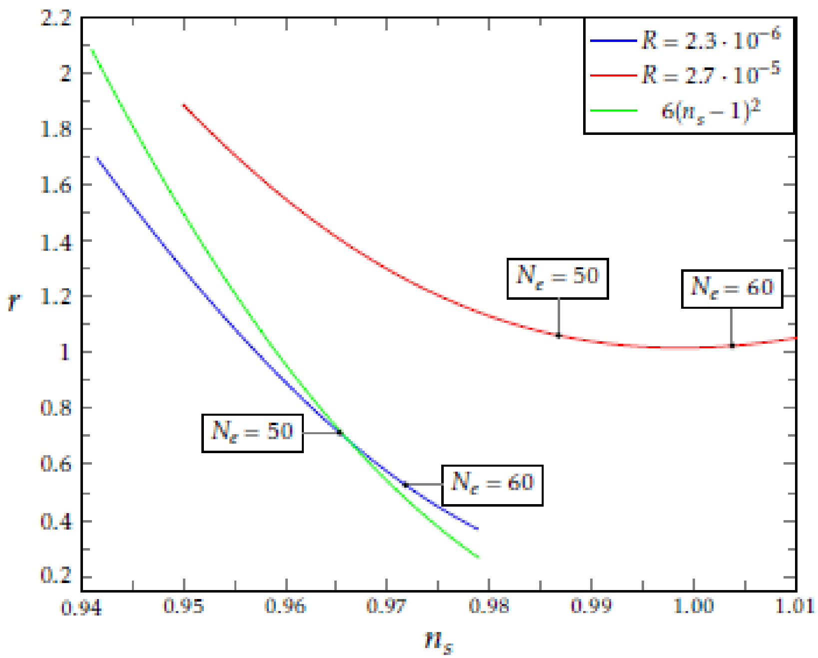
$$n_s = n_s(\varphi_*, R) = n_s(N_e, R) = n_s(w_{\rm rh}, T_{\rm rh}, R)$$

$$r = r(\varphi_*, R) = r(w_{\rm rh}, T_{\rm rh}, R)$$

Cosmological predictions





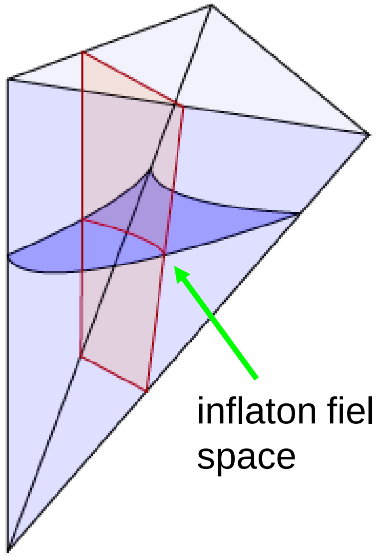


Geometrical bounds

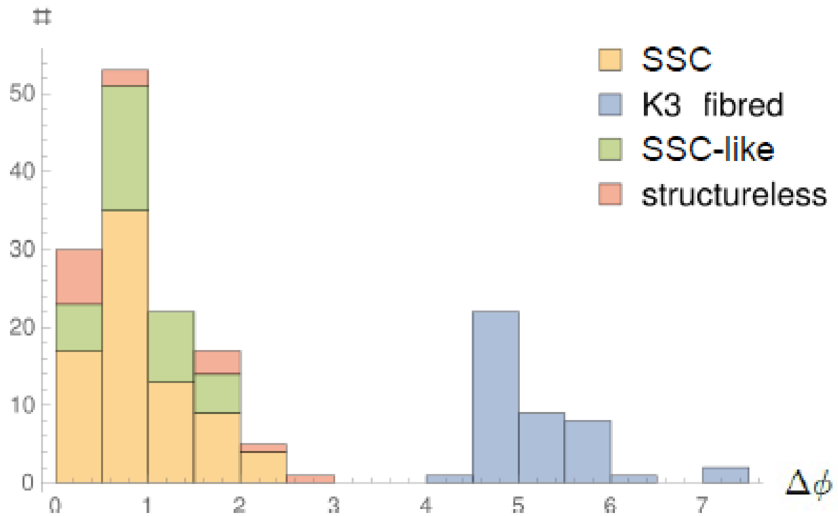
[MC, Ciupke, Mayrhofer, Shukla]

- Upper bounded inflaton range due to Kahler cone

$$\frac{\Delta\phi}{M_p} \leq c \ln \mathcal{V} \qquad\qquad c \sim O(1)$$



- Scan of $\Delta\varphi$ for all toric LVS vacua with $h^{1,1} = 3$, $\mathcal{V} = 10^5$ and $g_s = 0.1$



right ballpark to match $\delta\rho/\rho$

i) $\Delta\varphi > M_p$ only for examples we need for inflation (K3 fibrations)!

ii) agreement with swampland distance conjecture

Bound on tensor modes

[MC, Ciupke, Mayrhofer, Shukla]

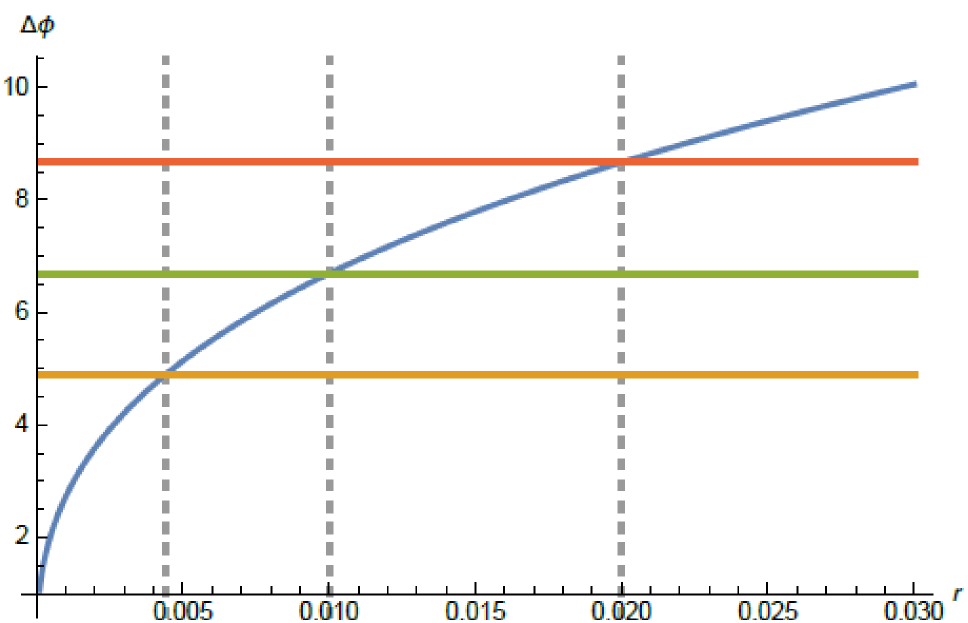
- Generic LVS inflationary model

$$V \simeq V_0 \left(1 - c_1\, e^{-c_2 \phi}\right) \longrightarrow \epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2 \simeq \frac{1}{2} c_1^2\, c_2^2\, e^{-2c_2\phi}$$

- For $\epsilon(\phi_{\rm end}) \simeq 1$ and $r(\phi_*) = 16\,\epsilon(\phi_*)$

$$N_e = \int_{\phi_{\rm end}}^{\phi_*} \sqrt{\frac{8}{r(\phi)}}\,{\rm d}\phi \longrightarrow \frac{\Delta\phi}{M_p} \simeq \frac{N_e}{2}\sqrt{\frac{r(\phi_*)}{2}}\,\ln\left(\frac{4}{\sqrt{r(\phi_*)}}\right)$$

- Combine with $\Delta\varphi/M_p \leq c \ln \mathcal{V}$ for $N_e = 50$



$\mathcal{V} = 10^3$

$\mathcal{V} = 10^4$

$\mathcal{V} = 10^5$

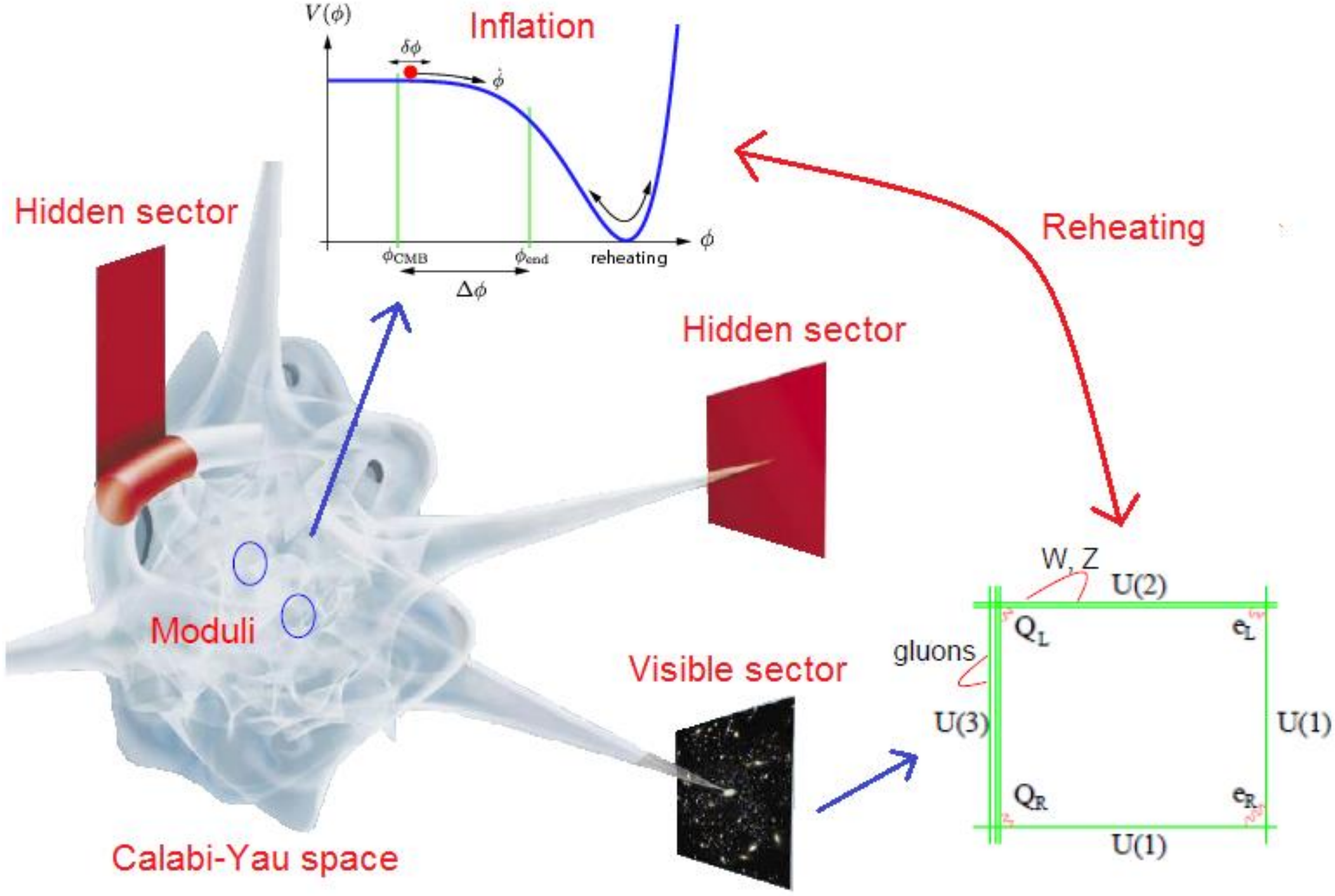
$\longrightarrow r \leq 0.01$

Observations sensitive to r of order 0.05 should not see tensors! BUT detectable by LiteBIRD and PICO!

Reheating

- End of inflation: inefficient particle production at preheating [Antusch,Cefalà,Krippendorf,Muia,Orani,Quevedo]

  → Inflaton energy transferred to SM via perturbative decay



SM and dark radiation

- Where is the SM?
- Ultra-light bulk axions from inflaton decay contribute to ΔN_{eff}
- Observational constraint: $N_{\rm eff} = 2.99 \pm 0.17$ Planck + galaxy BAO [Planck coll. 2018]

  $N_{\rm eff} = 3.41 \pm 0.22$ Planck + galaxy BAO + LyaF BAO + HST [Riess et al 2016]

Inflaton ϕ $\swarrow$ SM dof, $\searrow$ Bulk axions $\longrightarrow$ $\Delta N_{eff} > 0$

- Decay rates into bulk axions [Angus] [Hebecker,Mangat, Rompineve,Witkowski]

$$\begin{cases} \Gamma_{\Phi\to a_1 a_1} = \dfrac{1}{24\pi}\dfrac{m_\Phi^3}{M_{\rm P}^2} \\ \Gamma_{\Phi\to a_2 a_2} = \dfrac{1}{96\pi}\dfrac{m_\Phi^3}{M_{\rm P}^2} \end{cases} \longrightarrow \quad \Gamma_{\Phi\to{\rm hid}} = c_{\rm hid}\,\Gamma_0 \qquad \Gamma_0 = \frac{1}{48\pi}\frac{m_\Phi^3}{M_P^2} \qquad c_{\rm hid} = \frac{5}{2}$$

- SM on D3s at a singularity $\longrightarrow$ sequestering $\longrightarrow$ loop suppressed decay rates

$$\Gamma_{\Phi\to visible} \simeq \left(\frac{\alpha_{SM}}{4\pi}\right)^2 \Gamma_0 \quad \longrightarrow \quad \Delta N_{eff} \sim \left(\frac{4\pi}{\alpha_{SM}}\right)^2 \sim 10^4$$

Dark radiation overproduction!

$\longrightarrow$ SM on D7s wrapping inflaton cycle to increase branching ratio into visible dof

Reheating temperature

[MC, Piovano]

- SM on D7s wrapping τ_1 and τ_2 $\longrightarrow$ desequestering

$$M_{\rm soft} \simeq m_{3/2} \simeq 5\cdot 10^{15}\,{\rm GeV} \gg m_\phi \simeq 5\cdot 10^{13}\,{\rm GeV}$$

$\longrightarrow$ inflaton cannot decay to SUSY particles

- Leading inflaton decay into gauge bosons

$$\Gamma_{\Phi\to AA} = 12\gamma^2\Gamma_0 \qquad \gamma = \frac{\langle\tau_1\rangle}{\langle\tau_1\rangle - h(F)g_s^{-1}}$$

$$\longrightarrow \quad \Gamma_{\Phi\,\to\,{\rm vis}} = c_{\rm vis}\,\Gamma_0 \qquad c_{\rm vis} = 12\,\gamma^2$$

- Reheat temperature:

$$T_{\rm rh} \simeq 0.12\,\gamma\, m_\Phi\sqrt{\frac{m_\Phi}{M_p}} \simeq 3\gamma\cdot 10^{10}\ {\rm GeV} \simeq 10^{10}\ {\rm GeV} \quad\longrightarrow\quad g_*(T_{\rm rh}) = 106.5$$

- Oscillating scalar behaves as matter $\longrightarrow$ $w_{\rm rh} \simeq 0$ $\longrightarrow$ $N_e \simeq 52 + \frac{1}{3}\ln\gamma \simeq 52$

$$n_s = n_s(w_{\rm rh}, T_{\rm rh}, R) \quad\to\quad n_s = n_s(R)$$

$$r = r\,(w_{\rm rh}, T_{\rm rh}, R) \quad\to\quad r = r\,(R)$$

Dark radiation and tensors

[MC, Piovano]

- Fix R in $n_s(R)$ by matching Planck after computing ΔN_{eff}

  $\longrightarrow$ Predict tensor modes from $r(R)$

- Dark radiation prediction almost insensitive to Higgs coupling z:

$$\Delta N_{\text{eff}} = \frac{43}{7}\frac{\Gamma_{\Phi\to\text{hid}}}{\Gamma_{\Phi\to\text{vis}}}\left(\frac{g_*(T_{\text{dec}})}{g_*(T_{\text{rh}})}\right)^{1/3} \simeq \frac{0.6}{\gamma^2} \qquad \gamma = \frac{\langle\tau_1\rangle}{\langle\tau_1\rangle - h(F)g_s^{-1}}$$

- Expand F:

$$F = 2\pi n_1\hat{D}_1 + 2\pi n_2\hat{D}_2 + 2\pi n_3\hat{D}_3 \qquad n_i \in \mathbb{Z}$$

$$\longrightarrow \qquad h(F) = \frac{1}{2}k_{122}n_2^2 \geq 0$$

$$\longrightarrow \qquad \gamma \geq 1 \qquad \longrightarrow \qquad \Delta N_{\text{eff}} \leq 0.6$$

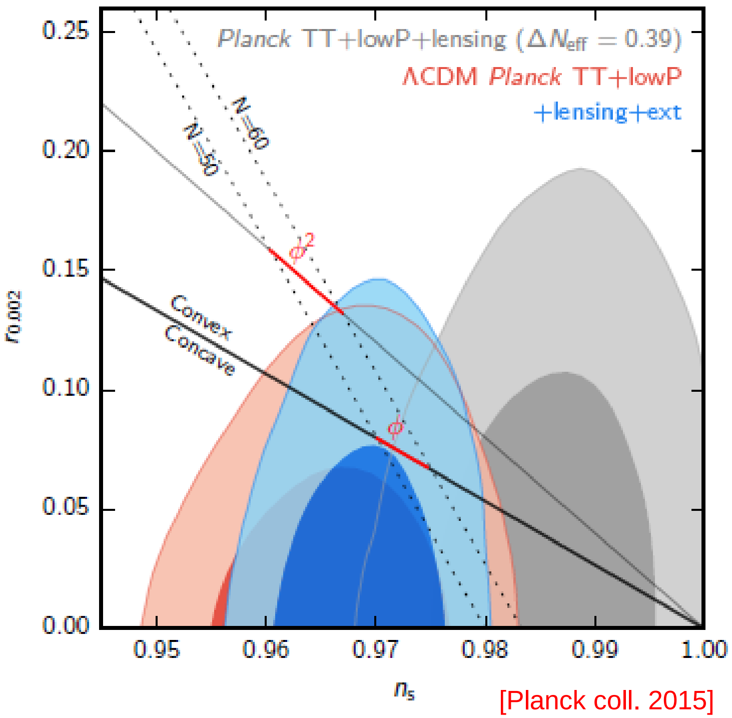
Fluxless case

[MC, Piovano]

- F = 0 case: $n_2 = 0$

→ $\gamma = 1$ $\langle \tau_1 \rangle = \frac{\alpha_{\text{vis}}^{-1}}{2} = 12.5$ $\Delta N_{\text{eff}} \simeq 0.6$ prior for Planck

- Cosmological prediction:



[Planck coll. 2015]

→ need to reproduce $n_s = n_s(R) \simeq 0.99$

→ horizon exit in steepening region with $R = R_0$

→ $r = r(R) \simeq 0.01$

$\tau_1 = 12.5$ small enough to get $N_e = 52$

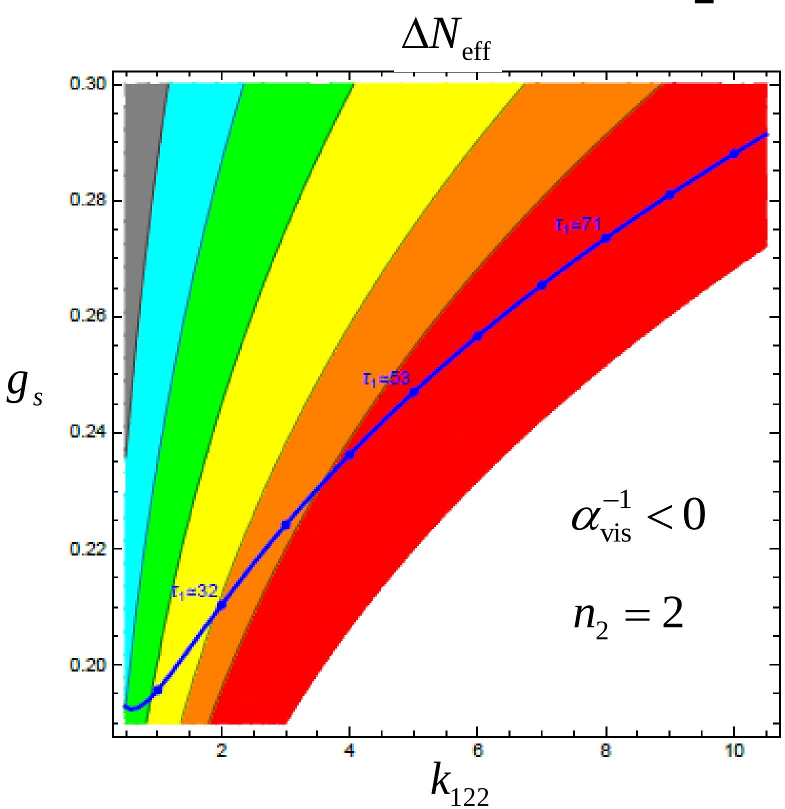
with $\Delta\varphi \leq \ln \mathcal{V}$ for $\mathcal{V} = 10^3$

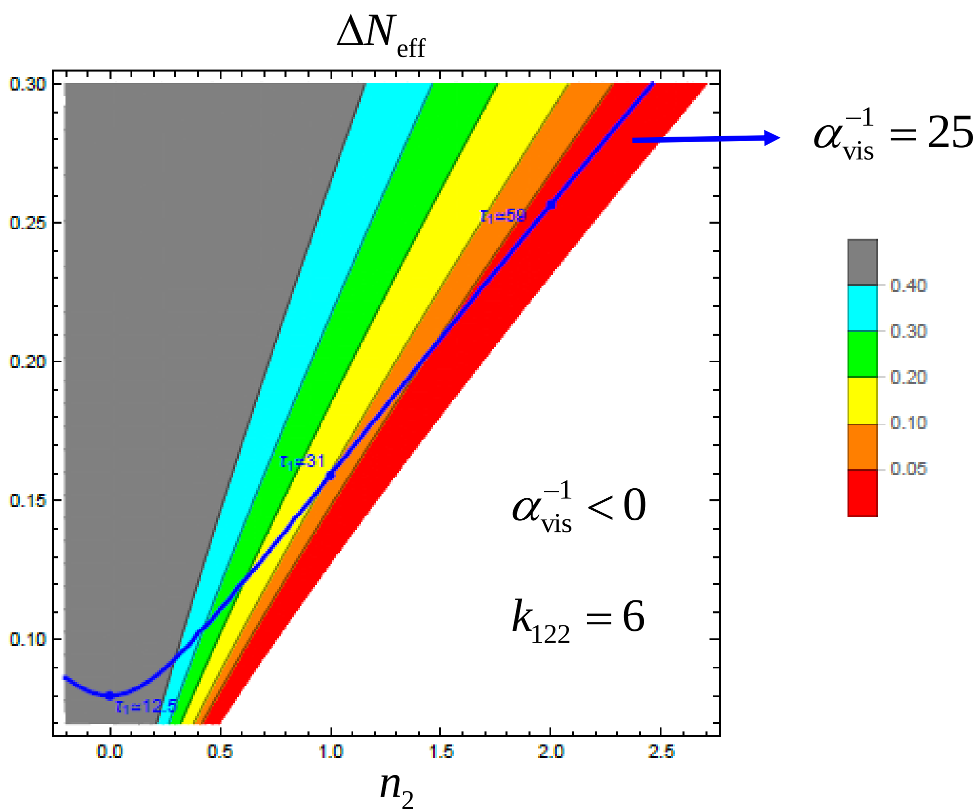
Fluxed case

[MC, Piovano]

- $F \neq 0$ case: $n_2 \neq 0$

  $\longrightarrow$ $\gamma > 1$ $\qquad \langle \tau_1 \rangle = \gamma \dfrac{\alpha_{\rm vis}^{-1}}{2} > 12.5$ $\qquad \Delta N_{\rm eff} \ll 0.6$ $\qquad$ prior for Planck





- Cosmological prediction: $\Delta N_{\rm eff} \leq 0.2$ $\longrightarrow$ need to reproduce $n_s = n_s(R) \simeq 0.965$

  $\longrightarrow$ horizon exit in plateau region with $R \lesssim 0.1\, R_0$ $\longrightarrow$ $r = r(R) \simeq 0.007$

- $\Delta N_{\rm eff} \lesssim 0.2$ implies $\tau_1 \gtrsim 20$: too large to get $N_e = 52$ with $\Delta\varphi \leq \ln \mathcal{V}$ for $\mathcal{V} = 10^3$?

  NO due to plateau!

Geometrical destabilisation?

[MC,Guidetti,Pedro,Vacca]

- Generic non-linear sigma model

$$\mathcal{L}/\sqrt{|g|} = \frac{1}{2}\gamma_{ij}(\phi_i)\partial_\mu\phi_i\partial^\mu\phi_j - V(\phi_i)$$

- Effective mass-squared of isocurvature perturbations for i=1,2:

$$m_{\rm eff}^2 = V_{\perp\perp} - \Gamma^i_{\perp\perp}V_i + \left(\varepsilon R + 3\eta_\perp^2\right)H^2 \qquad \eta_\perp = \frac{V_\perp}{H\left|\dot\phi\right|} \qquad \left|\dot\phi\right| = \sqrt{\gamma_{ij}\dot\phi_i\dot\phi_j}$$

field-space Ricci scalar　　　turning-rate of trajectory

- For R < 0 and geodesic motion with $\eta_\perp = 0$:

$$m_{\rm eff}^2 = V_{\perp\perp} - \Gamma^i_{\perp\perp}V_i - \varepsilon\left|R\right|H^2$$

→ geometrical destabilisation during inflation? (if $m_{\rm eff}^2 < 0$)

- Instability even for heavy fields with $V_{\perp\perp} >> H^2$ if $|R| = M_p / M >> 1$ even if $\varepsilon << 1$

[Renaux-Petel,Turzinsky]

→ premature end of inflation? Perturbation theory breakdown?

- No pathology since the instability is classical background solution: attractor → repulsor

→ new attractor solution where $m_{\rm eff}^2 > 0$ [MC,Guidetti,Pedro,Vacca]

Unstable ultra-light fields?

- Effective mass-squared of isocurvature perturbations with $R < 0$ and $\eta_\perp = 0$:

$$m_{\rm eff}^2 = V_{\perp\perp} - \Gamma^i_{\perp\perp} V_i - \varepsilon |R| H^2$$

destabilisation during inflation?

- In strings/SUGRA generically $R \sim O(1)$ and $R < 0$ since

$$K = -3\ln\left(T + \bar{T}\right) \longrightarrow R = -8/3$$

1) Non shift-symmetric heavy fields

$$V_{\perp\perp} \geq H^2 \gg \varepsilon |R| H^2 \sim \varepsilon H^2 \longrightarrow m_{\rm eff}^2 > 0$$

[MC,Guidetti,Pedro,Vacca]

2) Shift-symmetric ultra-light fields with $H^2 \gg V_{\perp\perp} \simeq 0$

$$m_{\rm eff}^2 = -\Gamma^i_{\perp\perp} V_i - \varepsilon |R| H^2 \longrightarrow m_{\rm eff}^2 < 0 \quad \text{if} \quad \Gamma^i_{\perp\perp} V_i > 0$$

- In Fibre Inflation $\eta_\perp = 0$

i) Heavy fields are stable

ii) Ultra-light fields: ϑ_2 axion is stable while ϑ_1 axion can be unstable! [MC,Guidetti,Pedro]

- Breakdown of perturbation theory? Kick along ϑ_1 and backreaction from $\eta_\perp \neq 0$?

- Potential phenomenological implications:

large non-Gauss. localised in k-space? PBHs? GWs at interferometric scales?

Unstable ultra-light fields?

[MC,Guidetti,Pedro]

- ϕ_1 = inflaton and ϕ_2 = ultra-light field $\Leftrightarrow$ $V_2 = 0$

$$\dot{\pi}_2 = -a^3\, V_2 = 0 \longrightarrow \pi_2 = a^3 f^2 \dot{\phi}_2 = \text{const} \qquad \gamma_{ij} = \begin{pmatrix} 1 & 0 \\ 0 & f^2(\phi_1) \end{pmatrix}$$

$$\longrightarrow \dot{\phi}_2(t) \simeq \dot{\phi}_2(0) \left(\frac{f(0)}{f(t)} \right)^2 e^{-3N_e}$$

- Isocurvature mass-squared with non-zero Christoffels:

$$m_{\text{eff}}^2 = -\Gamma^1_{22} V_1 + \left(\varepsilon R + 3\eta_\perp^2 \right) H^2$$

- 2 cases:

i) f decays exponentially with N_e $\longrightarrow$ $\dot{\phi}_2 \neq 0$ $\longrightarrow$ $\eta_\perp \neq 0$

$\longrightarrow$ $m_{\text{eff}}^2 > 0$ e.g. quintessence potentials

ii) f does not decay exponentially with N_e $\dot{\phi}_2 \to 0$ $\longrightarrow$ $\eta_\perp \simeq 0$

e.g. Fibre Inflation

$$m_{\text{eff}}^2 = -\Gamma^1_{22} V_1 + \varepsilon R H^2 = -\left(3\frac{f_1}{f} + \sqrt{2\varepsilon}\, \frac{f_{11}}{f} \right) \sqrt{2\varepsilon} H^2$$

- R negative and constant:

$$R = -2\frac{f_{11}}{f} = \text{const} \quad \Leftrightarrow \quad f(\phi_1) = A_+\, e^{\lambda\phi_1} + A_-\, e^{-\lambda\phi_1} \quad \text{with} \quad \lambda = \sqrt{\frac{|R|}{2}}$$

Unstable ultra-light fields?

[MC,Guidetti,Pedro]

- Isocurvature mass-squared simplifies to:

$$m_{\text{eff}}^2 \underset{\varepsilon \ll 1}{\simeq} -3\frac{f_1}{f}\sqrt{2\varepsilon}H^2 = \pm\lambda\, V_1$$

- Stability of ultra-light fields determined by the sign of V_1

- Fibre inflation:

i) ϑ_1 axion $\quad A_+ = 0 \longrightarrow m_{\text{eff},\vartheta_1}^2 \underset{\varepsilon \ll 1}{\simeq} -\lambda\, V_1$

ii) ϑ_2 axion $\quad A_- = 0 \longrightarrow m_{\text{eff},\vartheta_2}^2 \underset{\varepsilon \ll 1}{\simeq} +\lambda\, V_1$

- 2 cases:

i) $V_1 > 0$ (R-L inflation) $\longrightarrow$ ϑ_1 axion unstable, ϑ_2 axion stable

ii) $V_1 < 0$ (L-R inflation) $\longrightarrow$ ϑ_1 axion stable, ϑ_2 axion unstable

[MC,Burgess,Quevedo]
[MC,Ciupke,de Alwis,Muia]

[Broy,Ciupke,Pedro,Westphal]

- One axion is always potentially unstable!

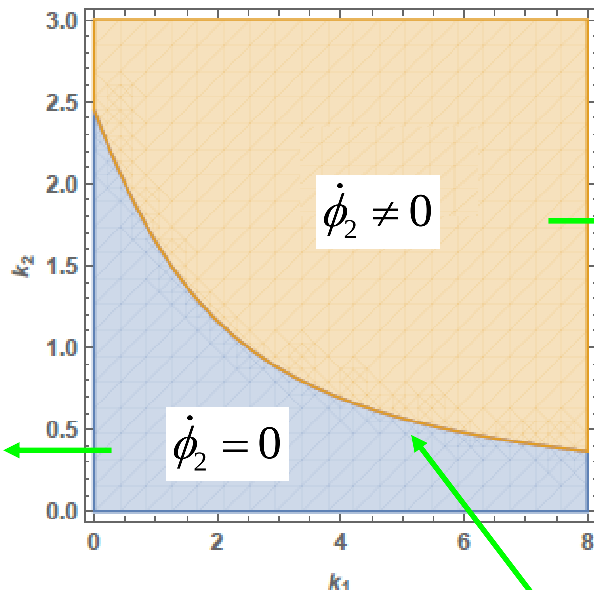
Stable ultra-light fields for quintessence

[MC,Guidetti,Pedro]

- Potential and kinetic function:

$$V = V_0 \, e^{-k_2 \phi_1} \qquad\qquad f = f_0 \, e^{-k_1 \phi_1}$$

- Solution of EOM gives



$\eta_\perp \neq 0 \longrightarrow m^2_{\text{eff}} > 0$

from turning rate

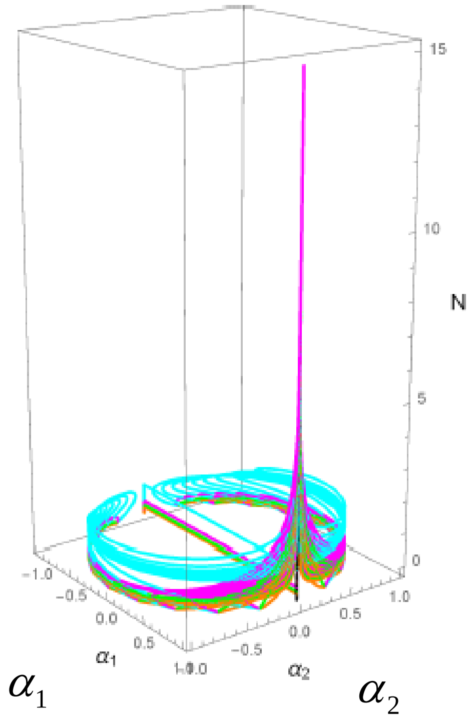
$m^2_{\text{eff}} > 0 \longleftarrow \eta_\perp = 0$

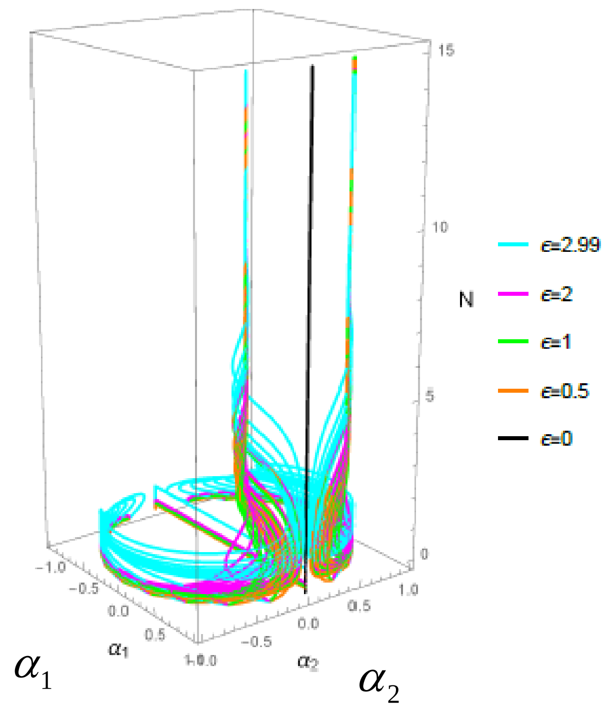
from Christoffels

$$k_2 = \sqrt{k_1^2 + 6} - k_1$$

Stable ultra-light fields for quintessence

[MC,Guidetti,Pedro]





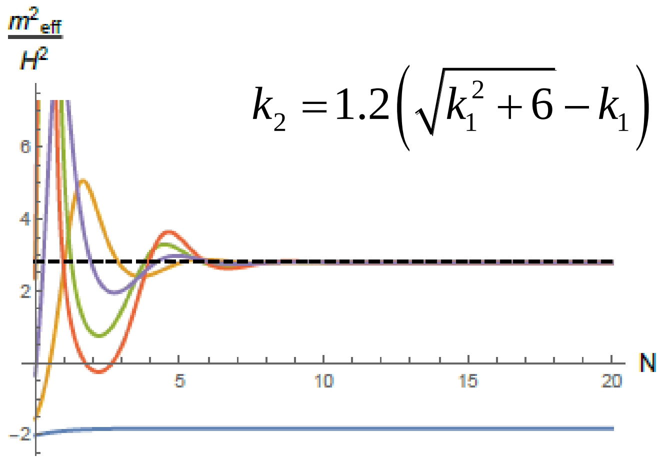
$$\alpha_i = \frac{\dot{\phi}_i}{\dot{\phi}_0} \qquad \alpha_1^2 + \alpha_2^2 = 1$$

$$k_2 = 0.8\left(\sqrt{k_1^2+6} - k_1\right)$$

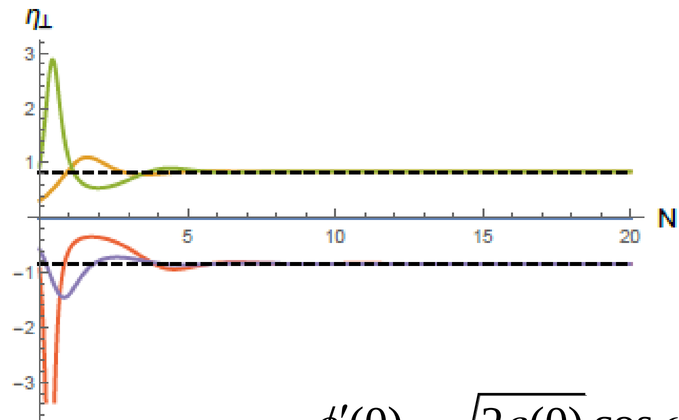
$$k_2 = 1.2\left(\sqrt{k_1^2+6} - k_1\right)$$

Stable ultra-light fields for quintessence

[MC,Guidetti,Pedro]



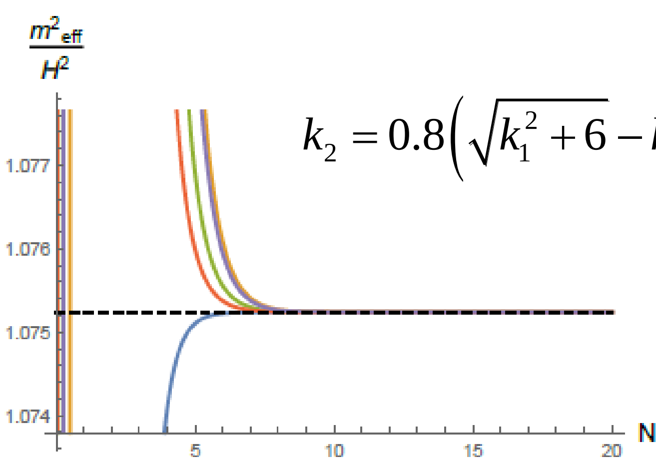
$$k_2 = 1.2\left(\sqrt{k_1^2+6}-k_1\right)$$



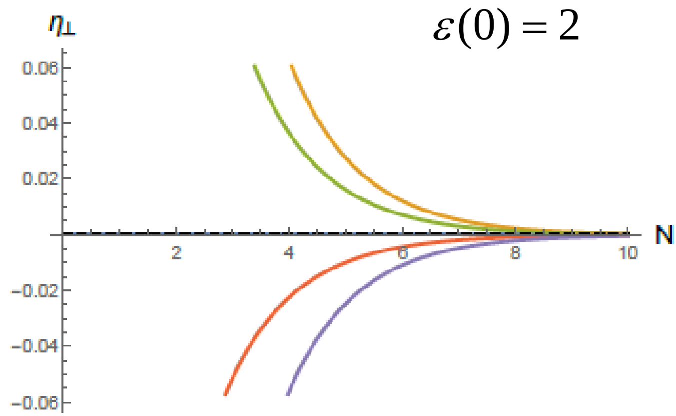
$$\phi_1'(0) = \sqrt{2\varepsilon(0)}\cos\omega$$

$$f\,\phi_2'(0) = \sqrt{2\varepsilon(0)}\sin\omega$$

$$\varepsilon(0) = 2$$



$$k_2 = 0.8\left(\sqrt{k_1^2+6}-k_1\right)$$



Ultra-light axions in Fibre Inflation

[MC,Guidetti,Pedro]

- Potential of Fibre Inflation:

$$V \simeq V_0 \left(3 - 4\, e^{-k\phi_1}\right) \qquad \phi_1(N_e) - \phi_1(0) \simeq \frac{1}{k} \ln\left(1 - \frac{4N_e}{9}\, e^{-k\phi_1(0)}\right)$$

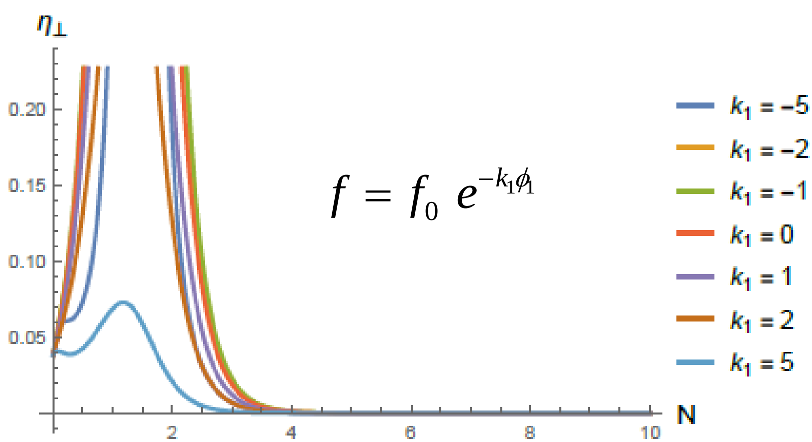
- Kinetic function:

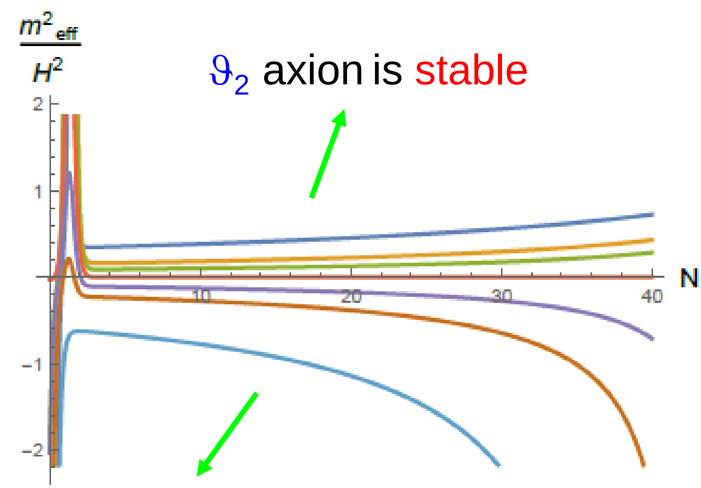
$$f^2(\phi_1) = A_-^2\, e^{-4k\phi_1} \qquad \vartheta_1 \text{ axion}$$

$$f^2(\phi_1) = A_+^2\, e^{2k\phi_1} \qquad \vartheta_2 \text{ axion}$$

- Geodesic motion:

$$\dot{\vartheta}_i(N_e) \simeq \dot{\vartheta}_i(0) \left(\frac{f(0)}{f(N_e)}\right)^2 e^{-3N_e} \simeq \dot{\vartheta}_i(0) \left(\frac{f(0)}{A_\pm}\right)^2 e^{-3N_e \pm ck\phi_1(N_e)} \to 0 \qquad \forall i = 1,2 \qquad \eta_\perp = 0$$





ϑ_2 axion is stable

ϑ_1 axion is unstable

$$\phi_1'(0) = \sqrt{2}\cos(7\pi/5) \qquad f\,\phi_2'(0) = \sqrt{2}\sin(7\pi/5)$$

Stable massive axions?

[MC,Guidetti,Pedro]

- Avoid axion instability by turning on a mass term
- Focus on ϑ_1 axion with $f^2(\phi_1) = A_-^2\, e^{-4k\phi_1}$
- Non-perturbative effects break axionic shift-symmetry $W = W_0 + A_3\, e^{-a_3 T_3} + A_1\, e^{-a_1 T_1}$

$\longrightarrow$ $V(\vartheta_1) = \Lambda \cos\left(a_1 \vartheta_1\right) \qquad \Lambda = \Lambda_0\left(\left\langle \tau_1 \right\rangle\right) e^{-a_1\langle\tau_1\rangle\, e^{2\phi_1/\sqrt{3}}}$

double exponential suppression and ϕ dependence!

- Isocurvature mass-squared:

$$m_{\rm eff}^2 = \frac{V_{\vartheta_1\vartheta_1}}{f^2} + \frac{f_{\phi_1}}{f} V_{\phi_1} + 3\frac{V_{\vartheta_1}^2}{\dot{\phi}_1^2 f^2} \underset{\varepsilon\ll 1}{\simeq} -\lambda \left|V_{\phi_1}\right| \left[1 - \frac{a_1^2}{\lambda f^2 \sqrt{2\varepsilon}} \left(\frac{9\delta^2}{2\varepsilon}\sin^2(a_1\vartheta_1) - \delta\cos(a_1\vartheta_1)\right)\right]$$

$$\delta \equiv \frac{\Lambda\left(\phi_1\right)}{V\left(\phi_1\right)}$$

- 2 options:

i) keep hierarchy and trust inflationary model:

$\delta \ll 1 \quad \longrightarrow \quad m_{\rm eff}^2 \underset{\varepsilon\ll 1}{\simeq} -\lambda \left|V_{\phi_1}\right| < 0$

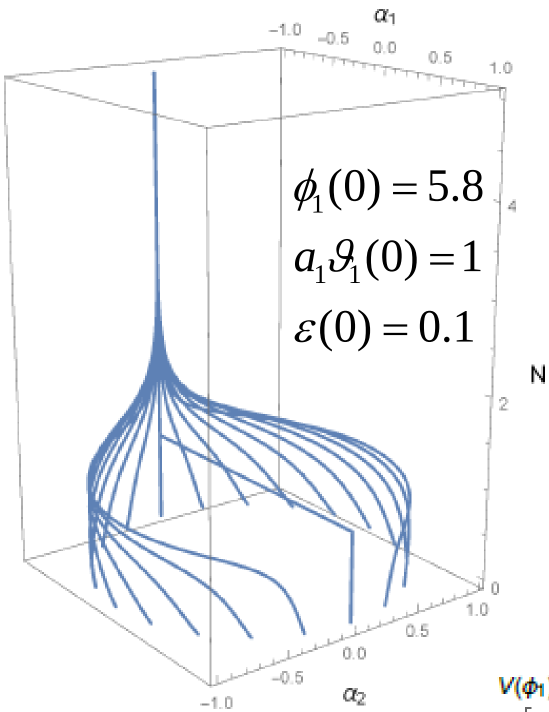
$\longrightarrow$ massive axions still unstable!

ii) make $m_{\rm eff}^2 > 0$ for $\delta \sim O(1)$

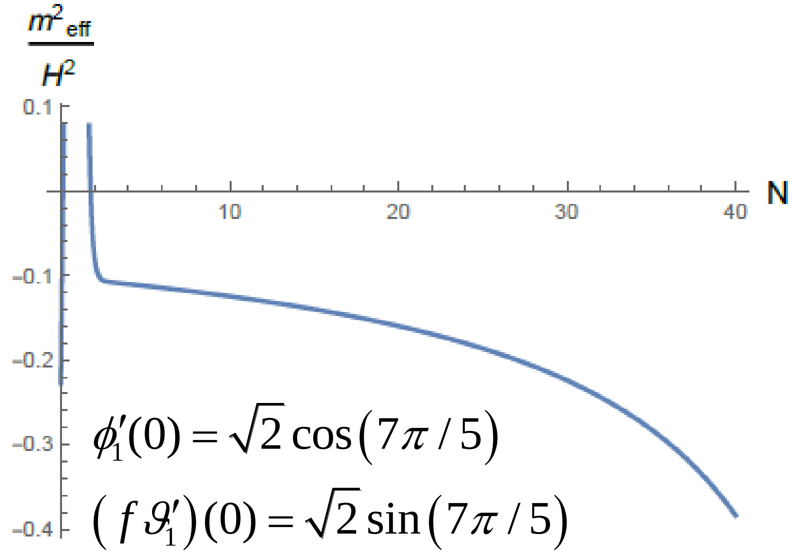
$\longrightarrow$ the dynamics changes and becomes 2-field!

Unstable massive axions

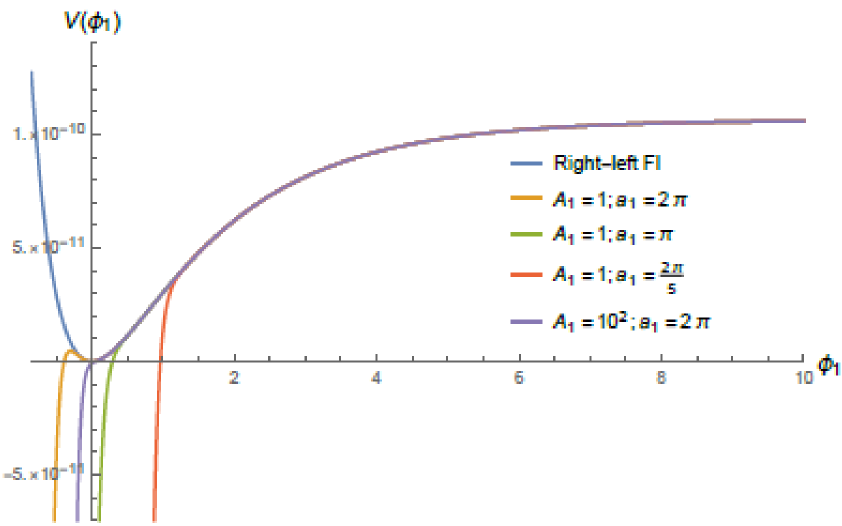
[MC,Guidetti,Pedro]



$$\phi_1(0) = 5.8$$
$$a_1\vartheta_1(0) = 1$$
$$\varepsilon(0) = 0.1$$



$$\phi_1'(0) = \sqrt{2}\cos\left(7\pi/5\right)$$
$$\left(f\vartheta_1'\right)(0) = \sqrt{2}\sin\left(7\pi/5\right)$$



Conclusions

1) Fibre Inflation models: natural inflationary directions

2) Moduli stabilisation: non-perturbative + α' effects + string loops

3) Effective symmetry: non-compact rescalings

4) Starobinsky-like inflation with large tensors: $0.005 \lesssim r \lesssim 0.01$

5) Global CY embedding: $h^{1,1} = 3$ case without chirality + chirality for $h^{1,1} \geq 4$

6) Compact inflaton field space with $\Delta\varphi/M_p \leq c \ln \mathcal{V}$ with $\Delta\varphi > M_p$ only for K3-fibrations

7) General prediction: $r \lesssim 0.01$ $\longrightarrow$ agreement with swampland distance conjecture

8) Reheating: visible sector on D7s wrapping inflaton cycle to avoid large ΔN_{eff}

9) $N_e \approx 52$ and $T_{rh} \approx 10^{10}$ GeV

   fluxed D7: $\Delta N_{eff} \approx 0$ $\longrightarrow$ $n_s \approx 0.965$ and $r \approx 0.007$
   fluxless D7: $\Delta N_{eff} \approx 0.6$ $\longrightarrow$ $n_s \approx 0.99$ and $r \approx 0.01$

10) 2 ultra-light axions can be dark radiation but also dark matter, curvaton or quintessence

11) Are ultra-light fields stable during inflation? Phenomenological implications?