Cosmology of Fibre Inflation Models

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Based on papers written with:
Burgess, Ciupke, Diaz, de Alwis, Guidetti, Mayrhofer, Muia, Pedro, Piovano, Quevedo, Shukla
Challenges for string inflation

- Conditions for viable string inflation:
  
  (i) approximate symmetry to control quantum corrections ➔ inflaton is a pseudo NG boson

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

  (iii) global CY embedding to check theoretical consistency

  (iv) understand post-inflationary cosmology to check phenomenological consistency ➔ make trustable predictions

- $n_s$ and $r$ depend on:

  i) $N_e$ which depends on post-inflation:
     
     reheating: $T_{re}$? $w_{re}$? 
     
     moduli domination: $N_{mod}$? 

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

  ii) fix $n_s$ by matching observations and then predict $r$
     
     BUT Planck value of $n_s$ depends on priors, e.g. $\Delta N_{eff} = 0$ ➔ $n_s = 0.966 \pm 0.006$
     
     $\Delta N_{eff} = 0.39$ ➔ $n_s = 0.983 \pm 0.006$

     can get different $r$! ➔ Compute amount of extra dark radiation $\Delta N_{eff}$

     ultra-light axions?
Moduli stabilisation

- General **Swiss-cheese** form of the CY volume
  \[ V = \frac{1}{6} \sum_{i,j,k=1}^{N_{\text{large}}} k_{ijk} t_i t_j t_k - \frac{1}{6} \sum_{s=1}^{N_{\text{small}}} k_{ssss} t_s^3 \]
  \[ N_{\text{large}} + N_{\text{small}} = h^{1,1} \]

- EFT coordinates: **Kahler moduli**
  \[ \tau_i = \text{Re}(T_i) = \frac{\partial V}{\partial t_i} \]

- Leading order: \( \alpha' \) + non-perturbative effects
  \[ K = -2 \ln \left( V + \frac{\xi}{2 g_s^{3/2}} \right) \]
  \[ W = W_0 + \sum_{s=1}^{N_{\text{small}}} A_s e^{-a_s T_s} \]

- **LVS models**: fix \( V + N_{\text{small}} \) del Pezzo moduli
  \[ V \approx e^{a_s \tau_s} \gg 1 \quad \tau_s \approx g_s^{-1} > 1 \quad \forall s = 1, \ldots, N_{\text{small}} \]
  \[ N_{\text{flat}} = h^{1,1} - N_{\text{small}} - 1 \text{ flat directions!} \]

- Flat directions lifted by **perturbative corrections**

  - Good **inflaton** candidates:
    1) Inflaton naturally lighter than \( H \)
    2) Flatness protected by approximate rescaling **shift symmetry**

  [Burgess, MC, Williams, Quevedo]
Perturbative corrections

- **String loops**: KK + winding 1-loop open string corrections  
  \[ K_{g_s}^{KK} = g_s \sum_i C_{KK_i}^{\perp} \frac{1}{\nu} \sim \sum_i \frac{m_{KK,i}^2}{\nu} \]

- **Higher derivatives**: \( \alpha'^3 F^4 \) terms from 10D \( R^2 G^4 \) term  
  \[ V_{g_s}^{W} = -2 \left( \frac{g_s}{8\pi} \right) \frac{W_0^2}{\nu^2} K_{g_s}^{W} \]

Dependence on all t-moduli!  
fix all LVS flat directions for arbitrary CY if \( \lambda < 0 \)

(\( \lambda < 0 \) with \( |\lambda| \sim 10^{-3} \) from dimensional reduction)
Global CY embedding

1. General requirements for successful global embedding:

   1) Search through the Kreuzer-Skarke list for toric CY 3-folds with:
      (i) fibration structure
      (ii) at least 1 rigid blow-up mode \( N_{small} \geq 1 \)
      (iii) at least 1 flat direction \( h^{1,1} \geq 2 + N_{small} \geq 3 \)

2) Choose and orientifold involution and a D3/D7 brane setup which satisfy tadpole cancellation

3) Fix all Kahler moduli inside Kahler cone

4) Generate \( g_s \) and \( F^4 \alpha' \) terms can drive inflation

5) Turn on gauge fluxes on D7s for a chiral visible sector

6) Get an explicit dS vacuum \( \rightarrow \) use T-branes!

   - For \( h^{1,1} = 3 \) cannot satisfy (5) and (6) since FI-terms lift flat directions
   - For \( h^{1,1} = 4 \) can potentially get a global CY embedding with chirality and dS
Explicit CY models

- $h^{1,1} = 3$: explicit brane set-up + moduli stabilisation without chirality [MC,Muia,Shukla]

- CY volume:
  \[ \mathcal{V} = t_1 t_2^2 + t_3^3 = \sqrt{\tau_1 \tau_2} - \tau_3^{3/2} \]

- Oguiso theorem: if $\mathcal{V}$ is linear in $t_1$
  \[ \tau_1 \] is a K3 or a T4 fibre over a P1 base $t_1$
  \[ \tau_1 \] is the inflaton with $\mathcal{V}$ constant

- $h^{1,1} = 4$: explicit brane set-up + moduli stabilisation + chirality [MC,Ciupke,Diaz,Guidetti,Muia,Shukla]

- CY volume:
  \[ \mathcal{V} = t_1 t_2 \tilde{t}_2 + t_3^3 = \sqrt{\tau_1 \tau_2 \tilde{\tau}_2} - \tau_3^{3/2} \]

- \( \mathcal{V} \) is linear in $t_1$, $t_2$ and $\tilde{t}_2$  \( \rightarrow \) 3 K3 fibrations
- Visible sector on $\tau_1$, $\tau_2$ and $\tilde{\tau}_2$
- Turn on gauge fluxes  \( \rightarrow \)  FI-term = 0 fixes $\tau_2 \sim \tilde{\tau}_2$
- reduce to $h^{1,1} = 3$ case
- String loops + $F^4$ terms give inflation without tuning + chiral visible sector!
Inflation

• Potential for canonical inflaton shifted from minimum:

\[ V_{\text{inf}} = \frac{A W_0^2}{(\tau_f)^2 V^2} \left( C_{\text{ds}} + e^{-2k\varphi} - 4e^{-k\varphi/2} + R_1 e^{k\varphi} + R_2 e^{k\varphi/2} \right) \]

\[ C_{\text{ds}} = 3 - R_1 - R_2 \]

\[ R_1 = \left( \frac{C_{f}^{KK} C_{b}^{KK}}{C_{W}} \right)^2 \frac{g_s^4}{18} \ll 1 \]

\[ R_2 = \frac{18 W_0^2}{\pi} \left( \frac{C_{f}^{KK}}{C_{W}^{5/3}} \right)^{4/3} |\lambda| \frac{g_s^5/6}{V^{1/3}} \ll 1 \]

(i) for \( R_2 \ll R_1 \ll 1 \) \( \rightarrow \) Fibre inflation \[ [\text{MC, Burgess, Quevedo}] \]

(ii) for \( R_1 \ll R_2 \ll 1 \) \( \rightarrow \) \( \alpha' \) inflation \[ [\text{MC, Ciupke, de Alwis, Muia}] \]

Starobinsky-like model with \( \Delta \varphi \simeq 5M_p \)

| \( R_2 \) | \( n_s \) | \( r \) | \( |W_0| \) | \( |\lambda| \) | \( \delta \) |
|---|---|---|---|---|---|
| 0 | 0.964 | 0.007 | 5.7 | 0 | 0.17 |
| \( 7 \times 10^{-4} \) | 0.970 | 0.008 | 6.1 | \( 1.5 \times 10^{-3} \) | 0.17 |
| \( 1.5 \times 10^{-3} \) | 0.977 | 0.012 | 6.7 | \( 2.7 \times 10^{-3} \) | 0.17 |

\[ R_1 = 10^{-6} \]

\[ \delta = \frac{H^2}{m_p^2} \simeq \frac{V_{\text{inf}}}{V_{\alpha'}} \ll 1 \]

BUT predictions depend on reheating

\[ n_s = n_s (\varphi^*, R) = n_s (N_e, R) = n_s (w_{rh}, T_{rh}, R) \]

\[ r = r (\varphi^*, R) = r (w_{rh}, T_{rh}, R) \]
Geometrical bounds

- **Compact** inflaton moduli space due to Kahler cone
  - Upper bounded inflaton range!
  \[ \frac{\Delta \phi}{M_p} \leq c \ln \mathcal{V} \]
  \[ c \sim O(1) \]

- **h^{1,1} = 3**: checked for all toric LVS vacua
  i) \( \Delta \phi > M_p \) only for K3 fibred examples
  ii) agreement with weak gravity conjecture

- **h^{1,1} > 3**: conjecture for volume of reduced moduli space \( \mathcal{M}_r \)
  - \( \Lambda \sim M_p / \mathcal{V}^{2/3} \) (KK scale)

- 3 classes of LVS models for \( h^{1,1} = 3 \):
  1) \( n_{\text{ddP}} = 2 \) and \( n_{K3f} = 0 \): Strong Swiss cheese
     \[ \mathcal{V} = \alpha \tau_b^{3/2} - \beta_1 \tau_s^{3/2} - \beta_2 \tau_s^{3/2} \]
  2) \( n_{\text{ddP}} = 1 \) and \( n_{K3f} = 1 \): K3 fibration
     \[ \mathcal{V} = \alpha \sqrt{\tau_f} \tau_b - \beta \tau_s^{3/2} \]
  3) \( n_{\text{ddP}} = 1 \) and \( n_{K3f} = 0 \): 2 subcases
     for \( \tau_s \to 0 \)
     - Structureless: \( \mathcal{V} = f_{3/2}(\tau_1, \tau_2) - \beta \tau_s^{3/2} \)
     - Strong Swiss cheese-like:
       \[ \mathcal{V} = \alpha \tau_b^{3/2} - \beta_1 \tau_s^{3/2} - \beta_2 (\gamma_1 \tau_s + \gamma_2 \tau_s^*)^{3/2} \]
Scanning results

- **Analytical proof + scanning results**
- **Scan of LVS geometries for** \( h^{1,1} = 2, 3, 4 \)

<table>
<thead>
<tr>
<th>( h^{1,1} )</th>
<th>( n_{CY} )</th>
<th>( n_{LVS} )</th>
<th>( % )</th>
<th>( n_{ddP = 1} )</th>
<th>( n_{ddP = 2} )</th>
<th>( n_{ddP = 3} )</th>
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<td>22</td>
<td>56.4%</td>
<td>22</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>305</td>
<td>132</td>
<td>43.3%</td>
<td>93</td>
<td>39</td>
<td>-</td>
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<tr>
<td>4</td>
<td>1997</td>
<td>749</td>
<td>37.5%</td>
<td>464</td>
<td>261</td>
<td>24</td>
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</tbody>
</table>

- **Classes of LVS models for** \( h^{1,1} = 3 \)

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<tr>
<th>( h^{1,1} )</th>
<th>( n_{CY} )</th>
<th>( n_{LVS} )</th>
<th>SSC</th>
<th>K3 fibred</th>
<th>SSC-like</th>
<th>structureless</th>
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</tr>
</tbody>
</table>

- **Scan of reduced moduli space size for** \( h^{1,1} = 3, \nu = 10^5 \) and \( g_s = 0.1 \)

- Right ballpark to match \( \delta \rho/\rho \)
Bound on tensor modes

- Generic LVS inflationary model

\[ V \simeq V_0 \left(1 - c_1 e^{-c_2 \phi} \right) \quad \rightarrow \quad \epsilon = \frac{1}{2} \left(\frac{V'}{V}\right)^2 \simeq \frac{1}{2} c_1^2 c_2^2 e^{-2c_2 \phi} \]

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

\[ N_e = \int_{\phi_{\text{end}}}^{\phi_*} \frac{8}{r(\phi)} \, d\phi \quad \rightarrow \quad \frac{\Delta \phi}{M_p} \simeq \frac{N_e}{2} \sqrt{\frac{r(\phi_*)}{2}} \ln \left( \frac{4}{\sqrt{r(\phi_*)}} \right) \]

- Combine with upper bound \( \Delta \phi / M_p \leq c \ln V \) for \( N_e = 50 \)

Observations sensitive to \( r(\phi_*) \) of order 0.05 should not see tensors!
Reheating

- End of inflation: transfer inflaton energy to SM dof
SM and dark radiation

- Where is the SM?
- Ultra-light bulk axions from inflaton decay contribute to $\Delta N_{\text{eff}}$
- Observational constraint: $\Delta N_{\text{eff}} \lesssim 1$

\[
\begin{align*}
\text{Inflaton } \phi \\
\text{SM dof} & \quad \text{Bulk axions} \\
\end{align*}
\]

\[\Gamma_{\Phi \rightarrow a_1 a_1} = \frac{1}{24\pi} \frac{m_{\Phi}^3}{M_P^2} \quad \Gamma_{\Phi \rightarrow \text{hidden}} = \frac{5}{2} \Gamma_0 \quad \Gamma_0 = \frac{1}{48\pi} \frac{m_{\Phi}^3}{M_P^2}\]

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

- SM on D3s at a singularity \[\Gamma_{\Phi \rightarrow \text{visible}} \approx \left(\frac{\alpha_{\text{SM}}}{4\pi}\right)^2 \Gamma_0\]

\[\Delta N_{\text{eff}} \sim \left(\frac{4\pi}{\alpha_{\text{SM}}^2}\right)^2 \sim 10^4\]

Dark radiation overproduction!

\[\text{SM on D7s wrapping inflaton cycle to increase branching ratio into visible dof}\]
Reheating and dark radiation

- SM con D7s wrapping bulk cycles $\tau_b$ and $\tau_f$ $\rightarrow$ desequestering
- $M_{soft} \sim m_{3/2} \sim 10^{14}$ GeV $\gg m_\Phi \sim 10^{12}$ GeV $\rightarrow$ inflaton cannot decay to SUSY particles
- Unsuppressed inflaton decay to SM Higgs + would-be GBs + massless gauge bosons

\[
\begin{align*}
\Gamma_{\Phi \rightarrow AA} &= N_g \Gamma_0 \\
\Gamma_{\Phi \rightarrow \text{Higgs}} &= f(\alpha, \beta) \frac{z^2}{16} \Gamma_0 \\
K_{\text{matter}} &= \tilde{K}_{H_u} \tilde{H}_u H_u + \tilde{K}_{H_d} \tilde{H}_d H_d + z \sqrt{\frac{\tau_f}{\mathcal{V}}} (H_u H_d + h.c.)
\end{align*}
\]

- Dark radiation predictions

\[
\Delta N_{\text{eff}} = \frac{43}{7} \frac{5}{2} \left( \frac{10.75}{g_*(T_{rh})} \right)^{1/3} \frac{1}{c_{\text{vis}}} \\
c_{\text{vis}} = 12 + f(\alpha, \beta) \frac{z^2}{16}
\]

- Reheating temperature:

\[
T_{rh} \simeq m_\Phi \sqrt{\frac{m_\Phi}{M_P}} \sim 10^9 \text{ GeV} \quad \rightarrow \quad g_*(T_{rh}) = 106.5 \quad \rightarrow \quad N_e \approx 52
\]

\[
\tan \beta = 1 \quad \beta = \alpha = \frac{\pi}{4} \quad \rightarrow \quad \Delta N_{\text{eff}} = \frac{114.4}{192 + 5z^2} \simeq 0.6 \quad \text{for} \quad z = 0
\]

\[
\Delta N_{\text{eff}} \approx 0.6 \quad \text{as a prior for Planck} \quad \rightarrow \quad n_s = n_s(N_e, \mathcal{R}) = n_s(\mathcal{R}) \approx 0.99
\]

\[
\text{fix } \mathcal{R} \quad \rightarrow \quad \text{prediction: } \quad r = r(N_e, \mathcal{R}) = r(\mathcal{R}) \approx 0.01
\]
PBH DM

- What is the origin of DM?
- Occam’s razor: no new particles/modification of gravity \[ \text{BHs as DM} \]
- PBHs form when large and rare fluctuations re-enter the horizon:

\[
M = \gamma \frac{4\pi}{3} \left( \frac{\rho_{\text{tot}}}{H^3} \right) f = 4\pi \gamma \frac{M_p^2}{H_f}
\]

- E-foldings-mass relation:

\[
\Delta N_{CMB}^{PBH} = 18.4 - \frac{1}{12} \ln \left( \frac{g_*}{g_{*0}} \right) + \frac{1}{2} \ln \gamma - \frac{1}{2} \ln \left( \frac{M}{M_\odot} \right)
\]

\[ \text{low-mass region: } \Delta N_{CMB}^{PBH} \approx 34.5 \]

No known astrophysical mechanism for

\[ 10^{-16} M_\odot \leq M_{\text{PBH}} \leq 10^{-14} M_\odot \]

\[ \text{BHs have to be primordial} \]

Lower bound from evaporation

\[ M_{\text{PBH}} \geq 10^{-17} M_\odot \]

See Diaz’s talk.
PBH formation
PBH abundance

• PBHs form when $\zeta \geq \zeta_c$ re-enter the horizon:

• Collapse fraction:

$$\beta_f(M) = \frac{\rho_{PBH}(M)}{\rho_{tot}} \Bigg|_f = \left[ \int_{\zeta_c}^{\infty} \frac{1}{\sqrt{2\pi \sigma_M^2}} e^{-\frac{\zeta^2}{2\sigma_M^2}} d\zeta \right] \approx \sigma_M \frac{1}{\sqrt{2\pi \zeta_c^2}}$$

$$\sigma_M^2 \approx \langle \zeta \zeta \rangle \approx P_k \ll \zeta_c$$

• Exponentially sensitive to critical value $\zeta_c \approx 1$

• PBHs redshift as matter → present abundance

$$\beta_o(M) = \Omega_{DM} \frac{\rho_{PBH}(M)}{\rho_{DM}} \Bigg|_o = 0.26 f_{PBH}(M) \quad \rightarrow \quad \beta_f(M) \approx 10^{-8} \sqrt{\frac{M}{M_\odot}} f_{PBH}(M)$$

• 100% of DM in PBHs in the low-mass region:

$$f_{PBH}(M) \approx 1 \quad M \approx 10^{-15} M_\odot \quad \rightarrow \quad \beta_f(M) \approx 3 \times 10^{-16}$$

$$P_k \Bigg|_{PBH} \approx 10^7 \times P_k \Bigg|_{CMB} \approx 10^{-2} \quad \frac{\delta \rho}{\rho} \approx 0.1$$

Perturbation theory under control?
PBHs from inflation

• For single field dynamics

• Power spectrum in slow-roll approximation:
  \[ P_k = \frac{H^2}{8\pi^2\varepsilon} \]
  \[ \varepsilon \approx \frac{1}{2} \left( \frac{V_\varphi}{V} \right)^2 \]

• Enhancement for \( \varepsilon \to 0 \iff V_\varphi \approx 0 \)
  Near inflection point

• \( \varepsilon \) controls the velocity:
  \[ \varepsilon = -\frac{\dot{H}}{H^2} = \frac{1}{2} \frac{\dot{\phi}^2}{H^2} \]
  \( \varepsilon_{PBH} \approx 10^{-7} \times \varepsilon_{CMB} \)
  Velocity varies a lot!

• Deceleration no-longer negligible
  Violation of slow-roll

• Need to solve Mukhanov-Sasaki equation for rescaled curvature perturbations:
  \[ u_k''(\tau) + \left( k^2 - \frac{z''}{z} \right) u_k(\tau) = 0 \]
  \[ \frac{z''}{z} = \left( aH \right)^2 \left[ 2 - \varepsilon + \frac{3}{2} \eta - \frac{1}{2} \varepsilon \eta + \frac{1}{4} \eta^2 + \frac{1}{2} \eta \kappa \right] \]

\[ \zeta = u / z \quad z \equiv \sqrt{2\varepsilon a} \]
\[ \eta = \frac{\dot{\varepsilon}}{\varepsilon H} \quad \kappa = \frac{\dot{\eta}}{\eta H} \]
Ultra slow-roll

- Klein-Gordon eq. in expanding universe:

\[ \ddot{\phi} + 3H \dot{\phi} + V_\phi = 0 \]

i) Constant velocity: \( \dot{\phi} \approx 0 \)

\[ \rightarrow \quad 3H \dot{\phi} \approx -V_\phi \quad \text{Slow roll} \]

ii) Near inflection point: \( V_\phi \approx 0 \)

\[ \rightarrow \quad \dot{\phi} \approx -3H \dot{\phi} \quad \text{Ultra slow-roll} \quad \rightarrow \quad \text{deceleration} \]

\[ \varepsilon = \frac{1}{2} \frac{\dot{\phi}^2}{H^2} \ll 1 \]

\[ \eta = 2 \left( \frac{\ddot{\phi}}{H \dot{\phi}} + \varepsilon \right) \approx -6 \]

- Power spectrum for super-horizon scales:

\[ P_k \propto H^{[\lambda]-1} a^{\lambda+|\dot{\lambda}|} \]

\[ \lambda \equiv 3 + 2\alpha \quad \dot{\phi} \equiv -(3 + \alpha) H \dot{\phi} \]

i) Constant mode for \( \lambda < 0 \) \( \iff \quad -3 \leq \alpha < -3/2 \)

ii) Growing mode for \( \lambda > 0 \) \( \iff \quad \alpha > -3/2 \)

\[ \rightarrow \quad \text{Ultra slow-roll + growing mode help to produce PBHs} \]

[Martin,Motohashi,Suyama]

[Motohashi,Starobinsky,Yokoyama]
PBHs from Fibre Inflation

- Original Fibre inflation potential not rich enough to generate PBHs
- Embedding in explicit CY threefolds with O3/O7, D3/D7, moduli stabilisation, tadpole cancellation and chiral matter
  
  more general structure of corrections

\[ \delta V_w = W_0^2 \frac{\tau_{K3}}{V^4} \left( D_w - \frac{G_w}{1 + R_w \frac{\tau_{K3}^{3/2}}{V}} \right) \]

Term responsible for near inflection point

potential rich enough to tune a near-inflation point:

- Parameters depend on flux quanta and CY intersections
  - Tuning freedom from string landscape
- Approximate shift symmetry for \( \tau_{K3} \)
  - Tuning is technically natural
Superhorizon evolution and power spectrum

\[ n_s = 0.9437 \]
\[ \frac{dn_s}{d \ln k} = -0.0017 \]
\[ r = 0.015 \]

3\(\sigma\) tension with data for \(n_s\) shared by other single field PBH models BUT…
Open issues

• **Right critical value?**
  Recently: use critical density, instead of curvature, perturbations
  \[ \zeta_c \approx 1 \rightarrow 0.5 \]
  \[ P_k|_{PBH} \approx 10^7 \times P_k|_{CMB} \approx 10^{-2} \rightarrow P_k|_{PBH} \approx 10^{-3} \]

  \[ \rightarrow \text{get a larger } n_s! \]

• **Perturbation theory under control?**
  Recently: backreaction of perturbations with stochastic analysis
  \[ P_k|_{PBH} \approx 10^{-3} \rightarrow P_k|_{PBH} \approx 10^{-6} \]

  \[ \rightarrow \text{Huge effect!} \]

• **Non-gaussianities?**
  Recently: increase PBH abundance
  \[ \text{get much larger } n_s \text{ and much less tuning!} \]

[Yoo, Harada, Garriga, Kohri]
[Germani, Musco]
[Ezquiaga, Garcia, Biagetti, Franciolini, Kehagias, Riotto]

\[ n_s \approx 0.5 \rightarrow 1 \]
\[ c \zeta \rightarrow 1 \]
\[ 10^{-3} \times \text{PBH} \text{ CMB} \text{ PBH} \rightarrow 10^{-6} \]

\[ 7 \times 10^{-2} \times \text{PBH} \text{ PBH} \rightarrow 10^{-3} \times \text{PBH} \text{ PBH} \rightarrow 10^{-6} \]

\[ k \times 10^{10} \]

\[ k \times 10^{10} \rightarrow k \times 10^{10} \]
Outlook

• **Goal:** understand PBH production from strings: generic mechanism, preferred PBH masses

• **To do:**

  i) Redo the analysis with $\zeta_c \approx 0.5$, quantum diffusion + non-Gaussianities

  ii) Consider more general Fibre Inflation potential

  iii) Find other single-field potentials from strings, axions? [Ozsoy, Parameswaran, Tasinato, Zavala]

  iv) Consider matter domination due to light moduli (axions) at horizon re-entry

  v) Find curvaton-like mechanism for PBH production, axions? [Ando, Inomata, Kawasaki, Mukaida, Yanagida]

  vi) Study oscillon (oscilloton) collapse into BHs at the end of inflation

      [Antusch, Cefalà, Krippendorf, Muia, Orani, Quevedo] [Helfer, Marsh, Clough, Fairbairn, Lim, Becerril]

      → much smaller and lighter BHs → reheating and DM from evaporation?

      [Lennon, March-Russell, Petrossian-Byrne, Tillim]
A geometrical instability?

- **Spectator fields** during inflation: heavy \((m_{\text{heavy}} \gg H)\) + light \((m_{\text{light}} \ll m_{\text{inf}} \ll H)\)
- Effective mass of isocurvature pert.

\[
m_{\text{eff}}^2 = V_{\perp \perp} - \Gamma^i_{\perp \perp} V_i + \left( \varepsilon R + 3\eta_{\perp}^2 \right) H^2 \quad \eta_{\perp} = \frac{\dot{\phi}}{H} \kappa^{-1}
\]

- Geometrical destabilisation during inflation in a non-linear sigma model?
- Dangerous even for heavy fields with geodesic trajectories \((\eta_{\perp} = 0)\) when \(R < 0\) since

\[
m_{\text{eff}}^2 = V_{\perp \perp} - \Gamma^i_{\perp \perp} V_i - \varepsilon |R| H^2 < 0 \quad \text{if} \quad |R| = M_p / M \gg 1
\]

- NB: \(R < 0\) generic in supergravity since \(K = -3 \ln(T + \bar{T})\) → \(R = -8 / 3\)

**BUT** \(m_{\text{eff}}^2 > 0\) if computed on attractor background trajectory with \(\eta_{\perp} \neq 0\)!

- Real issue for ultra-light fields with \(V_{\perp \perp} = 0\) when \(R < 0\)

\[
m_{\text{eff}}^2 = -\Gamma^i_{\perp \perp} V_i - \varepsilon |R| H^2 + 3\eta_{\perp}^2 H^2
\]

1) **Bending trajectory** with \(\eta_{\perp} \neq 0\) can give \(m_{\text{eff}}^2 > 0\)

   → Isocurvature pert. source curvature pert. → effectively single-field

2) **Geodesic trajectory** with \(\eta_{\perp} = 0\)

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

   → Isocurvature pert. grow → perturbation theory breaks down

   → non-perturbative analysis (numerical)

   → Intuition: kick along ultra-light direction and backreaction from \(\eta_{\perp} \neq 0\)?
Conclusions

1) **Type IIB Fibre Inflation** models: natural inflationary directions

2) **Moduli stabilisation**: non-perturbative + $\alpha'$ effects + string loops + $F^4$ terms

3) **Effective symmetry**: non-compact rescalings

4) Plateau-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 reduced moduli space with $\Delta \phi / M_p \leq c \ln \mathcal{V}$ with $\Delta \phi > M_p$ only for K3-fibrations

7) General prediction: $r \lesssim 0.01$ $\rightarrow$ agreement with weak gravity conjecture

8) **Reheating**: visible sector on bulk cycles due to generic $\Delta N_{\text{eff}} \neq 0$

9) $N_e \approx 52$ and $\Delta N_{\text{eff}} \approx 0.6$ $\rightarrow$ $n_s \approx 0.99$ and $r \approx 0.01$

10) Potential rich enough to have a plateau + near inflection point

11) Power spectrum enhancement due to ultra slow roll + growing mode

12) PBHs in the **low-mass region** as 100% of DM

13) Are **ultra-light fields** stable during inflation?