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}?

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

  ii) fix n_s by matching observations and then predict r

  BUT Planck value of n_s depends on priors, 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 ΔN_{eff}

  ultra-light axions?

Moduli stabilisation

- General Swiss-cheese form of the 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

$$\tau_i = \mathrm{Re}(T_i) = \frac{\partial \mathcal{V}}{\partial t_i}$$

- 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_{small} del Pezzo moduli

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

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

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

→ Good inflaton candidates:

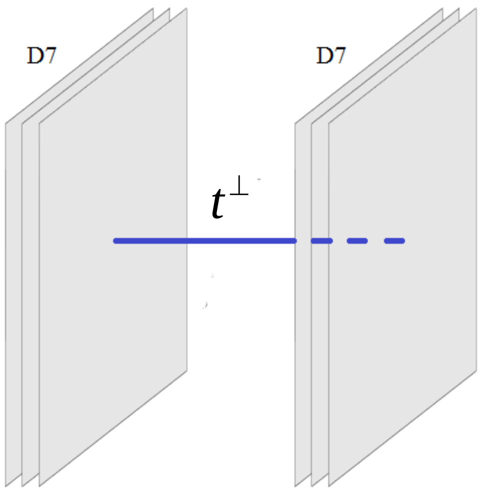
1) Inflaton naturally lighter than H
2) Flatness protected by approximate rescaling shift symmetry

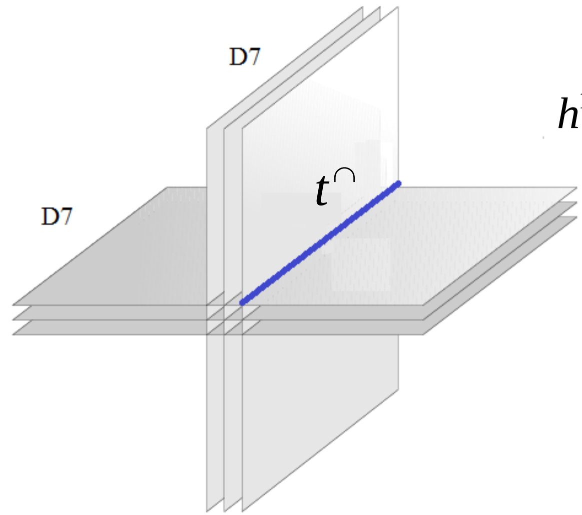
[Burgess, MC, Williams, Quevedo]

Perturbative corrections

- String loops: KK + winding 1-loop open string corrections [Berg,Haack, Kors] [Berg,Haack, Pajer]

$$K^{\rm KK}_{g_s} = g_s \sum_i \frac{C_i^{\rm KK} t_i^{\perp}}{\mathcal{V}} \sim \sum_i \frac{m_{{\rm KK},i}^{-2}}{\mathcal{V}} \qquad K^{\rm W}_{g_s} = \sum_i \frac{C_i^{\rm W}}{\mathcal{V} t_i^{\cap}} \sim \sum_i \frac{m_{{\rm W},i}^{-2}}{\mathcal{V}}$$





$$h^{1,0}\left(D7 \cap D7\right) \neq 0$$

$$V^{\rm KK}_{g_s} = g_s^2 \left(\frac{g_s}{8\pi}\right) \frac{W_0^2}{\mathcal{V}^2} \sum_{ij} C_i C_j K_{ij} \qquad V^{\rm W}_{g_s} = -2 \left(\frac{g_s}{8\pi}\right) \frac{W_0^2}{\mathcal{V}^2} K^{\rm W}_{g_s}$$

[MC, Conlon, Quevedo]

- Higher derivatives: α'^3 F^4 terms from 10D R^2 G^4 term [Ciupke, Louis, Westphal]

$$V_{F^4} = -\left(\frac{g_s}{8\pi}\right)^2 \frac{3^4 \lambda W_0^4}{g_s^{3/2} \mathcal{V}^4} \Pi_i t_i \qquad \Pi_m = \int_X c_2 \wedge \hat{D}_m$$

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

[MC,Ciupke, de Alwis, Muia]

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

[Green, Mayer, Weissenbacher]

Global CY embedding

See Guidetti's talk

- General requirements for successful global embedding: [MC,Muia,Shukla]

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

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 α' terms can drive inflation

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

6) Get an explicit dS vacuum → use T-branes! [MC, Quevedo, Valandro]

- 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

[MC, Ciupke, Diaz, Guidetti, Muia, Shukla]

Explicit CY models

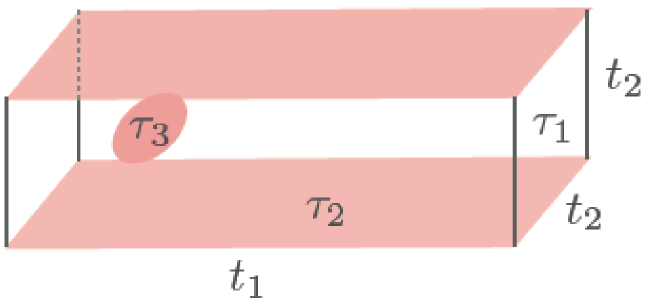
- $h^{1,1} = 3$: explicit brane set-up + moduli stabilisation without chirality [MC,Muia,Shukla]
- CY volume:

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

- Oguiso theorem: if $\mathcal{V}$ is linear in t_1

  → τ_1 is a K3 or a T^4 fibre over a P^1 base t_1

  → τ_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 $\tilde{t}_2$ → 3 K3 fibrations
- Visible sector on τ_1, τ_2 and $\tilde{\tau}_2$
- Turn on gauge fluxes → 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

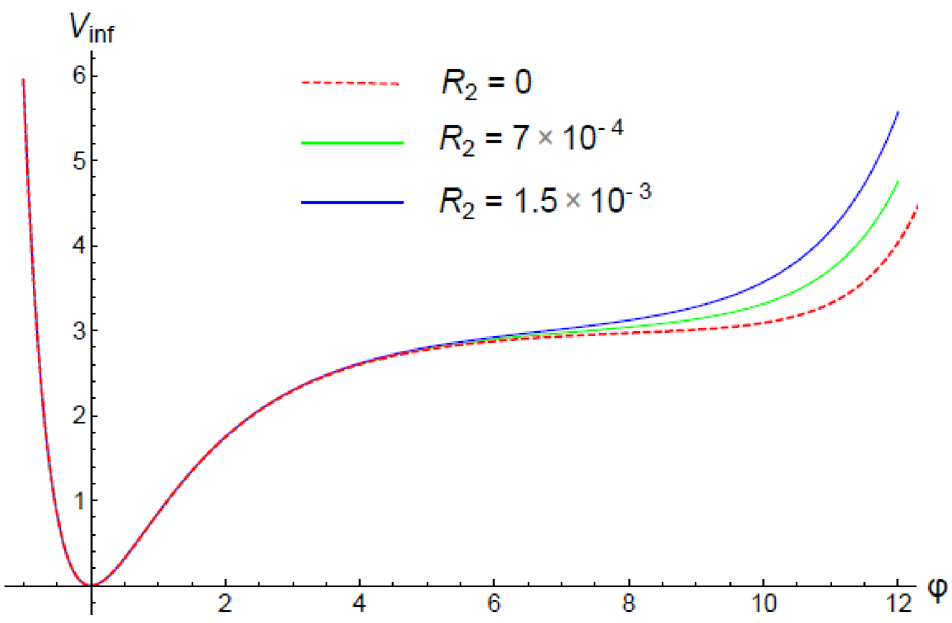
- Potential for canonical inflaton shifted from minimum: [MC, Muia, Shukla]

$$V_{\rm inf} = \frac{AW_0^2}{\langle\tau_f\rangle^2\mathcal{V}^2}\left(C_{\rm dS} + e^{-2k\varphi} - 4e^{-\frac{k\varphi}{2}} + \mathcal{R}_1\, e^{k\varphi} + \mathcal{R}_2\, e^{\frac{k\varphi}{2}}\right) \qquad C_{\rm dS} = 3 - \mathcal{R}_1 - \mathcal{R}_2$$

$$\mathcal{R}_1 = \left(\frac{C_f^{\rm KK}C_b^{\rm KK}}{C_{\rm W}}\right)^2 \frac{g_s^4}{18} \ll 1 \qquad \mathcal{R}_2 = \frac{18\,W_0^2}{\pi}\frac{\left(C_f^{\rm KK}\right)^{4/3}}{C_{\rm W}^{5/3}}\frac{|\lambda|\,g_s^{5/6}}{\mathcal{V}^{1/3}} \ll 1$$

(i) for $\mathcal{R}_2 \ll \mathcal{R}_1 \ll 1$ → Fibre inflation [MC, Burgess, Quevedo]

(ii) for $\mathcal{R}_1 \ll \mathcal{R}_2 \ll 1$ → α' inflation [MC,Ciupke, de Alwis, Muia]



Starobinsky-like model with $\Delta\varphi \simeq 5M_p$

$\mathcal{R}_2$	n_s	r	$\lvert W_0\rvert$	$\lvert\lambda\rvert$	δ
0	0.964	0.007	5.7	0	0.17
$7\cdot 10^{-4}$	0.970	0.008	6.1	$1.5\cdot 10^{-3}$	0.17
$1.5\cdot 10^{-3}$	0.977	0.012	6.7	$2.7\cdot 10^{-3}$	0.17

$$\mathcal{R}_1 = 10^{-6} \qquad \delta = \frac{H^2}{m_{\mathcal{V}}^2} \simeq \frac{V_{\rm inf}}{V_{\alpha'}} \ll 1$$

BUT predictions depend on reheating

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

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

Geometrical bounds

See Shukla's talk

- Compact inflaton moduli space due to Kahler cone

  → Upper bounded inflaton range! $\frac{\Delta\phi}{M_p} \leq c \ln \mathcal{V}$ $c \sim \mathcal{O}(1)$

  [MC, Ciupke, Mayrhofer, Shukla]

- $h^{1,1} = 3$: checked for all toric LVS vacua

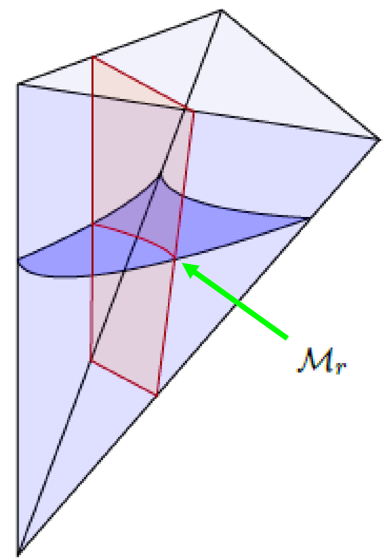
  i) $\Delta\varphi > M_p$ only for K3 fibred examples

  ii) agreement with weak gravity conjecture

- $h^{1,1} > 3$: conjecture for volume of reduced moduli space $\mathcal{M}_r$

$$\mathrm{Vol}(\mathcal{M}_r) \lesssim \left[\ln\left(\frac{M_p}{\Lambda}\right)\right]^{\dim(\mathcal{M}_r)}$$

$\Lambda \sim M_p/\mathcal{V}^{2/3}$ (KK scale)



- 3 classes of LVS models for $h^{1,1} = 3$:

1) $n_{\rm ddP} = 2$ and $n_{\rm K3f} = 0$: Strong Swiss cheese

$$\mathcal{V} = \alpha\,\tau_b^{3/2} - \beta_1\,\tau_{s1}^{3/2} - \beta_2\,\tau_{s2}^{3/2}$$

2) $n_{\rm ddP} = 1$ and $n_{\rm K3f} = 1$: K3 fibration

$$\mathcal{V} = \alpha\sqrt{\tau_f}\,\tau_b - \beta\,\tau_s^{3/2}$$

3) $n_{\rm ddP} = 1$ and $n_{\rm K3f} = 0$: 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:

$$\mathcal{V} = \alpha\tau_b^{3/2} - \beta_1\,\tau_s^{3/2} - \beta_2\,(\gamma_1\,\tau_s + \gamma_2\,\tau_*)^{3/2}$$

Scanning results

[MC, Ciupke, Mayrhofer, Shukla]

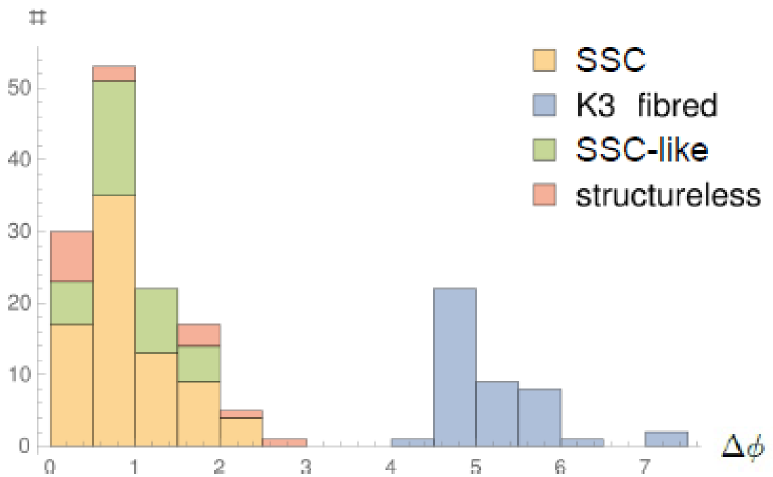
- Analytical proof + scanning results
- Scan of LVS geometries for $h^{1,1} = 2, 3, 4$

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

- Classes of LVS models for $h^{1,1} = 3$

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

- Scan of reduced moduli space size for $h^{1,1} = 3$, $\mathcal{V} = 10^5$ and $g_s = 0.1$



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

Bound on tensor modes

[MC, Ciupke, Mayrhofer, Shukla]

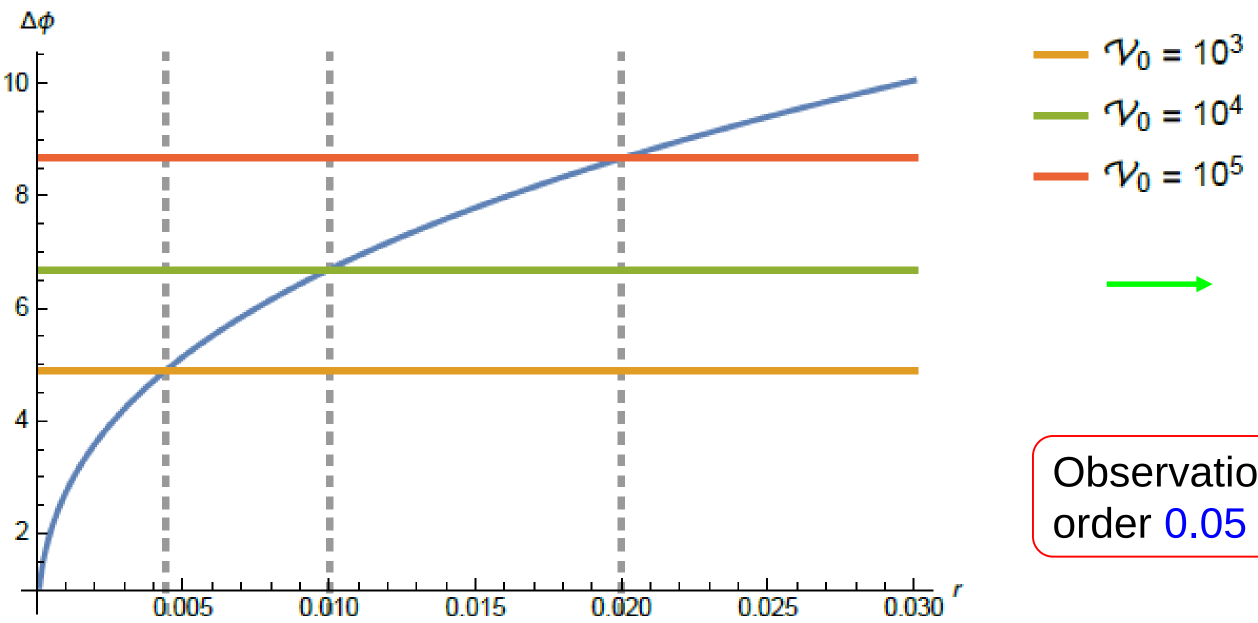
- Generic LVS inflationary model

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

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

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

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

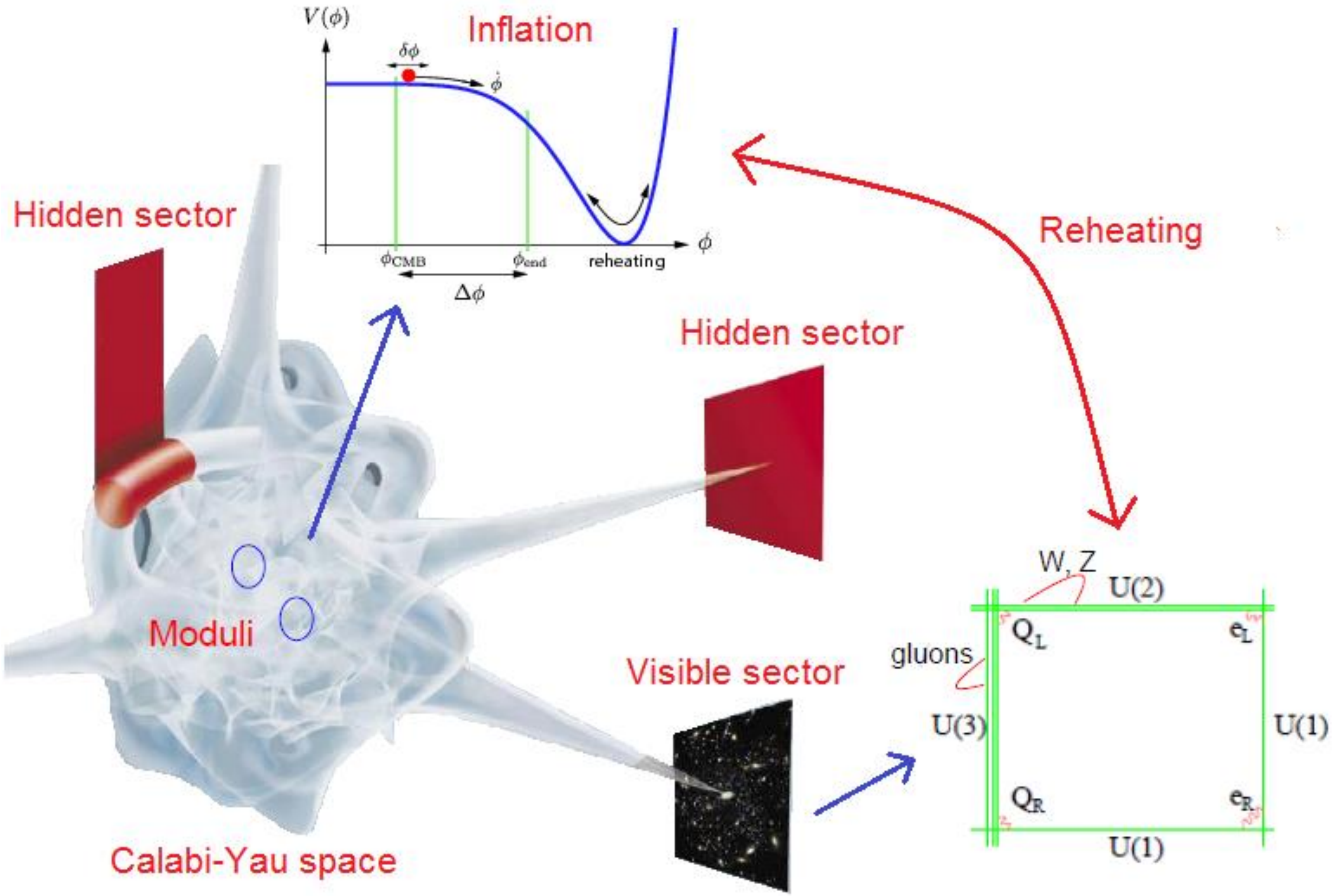


$\longrightarrow\ r(\phi_*) \lesssim 0.01$

Observations sensitive to $r(\varphi_*)$ 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 ΔN_{eff}
- Observational constraint: $\Delta N_{eff} \lesssim 1$

Inflaton ϕ

SM dof ← Inflaton ϕ → Bulk axions → $\Delta N_{eff} > 0$

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

$$\begin{cases} \Gamma_{\Phi \to a_1 a_1} = \frac{1}{24\pi}\frac{m_\Phi^3}{M_P^2} \\ \Gamma_{\Phi \to a_2 a_2} = \frac{1}{96\pi}\frac{m_\Phi^3}{M_P^2} \end{cases} \longrightarrow \quad \Gamma_{\Phi \to hidden} = \frac{5}{2}\Gamma_0 \qquad \Gamma_0 = \frac{1}{48\pi}\frac{m_\Phi^3}{M_P^2}$$

- SM on D3s at a singularity → sequestering → loop suppressed decay rates

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

Dark radiation overproduction!

→ SM on D7s wrapping inflaton cycle to increase branching ratio into visible dof

Reheating and dark radiation

[MC, Piovano]

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

$$\begin{cases} \Gamma_{\Phi\to AA} = N_g \Gamma_0 \\ \Gamma_{\Phi\to \mathrm{Higgs}} = f(\alpha,\beta)\dfrac{z^2}{16}\Gamma_0 \end{cases} \qquad N_g = 12 \qquad f(\alpha,\beta) = 3\sin^2(2\beta) + \sin^2(2\alpha)$$

$$K_{\mathrm{matter}} = \tilde{K}_{H_u}\bar{H}_u H_u + \tilde{K}_{H_d}\bar{H}_d H_d + z\frac{\sqrt{\tau_f}}{\mathcal{V}}(H_u H_d + h.c.)$$

- Dark radiation predictions

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

- Reheating temperature:

$$T_{rh} \simeq m_\phi \sqrt{\frac{m_\phi}{M_P}} \sim 10^9\ GeV \longrightarrow g_*(T_{rh}) = 106.5 \longrightarrow N_e \simeq 52$$

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

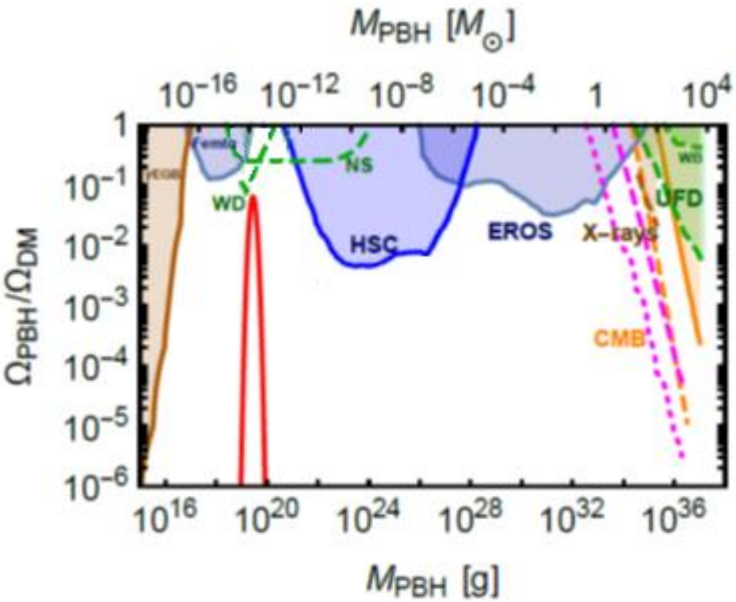
⟶ $\Delta N_{\mathrm{eff}} \approx 0.6$ as a prior for Planck ⟶ $n_s = n_s(N_e, \mathcal{R}) = n_s(\mathcal{R}) \simeq 0.99$

⟶ fix $\mathcal{R}$ ⟶ prediction: $r = r(N_e, \mathcal{R}) = r(\mathcal{R}) \simeq 0.01$

PBH DM

See Diaz's talk

- What is the origin of DM?
- Occam's razor: no new particles/modification of gravity → BHs as DM



No known astrophysical mechanism for

$$10^{-16}\ M_\odot \leq M_{PBH} \leq 10^{-14} M_\odot$$

→ BHs have to be primordial

Lower bound from evaporation

$$M_{PBH} \geq 10^{-17}\ M_\odot$$

- PBHs form when large and rare fluctuations re-enter the horizon:

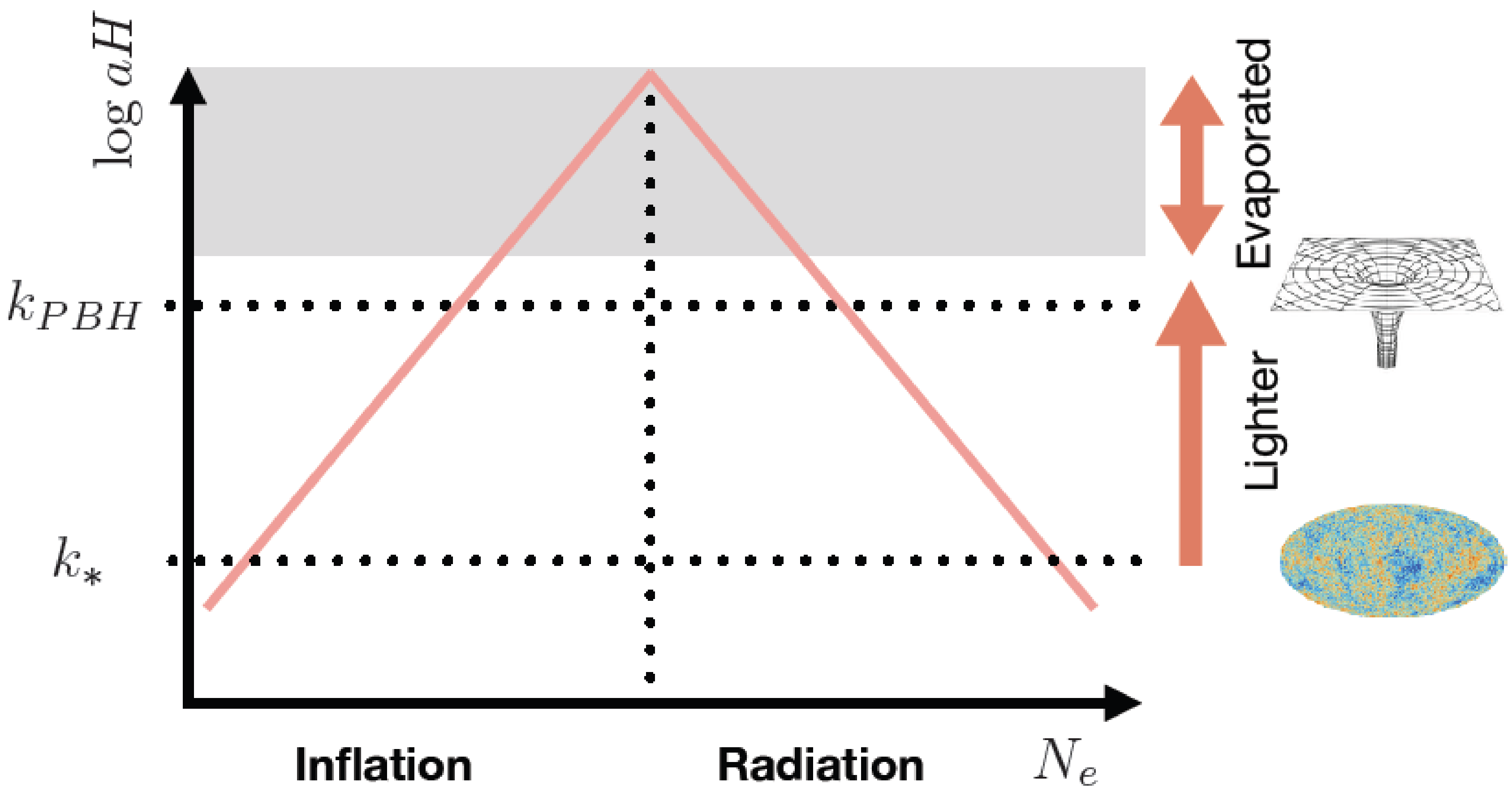
$$M = \gamma \frac{4\pi}{3} \frac{\rho_{tot}}{H^3}\bigg|_f = 4\pi\gamma \frac{M_p^2}{H_f}$$

- E-foldings-mass relation:

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

→ low-mass region: $\Delta N_{CMB}^{PBH} \simeq 34.5$

PBH formation



PBH abundance

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

- Collapse fraction:

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

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

- Exponentially sensitive to critical value $\zeta_c \simeq 1$

- PBHs redshift as matter ⟶ present abundance

$$\beta_o(M) = \Omega_{DM} \left.\frac{\rho_{PBH}(M)}{\rho_{DM}}\right|_o = 0.26\, f_{PBH}(M) \longrightarrow \beta_f(M) \simeq 10^{-8} \sqrt{\frac{M}{M_\odot}}\, f_{PBH}(M)$$

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

$$f_{PBH}(M) \simeq 1 \qquad M \simeq 10^{-15} M_\odot \longrightarrow \beta_f(M) \simeq 3\times 10^{-16}$$

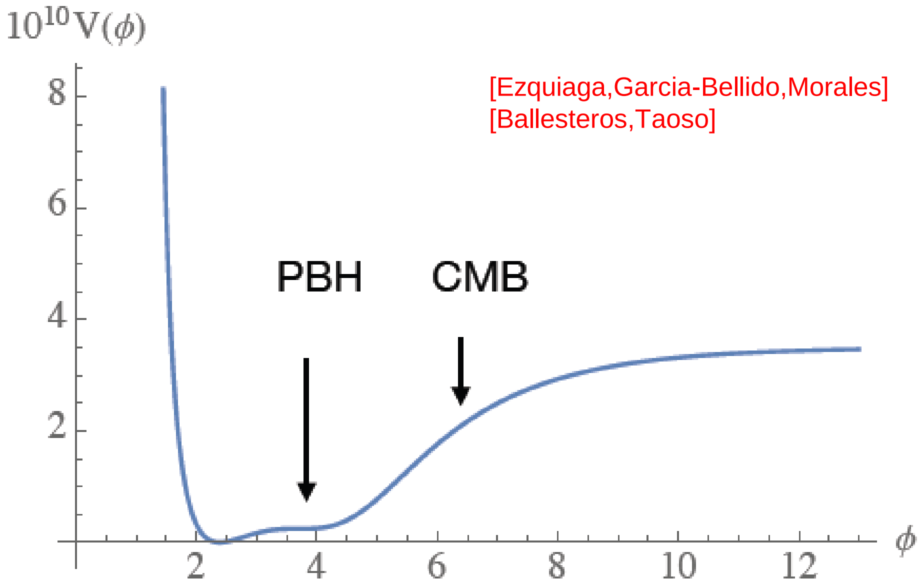
$$\longrightarrow \left. P_k \right|_{PBH} \simeq 10^7 \times \left. P_k \right|_{CMB} \simeq 10^{-2} \qquad \frac{\delta\rho}{\rho} \simeq 0.1$$

Perturbation theory under control?

PBHs from inflation

- For single field dynamics
- Power spectrum in slow-roll approximation: $P_k = \frac{H^2}{8\pi^2\varepsilon}$ $\varepsilon \simeq \frac{1}{2}\left(\frac{V_\varphi}{V}\right)^2$
- Enhancement for $\varepsilon \to 0 \Leftrightarrow V_\phi \simeq 0$

  → Near inflection point



- ε controls the velocity: $\varepsilon = -\frac{\dot{H}}{H^2} = \frac{1}{2}\frac{\dot{\varphi}^2}{H^2}$

  $\varepsilon_{PBH} \simeq 10^{-7} \times \varepsilon_{CMB}$

  → Velocity varies a lot!
- Deceleration no-longer negligible

  → Violation of slow-roll
- Need to solve Mukhanov-Sasaki equation for rescaled curvature perturbations:

$$u_k''(\tau) + \left(k^2 - z''/z\right)u_k(\tau) = 0 \qquad \zeta = u/z \qquad z \equiv \sqrt{2\varepsilon}a$$

$$\frac{z''}{z} = (aH)^2\left[2 - \varepsilon + \frac{3}{2}\eta - \frac{1}{2}\varepsilon\eta + \frac{1}{4}\eta^2 + \frac{1}{2}\eta\kappa\right] \qquad \eta = \frac{\dot{\varepsilon}}{\varepsilon H} \qquad \kappa = \frac{\dot{\eta}}{\eta H}$$

Ultra slow-roll

[Martin,Motohashi,Suyama]
[Motohashi,Starobinsky,Yokoyama]

- Klein-Gordon eq. in expanding universe:

$$\ddot{\varphi}+3H\dot{\varphi}+V_\varphi=0$$

i) Constant velocity: $\ddot{\varphi}\simeq 0$

→ $3H\dot{\varphi}\simeq -V_\varphi$ Slow roll

ii) Near inflection point: $V_\varphi\simeq 0$

→ $\ddot{\varphi}\simeq -3H\dot{\varphi}$ Ultra slow-roll → deceleration

$$\varepsilon=\frac{1}{2}\frac{\dot{\varphi}^2}{H^2}\ll 1 \qquad \eta=2\left(\frac{\ddot{\varphi}}{H\dot{\varphi}}+\varepsilon\right)\simeq -6$$

- Power spectrum for super-horizon scales:

$$P_k\propto H^{|\lambda|-1}a^{\lambda+|\lambda|} \qquad \lambda\equiv 3+2\alpha \qquad \ddot{\varphi}\equiv-(3+\alpha)H\dot{\varphi}$$

→ $\alpha=-3$ SR

→ $\alpha=0$ USR

i) Constant mode for $\lambda<0 \Leftrightarrow -3\le\alpha<-3/2$

ii) Growing mode for $\lambda>0 \Leftrightarrow \alpha>-3/2$

→ Ultra slow-roll + growing mode help to produce PBHs

PBHs from Fibre Inflation

[MC, Diaz, Pedro]

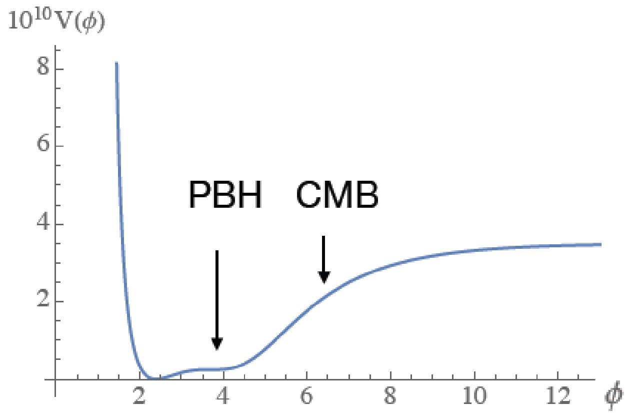
- Original Fibre inflation potential not rich enough to generate PBHs
- Embedding in explicit CY threefolds with O3/O7, D3/D7, moduli stabilisation, tadpole cancellation and chiral matter

→ more general structure of corrections

$$\delta V_{\rm W} = W_0^2 \frac{\tau_{\rm K3}}{\mathcal{V}^4}\left(D_{\rm W} - \frac{G_{\rm W}}{1 + R_{\rm W}\frac{\tau_{\rm K3}^{3/2}}{\mathcal{V}}}\right) \qquad D_{\rm W} \sim G_{\rm W} \sim R_{\rm W} \sim \mathcal{O}(1)$$

Term responsible for near inflection-point

→ potential rich enough to tune a near-inflection point:



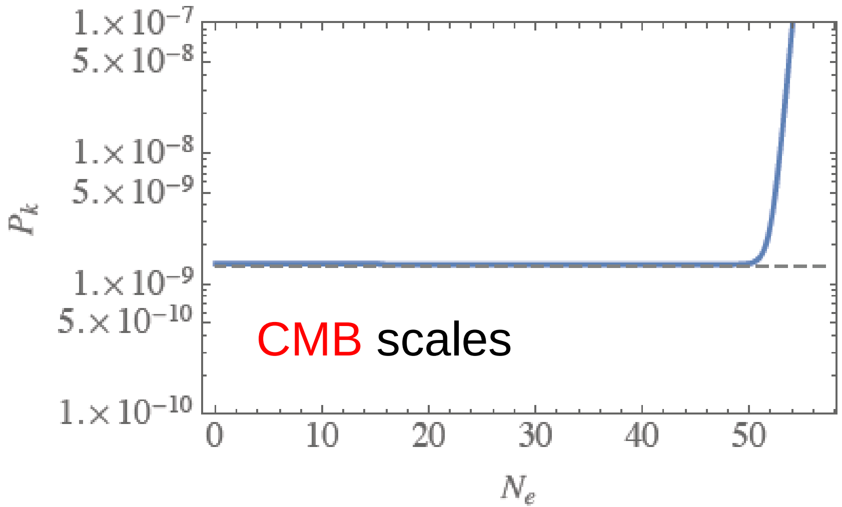
i) Parameters depend on flux quanta and CY intersections

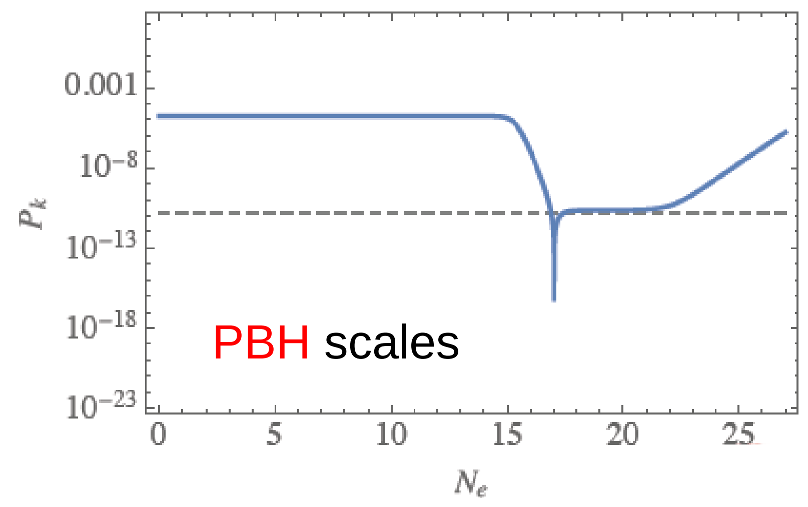
→ Tuning freedom from string landscape

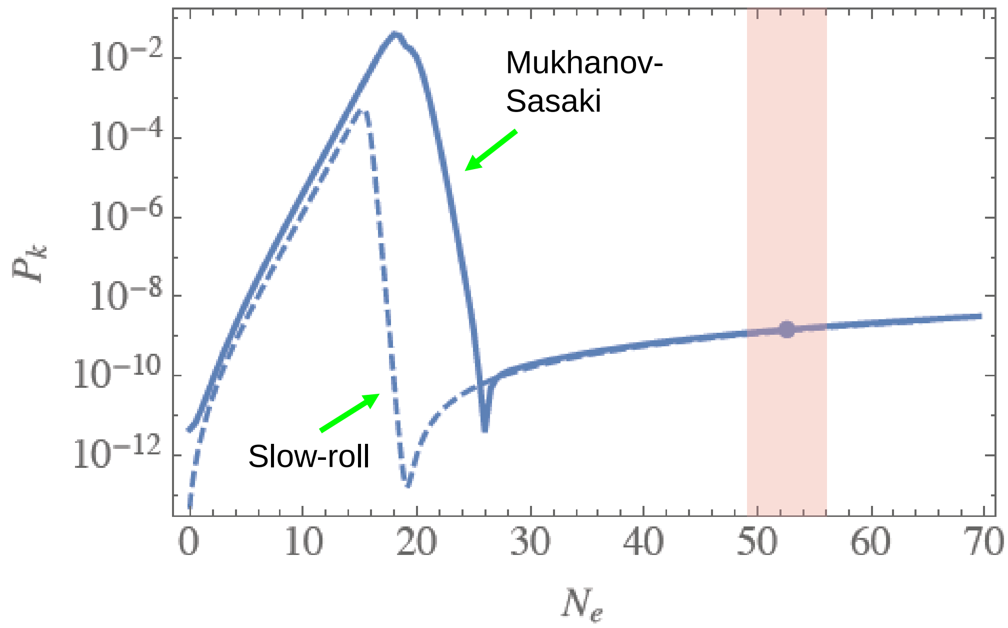
ii) Approximate shift symmetry for τ_{K3}

→ Tuning is technically natural

Superhorizon evolution and power spectrum







$$n_s = 0.9437$$

$$\frac{dn_s}{d \ln k} = -0.0017$$

$$r = 0.015$$

3σ 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

  $$\zeta_c \simeq 1 \;\rightarrow\; 0.5 \qquad P_k\big|_{PBH} \simeq 10^7 \times P_k\big|_{CMB} \simeq 10^{-2} \;\rightarrow\; P_k\big|_{PBH} \simeq 10^{-3}$$

  [Yoo,Harada,Garriga,Kohri]
  [Germani,Musco]

  → get a larger n_s!

- Perturbation theory under control?

  Recently: backreaction of perturbations with stochastic analysis

  [Ezquiaga,Garcia-Bellido]
  [Biagetti,Franciolini,Kehagias, Riotto]

  $$P_k\big|_{PBH} \simeq 10^{-3} \;\rightarrow\; P_k\big|_{PBH} \simeq 10^{-6}$$

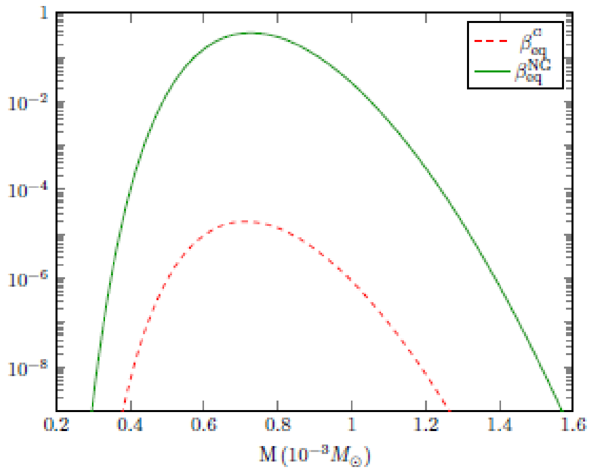
  Huge effect!?

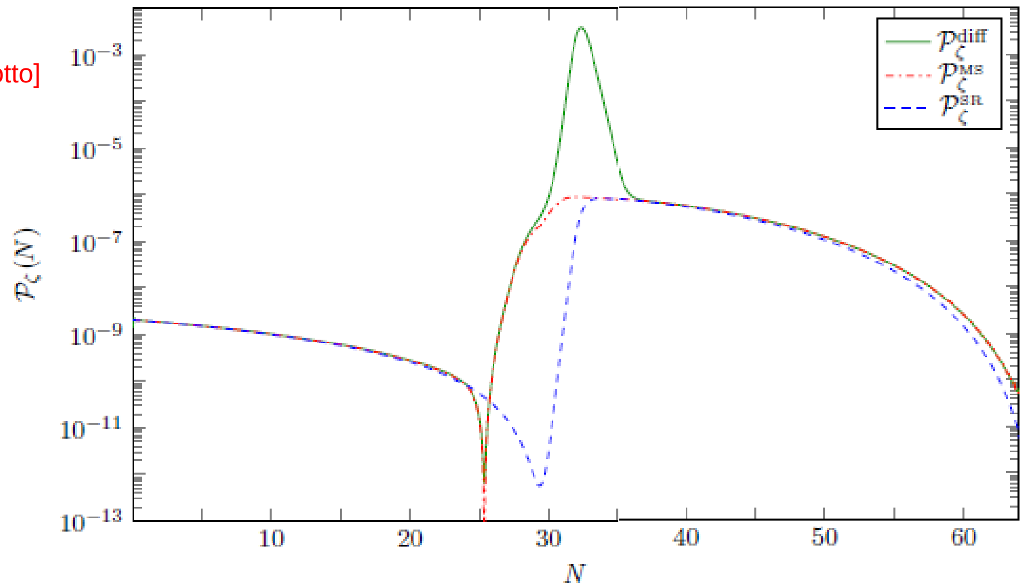
  → get much larger n_s and much less tuning!

- Non-gaussianities?

  Recently: increase PBH abundance

  [Ezquiaga,Garcia-Bellido][Franciolini,Kehagias,Matarrese,Riotto]





Outlook

- Goal: understand PBH production from strings: generic mechanism, preferred PBH masses
- To do:

i) Redo the analysis with $\zeta_c \simeq 0.5$, 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?

See Pedro's talk

- Spectator fields during inflation: heavy (m_{heavy} >> H) + light (m_{light} << m_{inf} << H)
- Effective mass of isocurvature pert.

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

- 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

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

[Renaux-Petel, Turzinsky]

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

BUT $m_{eff}^2 > 0$ if computed on attractor background trajectory with $\eta_\perp \neq 0$! [MC,Guidetti,Pedro,Vacca]

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

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

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

→ Isocurvature pert. source curvature pert. → effectively single-field [Achucarro et al]

2) Geodesic trajectory with $\eta_\perp = 0$

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

E.g.: T_1 axion in Fibre Inflation

→ 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 + α' 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 $\Delta\varphi/M_p \leq c \ln \mathcal{V}$ with $\Delta\varphi > M_p$ only for K3-fibrations

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

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

9) $N_e \approx 52$ and $\Delta N_{eff} \approx 0.6$ ⟶ $n_s \approx 0.99$ 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?