Polynomial Inflation and Its Aftermath

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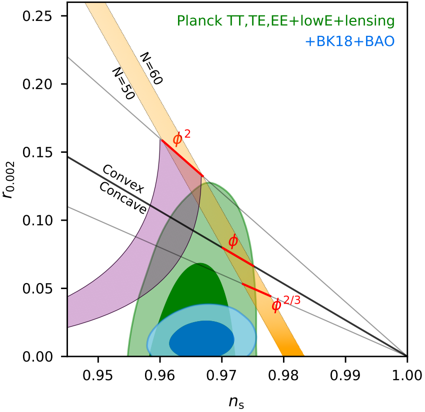
Outline

1. Polynomial Inflation and Predictions
2. (P)reheating
3. Dark Matter Production
4. Baryogenesis
5. Summary

Current Status of Monomial Inflation [2110.00483]



- Monomial: $V(\phi) \sim \phi^p$, tensor-to-scalar ratio

$$r \sim \left(\frac{V'}{V}\right)^2 \sim \frac{4p}{N}, \quad N = \int_{t_\star}^{t_e} H\,dt$$

- BICEP/Keck 2018: $r < 0.035 \Rightarrow p \lesssim 0.5$

Polynomial Inflation

- Alternative to monomial scenario

$$V(\phi) = \sum_{n=0}^{4} \alpha_n \phi^n$$

- Avoid trans-Planckian $\Rightarrow \phi < M_p \Rightarrow$ Small Field
- Reasonable to insist on renormalizability
- $V(\phi)$: most general renormalizable inflaton potential
- Question:

Can $V(\phi)$ flat enough to match the CMB data?

Polynomial Inflation Analysis

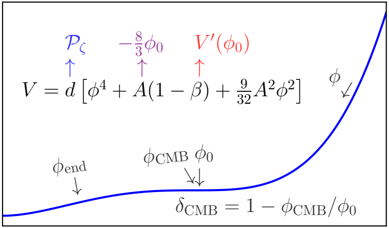
$$V(\phi) = d\,\phi^4 + c\,\phi^3 + b\,\phi^2$$

- Inflection-point at $\phi_0 = -\frac{3c}{8d}$ with $b = \frac{9c^2}{32d}$
- Reparametrization (d, A, β)

$$V(\phi) = d\left[\phi^4 + \frac{c}{d}(1-\beta)\,\phi^3 + \frac{9}{32}\left(\frac{c}{d}\right)^2\phi^2\right]$$
$$\equiv d\left[\phi^4 + A\,(1-\beta)\,\phi^3 + \frac{9}{32}A^2\phi^2\right]$$

  - $A \equiv c/d = -8/3\phi_0 \longleftrightarrow$ location ϕ_0
  - β: $\longleftrightarrow$ flatness $V(\phi_0)$; $V'(\phi_0) = 0$ if $\beta = 0$
  - d: $\longleftrightarrow$ amplitude (power spectrum)

Slow-Roll Analysis



- $n_s \simeq 1 - 48\delta_{\rm CMB}/\phi_0^2$
- $N_{\rm CMB} \propto \left(\pi/2 - \arctan\left(\delta_{\rm CMB}/\sqrt{2\beta}\right)\right)$
- $r \propto \beta^2$
- $\alpha \simeq -576(2\beta + \delta^2)/\phi_0^4$
- $\mathcal{P}_\zeta \simeq d\phi_0^6/(\delta^2 + 2\beta)^2$

- Fix parameters: $n_s = 0.9649$, $N_{\rm CMB} = 65$, $\mathcal{P}_\zeta = 2.1 \cdot 10^{-9} \Rightarrow$

$$\delta_{\rm CMB} = 7.31 \times 10^{-4}\phi_0^2$$
$$\beta = 9.73 \times 10^{-7}\phi_0^4$$
$$d = 6.61 \times 10^{-16}\phi_0^2$$

- Predictions for r and α?

Predictions for r and α

- r small

$$\frac{r}{7.09 \times 10^{-9} \phi_0^6} = 1 - 3.9 \cdot 10^{-2} (65 - N_{\rm CMB}) + 15.0\,(0.9649 - n_s) + 175\,(0.9649 - n_s)^2$$

- α hopefully testable [via S4 CMB, see e.g. 1611.05883]

$$\alpha = -1.43 \cdot 10^{-3} - 5.56 \cdot 10^{-5}\,(65 - N_{\rm CMB}) + 0.02\,(0.9649 - n_s) - 0.25\,(0.9649 - n_s)^2$$

- Central model parameters

$$\delta_{\rm CMB} = 7.31 \times 10^{-4} \phi_0^2;\ \beta = 9.73 \times 10^{-7} \phi_0^4;\ d = 6.61 \times 10^{-16} \phi_0^2$$

- Inflaton mass and Inflationary scale:

$$m_\phi^2 = \left.\frac{\partial^2 V}{\partial \phi^2}\right|_{\phi=0} \simeq 4 d \phi_0^2\,;\ H_{\rm inf} = \sqrt{\frac{V(\phi_0)}{3}} \simeq 8.6 \cdot 10^{-9} \phi_0^3$$

- Question: What's the lower bound for ϕ_0?

Reheating $\Rightarrow$ Lower Bound

- After inflation ends:
  - ϕ oscillates and transfers energy
- Decays:

$$\mathcal{L} \supset -g\phi|\phi'|^2 - y\phi\bar{\chi}\chi$$

- Rate (with $m_\phi \sim \phi_0^2$):

$$\Gamma_\phi \simeq \frac{g^2}{8\pi m_\phi};\ \frac{y^2}{8\pi} m_\phi$$

- Reheating Tem:

$$T_{\rm rh} \simeq 1.41 g_\star^{-1/4} \Gamma_\phi^{1/2}$$

- BBN: $T_{\rm rh} \gtrsim 4$ MeV [Hannestad '04] $\Rightarrow$

$$y\phi_0 \gtrsim 4.7 \times 10^{-17};\ \frac{g}{\phi_0} \gtrsim 2.4 \times 10^{-24}$$

- Remarks: Preheating not efficient here
  - EoM for ϕ':

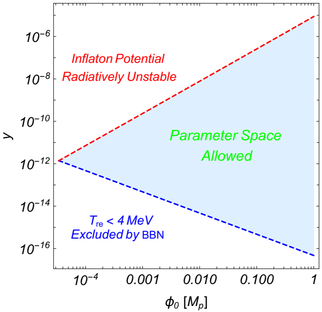
$$\ddot{\phi}'(\mathbf{k}, t) + \left(k^2/a^2 + g\phi\right)\phi'(\mathbf{k}, t) = 0$$

  - Though $m_{\phi'}^2 \sim g\phi \Rightarrow$ tachyonic instability [Dufaux, Felder et al. '06], however self-coupling $\lambda\phi'^4 \Rightarrow \lambda\langle\phi'^2\rangle\phi'^2 \Rightarrow$ positive mass term
  - Pauli blocking for χ
- Question: upper bounds for the couplings? $\Rightarrow$ Radiative stability

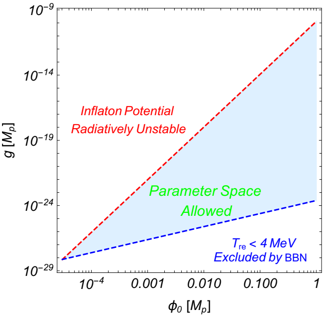
Radiative Stability ⇒ Upper Bound

- Require:
  $\Delta V_{1\text{-loop}}(\phi_0) \ll V(\phi_0)\,;\, \Delta V'_{1\text{-loop}}(\phi_0) \ll V'(\phi_0)\,;\, \Delta V''_{1\text{-loop}}(\phi_0) \ll V''(\phi_0)$

- Upper bound ($y\phi\bar{\chi}\chi$):

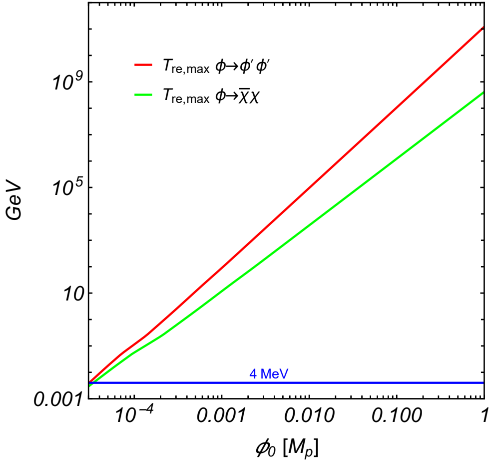


- Upper bound ($g\phi|\phi'|^2$):



- Radiative Stability + Reheating ⇒ Lower bound $\phi_0 > 3 \cdot 10^{-5} M_p$ [Drees, Xu '21]

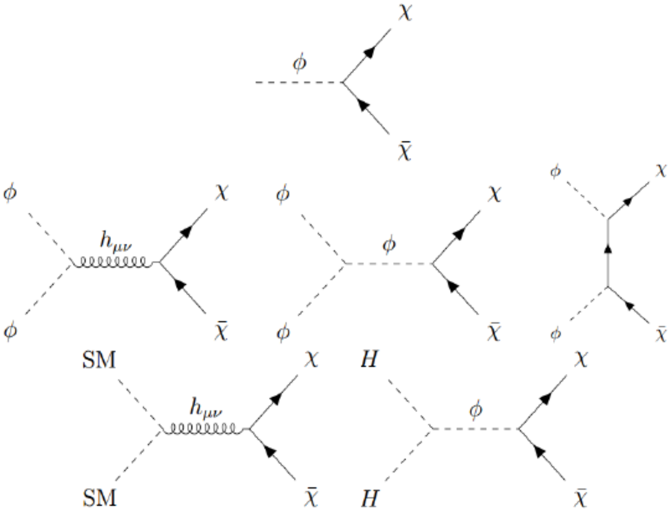
Reheating Temperature



- Bosonic: $4\,\text{MeV} \lesssim T_{\rm rh} \lesssim 10^{11}\,\text{GeV}$
- Fermionic: $4\,\text{MeV} \lesssim T_{\rm rh} \lesssim 10^{8}\,\text{GeV}$

DM Production: After Polynomial Inflation

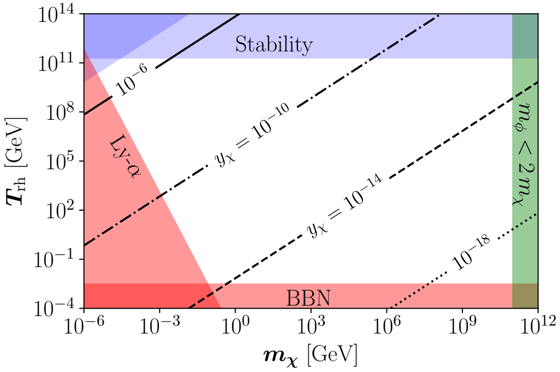
- Consider e.g. Fermionic DM $\mathcal{L}_\chi \supset y_\chi \phi \bar{\chi} \chi \Rightarrow$ 6 possible channels:



[Allahverdi, Drees '02; Mambrini, Olive '21; Bernal, Dutra et al '18; Clery, Mambrini et al. '22; Bernal, Xu '21]

Inflaton direct decay

- Parameter space: $y_\chi \simeq 1.2 \times 10^{-13} \sqrt{\frac{T_{\rm rh}}{m_\chi}}$



- Bounds:
  - Stability: $T_{\rm rh} < 1.2 \times 10^{11}$ GeV (Higgs loop), $y_\chi < 10^{-5}$ (DM loop)
  - BBN: $T_{\rm rh} \gtrsim 4$ MeV
  - Lyα on cold DM: $v_\chi = \frac{p_0}{m_\chi} \lesssim 10^{-8} c \Leftrightarrow \frac{m_\chi}{\rm keV} \gtrsim 2 \frac{m_\phi}{T_{\rm rh}}$
- DM mass: $\mathcal{O}(10^{-5})$ GeV $\lesssim m_\chi \lesssim \mathcal{O}(10^{11})$ GeV [Bernal, Xu '21]

Baryogenesis

- A simple and attractive scenario: Leptogenesis [Fukugita, Yanagida 1986]

$$\mathcal{L}_N \supset -\left(\frac{1}{2} M_N \overline{N_i^c} N_i + h.c.\right) - \left(Y_{\alpha i}\, \bar{L}_\alpha \tilde{H} N_i + h.c.\right)$$

- Lower bound on M_1 [Davidson Ibarra '02, Buchmuller, Bari, Plumacher '04]

$$Y_B \sim \frac{28}{79} Y_{B-L} \sim \frac{28}{79} \epsilon_1\, 10^{-4} \gtrsim 10^{-10} \Rightarrow M_1 \gtrsim 10^{10}\ \text{GeV}$$

with CP asymmetry parameter: $\epsilon_1 \lesssim 10^{-5} \left(\frac{M_1}{10^{11}\text{GeV}}\right)$

- Recall $T_{\text{rh}} \lesssim 10^{11}$ GeV $\Rightarrow$ Thermal leptogenesis works (need high T_{rh})

- Question

Can one has leptongenesis with lower T_{rh}?

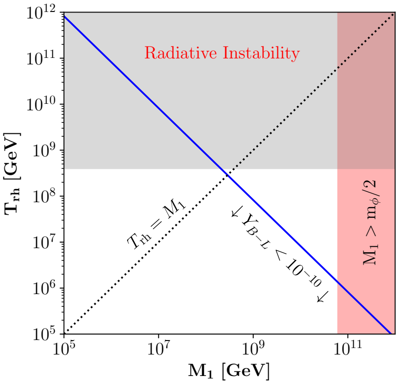
Non-thermal Leptogenesis [in preparation, Drees, Xu '22]

- Inflaton couples to RHN

$$\mathcal{L}_N \supset -\left(y_I\, \phi \overline{N_I^c} N_I + h.c.\right)$$

- Lepton yield

$$Y_{B-L} = \left(\frac{3}{2}\frac{T_{\rm rh}}{m_\phi}\right) \cdot \epsilon_I$$



Summary

- A simple polynomial model fits data very well:

$$V \equiv d\left[\phi^4 + A\,(1-\beta)\,\phi^3 + 9/32A^2\phi^2\right]$$

with $A = -8/3\phi_0\,;\,\beta = 9.73 \times 10^{-7}\phi_0^4/M_p^4\,;\,d = 6.61 \times 10^{-16}\phi_0^2/M_p^2.$

  - Parameter space: Reheating +Radiative Stability $\Rightarrow$ $\phi_0 > 3\cdot 10^{-5}M_p$
  - Predictions:
    1. $r \simeq 7.1\cdot 10^{-9}\phi_0^6/M_p^6$
    2. $\alpha \simeq -1.43\cdot 10^{-3}$ $\Rightarrow$ testable in future [S4 CMB]
  - Implications:
    1. Inflationary scale: $H_{\rm inf} \simeq 8.6\cdot 10^{-9}\phi_0^3/M_p^2 \Rightarrow H_{\rm inf}$ as low as 1 MeV!
    2. Reheating Tem: $T_{\rm re} \in \left[4\text{ MeV}, 10^{11}\text{ GeV}\right]$
- Dark Matter: $\mathcal{O}(10^{-5})$ GeV $\lesssim m_\chi \lesssim \mathcal{O}(10^{11})$ GeV
- Leptogenesis:
  1. thermal: $\mathcal{O}(10^{10})$ GeV $\lesssim M_1 \lesssim \mathcal{O}(10^{11})$ GeV
  2. non-thermal: $\mathcal{O}(10^{8})$ GeV $\lesssim M_1 \lesssim \mathcal{O}(10^{10})$ GeV

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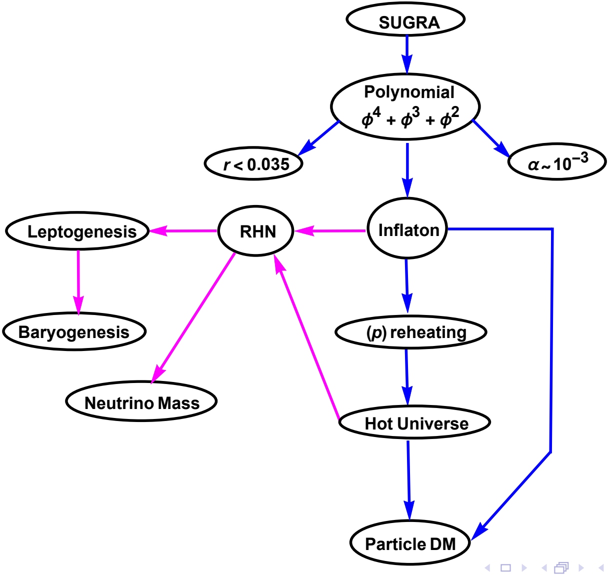
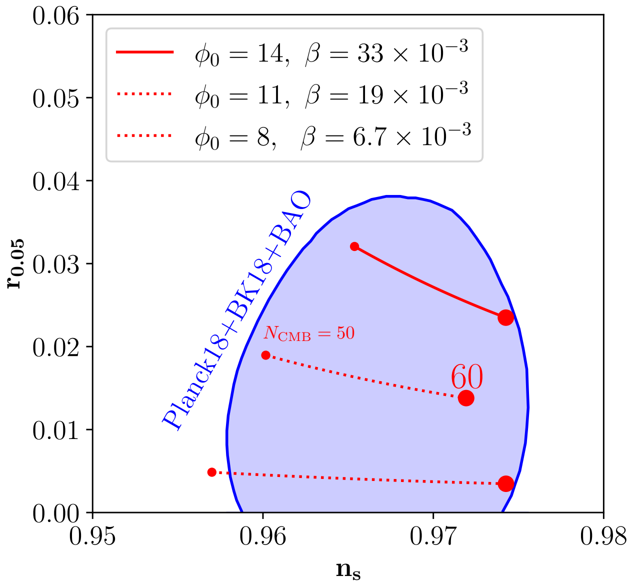


Thank you for your attention !

Backup: Large Field Scenario [to appear soon, Drees, Xu '22]



Backup: Polynomial Inflation in Supergravity

- Scalar Potential

$$V = e^K \left[(D_i W) K^{-1}_{i\bar{j}} (D_{\bar{j}} \bar{W}) - 3|W|^2 \right],$$

with $D_i W = \frac{\partial W}{\partial \Phi_i} + \frac{\partial K}{\partial \Phi_i} W$ and $K_{i\bar{j}} = \frac{\partial^2 K}{\partial \Phi_i \partial \bar{\Phi}_j}$

- η problem see, e.g. [1101.2488] for review

$$V \sim (1 + |\Phi_i|^2) |\frac{\partial W}{\partial \Phi_i}|^2 = V^{\text{global}} + |\Phi_i|^2 V^{\text{global}} \Rightarrow \eta = V''/V \sim 1$$

- Consider e.g. a Superpoetntial and Kähler potential [Nakayama, Takahashi and Yanagida '13]:

$$W = X(\alpha_1 \Phi + \alpha_2 \Phi^2)\,;\, K = \frac{1}{2}(\Phi + \Phi^\dagger)^2 + |X|^2$$

- Kähler potential admits a shift symmetry: $\Phi \to \Phi + iC$ [Kawasaki, Yamaguchi and Yanagida '00]
- $\phi \equiv \mathrm{Im}(\Phi)$ not appear in $K \Rightarrow$ free from η problem
- Reproduce the (single field) polynomial inflaton potential:

$$V(\phi) = \left(1 + \frac{1}{2}(\Phi^2 + \Phi^{\dagger 2} + 2\Phi\Phi^\dagger)\right)\left(\alpha_1\Phi + \alpha_2\Phi^2\right)\left(\alpha 1^\star \Phi^\dagger + \alpha_2^\star \Phi^{\dagger 2}\right) \supset \left(\frac{|\alpha_1|^2}{2}\phi^2 - \frac{\sqrt{2}|\alpha_1||\alpha_2|\sin\theta}{2}\phi^3 + \frac{|\alpha_2|^2}{4}\phi^4\right)$$