Polynomial Inflation

Yong Xu

MPIK, Theory Seminar, 13.12.2021

UNIVERSITÄT BONN

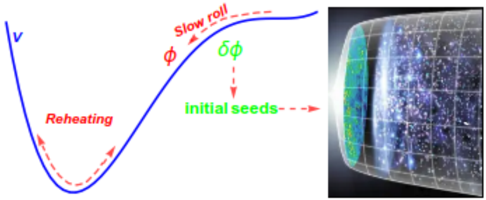
Bethe Center for Theoretical Physics

Outline

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

Inflation: a mini review

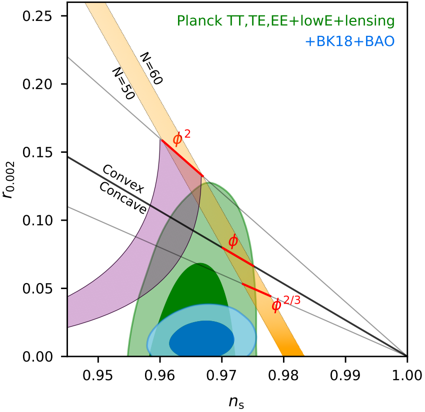
- An exponential expansion in the time $\sim 10^{-35} - 10^{-32}$ s after big bang
- It resolves: Horizon, Flatness, Molople Problems



- A notable prediction: $\delta\phi \Rightarrow \delta T_{\mu\nu} \Rightarrow \delta g_{\mu\nu} \Rightarrow$ gravitational wave

$$r = 16\epsilon = 16 \cdot \frac{1}{2}\left(\frac{V'}{V}\right)^2$$

Current Status of Monomial Inflation



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

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

- BK18: $r < 0.035 \Rightarrow p \lesssim 0.5$

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:

$$\boxed{\text{Can } V(\phi) \text{ flat enough to match the CMB data?}}$$

Polynomial Inflation Analysis

$$V(\phi) = \overset{\text{negligible}}{\cancel{C}} + d\,\phi^4 + c\,\phi^3 + b\,\phi^2 + e\,\overset{\text{shifted away}}{\cancel{\phi^1}}$$

- Large ϕ: $V \sim \phi^4$, Small ϕ: $V \sim \phi^2$ $\Rightarrow$Too steep ☹

Polynomial Inflation Analysis

$$V(\phi) = \overset{\text{negligible}}{\cancel{C}} + d\,\phi^4 + c\,\phi^3 + b\,\phi^2 + \overset{\text{shifted away}}{\cancel{e\,\phi^1}}$$

- Large ϕ: $V \sim \phi^4$, Small ϕ: $V \sim \phi^2$ $\Rightarrow$Too steep ☹
- Intermediate ϕ: V flat $\Leftarrow$ negative ϕ^3 term ☺

Polynomial Inflation Analysis

$$V(\phi) = \overset{\text{negligible}}{\cancel{C}} + d\,\phi^4 + c\,\phi^3 + b\,\phi^2 + e\,\overset{\text{shifted away}}{\cancel{\phi^1}}$$

- Large ϕ: $V \sim \phi^4$, Small ϕ: $V \sim \phi^2$ $\Rightarrow$Too steep ☹
- Intermediate ϕ: V flat $\Leftarrow$ negative ϕ^3 term ☺
- In particular $b = \frac{9c^2}{32d}$ $\Rightarrow$ inflection-point $\phi_0 = -\frac{3c}{8d}$

Polynomial Inflation Analysis

$$V(\phi) = \cancel{C} + d\,\phi^4 + c\,\phi^3 + b\,\phi^2 + e\,\cancel{\phi^1}$$

negligible — shifted away

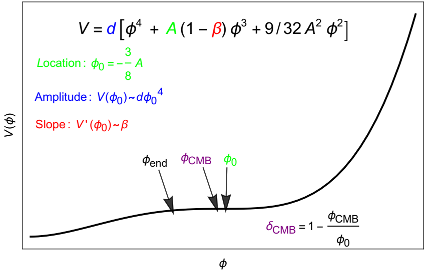
- Large ϕ: $V \sim \phi^4$, Small ϕ: $V \sim \phi^2$ $\Rightarrow$Too steep ☹
- Intermediate ϕ: V flat $\Leftarrow$ negative ϕ^3 term ☺
- In particular $b = \frac{9c^2}{32d}$ $\Rightarrow$ inflection-point $\phi_0 = -\frac{3c}{8d}$
- Three parameters (d, A, β) reparametrization:

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

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

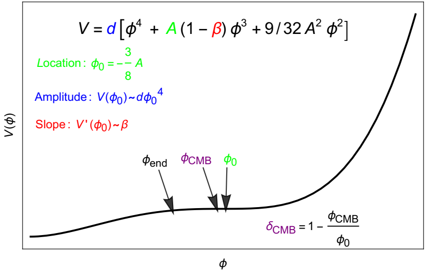
Slow-Roll Predictions

- Results:
  - $n_s \simeq 1 - 48\delta_{\rm CMB}/\phi_0^2$



- Need $\phi_{\rm CMB} \Rightarrow$ introduce δ: $\phi = \phi_0(1-\delta) \Rightarrow$ $\delta_{\rm CMB} = 1 - \phi_{\rm CMB}/\phi_0$

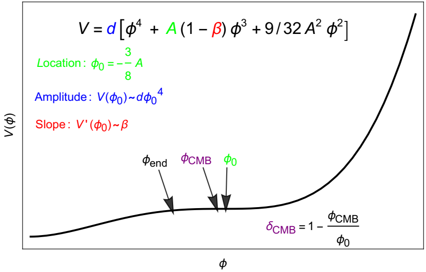
Slow-Roll Predictions



- Results:
  - $n_s \simeq 1 - 48\delta_{\rm CMB}/\phi_0^2$
  - $N_{\rm CMB} \propto \left(\pi/2 - \arctan\left(\delta_{\rm CMB}/\sqrt{2\beta}\right)\right)$

- Need $\phi_{\rm CMB} \Rightarrow$ introduce δ: $\phi = \phi_0(1-\delta) \Rightarrow$ $\delta_{\rm CMB} = 1 - \phi_{\rm CMB}/\phi_0$

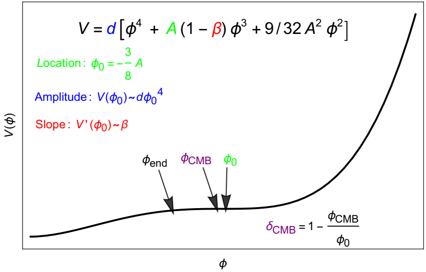
Slow-Roll Predictions



- Need $\phi_{\text{CMB}} \Rightarrow$ introduce δ: $\phi = \phi_0(1-\delta) \Rightarrow$ $\delta_{\text{CMB}} = 1 - \phi_{\text{CMB}}/\phi_0$

- Results:
  - $n_s \simeq 1 - 48\delta_{\text{CMB}}/\phi_0^2$
  - $N_{\text{CMB}} \propto \left(\pi/2 - \arctan\left(\delta_{\text{CMB}}/\sqrt{2\beta}\right)\right)$
  - $r \propto \left(2\beta + \delta^2\right)^2/\phi_0^2$

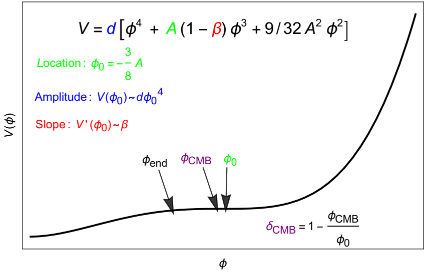
Slow-Roll Predictions



- Need $\phi_{\rm CMB}$ $\Rightarrow$ introduce δ: $\phi = \phi_0(1-\delta) \Rightarrow$ $\delta_{\rm CMB} = 1 - \phi_{\rm CMB}/\phi_0$

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

Slow-Roll Predictions

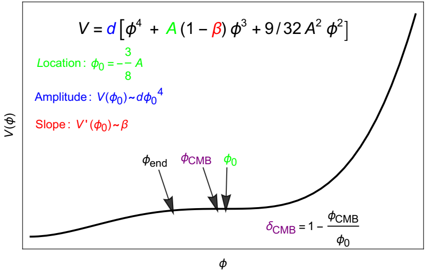


- Need $\phi_{\mathrm{CMB}} \Rightarrow$ introduce δ: $\phi = \phi_0(1-\delta) \Rightarrow$ $\delta_{\mathrm{CMB}} = 1 - \phi_{\mathrm{CMB}}/\phi_0$

- Results:
  - $n_s \simeq 1 - 48\delta_{\mathrm{CMB}}/\phi_0^2$
  - $N_{\mathrm{CMB}} \propto \left(\pi/2 - \arctan\left(\delta_{\mathrm{CMB}}/\sqrt{2\beta}\right)\right)$
  - $r \propto \left(2\beta + \delta^2\right)^2/\phi_0^2$
  - $\alpha \simeq -576(2\beta + \delta^2)/\phi_0^4$
  - $\mathcal{P}_\zeta \simeq d\phi_0^6/(\delta^2 + 2\beta)^2$
- $n_s = 0.9649$, $N_{\mathrm{CMB}} = 65$, $\mathcal{P}_\zeta = 2.1 \cdot 10^{-9} \Rightarrow$ fix parameters:

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

Slow-Roll Predictions



- Need $\phi_{\rm CMB} \Rightarrow$ introduce δ: $\phi = \phi_0(1-\delta) \Rightarrow$ $\delta_{\rm CMB} = 1 - \phi_{\rm CMB}/\phi_0$

- Results:
  - $n_s \simeq 1 - 48\delta_{\rm CMB}/\phi_0^2$
  - $N_{\rm CMB} \propto \left(\pi/2 - \arctan\left(\delta_{\rm CMB}/\sqrt{2\beta}\right)\right)$
  - $r \propto \left(2\beta + \delta^2\right)^2/\phi_0^2$
  - $\alpha \simeq -576(2\beta + \delta^2)/\phi_0^4$
  - $\mathcal{P}_\zeta \simeq d\phi_0^6/(\delta^2 + 2\beta)^2$
- $n_s = 0.9649,\ N_{\rm CMB} = 65,$ $\mathcal{P}_\zeta = 2.1 \cdot 10^{-9} \Rightarrow$ fix parameters:

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

- Predictions for r and α?

Predictions for r and α

- ☹ r not detectable

$$\frac{r}{7.09 \times 10^{-9} \phi_0^6} = 1 - 3.9 \cdot 10^{-2} (65 - N_{\mathrm{CMB}})$$

$$+ 15.0\,(0.9649 - n_s) + 175\,(0.9649 - n_s)^2$$

Predictions for r and α

- ☹ r not detectable

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

- ☺ α hopefully testable [S4 CMB]

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

Predictions for r and α

- ☹ r not detectable

$$\frac{r}{7.09\times10^{-9}\phi_0^6} = 1-3.9\cdot10^{-2}(65-N_{\rm CMB})$$
$$+15.0\,(0.9649-n_s)+175\,(0.9649-n_s)^2$$

- ☺ α hopefully testable [S4 CMB]

$$\alpha = -1.43\cdot10^{-3}-5.56\cdot10^{-5}\,(65-N_{\rm CMB})$$
$$+0.02\,(0.9649-n_s)-0.25\,(0.9649-n_s)^2$$

- Central model parameters

$$\delta_{\rm CMB} = 7.31\times10^{-4}\phi_0^2;\ \beta = 9.73\times10^{-7}\phi_0^4;\ d = 6.61\times10^{-16}\phi_0^2$$

- Inflaton mass and Inflationary scale:

$$m_\phi^2 = \left.\frac{\partial^2 V}{\partial\phi^2}\right|_{\phi=0} \simeq 4d\phi_0^2\,;\ H_{\rm inf} = \sqrt{\frac{V(\phi_0)}{3}} \simeq 8.6\cdot10^{-9}\phi_0^3$$

Predictions for r and α

- ☹ r not detectable

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

- ☺ α hopefully testable [S4 CMB]

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

- Central model parameters

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

- Inflaton mass and Inflationary scale:

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

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

Reheating $\Rightarrow$ Lower Bound

- After inflation ends:
  - $V \sim m_\phi^2 \phi^2$
  - ϕ oscillates and transfers energy

Reheating $\Rightarrow$ Lower Bound

- After inflation ends:
  - $V \sim m_\phi^2 \phi^2$
  - ϕ oscillates and transfers energy
- Decays to Bosons (e.g. Higgs) or Fermions (e.g. RHN)

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

- Decay rate ($m_\phi \sim \phi_0^2$):

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

Reheating $\Rightarrow$ Lower Bound

- After inflation ends:
  - $V \sim m_\phi^2 \phi^2$
  - ϕ oscillates and transfers energy
- Decays to Bosons (e.g. Higgs) or Fermions (e.g. RHN)

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

- Decay rate ($m_\phi \sim \phi_0^2$):

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

- Reheating Tem:

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

- BBN requires $T_{\rm rh} \gtrsim 4$ MeV $\Rightarrow$ Lower bounds

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

Reheating $\Rightarrow$ Lower Bound

- After inflation ends:
  - $V \sim m_\phi^2 \phi^2$
  - ϕ oscillates and transfers energy
- Decays to Bosons (e.g. Higgs) or Fermions (e.g. RHN)

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

- Decay rate ($m_\phi \sim \phi_0^2$):

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

- Reheating Tem:

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

- BBN requires $T_{\rm rh} \gtrsim 4$ MeV $\Rightarrow$ Lower bounds

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

- Remarks: Preheating negligible
  - EoM for ϕ':

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

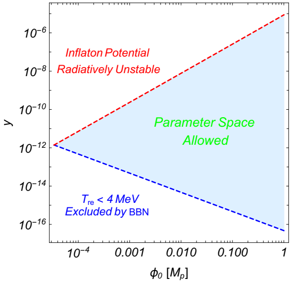
  - Though $m_{\phi'}^2 \sim g\phi \Rightarrow$ tachyonic resonance, still ok here, due to (sizeable) self-coupling $\lambda\phi'^4$ ($\Rightarrow$ back-reaction $m_{\phi'}^2 \sim \lambda\langle\phi'^2\rangle$)
  - Pauli blocking for $\chi \Rightarrow$ Preheating not efficient here
- Question: What are the upper bounds for the couplings? $\Rightarrow$ Radiative stability

Radiative Stability $\Rightarrow$ Upper Bound

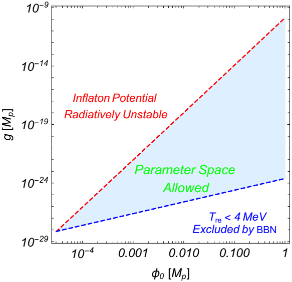
- Require: $\Delta V(\phi_0) \ll V(\phi_0)\,;\, \Delta V'(\phi_0) \ll V'(\phi_0)\,;\, \Delta V''(\phi_0) \ll V''(\phi_0)$,

$$\Delta V = \frac{1}{64\pi^2} \sum_{\psi=\phi',\chi} (-1)^{2s_\psi} g_\psi \widetilde{m}_\psi(\phi)^4 \left(\ln\left(\frac{\widetilde{m}_\psi(\phi)^2}{Q_0^2} \right) - \frac{3}{2} \right)$$

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

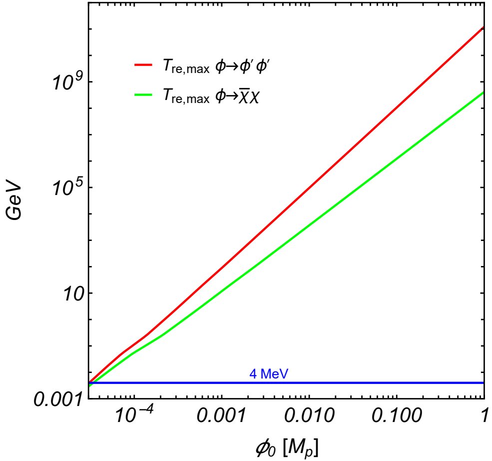


- Upper bound (coupling $g\phi|\phi'|^2$):



- Radiative Stability + Reheating $\Rightarrow$ Lower bound $\phi_0 > 3 \cdot 10^{-5} M_p$

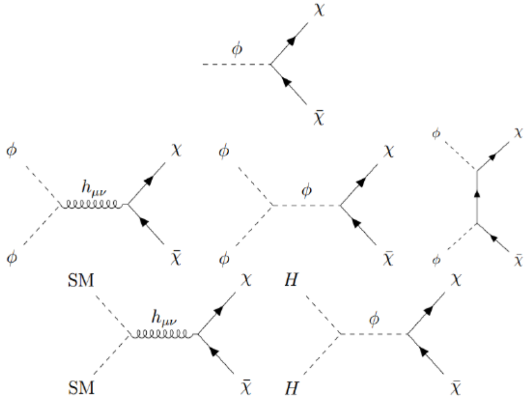
Reheating Temperature



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

DM Production: After Polynomial Inflation

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

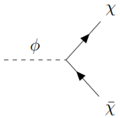


- Boltzmann equation (BEQ) :

$$\frac{dn}{dt} + 3H\,n = \gamma$$

γ denotes interaction rate density $\sim (\sigma v) n^2$

Inflaton direct decay



- Interaction rate density:

$$\gamma = 2\,\mathrm{Br}\,\Gamma\,\frac{\rho_\phi}{m_\phi}$$

- Branching ratio ($\mathrm{Br} \ll 1$):

$$\mathrm{Br} \propto \frac{y_\chi^2 m_\phi^2}{\lambda_{12}^2} \propto \frac{y_\chi^2 m_\phi M_P}{T_{\rm rh}^2}$$

- During reheating ($T_{\rm rh} < T < T_{\rm max}$):

$$\rho_\phi(T) \propto \frac{T^8}{T_{\rm rh}^4}\,;\, H(T) \propto \frac{T^4}{M_P\,T_{\rm rh}^2}$$

- Convenient to use $N = n\,a^3$, rewrite BEQ:

$$\frac{dN}{dT} \sim -\frac{M_P\,T_{\rm rh}^{10}}{T^{13}}\,a^3(T_{\rm rh})\,\gamma$$

- DM yield $Y \equiv n/s$:

$$Y_0 = \frac{\overset{T_{\rm rh}^2}{\cancel{N}}(T_{\rm rh})}{s(T_{\rm rh})\,a^3(T_{\rm rh})} \propto \frac{M_P\,\overset{T_{\rm rh}^2/M_P}{\cancel{\Gamma}}}{m_\phi\,T_{\rm rh}}\mathrm{Br} \propto \frac{T_{\rm rh}\,\mathrm{Br}}{m_\phi}$$

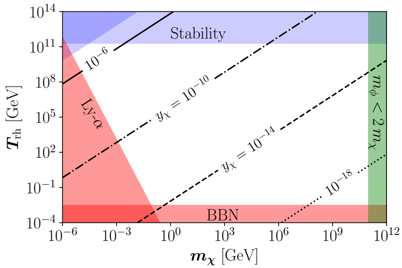
- To match the DM relics :

$$m_\chi\,Y_0 = \Omega_\chi h^2\,\frac{1}{s_0}\,\frac{\rho_c}{h^2} \simeq 4.3\times 10^{-10}\ \mathrm{GeV}$$

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

Inflaton direct decay

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

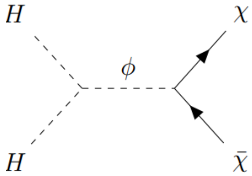


- Bounds:
  - Radiative stability: $T_{\rm rh} < 1.2 \times 10^{11}$ GeV (Higgs loop), $y_\chi < 10^{-5}$ (DM loop)
  - BBN: $T_{\rm rh} \gtrsim 4$ MeV
  - Lyα on cold DM: $v_\chi = \frac{p_0}{m_\chi} \lesssim 10^{-8}c \Leftrightarrow \frac{m_\chi}{\rm keV} \gtrsim 2\,\frac{m_\phi}{T_{\rm rh}}$

$$p_0 = \frac{a_{\rm in}}{a_0}\,p_{\rm in} = \frac{a_{\rm in}}{a_{\rm eq}}\,\frac{\Omega_R}{\Omega_m}\,\frac{m_\phi}{2} \simeq 3 \times 10^{-14}\,\frac{m_\phi}{T_{\rm rh}}\ {\rm GeV}\,,$$

- DM mass: $\mathcal{O}(10^{-5})$ GeV $\lesssim m_\chi \lesssim \mathcal{O}(10^{11})$ GeV

Higgs scattering and freeze-in



- Interaction rate density:

$$\gamma \equiv \frac{T}{8\pi^4} \int_{4m_\chi^2}^{\infty} d\mathfrak{s}\, \mathfrak{s}^{3/2}\, \sigma(\mathfrak{s})\, K_1\left(\frac{\sqrt{\mathfrak{s}}}{T}\right) \propto y_\chi^2\, \lambda_{12}^2\, \frac{T^6}{m_\phi^4}$$

- γ too small compared to Hubble rate $\Rightarrow$ freeze-in
- BEQ

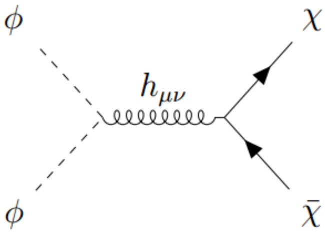
$$\frac{dY}{dT} = -\frac{135}{2\pi^3\, g_{\star s}} \sqrt{\frac{10}{g_\star}}\, \frac{M_P}{T^6}\, \gamma$$

- DM yield:

$$Y_0 \propto y_\chi^2\, \lambda_{12}^2\, \frac{M_P\, T_{\mathrm{rh}}}{m_\phi^4}$$

- However: $Y_0 \ll Y_0^{\mathrm{decay}}$ due to the bounds on couplings

Gravitational channel



- Unavoidable due to the coupling $\sim T^{\mu\nu} g_{\mu\nu}$
- Interaction rate density: (note: $n_\phi = \rho_\phi / m_\phi \sim T^8/(T_{\rm rh}^4 m_\phi)$)

$$\gamma \propto \left(\frac{1}{M_P^2}\right)^2 \left(\frac{T^8}{T_{\rm rh}^4} \frac{1}{m_\phi}\right)^2 m_\chi^2$$

- DM yield:

$$Y_0 \propto \frac{T_{\rm rh}\, m_\chi^2}{M_P^{5/2}\, m_\phi^{1/2}}$$

- Radiative upper bounds: $T_{\rm rh} \lesssim 10^{11}$ GeV

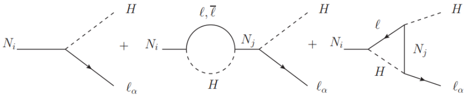
$$\Rightarrow Y_0^{\rm gra} \ll Y_0^{\rm required}$$

Bargoyenesis via Leptogenesis

1. Baryon (lepton) number violation
2. CP violation
3. Out of equilibrium

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

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



- CP asymmetry parameter ee e.g. [1301.3062]:

$$\epsilon_{i\alpha} = \frac{\gamma\left(N_i \to \ell_\alpha H\right) - \gamma\left(N_i \to \overline{\ell_\alpha} H^*\right)}{\sum_\alpha \gamma\left(N_i \to \ell_\alpha H\right) + \gamma\left(N_i \to \overline{\ell_\alpha} H^*\right)}$$

$$\epsilon_i \equiv \sum_\alpha \epsilon_{i\alpha} = \frac{1}{8\pi}\frac{1}{\left(Y^\dagger Y\right)_{ii}} \sum_{j\neq i} \mathrm{Im}\left[\left(Y^\dagger Y\right)^2_{ji}\right] g\left(\frac{M_j^2}{M_i^2}\right)$$

- Focus on the minimal case with $i = 1, 2$, and assume $M_2 \gg M_1$

Thermal Leptogenesis

- Neutrino Mass (after integrating out N)

$$\tilde{m}_\nu = -v^2 Y M^{-1} Y^T$$

- CP asymmetry parameter (rewrite Y with m_ν):

$$\epsilon_1 \sim 10^{-5} \left(\frac{M_1}{10^{11}\mathrm{GeV}} \right)$$

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

$$Y_{B-L} \sim 10^{-2} \epsilon_1 \kappa_f \lesssim \epsilon_1 10^{-4}$$

where κ_f efficiency parameter (due to wash-out effect)

- Need

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

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

$\boxed{\text{Can one has leptongenesis with lower } T_{\rm rh}?}$

Non-thermal Leptogenesis (preliminary)

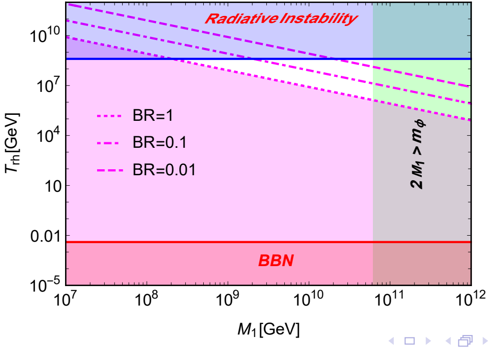
- Inflaton couples to RHN

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

- Lepton yield

$$Y_{B-L} = \frac{n_{B-L}}{s} = \left[\frac{3}{2}\frac{T_{\rm rh}}{m_\phi} \cdot \mathrm{BR}(\phi \to NN)\right] \cdot \epsilon_I$$

- Baryon number yield $Y_B = \frac{28}{79} Y_{B-L} \sim 10^{-10}$



Summary

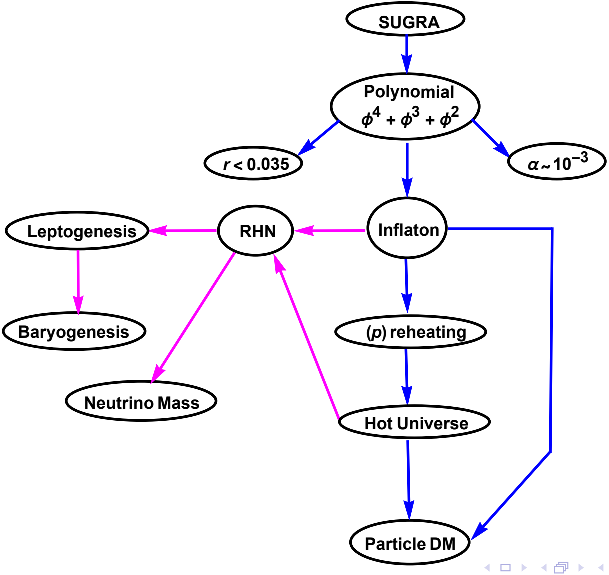
- A simple polynomial model fits data very well:

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

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

Polynomial Inflation and Its Aftermath



Thank you for your attention !

Backup: Realization of 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]

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

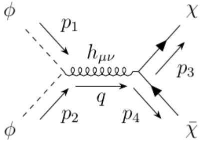
- Consider e.g. a Superpoetntial and Kähler potential [Nakayama, Takahashi and Yanagida '13]:

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

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

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

Backup: Gravitational Inflaton Annihilation [2102.06214]



- $\phi\phi h_{\mu\nu}$ vertice

$$-\frac{i}{2M_P}\left[p_{1\mu}p_{2\nu}+p_{1\nu}p_{2\mu}-\eta_{\mu\nu}\left(p_1\cdot p_2+m_\phi^2\right)\right]$$

- $\bar{\chi}\chi h_{\mu\nu}$ vertice

$$-\frac{i}{4M_P}\left[\left(p_3-p_4\right)_\mu\gamma_\nu+\left(p_3-p_4\right)_\nu\gamma_\mu-2\eta_{\mu\nu}\left(\not{p}_3-\not{p}_4-2m_\chi\right)\right]$$

- the amplitude:

$$\mathcal{M}^{\phi\chi}\propto\mathcal{M}_\phi^{\mu\nu}\Pi^{\mu\nu\rho\sigma}\mathcal{M}_{\rho\sigma}^{\chi}$$

where the propagator is:

$$\Pi^{\mu\nu\rho\sigma}=\frac{1}{2q^2}\left(\eta^{\rho\nu}\eta^{\sigma\mu}+\eta^{\rho\mu}\eta^{\sigma\nu}-\eta^{\rho\sigma}\eta^{\mu\nu}\right)$$