Thermal Inflation with a Waterfall Field Mass Coupled to a Light Auxiliary Scalar Field

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Outline

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1. Thermal Inflation
2. Our New Model
3. "End of Inflation" Mechanism
   - Generating ζ
   - Constraining the Free Parameters
   - Results

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4. Modulated Decay Rate

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    When temperature and mass terms of waterfall field are equal
- Solves the moduli problem

Our New Model

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ϕ: Drives thermal inflation: Waterfall Field

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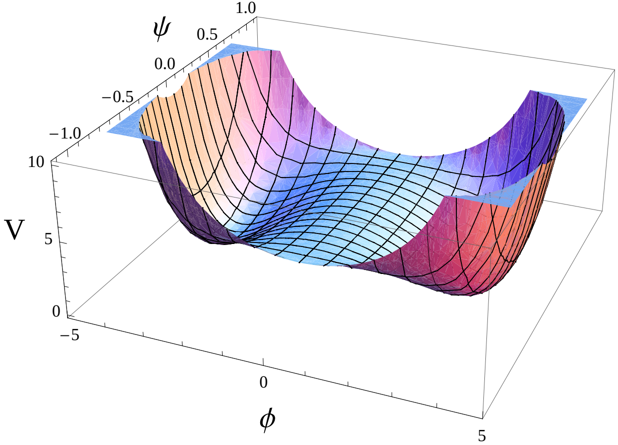
$$V(\phi, T, \psi) = V_0 + (g^2 T^2 - \frac{1}{2} m^2)\phi^2 + \lambda_n \frac{\phi^{2n+4}}{M_{Pl}^{2n}} + \frac{1}{2} m_\psi^2 \psi^2$$

where

$$m^2 \equiv m_0^2 - 2h_\alpha^2 \frac{\psi^{2\alpha}}{M_{Pl}^{2\alpha-2}}$$

$$\alpha, n \geq 1$$



Arbitrary Units

We don't get domain walls, as we can interpret ϕ as being the real part of a complex field, whose potential contains only 1 continuous VEV.

T_1 and T_2

From

$$\rho_r = \frac{\pi^2}{30} g_* T^4$$

we obtain

$$T_1 \sim V_0^{\frac{1}{4}}$$

$$T_2 = \frac{m}{\sqrt{2}g}$$

Other Quantities

$$\langle \phi \rangle = \left(\frac{m M_{Pl}^n}{\sqrt{(2n+4)\lambda_n}} \right)^{\frac{1}{n+1}}$$

$$V_0 \sim \left(\frac{m_0^{2n+4} M_{Pl}^{2n}}{\lambda_n} \right)^{\frac{1}{n+1}} \qquad (V = 0 \text{ at the VEV})$$

$$H_{TI} \sim \left(\frac{m_0^{n+2}}{\sqrt{\lambda_n} M_{Pl}} \right)^{\frac{1}{n+1}}$$

"End of Inflation" Mechanism: Generating ζ

δN Formalism

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e-foldings

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$$N \approx \ln \left(\frac{\sqrt{2} g V_0^{\frac{1}{4}}}{m} \right)$$

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δN Formalism

$$\zeta = \delta N = \frac{dN}{dm}\delta m + \frac{1}{2!}\frac{d^2 N}{dm^2}\delta m^2 + \frac{1}{3!}\frac{d^3 N}{dm^3}\delta m^3 + \ldots$$

Therefore we obtain, to 3rd order

$$\zeta = \delta N = -\frac{\delta m}{m} + \frac{1}{2}\frac{\delta m^2}{m^2} - \frac{1}{3}\frac{\delta m^3}{m^3}$$

Therefore we obtain, to 3rd order

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Substituting m and δm into this gives us

$$\zeta = \delta N = \frac{1}{\pi}\frac{\alpha h_\alpha^2 H_* \psi^{2\alpha-1}}{m^2 M_{Pl}^{2\alpha-2}} + \frac{1}{2\pi^2}\left(\frac{\alpha h_\alpha^2 H_* \psi^{2\alpha-1}}{m^2 M_{Pl}^{2\alpha-2}}\right)^2 + \frac{1}{3\pi^3}\left(\frac{\alpha h_\alpha^2 H_* \psi^{2\alpha-1}}{m^2 M_{Pl}^{2\alpha-2}}\right)^3$$

where we have used

$$\delta\psi = \frac{H_*}{2\pi}$$

as the most probable value of $\delta\psi$.

Constraining the Free Parameters

Primordial Inflation Scale

Constraining the Free Parameters

Primordial Inflation Scale

We want the scale of primordial inflation to be

$$V^{\frac{1}{4}} \lesssim 10^{14} \text{ GeV}$$

Therefore, from

$$3M_{Pl}^2 H_*^2 = V$$

we require

$$H_* \lesssim 10^{10} \text{ GeV}$$

Constraining the Free Parameters

Inflationary Dynamics

Constraining the Free Parameters

Inflationary Dynamics

In order that the ψ field does not affect the inflationary dynamics during thermal inflation, we require, from our definition of m,

$$m_0^2 \gg h_\alpha^2 \frac{\psi_*^{2\alpha}}{M_{Pl}^{2\alpha-2}}$$

Therefore we have

$$m \approx m_0$$

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  Make the field equation for ψ look like that of a free field, i.e. make the coupling term to ϕ in the field equation sub-dominant.

  From the field equation

$$\ddot{\psi} + 3H\dot{\psi} + \frac{\partial V}{\partial \psi} = 0$$

  we obtain

$$\ddot{\psi} + 3H\dot{\psi} + m_\psi^2 \psi + 2\alpha h_\alpha^2 \frac{\psi^{2\alpha-1}}{M_{Pl}^{2\alpha-2}} \phi^2 = 0$$

Therefore, in order that the field equation looks like that of a free field, we require

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- Substituting the observed spectrum value

$$\mathcal{P}_\zeta^{\frac{1}{2}} = 4.9 \times 10^{-5}$$

into our equation for ζ gives us the constraint

$$\psi_* \sim \left(\frac{10^{-4} m_0^2 M_{Pl}^{2\alpha-2}}{h_\alpha^2 H_*}\right)^{\frac{1}{2\alpha-1}}$$

- We require $\psi_* \gg \delta\psi_*$. Therefore we obtain, with $\delta\psi_* \sim H_*$,

$$\psi_* \gg H_*$$

and

$$\frac{\delta\psi_*}{\psi_*} \ll 1$$

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$$m^2_{\psi,eff} = m^2_\psi + (4\alpha^2 - 2\alpha)h^2_\alpha\phi^2\left(\frac{\psi}{M_{Pl}}\right)^{2\alpha-2}$$

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Therefore, we require

$$m_\psi \ll H_*$$

and

$$h_\alpha \phi_* \left(\frac{\psi_*}{M_{Pl}}\right)^{\alpha-1} \ll H_*$$

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This gives us the constraint

$$m_\psi \ll H_{TI}$$

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In order to keep $m_{\psi,eff}$ light, we therefore require

$$h_\alpha T \left(\frac{\psi_*}{M_{Pl}}\right)^{\alpha-1} \ll H_{TI}$$

Assuming that thermal equilibrium occurs only at the onset of thermal inflation, i.e. when $T \sim V_0^{\frac{1}{4}}$ and by substituting our expressions for H_{TI} and ψ_* into the above we obtain the constraint

$$h_\alpha \ll \frac{(10^4 H_*)^{\alpha-1}}{(\sqrt{\lambda_n}^{2\alpha-1} m_0^{2\alpha n-3n-2} M_{Pl}^{2\alpha+n})^{\frac{1}{2n+2}}}$$

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Rearranging this for m_0 gives us the constraint

$$m_0 \ll \left(\frac{(10^4 H_*)^{(2\alpha-2)(n+1)}}{h_\alpha^{2n+2} \sqrt{\lambda_n}^{2\alpha-1} M_{Pl}^{2\alpha+n}} \right)^{\frac{1}{2\alpha n-3n-2}}$$

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We have

$$\phi_* \propto \sqrt{\rho} \propto a^{-\frac{3}{2}}$$

As a grows exponentially during inflation, ϕ_* is driven rapidly to 0.

In order for the affect of the SUGRA correction on the potential to be present, we require ϕ to be light during primordial inflation, giving us

$$m_{\phi,eff} \ll H_*$$

During primordial inflation the effective mass of ϕ is

$$m^2_{\phi,\ prim.\ inf.} = -m_0^2 + 2h_\alpha^2 \frac{\psi_*^{2\alpha}}{M_{Pl}^{2\alpha-2}}$$

$$\sim -m_0^2$$

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Reason why we consider SUGRA correction is that if we ignored it, the constraints that we would obtain from keeping effective mass of ψ light when considering ϕ_* are much tighter.

Constraining the Free Parameters

Time for Transition from Thermal Inflation to Field Oscillation

[1] **D.H. Lyth**, *JCAP* **1205** (2012) 022

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In order for "end of inflation" mechanism to produce observed ζ, the transition from thermal inflation to field oscillation has to be sufficiently fast[1].

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$$H_{TI} \ll 10^{-5} m_0$$

From this and by requiring $H_{TI} \lesssim H_*$ and $\psi_* \gg H_*$ we obtain

$$\psi_* \gg 10^{-6} m_0$$

and

$$\frac{\delta\psi_*}{\psi_*} \ll 10^{6} \frac{H_*}{m_0}$$

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ψ Energy Density

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As ψ has acquired perturbations, we require it to not dominant energy density of universe after end of thermal inflation, at which time $m_{\psi,eff}$ is increased significantly, becoming larger than H.

This is so as not to allow ψ's perturbations to generate dominant contribution to ζ when ψ decays.

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Therefore we require

$$m^2_{\psi,osc}\psi^2_* \ll M^2_{Pl}H^2_{TI}$$

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We have

$$m_{\psi,osc}^2 = m_\psi^2 + (4\alpha^2 - 2\alpha) h_\alpha^2 \overline{\phi}^2 \left(\frac{\psi_*}{M_{Pl}}\right)^{2\alpha-2}$$

$$\sim h_\alpha^2 \langle\phi\rangle^2 \left(\frac{\psi_*}{M_{Pl}}\right)^{2\alpha-2}$$

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$$\sim h^2_\alpha \langle\phi\rangle^2 \left(\frac{\psi_*}{M_{Pl}}\right)^{2\alpha-2}$$

Substituting this and our expressions for $\langle\phi\rangle$ and H_{TI} into the previous equation gives us

$$h_\alpha \ll \frac{m_0 M^{\alpha-1}_{Pl}}{\psi^\alpha_*}$$

Substituting our expressions for $\langle\phi\rangle$, H_{TI} and $m^2_{\psi,osc}$ into

$$\frac{H_{TI}}{m_{\psi,osc}} < 1$$

gives us

$$h_\alpha > \frac{m_0 M_{Pl}^{\alpha-2}}{\psi_*^{\alpha-1}}$$

Constraining the Free Parameters

Other Constraints

Constraining the Free Parameters

Other Constraints

- We require

$$m \gtrsim 1 \text{ TeV}$$

If ϕ were to have couplings only of gravitational strength, then we would require $m \gtrsim 10$ TeV, so as to not affect BBN. However, as ϕ interacts with the thermal bath, ψ and Standard Model fields and given that we have not observed ϕ particles, the constraint on m is loosened down to 1 TeV.

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- To protect BBN we require

$$H_{TI} \gtrsim 10^{-3} \text{ GeV}$$

Constraining the Free Parameters

Combining Constraints

These are all of the constraints that come from the physics.

However, we obtain many more by substituting them into each other.

I will not show you these ones.

Results

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When all of the constraints on m_0 are applied, only a value of $m_0 \sim 10^3$ GeV is allowed, subject to the following values:

$$H_* \sim 10^{10}\ \text{GeV}$$

$$\alpha = 2$$

$$n = 1$$

$\lambda_1 \sim 10^{-4} - 10^{-3}$	$\lambda_1 \sim 10^{-2} - 1$
$h_2 \sim 10^{-6} - 10^{-5}$	$h_2 \sim 10^{-7} - 10^{-4}$
$g \sim 10^{-5} - 1$	$g \sim 10^{-5} - 1$

However, with these values, the constraints

$$m_\psi \gg \left(\frac{10^{-39}\ \text{GeV}^{13}}{M_{Pl}}\right)^{\frac{1}{12}} \frac{h_2^{\frac{1}{3}}}{\lambda_1^{\frac{1}{8}}}$$

and

$$m_\psi \ll H_{TI}$$

cannot both be satisfied.

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and

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cannot both be satisfied.

Therefore, there is no parameter space available for the "end of inflation" scenario.

Modulated Decay Rate

Modulated Decay Rate

Now we investigate the modulated decay scenario to see if it can produce the dominant contribution to the primordial curvature perturbation.

The decay rate of ϕ is

$$\Gamma \sim \frac{m^3_{\phi,osc}}{M^2_{Pl}}$$

where

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Differentiating this w.r.t. m gives us

$$\delta\Gamma \sim (2n+3)^{\frac{3}{2}} \frac{m^2}{M^2_{Pl}} \delta m$$

The ζ that is produced by a varying decay rate[2] going from field oscillation after thermal inflation to ϕ decay is given to 1st order by

$$\zeta_{osc \to dec} = \delta N_{osc \to dec} = -\frac{1}{6}\frac{\delta\Gamma}{\Gamma}$$

[2] **G. Dvali, A. Gruzinov and M. Zaldarriaga**, *Phys.Rev.* **D69** (2004) 023505

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Substituting our expressions for Γ and $\delta\Gamma$ into this gives us

$$\zeta_{osc\to dec} = \delta N_{osc\to dec} \sim -\frac{\delta m}{m}$$

This is of the same order as the ζ produced by the "end of inflation" mechanism.

[2] **G. Dvali, A. Gruzinov and M. Zaldarriaga**, *Phys.Rev.* **D69** (2004) 023505

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Substituting our expressions for ψ_* and $\langle\phi\rangle$ into the constraint gives us

$$m_\psi \gg \left(\frac{10^{-4}}{H_*}\right)^{\frac{\alpha-1}{2\alpha-1}} \left(\frac{h^{n+1} m_0^{2\alpha n+4\alpha-2n-3} M_{Pl}^{\alpha n-\alpha+1}}{\sqrt{(2n+4)\lambda_n}^{2\alpha-1}}\right)^{\frac{1}{(2\alpha-1)(n+1)}}$$

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When this and all other relevant constraints from "end of inflation" scenario are applied to modulated decay rate scenario, there is no parameter space available.

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- Model constrained from observation and theory
- **No parameter space available for the model and thus it is ruled out**
- *Paper to appear soon*

Thank you

Any questions?

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