Electrically charged curvaton

Michela D’Onofrio\textsuperscript{a,b}, Rose Lerner\textsuperscript{a,b}, Arttu Rajantie\textsuperscript{c}

\textsuperscript{a}University of Helsinki, \textsuperscript{b}Helsinki Institute of Physics, \textsuperscript{c}Imperial College London

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Introduction

- **Inflation** introduced to solve three problems of Standard Cosmology: flatness, horizon, unwanted relics.

- **Curvaton model:**
  - *inflaton* $\phi$ drives the expansion;
  - *curvaton* $\sigma$ produces curvature perturbations.

- **During inflation:** $\sigma$ is subdominant and light.

- **After inflation:** $\sigma$ decays and perturbations affect the Universe.
Motivation

- connect curvature perturbation to Standard Model;
- give $U(1)$-charge to curvaton;
  - $\rightarrow$ less free parameters!
  - $\rightarrow$ large coupling $g' \approx 0.36$, interesting curvaton–photon interactions;
- when curvaton decays, significant contribution to curvature perturbation.
Model

We assume the curvaton carries one unit of $U(1)$ weak hypercharge $Y = 1$. The Lagrangian is:

$$\mathcal{L}_\phi = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi)$$  \hspace{1cm} (1)

$$\mathcal{L}_\sigma = -m^2 \sigma^\dagger \sigma - \lambda (\sigma^\dagger \sigma)^2 - \frac{1}{4} F_{\mu \nu} F^{\mu \nu} + |(i \partial_\mu - g' A_\mu) \sigma|^2$$  \hspace{1cm} (2)

We obtain a curvaton e.o.m. which is exactly solvable only by non-perturbative methods.
Constraints on the Effective Potential

Due to the large value of $g' \approx 0.36$, the potential gains quantum corrections (Coleman-Weinberg)

$$V_{\text{eff}}(\sigma) = m^2 |\sigma|^2 + \frac{3 g'}{64 \pi^2} |\sigma|^4 \ln \frac{|\sigma|^2}{\mu^2}$$

which have impact on the parameter space.

A curvaton must satisfy:

- vacuum stability
- shallow potential
- linearity
Curvaton dynamics

The background curvaton has e.o.m.:

$$\ddot{\sigma} + 3H\dot{\sigma} + m^2\sigma = 0$$

with $H(t) = \frac{1}{2t}$ (radiation-dominated epoch).

The curvaton evolves in time as:

$$\sigma(t) \approx \frac{\sigma_*}{(mt)^{3/4}} \cos\left(mt - \frac{3\pi}{8}\right)$$
Possible evolution after Inflation

After the end of inflation, the curvaton is a **homogeneous condensate** that **oscillates** in its potential. Its evolution depends on interactions with other fields, which cause it to decay into curvaton particles.

- **Thermal bath** of photons
  
  \[ T \ll m \quad \rightarrow \quad \text{late decay} \]

  \[ T \gg m \quad \rightarrow \quad \sigma \text{ decays too quickly} \]

- **Parametric resonance**
  
  \[ \text{linear} \]

  \[ \text{nonlinear} \]

  \[ \text{thermal bath} \]
Interaction with Thermal Bath

Curvaton–photon interaction: \textit{condensate} $\rightarrow$ \textit{curvaton particles}.

\[
\Gamma_{\text{th}} \approx 0.03 \ g'^2 \ T
\]

\(T \ll m\): particles are non-relativistic and decay at a very late time.

\(T \gg m\): if inflaton decays into photons immediately after inflation $\rightarrow$ curvaton decays too quickly, and $\zeta$ too small (if chemical equilibrium)

Viable model if: (i) $\phi$ decays to hidden sector;

(ii) $\phi$ decays late $\rightarrow \phi^4$-potential.
Non-perturbative Decay

– Provided NO interaction with thermal bath:

- Curvaton produces photons non-perturbatively: parametric resonance
- Gauge field in the curvaton background follows Mathieu equation
- Solutions are either oscillatory or growing
- Growing solution = energy transfer from curvaton to photon
- Type of solution given by instability plot
Gauge field dynamics

The evolution of the gauge field follows Mathieu equation:

\[ B''(z, k) + \left( \Sigma_k(z) + 2q(z) \cos 2z \right) B(z, k) = 0 \]

where \( B(t, k) = a(t)^{1/2} A(t, k), \quad z = mt \) and coefficients:

\[ q(z) \approx \frac{g^{'2} \sigma_*^2}{m^2 z^{3/2}} \]
\[ \Sigma_k(z) \approx \frac{k^2}{2mH_\ast z} + \frac{3}{16z^2} + 2q(z) \]

\( k \) is the comoving momentum, and we have inserted the curvaton solution.
Instability plot of Mathieu equation

$q(z)$

$\Sigma(z)$
Amplification of gauge field

amplification of $A_\mu$

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Constraints on Parameter Space

\[ \frac{\sigma_*}{H_*} \]

\[ m/H_* \]

\( H_* > 3 \times 10^9 \text{ GeV} \)
\( H_* > 1 \times 10^9 \text{ GeV} \)
\( H_* > 2 \times 10^8 \text{ GeV} \)
Conclusions

- We explored the possibility of having a $U(1)$-charged curvaton.
- We connected SM to inflation and reduced the number of free parameters.
- Two different decay modes: interaction with thermal bath and parametric resonance.
- The model is allowed, although parameter space is restricted by theoretical and observational constraints.
- Non-perturbative calculations are needed to further investigate the model.