Electrically charged curvaton

Michela D’Onofrio$^a, b$, Rose Lerner$^a, b$, Arttu Rajantie$^c$

$^a$University of Helsinki, $^b$Helsinki Institute of Physics, $^c$Imperial College London

[JCAP - astro-ph/1207.1063]

COSMO 2013
Cambridge, 2-6 Sept 2013
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

why do we want a charged curvaton?

- connect curvature perturbation to Standard Model;
- give U(1)-charge to curvaton;
  - → less free parameters!
  - → 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:

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

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

- **VACUUM STABILITY:** Vacuum at $\sigma = 0$ must be true vacuum, otherwise tunneling to false vacuum $\rightarrow$ spontaneously break $U(1)$ symmetry, photon massive.

- **SHALLOW POTENTIAL:** in order to have a light curvaton ($m^2_{\text{eff}} \equiv V''_{\text{eff}}$), and $V_\sigma \ll V_\phi$.

- **LINEARITY:** $\sigma$ evolves linearly both during and after inflation.
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.

- Interaction with a thermal bath of photons
  - $T \ll m \rightarrow$ late decay
  - $T \gg m \rightarrow$ $\sigma$ decays too quickly

- Decay through parametric resonance
  - linear
  - nonlinear
  - thermal bath

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Interaction with Thermal Bath

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

\[ \Gamma_{\text{th}} \approx 0.03 \ g^\prime T \]

\( T \ll m \): 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)

\textbf{Viable model} if there are almost no photons after inflation in thermal bg:

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

\[
q(z) \approx \frac{g'^2 \sigma_*^2}{m^2 z^{3/2}}
\]

\[
\Sigma_k(z) \approx \frac{k^2}{2mH_* z} + \frac{3}{16z^2} + 2q(z)
\]

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

- shaded regions = stable bands;
- white regions = resonance bands with exponentially growing solutions;
- the solid line shows $\Sigma = 2q \Rightarrow k = 0$;
- starting position and speed depend on $m$ and $\sigma^*$.

As modes with $k > 0$ follow a similar evolution, but on a lower line, modes with higher $k$ spend less time in the instability bands $\rightarrow$ weaker resonance.
Amplification of the gauge field $A$ as a function of $mt$, for different $\sigma_*(H_*)$ and $m(H_*)$. Upper line: huge amplification, resonance is nonlinear. Lower line: linear evolution. Dashed line: nonlinearity condition.
Constraints on Parameter Space

Allowed region for a viable curvaton model which produces $\zeta = 10^{-5}$. The size of the allowed region reduces as $H_*$ reduces. For $H_* \lesssim 10^8$ GeV there is no allowed parameter space.
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$H_* > 3 \times 10^9$: regions 1, 2, 3 allowed

$10^9 < H_* < 3 \times 10^9$: regions 2, 3

$2 \times 10^8 < H_* < 10^9$: region 3

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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.