Electrically charged curvaton

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Introduction

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

- Curvaton model:

  inflaton ϕ drives the expansion;
  curvaton σ produces curvature perturbations.

- During inflation: σ is subdominant and light.

- After inflation: σ 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;

  $\longrightarrow$ less free parameters!

  $\longrightarrow$ 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:

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

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

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)

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

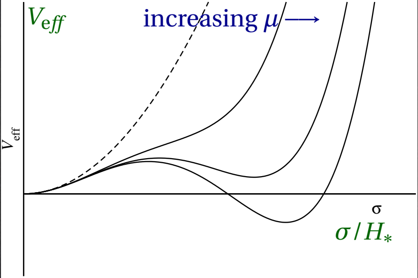
which have impact on the parameter space.

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 → spontaneously break U(1) symmetry, photon massive.



- SHALLOW POTENTIAL: in order to have a light curvaton ($m^2_{eff} \equiv V''_{eff}$), and $V_\sigma \ll V_\phi$.
- LINEARITY: σ evolves linearly both during and after inflation.

Curvaton dynamics

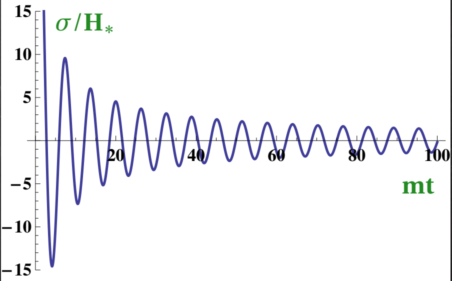
The background curvaton has e.o.m.:

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

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

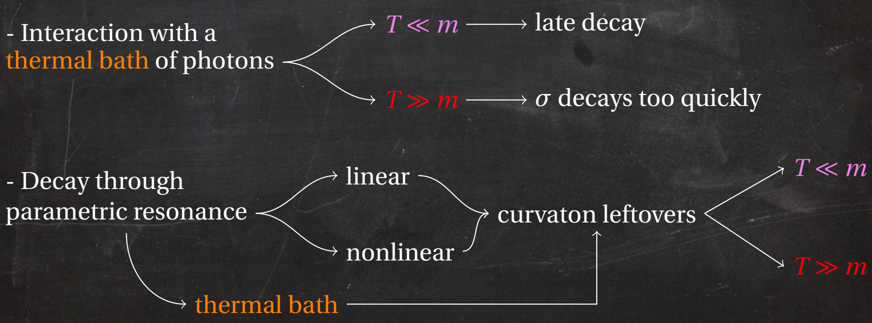
The curvaton evolves in time as:

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



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 Thermal Bath

Curvaton–photon interaction: condensate $\longrightarrow$ curvaton particles.

$$\boxed{\Gamma_{\rm th} \approx 0.03\, g'^2\, T}$$

$T \ll m$: 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 ζ too small (if chemical equilibrium)

Viable model if there are almost no photons after inflation in thermal bg:

(i) ϕ decays to hidden sector;

(ii) ϕ decays late $\rightarrow$ ϕ^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:

$$\mathbf{B}''(z,\mathbf{k}) + \left(\Sigma_k(z) + 2q(z)\ \cos 2z\right)\ \mathbf{B}(z,\mathbf{k}) = 0$$

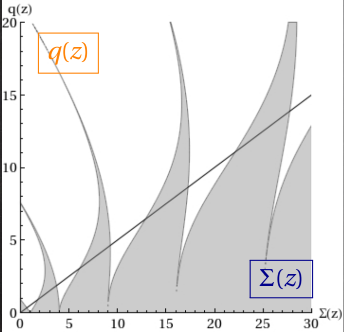
where $\mathbf{B}(t,\mathbf{k}) = a(t)^{1/2}\mathbf{A}(t,\mathbf{k})$, $z = mt$ and coefficients:

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

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

k is the comoving momentum, and we have inserted the curvaton solution.

Instability plot of Mathieu equation



- shaded regions = stable bands;

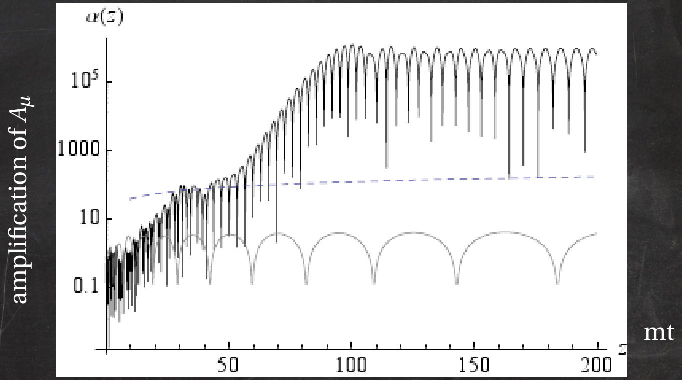
- white regions = resonance bands with exponentially growing solutions;

- the solid line shows $\Sigma = 2q \quad \Rightarrow \quad k = 0$;

- starting position and speed depend on m and σ_*;

- 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 $\longrightarrow$ weaker resonance.

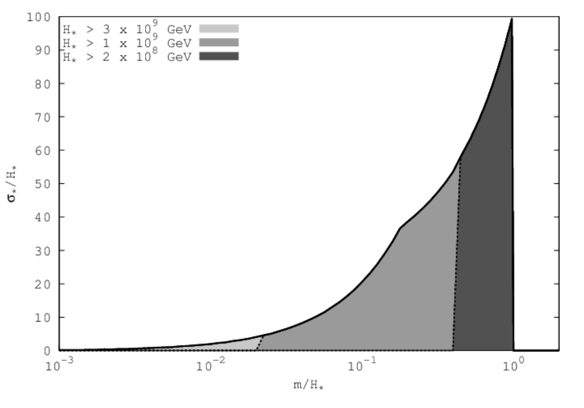
Amplification of gauge field



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

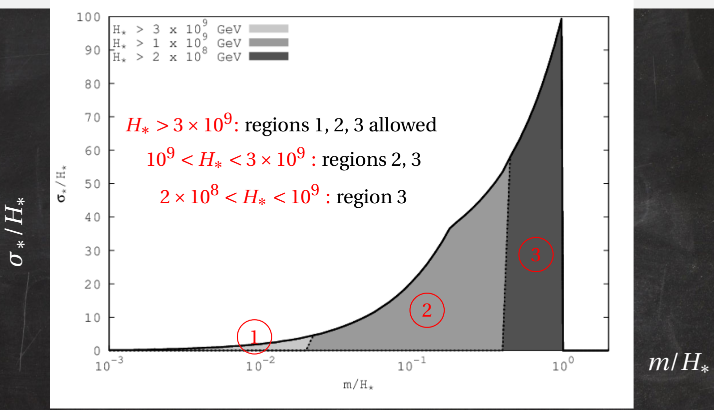
σ_*/H_*



m/H_*

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.

Constraints on Parameter Space



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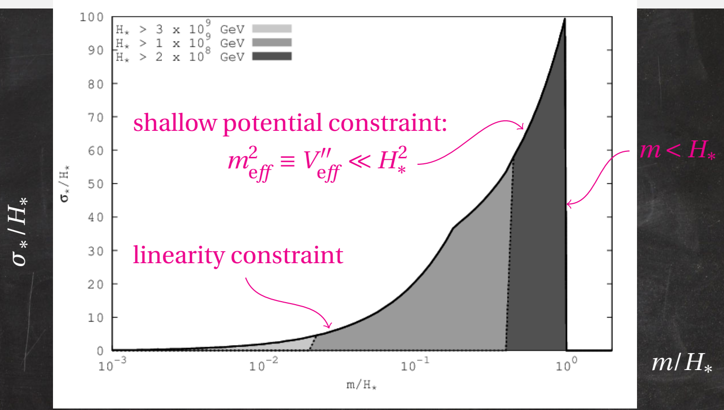

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Conclusions

- 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.