TeV mass curvaton

[arXiv:1007.0657]

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Curvaton scenario

- In the curvaton scenario the primordial perturbations are not sourced by the inflaton, but by another scalar field.
- Pick your favourite inflationary scenario and add another scalar field, the curvaton σ. It acquires scalar perturbations for superhorizon modes of the magnitude $\sim H_*/2\pi$.
- It has essentially one free initial condition, the initial field value σ_* or $r_* \equiv \frac{V(\sigma_*)}{3M_{\rm Pl}^2 H_*^2}$.
- Long after inflation has ended, the curvaton decays into radiation producing the observed primordial perturbations.

A TeV mass curvaton?

- The mass of the curvaton is *a priori* a free parameter, and many models with different masses have been studied.
- There are very compelling reasons to assume that there are some new physics at the TeV scale.
- The LHC is gathering data, and once the luminosity is upgraded, new results are expected to come "soon".
- *Any* scalar field found in the TeV scale might possibly work as a curvaton.

Bounds

- The curvaton must produce the amplitude of the primordial perturbations to match the observations, $\zeta \sim 1.9 \times 10^{-5}$:

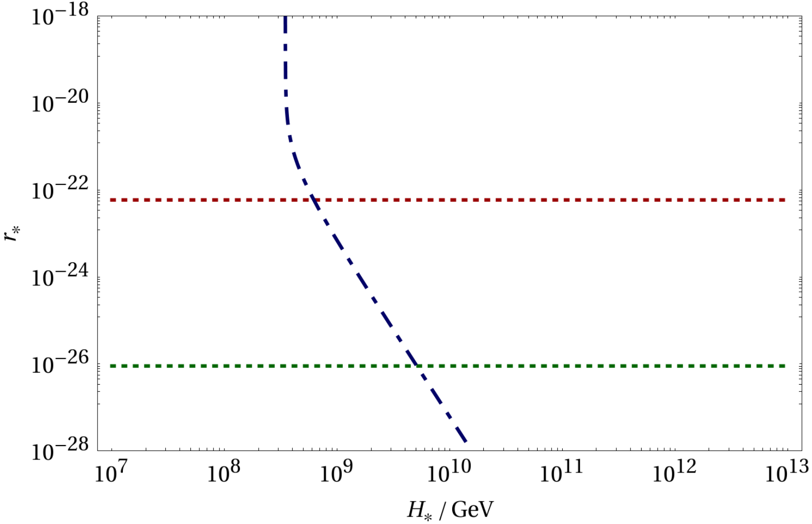
$$\zeta \simeq r_{\text{decay}} \frac{H_*}{2\pi\sigma_*} \quad \Rightarrow \quad r_* < \frac{1}{6} \frac{m^2}{\zeta^2 M_{\text{Pl}}^2}$$

- The curvaton will produce some amount non-Gaussianity. The rough estimate for f_{NL} is $1/r_{\text{decay}}$. Observationally we know that (roughly) $|f_{\text{NL}}| < 100$:

$$f_{\text{NL}} \sim \frac{1}{r_{\text{decay}}} \quad \Rightarrow \quad r_* > \frac{10^{-4}}{6} \frac{m^2}{\zeta^2 M_{\text{Pl}}^2}$$

- The primordial perturbations are known to be adiabatic to a great accuracy. Thus the curvaton must decay before DM decouples. We assume a very conservative[1] limit for the effective decay constant, $\Gamma > 10^{-17}$GeV.

[1] *Conservative* in the sense that the realistic limit is probably larger.



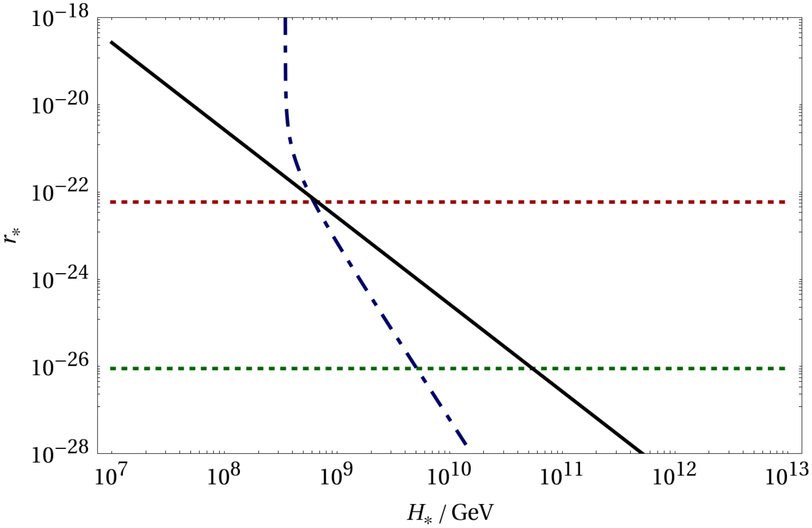
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
r_*
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
H_* / GeV

Could there be self-interactions?

- Add a monomial term to the potential, $V_{\text{int}} = \lambda \frac{\sigma^n}{M^{n-4}}$.
- For simplicity put $\lambda = 1$ and choose $M = M_{\text{Pl}}$. Now the self-interaction is either
  - originating from Planck scales,
  - originating from lower scale physics, with a very small coupling constant.

  Either way, the self-interaction is very weak.
- In order for the quadratic model to be a good approximation, the quadratic term must dominate the non-quadratic term throughout the evolution. Since the energy density of the curvaton is monotonously decreasing,

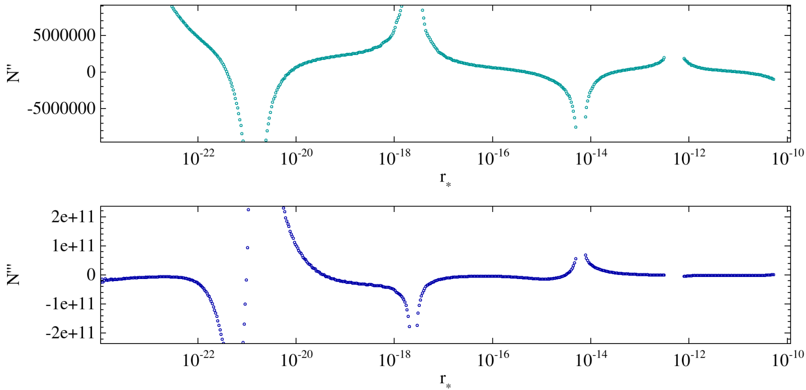
$$\frac{1}{2} m^2 \sigma_*^2 \gg \frac{\sigma_*^n}{M_{\text{Pl}}^{n-4}} \; .$$



This is for $n = 8$. For smaller values of n, the black line is even more to the left.

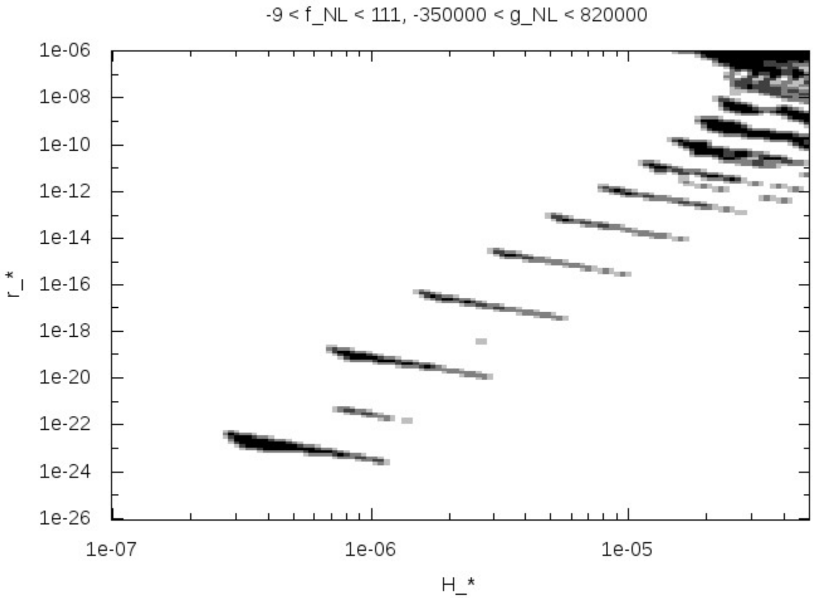
Effect of the self-interactions

- The dynamics of the self-interaction have been documented, see e.g. [arXiv:0906.3126] and [arXiv:0912.4657].
- The oscillations in the non-quadratic part of the potential are slow and non-linear, and cause oscillations of the derivatives of N in the parameter space.



Different values of n

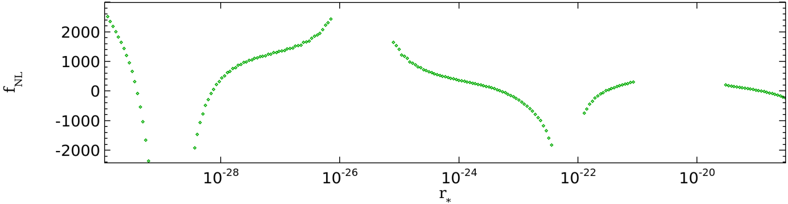
- The self-interactions decrease the amplitude of the perturbations *on average*.
- The oscillations can enhance the amplitude for some range of parameters.
- After scanning through different values of the potential ($n = 4, 6, 8$ and 10), we conclude that all other values of n are **disallowed**, except for $n = 8$.
- Only the σ^8-interaction enhances ζ enough, so that it can produce the observed amplitude of the perturbations while not decaying too late and not producing too large f_{NL} and g_{NL}.

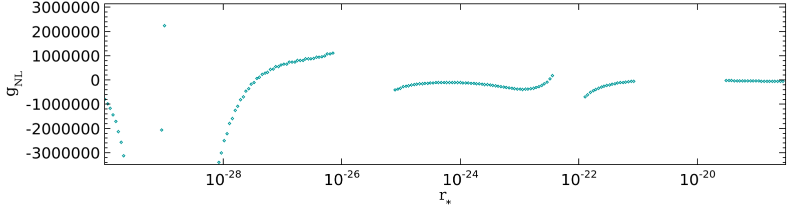


$\zeta = 19.1 \times 10^{-5}$, $\Gamma > 10^{-17}\text{GeV}$,
$-6 < f_{\rm NL} < 111$ and $-3.5 \times 10^5 < g_{\rm NL} < 8.2 \times 10^5$.

Large non-Gaussianity

- Even though the allowed regions have $-6 < f_{\rm NL} < 111$ and $-3.5 \times 10^5 < g_{\rm NL} < 8.2 \times 10^5$, most of the regions still have large $|f_{\rm NL}|$ and/or $|g_{\rm NL}|$.





Conclusions

- For a TeV mass curvaton, even very small self-interactions will always play a significant role in its evolution.
- For Planck scale suppressed monomials, only σ^8 can work.
- The self-interaction will produce large non-Gaussianity.
- Since there is no simple relation between f_{NL} and g_{NL}, the other one can be very large while the other one is very small.

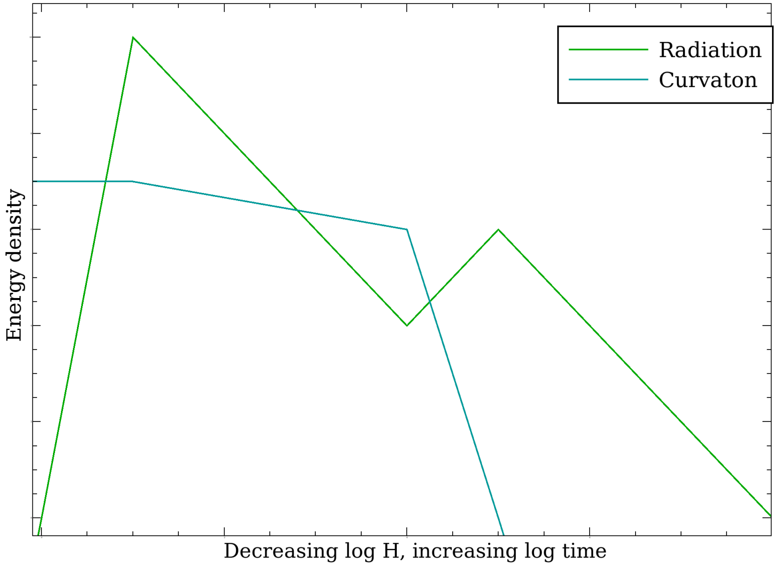
Backup

Solving the self-interacting model

- The introduction of the self-interaction makes the system non-linear, and the evolution of the background field value and the perturbation is different.
- Use the ΔN-formalism to solve the model. The system is described by

$$
\begin{aligned}
\ddot{\sigma} + (3H + \Gamma)\dot{\sigma} + V'(\sigma) &= 0 \\
\dot{\rho}_{\mathrm{r}} &= -4H\rho_{\mathrm{r}} + \Gamma\dot{\sigma}^2
\end{aligned}
$$

A rough sketch of a curvaton



- The final value of perturbations depends roughly on two factors:
  1. the initial amplitude of the perturbations, H_*/σ_*
  2. the efficiency of converting the curvaton perturbations to curvature perturbations
- First order approximation for the efficiency factor is the energy fraction in curvaton during the decay,

$$r_{\rm decay} \equiv \frac{\rho_\sigma}{\rho_{\rm r} + \rho_\sigma}\Big|_{\rm decay} .$$

- There are five free parameters m, n, Γ, λ and M and two initial conditions H_* and r_*.
- The equations of motion for the system are

$$\begin{aligned} \ddot{\sigma} + (3H + \Gamma)\dot{\sigma} + m^2\sigma + (n+4)\sigma^{n+3} &= 0 \\ \dot{\rho_{\rm r}} &= -4H\rho_{\rm r} + \Gamma\dot{\sigma}^2 \\ 3H^2 &= \rho_{\rm r} + \rho_\sigma \end{aligned}$$

Few words on numerics

- Only $n = 0$-case is solvable analytically, so the EOMs need to be solved numerically.
- Instead of calculating the evolution of σ and $\delta\sigma$ separately, use the ΔN -formalism which is more suited to numerics.
- Time is unphysical. Always compare quantities not with fixed time, but with fixed H.
- Solving the full EOM's becomes increasingly slow as the curvaton oscillates faster and faster in the quadratic regime. Hence one has to revert to approximate EOM's for ρ_σ at some point.

Qualitative behaviour of the solutions

- A field oscillating in a monomial potential $V \propto \sigma^{n+4}$ scales as

$$\rho_\sigma \propto a^{-6\frac{n+4}{n+6}} .$$

  However if $n \geqslant 6$, there are no oscillating solutions.
- The evolution of the curvaton hence should have four distinct phases:
  1. Slow-roll, $\sigma \sim \sigma_*$.
  2. Non-quadratic regime, $\rho_\sigma \propto a^{-6\frac{n+4}{n+6}}$.
  3. Quadratic regime, $\rho_\sigma \propto a^{-3}$.
  4. Decay when $H \sim \Gamma$.