# TeV Mass Curvaton

JCAP09(2010)030 [arXiv:1007.0657]

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COSMO/CosPA2010, Tokyo, September 2010

# Curvaton scenario

- In the curvaton scenario the primordial perturbations are not sourced by the inflaton, but by another scalar field, $\sigma$.
- In the simplest curvaton model the potential is quadratic, and there is essentially one free initial condition, the initial field value $\sigma_*$ 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.
- Motivation for a TeV mass curvaton is obvious: LHC is powering up, and there are strong hints that there is something just around the corner.

# Bounds

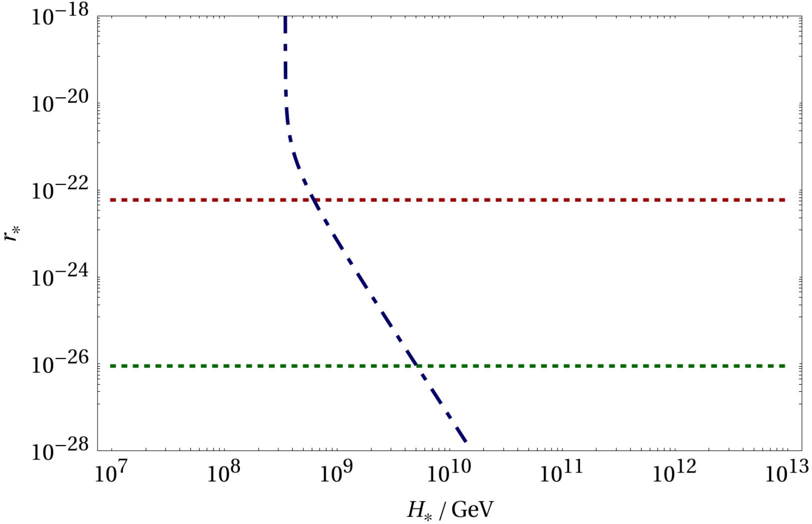
- The curvaton must produce the observed amplitude of the primordial perturbations, $\zeta \sim 1.9 \times 10^{-5}$:

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

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

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

- 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 limit for the effective decay constant, $\Gamma > 10^{-17}\text{GeV}$.



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

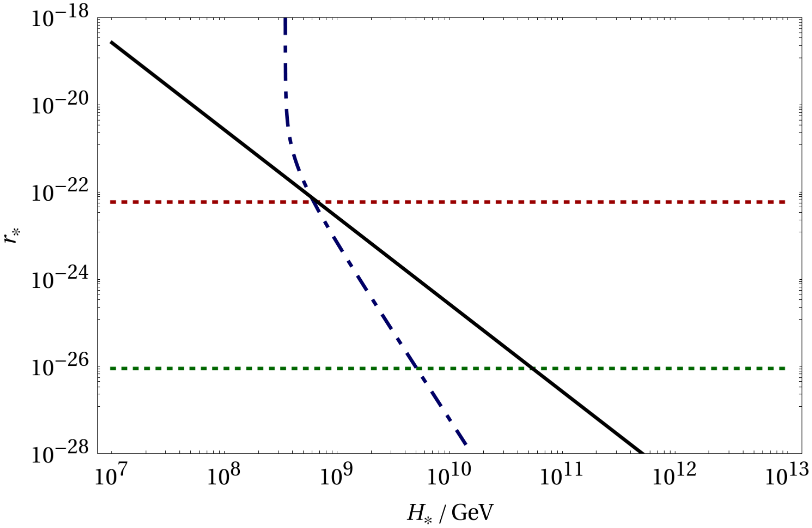
# Could there be self-interactions?

- The curvaton must have some interactions: It must decay!
- The most minimal addition to the potential is a monomial:

$$V_{\text{int}} = \lambda \frac{\sigma^n}{M^{n-4}}$$

- To be conservative, make the self-interaction very weak (for $n > 4$): Put $\lambda = 1$ and choose $M = M_{\text{Pl}}$.
- 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 decreases monotonously, we require

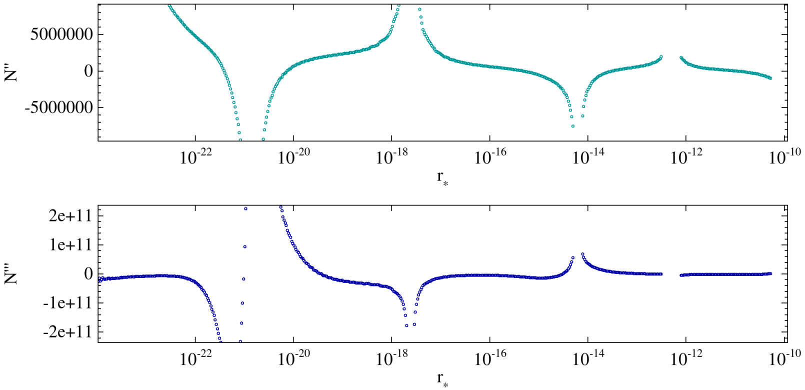
$$\frac{1}{2} m^2 \sigma_*^2 \gg \frac{\sigma_*^n}{M_{\text{Pl}}^{n-4}} \ .$$




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

# Effect of the self-interactions

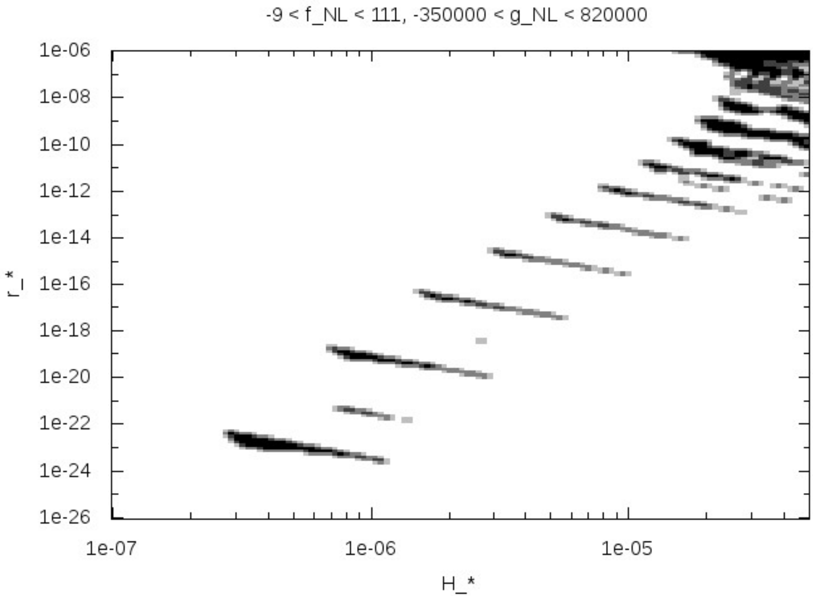
- The dynamics of the self-interaction of this type have been documented previously, see e.g. [arXiv:0906.3126] and [arXiv:0912.4657].
- On average, the self-interaction decreases the amplitude of the perturbations, $\rho \propto a^{-\frac{6n}{n+2}}$.
- The self-interaction makes the EOM non-linear, and causes slow oscillations. The phase of these oscillations freezes in when the quadratic oscillations start, and cause strong dependence on the initial conditions.




- For some initial conditions the perturbation is damped, but for some strongly enhanced. The values of $N'$ and higher derivatives oscillate *as a function of the initial conditions*.

## Different values of n

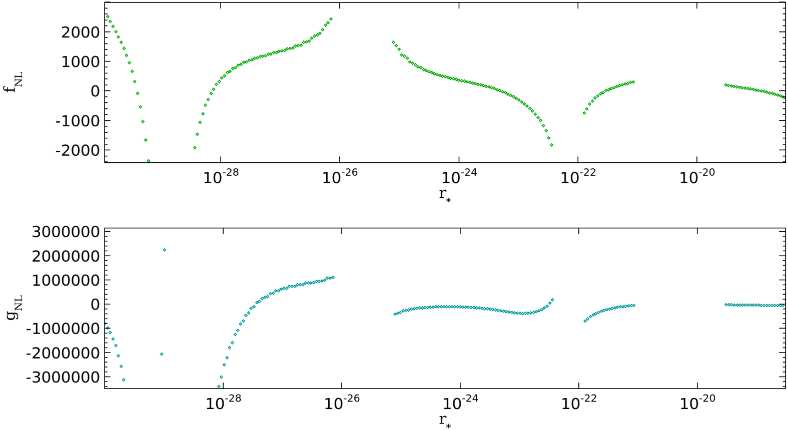
- We use $\delta N$-formalism to calculate $\Gamma$, $f_{\rm NL}$ and $g_{\rm NL}$, while keeping $\zeta$ fixed using a code developed for [arXiv:0906.3126].
- We scanned through different values of the potential, $n = 4, 6, 8$ and 10, and concluded that $n = 4$, 6 and 10 are disallowed.
- Only the $\sigma^8$-interaction enhances $\zeta$ enough, so that it can
  - produce the observed amplitude of the perturbations while
  - not decaying too late
  - and not producing too large $f_{\rm NL}$ and $g_{\rm NL}$.




$\zeta = 19.1 \times 10^{-5}$, $\Gamma > 10^{-17}\text{GeV}$,
$-6 < f_{\rm NL} < 111$ 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 curvaton with a TeV scale mass, even very weak self-interactions will always play a significant role in its evolution.
- For Planck scale suppressed monomials, only $V_{\rm int} \sim \sigma^8$ can work.
- The self-interaction will typically produce large non-Gaussianity.
- Since there is no simple relation between $f_{\rm NL}$ and $g_{\rm NL}$, the other one can be very large while the other one is very small.

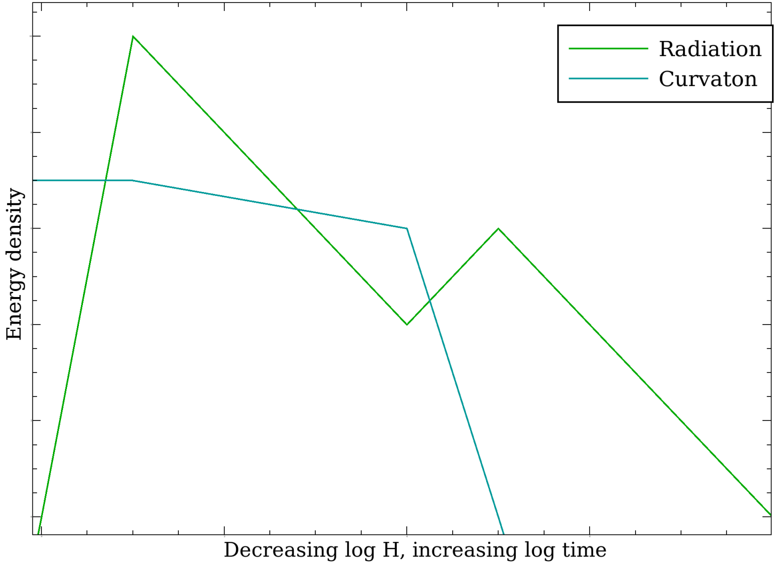
# Backup

# 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 $\Delta N$-formalism to solve the model. The system is described by

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

# A rough sketch of a curvaton



- The final value of perturbations depends roughly on two factors:
  1. the initial amplitude of the perturbations, $H_*/\sigma_*$
  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 $m$, $n$, $\Gamma$, $\lambda$ 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 $\sigma$ and $\delta\sigma$ separately, use the $\Delta N$ -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 $\rho_\sigma$ 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 $H \sim \Gamma$.