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G-Curvaton

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ABSTRACT

In this Letter, we study a curvaton model where the curvaton is acted by Galileon field. We calculate the power spectrum of fluctuation of G-Curvaton during inflation and discuss how it converts to the curvature perturbation after the end of inflation. We estimate the bispectrum of curvature perturbation induced, and show the dependence of non-Gaussianity on the parameters of model. It is found that our model can have sizable local and equilateral non-Gaussianities to up to $\mathcal{O}(10^2)$, which is illustrated by an explicit example.

1. Introduction

Inflation has now been considered as one of the most successful theory to describe our universe at early epochs [1–3]. Making our universe expand fast enough, it can naturally solve many notorious problems brought out by hot Big Bang, such as flatness problem, horizon problem, monopole problem and so on. Moreover, during inflation the quantum fluctuations generated at the initial stage can be stretched out of the horizon to form classical perturbations, which can provide seeds for the formation of the structure of our universe. An inflation model also succeeds in producing nearly scale-invariant power spectrum of scalar perturbation and tiny gravitational waves, which fits very well with today's observational data [4]. The non-Gaussian corrections of perturbations during inflation can also be large or not, according to various inflation models, which is waiting for constraints from new and more accurate data in the near future [5].

Usually, the perturbation of inflation is generated by the inflaton field itself, which is the simplest way to have curvature perturbation. However, it is not the only choice. Perturbations generated in such a way depends on the potential of the inflaton field, and thus puts very severe constraint on inflation models. In order to relax such a constraint, as Lyth and Wands have pointed out, perturbation can also be generated from another field that has nothing to do with the inflaton field, namely, the *curvaton* [6], see also relevant works on curvaton mechanism in Refs. [7,8] and earlier [9,10]. Curvaton field is usually assumed to be a scalar field with light mass and decoupled from all the other kinds of perturbations, thus the perturbation produced by curvaton can be independent on the nature of inflation. Moreover, since the curvaton is subdominant during inflation, it can only produce isocurvature perturbation. This isocurvature perturbation has to be converted into curvature perturbation at the end of inflation, so it depends on what happened after the inflation terminated. Usually, there are two cases in which this conversion can be available: First, when the inflaton decays into radiation after inflation, the curvaton field becomes dominate; second, the curvaton field decays as well before its domination, and reaches equilibrium with radiation that decays from inflaton. According to different case, the amount of the curvature perturbations converted from curvaton perturbations may be different. Curvaton scenarios have been widely studied in, for instance, [11].

In the original curvaton paper, it was suggested that curvaton is made of a canonical scalar field. However, other field models can be considered to act as a curvaton. People have considered curvaton of pseudo-Nambu–Goldstone–Boson [12], DBI-type [13] or its curvaton brane implement [14], multi-field [15], Lagrangian multiplier field [16], Horava–Lifshitz scenario [17] and so on. Very recently, a new kind of models has been proposed and studied extensively, which is called "Galileon" models [18]. The original version of these models is a generalization of an effective field description of the DGP model [19]. These models includes high derivative operator of the scalar field, however, due to some "delicated design", its equation of motion remains second order,[1] thus it can violate the NEC without incorporating

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[1] This idea is actually pioneered by Horndeski thirty years ago, in [20].

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any instability modes. Due to such an interesting property, such kind of model generically can admit superluminal propagation [21] and perhaps even closed timelike curves (CTCs) [22] (see also [23] for CTCs without Galileon). Moreover, these models can be applied onto various evolution period of our universe, such as dark energy [24,25], inflation [26–28], reheating [29], bouncing [30], the slow expansion scenario [31] of primordial universe [32,33], and so on. As an extension, these models can also be generalized to DBI version [34], the K-Mouflage scenario [35], the supersymmetric Galileon [36], the Kinetic Gravity Braiding models [24], the generic Galileon-like action [20,37,38] and others. See also e.g. Refs. [39–46] for various studies of their phenomenologies.

In the present work, we study the scenario where a Galileon field behaves as a curvaton, which we dubbed as "*G-Curvaton*" scenario. Due to the higher derivative term, Galileon is expected to have some features on generating perturbations, such as getting large tensor–scalar ratio in "G-inflation" scenario. Our paper is organized as follows: in Section 2 we review the original curvaton scenario, by taking curvaton to be the simplest one, i.e., the canonical scalar field. In Section 3 we study our "G-Curvaton" model. We first investigate its perturbation, obtaining a scale-invariant power spectrum. Then we discuss how it converts to the curvature perturbation at the end of inflation, considering both cases where curvaton decays before and after it dominate the universe. We also study the non-Gaussianities generated from our model, both local type and equilateral type. Finally we present an explicit example to show how the observable quantities could be effected. Section 4 comes our conclusion and discussions.

2. Review of the simplest curvaton model

In this section, we would like to review how the mechanism works for the simplest curvaton model, which is made of a canonical scalar field. The Lagrangian for the curvaton field is:

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

Note that here we are using the metric with notation $ds^2 = -dt^2 + a^2(t)\delta_{ij}\,dx^i\,dx^j$. As for curvaton, the effective mass of σ needs to be very light, which put the constraint $|V_{,\sigma\sigma}| \ll H^2$ to the potential $V(\sigma)$, where $V_{,\sigma\sigma} \equiv \partial^2 V/\partial\sigma^2$ and H denotes the Hubble parameter of the universe. Moreover, during inflation H is almost a constant. Thus in general, one may define the parameters

$$\epsilon \equiv -\frac{\dot{H}}{H^2}, \qquad \xi = \frac{V_{,\sigma\sigma}}{3H^2}, \tag{2}$$

which are required to be far smaller than 1 and slowly varying. Moreover, since curvaton is subdominant part of the universe during inflation, the energy scale of the potential should also be lower than that of inflation, namely $V(\sigma) \ll 3M_{pl}^2 H^2$.

Suppose the field generates fluctuation during inflation, namely $\sigma(x) \to \sigma_0(t) + \delta\sigma(t, \mathbf{x})$, then from Eq. (1) we can easily get the equation of motion for the field fluctuation $\delta\sigma$ as:

$$\delta\ddot{\sigma}_{\mathbf{k}} + 3H\delta\dot{\sigma}_{\mathbf{k}} + \left((k/a)^2 + V_{,\sigma\sigma}\right)\delta\sigma_{\mathbf{k}} = 0, \tag{3}$$

where $\delta\sigma_{\mathbf{k}}$ is the Fourier presentation of $\delta\sigma$ with momentum mode $\mathbf{k}$, and a is the scale factor. Note that here we have already neglected the coupling of $\delta\sigma_{\mathbf{k}}$ to the metric perturbation, as has been done in [6]. Thus the power spectrum of the field fluctuation $\delta\sigma_{\mathbf{k}}$ at the horizon crossing is given by

$$\mathcal{P}_\sigma \equiv \frac{k^3}{2\pi^2}|\delta\sigma_{\mathbf{k}}|^2 = \left(\frac{H_*}{2\pi}\right)^2, \tag{4}$$

where the star denotes the time of horizon exit, $k = a_* H_*$. The spectral index of the spectrum can also be given by:

$$n_\sigma - 1 \equiv \frac{d\ln\mathcal{P}_\sigma}{d\ln k} = -2\epsilon + 2\xi \ll 1, \tag{5}$$

which shows the nearly scale-invariance of the spectrum $\mathcal{P}_\sigma$.

However, since the curvaton is the subdominant part of the universe during inflation, the perturbation generated by it can only be of isocurvature type. This type of perturbation can only be converted into curvature perturbation when curvaton dominates, or becomes equilibrium with other part of the universe. Either these cases will not happen during inflation, however after inflation, when inflaton field decays into radiation whose energy density may decrease more rapidly than curvaton field, both the two cases will happen, depending on when the curvaton field will decay. In the case when the curvaton decays late, it will exceed over the radiation decayed from inflaton and dominate the universe, however in the case when the curvaton decays early, it may become equilibrium with the radiation. The curvature perturbations for a given matter with energy density ρ in spatial-flat slicing is given by [47]:

$$\zeta = -H\frac{\delta\rho}{\dot{\rho}}, \tag{6}$$

and the separately conserved curvature perturbations for radiation and curvaton field therefore read:

$$\zeta_r = -H\frac{\delta\rho_r}{\dot{\rho}_r} = \frac{1}{4}\frac{\delta\rho_r}{\rho_r}, \tag{7}$$

$$\zeta_\sigma = -H\frac{\delta\rho_\sigma}{\dot{\rho}_\sigma} = \frac{\delta\rho_\sigma}{3(\rho_\sigma + p_\sigma)}, \tag{8}$$

respectively, where p_σ is the pressure of the curvaton field. Using these results, and assuming that the isocurvature perturbation convert to curvature perturbation instantly, then the curvature perturbation generated by such conversion reads:

$$\zeta = \frac{4\rho_r\zeta_r + 3(\rho_\sigma + p_\sigma)\zeta_\sigma}{4\rho_r + 3(\rho_\sigma + p_\sigma)} \simeq \frac{3(\rho_\sigma + p_\sigma)\zeta_\sigma}{4\rho_r + 3(\rho_\sigma + p_\sigma)}, \tag{9}$$

where in the last step we neglected the curvature perturbation of radiation, ζ_r. Define the energy density ratio of σ over radiation, $r \equiv \rho_\sigma/\rho_r$, then in the first case where the curvaton dominates, we have $r \gg 1$, Eq. (9) becomes:

$$\zeta \simeq \zeta_\sigma, \tag{10}$$

while in the second case where σ become equilibrium with radiation, we have $\rho_\sigma \ll \rho_r$, Eq. (9) becomes:

$$\zeta \simeq \frac{3}{4} r(1 + w_\sigma)\zeta_\sigma, \tag{11}$$

where $w_\sigma \equiv p_\sigma/\rho_\sigma$ is the equation of state of the curvaton field.

Furthermore, we investigate the non-Gaussianities of the perturbation generated by the curvaton field. The local type non-Gaussianities of curvature perturbation are given by:

$$\zeta = \zeta_g + \frac{3}{5} f_{NL}^{local} \zeta_g^2, \tag{12}$$

where the subscript "g" denotes the Gaussian part of ζ while f_{NL} is the so-called non-linear estimator. For local type, f_{NL}^{local} can be estimated by using the so-called δN formalism, where δN is the variation of the number of efolds N of inflation [48]:

$$\zeta = \delta N = N_{,\sigma}\delta\sigma + \frac{1}{2} N_{,\sigma\sigma}\delta\sigma^2 + \cdots, \tag{13}$$

where $N_{,\underbrace{\sigma\cdots\sigma}_{n}} \equiv \partial^n N/\partial\sigma^n$ and the same notations hereafter. Comparing Eqs. (12) and (13) one can easily find that f_{NL}^{local} can be presented using $N_{,\sigma}$ and $N_{,\sigma\sigma}$, namely,

$$f_{NL}^{local}\big|_\zeta = \frac{5}{6}\frac{N_{,\sigma\sigma}}{N_{,\sigma}^2}. \tag{14}$$

For non-local type, however, things will become a little bit more complicated, since non-Gaussianities also exist in the field fluctuation $\delta\sigma$ itself, and δN formalism will not be valid any longer. In this case, we could express the 3-point correlation function of ζ as:

$$\langle|\zeta(k_1)\zeta(k_2)\zeta(k_3)|\rangle = (2\pi)^3\delta^3\Big(\sum_i k_i\Big)\mathcal{B}(k_1, k_2, k_3) \tag{15}$$

where $\mathcal{B}(k_1, k_2, k_3)$ is the shape of the non-Gaussianities and

$$\langle|\zeta(k_1)\zeta(k_2)\zeta(k_3)|\rangle = -i\mathcal{T}\int_{t_0}^{t} dt' \langle\big|\big[\zeta(t, k_1)\zeta(t, k_2)\zeta(t, k_3), \mathcal{H}_{int}^p(t')\big]\big|\rangle, \tag{16}$$

with $\mathcal{H}_{int}^p$ being interaction Hamiltonian of curvaton in momentum space. The non-linear estimator is defined as:

$$f_{NL}^{nonlocal}\big|_\zeta \equiv \frac{10}{3}\frac{\prod_{i=1}^3 k_i^3}{(2\pi)^4\sum_{i=1}^3 k_i^3}\frac{\mathcal{B}(k_1, k_2, k_3)}{[\mathcal{P}_\zeta(k_1)\mathcal{P}_\zeta(k_2) + 2\,perm.]}. \tag{17}$$

3. The G-Curvaton model

In this section, we study our model of which the curvaton field is of Galileon type. For simplicity but without losing generality, we consider the Lagrangian of curvaton has the general third order Galileon field, which is given by [18,24]:

$$\mathcal{S}_{GC} = \int d^4x\sqrt{-g}\big[K(\sigma, X) - G(\sigma, X)\Box\sigma\big], \tag{18}$$

where K and G are generic functions of σ and $X \equiv -\partial_\mu\sigma\partial^\mu\sigma/2$ is the kinetic term of the field σ. The Lagrangian used is inspired by the original Galileon construction but does not respect the Galileon symmetry, which was called 'Generalized Galileons' by Deffayet et al. [24]. Note that more generalized Galileon model containing higher order operators of $\Box\sigma$ or the couplings of σ to the gravitational part was constructed in Ref. [37]. From action (18), the energy–momentum tensor $T_{\mu\nu}$ has the form of:

$$T_{\mu\nu} = K_{,X}\partial_\mu\sigma\partial_\nu\sigma + Kg_{\mu\nu} - \partial_\mu G\partial_\nu\sigma - \partial_\mu G\partial_\nu\sigma + g_{\mu\nu}\partial_\lambda G\partial^\lambda\sigma - G_{,X}\Box\sigma\partial_\mu\sigma\partial_\nu\sigma. \tag{19}$$

Taking the homogeneous and isotropic background where $T_{\mu\nu}$ has the form of $\mathrm{diag}\{\rho_\sigma, a^2(t)p_\sigma, a^2(t)p_\sigma, a^2(t)p_\sigma\}$, we can further obtain the energy density and pressure of σ as:

$$\rho_\sigma = 2K_{,X}X - K + 3HG_{,X}\dot\sigma^3 - 2G_{,\sigma}X, \tag{20}$$

$$p_\sigma = K - 2(G_{,\sigma} + G_{,X}\ddot\sigma)X. \tag{21}$$

Moreover, by varying action (18) with respect to σ, we obtain the equation of motion for σ:

$$\begin{aligned} & K_{,X}\Box\sigma - K_{,XX}(\partial_\mu\partial_\nu\sigma)\big(\partial^\mu\sigma\partial^\nu\sigma\big) - 2K_{,X\sigma}X + K_{,\sigma} - 2(G_{,\sigma} - G_{,X\sigma}X)\Box\sigma \\ & \quad + G_{,X}\big[(\partial_\mu\partial_\nu\sigma)\big(\partial^\mu\partial^\nu\sigma\big) - (\Box\sigma)^2 + R_{\mu\nu}\partial^\mu\sigma\partial^\nu\sigma\big] + 2G_{,X\sigma}(\partial_\mu\partial_\nu\sigma)\big(\partial^\mu\sigma\partial^\nu\sigma\big) \\ & \quad + 2G_{,\sigma\sigma}X - G_{,XX}\big(\partial^\mu\partial^\lambda\sigma - g^{\mu\lambda}\Box\sigma\big)\big(\partial_\mu\partial^\nu\sigma\big)\partial_\nu\sigma\partial_\lambda\sigma = 0, \end{aligned} \tag{22}$$

which can be simplified in FRW universe where the background are homogeneous and isotropic:

$$\begin{aligned} & K_{,X}(\ddot\sigma + 3H\dot\sigma) + 2K_{,XX}X\ddot\sigma + 2K_{,X\sigma}X - K_{,\sigma} - 2(G_{,\sigma} - G_{,X\sigma}X)(\ddot\sigma + 3H\dot\sigma) \\ & \quad + 6G_{,X}\big[(HX)^{\cdot} + 3H^2X\big] - 4G_{,X\sigma}X\ddot\sigma - 2G_{,\sigma\sigma}X + 6HG_{,XX}X\dot X = 0. \end{aligned} \tag{23}$$

3.1. Scale-invariant power spectrum for field fluctuation

To study the perturbations of the curvaton field, we can split the scalar field σ into $\sigma(x) \to \sigma_0(t) + \delta\sigma(t, \mathbf{x})$, where σ_0 represents the spatially homogeneous background field, and the $\delta\sigma$ stands for the linear fluctuation which corresponds to the isocurvature perturbation during inflation. Taking the spatial-flat gauge and using the assumption that there is no coupling between $\delta\sigma$ and other perturbations, one can have the equation of motion for field fluctuation in momentum space $\delta\sigma_{\mathbf{k}}$ as:

$$\delta\ddot\sigma_{\mathbf{k}} + \left(3 + \frac{\dot{\mathcal{D}}}{H\mathcal{D}}\right)H\delta\dot\sigma_{\mathbf{k}} + \frac{c_s^2k^2}{a^2}\delta\sigma_{\mathbf{k}} + \mathcal{M}_{eff}^2\delta\sigma_{\mathbf{k}} = 0, \tag{24}$$

where we have defined $c_s^2 \equiv \mathcal{C}/\mathcal{D}$, with

$$\mathcal{C} = K_{,X} + 2G_{,X}(\ddot\sigma_0 + 2H\dot\sigma_0) + 2G_{,XX}X\ddot\sigma_0 - 2(G_{,\sigma} - G_{,X\sigma}X), \tag{25}$$

$$\mathcal{D} = K_{,X} + 2K_{,XX}X + 6HG_{,X}\dot\sigma_0 - 2(G_{,\sigma} + G_{,X\sigma}X) + 6HG_{,XX}X\dot\sigma_0. \tag{26}$$

Note that in order to avoid ghost or gradient instabilities in our model, one must require $\mathcal{C} \geqslant 0$, $\mathcal{D} > 0$, which leads to the non-negativity of the sound speed squared: $c_s^2 \geqslant 0$. The effective mass squared is:

$$\mathcal{M}_{eff}^2 = \frac{1}{a^3}\frac{d}{dt}\big[a^3\big(K_{,X\sigma}\dot\sigma_0 + 3HG_{,X\sigma}\dot\sigma_0^2 - G_{,\sigma\sigma}\dot\sigma_0\big)\big] - K_{,\sigma\sigma} + G_{,\sigma\sigma}\Box\sigma_0. \tag{27}$$

For later convenience, we also introduce the following "slow variation" parameters:

$$\epsilon_G = -\frac{\dot H}{H^2}, \qquad s_G = \frac{\dot c_s}{Hc_s}, \qquad \delta_G = \frac{\dot{\mathcal{D}}}{H\mathcal{D}}, \qquad \xi_G = \frac{\mathcal{M}_{eff}^2}{3H^2}, \tag{28}$$

which are assumed to be small but not neglected. When reduced to the simplest curvaton model given by (1), $\epsilon_G = \epsilon$, $\xi_G = \xi$ and $s_G = \delta_G = 0$.

For solving Eq. (24) and computing the power spectrum, it is convenient to turn to the conformal coordinate where conformal time τ is defined as $d\tau \equiv dt/a$. Using a new variable $u_{\mathbf{k}} \equiv z\delta\sigma_{\mathbf{k}}$ where $z \equiv a\sqrt{\mathcal{D}}$, the equation of motion can be written in the Fourier space as

$$u_k'' + \left(c_s^2k^2 - \frac{z''}{z}\right)u_k = 0, \tag{29}$$

and the prime denotes differentiation with respect to τ. Under the slow roll approximation where all the parameters in (28) are small, we find:

$$\frac{z''}{z} \simeq \frac{2}{\tau^2}. \tag{30}$$

Thus we finally can obtain the power spectrum of $\delta\sigma_{\mathbf{k}}$ at horizon crossing as (using definition (4)):

$$\mathcal{P}_{\delta\sigma_{\mathbf{k}}} = \frac{H_*^2}{4\pi^2c_s^3\mathcal{D}} \tag{31}$$

with the spectral index given by

$$n_\sigma - 1 = \frac{d\ln\mathcal{P}_\sigma}{d\ln k} = -2\epsilon_G - 3s_G - \delta_G + 2\xi_G \ll 1. \tag{32}$$

From Eq. (32) we can see that the isocurvature perturbation generated by our curvaton field can give rise to a very flat power spectrum which is nearly scale-invariant. Moreover, comparing to usual curvaton case (4), the amplitude of the power spectrum is suppressed by Galileon-like non-linear terms such as $\mathcal{D}$, however, when $G(\sigma, X) = 0$ and $K(\sigma, X) = X - V(\sigma)$, the result exactly reduces to that of usual curvaton case. When $G(\sigma, X) = 0$ and $K(\sigma, X)$ is DBI-type, the result is that of DBI-curvaton [13]. The result given here is also consistent with the case where Galileon field act as an inflaton field and generate curvature perturbations [26],[2] and the similar property has also been found in other featured inflation models, such as DBI inflation [49].

[2] Strictly speaking, as authors of Ref. [26] pointed out themselves, what they calculated is not usual comoving curvature perturbation but another variable which coincide with comoving curvature perturbation only in large scales.

3.2. Generating the curvature perturbation from curvaton

From last paragraph we learned that our G-Curvaton model is able to give rise to perturbations with nearly scale-invariant power spectrum, however these perturbations are of isocurvature ones. As has been mentioned before, curvature perturbations can be obtained after inflation, so now we consider the epoch when inflation has ceased and the inflaton has already decayed to radiation, during which the universe is filled with the curvaton field ρ_σ and the radiation ρ_r. From this moment on, the isocurvature perturbations began to convert into curvature ones, and this conversion will complete in two possible cases, namely, either when the curvaton dominates the universe, or decay as well, whichever is earlier.[3] We assume that the conversion as well as curvaton decay happens instantaneously, so that we can separately consider the curvature perturbations for each component (radiation and curvaton) and just use Eq. (9) to calculate the final total curvature perturbation of the universe. From Eqs. (8) and (9) we know that the final curvature perturbation can be expressed as:

$$\zeta = \frac{\delta\rho_\sigma}{4\rho_r + 3(\rho_\sigma + p_\sigma)}, \tag{33}$$

where the density perturbation $\delta\rho_\sigma$ can further be expanded with respect to $\delta\sigma$. The linear order of $\delta\rho_\sigma$ is given by:

$$\begin{aligned}\delta^{(1)}\rho_\sigma &\simeq \rho_{\sigma,\sigma}\delta\sigma \\ &= \big(2K_{,X\sigma}X - K_{,\sigma} + 3HG_{,X\sigma}\dot{\sigma}_0^3 - 2G_{,\sigma\sigma}X\big)\delta\sigma,\end{aligned} \tag{34}$$

while the second order of $\delta\rho_\sigma$ reads:

$$\begin{aligned}\delta^{(2)}\rho_\sigma &\simeq \frac{1}{2}\rho_{\sigma,\sigma\sigma}\delta\sigma^2 \\ &= \frac{1}{2}\big(2K_{,X\sigma\sigma}X - K_{,\sigma\sigma} + 3HG_{,X\sigma\sigma}\dot{\sigma}_0^3 - 2G_{,\sigma\sigma\sigma}X\big)\delta\sigma^2\end{aligned} \tag{35}$$

respectively.

Now we can consider the two cases separately. First, if the curvaton dominates the energy density before decays, we can use Eqs. (8), (10) as well as (34) to have the final curvature perturbation as:

$$\begin{aligned}\zeta^{(I)} &\simeq \frac{\delta^{(1)}\rho_\sigma}{3(\rho_\sigma + p_\sigma)} \simeq \frac{\rho_{\sigma,\sigma}}{3(\rho_\sigma + p_\sigma)}\delta\sigma \\ &= \frac{1}{3}\left(\frac{K_{,X\sigma}\dot{\sigma}_0^2 - K_{,\sigma} + 3HG_{,X\sigma}\dot{\sigma}_0^3 - G_{,\sigma\sigma}\dot{\sigma}_0^2}{K_{,X}\dot{\sigma}_0^2 + 3HG_{,X}\dot{\sigma}_0^3 - 2G_{,\sigma}\dot{\sigma}_0^2 - G_{,X}\ddot{\sigma}_0\dot{\sigma}_0^2}\right)\delta\sigma,\end{aligned} \tag{36}$$

and the power spectrum of curvature perturbation is:

$$\begin{aligned}\mathcal{P}_\zeta^{(I)} &\equiv \frac{k^3}{2\pi^2}|\zeta|^2 \\ &= \frac{1}{9}\left(\frac{H_*^2}{4\pi^2 c_s^3\mathcal{D}}\right)\left(\frac{K_{,X\sigma}\dot{\sigma}_0^2 - K_{,\sigma} + 3HG_{,X\sigma}\dot{\sigma}_0^3 - G_{,\sigma\sigma}\dot{\sigma}_0^2}{K_{,X}\dot{\sigma}_0^2 + 3HG_{,X}\dot{\sigma}_0^3 - 2G_{,\sigma}\dot{\sigma}_0^2 - G_{,X}\ddot{\sigma}_0\dot{\sigma}_0^2}\right)^2,\end{aligned} \tag{37}$$

where we also made use of our previous results (31). Second, if the curvaton decays before its dominance, it will only contribute part of the energy density of the universe with some fraction r as defined before. Using Eq. (11), in this case the curvature perturbation is given by

$$\begin{aligned}\zeta^{(II)} &\simeq \frac{r}{4}\frac{\delta^{(1)}\rho_\sigma}{\rho_\sigma} \simeq \frac{r}{4}\frac{\rho_{\sigma,\sigma}}{\rho_\sigma}\delta\sigma \\ &= \frac{r}{4}\left(\frac{K_{,X\sigma}\dot{\sigma}_0^2 - K_{,\sigma} + 3HG_{,X\sigma}\dot{\sigma}_0^3 - G_{,\sigma\sigma}\dot{\sigma}_0^2}{K_{,X}\dot{\sigma}_0^2 - K + 3HG_{,X}\dot{\sigma}_0^3 - G_{,\sigma}\dot{\sigma}_0^2}\right)\delta\sigma,\end{aligned} \tag{38}$$

and the curvature perturbation power spectrum is:

$$\begin{aligned}\mathcal{P}_\zeta^{(II)} &= \frac{r^2}{16}\left(\frac{K_{,X\sigma}\dot{\sigma}_0^2 - K_{,\sigma} + 3HG_{,X\sigma}\dot{\sigma}_0^3 - G_{,\sigma\sigma}\dot{\sigma}_0^2}{K_{,X}\dot{\sigma}_0^2 - K + 3HG_{,X}\dot{\sigma}_0^3 - G_{,\sigma}\dot{\sigma}_0^2}\right)^2\frac{k^3}{2\pi^2}|\delta\sigma|^2 \\ &= \frac{r^2}{16}\left(\frac{H_*^2}{4\pi^2 c_s^3\mathcal{D}}\right)\left(\frac{K_{,X\sigma}\dot{\sigma}_0^2 - K_{,\sigma} + 3HG_{,X\sigma}\dot{\sigma}_0^3 - G_{,\sigma\sigma}\dot{\sigma}_0^2}{K_{,X}\dot{\sigma}_0^2 - K + 3HG_{,X}\dot{\sigma}_0^3 - G_{,\sigma}\dot{\sigma}_0^2}\right)^2.\end{aligned} \tag{39}$$

Here the supscripts (I) and (II) refer to the two cases respectively.

From Eqs. (37) and (39) one can see that comparing to usual curvaton case, the amplitude of curvature perturbation will also be modified with a different prefactor, which contains contribution from the high derivative term $G(\sigma, X)$. So one can naturally expect G-Curvaton model has some feature that could be distinguished from usual K-essence curvaton models.

[3] Actually, besides the standard model radiation, the curvaton can also decay into other products such as dark radiation or dark matter. In that case, there may have residual isocurvature perturbations and the non-Gaussianities may also be different [50] (see also [51] for a review). In this Letter we assume that curvaton decays to standard model radiation for simplicity. We thank A. Mazumdar for point out this for us via private communication.

3.3. Non-Gaussianities generated by G-Curvaton

In this paragraph, we extend our study to non-linear perturbations of our model, i.e., non-Gaussianities. First of all, we consider the local type non-Gaussianities generated by the curvaton model. For local type, the non-linear parameter f_{NL}^{local} has been defined in (12). From Eqs. (33)–(35) and using the δN formalism (13), we can also express f_{NL}^{local} in terms of energy density as:

$$f_{NL}^{local}\big|_\zeta = \frac{5}{6}\big[4\rho_r + 3(\rho_\sigma + p_\sigma)\big]\frac{\rho_{\sigma,\sigma\sigma}}{\rho_{\sigma,\sigma}^2}. \tag{40}$$

Now we consider the two cases separately. For the first case where curvaton dominates the energy density before decays, one gets:

$$\begin{aligned} f_{NL}^{local}\big|_\zeta^{(I)} &\simeq \frac{5}{2}\frac{(\rho_\sigma + p_\sigma)\rho_{\sigma,\sigma\sigma}}{\rho_{\sigma,\sigma}^2} \\ &= \frac{5}{2}\left[\frac{(K_{,X}\dot\sigma_0^2 + 3HG_{,X}\dot\sigma_0^3 - 2G_{,\sigma}\dot\sigma_0^2 - G_{,X}\ddot\sigma_0\dot\sigma_0^2)(K_{,X\sigma\sigma}\dot\sigma_0^2 - K_{,\sigma\sigma} + 3HG_{,X\sigma\sigma}\dot\sigma_0^3 - G_{,\sigma\sigma\sigma}\dot\sigma_0^2)}{(K_{,X\sigma}\dot\sigma_0^2 - K_{,\sigma} + 3HG_{,X\sigma}\dot\sigma_0^3 - G_{,\sigma\sigma}\dot\sigma_0^2)^2}\right], \end{aligned} \tag{41}$$

and for the second case where the curvaton decays and never dominates the energy density, we have

$$\begin{aligned} f_{NL}^{local}\big|_\zeta^{(II)} &\simeq \frac{10}{3r}\frac{\rho_\sigma\rho_{\sigma,\sigma\sigma}}{\rho_{\sigma,\sigma}^2} \\ &= \frac{10}{3r}\left[\frac{(K_{,X}\dot\sigma_0^2 - K + 3HG_{,X}\dot\sigma_0^3 - G_{,\sigma}\dot\sigma_0^2)(K_{,X\sigma\sigma}\dot\sigma_0^2 - K_{,\sigma\sigma} + 3HG_{,X\sigma\sigma}\dot\sigma_0^3 - G_{,\sigma\sigma\sigma}\dot\sigma_0^2)}{(K_{,X\sigma}\dot\sigma_0^2 - K_{,\sigma} + 3HG_{,X\sigma}\dot\sigma_0^3 - G_{,\sigma\sigma}\dot\sigma_0^2)^2}\right], \end{aligned} \tag{42}$$

respectively.

Then we turn to the non-local type of non-Gaussianities. The non-local type of non-Gaussianities is more complicated, as described in Eqs. (15)–(17). The interaction Hamiltonian is $\mathcal{H}_{int}^p = -\mathcal{L}_3$, where $\mathcal{L}_3$ is the 3-rd order perturbed Lagrangian. Starting from action (18) and after straightforward but rather tedious calculation, we get the interaction Hamiltonian at the leading order with respect to slow roll parameters:

$$\begin{aligned} H_{int}^p \supset \int \frac{d^3k_1 d^3k_2 d^3k_3}{(2\pi)^9}(2\pi)^3\delta^3(\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3)\big\{&+aL_1(\mathbf{k}_2\cdot\mathbf{k}_3)\delta\dot\sigma(t,\mathbf{k}_1)\delta\sigma(t,\mathbf{k}_2)\delta\sigma(t,\mathbf{k}_3) + a^3L_2\delta\dot\sigma(t,\mathbf{k}_1)\delta\dot\sigma(t,\mathbf{k}_2)\delta\dot\sigma(t,\mathbf{k}_3) \\ &+ aL_3(\mathbf{k}_2\cdot\mathbf{k}_3)\delta\dot\sigma(t,\mathbf{k}_1)\delta\sigma(t,\mathbf{k}_2)\delta\sigma(t,\mathbf{k}_3) + a^{-1}L_4(\mathbf{k}_1\cdot\mathbf{k}_2)\mathbf{k}_3^2\delta\sigma(t,\mathbf{k}_1)\delta\sigma(t,\mathbf{k}_2)\delta\sigma(t,\mathbf{k}_3)\big\}, \end{aligned} \tag{43}$$

where we have defined

$$L_1 = G_{,XX0}\dot\sigma_0^2, \tag{44}$$

$$L_2 = \frac{1}{2}\left(5HG_{,XX0}\dot\sigma_0^2 + 2HG_{,X0} + \frac{1}{3}K_{,XXX0}\dot\sigma_0^3 + HG_{,XXX0}\dot\sigma_0^4 + K_{,XX0}\dot\sigma_0\right), \tag{45}$$

$$L_3 = -\frac{1}{2}\big(K_{,XX0}\dot\sigma_0 + 2G_{,XX0}\dot\sigma_0\ddot\sigma_0 + 3HG_{,XX0}\dot\sigma_0^2 + 4HG_{,X0}\big), \tag{46}$$

$$L_4 = -\frac{1}{2}G_{,X0}. \tag{47}$$

Moreover, from the solution of the canonical variable u_k we can obtain the mode solution of the perturbation variable (in conformal time) $\delta\sigma(\tau,k)$ as:

$$\delta\sigma(\tau,\mathbf{k}) = q(\tau,\mathbf{k})a_{\mathbf{k}} + q^*(\tau,\mathbf{k})a_{-\mathbf{k}}^\dagger, \qquad q(\tau,\mathbf{k}) = \frac{iH}{\sqrt{2\mathcal{D}c_s^3k^3}}(1+ic_sk\tau)e^{-ic_sk\tau}, \tag{48}$$

where $a_{\mathbf{k}}$ and $a_{-\mathbf{k}}^\dagger$ are production and annihilation operators respectively. By substituting Eqs. (43)–(48) into (16), one can get the result of 3-point correlation function $\langle|\delta\sigma(k_1)\delta\sigma(k_2)\delta\sigma(k_3)|\rangle$. Note that when carrying out integrations with respect to conformal time τ, we assume that the L_i's $(i = 1,2,3,4)$ are all slow varying and can be roughly taken out of the integrations, which greatly simplify our calculation. Similar assumptions has been made when calculating more general single field inflation with nonminimal coupling to Gravity as well as Gauss–Bonnet terms [43] though more rigid calculation with nonminimal coupling only was performed in [52]. The final shape of $\langle|\delta\sigma(k_1)\delta\sigma(k_2)\delta\sigma(k_3)|\rangle$ than reads:

$$\begin{aligned} \mathcal{B}_{\delta\sigma}(k_1,k_2,k_3) = {}& \frac{3L_1H^6}{\mathcal{D}^3c_s^8k_1k_2k_3K^3} - \frac{3L_2H^5}{\mathcal{D}^3c_s^6k_1k_2k_3K^3} + \frac{L_3H^5}{4\mathcal{D}^3c_s^8k_1^3k_2^3k_3^3K^3}\left(6k_1k_2k_3\sum_i k_i^3 + 2\sum_{i\neq j}k_i^2k_j^4 + 3\sum_{i\neq j}k_ik_j^5 + \sum_i k_i^6\right) \\ &+ \frac{L_4H^6}{2\mathcal{D}^3c_s^{10}k_1^3k_2^3k_3^3K^4}\left(2\sum_{i\neq j}k_i^2k_j^5 - 7\sum_{i\neq j}k_i^4k_j^3 + 4\sum_{i\neq j}k_ik_j^6 - 18k_1^2k_2^2k_3^2\sum_i k_i \right. \\ &\left. - 4k_1k_2k_3\sum_{i\neq j}k_i^3k_j - 24k_1k_2k_3\sum_{i>j}k_i^2k_j^2 + 12k_1k_2k_3\sum_i k_i^4 + \sum_i k_i^7\right), \end{aligned} \tag{49}$$

and the corresponding non-linear estimator f_{NL} can be calculated according to Eq. (17). As an example, here we consider the equilateral case where $k_1 = k_2 = k_3$, in which the estimator then reduces to:

$$f_{NL}^{equil}\big|_{\delta\sigma} = \frac{10}{27}\left(\frac{L_1 H^2}{9\mathcal{D}c_s^2} - \frac{L_2 H}{9\mathcal{D}} + \frac{17L_3 H}{36\mathcal{D}c_s^2} - \frac{13L_4 H^2}{18\mathcal{D}c_s^4}\right), \tag{50}$$

while using δN formalism (13), the non-linear estimator for curvature perturbation reads:

$$f_{NL}^{equil}\big|_{\zeta} = N_{,\sigma} f_{NL}^{equil}\big|_{\delta\sigma}. \tag{51}$$

From Eqs. (33) and (34), we can easily get $N_{,\sigma} = \rho_{\sigma,\sigma}/[4\rho_r + 3(\rho_\sigma + p_\sigma)]$, which gives

$$\begin{aligned} f_{NL}^{equil}\big|_{\zeta}^{(I)} &= \frac{\rho_{\sigma,\sigma}}{3(\rho_\sigma + p_\sigma)} f_{NL}^{equil}\big|_{\delta\sigma} \\ &= \frac{10\rho_{\sigma,\sigma}}{81(\rho_\sigma + p_\sigma)}\left(\frac{L_1 H^2}{9\mathcal{D}c_s^2} - \frac{L_2 H}{9\mathcal{D}} + \frac{17L_3 H}{36\mathcal{D}c_s^2} - \frac{13L_4 H^2}{18\mathcal{D}c_s^4}\right) \end{aligned} \tag{52}$$

for the case of which curvaton dominates before decays, and

$$\begin{aligned} f_{NL}^{equil}\big|_{\zeta}^{(II)} &= \frac{r\rho_{\sigma,\sigma}}{4\rho_\sigma} f_{NL}^{equil}\big|_{\delta\sigma} \\ &= \frac{5r\rho_{\sigma,\sigma}}{54\rho_\sigma}\left(\frac{L_1 H^2}{9\mathcal{D}c_s^2} - \frac{L_2 H}{9\mathcal{D}} + \frac{17L_3 H}{36\mathcal{D}c_s^2} - \frac{13L_4 H^2}{18\mathcal{D}c_s^4}\right) \end{aligned} \tag{53}$$

for the case of which curvaton decays and never dominates.

3.4. A concrete G-Curvaton model

In previous parts of this section, we have presented the whole process of how our G-Curvaton model works, including its background evolution, scale-invariant isocurvature perturbation generation, curvature perturbation conversion as well as different types of non-Gaussianities. However, due to the involvement of our model, especially containing high derivative terms, the above general analysis can only be rather qualitative. Moreover, unlike the usual curvaton model, there are many uncertainties in our model with general form (18) and it can have various decaying mechanisms, each of which may have different results for curvature perturbations and non-Gaussianities. In order to make things more specific, it is necessary to focus on some explicit models to see how our models can be different from the usual curvaton models.

Before constructing models, let's investigate how many constraints we have to consider for our model. First of all, as was mentioned in previous section, a curvaton model must have light mass, that is, $\mathcal{M}_{eff}^2 \ll H^2$. In slow roll approximation, we have $\dot\sigma \ll M_{pl}^2$, so the first term of Eq. (27) can then be neglected, which makes $\mathcal{M}_{eff}^2 \simeq -K_{,\sigma\sigma} + 3HG_{,\sigma\sigma}\dot\sigma$. Therefore, if we choose $|K_{,\sigma\sigma}|$ and $|G_{,\sigma\sigma}|$ to be small enough, it will be safe for curvaton. Another way is both $K_{,\sigma\sigma}$ and $3H\dot\sigma G_{,\sigma\sigma}$ may be large in amplitude, but are of similar value and opposite sign. In this case, they can be canceled to have a relatively small value, which may need some fine tuning in the model. The second constraint comes from the observations. The current observation data gives very tight constraint on the amplitude of the curvature perturbations, for example, the WMAP-7 measurement of the CMB quadrupole anisotropy requires $\mathcal{P}_\zeta \sim 2.4 \times 10^{-9}$ [53]. In order for the amplitude of the curvature perturbation in (37) and (39) to meet the data, one can further constrain the form of Lagrangian of our model, namely $K(\sigma, X)$ and $G(\sigma, X)$ and their field dependence.

Taking account to both constraints from above, we can consider that our model may have the Lagrangian with form of:

$$K(\sigma, X) = X - V(\sigma), \qquad G(\sigma, X) = -g(\sigma)X \tag{54}$$

as an example. Here we require both $V_{,\sigma\sigma}$ and $g_{,\sigma\sigma}$ be small enough to give rise to small effective mass needed for curvaton. For background evolution, from Eqs. (20), (21) and (23), we have the following equations:

$$\rho_\sigma = X\big(1 - 6gH\dot\sigma_0 + g_{,\sigma}\dot\sigma_0^2\big) + V, \tag{55}$$

$$\rho_\sigma + p_\sigma = 2X\big(1 + g\ddot\sigma_0 - 3gH\dot\sigma_0 + g_{,\sigma}\dot\sigma_0^2\big), \tag{56}$$

$$\ddot\sigma_0 + 3H\dot\sigma_0 + 2g_{,\sigma}\dot\sigma_0^2\ddot\sigma_0 + \frac{1}{2}g_{,\sigma\sigma}\dot\sigma_0^4 - 3g\dot H\dot\sigma_0^2 - 6gH\dot\sigma_0\ddot\sigma_0 - 9gH^2\dot\sigma_0^2 + V_{,\sigma} = 0. \tag{57}$$

For perturbations, from Eqs. (25) and (26) we can get:

$$\mathcal{C} = 1 - 2g\ddot\sigma_0 - 4gH\dot\sigma_0, \qquad \mathcal{D} = 1 + 4g_{,\sigma}X - 6gH\dot\sigma_0 \tag{58}$$

for our model, which can give the sound speed squared $c_s^2 = \mathcal{C}/\mathcal{D}$. One can also get the power spectrum and non-Gaussianities of curvature perturbations by making use of the explicit form (54) in the corresponding formulae that has been derived in the above sections.

For later convenience, let us first introduce some more "slow-variation" parameters, namely

$$\eta \equiv \frac{\ddot\sigma_0}{H\dot\sigma_0}, \qquad \alpha \equiv \frac{\dot g}{gH}, \qquad \beta \equiv \frac{\dot g_{,\sigma}}{g_{,\sigma}H}, \qquad \gamma \equiv \frac{\dot g_{,\sigma\sigma}}{g_{,\sigma\sigma}H}. \tag{59}$$

We can always choose the form of $g(\sigma)$ such that the last three parameters $|\alpha|$, $|\beta|$, $|\gamma| \ll 1$ all the time. However, $|\eta|$ can only be small when the field remains slow-rolling. This is important because in curvaton scenario, curvature perturbations are produced *after* the end of inflation, and in that case, the slow-rolling of the curvaton field is not always satisfied.

Now let's turn on to the two cases of generating curvature perturbations one by one. In the first case the curvature perturbation is generated when curvaton dominates the universe. That requires the decaying of the curvaton is slower than that of radiation which is transferred from inflaton. For instance, it is reasonable to assume that the curvaton field is still slow-rolling, and exit in a few number of efolds, so it will not lead to another period of rapid acceleration [26]. Substituting (54) into Eqs. (37), (41) and (52) and letting all the slow variation parameters defined in (59) be small, we can get:

$$\mathcal{P}_\zeta^{(I)} \simeq \left(\frac{H_*^2}{4\pi^2 c_s^3 \mathcal{D}}\right)(H/\dot{\sigma}_0)^2, \tag{60}$$

$$f_{NL}^{local}\big|_\zeta^{(I)} \simeq \frac{5}{6}\left[\frac{(3\alpha gH\dot{\sigma}_0 - 6\epsilon gH\dot{\sigma}_0 + \epsilon)}{(1-3gH\dot{\sigma}_0)}\right], \tag{61}$$

$$f_{NL}^{equil}\big|_\zeta^{(I)} \simeq \frac{10gH\dot{\sigma}_0}{243\mathcal{D}}\left(\frac{(3-\epsilon)gH\dot{\sigma}_0 - 1}{1-3gH\dot{\sigma}_0}\right)\left(1+\frac{17}{2c_s^2}-\frac{13}{4c_s^4}\right)(H/\dot{\sigma}_0)^2. \tag{62}$$

Similarly, in the second case the curvature perturbation is generated when the curvaton decays and becomes equilibrium with radiation, and thus the energy density of curvaton has the same scaling as that of radiation with the ratio $r = \rho_\sigma/\rho_r$. Again using (54) with Eqs. (39), (42) and (53), letting α, β and γ be small but retaining η for the reason given above, we can get:

$$\mathcal{P}_\zeta^{(II)} \simeq \frac{(1+r)^2}{16}\left(\frac{H_*^2}{4\pi^2 c_s^3 \mathcal{D}}\right)\left[(3-\epsilon+2\eta)gH\dot{\sigma}_0 - \frac{1}{3}(\eta+3)\right]^2 (H/\dot{\sigma}_0)^{-2}, \tag{63}$$

$$f_{NL}^{local}\big|_\zeta^{(II)} \simeq \frac{20\epsilon}{(r+1)}\left[\frac{(-6(3-\epsilon+2\eta)gH\dot{\sigma}_0 + (\eta+3))}{(3(3-\epsilon+2\eta)gH\dot{\sigma}_0 - (\eta+3))^2}\right](H/\dot{\sigma}_0)^2, \tag{64}$$

$$f_{NL}^{equil}\big|_\zeta^{(II)} \simeq \frac{5(r+1)gH\dot{\sigma}_0}{486\mathcal{D}}\left[(3-\epsilon+2\eta)gH\dot{\sigma}_0 - \frac{1}{3}(\eta+3)\right]\left(1+\frac{17}{2c_s^2}-\frac{13}{4c_s^4}\right). \tag{65}$$

From above we can see that another variable that appears repeatedly is $gH\dot{\sigma}_0$. Defining $x := gH\dot{\sigma}_0$, and in order to avoid ghost and gradient instability, x should be smaller than unity. We consider two asymptotic cases: (i) x could be positive or negative, with $|x| \ll 1$ and (ii) x is negative, with $|x| \gg 1$, which means that the Galileon term plays an unimportant/important role at the end of inflation respectively. The spectrum and non-Gaussianities of the curvature perturbation can be reduced as:

(i) $|x| \ll 1$: $c_s^2 \simeq 1$

$$\mathcal{P}_\zeta^{(I)} \simeq \left(\frac{H_*^2}{4\pi^2}\right)(H/\dot{\sigma}_0)^2, \qquad f_{NL}^{local}\big|_\zeta^{(I)} \simeq \frac{5}{6}\epsilon, \qquad f_{NL}^{equil}\big|_\zeta^{(I)} \simeq -\frac{125x}{486}(H/\dot{\sigma}_0)^2, \tag{66}$$

$$\mathcal{P}_\zeta^{(II)} \simeq \frac{(1+r)^2}{144}\left(\frac{H_*^2}{4\pi^2}\right)\frac{(\eta+3)^2}{(H/\dot{\sigma}_0)^2}, \qquad f_{NL}^{local}\big|_\zeta^{(II)} \simeq \frac{20\epsilon(H/\dot{\sigma}_0)^2}{(r+1)(\eta+3)}, \qquad f_{NL}^{equil}\big|_\zeta^{(II)} \simeq -\frac{125(r+1)x}{5832}(\eta+3), \tag{67}$$

(ii) $|x| \gg 1$: $c_s^2 \simeq \frac{\eta+2}{3}$ (η is small for Case I)

$$\mathcal{P}_\zeta^{(I)} \simeq \frac{1}{4|x|}\sqrt{\frac{3}{2}}\left(\frac{H_*^2}{4\pi^2}\right)(H/\dot{\sigma}_0)^2, \qquad f_{NL}^{local}\big|_\zeta^{(I)} \simeq \frac{5}{6}(2\epsilon-\alpha), \qquad f_{NL}^{equil}\big|_\zeta^{(I)} \simeq -\frac{35(3-\epsilon)}{17496}(H/\dot{\sigma}_0)^2, \tag{68}$$

$$\mathcal{P}_\zeta^{(II)} \simeq \frac{(1+r)^2|x|}{32}\sqrt{\frac{3}{(\eta+2)^3}}\left(\frac{H_*^2}{4\pi^2}\right)\frac{(3-\epsilon+2\eta)^2}{(H/\dot{\sigma}_0)^2}, \qquad f_{NL}^{local}\big|_\zeta^{(II)} \simeq \frac{40\epsilon(H/\dot{\sigma}_0)^2}{3(r+1)(3-\epsilon+2\eta)|x|},$$

$$f_{NL}^{equil}\big|_\zeta^{(II)} \simeq \frac{5(r+1)(3-\epsilon+2\eta)(103+118\eta+4\eta^2)}{11664|x|(2+\eta)^2}, \tag{69}$$

respectively.

From the above results we can have a couple of comments on the perturbations of our G-Curvaton model. Besides the slow variation parameters which are roughly of order 1, now we have three more free parameters, namely the value of x, H and $\dot{\sigma}_0$ at the end of inflation, to determine $\mathcal{P}_\zeta$ and f_{NL}. Considering the constraints from CMB that the amplitude of power spectrum to be nearly 10^{-9}, we still have large parameter space to have considerable large non-Gaussianities. For instance, for Case I the curvaton field is still slow-rolling at the end of inflation, where $|\dot{\sigma}_0|$ is small compared to H. If it satisfies $|\dot{\sigma}_0| \sim 10^{-3}H$, then from the power spectrum we have $H \sim 10^{-8}$, which is slightly lower than that of chaotic inflation. For subcase where $|x| \ll 1$, we can have $f_{NL}^{equil} \sim 10^2$ just by requiring $|g| \sim 10^{-13}$. For subcase where $|x| \gg 1$, however, we can have $f_{NL}^{equil} \sim 10^2$ by requiring $|g| \sim 10^{18}$. Moreover, in both cases f_{NL}^{local} remains of order unity. For Case II, the energy density of σ is comparable to H, which roughly gives $\dot{\sigma}_0^2[1+\mathcal{O}(1)x] \sim H^2$. In subcase $|x| \ll 1$, we have $|\dot{\sigma}_0| \sim H$, which gives $H \sim 10^{-5}$ in order to meet the constraint on power spectrum. This in turn gives small f_{NL}^{equil} with f_{NL}^{local} roughly of $\mathcal{O}(10)$. In subcase $|x| \gg 1$, however, we obtain $|g\dot{\sigma}_0^3| \sim H$. If further it satisfies, i.e., $|\dot{\sigma}_0| \sim 10^{-1}H$, it will lead to $H \sim 10^{-2}$ from constraint on power spectrum, which in turn gives $\dot{\sigma}_0 \sim 10^{-3}$ as well as $|g| \sim 10^7$. Then the non-linear estimator f_{NL}^{local} is roughly of $\mathcal{O}(10)$, and f_{NL}^{equil} becomes of order unity.[4] Moreover, due to the non-linear effects of the Galileon term $G(X,\sigma)\Box\sigma$ in our model, it can be expected that large tensor-to-scalar ratio can be generated as well as large non-Gaussianities [26], which can be distinguishable from the standard curvaton model, of which large non-Gaussianities are also accompanied with lower energy scale of inflation, which leads to small tensor-to-scalar ratio (cf. the second paper in [11]).

4. Conclusion and discussions

In this Letter, we investigated G-Curvaton scenario, where the curvaton field is acted by Galileon action. This opens a new access of curvaton scenarios that the fluctuations could be affected by non-linear terms. After reviewing the standard curvaton mechanism, we started from the action of Galileon field and calculated the spectrum of the field perturbation. The power spectrum is suppressed by $\mathcal{D}$ given in (26), rather than $K_{,X}$ in the normal single field case. We studied the generation of curvature perturbations in both two possible cases, and apart from curvature perturbation, we obtained non-Gaussianities of both local and non-local types.

We have shown, in this work, that there is large possibilities for G-Curvaton to have consistent power spectrum and large non-Gaussianities. We presented a concrete model of G-Curvaton as an illustration. With proper choice of the parameters, the non-linear estimator could be made of $\mathcal{O}(10^2)$. However, because of the large parameter space, the conclusion is still highly model dependent. We can expect future observational data to have more rigid constraints on the G-Curvaton scenario, for example, if future observations can observe large non-local non-Gaussianity compared to local one, more or less we can say that it *might* due to some non-linear effects such as Galileon.

Moreover, since the Galileon field can violate the NEC without the ghost and gradient instabilities, G-Curvaton can naturally incorporate a model of curvaton with NEC violation, which might be interesting for studying. Here, we focus on the inflationary background, however, in principle, G-Curvaton can also be embedded into alternative models to inflation, which will make the curvature perturbation induced in corresponding model have more fruitful predictions. For phenomenological aspect, there are also a couple of implications that merits thinking of: one example is that large non-Gaussianities could be accompanied with large tensor-to-scalar ratio as well, which is different from usual curvaton models and thus can be used as a distinguishment observationally; another is that due to the non-linear effects from Galileon term, the decaying process of the curvaton might also be modified, which may in turn change the speed and amount of the generated products during reheating [29].[5] We hope that some upcoming works could gain more clear insights into G-Curvaton scenario.

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