Thermal non-Gaussianity in Near-Milne universe

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Abstract

The thermal non-Gaussianity in Near-Milne universe is investigated in this letter. Through classifying thermal fluctuations into two types, one characterized by a phase transition and the other without phase transition, we show that for fluctuations undergoing a phase transition, the non-Gaussianity depends linearly on $k$, but in non-phase transition case it is proportional to $k^{-3\gamma}$, $\gamma > 0$. Moreover, if the phase transition scenario is similar to that in holographic cosmology, we find that the non-Gaussianity $f_{NL}^{equil}$ can reach $O(1)$ or larger than $O(1)$ by fine tuning of the equation of state $\omega_C$. Especially at the limit of $\omega_C \rightarrow -5/3$, the non-Gaussianity can be very large. On the other hand, for non-phase transition case, the non-Gaussianity estimator $f_{NL}^{equil}$ is approximately $f_{NL}^{equil} \simeq 5/108$ when the energy is sub-extensive, especially when $\gamma \rightarrow 0^+$. However, when $\gamma \rightarrow 4$, large non-Gaussianity can be obtained.
I. INTRODUCTION

The non-Gaussianity of the Cosmic Microwave Background (CMB) has been playing a crucial role in the investigation of the very early universe, since it has become a distinct feature among all kinds of inflation models and their alternatives. For instance, for single field slow roll inflation, the non-Gaussianity is too small to be detected in near future [1, 2], however, for models beyond single field slow roll inflation, the non-Gaussianity large enough to be observable can be predicted [3–11]. Recently, WMAP 5-year data indicates that at 95% confidence level, the primordial non-Gaussianity parameters for the local and equilateral models are in the region $-9 < f_{\text{local}}^\text{NL} < 111$ and $-151 < f_{\text{equil}}^\text{NL} < 253$, respectively [12]. If this result is confirmed by future experiments, such as the Planck satellite, then it will be a great challenge to many inflation models.

In this letter, we intend to explore the thermal non-Gaussianity in Near-Milne universe. We find that thermal fluctuations in Near-Milne universe can result in a large non-Gaussianity, similar to the case in holographic cosmology [10]. Treating thermal fluctuations as the origin of primordial fluctuations in cosmology was advocated by Peebles [13]. Subsequently, Magueijo et al. have more explicitly explored the possibility that primordial thermal fluctuations, instead of quantum fluctuations, might seed the structure of our universe [14–16]. Unfortunately, they find that the spectral index of thermal fluctuations is either too red ($n_s = 0$) or too blue ($n_s = 4$), failing to generate a nearly scale invariant spectrum [17, 19]. Therefore, in order to produce nearly scale invariant fluctuations, thermal scenarios call for new physics. For instance, a thermal scenario with new physics effects to change the equation of state of thermal matter can produce nearly scale invariant spectrum. This happens in non-commutative inflation [14, 20, 21], and in loop quantum cosmology [18, 22]. It can also occur in string gas cosmology with a Hagedorn phase [23] or in holographic cosmology with a phase transition [17], in which the energy becomes strongly non-extensive, specifically proportional to the area of the system surface. Recently, it has also been studied that thermal fluctuations in a non-singular bouncing cosmology may produce scale invariant fluctuations as well as a large non-Gaussianity [24]. Besides all above approaches, postulating a mildly sub-extensive contribution to the energy density in Near-Milne universe can lead to a scale-invariance spectrum as well [19]. In this letter, we intend to investigate the thermal non-Gaussianity in this context, following the strategy developed in Ref. [25], which has also
been used to investigate the non-Gaussianity in string gas cosmology \cite{26} and holographic cosmology \cite{10}.

The outline of this letter is following. In section II we firstly calculate the thermal non-Gaussianity in Near-Milne universe by classifying the thermal fluctuation into phase transition type and non-phase transition type. We summarize our results and discuss some open questions in section III.

II. THERMAL NON-GAUSSIANITY IN NEAR-MILNE UNIVERSE

In cosmology the primordial scale invariance due to thermal fluctuation is usually implemented through two ways, phase transition or non-phase transition. For instance, in holographic cosmology as well as string gas cosmology, the thermal fluctuation undergoes a phase transition, in which the final spectrum is proportional to the equal temperature spectrum. On the other hand, in semi-classical loop quantum cosmology there is non-phase transition, in which comoving scales $k$ start thermalized inside the horizon, and then there exists a mechanism pushing sub-horizon thermal modes outside the horizon, where they freeze and become non-thermal. While in Near-Milne universe, the primordial scale invariance can be realized through either phase transition or non-phase transition \cite{19}. Therefore, in this letter, we will consider the thermal non-Gaussianity in Near-Milne universe by classifying thermal fluctuations into phase transition type and non-phase transition type.

Before discussing the non-Gaussianity, a key issue which has to be addressed is on what scale the initial conditions should be imposed. In Ref.\cite{25}, the thermal horizon $R$ is considered as a free parameter. Then, if thermal horizon is smaller than Hubble horizon scale at the horizon crossing, a large non-Gaussianity can be obtained. In Ref.\cite{21}, the thermal correlation length $R = T^{-1}$ is adopted, which is a lower bound and so will lead to larger non-Gaussianity. In our work, we will adopt the Hubble scale $R = H^{-1}$, beyond which causality prohibits local causal interactions \cite{28}. Therefore we will calculate the spectrum at $R = H^{-1}$, i.e. $k = a/R = aH$. 
A. the case of phase transition

In this subsection, we will firstly calculate the 2-point correlations, 3-point correlations and the power spectrum, then give the thermal non-Gaussianity in Near-Milne universe.

Fluctuations in a thermal ensemble can be derived from the thermodynamic partition function

$$Z = \sum_r e^{-\beta E_r},$$  \hspace{1cm} (1)

where the summation runs over all states. $E_r$ is the energy of state $r$, and $\beta = T^{-1}$.

Now, to derive a scale invariant spectrum we adopt the assumption proposed in [19] that both energy and entropy are sub-extensive such that they can be expressed as

$$U = \rho C(T) V^{1-\gamma},$$  \hspace{1cm} (2)

$$S = s C(T) V^{1-\gamma},$$  \hspace{1cm} (3)

with $\gamma > 0$. Then, the 2-point correlation function for the energy density fluctuations is given by

$$\langle \delta \rho^2 \rangle = \left\langle \delta U^2 \right\rangle \frac{1}{V^2} \frac{d^2 \log Z}{d\beta^2} = - \frac{1}{V^2} \frac{d\left\langle U \right\rangle}{d\beta} = \frac{T^2 \rho'_c}{V^{1+\gamma}}.$$  \hspace{1cm} (4)

Similarly, the 3-point correlation function can be expressed as

$$\langle \delta \rho^3 \rangle = \left\langle \delta U^3 \right\rangle \frac{1}{V^3} \frac{d^3 \log Z}{d\beta^3} = \frac{1}{V^3} \frac{d\left\langle U \right\rangle}{d\beta^2} = \frac{T^3(2\rho'_c + T \rho''_c)}{V^{2+\gamma}}.$$  \hspace{1cm} (5)

Performing the Fourier transformation, the density fluctuations $\delta \rho_k$ in momentum space can be related to the fluctuation $\delta \rho$ in position space by

$$\delta \rho_k = k^{-\frac{3}{2}} \delta \rho.$$  \hspace{1cm} (6)

Now to obtain the power spectrum of fluctuations we consider the perturbation of $FRW$ metric. In longitudinal gauge (see [29, 31]), and in the absence of anisotropic matter stress, the metric takes the form

$$ds^2 = a^2(\eta)[d\eta^2(1 - 2\Phi) + (1 + 2\Phi)dx^2],$$  \hspace{1cm} (7)

where $\Phi$ represents the fluctuations in the metric. We assume that the perturbations are deep in the horizon, which means $k \gg H$. Then the perturbation equation of the metric in Eq.(7) may be reduced to the Poisson equation

$$k^2 \Phi_k = 4\pi G a^2 \delta \rho_k.$$  \hspace{1cm} (8)
Therefore, the 2-point correlation function for $\Phi_k$ at $k = a/R$ is given by

$$\langle \Phi_k^2 \rangle = (4\pi G)^2 R^{1-3\gamma} T^2 \rho'_C k^{-3},$$  \hspace{1cm} (9)$$

while the 3-point correlation function is

$$\langle \Phi_k^3 \rangle = (4\pi G)^3 R^{-3\gamma} T^3 (2\rho'_C + T \rho''_C) k^{-\frac{9}{2}}.$$  \hspace{1cm} (10)$$

At first, consider the case with a fixed temperature, the equal-time power spectrum is

$$P_\Phi = 8G^2 T^2 \rho'_C R^{1-3\gamma} = 8G^2 T^2 \rho'_C (\frac{a}{k})^{1-3\gamma}.$$  \hspace{1cm} (11)$$

We can immediately see that for $\gamma = 1/3$ the fixed temperature power spectrum is scale-invariant. We notice that in this case, the energy scales like $R^2$, which is similar to the case in thermal holographic cosmology and string gas cosmology. As a matter of fact, it is this modification that make it possible to obtain scale invariant spectrum in all scenarios above.

Next, we calculate the thermal non-Gaussianity in Near-Milne universe. Note that $\Phi$ perturbs CMB through the so-called Sachs-Wolfe effect \[32\]. However, it is useful to introduce a second variable, $\zeta$, which is the primordial curvature perturbation on comoving hypersurfaces \[33, 34\]. Then the non-Gaussianity estimator $f_{NL}^{\text{equil}}$ can be calculated theoretically by

$$f_{NL}^{\text{equil}} = \frac{5}{18} k^{-\frac{3}{2}} \frac{\langle \zeta_k^3 \rangle}{\langle \zeta_k^2 \rangle^2}.$$  \hspace{1cm} (12)$$

The variables $\Phi$ and $\zeta$ are related by

$$\zeta = \Phi - \frac{H}{\dot{H}} (\dot{\Phi} + H \Phi).$$  \hspace{1cm} (13)$$

In general the variable $\zeta$ remains nearly constant at super-horizon scales for adiabatic fluctuations but $\Phi$ not \[29\]. However, if the equation of state is constant, then $\Phi$ also remains constant at super-horizon. Therefore the relation in \[13\] reduces to \[35\],

$$\zeta = \frac{5 + 3\omega}{3 + 3\omega} \Phi.$$  \hspace{1cm} (14)$$

We point out that the primordial curvature variable $\zeta$ is independent of $\omega$, but the variable $\Phi$, which perturbs the CMB, varies with the change of the equation of state $\omega$. For more detailed discussion on the variables $\zeta$ and $\Phi$, we refer to \[21, 29, 36\].
Finally, combining Eqs. (9), (10), (12) and (14), the non-Gaussianity estimator $f_{\text{NL}}^{\text{equil}}$ can be expressed as

$$f_{\text{NL}}^{\text{equil}} = \frac{5}{6} \frac{1 + \omega_C}{5 + 3 \omega_C} \frac{(2 \rho'_C + T \rho''_C)}{4 \pi G R^2 - 3 \gamma T (\rho'_C)^2} = \frac{5}{6} \frac{1 + \omega_C}{5 + 3 \omega_C} \frac{(2 \rho'_C + T \rho''_C) k}{4 \pi G T (\rho'_C)^2 a}. \quad (15)$$

The condition for modes exiting and re-entering the Hubble radius is $k = a H = a_r H_r$ and $k_0 = a_0 H_0$, where $H$, $a$ and $H_r$, $a_r$ represent the values of exiting or re-entering the Hubble radius, respectively, whereas $H_0$, $T_0$, and $k_0$ is today’s values. For simplicity, we only consider all the process occurs in radiation-dominated era such that the relation between the scale factor and the temperature is $a = \frac{t}{t_0}$. As a result, the non-Gaussianity estimator $f_{\text{NL}}^{\text{equil}}$ becomes

$$f_{\text{NL}}^{\text{equil}} = \frac{5}{6} \frac{1 + \omega_C}{5 + 3 \omega_C} \frac{(2 \rho'_C + T \rho''_C) H_0}{4 \pi G (\rho'_C)^2} \times k \times \frac{10^{-30}}{k_0}, \quad (16)$$

where $a_c$ is the scale factor during the phase transition and we have neglected the variation in $a_c$. From above equation, we find that if there exist a phase transition process to render the above process, as described in holographic cosmology, then all the things will be almost the same. For instance, if $\omega_C \rightarrow -1$, the non-Gaussianity will be suppressed as in usual inflationary scenario. If the matter is phantom-like, the non-Gaussianity $f_{\text{NL}}^{\text{equil}}$ can reach $\mathcal{O}(1)$ or larger than $\mathcal{O}(1)$ by fine tuning of the equation of state $\omega_C$. Especially at the limit $\omega_C \rightarrow -5/3$, the non-Gaussianity can be very large. Moreover, the non-Gaussianity estimator $f_{\text{NL}}^{\text{equil}}$ depends linearly on the mode $k$.

**B. the case of non-phase transition**

In this subsection we consider thermal fluctuations without undergoing a phase transition process. Firstly we address the issue on thermodynamical constraints. It has been noticed [37–39] that the state parameter $\omega$ and the Stephan-Boltmann law are linked by a thermodynamic relation (we refer to Refs. [18, 19, 25]). Suppose that both energy and entropy are extensive, if the state parameter $\omega$ is a constant and $\rho = A T^m$, then one can obtain a thermodynamic constraint

$$m = 1 + \frac{1}{\omega}. \quad (17)$$
It has been realized in [18, 19] that it is this constraint that prevents us from achieving a scale invariant \( (n_s = 1) \) spectrum for the energy density perturbation, but a spectrum with \( n_s = 4 \) regardless the value of \( \omega \). However, in Near-Milne universe with sub-extensive energy and pressure, for \( p_C = \omega_C \rho_C \) and \( \rho_C \propto T^{mc} \), the thermodynamic constraint can be modified as [19],

\[
m_C = 1 + \frac{1 - \gamma}{\omega_C}. \tag{18}
\]

Next, with such a modified constraint we derive the condition for scale-invariance and calculate the thermal non-Gaussianity. We assume that the modes freeze for \( k = aH \), then using Eq. (11) and Friedmann equation \( H \propto \sqrt{\rho_C} \), outside the horizon we have

\[
\frac{d\ln P_\Phi}{d\ln T} = 2 + T\frac{\rho''_C}{\rho_C} - \frac{1 - 3\gamma}{2} T\frac{\rho'_C}{\rho_C}. \tag{19}
\]

Using the relation \( \rho_C \propto T^{mc} \), the above equation can be re-expressed as

\[
\frac{d\ln P_\Phi}{d\ln T} = 1 + \frac{m_C}{2} (1 + 3\gamma). \tag{20}
\]

Furthermore, since \( k = aH \propto a\sqrt{\rho_C} \) and \( a \propto \rho^{-\frac{1}{3(1 + \omega_C)}} \), it can be found that

\[
\frac{d\ln k}{d\ln T} = \frac{3\omega_C + 1}{6(1 + \omega_C)} \frac{T \rho'_C}{\rho_C} = \frac{(3\omega_C + 1)m_C}{6(1 + \omega_C)}. \tag{21}
\]

Combining Eq. (20) and Eq. (21), we can derive the spectral index as

\[
n_s - 1 = \frac{d\ln P_\Phi}{d\ln k} = \frac{3(1 + \omega_C)[2 + m_C(1 + 3\gamma)]}{m_C(3\omega_C + 1)}. \tag{22}
\]

Therefore the condition for scale-invariance is

\[
m_C = -\frac{2}{1 + 3\gamma}. \tag{23}
\]

With the use of the modified constraint (18), the condition for scale-invariance can be re-expressed as

\[
\omega_C = -\frac{(1 - \gamma)(1 + 3\gamma)}{3(1 + \gamma)} \approx -\frac{1}{3}(1 + \gamma). \tag{24}
\]

In hence for sub-extensive energy with \( \gamma > 0 \) we have \( \omega_C < -1/3 \), which can provide an acceleration mechanism.

Now, we consider the non-Gaussianity. Similarly, the non-Gaussianity estimator \( f_{NL}^{\text{equil}} \) takes the form

\[
f_{NL}^{\text{equil}} = \frac{5}{6} \frac{1 + \omega_C}{3\omega_C} \frac{(2\rho'_C + T\rho''_C)}{4\pi GR^2 - 3\gamma T(\rho'_C)^2}. \tag{25}
\]
As discussed previously if we take $R = H^{-1}$ and employ Friedmann equation, then the non-Gaussianity estimator $f_{NL}^{\text{equil}}$ can be expressed as

$$f_{NL}^{\text{equil}} = \frac{5(1 + \omega_C)}{9(5 + 3\omega_C)} \frac{\rho_C(2\rho_C' + T\rho_C'')}{T(\rho_C')^2} H^{-3\gamma}.$$ (26)

Using Eq.(23),(24) and $\rho_C = ATmC$, we can further simplify Eq.(26) as

$$f_{NL}^{\text{equil}} = \frac{5(2 - \gamma)(1 - 3\gamma)}{54(4 - \gamma)} H^{-3\gamma}.$$ (27)

Similarly, the above equation can be approximately re-expressed as

$$f_{NL}^{\text{equil}} = \frac{5(2 - \gamma)(1 - 3\gamma)}{54(4 - \gamma)} \left( \frac{H_0}{T_0} \right)^{-3\gamma} \left( \frac{k}{k_0} \right)^{-3\gamma} = \frac{5(2 - \gamma)(1 - 3\gamma)}{54(4 - \gamma)} \times (10^{-30}T)^{-3\gamma} \left( \frac{k}{k_0} \right)^{-3\gamma}.$$ (28)

From the above equation, we can immediately find that the non-Gaussianity is proportional to $k^{-3\gamma}$ with $\gamma > 0$. It is very different from the cases in string gas cosmology, holographic cosmology or phase transition case of Near-Milne universe, in which the non-Gaussianity depends linearly on $k$. However, in the non-phase transition case, the dependence on $k$ is correlated with the value of parameter $\gamma$.

When the energy is sub-extension, especially when $\gamma \to 0^+$, the non-Gaussianity estimator $f_{NL}^{\text{equil}}$ is approximately evaluated as $f_{NL}^{\text{equil}} \simeq 5/108$. However, if we relax this condition and consider that the energy is not sub-extensive, we find that as $\gamma \to 1/3$ and $\gamma \to 2$, the non-Gaussianity is suppressed, whereas as $\gamma \to 4^-$, the large and positive non-Gaussianity can be obtained. Therefore, through an appropriate choice of the parameter $\gamma$, we can make the non-Gaussianity $f_{NL}^{\text{equil}} \sim \mathcal{O}(1)$ or larger than $\mathcal{O}(1)$. In addition, we must notice that if $\gamma > 4$, the non-Gaussianity will be negative.

### III. Conclusion and Discussion

In this letter we have discussed the non-Gaussianity in Near-Milne universe. We find that in the phase transition case, the non-Gaussianity depends linearly on $k$ at fixed temperature, but in non-phase transition case it is proportional to $k^{-3\gamma}$, $\gamma > 0$. Furthermore, if the phase transition scenario is analogous to the one described in holographic cosmology, then all the results are almost the same. More discussions can be found in Ref.[10]. However, we must point out that the mechanism of phase transition plays an important role in this scenario. If the mechanism is different from the case in holographic cosmology, all the things
could change. Currently how to implement the phase transition is still an open question. We expect that we can make further investigations on this issue in the future. Moreover, it is worthwhile to notice that the non-Gaussianity estimator \( f_{NL}^{\text{equl}} \) also depends on the formulation of the Stephan-Boltzmann law in this case.

In the case of non-phase transition, we have demonstrated that by appropriate choice of the parameter \( \gamma \), we can make the non-Gaussianity \( f_{NL}^{\text{equl}} \sim O(1) \) or larger than \( O(1) \). If the energy is sub-extensive, especially when \( \gamma \to 0^+ \), the non-Gaussianity estimator is approximately \( f_{NL}^{\text{equl}} \simeq 5/108 \). However, when \( \gamma \to 4^- \), the large non-Gaussianity can be obtained. Furthermore, if \( \gamma > 4 \), the non-Gaussianity will be negative. In addition, we note that when \( \gamma \to 4 \), the effective state parameter \( \omega_C \to -5/3 \). As pointed out in Ref. \[10\], when \( \omega \to -5/3 \), \( \zeta \to 0 \), so the non-Gaussianity estimator \( f_{NL}^{\text{equl}} \to \infty \). Here we can see this from the expression \( \[12\] \) of the non-Gaussianity estimator \( f_{NL}^{\text{equl}} \) and the relation \( \[14\] \) as well.

Finally, we would like to point out that in order to bypass the above process, we have to accept negative temperatures \[39, 40\]. For more detailed discussion, we refer to Ref. \[19\]. In the future, we will consider the thermal non-Gaussianity in semi-classical loop cosmology \[27\].

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