Exploring Inflationary Initial State With Large Scale Structure Observations

Debabrata Chandra\textsuperscript{1} and Supratik Pal\textsuperscript{2}

\textit{Physics and Applied Mathematics Unit, Indian Statistical Institute, 203 B.T. Road, Kolkata 700 108, India}

\textbf{Abstract}. We investigate for possible constraints on inflationary initial state from Large Scale Structure (LSS) observations. Using a model-independent framework, we build the template for the generic initial state and construct the matter power spectrum through time evolution of the primordial power spectrum. We then make use of the LSS data separately from the Sloan Digital Sky Survey - Data Release 7 (SDSS-DR7) sample of Luminous Red Galaxies (LRG) and WiggleZ Dark Energy Survey, and explore the plausible constraints on initial vacuum by applying Bayesian parameter estimation method with Markov Chain Monte Carlo (MCMC) simulation. Our analysis reveals that, along with the usual Bunch-Davies vacuum, non-Bunch-Davies initial states are also fairly allowed so far as present LSS data is concerned.

\textsuperscript{1}Electronic address: deb.iitdelhi@gmail.com
\textsuperscript{2}Electronic address: supratik@isical.ac.in
1 Introduction

With the relentless advancement in observational cosmology in the last decade coupled with a few new cosmological missions chipping in, we are entering an era of precision cosmology. Observational cosmology is progressively imparting stringent constraints on the cosmological parameters that in turn helps us understand the physics of our universe better and better. However, in spite of the profound success of observational cosmology, we are still left with conclusive determination of couple of fundamental parameters that are essential ingredients in improving our understanding of the origin and dynamics of the universe.

Over the past few decades, inflationary paradigm, supported by observational data from WMAP[1] and Planck[2], explains the physics of the early universe quite satisfactorily. Among all its successes, inflationary paradigm provides an ingenious mechanism to explain the formation of seeds of classical perturbations, that have imprints on the cosmic microwave background (CMB) anisotropy and, subsequently in Large Scale Structure (LSS) data [3]. However, in spite of all the successes of inflation, there are few pivotal questions that are haunting us for long. Some of these yet-unanswered questions to the building blocks of inflationary dynamics are the following: (i) What is the energy scale of inflation? [4] (ii) What is/are the behavior of the (self) interactions of the field(s) involved in driving inflation? [5] (iii) What is the exact nature of the inflationary initial state? [6, 7] This article is solely devoted to the investigation for any possible answer to the last question from existing LSS surveys by educing all the precious information about the initial state.

Despite investing a plethora of quality research towards probing the physics of inflation in both ways, theoretically and experimentally, the true behaviour of the initial condition of the inflationary fluctuations is an enigma to the fraternity. However, before all of these, one first needs to know whether or not exploring the nature of the primordial initial state at all has any significance. To be honest, the subject is itself debatable. So, let us first point out two distinct perceptions on the significance of probing inflationary initial state: (i) Because of the superluminal exponential expansion of the universe during inflation, the signature of any non-trivial initial condition should be washed away, and all we are left with is the Bunch-Davies (BD) vacuum which is nothing but the lowest energy state [8], and is hence trivial;
Due to the underlying physical processes, once the quantum fluctuations choose to raise its vacuum to some non-trivial initial state, then its impression does not get faded away, if the primordial fluctuations were linear in nature, thereby BD vacuum is not restored. Reason behind this is quite obvious, the role of initial condition is very straightforward in linear perturbation theory, it comes into play through the solution of the differential equation of the inflaton fluctuations, aka Mukhanov-Sasaki equation, representing the equation of motion of the inflaton fluctuations, which get reflected directly on the CMB and LSS through the evolution of the inflaton perturbations. Thus any sort of customization on the inflaton initial condition would be directly imprinted on the early universe and late time physics through evolution of the primordial perturbations. As it stands, these are two conflicting statements and the debate is yet to be settled.

One should however note that between the two different views on the importance of primeval initial condition the non triviality of the initial condition have drawn more attention of the community, because of several reasons: (i) Just adequate amount of inflation may cause to deflect the initial state from the BD vacuum to a non-trivial vacuum, because, if the duration of inflation were just as enough as to solve the cosmological horizon and homogeneity problem then the largest modes we are seeing today should generate from non-trivial initial state, before inflation got settled to its attractor [10]. (ii) Some features (eg. periodic features) in inflationary model may cause deviation of inflationary initial state from BD to a non-trivial one [11]. (iii) A different background dynamics (eg. fluid dominated era) before inflationary epoch allows inflation to occur from a initial state other than BD (with non zero particle) [12]. (iv) Trans-Planckian physics can also act as one of the reason for compelling inflation to start from a non vacuum initial state [13]. (v) Multifield inflationary models too posses non Bunch-Davies(NBD) initial state [14]. On top of that, from theoretical point of view both BD and NBD initial state have sufficient motivations to come up with. So, it is crucial to know more about the exact nature of initial condition making use of any possible imprints on observational data.

Our primary goal is to do a systematic, stepwise, model-independent development that would possibly help us investigate the nature of the primordial initial condition from observations, without giving priority to any specific theoretical mechanism to set individual initial states. In an earlier work, we have already made some progress in this direction by using the latest Cosmic Microwave Background (CMB) observations from Planck 2015 data [7], and have found the possible existence of non-standard initial state of the inflaton fluctuations along with the usual BD vacuum. In this current work we would like to progress in the same vein and make use of a different observation, namely, the Large Scale Structure (LSS) observations, to complement our knowledge elicited from CMB.

LSS has tremendous potential to tell us about the initial condition and the successive evolution of the universe [15]. LSS data provide us with ample amount of information about the structure formations. However, extracting primordial information from LSS data is a very grueling venture, because, there are plenty sources of late-time non-linearities and noise, which makes the job quite arduous. Yet there are few advantages that makes it a very tempting avenue for the community, such as LSS data contain much more information in comparison to CMB as it probes far more number of scales than CMB[16]. Apart from that, LSS observations bestow us the opportunity to get a glimpse of the evolution of our universe by providing a redshift dependent data set, which allows us to get a 3 dimensional (3D) view of the scales through redshift binning of the observed sky instead of getting a snapshot of a particular epoch like CMB sky, that is the snapshot of the last scattering surface. Hence, we
intend to study the impression of primordial initial state on LSS, thereby try to constrain
the nature of primordial initial state from LSS. To this end, we will make use of two different
LSS dataset, namely, (i) the Sloan Digital Sky Survey - Data Release 7 (SDSS-DR7) sample
of Luminous Red Galaxies (LRG)[17] and (ii) WiggleZ Dark Energy Survey[18]. We will
perform two separate analysis by using these two datasets separately, that will also help us
in having a comparative analysis of the results from two different LSS datasets.

The plan of the paper is as follows: In Section 2, we will describe a generic, model-
independent parameterization of the primordial power spectrum that takes into account both
BD and any non-trivial initial state. Section 3 is dedicated to give a very brief textbook review
on the building of the dark matter power spectrum template from primordial power spectrum,
so as to correlate with our analysis that follows is the next Section along with the data used
in our analysis. In Section 5 we discuss the results from our analysis, separately for WiggleZ
and SDSS-DR7 LRG data. Finally we summarize our results with possible future directions.

2 Parameterization of the power spectrum

In this section we will discuss about the template of the inflationary power spectrum, which
we are using throughout our analysis to constrain the initial state from LSS, consistent with
the notations of this article. A generic parameterization for the primordial power spectrum
of scalar fluctuations can be given by

\[ P(k)_{NBD} = \frac{k^3}{2\pi^2} |\zeta(k)|^2 = P(k)_{BD} \left[ |\alpha_k|^2 + |\beta_k|^2 - 2Re(\alpha_k\beta_k^*) \right] \]

(2.1)

where, \( \zeta \) stands for comoving curvature perturbation, \( P(k)_{NBD} \) and \( P(k)_{BD} \) are the power
spectrum for non Bunch-Davies and Bunch-Davies initial condition respectively. The power
spectrum for Bunch-Davies initial condition is defined as

\[ P(k)_{BD} = A^s_s \left( \frac{k}{k^*_s} \right)^{(n^*_s-1)} \]

(2.2)

where, \( A^s_s, n^*_s \) are the scalar amplitude, spectral index and \( k^*_s \) is the pivot scale. It is straight-
forward to verify that this parameterization is quite generic to mimic almost all the physical
mechanisms and different models of inflation (some of them have been discussed in the Intro-
duction section (1)), and it has been widely used by the community to introduce the generic
(non-vacuum or non-standard) initial condition into the primordial power spectrum[25]. For
detailed derivation of the power spectrum of this form assumed for the BD/NBD case the
interested reader can go through the previous article by the same authors [7].

Now, \( \alpha_k \) and \( \beta_k \) are known as Bogolyubov coefficients (BCS), which parameterize the
initial state of the primordial fluctuations. This form (2.1) of power spectrum arises, when the
general solution of the equation of motion, usually known as Mukhanov-Sasaki equation, of
the mode function representing the scalar fluctuations, are written in Hankel function basis,
instead of considering only the positive frequency solution, which is being considered only
for BD case. BCS \( \alpha_k \) and \( \beta_k \) satisfies a relation, which follows directly from the Wronskian
condition of the mode function.

\[ |\alpha_k|^2 - |\beta_k|^2 = 1 \]

(2.3)

One should note that the given normalization condition is a generic one, which is satisfied
by the BCS irrespective of the physical processes are being addressed. We will use the above
normalization relation (2.3) later on during further parameterization of the BCS as per the need of our analysis.

A brief discussion on BD vacuum and BCS is in order. BD vacuum is defined as the lowest energy state of the quantum fluctuations in de Sitter background, actually it is an analogue of the Minkowski vacuum in flat spacetime, as a result it has always been a favoured choice for cosmological vacuum. In Hankel function basis assuming $\alpha_k = 1$ and $\beta_k = 0$ into the general solution of the mode function, simply boils down to BD initial condition, or simply in Hankel function basis BD vacuum is parameterized by $\beta_k = 0$. Thus, a slightest departure of the value of $\beta_k$ from 0 is sufficient to conclude the existence of a non-trivial initial state.

As already pointed out, the true nature of the initial condition of the inflaton fluctuations is still unknown to us. In principle, the behaviour of the initial state is dependent on scales, hence are BCS, since the initial condition of the primordial perturbations is characterized by BCS. If the initial condition is NBD in nature then only the question of scale dependence is arising otherwise for BD case the BCS are merely constants ($\alpha_k = 1$ and $\beta_k = 0$). Theoretically the nature of the primordial initial state or BCS has been investigated but depending upon different physical scenarios the scale dependence and the amplitude of the BCS varies. However, we still do not even know what is the actual amplitude of the BCS, so it is needless to say that, probing scale dependence of the BCS in a model independent way is a far-fetched idea. It may also be pointed out that, although in principle BCS are scale dependant quantities that may take different values for different modes, BCS are itself small quantities and its variation with scale would be even more smaller than that. As a result, we have safely assumed the BCS as constants, without taking into account their minor scale dependence, if any, rather considered their average values over scales as their amplitudes. Further, in this article, we refrain ourselves from considering any particular form and amplitude of the BCS a-priori, rather we plan to consider only the amplitude of the BCS for the time being as the subject of focus in this present article, so that we can say something about the very nature of the BCS directly from observations only, without considering any specific model as such.

Satisfying the Wronskian condition (2.3), we further parameterize $\alpha_k$ and $\beta_k$ in a scale independent form as argued above with keeping it in mind that BCS are complex in nature:

$$\alpha_k = \cosh \theta$$

$$\beta_k = e^{-i\delta} \sinh \theta$$

$$P(k)_{NBD} = A_s \left( \frac{k}{k_s} \right)^{(n_s-1)} \left[ 1 + 2 \sinh^2 \theta - 2 \sin \theta \cosh \theta \cos \delta \right]. \quad (2.4)$$

We will make use of this expression of NBD power spectrum to model the dark matter power spectrum, which we will later use to constrain the BCS from LSS observations in subsequent sections of this article.

### 3 From inflationary initial condition to structure formation

Thus far, we have discussed the parameterization of the primordial power spectrum for non-trivial initial condition in which the information about the initial state of inflation is embedded in terms of BCS($\alpha_k$ and $\beta_k$). As mentioned earlier the sole motive of this analysis is to provide constraints on $\alpha_k$ and $\beta_k$ directly from LSS observations like SDSS and Wiggle Z, for that
purpose we need to relate the primordial power spectrum with dark matter power spectrum. For a consistent development of the analysis, let us do a very brief textbook review of structure formation from inflationary initial condition, that will be useful in the subsequent sections. For an extensive review one can see [19–21]. The matter density fluctuations are related to primordial fluctuations through gravitational potential. The relation between primordial curvature perturbations and primordial gravitational potential is as follows,

$$\zeta(k) = \frac{3}{2} \Phi_p(k)$$

(3.1)

where, $\Phi_p(k)$ is primordial gravitational potential. From perturbed Poisson and Euler equations for large scale and no radiation limit, one get the relation between primordial gravitational potential and the matter density perturbations,

$$\delta(k, a) = \frac{3}{5} \frac{k^2 T(k, D(a))}{\Omega_m H_0^2} \Phi_p(k)$$

(3.2)

where, $\Omega_m$ and $H_0$ are respectively matter density fraction and Hubble parameter at present time and $\delta(k, a)$ is the matter density contrast. $T(k)$ and $D(a)$ are known as Transfer function and Growth factor respectively. Modifications in growth of different modes due to different epoch of horizon re-entry is being described by Transfer function ($T(k)$). At sufficiently large scales transfer function goes to one. After the epoch of matter-radiation equality growth of the density fluctuations are represented by Growth factor ($D(a)$), which takes the value one at present epoch ($D(0) = 1$).

Relating equation (2.1), (3.1) and (3.2) we reach at:

$$P_m(k, z) = \frac{8\pi^2}{25} \frac{k^2 T(k, D(z))^2}{\Omega_m^2 H_0^4} P(k)_{NBD}$$

(3.3)

The process of the formation of dark matter fluctuations from primordial perturbations is given by the above expression, where $P_m(k, z)$ stands for dark matter power spectrum. The transfer function and the growth function can be evaluated numerically by CAMB code [24] for $\Lambda CDM$ Universe. The equation (3.3) represents the linear matter power spectrum. We will use the power spectrum of the halo density field of the LSS observations for our analysis to relate with SDSS and Wiggle Z observations. So, to construct the template of the halo density field the prescription is very simple, we have to put the linear power spectrum into halo fit following the instructions made by [22, 23]. After that there has several real world effects like non-linearities, redshift-space distortions to incorporate with the halo power spectrum. Although the effect of redshift space distortions is not much effective in linear region because, when the angle average of the power spectrum is considered to address the mean effect of the redshift space distortions it behaves as a mere amplitude enhancement of the power spectrum, which simply gets marginalized during the marginalization of the unknown amplitude as nuisance parameter. Now, there is another real-world effect, that is actually nonlinear in nature, consequently it affects the scales of the power spectrum. This nonlinear scale-dependent effect is widely known as Finger-of-God effect. Although the Finger-of-God effect instigate the behaviour of the scales, but the span of scale we are examining doesn’t get strongly influenced by this effect[17], thereby we haven’t include this effect in our analysis.

Till date the observations draw inference on cosmological parameters by considering the initial condition as BD condition[2]. Consequently, the transfer functions or the halo fit models have been developed thus far to match the present day LSS observations follows initial
state as trivial BD vacuum. So, to carry the signature of a generic inflationary initial state from primordial epoch to late time sky one may in principle have to slightly modify the transfer function and the halo fit model, which will incorporate the behaviour of primordial initial state. Obviously that won’t be much different from the existing widely used transfer functions and halo fit models as the correction due to non-standard initial vacuum would be small.

In our preliminary analysis we have considered the usual transfer function and halo fit model to evolve the primordial perturbations to late time sky keeping in mind that the correction contribution due to non-trivial initial condition is small.

4 Analysis and Data

Let us now discuss the statistical methods used in the present analysis for finding out possible constraints on the initial condition. For our analysis, we have applied Bayesian inference method with following four model parameters:

\[
\{ \theta, \delta, \ln(10^{10}A_s), n_s \}
\]

where, the model parameters are respectively, parameterized BCS \((\theta, \delta)\), the amplitude of the primordial power spectrum \(\ln(10^{10}A_s)\) at the pivot scale \(k_* = 0.05/\text{Mpc}\), and the spectral index\(n_s\) of the primordial inflaton perturbations, as demonstrated in Section 2. For performing Bayesian inference analysis we have set Gaussian prior with infinite variance for all the parameters. Now to analyze BCS we will take shelter of MCMC simulation technique, using the principle of Bayesian inference. For that purpose we need to construct our likelihood function \(L(\text{data}; \alpha)\), where \(\alpha\) represents the model parameters to be estimated (in the present analysis, they are \(\theta, \delta, \ln(10^{10}A_s)\) and \(n_s\)), and \(\text{data}\) stands for the observational data of our consideration (in the present problem, WiggleZ and SDSS-DR7 LRG power spectrum data, taken separately). For our model the likelihood is defined as following:

\[
L(P^{\text{obs}}, \alpha) = \frac{1}{(2\pi)^{n/2}|\text{Cov}|^{1/2}} e^{-\chi^2/2}
\]

where,

\[
\chi^2 = (P^{\text{obs}} - P^{\text{th}})^T[Cov]^{-1}(P^{\text{obs}} - P^{\text{th}}).
\]

Here \(P^{\text{obs}}\) is data vector for power spectrum and \(P^{\text{th}}\) is our theoretical model template of the power spectrum discussed in section 3, and \(\text{Cov}\) stands for covariance matrix.

With the likelihood function and the data as defined above, we develop a code using the Markov Chain Monte Carlo (MCMC) analysis based on Metropolis Hastings algorithm in order to constrain our model parameters. To sample the parameter space of the model parameters we use the random walk metropolis algorithm and Cholesky decomposition. We have monitored the convergence of the chains by available MCMC convergence tests. Along with such statistical convergence test, we have followed some visual monitoring test too, in order to keep a track on the convergence of the chain, using parameter trace plot, which gives the plot of the value of the parameter versus iteration for each parameter. To ensure the convergence and a better sampling we ran all the chains starting from random initial points. And we set the running time accordingly to confirm the convergence of each chain along with small relative errors of the means.
As mentioned earlier, the data we use are WiggleZ [18] and SDSS data [17] from emission line galaxies and luminous red galaxies respectively. The WZ galaxies are basically the blue galaxies, known as star-forming galaxies, usually avoid to stay around the centre of cluster-size dark matter halos because it is being predicted that these galaxies do not prefer to occupy the dense regions of the halos[26] and the LRG are massive galaxies that tend to populate the dense part of the halos hence choose to remain at the centre of the cluster-size dark matter halos[27]. The power spectrum constructed from the LRG catalog gives an estimate of the power spectrum of the massive host halos of the LRG. The two observations are quite different in nature from various aspects such as their sensitivity towards the nonlinearities and non-linear redshift space distortions and most importantly the bias of the two tracers are absolutely different. So, we have performed two separate analysis by using these two datasets separately, that will also help us in having a comparative analysis of the results from two different LSS datasets. The power spectrum we use is the power spectrum of the halo density field, which are derived from the SDSS DR7 (LRG) survey[17] and WiggleZ Dark Energy Survey[18]. For our analysis we have used the WiggleZ matter power spectrum data, which involves four different redshift ranges respectively $0.1 < z < 0.3, 0.3 < z < 0.5, 0.5 < z < 0.7, 0.7 < z < 0.9$, the effective redshift for these four redshift bins are $z = 0.22, 0.41, 0.6, 0.78$ while the SDSS-DR7 LRG survey probes at redshift around $z \sim 0.35$ but being normalized to redshift $z = 0$. For SDSS-DR7 survey the range of scale probed is from $0.02 \ h \ Mpc^{-1}$ to $0.2 \ h \ Mpc^{-1}$ [17]. For WZ we have considered only the region within $k < k_{nl} = 0.2 \ h \ Mpc^{-1}$ of the data set, the essence of which is that, it minimizes the uncertainties cause due to non-linear contributions, as has been explained in [28].

5 Results

Having demonstrated the methodology and the data specifications of our analysis, we are now in a position to present our results obtained from Bayesian inference technique using MCMC simulation. As has been explained, our prime target in this article is to find the constraints on the initial state of the primordial fluctuations in a model-independent way. In order to do so we investigate the possible constraints on the Bogolyubov coefficients, as BCS tell about the nature of the initial states, and individual initial states from particular models can readily be cast in the form of BCS. We have discussed, with elaborations, how to quantify initial state using BCS in section 2. In a nutshell, $\alpha_k = 1$ and $\beta_k = 0$ in equation (2.1) or (2.3) represents BD initial condition for inflationary quantum perturbations, any value of $\beta_k$ other than zero implies deviation from BD initial condition. To satisfy the Wronskian condition we further parameterize the $\alpha_k$ and $\beta_k$ as $\alpha_k = \cosh \theta$ and $\beta_k = e^{-i\delta} \sinh \theta$. Now, since $\beta_k = 0$ implies $\theta = 0$, so any deviation from $\theta = 0$ is equivalent to deviation from $\beta_k = 0$, which in turn predict the existence of the NBD initial condition. Below we shall show the results obtained from two LSS surveys separately.

5.1 Constraints from Wiggle Z observations

Here we shall present the results obtained from the Wiggle Z survey, by making use of the data discussed in details in section 4. The results appear in Figure 1(5.1), Figure 2(5.1) and subsequently in Table 1(5.2). Figure 1(5.1) and Figure 2(5.1) respectively represent the posterior probability and the scattered plot of the parameters $\theta, \delta, \ln(10^{10}A_s)$ and $n_s$ and in Table 1(5.2) we have specified the mean values of the model parameters along with their $1\sigma$
error bars and corresponding $\chi^2$ for this data. We will elaborate on the results in a bit details later in this section.

Figure 1. The posterior of the model parameters $\theta$, $\delta$, $\ln(10^{10}A_s)$ and $n_s$ are being shown above for the Wiggle Z survey.

Figure 2. This figure follows from the Wiggle Z survey, and depicts the parameter space among four model parameters $\theta$, $\delta$, $\ln(10^{10}A_s)$ and $n_s$.

5.2 Constraints from SDSS-DR7

Let us now demonstrate the results obtained from the Sloan Digital Sky Survey - Data Release 7 (SDSS-DR7) sample of Luminous Red Galaxies (LRG)\cite{17} as discussed in section 4. The
results are shown in Figure 3(5.2), Figure 4(5.2) and in the Table 1(5.2). As in the previous case, Figure 3(5.2) and Figure 4(5.2) respectively represent the posterior probability and the scattered plot of the model parameters $\theta$, $\delta$, $\ln(10^{10}A_s)$ and $n_s$ and in Table 1(5.2) we have described the constraints on the model parameters as the mean values with their associated $1\sigma$ error bars, along with corresponding $\chi^2$ for this data.

**Figure 3.** The figure shows the posterior of $\theta$, $\delta$, $\ln(10^{10}A_s)$ and $n_s$ obtained from the SDSS-DR7 survey.

**Figure 4.** This figure depicts the parameter space among four model parameters $\theta$, $\delta$, $\ln(10^{10}A_s)$ and $n_s$ for the SDSS-DR7 Survey.
Table 1. The above table designate the constraints on the values of the model parameters $\theta$, $\delta$, $\ln(10^{10}A_s)$ and $n_s$ obtained from SDSS-DR7 and Wiggle Z surveys. For all the parameters we report the mean values and the associated $1\sigma$ error bars.

| Data       | $\theta$         | $\delta$        | $\ln(10^{10}A_s)$ | $n_s$            | $\chi^2$ |
|------------|------------------|-----------------|--------------------|------------------|----------|
| SDSS-DR7   | $0.7217 \pm 0.5879$ | $0.5684 \pm 0.4942$ | $3.3359 \pm 0.5661$ | $0.9711 \pm 0.0136$ | 19.6387  |
| Wiggle Z   | $0.4682 \pm 0.0322$ | $0.1226 \pm 0.0962$ | $3.0863 \pm 0.1850$ | $0.9771 \pm 0.0548$ | 11.9005  |

A detailed analysis of the results obtained is in order. First of all, the constraints on the primordial scalar amplitude ($\ln(10^{10}A_s)$) and the spectral index($n_s$) shown in Table 1(5.2) as obtained from these two individual LSS datasets are consistent among themselves, and with the latest CMB observations from Planck 2015 [2]. The slight difference in the shape of the posterior probabilities and the scattered plots is due to the intrinsic differences in the two datasets, that might have appeared either due to the differences in sensitivity towards nonlinearities or due to the bias of the tracers. Although both the observations are intrinsically very distinct from each other, the striking resemblance between the results obtained from them is itself much appealing. Nevertheless, as is well known obtaining results from two different observations also helps us in narrowing down the parameter space of the model parameters.

As we can see from Table 1(5.2) and the corresponding plots, the results from both the surveys tell us that the values of BCS ($\theta$, $\delta$) are non-zero at $1\sigma$ CL. However, this does not essentially mean that BD vacuum is ruled out at $1\sigma$, though it may wrongly point out to that. At this stage of investigation, rather, a more sensible statement is that there is a fair chance for the initial state of the inflaton fluctuations to be non-vacuum in nature. There are two-fold reasons behind this statement: First, the BCS are scale-dependent, at least in principle, so, without considering the actual scale dependence of the BCS, if any, it would not be wise to comment conclusively on whether or not the BCS are NBD in nature for all the modes. It may so happen that for some modes it is BD and for some particular modes the initial state could be NBD. Whether or not BD is ruled out can conclusively be stated only when one takes into account the scale-dependence, if any, of BCS, which we did not do in our analysis. Consequently, the results affect the amplitude of power spectrum only. Therefore, any conclusive comment on initial condition before knowing its actual scale dependence would be imprecise. However, a word of caution is that whereas this can be done in principle, this may wash away our primary target, namely a model independent analysis of the whole scenario.

The second reason for refraining us from making any conclusive comment is due to the choice of the transfer function and the halo fit model for the construction of the theoretical template of the LSS power spectrum, as discussed in section 3. In order to study the true imprints of the primordial initial state on late time, one should, in principle, propose an altogether new, reconstructed (but presumably not too different from the standard one) transfer function from say, a modified halo fit model, which will include the non-trivial effects of the primordial power spectrum for a generic initial state. But for our analysis we have assumed the standard transfer function and halo fit model. Of course this is justified to a good extent because of the small amplitude of the BCS, the correction to the transfer function
and the halo fit presumably would not be very much significant. However, as long as one is not considering the reconstructed transfer function and halo fit model, making any conclusive comment would not be wise. So, all we can say at this stage is that both BD and NBD initial states are allowed at 1σ from Wiggle Z and SDSS-DR7 data for LSS. This is in tune with our previous conclusions using CMB data [7].

6 Summary and future directions

In this article we make an attempt to investigate the nature of the primordial initial state directly from observations. This is a part of the systematic, stepwise development we have been planning to do, and, is in some sense a sequel of our previous article based on CMB data [7]. This article in particular makes use of Large Scale Structure data and attempts to find out possible constraints on initial conditions therefrom, without giving priority to any specific theoretical mechanism to set individual initial states. We build the generic template of the primordial power spectrum by taking into account the effect of both the non-standard initial state and the standard BD vacuum. Therefrom we develop the LSS power spectrum using the standard transfer function for halo fit model. We then try to constrain this generic power spectrum using two different LSS dataset, namely, the WiggleZ Dark Energy Survey and the Sloan Digital Sky Survey - Data Release 7 (SDSS-DR7) sample of Luminous Red Galaxies (LRG), and apply the Bayesian inference algorithm to constrain the generic initial state. Our primary investigations from the statistical inference drawn results in a consistent power spectrum and spectral index from the individual datasets which is in turn consistent with latest CMB data from Planck 2015. Nevertheless, our analysis also gives us a hint that the initial state can well be a non-vacuum one due to the existence of non-zero BCS from LSS data.

However, the template we construct in order to constrain the initial vacuum is limited in the sense that we assume the BCS to be constants for all the scales, which may not be absolutely true. Such an assumption forbids us from making any strong comment on the exact nature of the initial state, as we can at best constrain the amplitude of the power spectrum using these templates. We had to make such a compromise in our analysis because in order to incorporate the scale dependence of BCS, one may have to take shelter of particular physical process depending on models. Whereas this can be done in principle, this may in turn wash away the basic essence of the primary target of the present paper, which was to do a model independent analysis of the scenario. However, we are already exploring situations where one can build a somewhat phenomenological scale dependent structure of the initial state, and make a more or less generic comment therefrom. This is our next venture in this direction of probing the inflationary initial state. Nevertheless, in order to extend our analysis towards a systematic, stepwise development of the problem, one needs to constrain the initial state using other dataset as well. One can also forecast on different observations based on a similar analysis. Further, it was pointed out in the article that, for simplicity, we have assumed the standard transfer function with halo fit model in our analysis. To be honest, in this scenario one needs to do a reconstruction of transfer function to reflect any non-trivial effect of generic initial condition on the primordial power spectrum. We plan to explore in these directions in near future.

To conclude, the article is indeed a small step forward towards answering one of the yet-unanswered fundamental questions related to inflationary paradigm, namely the nature
of inflationary initial state, using LSS data. However, much work needs to be done before one can make any decisive comment on the exact nature of the primordial initial state.

Acknowledgments

DC thanks ISI Kolkata for financial support through Senior Research Fellowship. We gratefully acknowledge the computational facilities of ISI Kolkata.

References

[1] C. L. Bennett et al. [WMAP collaboration], [arXiv:1212.5225] [astro-ph.CO].
[2] P. A. R. Ade et al. [Planck collaboration], [arXiv:1502.01589] [astro-ph.CO].
[3] A. H. Guth, S. Y. Pi, Phys.Rev.Lett. 49, 1110 (1982);
A. A. Starobinsky, Phys.Lett.B117, 175 (1982);
S. W. Hawking, Phys.Lett.B115, 295 (1982);
J. M. Bardeen, P. J. Steinhardt, and M. S. Turner, Phys.Rev.D28, 679 (1983);
V. F. Mukhanov and G. V. Chibisov, JETP Lett. 33, 532 (1981).
[4] M. Mirbabayi, L. Senatore, E. Silverstein, and M. Zaldarriaga, Phys.Rev.D 91 (2015) 063518
[arXiv:1412.0665] [hep-th].
[5] N. Bartolo, E. Komatsu, S. Matarrese, and A. Riotto, Phys.Rept. 402 (2004) 103
[arXiv:astro-ph/0406398].
[6] J. Martin and R. H. Brandenberger, Phys.Rev.D 63 (2001) 123501 [arXiv:hep-th/0005209].
[7] D. Chandra and S. Pal, Class.Quant.Grav. 35, 015008 (2017) [arXiv:1606.09098] [hep-th].
[8] T. S. Bunch and P. C. W. Davies, Proc. Roy. Soc. Lond. A 360, 117 (1978).
[9] R. Easther, B. R. Greene, W. H. Kinney, G. Shiu, Phys.Rev.D64, 103502 (2001)
[arXiv:hep-th/0104102].
[10] X. Chen, Y. Wang, JCAP 1407, 004 (2014) [arXiv:1306.0609] [hep-th].
[11] X. Chen, JCAP 1012:003.2010 [arXiv:1008.2485] [hep-th].
[12] M. Gasperini, M. Giovannini and G. Veneziano, Phys.Rev.D48:439-443,1993
[arXiv:gr-qc/9306015];
K. Bhattacharya, S. Mohanty and R. Rangarajan, Phys.Rev.Lett.96:121302,2006
[arXiv:hep-ph/0508070];
K. Bhattacharya, S. Mohanty and A. Nautiyal, Phys.Rev.Lett.97:251301,2006
[arXiv:astro-ph/0607049];
I. Agullo and L. Parker, Phys.Rev.D83:063526,2011 [arXiv:1010.5766] [astro-ph.CO];
M. Giovannini, Phys.Rev.D88, no. 2, 021301 (2013) [arXiv:1304.4832] [astro-ph.CO];
[13] U. H. Danielsson, Phys.Rev.D66 (2002) 023511 [arXiv:hep-th/0203198];
J. Martin and R. H. Brandenberger, Phys.Rev.D63:123501, 2001 [arXiv:hep-th/0005209];
A. Kempf, Phys.Rev.D63 (2001) 083514 [arXiv:astro-ph/0009209];
Phys.Rev.D67 (2003) 063508 [arXiv:hep-th/0110226]; Phys.Rev.D66:023518.2002
[arXiv:hep-th/0204129];
N. Kaloper, M. Kleban, A. E. Lawrence, S. Shenker, Phys.Rev.D66 (2002) 123510
[arXiv:hep-th/0201158];
K. Schalm, G. Shiu, J. P. V. D. Schaar, JHEP 0404:076,2004 [arXiv:hep-th/0401164];
261-273 [arXiv:gr-qc/0411056];
A. Ashoorioon, A. Kempf, R. B. Mann, Phys.Rev. D71 (2005) 023503 [arXiv:astro-ph/0410139];
A. Ashoorioon, J. L. Hovdebo, R. B. Mann, Nucl.Phys. B727 (2005) 63-76 [arXiv:gr-qc/0504135];
L. Hui and W. H. Kinney, Phys.Rev.D65 (2002) 103507 [arXiv:astro-ph/0109107];
A. Ashoorioon, K. Dimopoulos, M. M. Sheikh-Jabbari and G. Shiu, JCAP 02 (2014) 025
[arXiv:1306.4914];
A. Ashoorioon, K. Dimopoulos, M. M. Sheikh-Jabbari and Gary Shiu, Physics Letters B 737
(2014) 98.

[14] G. Shiu and J. Xu, Phys.Rev.D84,103509 (2011) [arXiv:1108.0981];
A. Ashoorioon, A. Krause, K. Turzynski, JCAP 0902:014,2009 [arXiv:0810.4660] [hep-th];
A. Ashoorioon, A. Krause, [arXiv:hep-th/0607001].

[15] M. Alvarez et al., [arXiv:1412.4671] [astro-ph.CO].
[16] J. J. M. Carrasco, M. P. Hertzberg and L. Senatore, JHEP 1209 (2012) 082, [arXiv: 1206.2926]
[astro-ph.CO].
[17] A. B. Reid et. al., Mon. Not. R. Astron. Soc 404 (2010) 60-85 [arXiv:0907.1659] [astro-ph.CO].
[18] D. Parkinson et. al., Phys. Rev. D. 86 (2012) 103518 [arXiv:1210.2130] [astro-ph.CO].
[19] S. Weinberg, Cosmology, Oxford Univ. Press (2008).
[20] P. J. E. Peebles, 1980, Large-Scale Structure of the Universe (Princeton: Princeton Univ.
Press).
[21] S. Dodelson, 2003, Modern Cosmology (New York: Academic press).
[22] R. E. Smith et al. Mon.Not.Roy.Astron.Soc 341 (2003) 1311 [arXiv:astro-ph/0207664].
[23] R. Takahashi et al. [arXiv:1208.2701] [astro-ph.CO].
[24] A. Lewis, A. Challinor and A. Lasenby, Astrophys. J. 538, 473 (2000) [arXiv:astro-ph/9911177].
[25] R. O’Connell and R. Holman, [arXiv: 1109.1562] [hep-th].
[26] M. J. Drinkwater et al., MNRAS 401, 1429 (2010), [arXiv: 0911.4246] [astro-ph.CO].
[27] D. J. Eisenstein et al., AJ 122, 2267 (2001), [arXiv: astro-ph/0108153].
[28] S. Riemer-Sorensen et al., Phys. Rev. D85, 081101 (2012), [arXiv: 1112.4940] [astro-ph.CO].