I. INTRODUCTION

Current data is remarkably consistent with predictions of the simplest models of inflation. To a high degree of accuracy, the Universe appears to be flat and have nearly scale-invariant, isotropically distributed, Gaussian, and adiabatic primordial perturbations\(^1\,^2\). However, there are still potentially large improvements to be implemented in the precision and the length scales of the primordial perturbations that will be probed. Therefore, it is important to investigate possible deviations from this simple picture that may in future be detectable. In this article, we concentrate on features in the primordial power spectrum that may be caused by bursts of particle production during inflation\(^3\,^4\,^5\). This can happen when the motion of the inflaton causes the mass of another field to pass through zero. The resultant production of particles leads to a corresponding bump like feature in the primordial power spectrum at around the scales which are then leaving the Hubble horizon.

A feature in the primordial power will translate to a corresponding feature in the cosmic microwave background (CMB) angular power spectrum and the matter power spectrum. The matter power spectrum may be probed in many ways, and in this article we concentrate on galaxy redshift surveys and cluster surveys.

Currently, there is no detection of such features in the data, but only wave-numbers of \(k \lesssim 0.1 \text{h \ Mpc}^{-1}\) have been probed and only to accuracies of about 5%\(^3\). The Planck CMB survey can probe smaller length scales due to higher resolution and lower noise and so will help improve the constraints up to to \(k \sim 0.2 \text{h \ Mpc}^{-1}\) where noise, beam size limitations and foregrounds start to dominate. In general astro-physical foregrounds prevent one probing the primordial power spectrum beyond about \(k \sim 0.5 \text{h \ Mpc}^{-1}\) using the CMB. Future galaxy redshift surveys such as are planned with the Square Kilometer Array\(^1\) (SKA), will also probe \(k \sim 0.1 \text{h \ Mpc}^{-1}\) to much higher accuracy due to the huge volumes that they will encompass but will be limited to \(k \lesssim 0.2 \text{h \ Mpc}^{-1}\) by non-linear effects. While, \(k \lesssim 2 \text{h \ Mpc}^{-1}\) may be probed by very high redshift galaxy surveys, such as the Cosmic Inflation Probe\(^2\) (CIP), where non-linear growth has yet to dominate.

In this article, we will make forecasts on how well the amplitude of a particle production-induced feature can be constrained by future large scale structure surveys. We begin in Section II with a summary of how particle production can generate a bump-like feature. In Section III we give an overview of Fisher information matrices, a conventional method of predicting constraints on a set of parameters, for CMB, galaxy and cluster surveys. Predictions for constraints on the feature amplitude and position combined with other cosmological parameters are given in Section IV. We discuss our results in Section V.

II. PARTICLE PRODUCTION

Recently, a mechanism has been proposed that will generate a bump-like feature through particle production during inflation\(^3\,^4\,^5\). In this scenario, the production of massive iso-inflaton particles during inflation gives rise to potentially quantitatively observable features in the primordial power spectrum. The fields simply interact via the coupling

\[ \mathcal{L}_{\text{int}} = -\frac{g_{\text{int}}}{2} (\phi - \phi_0)^2 \chi^2, \]

where \(g_{\text{int}}\) is the interaction coupling constant. \(\phi\) and \(\chi\) are the inflaton and iso-inflaton fields respectively. When \(\phi\) passes through \(\phi_0\) there is a non-adiabatic change in the mass of \(\chi\) and as a result a burst of particle production. This rapidly drains energy from the \(\phi\) field which
can lead to a transient violation of slow roll and hence an associated “ringing” in the primordial curvature fluctuations which is similar to that seen in models with a sharp feature in the potential, \[ \delta \chi \]'s in different positions, which associates with different \( g_m \)'s. However, we restrict to the case of only one feature presents. The overall effect is a bump-like feature which can approximately be described by a parametric form as

\[
\mathcal{P}(k) = \Delta_s^2 \left( \frac{k}{k_{\text{pivot}}} \right)^{n_s - 1} + A_{\text{IR}} \left( \frac{\pi c}{3} \right)^{3/2} \left( \frac{k}{k_{\text{IR}}} \right)^3 e^{-3 \left( \frac{k}{k_{\text{IR}}} \right)^2},
\]

where \( \Delta_s^2 \) is the scalar amplitude describing the normalisation of the power spectrum. \( n_s \) and \( k_{\text{pivot}} \) is the tilt and the pivot wavenumber respectively. The first term on the RHS of Eq. (2) is the standard power-law power spectrum and the second term contains the features generated by particle creation which is parameterised by an amplitude, \( A_{\text{IR}} \) and position \( k_{\text{IR}} \) as shown in FIG. 1. The normalisation is chosen so that \( A_{\text{IR}} \) is the amplitude of the feature at its peak \( k_{\text{IR}} \). The relation to the coupling constant is given by

\[
A_{\text{IR}} \approx 1.01 \times 10^{-6} g_m^{15/4}.
\]

FIG. 1: The primordial power spectrum plus particle creation features with \( A_{\text{IR}} = 1.25 \times 10^{-10} \) at position \( k_{\text{IR}} = 0.1 \) h Mpc\(^{-1} \) (red dashed).

### III. FISHER MATRIX CALCULATION

We use the Fisher Information Matrix \([15]\) to make predictions for constraints of cosmological parameters for future surveys. The statistics that will be implemented are cluster number counts, the cluster/galaxy power spectrum and the cosmic microwave background power spectrum.

#### A. Cluster Number Count

The simplest statistics we can extract from a cluster survey is the number count.

1. **Differential Halo Mass Function**

In order to predict the number density of collapsed objects in the Universe, a statistical concept of halo or mass distribution is used here. The **differential halo mass function**, or **halo mass function** for short, is defined as the redshift-dependent distribution of the number of collapsed dark matter haloes per unit mass interval in a unit co-moving volume. The halo mass function is given by

\[
\frac{dn}{dM} = \rho_m \frac{d \ln \sigma^{-1}}{dM} f(\sigma),
\]

where \( \frac{dn}{dM} \) is the differential halo mass function, \( \rho_m \) is the matter density, and \( f(\sigma) \) is called the **mass fraction**. The smoothed variance is calculated as

\[
\sigma^2(R, z) = \frac{D(z)^2}{2\pi^2} \int_0^\infty P(k) W^2(k, R) k^2 dk,
\]

where \( D(z) \) is the linear growth function normalised to 1 at the present epoch. \( W(k, R) \) is the Fourier-space top-hat window function. \( R \) is the smoothing radius for a comoving sphere enclosing a mass of

\[
M = 4\pi \frac{R^3}{3} \rho_m.
\]

The top hat smoothing in Eq. (5) suppresses the contribution of any change to the primordial power spectrum located at wave number \( k_{\text{IR}} \gg 1/R \). Combined with Eq. (6), this implies that a change in the primordial power spectrum at \( k_{\text{IR}} \) has a suppressed effect on the number density on mass scales satisfying

\[
\frac{M}{h^{-1} M_\odot} \gg 10^{12} \left( \frac{k_{\text{IR}}}{h \text{Mpc}^{-1}} \right)^{-3}.
\]

The **mass fraction** is defined as a fraction of mass in collapsed haloes per unit interval in \( \ln \sigma^{-1} \). The halo mass function is described by a pair of parameters, \( f(\sigma) \) and \( \ln \sigma^{-1} \). Both of these parameters are a natural way of parameterising the mass function from different cosmological models with the fewest number of parameters. All the cosmological parameters are embedded in \( \sigma \). \( f(\sigma) \) is the fraction of the density fluctuation that eventually
collapse into non-linear objects. We used the mass function by Jenkins et al. (2001) [10]:

\[ f(\sigma) = 0.315 \exp \left( -\ln \sigma^{-1} + 0.61^{3.8} \right). \]  \hspace{1cm} (8)

2. Number Count Fisher Matrix

For a survey which covers \( f_{\text{sky}} \) fraction of the sky, a theoretically expected value of the number of clusters in the \( i \)th redshift bin at central redshift \( z_i \) and a width of \( \Delta z \) is given by

\[ \bar{N}(M > M_{\text{lim}}, z_i) = f_{\text{sky}} \int_{z_i - \frac{1}{2}\Delta z}^{z_i + \frac{1}{2}\Delta z} \frac{dV}{dz} dz \int_{M_{\text{lim}}}^{\infty} \frac{dM}{dM}(M, z) dM. \]  \hspace{1cm} (9)

The differential co-moving volume, \( dV/dz \), is

\[ \frac{dV}{dz} = \frac{4\pi}{H(z)} \left[ \int_{z_0}^{z} \frac{dz'}{H(z')} \right]^2, \]  \hspace{1cm} (10)

where \( H(z) \) is the Hubble parameter at redshift \( z \). Eq. (9) includes all the clusters above a threshold mass of \( M_{\text{lim}} \). The mass threshold can, in general, be redshift-dependent which is normally given in terms of a survey-specific selection function. To investigate generally how cluster surveys can be used to probe features, we will use a simple redshift-independent effective mass threshold for cluster surveys which yields an equivalent number of clusters over the entire survey volume.

Given a set of parameters of interest, \( \Theta = (\theta_1, \theta_2, \ldots, \theta_m) \), an element \( \theta_{\mu} \) and \( \theta_{\nu} \) of a Fisher matrix for number count is [17]

\[ F_{\mu \nu} = \sum_{i=1}^{N_{\text{bins}}} \frac{1}{N_i} \frac{\partial \bar{N}_i}{\partial \theta_{\mu}} \frac{\partial \bar{N}_i}{\partial \theta_{\nu}}, \]  \hspace{1cm} (11)

where \( F_{\mu \nu} \) is a sum of all redshift bins in the survey.

B. Power Spectrum

We also consider cosmological constraints from measurements of the matter power spectrum.

1. Galaxy Power Spectrum

Galaxies are moving away from us along with the Hubble flow. The perturbation of the velocity of the galaxies is called the peculiar velocity which is the motion of the galaxies relative to the Hubble flow. It changes the observed Doppler shift and, hence, the distance inferred from redshift measurement. Kaiser (1987) [13] showed that the power spectrum derived from a redshift survey, \( P_s(k) \), is given by

\[ P_s(k, \mu) = \left[ 1 + \beta \mu^2 \right] b^2 P(k), \]  \hspace{1cm} (12)

where \( P(k) \) and \( P_s(k) \) are the matter power spectrum and the redshift power spectrum respectively, \( \mu \equiv \hat{k} \cdot \hat{n} \) is the cosine of the angle between \( \mathbf{k} \) and the line of sight, \( \beta \) is

\[ \beta = \frac{1}{b} \frac{d \ln D}{d \ln a}, \]  \hspace{1cm} (13)

where \( D \) is the linear growth function normalised to 1 at the present epoch, and \( b \equiv \delta_s/\delta \) is the galaxy bias. The bias for galaxy surveys is normally estimated from the data and the uncertainty in bias is propagated into the other parameter constraints. However, to include non-linear effects, we applied a Taylor-like expansion to the bias as

\[ b^2 = b_0^2 \left[ 1 + a_1 \delta k + a_2 \delta^2 k \right], \]  \hspace{1cm} (14)

where \( b_0 \) is a scale independent bias. \( a_1 \) and \( a_2 \) are the first and the second order term respectively [19].

The linear theory matter power spectrum is related to the primordial power spectrum by

\[ P(k) \propto T^2(k) k P(k) \]  \hspace{1cm} (15)

where \( T \) is the transfer function. So a narrow feature in the primordial power spectrum will be transferred to a narrow feature in the matter power spectrum at about the same comoving wavenumber, see FIG. 2.
2. Cluster Power Spectrum

The Poisson approximation for cluster number counts is not strictly accurate for larger surveys [20]. There is an additional sample variance which can be used to help constrain the mass scaling relation. We account for this by incorporating an additional constraint from the power spectrum of the clusters. The way of doing this is similar to that of galaxies. However, in the case of cluster bias, we use an effective linear halo bias

$$b_{\text{eff}}(z) = \frac{\int_{M_{\text{lim}}}^{\infty} dM \ b(M, z) dn/dM}{\int_{M_{\text{lim}}}^{\infty} dM \ dn/dM},$$

where $dn/dM$ is the differential mass function (See Eq. [4]) and $b(M, z)$ can be calculated from halo bias [21] as

$$b(\nu) = 1 + \frac{a \nu - 1}{\delta_c} + \frac{2 p}{\delta_c [1 + (a \nu)^p]}^3,$$

where $\nu = (\delta_c / \sigma)^2$ with $\delta_c = 1.69$, $a = 0.75$ and $p = 0.3$.

3. Power Spectrum Fisher Matrix

We may write the appropriate Fisher Matrix for the power spectrum by assuming the likelihood function to be Gaussian as [22]

$$F_{\mu \nu} = \frac{1}{2} \int_{k_{\text{min}}}^{k_{\text{max}}} \frac{d^3k}{(2\pi)^3} \frac{\partial \ln P_x(k)}{\partial \theta_\mu} \frac{\partial \ln P_x(k)}{\partial \theta_\nu}. $$

We set $k_{\text{max}}$ to be the wavenumber where non-linear effects start to become non-negligible. From [23] where $\sigma(R_{\text{nl}}) = 0.5$ and $k_{\text{max}} = k_{\text{nl}} = \pi/2/R_{\text{nl}}$. We set $k_{\text{min}} = 1.0 \times 10^{-4}$ Mpc$^{-1}$ for the lower limit. The effective survey volume, $V_{\text{eff}}$, is a given by

$$V_{\text{eff}}(k, \mu) = \int d^3r \left[ \frac{n(r) P_x(k, \mu)}{\bar{n} P_x(k, \mu) + 1} \right]^2 \approx \left[ \frac{\bar{n} P_x(k, \mu)}{\bar{n} P_x(k, \mu) + 1} \right]^2 V_{\text{survey}}. $$

where $n(r)$ is the number density at position $r$ and $\bar{n}$ is the average number density for the survey. The effective volume is due to a finite survey volume and incomplete sampling of the underlying density field. These are known as sample variance and shot noise respectively. The uncertainty is propagated through the calculation by the weighing factor $[n(r) P_x / (n(r) P_x + 1)]^2$. For galaxy surveys where the number density is high i.e. $\bar{n} P_x(k, \mu) \gg 1$, the effective survey volume is then $V_{\text{eff}} \approx V_{\text{survey}}$.

C. CMB

The primordial power spectrum is probed over a wide range of wave numbers by measurements of the primary CMB anisotropies (see for example [24]). Both the temperature ($T$) and $E$-mode of the polarization ($E$) probe scalar perturbations.

$$F_{\ell \ell'} = \frac{\ell \ell' C_{\ell}^X}{2 \pi} = \int d\ln k \ (T_X^k(k))^2 \tilde{P}(k),$$

where $X \in T, E$ for auto-correlation function ($TT, EE$). For the cross-correlation power spectrum ($TE$),

$$F_{\ell \ell'} = \frac{\ell \ell' C_{\ell}^{X'Y}}{2 \pi} = \int d\ln k \ T_X^k(k) T_{Y}^{k'}(k) \tilde{P}(k). $$

The projection of a mode of wave-number $k$ on to the surface of last scattering (a sphere of comoving radius $D_s$) results in the CMB transfer functions having the form $T_X^k \sim j_l(k D_s)$. Where $j_l$ is the spherical Bessel function of order $\ell$ which peaks at $\ell \approx k D_s$. Therefore a bump in the primordial power spectrum at wave-number $k_i$ is mapped onto a bump in CMB angular power spectrum at

$$\ell \sim k_{\text{IR}} D_s \approx 10^4 \frac{k_{\text{IR}}}{h \text{Mpc}^{-1}},$$

see FIG. 3.

The foreground contribution from secondary sources which will probably be hard to completely remove for $\ell > 2000$ for both temperature and polarization. For this reason, as done by [24] and [25], we will restrict ourselves to $\ell \leq 2000$ when evaluating the forecasted marginalized errors.

The CMB Fisher matrix is given by (see for example [26])

$$F_{ij} = \sum_{X} \sum_{X'} \frac{\partial C_{\ell X}^{X}}{\partial \theta_i} \text{Cov}^{-1}(C_{\ell X}^{X'}, C_{\ell X'}^{X}) \frac{\partial C_{\ell X'}^{X'}}{\partial \theta_j},$$

FIG. 3: The CMB angular power spectrum from a featureless primordial power spectrum (blue solid) and the CMB angular power spectrum from a primordial power spectrum with a particle creation feature which has $A_{\text{IR}} = 1.25 \times 10^{-10}$ at position $k_{\text{IR}} = 0.1 h \text{Mpc}^{-1}$ (red dashed).
TABLE I: Planck Instrument Characteristics

| Center Frequency (GHz) | 70 | 100 | 143 | 217 |
|------------------------|----|-----|-----|-----|
| $\theta$ (FWHM arcmin) | 14 | 10 | 7.1 | 5.0 |
| $\sigma_T$ (µK)        | 12.8 | 6.8 | 6.0 | 13.1 |
| $\sigma_B$ (µK)        | 18.2 | 10.9 | 11.4 | 26.7 |

where the covariance matrix can be obtained from $20$ and it depends on the temperature noise per pixel ($\sigma_T$), the polarization noise per pixel ($\sigma_B$), the pixel area in radians squared ($\theta^2 = 4\pi/N_{\text{pix}}$), and the beam window function which we approximate as Gaussian ($B_r \approx \exp(-\ell(\ell+1)\sigma_T^2$).

IV. FORECAST CONSTRAINTS

With the descriptions of Fisher information matrices in Section[11] we can make predictions for future upcoming surveys. We also test our Fisher matrix formalism on some current surveys and compare to published results. For the CMB we take the Planck$^3$ and WMAP$^4$ surveys. The values for Planck are taken from the Planck blue book$^5$ and are listed in TABLE [1] (note that $\theta$ needs to be converted to radians). We use $\sigma_B = \theta/\sqrt{8\log 2}$ and combine the different frequency bands as specified in $27$. We take the range in $\ell$ to be 2 to 2000. At higher $\ell$, secondary sources of temperature and polarization will likely prohibit the extraction of cosmological information from the primary CMB.

For galaxy surveys, we consider the Cosmic Inflation Probe$^6$ (CIP) $28$, which is a space-based mission aimed to measure the linear galaxy power spectrum over $k \sim 0.03 - 2.0$ $h$ Mpc$^{-1}$ to better than 1%. The primary science goal of the CIP is to provide constraint on inflation models by observing $\text{H}_\alpha$. The CIP survey will cover 1,000 square degrees and will be capable of detecting more than $10^8$ galaxies between redshift range of 1.8 - 6.5. We follow the CIP model from by having redshift bins at $z = 2.0 - 3.5, 3.5 - 5.0, 5.0 - 6.5$ and having an average galaxy number density of $1.0 \times 10^{-2}, 5.3 \times 10^{-3}$ and $1.3 \times 10^{-3}$ $h_3$ Mpc$^{-3}$ respectively which is equivalent to $\sim$100 million of galaxies within the survey volume of $\sim$15.0 $h^{-1}\text{Gpc}^3$. We restrict our calculation to $k_{\text{max}} = 0.5, 1.0, 2.0$ $h$ Mpc$^{-1}$ for the three bins respectively (See Eq. [18]).

The Sloan Digital Sky Survey$^7$ (SDSS) $29$ is a ground-based optical survey using a 2.5 meter telescope at Apache Point Observatory, New Mexico. It final data set (DR7) includes more than 230 million celestial objects and spectra of about 930,000 galaxies and 120,000 quasars over an area of 8,400 square degree in five optical bandpasses to redshift about 1.0. We follow the SDSS survey model from Pritchard & Pierpaoli (2008)$^{30}$. We estimate the bias for the SDSS survey as 2.25 (ie. $b = \sigma_{s,g}/\sigma_s$ where $\sigma_{s,g} = 1.8$ and $\sigma_s = 0.8$) and $\bar{n} = 1.0 \times 10^{-4}$ $h^3$ Mpc$^{-3}$. The Square Kilometre Array$^8$ (SKA) is a large-scale radio telescope which aims to cover the frequency range from 60 MHz to 35 GHz and 20,000 square degree of the sky. The main science goal of the SKA project is to study the HI content of galaxies to cosmologically significant distances, $z \sim 2.0$, and to make reionisation maps using 21 cm transition of neutral hydrogen. The SKA project is currently in a design phrase and the telescope site will be decided in 2012. We consider the galaxy redshift survey component of SKA (see for example $31$). It also may be possible to use the 21 cm absorption component of the SKA to probe reionization and matter power spectrum at a higher redshift (see for example $32$). We shall consider the SKA survey as a stereotype of a cosmic variance-limited galaxy redshift survey by assuming that the number density is so high that $n\bar{n} \gg 1.0$. Hence, the effective survey volume is equivalent to the survey volume (see Eq. [19]) from $z = 0.0 - 2.0$. The set of parameter of all the galaxy surveys will include bias as an additional parameter reflecting the fact that we do not know accurately the value of the bias. The uncertainty in bias will propagate into the parameter constraints.

For cluster surveys, we consider an all-sky Extended Röntgen Survey with an Imaging Telescope Array$^9$ (eROSITA) which is a high sensitivity all-sky X-ray survey in the 0.2-12 keV energy band. The key science goal for eROSITA is to constrain the properties of dark energy using high redshift clusters of galaxies. It will have a capability to measure the spatial correlation features and evolution of a sample of about 50,000 galaxy clusters over a redshift range of 0.0 - 2.0 and will be able to find collapsed objects with mass above $3.5 \times 10^{14}$ $h^{-1}M_{\odot}$. Our calculation of the expected cluster counts is in a good agreement with the all-sky eROSITA cluster count given in eROSITA documentation. We model the eROSITA survey by having redshift bins at $z = 0.0 - 2.0$. We also assume a 10% prior on the mass threshold determination for the eROSITA survey. The set of parameters of eROSITA will include the mass threshold as an additional parameter reflecting the fact that we do not know accurately the mass of a cluster. The uncertainty in mass threshold will propagate into the parameter constraints.

The SuperNova/Acceleration Probe$^{10}$ (SNAP) survey $33, 34$ is a space-based experiment aiming to study dark

$^3$ http://www.rssd.esa.int/index.php?project=planck
$^4$ http://map.gsfc.nasa.gov/
$^5$ http://www.rssd.esa.int/SA/Planck/docs/Bluebook-ESA-SCI(2005)1_V2.pdf
$^6$ See http://www.cfa.harvard.edu/cip/
$^7$ See http://www.sdss.org/
$^8$ See http://www.skatelescope.org/
$^9$ See http://www.mpe.mpg.de/heg/www/Projects/EROSITA/main.html
$^{10}$ See http://snap.lbl.gov
energy and dark matter. We forecast the SNAP cluster lensing survey constraints [35] (also see [36–39]). Here we take $z = 0.0 - 1.4$, $\Delta z = 0.2$, $f_{\text{sky}} = 0.024$, and a mass limit of $10^{14} h^{-1} M_\odot$. This roughly matches the number of clusters found using the more accurate selection function of [35] when we use their fiducial model cosmological parameters. Also, [38] found that the signal-to-noise ratio of a more realistic selection function was about the same as taking a mass limit of $10^{14} h^{-1} M_\odot$. Our SNAP selection function is biased to slightly higher redshifts than that of [35], but we expect this not to alter our predicted constraints significantly. We do not include the mass threshold into our analysis for the SNAP weak lensing survey as the weak lensing technique can be used to determine the cluster mass accurately.

A summary of all galaxy and cluster survey parameters is given in TABLE I. We combined both statistical measurements from cluster number counts and the power spectrum in our predictions for the eROSITA and SNAP surveys. For the cluster surveys, we estimated the effective bias using Eq. (16).

We follow the work done by Barnaby & Huang (2009) [3] where they found a $2\sigma$ constraint on the amplitude of the feature of about $2.5 \times 10^{-10}$ on scale $k \sim 0.006 - 0.1 \text{ Mpc}^{-1}$. We conservatively define our fiducial value for the amplitude as $A_{\text{IR}} = 1.25 \times 10^{-10}$ and the feature at positions $k_{\text{IR}} = 0.1, 0.4$ and $1.0 \text{ Mpc}^{-1}$. A survey $k_{\text{max}}$ limits the range of feature positions it can probe. The SDSS and SKA survey can only probe the feature at $k = 0.1 \text{ Mpc}^{-1}$ while CIP is the deepest survey that can probe all of the above feature positions. The eROSITA and SNAP survey probe only the $k = 0.1 \text{ Mpc}^{-1}$ and $k = 0.4 \text{ Mpc}^{-1}$ features, whereas the latter is probed by the number count component.

We define our fiducial set of parameters as the flat $\Lambda$CDM set of parameters with running of the spectral index, $\alpha_s$, plus the amplitude and the position of the feature $\Theta = (\omega_s, \alpha_s, \Omega_m, n_s, \alpha_s, \Delta^2_s, \tau) = (0.0227, 0.1107, 0.738, 0.969, 0.0, 2.15 \times 10^{-9}, 0.086)$ and $k_{\text{pivot}} = 0.05 \text{ Mpc}^{-1}$. Our fiducial cosmological parameters are consistent with the WMAP7 maximum likelihood values [2] although their $k_{\text{pivot}} = 0.002 \text{ Mpc}^{-1}$. We assume a negligible neutrino mass, but we checked that adding a non-negligible mass would not significantly change our results. The constraints for the fiducial parameters without a feature are given in TABLE II. For features, we show the marginalized constraints on $A_{\text{IR}}$, $k_{\text{IR}}$, $n_s$, and $\alpha_s$ in TABLE III and TABLE IV for features at $k_{\text{IR}} = 0.1, 0.4$ and $1.0 \text{ Mpc}^{-1}$ respectively. The other cosmological parameters are included in the marginalization, but they are not particularly degenerate with the features. We use a modified version of the CAMB package to generate the power spectrum for our analysis.

![FIG. 4: Marginalised probability contours containing 68% of the posterior probability between $\alpha_s$ and $A_{\text{IR}} = 1.25 \times 10^{-10}$.](http://camb.info/)

![FIG. 5: 1-\sigma marginalised constraints on the amplitude and position of particle production feature for Planck, Planck + SKA and Planck + CIP. The uncertainty in $k_{\text{IR}}$ is multiplied by 5 to make them more visible.](http://camb.info/)

V. DISCUSSION

For the standard cosmology, our cosmological constraints are in good agreement with previous work. For example, our CIP constraints for $n_s$ and $\alpha_s$ are consistent with [32][31], our results for SDSS and SKA are consistent with [30]. Our best constraint for $(n_s, \alpha_s)$ derives from CIP + Planck and SKA + Planck which are $(0.002, 0.0032)$ and $(0.0016, 0.0019)$ respectively. However, since CIP and SKA surveys probe the power spectrum at exclusively different redshift range, we can consider them

\[11\] http://camb.info/
as two independent surveys. The combined CIP + SKA + Planck improves the constraints to (0.0014, 0.0017).

From TABLE IV we investigate the effect of a feature on cosmological parameters on scales $k = 0.1, 0.4$ and $1.0 \ h\ Mpc^{-1}$ respectively. The WMAP+SDSS constraints for the $0.1 \ h\ Mpc^{-1}$ feature are consistent with those found for the actual data [3]. As the CMB is limited to $\ell \leq 2000$, it can only directly constrain the $k = 0.1 \ h\ Mpc^{-1}$ feature. It may be possible to extend this range somewhat for polarization, but probably not enough to completely encompass the width of the $0.4 \ h\ Mpc^{-1}$ centred feature. The cluster surveys were only able to help directly constrain the feature at $0.1 \ h\ Mpc^{-1}$. Although in previous work [42], we found that cluster surveys could constrain the primordial power spectrum directly at scales of $0.4 \ h\ Mpc^{-1}$, this was for a linear piecewise binning of the primordial power spectrum where the location of the feature did not need to be constrained.

With features at different positions, the constraint on $n_s$ remains almost the same while the constraints on $\alpha_s$ are worsened by about a factor of 2. The degeneracies between $A_{IR}$ and $k_{IR}$ have a significant impact on the running as a variation in $\alpha_s$ could be made on a more localised scale than a variation in $n_s$. However, there is more of an improvement on $\alpha_s$ with CIP + Planck. FIG. 4 shows that CIP could be used to break the degeneracy between $A_{IR}$ and $\alpha_s$ while SKA only provides a tightened constraint but the degeneracy is still in the same direction. CIP is in a different direction as it has most of its constraining power at higher $k$ values and so the degeneracy between $A_{IR}$, $\Delta_R^2$, and $\alpha_s$ is different.

Our inference of $\sigma_{A_{IR}}$ and $\sigma_{\alpha_s}$ is summarised in FIG. 5. As can be seen, Planck will improve the constraint at the $0.1 \ h\ Mpc^{-1}$ scale by about a factor of about 10 in comparison to WMAP. The addition of SKA further improves the constrain by another factor of about 5. On wavenumbers up to about $1.0 \ h\ Mpc^{-1}$ CIP combined with Planck could provide similar constraints.

Even smaller scales are constrainable, but then CIP would not be able to probe the full extent of the feature. Also, it may be possible to further improve the constraints by including the non-Gaussianity associated with the feature [5].

Even though the excess in cluster number count can be easily obtained from cluster surveys (See FIG. 6 for eROSITA), they do not give better constraints in comparison to galaxies surveys partly due to low number statistics. In addition, the cluster number counts are not good at simultaneous determining the amplitude of the features and the positions due to the degeneracy in cluster counts. Because the number of clusters is determined by the integral of $P(k)$ (See Eq. 4 and Eq. 5) the features with different amplitude and position can conspire to yield the same integral, hence, number counts. FIG. 7 shows the contour plot of excesses in number counts for different amplitude and position of the features.

In summary, we have demonstrated that future surveys can potentially probe the primordial power spectrum, for particle production-induced features, significantly more accurately and to significantly smaller length scales than at present. Even if no features are detected, at least the simplest models will have been tested much more precisely and on a much greater range of scales.
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**TABLE II: Details for galaxy and cluster surveys.**

| Survey     | $z$          | $\Delta z_{\text{bin}}$ | $V_{\text{survey}}$ ($h^{-3}$ Gpc$^3$) | $k_{\text{max}}$ ($h$ Mpc$^{-1}$) | $b$ | $M_{\text{lim}}$ ($h^{-1}$ $M_\odot$) | $f_{\text{sky}}$ |
|------------|--------------|--------------------------|----------------------------------------|----------------------------------|-----|--------------------------------------|-----------------|
| Galaxy Survey |             |                          |                                        |                                  |     |                                      |                 |
| CIP        | 2.0 – 6.5   | 1.5                      | 15.0                                   | 2.0                              | 1.0 | N/A                                  | 0.024           |
| SDSS       | 0.0 – 0.6   | 0.6                      | 1.0                                    | 0.1                              | 2.25| N/A                                  | 0.3             |
| SKA        | 0.0 – 2.0   | 2.0                      | 100                                    | 0.4                              | 1.0 | N/A                                  | 0.5             |
| Cluster Survey |         |                          |                                        |                                  |     |                                      |                 |
| SNAP       | 0.0 – 1.4   | 0.2                      | 2.76                                   | 0.15                             | 2.0 | $10^{14}$                            | 0.024           |
| eROSITA    | 0.0 – 2.0   | 0.2                      | 220                                    | 0.2                              | 9.0 | $3.5 	imes 10^{14}$                 | 1.0             |

**TABLE III: Constraints on fiducial cosmology**

| Survey                     | $\sigma_{\omega_b}$ | $\sigma_{\omega_c}$ | $\sigma_{\Omega_{\Lambda}}$ | $\sigma_{\sigma_8}$ | $\sigma_{\Delta_2}$ ($10^{-3}$) | $\sigma_T$ | $\sigma_{M_{\text{lim}}}$ ($10^{14}$ $h^{-1}$ $M_\odot$) | $\sigma_b$ | $\sigma_{\alpha_1}$ | $\sigma_{\alpha_2}$ ($h^{-1}$ Mpc) | $\sigma_{\alpha_3}$ | $\sigma_{\alpha_4}$ ($h^{-2}$ Mpc$^2$) |
|---------------------------|----------------------|----------------------|-------------------------------|----------------------|---------------------------------|------------|----------------------------------------------------|-----------------|----------------------|--------------------------------------|----------------------|--------------------------------------|
| Galaxy Survey             |                      |                      |                               |                      |                                 |            |                                                    |                 |                      |                                      |                      |                                      |
| CIP                       | 0.0022               | 0.0086               | 0.0043                        | 0.027                | 0.082                           | 0.23       | N/A                                                | N/A             | 0.0057               | 0.039                               | 0.024               |                                      |
| CIP + WMAP                | 0.00026              | 0.00070              | 0.0015                        | 0.0047               | 0.0037                          | 0.024      | N/A                                                | N/A             | 0.0055               | 0.037                               | 0.021               |                                      |
| CIP + Planck              | 0.000099             | 0.00026              | 0.0012                        | 0.0020               | 0.0032                          | 0.013      | N/A                                                | N/A             | 0.0043               | 0.029                               | 0.019               |                                      |
| SDSS + WMAP               | 0.00046              | 0.0036               | 0.020                         | 0.021                | 0.017                           | 0.055      | N/A                                                | N/A             | 0.17                 | 4.44                                | 32.89               |                                      |
| SDSS + Planck             | 0.00013              | 0.0010               | 0.0055                        | 0.0031               | 0.0049                          | 0.020      | N/A                                                | N/A             | 0.15                 | 4.33                                | 32.82               |                                      |
| SKA                       | 0.00064              | 0.0028               | 0.0016                        | 0.0096               | 0.0033                          | 0.077      | N/A                                                | N/A             | 0.0029               | 0.028                               | 0.041               |                                      |
| SKA + WMAP                | 0.00017              | 0.00061              | 0.00055                       | 0.0028               | 0.020                           | 0.018      | N/A                                                | N/A             | 0.0025               | 0.026                               | 0.037               |                                      |
| SKA + Planck              | 0.000082             | 0.00016              | 0.00035                       | 0.0016               | 0.0019                          | 0.0069     | N/A                                                | N/A             | 0.0022               | 0.022                               | 0.032               |                                      |
| Cluster Survey            |                      |                      |                               |                      |                                 |            |                                                    |                 |                      |                                      |                      |                                      |
| eROSITA + WMAP            | 0.00037              | 0.0021               | 0.011                         | 0.013                | 0.0082                          | 0.046      | 0.19                                               | N/A             | N/A                  | N/A                                 |                     |                                      |
| eROSITA + Planck          | 0.00013              | 0.001               | 0.0052                        | 0.003                | 0.0041                          | 0.040      | 0.0043                                             | N/A             | N/A                  | N/A                                 |                     |                                      |
| SNAP + WMAP               | 0.00039              | 0.0017               | 0.010                         | 0.017                | 0.015                           | 0.042      | N/A                                                | N/A             | N/A                  | N/A                                 |                     |                                      |
| SNAP + Planck             | 0.00012              | 0.00066              | 0.0036                        | 0.0027               | 0.0049                          | 0.018      | N/A                                                | N/A             | N/A                  | N/A                                 |                     |                                      |
| CMB                       |                      |                      |                               |                      |                                 |            |                                                    |                 |                      |                                      |                      |                                      |
| WMAP                      | 0.0006              | 0.0057               | 0.032                         | 0.030                | 0.021                           | 0.06       | 0.012                                              | N/A             | N/A                  | N/A                                 |                     |                                      |
| Planck                    | 0.00013              | 0.0011               | 0.0057                        | 0.0031               | 0.0049                          | 0.02       | 0.004                                              | N/A             | N/A                  | N/A                                 |                     |                                      |
TABLE IV: Forecasted 1-σ marginalised uncertainties for fiducial $k_{IR} = 0.1 \text{h Mpc}^{-1}, A_{IR} = 0.125 \times 10^{-9}$.

| Survey               | $\sigma_{A_{IR}}$ ($\times 10^{-9}$) | $\sigma_{\beta_{IR}}$ (h Mpc$^{-1}$) | $\sigma_{\alpha_s}$ | $\sigma_{\alpha_x}$ |
|----------------------|--------------------------------------|--------------------------------------|---------------------|---------------------|
| Galaxy Survey        |                                      |                                      |                     |                     |
| CIP                  | 0.016                                | 0.0037                               | 0.027               | 0.0083              |
| CIP + WMAP           | 0.0085                               | 0.0024                               | 0.0047              | 0.0038              |
| CIP + Planck         | 0.0066                               | 0.0015                               | 0.0024              | 0.0034              |
| SDSS + WMAP          | 0.18                                 | 0.027                                | 0.063               | 0.034               |
| SDSS + Planck        | 0.013                                | 0.0023                               | 0.0043              | 0.0079              |
| SKA                  | 0.0039                               | 0.0016                               | 0.0083              | 0.0049              |
| SKA + WMAP           | 0.0032                               | 0.0014                               | 0.0030              | 0.0026              |
| SKA + Planck         | 0.0030                               | 0.0010                               | 0.0016              | 0.0023              |
| Cluster Survey       |                                      |                                      |                     |                     |
| eROSITA + WMAP       | 0.10                                 | 0.025                                | 0.033               | 0.015               |
| eROSITA + Planck     | 0.011                                | 0.0022                               | 0.0040              | 0.0057              |
| SNAP + WMAP          | 0.075                                | 0.027                                | 0.038               | 0.025               |
| SNAP + Planck        | 0.012                                | 0.0023                               | 0.0038              | 0.0075              |
| CMB                  |                                      |                                      |                     |                     |
| WMAP                 | 0.19                                 | 0.027                                | 0.064               | 0.035               |
| Planck               | 0.013                                | 0.0023                               | 0.0044              | 0.0079              |

TABLE V: Forecasted 1-σ marginalised uncertainties for fiducial $k_{IR} = 0.4 \text{h Mpc}^{-1}, A_{IR} = 0.125 \times 10^{-9}$.

| Survey               | $\sigma_{A_{IR}}$ ($\times 10^{-9}$) | $\sigma_{\beta_{IR}}$ (h Mpc$^{-1}$) | $\sigma_{\alpha_s}$ | $\sigma_{\alpha_x}$ |
|----------------------|--------------------------------------|--------------------------------------|---------------------|---------------------|
| Galaxy Survey        |                                      |                                      |                     |                     |
| CIP                  | 0.017                                | 0.015                                | 0.026               | 0.0084              |
| CIP + WMAP           | 0.0075                               | 0.0070                               | 0.0048              | 0.0039              |
| CIP + Planck         | 0.0072                               | 0.0066                               | 0.0021              | 0.0033              |

TABLE VI: Forecasted 1-σ marginalised uncertainties for fiducial $k_{IR} = 1.0 \text{h Mpc}^{-1}, A_{IR} = 0.125 \times 10^{-9}$.

| Survey               | $\sigma_{A_{IR}}$ ($\times 10^{-9}$) | $\sigma_{\beta_{IR}}$ (h Mpc$^{-1}$) | $\sigma_{\alpha_s}$ | $\sigma_{\alpha_x}$ |
|----------------------|--------------------------------------|--------------------------------------|---------------------|---------------------|
| Galaxy Survey        |                                      |                                      |                     |                     |
| CIP                  | 0.031                                | 0.096                                | 0.027               | 0.0096              |
| CIP + WMAP           | 0.023                                | 0.087                                | 0.0046              | 0.0043              |
| CIP + Planck         | 0.022                                | 0.086                                | 0.0020              | 0.0036              |