FORECASTS ON THE DARK ENERGY AND PRIMORDIAL NON-GAUSSIANITY OBSERVATIONS WITH THE TIANLAI CYLINDER ARRAY

YIDONG XU1, XIN WANG2, AND XUELEI CHEN1,3
1 National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
2 Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
3 Center for High Energy Physics, Peking University, Beijing 100871, China
Received 2014 August 11; accepted 2014 October 24; published 2014 December 18

ABSTRACT

The Tianlai experiment is dedicated to the observation of large-scale structures (LSS) by the 21 cm intensity mapping technique. In this paper, we make forecasts concerning its ability to observe or constrain the dark energy parameters and the primordial non-Gaussianity. From the LSS data, one can use the baryon acoustic oscillation (BAO) and growth rate derived from the redshift space distortion (RSD) to measure the dark energy density and equation of state. The primordial non-Gaussianity can be constrained either by looking for scale-dependent bias in the power spectrum, or by using the bispectrum. Here, we consider three cases: the Tianlai cylinder array pathfinder that is currently being built, an upgrade of the Pathfinder Array with more receiver units, and the full-scale Tianlai cylinder array. Using the full-scale Tianlai experiment, we expect $\sigma_{e\nu} \sim 0.082$ and $\sigma_{e\nu} \sim 0.21$ from the BAO and RSD measurements, $\sigma_{\text{local}} \sim 14$ from the power spectrum measurements with scale-dependent bias, and $\sigma_{\text{fNL}} \sim 22$ and $\sigma_{\text{fNL}} \sim 157$ from the bispectrum measurements.

Key words: cosmological parameters – large-scale structure of universe

1. INTRODUCTION

Baryon acoustic oscillations (BAO) are the frozen sound waves that were present in the photon-baryon plasma prior to the recombination epoch, and they imprint features on the cosmic microwave background (CMB) as well as large-scale structures (LSS) in the later universe. The (comoving) characteristic scale of the BAO is determined by the sound horizon at the last scattering surface:

$$s = \int_0^{t_{\text{re}}}(1 + z)dz = \int_{z_{\text{rec}}}^{\infty} \frac{c_s dz}{H(z)},$$

where $c_s$ is the sound speed, $H(z)$ is the Hubble expansion rate, and $t_{\text{re}}$ and $z_{\text{rec}}$ are the recombination time and redshift, respectively. The BAO scale provides a standard ruler to measure the angular diameter distance $D_a(z)$ and the Hubble parameter $H(z)$ (Seo & Eisenstein 2003; Blake & Glazebrook 2003), and hence serves as a promising tool to constrain the properties of dark energy, which determines the expansion rate of the universe. This technique has successfully been used to place cosmological constraints on dark energy parameters from optical surveys (e.g., Anderson et al. 2014).

In addition to observing the cosmic expansion history through the BAO features in the matter power spectrum, a LSS measurement can also provide the structure growth rate $f(z)$ from redshift space distortions (RSDs). The RSD features in the galaxy distribution have also been used to constrain the cosmological parameters and to distinguish dark energy and various modified gravity models (e.g., Guzzo et al. 2008; Wang 2008; Linder 2008; Beutler et al. 2014; Samushia et al. 2014). The BAO and RSD features complement each other, and may also help break the degeneracy in dark energy and modified gravity models.

The LSS in the universe could also be measured through the 21 cm emission from neutral hydrogen (H I) in galaxies, though current radio observations of H I in galaxies, e.g., the ALFALFA survey (Giovanelli et al. 2005), are limited to redshift $z \lesssim 0.2$ at the present time. While some telescopes that are currently being constructed, e.g., FAST (Nan et al. 2000), ASKAP (Johnston et al. 2008; Booth et al. 2009), and MeerKAT (Nan et al. 2000), will have much greater sensitivities, an H I survey of galaxies at high redshift would still be a challenging task. Even for the Square Kilometer Array, with its wide area H I galaxy survey, the power to constrain cosmological parameters is only comparable to the existing optical galaxy surveys (Rawlings et al. 2004; Abdalla et al. 2010).

However, power spectrum constraints on cosmological parameters can be efficiently obtained using dedicated telescopes with lower resolution than galaxy surveys. Instead, one could observe in the intensity mapping mode, in which each pixel or voxel contains many galaxies. Many epoch of reionization experiments are in fact intensity mapping experiments, and the same method can also be used to observe LSS in the redshift range $0 < z < 3$, which is predicted to be more sensitive to cosmological parameters than current galaxy surveys (Chang et al. 2008; Peterson et al. 2009). This method has been tested with existing telescopes such as the Green Bank Telescope and the Parkes telescope, and has detected positive cross-correlation between 21 cm and optical galaxies (Chang et al. 2010; Masui et al. 2013; Switzer et al. 2013). However, the time available on these general purpose telescopes is limited. It has been argued that large cylindrical reflectors can be cheaply made and used in hydrogen survey experiments (Peterson et al. 2006).

In a cylinder array designed for this purpose, a number of cylinder reflectors are fixed on the ground, pointing to the zenith along the north–south direction and in parallel with each other. Receiver feeds are placed along the focus line of each of the cylinders, forming an interferometer array. As the Earth rotates, the array will drift scan the visible sky. For observation of the BAO features in the LSS, which can be used to probe dark energy properties, a cylinder array size of 100–150 m would be optimal (Ansari et al. 2008, 2012; Seo et al. 2010).
The Tianlai project\footnote{http://tianlai.bao.ac.cn. The word Tianlai means “heavenly sound” in Chinese. This phrase first appeared in the work of the ancient Chinese philosopher Chuang Tzu (369BC–286BC).} is an experimental effort in this direction (Chen 2011, 2012). Tentatively, in this paper, we will assume that the full-scale Tianlai experiment will consist of eight adjacent cylinders, each 15 m wide and 120 m long, with a total of about 2000 dual polarization units covering the frequency range of 400–1420 MHz, corresponding to 0 < z < 2.5. We will assume a system temperature of 50 K.

At present, a pathfinder experiment is being built in a radio quiet site at Honglixia, Balikun County, Xinjiang Autonomous Region, China. This pathfinder consists of both a cylinder array and a dish array. The dish array will include 16 steerable 6 m dishes, and will be discussed in a separate paper; here, we will focus on the cylinder array. The cylinder pathfinder array includes three adjacent cylindrical reflectors, each 15 m wide and 40 m long. It will focus on observing at the frequency range of 700–800 MHz. Currently, the pathfinder cylinders have a total of 96 receivers, with an average of 32 on each. With a margin of 5 m on each of the two ends of the cylinder, the distance between the feeds is around 97 cm, which is greater than one wavelength at z = 1 (\(\lambda_{\text{obs}} = 2.1(1 + z)\)) cm. After a period of experiment, we plan to expand the total number of dual polarization receivers to 216, so that on each cylinder there will be on average 72 dual polarization receivers. We will call this the pathfinder+ experiment. Using the pathfinder and pathfinder+ experiments, we hope to demonstrate the feasibility of intensity mapping using the cylinder array before building the full-scale experiment. These configuration parameters for the cylinder pathfinder, pathfinder+, and full-scale experiment are listed in Table 1.

| Cylinders  | Width | Length | Dual Pol. Units/Cylinder | Frequency |
|------------|-------|--------|--------------------------|-----------|
| Pathfinder | 3     | 15 m   | 40 m                     | 32        | 700–800 MHz   |
| Pathfinder+| 3     | 15 m   | 40 m                     | 72        | 700–800 MHz   |
| Full scale | 8     | 15 m   | 120 m                    | 256       | 400–1420 MHz  |

Another potentially interesting application of a 21 cm intensity mapping experiment is to look for and constrain the primordial non-Gaussianity. The primordial density perturbations, which originated during the inflation era and gave rise to the various structures today, link the observable universe to the very early phase of the universe. While the simplest slow-roll inflation model predicts very weak primordial non-Gaussianity in the density perturbations with an amplitude below the detectable level, many other inflation mechanisms could result in observable non-Gaussiansities (see Bartolo et al. 2004; Chen 2010 for reviews). Any observational constraint on the level of the primordial non-Gaussianity can be a powerful probe of the dynamics of inflation.

Various observational approaches, such as the angular bispectrum of the CMB, high-order correlations of the three-dimensional galaxy distribution, the abundance of rare objects, and the large-scale clustering of halos, have been developed to constrain the level of primordial non-Gaussianity, specifically the nonlinearity parameter \(f_{\text{NL}}\) (see Liguori et al. 2010; Verde 2010 for reviews). By combining large-scale clustering measurements from galaxy surveys with their cross-correlations with the CMB from the Wilkinson Microwave Anisotropy Probe (WMAP) with nine year data, Giannantonio et al. (2014) obtained \(-37 < f_{\text{NL}} < 25\) at 95% confidence for the local-type configuration. The latest and tightest constraints on \(f_{\text{NL}}\) come from measurements of the CMB angular bispectrum by Planck, which are \(f_{\text{NL}}^{\text{local}} = 2.7 \pm 5.8\), \(f_{\text{NL}}^{\text{equl}} = -42 \pm 75\), and \(f_{\text{NL}}^{\text{ortho}} = -25 \pm 39\) (68% CL) for the primordial local, equilateral, and orthogonal bispectrum amplitudes, respectively (Planck Collaboration et al. 2014b). Using the large-scale clustering of tracers of dark matter in the later universe, the two most commonly used probes for primordial non-Gaussianity are the scale-dependent bias in the observed power spectrum and the bispectrum.

In this paper, we make simple forecasts concerning the constraining power of the Tianlai experiment under the assumption of perfect foreground removal and no systematics. We will make our forecasts primarily for the full-scale experiment, which is designed to measure the LSS and cosmological parameters. We will also make some forecasts concerning the pathfinder and pathfinder+ experiments, which are only used to test the key technology for the full-scale experiment and are not expected to achieve any good precision.

The paper is organized as follows. In Section 2, we present the signal power spectrum, as well as the detailed formalism for estimating the noise power spectrum for an interferometer array, and we forecast the measurement error of the power spectrum by the Tianlai arrays. Based on the power spectrum measurement, we forecast constraints on the dark energy parameters obtainable from Tianlai BAO and RSD observations in Section 3. In Section 4, we briefly review the imprint of primordial non-Gaussianity on the LSS. In Section 4.1, we study the constraint that can be obtained by considering the scale-dependent bias in the power spectrum, and in Section 4.2 we apply the bispectrum method. We conclude in Section 5.

\[ P_{\text{obs}}(k_{\text{ref}}, k_{\text{int}}) = \frac{D_A(z)^2 D_H(z)}{D_A(z)^2 P_{\text{ref}}(z)} \left( b^{H_0}(z) + f(z) \frac{k^2}{k_{\perp}^2 + k_{\parallel}^2} \right)^2 \]

\[ \times G(z)^2 P_{\text{shot}}(k) + P_{\text{shot}}. \]
Thus the present density and equation of state parameters of dark energy can be constrained by measuring the acoustic peaks on the power spectrum.

The RSD of the power spectrum also provides information on the growth history of the universe. The linear growth rate $f(z)$ affects the observed power spectrum (Equation (2)) through the RSD factor $\beta$, by

$$\beta = f(z)/f_{\text{H}1}(z),$$

and through the linear growth factor $G(z)$, which is related to $f(z)$ by

$$f = \frac{d \ln G(a)}{d \ln a} = -\left(1 + z\right)\frac{d G(z)}{G(z)} \frac{dz}{dz}.$$  

(6)

Since the growth factor $G(z)$ is degenerate with the H1 bias factor, here we focus on the growth rate obtained from the RSD, and will discuss the measurement error on $f(z)$.

The redshift space power spectrum measured from 21 cm intensity mapping could also be used as a test for gravity (Hall et al. 2013; Masui et al. 2010), or provide extra information on dark energy if general relativity is assumed. For dark energy models, the growth rate can be parameterized as $f(z) = \Omega_m^a(z)$ with $\Omega_m^a(z) \approx 0.55$ for the $\Lambda$CDM+GR model. The value of $\alpha$ in other dark energy models with $w$ other than $-1$ does not deviate from $\Omega_m^a(z)$ significantly.

The intensity mapping observation directly measures the 21 cm brightness temperature, and the measured 21 cm power spectrum, $P_\text{int}(k) = \tilde{T}_\text{spec}(k)P_\text{obs}(k)$, is the power spectrum of brightness temperature $\delta T$ due to 21 cm emission, in which the average signal temperature $\tilde{T}_\text{spec}$ has been estimated (Barkana & Loeb 2007; Chang et al. 2008; Seo et al. 2010) to be

$$\tilde{T}_\text{spec} = 190 x_{\text{H}1}(z) \Omega_{\text{H}1,0} h (1 + z)^2 \frac{M}{H_0} \text{mK},$$

(7)

where $x_{\text{H}1}(z)$ is the neutral fraction of hydrogen at redshift $z$ and $\Omega_{\text{H}1,0}$ is the ratio of the hydrogen mass density to the critical density at $z = 0$.

After the completion of cosmic reionization, the H1 gas in the universe was mostly distributed in galaxies hosted by halos. Therefore, we model the H1 bias factors as halo bias factors weighted by the neutral hydrogen mass density hosted by these halos (Gong et al. 2011):

$$b_{\text{H}1}(z) = \frac{\int_{M_{\text{min}}}^{M_{\text{max}}} dM n(M, z) M_{\text{H}1}(M) b_{\text{H}1}(M, z)}{\rho_{\text{H}1}},$$

(8)

for $i = 1$ and 2, where $\rho_{\text{H}1}$ is the mass density of H1 gas, $n(M, z)$ is the halo mass function for which we use Sheth & Tormen’s formalism (Sheth & Tormen 1999), $M_{\text{H}1}(M)$ is the H1 mass in a halo of mass $M$, and $b_{\text{H}1}(M, z)$ and $b_{\text{H}2}(M, z)$ are halo bias parameters. The mass density of H1 clouds is given by

$$\rho_{\text{H}1} = \int_{M_{\text{min}}}^{M_{\text{max}}} dM n(M, z) M_{\text{H}1}(M).$$

(9)

Following Gong et al. (2011), we take $M_{\text{min}} = 10^8 h^{-1} M_\odot$ for halos to retain their neutral gas (Loeb & Barkana 2001), and take $M_{\text{max}} = 10^{13} h^{-1} M_\odot$ for the gas to have sufficient time to cool and form galaxies.

As for the relation between the H1 gas mass $M_{\text{H}1}$ and the host halo mass $M$, we use the fitting result from Gong et al. (2011), which is based on numerical simulation and consistent with observations:

$$M_{\text{H}1}(M) = A \times \left(1 + \frac{M}{c_1}\right)^b \left(1 + \frac{M}{c_2}\right)^d,$$

(10)

for $M > 10^{10} M_\odot$, and $M_{\text{H}1}(M) = X_{\text{H}1}^\text{gal} (q_0/M_\odot) M$ with $X_{\text{H}1}^\text{gal} = 0.15$ for $M \leq 10^{10} M_\odot$. The best-fit parameters are $A = 2.1 \times 10^8$, $c_1 = 1.0 \times 10^{11}$, $c_2 = 4.55 \times 10^{11}$, $b = 2.65$, and $d = -2.64$ for redshift $z = 1$. As the $M_{\text{H}1} - M$ relation does not change much from $z = 1$ to $z = 3$ (Gong et al. 2011), we use fixed values of these parameters throughout our calculation.

The halo bias factors can be obtained from the halo model (see Cooray & Sheth 2002 for a review). The linear and the first nonlinear bias factors of halos are (Scoccimarro et al. 2001; Mo et al. 1997)

$$b_1(M, z) = 1 + \epsilon_1 + E_1,$$

(11)

$$b_2(M, z) = 2(1 + a_2) (\epsilon_1 + E_1) + \epsilon_2 + E_2,$$

(12)

where

$$\epsilon_1 = \frac{q v - 1}{\delta_{\text{nc}}(z)}, \quad \epsilon_2 = \frac{q v}{\delta_{\text{nc}}(z)} \left(\frac{q v - 3}{\delta_{\text{nc}}(z)}\right),$$

(13)

and

$$E_1 = \frac{2p/\delta_{\text{nc}}(z)}{1 + (q v)^2}, \quad E_2 = \frac{1 + 2p}{E_1} + 2\epsilon_1.$$  

(14)

Here, $a_2 = -17/21$, $\nu = \delta_{\text{nc}}(z)/\sigma^2(M)$, and $\delta_{\text{nc}}(z) = 1.686/G(z)$ is the critical overdensity required for spherical collapse at $z$, extrapolated to the present time using linear theory. For Sheth & Tormen’s halo mass function (Sheth & Tormen 1999), $p \approx 0.3$ and $q = 0.707$.

### 2.2. Generalized Noise Power Spectrum

The fundamental observable of a radio interferometer is the visibility, which is the correlation between the outputs of two receivers for a given baseline. For a given sky brightness distribution $I(\hat{n}, \nu)$, where $\hat{n}$ and $\nu$ are the sky position and the observing frequency, respectively, the corresponding visibility, in units of flux density, can be written as the Fourier transform of the sky brightness weighted by the beam pattern $A(\hat{n})$ of the two receivers:

$$V_{\alpha\beta}(\nu) = \int d^2\hat{n} e^{-i2\hat{n} \cdot \hat{u}_{\alpha\beta}} A_{\alpha}(\hat{n}, \nu) A^*_{\beta}(\hat{n}, \nu) I(\hat{n}, \nu),$$

(15)

where $A_{\alpha\beta}$ denotes the baseline vector in units of wavelength. Here, in the second equality, we have used the flat-sky approximation, and $\hat{u}_{\alpha\beta}$ is the component of $u_{\alpha\beta}$ perpendicular to the line of sight. In a large-scale survey like Tienlai, the flat-sky assumption will certainly break down, and so a full-sky representation based on the spherical harmonic expansion has been developed (Shaw et al. 2014). Here, we use the flat-sky approximation and Fourier expansion, as it is still sufficient for forecasting.

For radio interferometers, it is convenient to define the equivalent visibility in units of brightness temperature, using the Rayleigh–Jeans approximation, so that

$$V_{\alpha\beta}(\nu) = \int d^2\hat{n} e^{-i2\hat{n} \cdot \hat{u}_{\alpha\beta}} A_{\alpha}(\hat{n}, \nu) A^*_{\beta}(\hat{n}, \nu) \delta T_\nu(\hat{n}, \nu).$$

(16)
The thermal noise of the measurement can be written as
\[ \delta V_{a\beta,[K\text{MHz}]}(u_\perp, u_t) = \frac{\lambda^2 T_{\text{sys}}}{A_e \Delta v t_u}, \] (17)
where \( \Delta v \) is the observed full bandwidth, \( t_u \) is the integration time of this baseline, \( T_{\text{sys}} \) is the system temperature per polarization (we assume \( T_{\text{sys}} = 50 \text{ K} \) in this paper), and \( A_e \) is the effective collecting area of each element. We can make a further Fourier transform of the visibility with respect to \( v \), to obtain the so-called visibility delay spectrum (Parsons et al. 2012),
\[ V_{a\beta,[K\text{MHz}]}(u_\perp, u_t) = \int dv e^{-i 2\pi v t_u} V_{a\beta,[K]}(u_\perp, v). \] (18)
Now the three-dimensional vector \( u \equiv \{u_\perp, u_t\} \) is the Fourier conjugate of the sky position vector \( \theta = \{\tilde{n}, v\} \). The thermal noise in this representation is then (Morales 2005)
\[ \Delta T_N(u) = \frac{T_{\text{sys}}}{\sqrt{\Delta v t_u}} \left( \frac{\lambda^2 \Delta v}{A_e} \right). \] (19)
Here, the factor \( \lambda^2 \Delta v / A_e \) represents the Fourier space resolution of the observation, in the sense that any two vectors within it will be highly correlated.

For the extraction of cosmological information, we are interested in the correlation function of the visibilities measured at the discrete baselines \( u_i \) and \( u_j \). If we neglect the correlation of thermal noise errors between measurements, then the noise covariance matrix for visibilities is approximately diagonal, and can be written as (McQuinn et al. 2006; Bharadwaj & Pandey 2003)
\[ C_N(u_i, u_j) = \langle \Delta T_N(u_i) \Delta T_N^\ast(u_j) \rangle = \left( \frac{\lambda^2 T_{\text{sys}} \Delta v}{A_e} \right)^2 \delta_{ij} \frac{\Delta v}{t_u}. \] (20)
The integration time for the baseline \( u \) can be written as
\[ t_u = \frac{A_e}{\lambda^2} n(u_\perp) t_{\text{int}}, \] (21)
where \( n(u_\perp) \) is the baseline number density of the interferometer in the \( u-v \) plane, and \( A_e / \lambda^2 \approx \delta u \delta v \) is the \( u-v \) space resolution. For an observation with a survey area of \( \Omega_{\text{map}} \) larger than the field of view \( \Omega_{\text{FOV}} \) and uniform survey coverage, the integration time of each pointing \( t_{\text{int}} = t_{\text{tot}}(\Omega_{\text{FOV}} / \Omega_{\text{map}}) \).

The sample variance contribution to the covariance matrix is (McQuinn et al. 2006)
\[ C_{SV}(u_i, u_j) = \langle \delta T_N(u_i) \delta T_N^\ast(u_j) \rangle \approx \delta_{ij} \int d^3 u |R(u_i-u)|^2 P_{\Delta T}(u) \approx \delta_{ij} \frac{\lambda^2 \Delta v^2}{r_s^2(z) \Delta r(z) A_e} P_{\Delta T}(k_i \perp, k_i \perp), \] (22)
where \( P_{\Delta T} \) is the 21 cm signal power spectrum. Here, \( R(u_i-u) \) is the response function for a given baseline \( u_i \), which is defined as the Fourier transform of the primary beam \( A_a(\tilde{n}, v) \Lambda_p^2(\tilde{n}, v) \) in Equation (15). The Kronecker \( \delta_{ij} \) arises due to the choice of a pixel size that is approximately the same as the support of function \( R(u) \). The integration of \( |R|^2 \) then introduces a factor that approximately equalizes the inverse of the Fourier space resolution, \( \lambda^2 \Delta v / A_e \), due to the normalization of \( R(u) \). Here, \( \Delta r = y(z) \Delta v \) is the spatial resolution corresponding to the bandwidth \( \Delta v \). The comoving angular diameter distance \( r_s(z) \) and the factor \( y(z) = \lambda z (1 + z)^2 / H(z) \) are used to convert the power spectrum from \( u \) space to the comoving \( k \) space:
\[ u_\perp = \frac{r_s(z) k_\perp}{2\pi}, \quad u_\parallel = \frac{y(z) k_\parallel}{2\pi}. \] (23)

Given the total covariance matrix \( C = C_N + C_{SV} \), one could then estimate the measurement uncertainty of the bandpower from the Fisher matrix
\[ F_{ab} = \text{Tr} \left( C^{-1} \frac{\partial C}{\partial P_a} C^{-1} \frac{\partial C}{\partial P_b} \right), \] (24)
where the parameter \( P_a \) is the bandpower \( P_a = P_{\Delta T}(k_a) \). For diagonal \( C \), the measurement error \( \delta P_{\Delta T} \) is
\[ \delta P_{\Delta T}(k_i) = \frac{1}{\sqrt{N_i(k_i)}} \frac{A_e^2 \Delta r}{\lambda^2 \Delta v^2} \left[ C_N(k_i, k_i) + C_{SV}(k_i, k_i) \right] \]
\[ = \frac{1}{\sqrt{N_i(k_i)}} \left[ P_N(k_i) + P_{SV}(k_i) \right], \] (25)
where the number of modes \( N_i(k) = k_\perp d k_\perp d k_\parallel V / (2\pi)^2 \), with \( V \) being the survey volume. Here we have denoted the signal power spectrum in the sample variance term as the sample variance power spectrum, i.e., \( P_{SV}(k_i) = P_{\Delta T}(k_i) \), and the noise power spectrum \( P_N(k) \) is
\[ P_N(k, z) = \frac{4\pi f_{\text{sky}} \lambda^2 T_{\text{sys}} y(z) r_s(z)^2}{A_e \Omega_{\text{map}} / 4\pi} \left( \frac{\lambda^2}{A_e n(k_\perp)} \right), \] (26)
where \( f_{\text{sky}} \) is the fraction of the sky coverage, i.e., \( f_{\text{sky}} = \Omega_{\text{map}} / 4\pi \), and \( \Omega_{\text{FOV}} \) is the field of view of a single pointing.

2.3. Tianlai Noise Power Spectra

We first calculate the baseline distribution function \( n(u_\perp) \) of the interferometer. In a real interferometer, for a pair of antennae with separation \( u \), the output is actually the average of the visibility on a region of the \( u-v \) plane centered at \( u \). Instead of the discrete histogram, therefore, we incorporate the response function of an antenna pair \( R(u) \) (Ansari et al. 2012) and derive a continuous function \( n(u_\perp) \) with the caveat that only \( n(u_\perp) A_e / \lambda^2 \) is physically meaningful in this formalism. For the Tianlai cylinder array with receivers fenced along the focal lines of the cylinders, the pair response pattern of a cylinder can be approximated as a two-dimensional triangular function with rectangular support (Thompson et al. 2001; Ansari et al. 2008, 2012), which is set by the cylinder width \( W \) in the east–west direction, \( \Delta u_W = W / \lambda \), and the feed length \( L \) in the north–south direction, \( \Delta u_L = L / \lambda \):
\[ R(u_\perp) = \left( \frac{\lambda^2}{A_e} \right) \Lambda \left( \frac{u_L}{\Delta u_L} \right) \Lambda \left( \frac{u_W}{\Delta u_W} \right). \] (27)
Here, the triangular function \( \Lambda(x) \) is defined as \( 1 - |x| \) for \( |x| < 1 \), and 0 otherwise. The baseline number density \( n(u_\perp) \) could be obtained simply by summing up \( R(u) \) for all of the baselines, i.e.,
\[ n(u_\perp) = \sum_i R(u_\perp - u_i^\perp). \] (28)
The baseline number density \(n(b)\) is normalized so that the half-plane integral would give a total baseline number of \(n_b = n_\text{r}(n_\text{r} - 1)/2\), where \(n_\text{r}\) is the total number of receivers.

In the left panel of Figure 1, we plot the baseline distribution \(n(r)\) of the different configurations of Tianlai. Besides the baseline distance \(r\) in the interferometer frame, we also show on the upper abscissa the cosmological scales that the array could significantly improve. Baselines are increased, and therefore the sensitivity will be improved.

The right panel of Figure 1, we plot the measurement error on the power spectrum due to thermal noise, \(P^T(k) = P^N(k)/\sqrt{N_c(k)}\) (solid lines), and that from sample variance, \(P^{SV}(k) = P^{SV}(k)/\sqrt{N_c(k)}\) (dashed lines). The case for Tianlai pathfinder+ is shown as the magenta lines, while the cases for full-scale Tianlai at various frequencies are shown as other colors. The 21 cm signal power spectra, \(P_{21}(k)\), at corresponding redshifts are shown by dotted lines with corresponding colors, assuming a constant H\(_\text{i}\) fraction \(\xi_{\text{HI}} = 0.008\) at all redshifts. Here we adopt a wavenumber bin width of \(\Delta k = 0.005\, \text{hMpc}^{-1}\) and \(\Delta z = 0.2\).

### 2.4. The Power Spectrum with Expected Tianlai Errors

As discussed in Section 2.2, the measurement error of the power spectrum is a sum of the sampling error and thermal noise. Since the measured 21 cm power spectrum is proportional to the H\(_\text{i}\) power spectrum by a factor of \(T^2_{\text{sig}}\), we use the measurement error on the H\(_\text{i}\) power spectrum for the Fisher forecasts in the following sections:

\[
\Delta P_{\text{obs}}(k) = \frac{1}{\sqrt{N_c}} \left[ P_{\text{obs}}(k) + N(k) \right],
\]

where \(N(k)\) is related to the thermal noise power by \(P^N = T^2_{\text{sig}} N(k)\), and \(N_c\) is the number of independent modes in that pixel in Fourier space, as discussed in Section 2.2.

The instantaneous field of view of a cylindrical radio telescope is narrow in right ascension but very broad in declination, limited primarily by the illumination angle of the feeds. The rotation of the Earth results in a broad coverage in right ascension. The illumination angle of the feeds of Tianlai is about 120°. Assuming a latitude of \(\theta_{\text{lat}} = 44°\), the Tianlai array covers the declination angle from −16° to 90°. Considering the masking effects in order to avoid the disk area of the Milky Way and bright radio sources, we conservatively assume a survey area of 10,000 deg\(^2\) throughout.

The left panel of Figure 2 shows the power spectrum at \(z = 1\) with measurement errors expected from the Tianlai pathfinder (shaded area) and the pathfinder+ (error bars), while the right panel shows the relative power spectrum with respect to the smooth power spectrum with errors expected from the Tianlai pathfinder+ (shaded area) and the full-scale Tianlai (error bars), respectively. The integration time is assumed to be one year. Note that the error bar for \(P(k)\) depends on the binning of \(k\). Here, we have chosen a bin width of \(\Delta k = 0.005\, \text{hMpc}^{-1}\). If a different bin width is chosen, then the error bar on power...
spectrum can be obtained by scaling, but the constraints on our interested parameters are insensitive to the choice of binning.

3. FISHER FORECAST ON THE CONSTRAINT ON DARK ENERGY

From the power spectrum measurement at a given redshift, the Fisher information matrix can be written as (Tegmark 1997; Seo & Eisenstein 2003; Mao et al. 2008)

$$ F_{\alpha \beta} = \sum_k \left[ \frac{\partial P_{\text{obs}}(k)}{\partial \alpha} \frac{\partial P_{\text{obs}}(k)}{\partial \beta} \right] / [\Delta P_{\text{obs}}(k)]^2. $$

(30)

Here, the free parameters $\alpha$ and $\beta$ are taken from $\{D_A(z_i), H(z_i), h_{1,i}, f(z_i), P_{\text{shot,i}}\}$ for each redshift bin $z_i$. The nuisance parameters in the model $\{h_{1,i}, P_{\text{shot,i}}\}$ can be marginalized by selecting the submatrix of $F^{-1}_{\alpha \beta}$ with only the appropriate columns and rows. We can then derive the measurement errors on the expansion and structure growth history parameters.

For the Tianlai pathfinder and pathfinder+ experiment, the observation frequency range is 700–800 MHz, and we divide this frequency band into three bins with equal bandwidth and obtain estimates of measurement errors for the corresponding redshift bins. For the planned full-scale Tianlai experiment, the frequency range of 400–1420 MHz is equally divided into eight bins; the bin size in this latter case is larger than in the pathfinder case, but the bin size $\Delta z$ does not really matter in the end.

We plot the measurement errors on the angular diameter distance $D_A(z_i)$, the Hubble expansion rate $H(z_i)$, and the growth rate $f(z_i)$ in the left, central, and right panels of Figure 3, respectively, for the pathfinder+ (blue error bars) and the full-scale Tianlai experiments (red error bars). The integration time is assumed to be one year in all cases. We see that the pathfinder+ experiment can obtain a useful measurement on $D_A(z)$ and $H(z)$ at $z = 1$. For the growth rate $f$, the errors are larger, but we could still obtain a useful check against certain modified gravity models. The full-scale experiment can offer good precision throughout the interested parameter ranges.

From the cosmographic measurements $D_A(z), H(z), f(z)$, one can constrain the cosmological model parameters. In this paper, we consider a redshift-dependent equation of state for the dark energy parameterized in the form of (Chevallier & Polarski 2001)

$$ w(z) = w_0 + w_a[1 - a(z)] = w_0 + w_a \frac{z}{1 + z}. $$

(31)

The Fisher matrix of the dark energy parameters $w_0$ and $w_a$ is obtained by converting from the parameter space $\{p_a\} = \{D_A, H, f_i\}$ to the dark energy parameter space $\{q_a\} = \{w_0, w_a, \Omega_X\}$, using

$$ F^{DE}_{mn} = \sum_{a,\beta} \frac{\partial p_a}{\partial q_m} F^{-1}_{\alpha \beta} \frac{\partial p_\beta}{\partial q_a}. $$

(32)

To help break the parameter degeneracy between parameters, we combine the BAO data from the Tianlai intensity mapping observation with the data obtained from CMB observations. The total Fisher matrix is given by (Wang et al. 2009)

$$ F^{\text{tot}}_{\alpha \beta} = F^{\text{CMB}}_{\alpha \beta} + \sum_i F^{\text{IM}}_{\alpha \beta}(z_i), $$

(33)

where $F^{\text{IM}}_{\alpha \beta}(z_i)$ is the Fisher matrix derived from the $i$th redshift bin of the LSS intensity mapping and $F^{\text{CMB}}_{\alpha \beta}$ is the CMB Fisher matrix.

The 1$\sigma$ and 2$\sigma$ measurement error contours for the variable dark energy equation of state parameters $w_0$ and $w_a$ are shown in Figure 4 for the full-scale Tianlai experiment. Here, we have assumed that the frequency range probed is 400–1420 MHz, the usable survey area is 10,000 deg$^2$, and the integration time is one year. The measurement error is obtained based on a joint constraint with the CMB data, but no other observational data. We expect $\sigma_{w_0} \approx 0.0815$ and $\sigma_{w_a} \approx 0.210$. This is comparable

Figure 2. Left panel: the measurement errors on the power spectrum at $z = 1$ for the Tianlai pathfinder (shaded area) and the pathfinder+ (error bars). Right panel: the relative one with respect to the smooth power spectrum with errors expected from the Tianlai pathfinder+ (shaded area) and the full-scale Tianlai (error bars). The assumed survey area is 10,000 deg$^2$, and the integration time is one year. The wavenumber bin width for this plot is $\Delta k = 0.005$ h Mpc$^{-1}$. 
4. FISHER FORECASTS FOR THE PRIMORDIAL NON-GAUSSIANITY

Typical single-field slow roll inflation models predict that the primordial density fluctuations follow the Gaussian distribution, though the density distribution deviates from Gaussianity as the structures grow and nonlinearities appear. Detection of or constraint on the primordial non-Gaussianity will provide invaluable information concerning the origin of the universe.

Compared with the observable galaxies that correspond to high-density peaks of the matter density distribution, the neutral hydrogen gas that exists in galaxies of almost all mass scales is a less biased tracer of the underlying matter density, allowing the primordial non-Gaussianity to be investigated from a different perspective.

The non-Gaussianity of the primordial density fluctuations can induce a scale-dependent and redshift-dependent $H_\text{I}$ bias, similar to other biased tracers (Dalal et al. 2008; Matarrese & Verde 2008). This effect can be used to constrain the primordial non-Gaussianity. Camera et al. (2013) has demonstrated that a small but compact array working at $\sim 400 \text{ MHz}$ could possibly place tight constraints on $f_{NL}$ with an error close to $\sigma_{f_{NL}} \sim 1$. We will make a forecast for determining such constraints with the Tianlai experiment.

Once the LSS of the 21 cm brightness temperature fluctuations are mapped out, this same set of data can also be used to measure the bispectrum of $H_\text{I}$ gas distribution. The $H_\text{I}$ bispectrum consists of contributions from primordial non-Gaussianity, the nonlinear gravity evolution, and the nonlinear $H_\text{I}$ bias. The relative importance of primordial non-Gaussianity increases toward higher redshifts (Sefusatti & Komatsu 2007; Jeong & Komatsu 2009). The 21 cm experiment can in principle observe the LSS at relatively high redshifts from the ground without being affected significantly by the atmosphere, which is an advantage of this method, though at present 21 cm observations are still limited to lower redshifts than for optical observations. Using the 21 cm bispectrum from the dark ages, Pillepich et al. (2007) found that very low frequency radio observations with high angular resolution could potentially detect primordial non-Gaussianity with $f_{NL} \sim 1$. Here, we focus on the $H_\text{I}$ bispectrum after reionization and assess the constraining power of the 21 cm bispectrum measured by the Tianlai experiment.

4.1. Constraints on $f_{NL}$ from the $H_\text{I}$ Power Spectrum

The non-Gaussianity in the primordial density fluctuations can result in a scale-dependence in the halo bias, which originates from coupling between large- and small-scale modes (Dalal et al. 2008; Matarrese & Verde 2008). For the standard local-type primordial non-Gaussianity, the scale-dependent non-Gaussian correction to the linear halo bias, to leading order, is (see, e.g., Desjacques et al. 2011; Adshade et al. 2012; D’Aloisio et al. 2013)

$$\Delta b^d(k, z) = \frac{2 f_{NL} (b^G - 1) \delta_c}{M(k, z)},$$

(34)

where $b^G$ is the linear halo bias for the Gaussian density field, $\delta_c = 1.686$ is the critical overdensity for spherical collapse, and $M(k, z)$ relates the density fluctuations in Fourier space, $\delta_k$, to the primordial curvature perturbation, $\Phi_k$, via the Poisson equation:

$$\delta_k(z) = M(k, z) \Phi_k,$$

(35)
The Astrophysical Journal

The power spectrum of the density fluctuations of H I gas is

\[ P_\text{HI}(k,z) = \left[ b_{\text{HI}}^3(k,z) \right] P_\text{L}(k,z), \]

where \( b_{\text{HI}}^3 \) is related to the corrected linear halo bias via the model described in Section 2.1. The observed power spectrum in redshift space after averaging over angles in \( k \) space is (Peacock 1997)

\[ P_\text{k}(k,z) = a^R_\beta(\beta) P_{\text{HI}}(k,z), \]

where \( a^R_\beta(\beta) = 1 + (2/3)\beta + (1/5)\beta^2 \) with \( \beta = \Omega_m^{0.55}(z)/b_{\text{HI}}^3 \).

We apply the same Fisher matrix as Equation (30), but here we take \( f_{NL} \) as the single parameter and fix all of the other cosmological parameters.

When information from all of the available wavenumbers in the Fisher matrix, \( k_{\text{max}} \), is limited by the Nyquist frequency, \( k_{\text{Nyq}} = \pi/\text{resolution} \), which arises from the non-zero beam size of the cylinder array (Seo et al. 2010), as well as by the nonlinear wavenumber cutoff, \( k_{\text{nonl}} \), above which the linear power spectra are not accurate. Here, we adopt conservative values for \( k_{\text{nonl}} \) by requiring \( \sigma(R = \pi/2k_{\text{nonl}}; z) = 0.5 \) at each redshift bin (Seo & Eisenstein 2003). Therefore, \( k_{\text{max}} = \text{MIN}[k_{\text{Nyq}}, k_{\text{nonl}}] \). Effectively, \( k_{\text{max}} \) is limited by the Nyquist wavenumber for the local model and the full-scale Tianlai, \( k_{\text{max}} \) is mostly set by the nonlinear cutoff, except for the highest redshift bin. On the other hand, \( k_{\text{min}} \) is set by the scale defined by the size of each redshift bin.

Using the same survey parameters and redshift bins as in Section 3, we find that the constraint on the nonlinear parameter \( f_{NL} \) for the local model is quite weak for the field model and the full-scale Tianlai experiment. With the full-scale Tianlai experiment, we can achieve \( \sigma_{f_{NL}} \sim 14 \). The exact numbers of the predicted 1σ errors for Tianlai pathfinders and for the full-scale Tianlai are listed in Table 2.

4.2. Constraints on \( f_{NL} \) from the H I Bispectrum

On large scales, the matter bispectrum is well described by the tree-level expression and the loop corrections remain very small (Tasinato et al. 2013; Gong & Takahashi 2014). Higher-order terms such as the trispectrum could contribute significantly to the bispectrum of high-density peaks (Sefusatti & Komatsu 2009; Jeong & Komatsu 2009), but as the H I gas is much less biased than observable galaxies—for the Tianlai experiment, the H I bias is not far from one—we expect such contribution to be less significant, though the exact amount cannot be obtained without going through lengthy calculations. Here, we neglect the higher-order terms and account only for the tree-level matter bispectrum, and we reserve the investigation of the contribution from matter trispectrum to the H I bispectrum to future works. If such a contribution is significant, then it would increase the H I bispectrum and we would obtain a stronger constraint on \( f_{NL} \); therefore, our current estimate may be regarded as a relatively conservative one.

Since we are interested in predicting the constraining power of H I bispectrum observations on the primordial non-Gaussianity, i.e., the parameter \( f_{NL} \), in the following, we will focus on the reduced H I bispectrum, \( Q_{\text{HI}} \), which is much less sensitive to other cosmological parameters (Sefusatti & Komatsu 2007). In the real experiments, we always measure the 21 cm brightness temperature in redshift space. Similar to the tree-level expression for the observed galaxy bispectrum (Sefusatti & Komatsu 2007), the reduced H I bispectrum in redshift space after averaging over angles in \( k \) space is

\[ Q_{\text{k}}(k_1, k_2, k_3) = \frac{a^R_\beta(\beta)}{a^R_\beta(0)^2} \left[ \frac{1}{b_{\text{HI}}^3} Q_{\text{tree}}^{\text{k}}(k_1, k_2, k_3) + \frac{b_{\text{HI}}^3}{(0)^2} \right], \]

where \( a^R_\beta(\beta) = 1 + (2/3)\beta + (1/9)\beta^2 \) converts the bispectrum from real space to redshift space, and \( Q_{\text{tree}}^{\text{k}} \) is the reduced tree-level bispectrum of underlying matter. The first term includes the contributions from primordial non-Gaussianity and nonlinear gravitational evolution, and the second term represents the contribution from the nonlinear bias of H I gas.

The reduced matter bispectrum can be written as the sum of two contributions:

\[ Q_{\text{tree}}^{\text{k}}(k_1, k_2, k_3) = Q_{\text{L}}(k_1, k_2, k_3) + Q_{\text{G}}(k_1, k_2, k_3) \]

\[ = \frac{B_{\text{L}}(k_1, k_2, k_3)}{B_{\text{L}}(k_1, k_2, k_3) + (2 \text{ perm.})} + \frac{B_{\text{G}}(k_1, k_2, k_3)}{B_{\text{L}}(k_1, k_2, k_3) + (2 \text{ perm.})}. \]

where \( + (n \text{ perm.}) \) stands for the sum of \( n \) additional terms permuting \( k_1, k_2, \) and \( k_3 \). The matter bispectrum due to gravity alone, \( B_{\text{G}} \), is given by the second-order perturbation theory (Fry 1984; Bernardeau et al. 2002), and the matter bispectrum contributed from primordial non-Gaussianity, \( B_{\text{L}} \), is related to the bispectrum of curvature perturbations, \( B_{\Phi} \), by

\[ B_{\Phi}(k_1, k_2, k_3) = \mathcal{M}(k_1; z) \mathcal{M}(k_2; z) \mathcal{M}(k_3; z) \]

\[ B_{\Phi}(k_1, k_2, k_3). \]

We consider two models of primordial non-Gaussianity here, i.e., the local model and the equilateral model, but the same forecast can also be applied to other models of interest. The local model is physically motivated, in this case the contributions from the squeezed triangular configurations dominate. The leading contribution to the \( f_{NL} \) expansion of the bispectrum of the curvature perturbation is

\[ B_{\Phi}(k_1, k_2, k_3) \simeq 2 f_{NL} \mathcal{A}_{\Phi} \left[ \frac{1}{k_1^{4-n} k_2^{4-n} k_3^{4-n}} + (2 \text{ perm.}) \right], \]

where \( \mathcal{A}_{\Phi} \equiv P_{\Phi}/k^{n-4}, \) and \( P_{\Phi}(k) \) is the curvature power spectrum. The equilateral model is a good approximation to...
the higher derivative models (Creminelli 2003) and the DBI inflationary model (Alishahiha et al. 2004). The bispectrum of the curvature perturbation for the equilateral model is

\[
B_{\phi}^{\text{equil}} = 6 f_{\text{NL}} \Delta \phi \left[ -\frac{1}{k_1^{4-n} k_2^{4-n} k_3^{4-n}} + \frac{2}{(k_1 k_2 k_3)^{24-n}/3} + (5 \text{ perm.}) \right].
\]

(42)

Following Scoccimarro et al. (1998), a bispectrum estimator for a cubic survey volume of \( V \) can be defined as

\[
\hat{B}(k_1, k_2, k_3) \equiv \frac{V_t}{V_B(k_1, k_2, k_3)} \int d^3 q_1 \int d^3 q_2 \int d^3 q_3 \delta_D(q_1 + q_2 + q_3) \delta(q_1) \delta(q_2) \delta(q_3),
\]

(43)

where \( V_t \equiv (2\pi)^3 / V \) is the elemental volume in \( k \) space of the observation cells, and each integration is over the range \([k_1 - \Delta k, k_1 + \Delta k / 2]\) centered on \( k_1 \), with \( \Delta k \) equal to a multiple of \( k_t \). Here, \( \delta_D(q_1 + q_2 + q_3) \) is the Dirac delta function which ensures that the vectors \( q_1, q_2, \) and \( q_3 \) form a triangle, while \( V_B(k_1, k_2, k_3) \) is the normalization factor given by

\[
V_B \equiv \int d^3 q_1 \int d^3 q_2 \int d^3 q_3 \delta_D(q_1 + q_2 + q_3) \simeq 8\pi^2 k_1 k_2 k_3 \Delta k_1 \Delta k_2 \Delta k_3.
\]

(44)

In the following, we assume \( \Delta k = k_t \) so as to take into account all “fundamental” triangular configurations.

To leading order, the variance of this estimator is (Scoccimarro et al. 1998)

\[
\Delta B_{\phi}^2(k_1, k_2, k_3) \simeq (2\pi)^3 V_t \frac{s_{123}}{V_B} P_{\text{tot}}(k_1) P_{\text{tot}}(k_2) P_{\text{tot}}(k_3),
\]

(45)

where \( s_{123} = 6, 2, 1 \), respectively, for equilateral, isoceles, and general triangles, and \( P_{\text{tot}}(k) \) is the total measured power spectrum including the redshift space \( H \) power spectrum, \( P_s(k) = d^3 n(k) P_{\text{H}}(k) \), and the noise power spectrum \( N(k) \).

The Fisher matrix for observations of reduced bispectrum at a given redshift bin can be written as

\[
F_{\alpha\beta} = \sum_{k_1 = k_{\min}}^{k_{\max}} \sum_{k_2 = k_{\min}}^{k_{\max}} \sum_{k_3 = k_{\min}}^{k_{\max}} \frac{\partial Q_1}{\partial \alpha} \frac{\partial Q_1}{\partial \beta} \frac{1}{\Delta Q_1^2},
\]

(46)

where \( \Delta Q_1^2 \) is the variance of the reduced H1 bispectrum measured in redshift space, and \( \alpha \) and \( \beta \) represent the parameters we are interested in, i.e., \( f_{\text{NL}} \), and \( b_1^H(z_t) \) and \( b_2^H(z_t) \) for each redshift bin \( z_t \) of the survey. The three sums are over all of the combinations of \( k_1, k_2, \) and \( k_3 \) that form triangles, in steps of \( \Delta k \), with \( k_{\max} = \max(k_{\min}, |k_1 - k_2|) \). In each redshift bin, we divide the survey volume into cubes and \( k_{\min} \) is still set by the Nyquist frequency or the smallest scale at which we can trust our model for the H1 bispectrum. Here, we assume that the tree-level bispectrum breaks down below the nonlinear scale cutoff, so that \( k_{\max} = \text{Min}[k_{\text{Nyq}}, k_{\text{min}}] \). If we assume that the variance of the H1 bispectrum \( \Delta B_{\phi} \) dominates over the variance of the H1 power spectrum \( \Delta P_s \), then the variance of the reduced H1 bispectrum in redshift space can be written as (Sefusatti & Komatsu 2007)

\[
\Delta Q_1^2(k_1, k_2, k_3) \simeq \frac{\Delta B_{\phi}^2(k_1, k_2, k_3)}{(P_s(k_1) P_s(k_2) + (2 \text{ perm.}))^2}
\]

(47)

with \( \Delta B_{\phi}^2 \) given by Equation (45).

We assume the fiducial values of \( f_{\text{NL}} \) bias parameters as given in Section 2.1, and take the fiducial value of \( f_{\text{NL}} = 0 \) for both the local and equilateral models. Assuming one year’s integration time and a total survey area of 10,000 deg², the marginalized 1σ errors on \( f_{\text{NL}}^{\text{local}} \) and \( f_{\text{NL}}^{\text{equil}} \) are listed in Table 3. Again, we find that the pathfinder and pathfinder+ data are insufficient to provide much constraint to the bispectrum, due to the large error in its measurement. With the full-scale Tianlai experiment, we could achieve \( \sigma_{f_{\text{NL}}} \sim 22 \) for the local model and \( \sigma_{f_{\text{NL}}} \sim 157 \) for the equilateral model.

### 5. Conclusions

In this work, we assess the ability of the Tianlai experiments to constrain various cosmological parameters, specifically the dark energy equation of state and the level of primordial non-Gaussianity. We use the Fisher information matrix method, which is widely used for making such predictions. We have compared our results with other predictions of 21 cm intensity mapping experiments (Chang et al. 2008; Ansari et al. 2008; Seo et al. 2010; Ansari et al. 2012; Alonso et al. 2014), and found that they generally yield similar results when the same conditions are assumed.

Currently, our plan is to first test the principle and key technologies with a smaller-scale pathfinder experiment and then upgrade to the pathfinder+ experiment, before eventually building the full-scale Tianlai experiment. The goal of the pathfinders is to test the technologies and feasibility of H1 intensity mapping observations with cylinder arrays, and as shown in this work, we expect to be able to measure the H1 power spectrum with the pathfinders, but the constraints that could be obtained on cosmological parameters would be fairly weak.

The full-scale Tianlai experiment will significantly tighten the constraints by adding the number of receivers, thereby increasing the effective collecting area of the cylinders, and by expanding the scale of the cylinders, thereby increasing the spatial resolution. Assuming an integration time of one year and a survey area of 10,000 deg², we expect \( \sigma_{w_L} \sim 0.082 \) and \( \sigma_{w_R} \sim 0.21 \) from the BAO and RSD measurements. This is comparable to the expected precision from stage IV dark energy experiments as defined by the DETF report (Albrecht et al. 2006), while the cost would only be a small fraction of such experiments.

| Table 3 | The Marginalized 1σ Errors of \( f_{\text{NL}} \) Using the H1 Bispectrum Measured by Tianlai |
|----------|--------------------------------------------------|
| \( N_{\text{tot}} \) per cylinder | Pathfinder | Pathfinder+ | Full Scale |
| \( \sigma_{f_{\text{NL}}}^{\text{local}} \) | 70814 | 2272 | 21.7 |
| \( \sigma_{f_{\text{NL}}}^{\text{equil}} \) | 79427 | 2754 | 157 |
The primordial non-Gaussianity can be constrained by looking for a scale-dependent bias of the power spectrum, or through bispectrum measurement. We find $\sigma_{f_{\text{NL}}}^{\text{local}} \sim 14$ from the power spectrum measurements with scale-dependent bias, and $\sigma_{f_{\text{NL}}}^{\text{equil}} \sim 22$ and $\sigma_{f_{\text{NL}}}^{\text{local}} \sim 157$ from the bispectrum measurements. The constraints on primordial non-Gaussianity from LSS observations including this one are generally weaker than from high-precision CMB observations, but they probe different scales, so it is still very important to conduct such observations.

In making these forecasts, we have assumed that the foregrounds can be effectively removed, and that their residuals only affect the overall system temperature. In fact, due to the complicated system responses and our imperfect knowledge from calibration, the foreground removal will not be as effective, and the foreground may also introduce non-Gaussian features that could potentially contaminate the measurement of the primordial non-Gaussianity. These problems may degrade the measurement precision (Ansari et al. 2012). Therefore, the results presented here should be regarded as an ideal case. We plan to make more detailed simulations to assess the effects of calibration and foreground subtraction on the measurement process for the Tianlai experiments in the near future.

We thank Fengqun Wu, Yi Mao, Hong Guo, Junqing Xia, and Kwan Chuen Chan for many helpful discussions. This work is supported by the MoST 863 program grant 2012A112701, the NSFC grants 11137302 and 11303034, and the CAS Strategic Priority Research Program “The Emergence of Cosmological Structures” grant No. XDB09000000.