Cosmological Constraints from Line Intensity Mapping with Interlopers

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Abstract

Understanding the formation and evolution of the universe is crucial for cosmological studies, and line intensity mapping provides a powerful tool for this kind of study. We propose to make use of multipole moments of a redshift-space line intensity power spectrum to constrain the cosmological and astrophysical parameters, such as the equation of state of dark energy, massive neutrinos, primordial non-Gaussianity, and star formation rate density. As an example, we generate mock data of multipole power spectra for Hα 6563 Å, [O III] 5007 Å, and [O II] 3727 Å measured by the SPHEREx experiment at $z = 1$ considering contaminations from interloper lines, and use the Markov Chain Monte Carlo method to constrain the parameters in the model. We find a good fitting result of the parameters compared to their fiducial values, which means that the multipole power spectrum can effectively distinguish signal and interloper lines, and break the degeneracies between parameters, such as line mean intensity and bias. We also explore the cross-power spectrum with the Chinese Space Station Telescope spectroscopic galaxy survey in the constraints. Since more accurate fitting results can be obtained by including measurements of the emission lines at higher redshifts out to at least $z = 3$, and cross-correlations between emission lines can be involved, line intensity mapping is expected to offer excellent results in future cosmological and astrophysical studies.

Unified Astronomy Thesaurus concepts: Cosmology (343); Cosmological parameters from large-scale structure (340)

1. Introduction

A number of fundamental cosmological problems can be explored by galaxy surveys for probing cosmic large-scale structure. Ongoing and upcoming galaxy surveys, such as the Sloan Sky Digital Survey (SDSS),6 the Dark Energy Spectroscopic Instrument (DESI),7 the Large Synoptic Survey Telescope (LSST)8 (Ivezić et al. 2008; Abell et al. 2009), the Euclid space telescope9 (Laureijs et al. 2011) and the Chinese Space Station Telescope (CSSST) (Zhan 2011, 2018; Cao et al. 2018; Gong et al. 2019), will provide great information and insights on solving these problems. In traditional galaxy surveys, individual galaxies are resolved via high spatial resolution, and three-dimensional (3D) or two-dimensional (2D) angular correlation functions or power spectra in Fourier space can be derived for illustrating cosmic large-scale structure. However, these surveys are usually quite time-consuming for collecting sufficient large galaxy samples, and it is quite challenging for them to observe faint galaxies at high redshifts, which are particularly valuable and important for cosmological studies. In contrast, line intensity mapping is a good option to overcome these difficulties.

Instead of observing individual galaxies, intensity mapping is dedicated to measuring cumulative fluxes in a voxel defined by instrumental spatial and frequency resolutions. Therefore, no matter whether from bright or faint galaxies, fluxes in a voxel will be detected as a signal in intensity mapping. Since huge numbers of galaxies can be included in a observed voxel, intensity mapping is quite efficient as a cosmological probe. Besides, because atomic and molecular emission lines are good tracers of galaxies, line intensity mapping is a suitable tool for measuring cosmic large-scale structure and galaxy formation and evolution. A number of works have discussed relevant issues about the epoch of reionization (EoR) and post-EoR at $z < 6$ (e.g., Visbal & Loeb 2010; Carilli 2011; Gong et al. 2011, 2012, 2013, 2014, 2017; Lidz et al. 2011; Silva et al. 2013, 2015; Pullen et al. 2014; Uzgil et al. 2014; Yue et al. 2015; Chen et al. 2016; Fonseca et al. 2016, 2018; Lidz & Taylor 2016; Padmanabhan 2018; Moradinezhad Dizgah & Keating 2019). However, there is a problem for line intensity mapping, in that interloper lines redshifted into the same voxel of the signal line can result in significant contamination, and it is then difficult to distinguish a signal line from interlopers.

A common method of reducing interloper contamination is cross-correlating intensity maps with other kinds of surveys, such as traditional galaxy surveys. Although this has been proved to be feasible (e.g., Chang et al. 2010), the autocorrelation of the signal line is hard to direct measure in this method. Another way is to mask the bright voxels in the survey volume, under the assumption that interloper lines are always much brighter than the signal line. This method is simple and effective, but information in the masked voxels is wastefully discarded. On the other hand, if we have a good understanding of interloper lines and could recognize specific features of them, they can be distinguished, and more importantly, can be seen as “signals” as well. That is to say, interloper lines can also potentially be used for extracting...
Reionization, and Ices Explorer

power spectra for the three emission lines with interlopers at massive neutrinos, and primordial non-Gaussianity in the current cosmological observations, visbal & loeb (2010) and gong et al. (2014) find that the signal and interloper lines have different shapes in a redshift-space line intensity power spectrum along wavenumbers perpendicular and parallel to the line of sight, which can be adopted for distinguish interlopers from signals. this method is further developed and discussed in detail in lidz & taylor (2016).

in this work, we explore the constraints on cosmological and astrophysical parameters using multipole moments of a redshift-space line intensity power spectrum. as an example, we take multipole intensity power spectra of hα 6563 Å, [o iii] 5007 Å, and [o ii] 3727 Å measured by the SPHEREx (Spectro-Photometer for the History of the universe, Epoch of Reionization, and Ices Explorer) experiment in the discussion. we consider the time-variable equation of state of dark energy, massive neutrinos, and primordial non-Gaussianity in the cosmological model. we generate mock data of total multipole power spectra for the three emission lines with interlopers at z = 1, and include the cross-correlation with the CSST galaxy survey. the markov chain monte carlo (mcmc) method is adopted to constrain the parameters.

the paper is organized as follows: in section 2, we show the detailed cosmological models we consider in this study. in section 3, we discuss the estimate of line mean intensity. in section 4, the calculations of multipole moments of the intensity power spectrum of signal and interloper lines have been shown. in section 5, we generate mock data of multipole intensity power spectra based on measurements by the SPHEREx experiment. in section 6, we discuss cross-correlation with the CSST galaxy survey. in section 8, we show the fitting results of cosmological and astrophysical parameters involved in the model. we summarize our results in section 9.

2. cosmological model

We assume a flat space of the universe in this work, and consider a dark energy model with a time-variable equation of state, massive neutrinos, and primordial non-Gaussianity in the cosmological model. the details of the model are discussed as follows.

2.1. Dark Energy

The properties of dark energy can be represented by its equation of state w = p/ρ, where p and ρ are the pressure and energy density, respectively. The equation of state of dark energy can take the values w < −1 (e.g., phantom), w = −1 (cosmological constant) and −1 < w < 0 (e.g., quintessence). in our model, we make use of a time-variable equation of state of dark energy, i.e., Chevallier–Polarski–Linder parameterization (Chevallier & Polarski 2001; Linder 2003), which takes the form

\[ w(z) = w_0 + \frac{w_a}{1 + z}, \]

where w_0 and w_a are the free parameters. as measured by current cosmological observations, w_0 and w_a should be around −1 and 0, respectively. then, the Hubble parameter in the flat space can be calculated by

\[ H(z) = H_0[1 + \Omega_M(1 + z)^3 + (1 - \Omega_M) + (1 + z)^{3(1 + w_0 + w_a)}e^{-3w_a z/(1 + z)}]^{1/2}. \]

here H_0 = 100 h km s^{-1} Mpc^{-1} is the Hubble constant. the Hubble parameter can characterize the kinetic expansion of the universe. on the other hand, the dynamic evolution of the structure of matter distribution can be evaluated by the linear growth factor for matter perturbation modes, which is given by Heath (1977) and Peebles (1980)

\[ g(a) = \frac{5}{2} \frac{\Omega_M H(a)}{a H_0} \int_0^a \frac{da'}{a'^3 [H(a')/H_0]^3}, \]

where a = 1/(1 + z) is the scale factor. when calculating the matter power spectrum, the normalized growth factor at z = 0 is always adopted, and it is defined as

\[ D(z) = \frac{1}{1 + z} \frac{g(z)}{g(0)}. \]

Finally, the linear matter power spectrum can be estimated as

\[ P_m^{lin}(k, z) = A_s k^{ns} T^2(k) D^2(z), \]

where A_s is the primordial amplitude which can be replaced by the amplitude of current fluctuation on an 8 Mpc h^{-1} scale (i.e., σ_8), n_s is the primordial spectral index, and T(k) is the transfer function. as we see later, the linear matter power spectrum is suitable and good enough for our discussion, since we are mainly focusing on the linear regime.

2.2. Massive Neutrinos

Neutrinos are relativistic and couple with other species in the early universe when radiation is dominant. as the universe expands and cools down, they decouple and redshift adiabatically. at that time, the relativistic neutrinos travel at the speed of light, but when they become nonrelativistic, the thermal velocity decreases to

\[ v_\text{th}(z) \simeq \frac{3T_{\nu}}{m_{\nu}} \simeq 151(1 + z) \left(\frac{1 \text{ eV}}{m_{\nu}}\right) \text{ km s}^{-1}. \]

Here m_{\nu} is neutrino mass, and T_{\nu} is neutrino temperature. As collisionless fluid, the nonrelativistic subelectronvolt neutrinos act as hot dark matter, that can free stream from high to low matter density regions and suppress fluctuations at scales smaller than the thermal free-streaming length. the wavenumber of free streaming is given by

\[ k_{FS}(z) = \frac{3}{2} \frac{H(z)}{v_\text{th}(z)(1 + z)}. \]

Given low neutrino energy density, the suppressing of the matter power spectrum at small scales k > k_{FS} can be approximated as (Hu & Eisenstein 1998)

\[ \frac{\Delta P_m}{P_m} \simeq -8 \frac{\Omega_{\nu}}{\Omega_M}, \]

where \( \Omega_\nu = \sum m_{\nu}/(93.14 \text{ eV}) \) is the present neutrino energy density parameter. Note that the accurate suppressing fraction needs to be obtained by numerically solving the Boltzmann equation, and equation (8) is only valid for small neutrino fraction with f_\nu = \Omega_{\nu}/\Omega_M \lesssim 0.07 (or \sum m_{\nu} \lesssim 1 \text{ eV}) (see e.g., Brandbyge et al. 2008; Bird et al. 2012). For simplicity, we will adopt it in the discussion, since it is a good approximation as
we show in Section 8, and should be sufficient for the purpose of this study.

For neutrinos becoming nonrelativistic during the matter domination era, the free-streaming scale leads to a maximum scale, whose wavenumber is given by

$$k_{\text{nr}} \simeq 0.018 \left(\frac{m_{\nu}}{\text{eV}}\right)^{1/2} \Omega^{-1/2} \Omega_{\text{M}}^{1/2} \text{h Mpc}^{-1}.$$  \quad \text{(9)}$$

On the scales much larger than the free-streaming scale, i.e., $k < k_{\text{nr}}$, the neutrino thermal velocity is less than the escape velocity of gravitational potential wells, and does not affect matter fluctuations. This means that, on these scales, neutrino perturbations are identical to perturbations of cold dark matter. Therefore, different neutrino mass can only significantly affect the matter power spectrum at small scales where $k > 0.1 \text{Mpc}^{-1} h$ in practice. We can then calculate the suppressed matter power spectrum with massive neutrinos by the formulae shown above.

2.3. Primordial Non-Gaussianity

The primordial fluctuation is the seed of the cosmic large-scale structure. It is usually related to a inflation period in the very early universe. The standard single-field slow-roll inflation model predicts that primordial fluctuations should be Gaussian distributed (Acquaviva et al. 2003; Creminelli et al. 2003). However, other models such as multifield inflation can result in significant non-Gaussian primordial non-Gaussianity (Linde & Mukhanov 1997). This leads the density fluctuations to be

$$\Phi(x) = \phi(x) + f_{\text{NL}}[\phi^2(x) - \langle \phi^2 \rangle],$$  \quad \text{(10)}$$

where $\Phi(x)$ is Bardeen’s gauge-invariant potential at position $x$, $\phi$ is Gaussian random field, and $f_{\text{NL}}$ is the parameter indicating the overall amplitude of primordial non-Gaussianity.

The primordial non-Gaussianity can be described by high-order correlation functions, such as bispectrum in Fourier space. Generally speaking, it has three shapes, i.e., local, equilateral, and orthogonal. Here we will focus on the local shape, which has a distinct scale-dependent bias for the power spectra of tracers. This bias can be written as a linear bias with a scale-dependent correction, which is given by

$$b_{\text{NG}}(M, k, z) = b(M, z) + \Delta b(M, k, z).$$  \quad \text{(11)}$$

The scale-dependent correction can be estimated by (Dalal et al. 2008; Slosar et al. 2008)

$$\Delta b(M, k, z) = f_{\text{NL}}[b(M, z) - 1] \delta_k \frac{3 \Omega_{\text{M}} H_0^2}{k^2 T(k) D(z) c^2},$$  \quad \text{(12)}$$

where $\delta_k = 1.686$ is the density contrast factor for a spherical collapse of an overdensity region, $T(k)$ is the transfer function, $D(z)$ is the growth factor normalized at $z = 0$, and $c$ is the speed of light. As we discuss in Section 4.1, when using dark matter halos as tracers, $b_{\text{NG}}(M, k, z)$ can be calculated by the halo model, and it will cause the bias of the emission line to be scale dependent in intensity mapping. Since the scale-dependent bias correction $\Delta b$ is only considerable at large scales, the primordial non-Gaussianity can be only effectively constrained at $k < 0.02 \text{Mpc}^{-1} h$.

3. Line Mean Intensity

In this study, we consider four optical emission lines as signal and interloper lines, which are H$\alpha$, [O III] 5007 Å, [O II] 3727 Å, and H$\beta$ 4861 Å. As shown in Gong et al. (2017), the mean intensity of the lines can be estimated by three methods, i.e., observed line luminosity functions, cosmological simulations, and the star formation rate density (SFRD) derived from observations. These three methods are in good agreement in line intensity predictions, and we will adopt the SFRD method here since it is more convenient in our theoretical predictions.

The line mean intensity as a function of redshift can be expressed as

$$I_{\text{line}}(z) = \int_{M_{\text{min}}}^{M_{\text{max}}} \frac{dM}{dM} \frac{L_{\text{line}}(M, z)}{4 \pi D_L^2(z)} y(z) D_A^2,$$  \quad \text{(13)}$$

where $M_{\text{min}} = 10^8 M_{\odot} h^{-1}$ and $M_{\text{max}} = 10^{13} M_{\odot} h^{-1}$ are the minimum and maximum halo masses we use, $dn/dM(M, z)$ is the halo mass function (Sheth & Tormen 1999), and $D_L(z)$ and $D_A(z)$ are the luminosity and comoving angular diameter distance at $z$, respectively. $y(z) = dr/dv = \lambda_{\text{line}}(1 + z)^2 / H(z)$, where $r$ is the comoving distance, $\lambda_{\text{line}}$ is the rest-frame wavelength of emission lines, and $H(z)$ is the Hubble parameter. $I_{\text{line}}(M, z)$ is the line luminosity, which can be related to the star formation rate (SFR). For the four emission lines we consider in this work, the $I_{\text{line}}$–SFR relations are given by Kennicutt (1998), Ly et al. (2007), and Gong et al. (2014, 2017)

$$\text{SFR}(M_{\odot} \text{ yr}^{-1}) = (7.9 \pm 2.4) \times 10^{-42} L_{\text{H}\alpha},$$ \quad \text{(14)}$$

$$\text{SFR}(M_{\odot} \text{ yr}^{-1}) = (7.6 \pm 3.7) \times 10^{-42} L_{\text{[O III]}},$$ \quad \text{(15)}$$

$$\text{SFR}(M_{\odot} \text{ yr}^{-1}) = (1.4 \pm 0.4) \times 10^{-41} L_{\text{[O II]}},$$ \quad \text{(16)}$$

For the H$\beta$ line, we adopt a relation $H\beta/H\alpha = 0.35$ (Osterbrock & Ferland 2006). This relation is found to be in good agreement with observations and simulations (Gong et al. 2017).

The SFR can be simply evaluated by assuming that it is proportional to the halo mass $M$, which is a good approximation at $M \lesssim 10^{12} M_{\odot}$ (see, e.g., Gong et al. 2017), and we have

$$\text{SFR}(M, z) = f_{s}(z) \frac{\Omega_b}{\Omega_{\text{M}}} \frac{1}{\Omega_{s}} M,$$  \quad \text{(17)}$$

where $t_s = 10^8 \text{yr}$ is the typical star formation timescale, and $f_s(z)$ is the star formation efficiency at $z$, which can be estimated by SFRD$(z) = \int dM dM \text{ SFR}(M, z)$, Following Hopkins & Beacom (2006), we use the fitting formula (Cole et al. 2001)

$$\text{SFRD}(z) = \frac{a + bz}{1 + (z/c)^d} h (M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}),$$  \quad \text{(18)}$$

where $a = 0.0118$, $b = 0.08$, $c = 3.3$, and $d = 5.2$ with the initial mass function given by Baldry & Glazebrook (2003).

We can then calculate the line mean intensity using Equations (13)–(18). The uncertainties of the mean intensity are also considered by including the errors from the $L_{\text{line}}$–SFR relations shown in Equations (14)–(16) and the SFRD shown in Equation (18) given by Hopkins & Beacom (2006). These uncertainties, including that of the relation between SFR and
halo mass given by Equation (17), can affect the strength of line mean intensity, consequently change the amplitude of line intensity power spectrum, and finally impact the constraints on the cosmological and astrophysical parameters.

Besides this, the dust extinction effect is also involved in this analysis. We make use of magnitude-averaged mean dust extinction laws, which give $A_{H\alpha} = 1.0$ mag, $A_{OIII}$ = 1.32 mag, $A_{OII}$ = 0.62 mag, and $A_{H\beta}$ = 1.38 mag for the four lines we consider (Kennicutt 1998; Calzetti et al. 2000; Hayashi et al. 2013; Khostovan et al. 2015; Gong et al. 2017). The uncertainties and dust extinction effects of the line mean intensity will be passed into the estimates of line power spectra as shown in the next section.

4. Line Intensity Power Spectrum

In this section, we show the predictions of the signal power spectra of H\(\alpha\), [O III] and [O II] lines at $1 \leq z \leq 3$, and the observed power spectra of the three emission lines considering interlopers and uncertainties at $z = 1$ as examples.

4.1. Signal Power Spectrum

We adopt multipole moments of redshift-space line intensity power spectrum as the estimator. Considering the Alcock–Paczynski (AP) effect (Alcock & Paczynski 1979), it can be written as

$$P_{l,\text{line}}(k) = \frac{2\ell + 1}{2\pi} \int_{-1}^{1} d\mu \, P_{\text{line}}(k', \mu') L_{\ell}(\mu).$$

(19)

Here \(\ell\) is the multipole and \(k = \sqrt{k_1^2 + k_2^2}\) is the wavenumber, where \(k_1\) and \(k_2\) are the components which are parallel and perpendicular to the line of sight, respectively. \(\mu = k_2/k\) is the cosine of the angle between the direction of the wavenumber and the line of sight. \(k' = \sqrt{k_1'^2 + k_2'^2}\) and \(\mu' = k_2'/k'\) are the apparent wavenumber and cosine of angle, where \(k_1' = k_1/\alpha_1\) and \(k_2' = k_2/\alpha_1\). \(\alpha_1 = D_A(z)/D_A(z)\) and \(\alpha_0 = H^\text{fid}(z)/H(z)\) are the scaling factors in the transverse and radial directions, respectively. \(D_A(z)\) and \(H(z)\) are the angular diameter distance and Hubble parameter at redshift $z$, respectively, and the superscript “fid” means the quantities in the fiducial cosmology. $L_{\ell}(\mu)$ indicates Legendre polynomials, of which only the first three nonvanishing orders \(\ell = 0, 2, 4\) are considered here, and they take the values 1, 1/(2(3\(\mu^2 - 1\)), and 1/(8(3\(5\mu^4 - 30\mu^2 + 3\), respectively. $P_{\text{line}}^{\text{iso}}(k', \mu')$ is the apparent redshift-space line intensity power spectrum. By assuming that there is no peculiar velocity bias, it can be estimated by

$$P_{\text{line}}^{\text{s}}(k', \mu', z) = P_{\text{line}}^{\text{clus}}(k', z)(1 + \beta \mu'^2)^2 \times D(k', \mu', z) + P_{\text{line}}^{\text{shot}}(z),$$

(20)

where the superscript (s) denotes the quantity in redshift space. $P_{\text{line}}^{\text{clus}}(k', z)$ is the apparent real-space clustering line intensity power spectrum, and $P_{\text{line}}^{\text{shot}}(z)$ is the shot-noise power spectrum, which is not affected by the redshift-distortion effect. $\beta = f/b_{\text{line}}(z)$ where $f = d \ln D(a)/d \ln a$ is the growth rate. Here $D(a)$ is the growth factor normalized at $z = 0$, and $b_{\text{line}}$ is the line mean bias. Note that this redshift-distortion effect can also help to break the degeneracy between the line bias and mean intensity (Chen et al. 2016; Lidz & Taylor 2016). The factor $D(k', \mu')$ is the damping term at small scales, which is given by

$$D(k', \mu') = \exp[-(k'\mu'/\sigma_D)^2].$$

(21)

Here $\sigma_D$ denotes the effects of velocity dispersion and spectral resolution. In the linear regime at large scales where the intensity mapping is focused on, we find that this damping term does not importantly affect the result.

The clustering line intensity power spectrum $P_{\text{line}}^{\text{clus}}$, can be calculated by

$$P_{\text{line}}^{\text{clus}}(k, z) = \bar{b}_z^2 P_{\text{line}}^2(z) P_m(k, z),$$

(22)

where $P_m(k, z)$ is the matter power spectrum. Note that the matter power spectrum needs to be multiplied by a factor of $(1 + \Delta P_m/P_m)$ as indicated in Equation (8) when massive neutrinos are involved in the model. The mean line bias takes the form

$$\bar{b}_z = \frac{\int_{M_{\text{min}}}^{M_{\text{max}}} dM \frac{dn}{dM} L_{\text{line}}(M, z) b(M, z)}{\int_{M_{\text{min}}}^{M_{\text{max}}} dM \frac{dn}{dM} L_{\text{line}}(M, z)}.$$ 

(23)

We consider H\(\alpha\), [O III], and [O II] as the signal lines in this study, since they are usually bright and relatively easy to detect (Gong et al. 2017). In Figure 1, we show the multipole moments $P_0$, $P_2$, and $P_4$ of the redshift-space power spectra of the H\(\alpha\), [O III], and [O II] lines at $z = 1, 1.5, 2, 2.5$, and 3. We find that the multipole power spectra at $z = 1, 1.5$, and $2$ have a similar amplitude, while the ones at $z = 2.5$ and $3$ decline significantly, which is due to the cosmic star formation history as indicated by SPRD(z). In the following discussion, as examples, we will focus on the power spectra at $z = 1$ to show the contamination due to interlopers, uncertainties, and detectability. At this redshift, dark energy begins to dominate the evolution of the universe, the signals of line intensity mapping are relatively strong as shown in Figure 1, and several spectroscopic galaxy surveys can be used to perform cross-correlation for further improving the strength of the cosmological constraint as discussed in Section 6.

4.2. Observed Power Spectrum

In observations, the signal of the emission line can be contaminated by the continuum emission and interloper lines redshifted to the same frequency. The continuum contamination can be effectively removed by the smooth feature of its spectrum as a function of frequency (e.g., Silva et al. 2015; Yue et al. 2015). Therefore, the main contamination actually comes from interloper lines, especially the ones at lower redshifts. As discussed in Gong et al. (2017), the contamination on H\(\alpha\) 6563 Å can be neglected, H\(\alpha\) 6563 Å at lower redshift can
contaminate [O III] 5007 Å, and Hα 6563 Å, [O III] 5007 Å, and Hβ 4861 Å can be significant foregrounds for [O II] 3727 Å at a higher redshift. Considering the contamination from interloper lines, the observed power spectrum of an emission line is composed of a signal power spectrum and all components from interlopers, which is given by 

\[ P_{\text{obs}}(k, z) = P_{s}(k, z) + \sum_{i = 1}^{N} P_{i}^{\text{pro}}(k_i, z). \]  

Here \( P_{s}(k, z) \) is the signal power spectrum given by Equation (19). \( P_{i}^{\text{pro}}(k_i, z) \) is the \( i \)th interloper power spectrum, which is projected to the signal redshift \( z \). \( k_i \) is the wavenumber at the redshift of a interloper line \( z_i \), and we have \( k_i = \sqrt{A_s^2 k_{s}^2 + A_i^2 k_{i}^2} \). \( A_s \) and \( A_i \) are the factors to transfer \( k \) to \( k_i \), which are given by \( A_s = r_s/r_i \) and \( A_i = \gamma_i/\gamma_s \), where the subscripts “s” and “i” denote “signal” and “interloper,” respectively. The projected interloper power spectrum can then be calculated by projecting the interloper power spectrum at \( z_i \) to the signal redshift \( z \), which is given by Visbal & Loeb (2010)
and Gong et al. (2014)

\[ P^\text{tri}_{\alpha}(k, \z) = A^2_{\text{tri}} P_{\text{tri}, \alpha}(k, \z). \]  

Unlike the signal power spectrum, the projected interloper power spectrum \( P^\text{tri}_{\alpha}(k, \z) \) is anisotropic in the \( k_\parallel - k_\perp \) space, which can be used to recognize and remove the effect of interloper lines (Gong et al. 2014; Lidz & Taylor 2016).

In Figure 2, the observed multipole moments of power spectra \( P_0, P_2 \) and \( P_4 \) for \( \text{H}_\alpha, [\text{O \text{III}}] \) and \( [\text{O \text{II}}] \) at \( z = 1 \) with interloper lines are shown. The uncertainties are also shown in shaded regions by considering the uncertainties of SFR-line luminosity relations and SFRD. For comparison, both projected and original power spectra of the interloper lines are shown in dashed–dotted and dashed curves, respectively. For \( \text{H}_\alpha \) observation at \( z = 1 \) (left panels of Figure 2), we assume there is no strong interloper line can contaminate the \( \text{H}_\alpha \) signal significantly (Gong et al. 2017). We find that the shot-noise term (red dotted line) will not affect the total observed \( P_0 \) (red solid curve) in the linear regime \( k \lesssim 0.1 \text{ Mpc}^{-1} h \), which is also true for the \([\text{O III}]\) and \([\text{O II}]\) cases. In the \([\text{O III}]\) observation at \( z = 1 \) (middle panels of Figure 2), the projected \( \text{H}_\alpha \) power spectra from \( z = 0.53 \) (red dashed–dotted) are stronger than \([\text{O III}]\) by a factor of three to four at large scales, and can be considerably affect the \([\text{O III}]\) measurement. This is the same for the \([\text{O II}]\) case (right panels of Figure 2), the projected \( \text{H}_\alpha \) from \( z = 0.14 \) (red dashed–dotted) and \([\text{O III}]\) from \( z = 0.49 \) (orange dashed–dotted) can significantly contaminate the \([\text{O II}]\) measurement at \( z = 1 \). On the other hand, the \( \text{H}\beta \) from \( z = 0.53 \) (green dashed–dotted) seems too weak to affect the result.

In order to remove or reduce the contamination of the interloper lines, we try to distinguish them by the differences of features on the multipole power spectra between the signal and interlopers. Following Lidz & Taylor (2016), we calculate the ratio of \( P_2 \) and \( P_4 \) for \( \text{H}_\alpha, [\text{O III}] \), and \([\text{O II}]\) lines at \( z = 1 \) and their interlopers as shown in Figure 3. We define \( R_2(k) = P_2(k)/P_0(k) \) and \( R_4(k) = P_4(k)/P_0(k) \). We can find that the shapes of \( R_2(k) \) and \( R_4(k) \) of the interloper lines are different from that of the signal lines. For \( R_2 \) curves, unlike continuous declines for the signal line, the interloper curves first rise up and then decrease around \( k = 0.02 \text{ Mpc}^{-1} h \). In the \( R_4 \) case, they are always positive for the interloper lines we study, while it is less than 0 at large scales at \( k \lesssim 0.05 \text{ Mpc}^{-1} h \) for the signal line. Besides, as can be seen, especially for the \([\text{O II}]\) case (right panel of Figure 3), the wider the redshift intervals between the signal and interlopers, the larger the differences of their \( R_2(k) \) and \( R_4(k) \). This is quite useful for
distinguishing the interlopers, since the projection effect becomes stronger for larger redshift intervals between the signal and interloper lines (e.g., see the \( P_{0,0}^{[O\,\text{III}]} \) case by comparing the dashed–dotted and dashed curves shown in the top-right panel of Figure 2). This implies that although the contamination effect could be larger for interloper lines from a lower redshift, they should be easier to identify by comparing their \( R_2 \) and \( R_4 \) to the signal line, or using all information from \( P_0, P_2, \) and \( P_4 \). This is also the concept we adopt to deal with the interloper lines in this work.

We should also note that there could be more information mined in the full redshift-space distortion power spectrum \( P(k, \mu) \) beyond the multipole moments \( P_0, P_2, \) and \( P_4 \), considering the AP effect and interloper lines. This means that the \( P(k, \mu) \) could potentially provide more stringent constraints on the cosmological and astrophysical parameters, although it may not be as efficient as the multipole moments. We will explore this issue quantitively in our future work.

### 5. Line Detection

Here we adopt the SPHEREx experiment to perform the measurements.\(^{11}\) SPHEREx is a proposed near-infrared space telescope exploring from 0.75–5.0 \( \mu \)m (Dore et al. 2014, 2016, 2018). It has a diameter of 20 cm, and can obtain spectra with a 6.2 \( \times \) 6.2 arcsec\(^2\) pixel size. The spectral resolutions are different in its four bands, that we have \( R = 41 \) in 0.75 < \( \lambda \) < 2.42 \( \mu \)m, \( R = 35 \) in 2.42 < \( \lambda \) < 3.82 \( \mu \)m, \( R = 110 \) in 3.82 < \( \lambda \) < 4.42 \( \mu \)m, and \( R = 130 \) in 4.42 < \( \lambda \) < 5.00 \( \mu \)m. In our study, we only consider the first two bands for measuring \( \text{H}\alpha, \text{[O\,III]} \) and \([\text{O\,II}]\) lines at \( z \leq 3 \). We explore the detectability of the lines using its deep survey within 200 deg\(^2\).

The covariance matrix of observed line power spectrum at a given redshift can be estimated by (see, e.g., Chung 2019)

\[
\text{Cov}[P_{\ell,\text{obs}}(k, z), P_{\ell',\text{obs}}(k, z)] = \frac{(2\ell + 1)(2\ell' + 1)}{N_m(k, z)} \times \int d\mu L_\ell(\mu)L_{\ell'}(\mu)[P_{\text{obs}}(k, \mu, z) + P_N(z)]^2, \tag{27}
\]

where \( P_{\text{obs}}(k, \mu, z) \) is the observed redshift-space total line power spectrum, which is composed of signal and projected interloper power spectra. The error of \( P_{\ell,\text{obs}}(k, z) \) is then can be calculated by \( \Delta P_{\ell,\text{obs}}(k, z) = \sqrt{\text{Cov}[P_{\ell,\text{obs}}(k, z), P_{\ell,\text{obs}}(k, z)]} \) where \( \ell = \ell' \). \( P_N(z) \) is the noise power spectrum determined by instrumental noise. It is given by

\[
P_N(z) = V_{\text{pix}}(z) \frac{\sigma_{\text{pix}}^2}{I_{\text{pix}}}, \tag{28}
\]

Here \( V_{\text{pix}}(z) \) is the pixel volume at \( z \) which can be calculated by the SPHEREx spatial and frequency resolutions, and \( \sigma_{\text{pix}}^2/I_{\text{pix}} \) is the squared instrument thermal noise per survey pixel, where \( I_{\text{pix}} \) denotes the integration time per pixel. We adopt 2.2, 3.1 and 3.9 nW m\(^{-2}\)sr\(^{-1}\) for SPHEREx \( \text{H}\alpha, \text{[O\,III]} \) and \([\text{O\,II}]\) surveys at \( z = 1 \), respectively. \( N_m(k, z) \) is the number of Fourier modes in a wavenumber interval \( \Delta k \) at \( k \) in the upper-half wavenumber plane. As an approximation, it can be estimated by

\[
N_m(k, z) = 2\pi k^2 \Delta k \frac{V_2(z)}{(2\pi)^3}, \tag{29}
\]

where \( V_2 \) is the total survey volume at \( z \). In practice, we perform a real counting of the modes to obtain an exact \( N_m \) in each wavenumber interval. This can avoid discrepancy between the real \( N_m \) and the one given by Equation (29), especially at small scales (large \( k \)). Then the signal to noise ratio (S/N) can be calculated by

\[
S/N(z) = \sqrt{\sum_{k \text{ bin}} \frac{P_{\ell,\text{obs}}(k, z)}{\Delta P_{\ell,\text{obs}}(k, z)}}, \tag{30}
\]

Here the \( k \) range is determined by survey volume and spatial and frequency resolution. Considering the spatial and frequency resolutions of SPHEREx and avoiding nonlinear effect, we take 0.01 < \( k \) < 0.3 Mpc\(^{-1}\)\( h \) in our analysis. Note that the low \( k \) modes can be lost due to instrumental and foreground contaminations in intensity mapping surveys, which can impact constraints on the parameters that are sensitive to low \( k \) modes, such as \( f_{\text{NL}} \) (Dizgah & Keating 2019).

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\(^{11}\)http://spherex.caltech.edu/
In Figure 2, we show the error $\Delta P_{\text{obs}}$ of the observed total multipole power spectra $P_0$, $P_2$, and $P_4$ (bottom panels) for $\text{H}_\alpha$, [O III], and [O II] lines at $z = 1 \pm 0.2$. According to the covariance matrix derived from Equation (27), a random shift from Gaussian distribution is added in each data point. As can be seen, we can obtain good measurements on total power spectra of each line, and we have $S/N = 10.4, 7.7, \text{and } 5.8$ for the $\text{H}_\alpha$ line, 12.7, 9.1, and 6.9 for the [O III] line, and 19.1, 9.5, and 7.2 for the [O II] line, for $P_0$, $P_2$, and $P_4$, respectively. Although the signal power spectra of [O II] (blue dashed curve in the top-right panel) and [O III] (orange dashed curve in the top-middle panel) are lower than $\text{H}_\alpha$ (red shot-long dashed curve in the top-left panel), we find that they have larger S/N, since they suffer strong contamination (dashed-dotted curves) from other lines at lower redshifts which can boost up their total power spectra. Note that a higher S/N with a higher amplitude of the total power spectrum does not mean we can obtain more stringent constraints on the cosmological and astrophysical parameters we are interested in. Since we will consider both signal and interlopers in our fitting process, a high total power spectrum, such as [O II], has more components from interlopers with more free parameters. As we discuss in Section 8, it is possible that this can somehow loosen the constraint on some parameters.

6. Cross-correlation with a Galaxy Survey

An effective way to reduce contamination is cross-correlating an intensity mapping survey with other kinds of surveys, such as a galaxy survey (see, e.g., Chang et al. 2010). In this work, we take the CSST spectroscopic galaxy survey for discussion. CSST is a two meter space telescope established by the space application system of the China Manned Space Program (Zhan 2011, 2018; Cao et al. 2018; Gong et al. 2019). It has seven photometric imaging and three slitless spectroscopic lines at $255$–$1000$ nm, and will simultaneously cover about 17,500 deg$^2$ with a field of view of 1.1 deg$^2$. The magnitude limit can reach $r \sim 26$ AB mag for 5σ point-source detection in the photometric survey, and $\sim 23$ for the spectroscopic survey. The galaxy distribution has a peak around $z = 0.7$ and 0.3, and can extend to as high as $z = 5$ and 2 for its photometric and spectroscopic surveys, respectively. In particular, the CSST spectroscopic survey has a spectral resolution $R \gtrsim 200$, and can obtain a galaxy number density $n_{\text{gal}} \sim 5 \times 10^{-7}$ (Mpc/h)$^3$ at $z \sim 1$ (Gong et al. 2019).

The apparent redshift-space cross-power spectrum of line intensity map and galaxy survey can be estimated by

$$P_{\text{cross}}^{(s)}(k', \mu', z) = P_{\text{cross}}^{(s)}(k', z)(1 + \beta_\mu k'^2)(1 + \beta_\ell k'^2) \times D_\ell(k', \mu', z) + P_{\text{shot}}^{(s)}(z).$$

Here $\beta_\ell = f(z)/b_\ell(z)$, where $b_\ell$ is the galaxy bias (Gong et al. 2019), and $D_\ell$ is the damping term at small scales for both line intensity and galaxy surveys. At the linear regime we are interested in, we actually find that this term cannot significantly affect the results. The apparent real-space clustering cross-power spectrum is given by

$$P_{\text{cross}}^{(s)}(k', z) = \bar{b}_\text{line}(z)b_g(z)\bar{L}_{\text{line}}(z)P_m(k', z).$$

Assuming that all galaxies observed in a traditional survey have emission lines that can be detected in an intensity mapping survey, the shot-noise term takes the form

$$P_{\text{shot}}^{(s)}(z) = \frac{1}{n_{\text{gal}}(z)} \int_{M_{\min}}^{M_{\max}} dm \frac{dn}{dm} \int \frac{L_{\text{line}}}{4\pi D_L^2(z)}(z)D_A^2 \left[ L_{\text{line}} \right].$$

As we mentioned in Section 4.1, the line mean bias needs to be replaced by a scale-dependent bias $\bar{b}_\text{line}(k', z)$ when considering primordial non-Gaussianity, and a factor $(1 + \Delta P_m/P_m)$ should be multiplied on the matter power spectrum $P_m$ for massive neutrinos included in the model.

Then the multipole moments of the cross-power spectrum $P_L^{(s)}(k, z)$ can be obtained by replacing $P_{\text{cross}}^{(s)}(k', \mu')$ by $P_{\text{cross}}^{(s)}(k', \mu')$ in Equation (19). The covariance of the multipole moments of the cross-power spectrum can be estimated by

$$\text{Cov}[P_L^{(s)}(k, z), P_L^{(s)}(k, z)] = \frac{(2l + 1)(2l' + 1)}{2N_{\text{cross}}(k, z)} \times \int_0^1 d\mu \ell_L(\mu)\ell_L'(\mu)[P_2^{(s)}(k, \mu, z) + P_{\text{shot}}^{(s)}] P_{\text{gal}}^{(s)}].$$

Here $P_L^{(s)}(k, u, z) = P_L^{(s)}(u, k, z)$ is the total redshift-space line power spectrum, and $P_{\text{gal}}^{(s)}(k, u, z) = P_{\text{gal}}^{(s)}(u, k, z) + 1/n_{\text{gal}}(z) + N_{\text{sys}}$ is the total redshift-space galaxy power spectrum, where $N_{\text{sys}}$ is the systematic noise.
The detailed calculation of $P_{\text{tot}}^\text{gal}$ can be found in Gong et al. (2019). $N_{m}^{\text{cross}}$ is the number of modes for the cross-power spectrum, which can be obtained by counting the $k$ modes in each wavenumber interval, considering the survey designs of both SPHEREx and CSST.

In Figure 4, we show the multipole moments of the cross-power spectra of H$_\alpha$, [O III], and [O II] and the CSST spectroscopic galaxy survey at $z=1$ in the left, middle, and right panels, respectively. We can see that there are no interlopers appearing in the cross-power spectrum, unlike in the auto power spectrum shown in Figure 2, the cross-power spectra can reflect the strengths of the signal lines H$_\alpha$, [O III], and [O II] at $z=1$. The measurements of the cross-power spectrum have relatively high S/N, which can be obtained by replacing $P_{\ell,\text{obs}}$ and $\Delta P_{\ell,\text{obs}}$ by $P_{\ell}^{\text{cross}}$ and $\Delta P_{\ell}^{\text{cross}}$ in Equation (30). We find that, for $P_{0}$, $P_{2}$, and $P_{4}$, $\text{S/N} = 35.3$, 3.7, and 1.8 for H$_\alpha \times$ gal, 26.6, 2.7, and 1.4 for [O III] \times gal, and 28.0, 2.9, and 1.4 for [O II] \times gal, respectively. We can find that H$_\alpha \times$ gal power spectrum has the highest amplitude with largest S/N, while [O III] \times gal and [O II] \times gal are lower and have similar detectability.

In addition to cross-correlating with a traditional galaxy survey, we can also calculate the cross-correlations between emission lines, such as the cross-correlations of H$_\alpha$, [O III], and [O II] at the same redshift between different frequency channels, or cross-correlate with the 21 cm line measured by radio telescopes, e.g., the Square Kilometer Array, Canadian Hydrogen Intensity Mapping Experiment, and Tianlai project (Lidz & Taylor 2016; Gong et al. 2017). This kind of cross-correlation is also helpful to reduce instrumental noise and contamination of interloper lines, and hence can improve the constraint results. In this study, the cross-correlation with a galaxy survey is sufficient and probably the best choice for discussion, and we will discuss other cross-correlations in detail in future work.

7. Model Fitting

After generating mock data of multipole auto- and cross-power spectra for H$_\alpha$, [O III] and [O II] lines, we make use of the MCMC method to explore the constraints on the parameters of cosmological and astrophysical models. We have nine cosmological parameters in the model, and their fiducial values are $\Omega_b = 0.05$, $\Omega_M = 0.3$, $\sigma_8 = 0.8$, $n_s = 0.96$, $h = 0.7$, $w_0 = -1$, $w_a = 0$, $\sum m_\nu = 0$, $f_{\text{NL}} = 0$. Besides, we also set SFRD, mean line bias $b_{\text{line}}$ and total shot-noise power spectrum $P_{\text{shot}}^\text{tot}$ as free parameters for both signal and interloper lines. When the cross-power spectrum is involved in the constraints, the galaxy bias $b_g$ and shot-noise $P_{\text{shot}}^\text{cross}$ are included as free parameters. Hence, in total we have 12 (9 cosmological parameters + SFRD$_{H\alpha}$ + $b_{H\alpha}$ + $P_{\text{shot}}^{H\alpha}$) and 14 ($+b_g + P_{\text{cross}}^\text{shot}$)
free parameters for Hα auto- and cross-power spectra, 14 (9 cosmological parameters + SFRD$_{[\text{O} \text{III}]}$ + $b_{[\text{O} \text{III}]} + b_{\text{int,} \text{H}_\alpha} + P_{\text{shot}}$) and 16 (+ $b_g + P_{\text{cross}}$) for [O III], and 18 (9 cosmological parameters + SFRD$_{[\text{O} \text{II}]}$ + $b_{[\text{O} \text{II}]} + b_{\text{int,} \text{H}_\alpha} + b_{\text{int,} \text{H}_\text{II}} + P_{\text{shot}}$) and 20 (+ $b_g + P_{\text{cross}}$) for [O II], respectively.

We adopt the $\chi^2$ method to perform the fitting process, and the $\chi^2$ for a multipole power spectrum is given by

$$
\chi^2 = \sum_{k \text{ bin}} [P^\text{th}_{ij}(k) - P^\text{obs}_{ij}(k)] \text{Cov}^{-1}_{ij} [P^\text{th}_{ij}(k) - P^\text{obs}_{ij}(k)],
$$

where $P^\text{th}$ and $P^\text{obs}$ are the theoretical and observed multipole power spectra with $\ell = 0, 2$, and 4, respectively. Cov$_{ij}$ is the

Figure 6. The 1D PDFs of $\sum m_i$ and $f_{NL}$ derived from the constraints by Hα (left), [O III] (middle), and [O II] (right) intensity mapping. The solid and dashed curves denote the results from fitting line autopower spectra only and cross-power spectra included cases, respectively.

Figure 7. The contour maps of SFRD vs. $\bar{b}_{\text{line}}$ of signal lines at $z = 1$. The left, middle and right panels show the constraint results from the autopower spectra only (solid), and cross-power spectra included (dashed) for Hα, [O III] and [O II] lines, respectively. The gray dashed lines indicate the fiducial values of SFRD and line bias at $z = 1$. 
covariance of the power spectrum. The chi-square of the line autopower spectrum \( \chi^2_{\text{auto}} \) can be obtained by using Equations (25) and (27), and Equations (31) and (34) for calculating \( \chi^2_{\text{cross}} \). Then the total chi-square is given by

\[
\chi^2_{\text{tot}} = \chi^2_{\text{auto}} + \chi^2_{\text{cross}}.
\]

The likelihood function can be calculated by \( \mathcal{L} \sim \exp(-\chi^2/2) \).

In the MCMC technique we adopt, the Metropolis–Hastings algorithm is used to determine the accepted probability of a new chain point (Metropolis et al. 1953; Hastings 1970). The proposal density matrix is obtained from a Gaussian sampler with adaptive step size (Doran & Muller 2004). The flat priors are assumed for all the free parameters with large parameter ranges. We run 20 parallel chains for each case we study, and get about 100,000 chain points for each chain after a convergence criterion is fulfilled (Gelman & Rubin 1992). After performing the burn-in and thinning processes for each chain, we combine all chains together. Finally, we obtain about 10,000 chain points for plotting 1D and 2D probability distribution functions (PDFs) of the free parameters.

8. Constraint Results

In Figure 5, we show the contour maps of \( \Omega_M \) versus \( \sigma_8 \) and \( w_0 \) versus \( w_a \) in the upper and lower panels for \( \text{H}_\alpha \), [O III] and [O II] observations, respectively. The constraint results from the line autopower spectrum only that was measured by the SPHEREx experiment are shown in solid contours, and the

![Figure 8. The contour maps of SFRD vs. \( \bar{b}_{\text{H}\alpha} \) at the redshifts of interloper lines for \( \text{H}_\alpha \), [O III], and [O II] intensity mapping at \( z = 1 \). The solid and dashed contours are the constraint results from auto-only and cross-power spectra included, respectively. In the top-left panel, the result of the interloper line \( \text{H}_\alpha \) at \( z = 0.53 \) for the [O III] survey at \( z = 1 \) is shown. In the top-right, bottom-left and bottom-right panels, the results of the interloper lines \( \text{H}_\alpha \) at \( z = 0.14 \), H\( \beta \) at \( z = 0.53 \), and [O III] at \( z = 0.49 \) for the [O II] survey at \( z = 1 \) are shown, respectively.](image)
dashed contours denote the results when including the cross-power spectrum detected by the CSST galaxy survey. As can be seen, the constraint results are consistent with the fiducial values of the parameters (in gray parallel and vertical lines) in a 1σ confidence level (C.L.). We can find that the constraint results of the [O III] and [O II] lines are basically better ($w_0$ versus $w_a$) than or comparable ($\Omega_m$ versus $\sigma_8$) to H0, although interlopers appear in the two former lines. After including the cross-power spectrum with the CSST galaxy survey, the constraints can be evidently further improved as shown in dashed contours.

In Figure 6, the 1D PDFs of $\sum m_\nu$ and $f_{NL}$ are shown. The solid and dashed curves are for the line auto-only and cross-power spectrum included cases, respectively. We find that the total neutrino mass can be constrained as $\sum m_\nu \lesssim 0.3$ eV at 1σ C.L. for all the three emission lines, and the results can be more stringent when including the cross-power spectra. For the primordial non-Gaussianity parameter, we find that $|f_{NL}| \lesssim 15$ for the H$\alpha$ line, and $|f_{NL}| \lesssim 10$ for the [O III] and [O II] lines. When considering the cross-power spectrum with the CSST galaxy survey, $f_{NL}$ can be further constrained as $|f_{NL}| \lesssim 7$ for the [O III] and [O II] lines, and $|f_{NL}| \lesssim 11$ for the H$\alpha$ case. Like the constraints on $\Omega_m$ versus $\sigma_8$ and $w_0$ versus $w_a$ shown in Figure 5, [O III] and [O II] line intensity mapping can provide good constraints on neutrino mass and primordial non-Gaussianity in our method, which are even better than that from the H$\alpha$ line without the contamination of interloper lines. This indicates that if we have a good understanding of the interloper lines, they can actually be seen as signals as well, and can help to constrain the cosmological parameters at different epochs of the universe.

In Figures 7 and 8, we show the contour maps of SFRD versus $b_{line}$ for H$\alpha$, [O III], and [O II] at $z=1$ and that for the interloper lines at corresponding redshifts, respectively. We find that the constraint results are consistent with the fiducial values of SFRD and $b_{line}$ in 1σ C.L. After adding the cross-power spectra in the fitting process, we can get apparently better constraint results. We also find that the contours of SFRD versus $b_{line}$ are not regular, that even the degeneracy direction is not quite obvious in some cases. This is because the “nuisance” parameters, such as SFRD and line bias parameters of the other (signal or interloper) lines and shot-noise terms, can significantly disturb the shape of the parameter space and result in irregular parameter contours.

In addition, we can find that the perfect degeneracy between SFRD (or mean intensity $I_{line}$, see Equations (15)–(18) for details) and line bias $b_{line}$ can be broken to some extent by adopting multipole moments of the power spectrum with redshift distortion as shown in both Figures 7 and 8. This provides support for the discussion in Section 4.1 about the advantage of using a redshift-space power spectrum (Chen et al. 2016; Lidz & Taylor 2016). Besides, since we can obtain good constraints on SFRD and $b_{line}$ for both the signal and interloper lines, it implies that the power spectra of the signal and interloper lines can be distinguished in the fitting process, as we discuss and show in Section 4.2 and Figure 3. This proves that the multipole moments of the redshift-space power spectrum are feasible and effective for extracting the information of the cosmological and astrophysical quantities.

We show the best-fitting SFRD and 1σ error for the signal and interloper lines as a function of redshift in Figure 9. The gray dashed curve denotes the fiducial values of SFRD at different redshifts given by Hopkins & Beacom (2006). We can see the fitting results are consistent with the fiducial values at 1σ C.L. We notice that our results are worse than the prediction given by Gong et al. (2017). This is because it is actually an optimistic estimate in Gong et al. (2017), that only SFRD is set as a free parameter and the Fisher matrix method is simply adopted in that work. In this study, we have included a much larger number of components and free parameters in the model, and use the MCMC technique with mock data to obtain more realistic and reliable results.

We should also note that the constraint results shown in this section are only derived from the observations at $z=1$ as an example. At $z>1$, the constraints may not be as strong as that at $z=1$ considering the strength of the signal line, interloper lines, and cross-correlations with ordinary galaxy surveys. However, in a real survey like SPHEREx, more lower and higher redshifts of the signal lines will be explored at different bands in the meantime, and a lot more data can be obtained and used to constrain the cosmological and astrophysical parameters simultaneously. This will undoubtedly provide tighter constraints on these parameters, and can be even better than an ordinary galaxy survey, especially for the universe at high redshifts.

9. Summary

In this work, we proposed using the multipole moments of the redshift-space intensity power spectrum of emission lines for constraining the cosmological and astrophysical parameters. In principle, the multipole power spectrum can effectively distinguish the signal and interloper emission lines, and break degeneracy between the line mean intensity and bias in the model.

We include the time-variable equation of state of dark energy, massive neutrinos, and primordial non-Gaussianity in
the model, which can change both kinematical and dynamical evolution of the universe. The mean line intensity is estimated by the SFRD derived from observations. Then we calculate the multipole moments of redshift-space intensity power spectra of \( \text{H}\alpha \) 6563 Å, [O III] 5007 Å, and [O II] 3727 Å at \( 1 \lesssim z \lesssim 3 \). In order to discuss the observed power spectra with interloper lines, we evaluate the total observed multipole power spectra of the three emission lines at \( z = 1 \), and the uncertainties of the power spectra from observations are also estimated.

In the discussion of line detection, we take the SPHEREx experiment as an example to explore the measurements of the three emission lines, and also compute cross-power spectra by including the CSST spectroscopic galaxy survey. The MCMC method is adopted for fitting the cosmological and astrophysical parameters in the model for the three emission lines with interlopers.

We find that the cosmological and astrophysical parameters can be properly constrained, and the best fits are consistent with the fiducial values in \( 1\sigma \) C.L. This provides strong support for the advantages of the multipole power spectrum for extracting information of cosmological and astrophysical quantities, and proves that this method is feasible and effective. The constraints can be further improved by involving the measurements from other redshifts and cross-correlations between different lines, which can even get better results than traditional galaxy surveys, especially for probing the universe at high redshifts.

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