COSMOLOGICAL DEPENDENCE OF THE MEASUREMENTS OF LUMINOSITY FUNCTION, PROJECTED CLUSTERING AND GALAXY–GALAXY LENSING SIGNAL

Surhud More
Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-shi, Chiba 277-8583, Japan; surhud.more@ipmu.jp

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ABSTRACT

Observables such as the galaxy luminosity function, $\Phi(M)$, projected galaxy clustering, $w_p(r_p)$, and the galaxy–galaxy lensing signal, $\Delta\Sigma(r_p)$, are often measured from galaxy redshift surveys assuming a fiducial cosmological model for calculating distances to, and between galaxies. There are a growing number of studies that perform joint analyses of these measurements and constrain cosmological parameters. We quantify the amount by which such measurements systematically vary as the fiducial cosmology used for the measurements is changed, and show that these effects can be significant at high redshifts ($z \sim 0.5$). Cosmological analyses (or halo occupation distribution analyses) that use the luminosity function, clustering and the galaxy–galaxy lensing signal but ignore such systematic effects may bias the inference of the parameters. We present a simple way to account for the differences in the cosmological model used for the measurements and those used for the prediction of observables, thus allowing a fair comparison between models and data.

Key words: cosmology: observations – dark matter – galaxies: distances and redshifts – large-scale structure of universe

Online-only material: color figures

1. INTRODUCTION

Large scale galaxy surveys such as the Sloan Digital Sky Survey (SDSS hereafter) have revolutionized the field of galaxy formation and cosmology. Data from such surveys has enabled precise measurements of galaxy abundance (see, e.g., Blanton et al. 2003), galaxy clustering as a function of luminosity (see, e.g., Zehavi et al. 2011) and the galaxy–galaxy lensing signal (see, e.g., Sheldon et al. 2004; Mandelbaum et al. 2006, 2013). These measurements have been used to constrain an important outcome of galaxy formation processes, the relationship between galaxy luminosity (or stellar mass) and the underlying halo mass (Cacciato et al. 2009, 2013; Leauthaud et al. 2012; Tinker et al. 2013). It has also been argued that a joint analysis of these measurements can be used to constrain cosmological parameters, such as the matter density parameter and the amplitude of cosmological fluctuations using data on small scales (see, e.g., Seljak et al. 2005; Yoo et al. 2006; Cacciato et al. 2009; van den Bosch et al. 2013; More et al. 2013) and on large scales (Baldauf et al. 2010; Mandelbaum et al. 2013). Cosmological constraints have been obtained using the clustering of galaxies combined with other observables such as the mass-to-light ratio on cluster scales (van den Bosch et al. 2003, 2007; Tinker et al. 2005), the mass-to-number ratio (Tinker et al. 2012) or the galaxy–galaxy lensing signal (Cacciato et al. 2013; Mandelbaum et al. 2013).

To measure observables such as the luminosity function, the projected clustering signal and galaxy–galaxy lensing, the galaxy angular positions and redshifts are converted to distances between us and the galaxies and between the galaxies themselves. These conversions are cosmology-dependent. It would be incorrect to assume that the measurements do not change when the cosmological model used to analyze the data is changed. Fitting analytical models to the same measurements with varying cosmological parameters can affect the constraints derived on these parameters. Such problems can be mitigated if instead the angular clustering of galaxies and angular galaxy–shear (or shear–shear) correlation measurements are used (see, e.g., Oguri & Takada 2011), which do not require the assumption of a fiducial cosmological model.

The objective of this Letter is to quantify the effect of changing the fiducial cosmological model used to measure the particular set of observables, $\Phi(M)$, $w_p(r_p)$ and $\Delta\Sigma(r_p)$, and show that it is straightforward to account for such biases. In Section 2, we quantify the sensitivity of each of these measurements to the assumed cosmological model. In Section 3, we use the example of the projected clustering signal to demonstrate that the effect on measurements of the changing reference model can be accounted for in a simple manner, and we summarize the results in Section 4. Since the set of observables we consider are often measured in units which keeps their dependence on the Hubble parameter $h = H_0/100$ km s$^{-1}$ Mpc$^{-1}$ transparent (for example, $w_p(r_p)$ is measured in $h^{-1}$ Mpc), we will not explore differences in cosmological models with different values of $h$.

2. ANALYTICAL ESTIMATES

2.1. Galaxy Luminosity Function

The galaxy abundance is quantified by measurements of the luminosity function, $\Phi(M)dM$, which reflects the average number density of galaxies within the absolute magnitude range $M \pm dM/2$. Luminosity functions are often determined from flux-limited surveys and require us to convert the apparent magnitude, $m$, of a galaxy into an absolute magnitude, and obtain the maximum distance out to which a galaxy with a given luminosity could have been observed given the flux limit of the survey. These conversions are dependent on the assumed cosmology in the following manner.

The apparent magnitude of a galaxy at redshift $z$ is related to the absolute magnitude via the distance modulus $\mu(z) = 5.0 \log(D_{\text{lim}}[z, \Omega]) + 25$, $M = m - \mu(z)$, (1)
where \( D_{\text{lum}}(z, \Omega) \) is the luminosity distance (in units of \( h^{-1} \) Mpc) in a particular cosmological model, \( \Omega \). The maximum comoving distance, \( \chi_{\text{max}} \), from which this object can be observed given the magnitude limit \( m_{\text{lum}} \) of the survey is given by

\[
\chi_{\text{max}} = \frac{1}{1+z} 10^{0.2(m_{\text{lum}} - M - 25)}. \tag{2}
\]

Thus differences in cosmology change the luminosity of galaxies and the change in \( \chi_{\text{max}} \) affects the normalization of the luminosity function.

To estimate the amount by which the luminosity function changes due to a change in the cosmological model, let us assume that the luminosity function changes extremely weakly with redshift within the survey area used to estimate it using some fiducial cosmological model.\(^1\) The luminosity function \( \Phi(M, \Omega) \), measured in some fiducial cosmological model \( \Omega \), can be used to calculate the redshift dependence of the apparent magnitude counts \( N(m, z) dmdz \) per unit steradian, which is the observable in a true sense,

\[
N(m, z) dmdz = \Phi(m - \mu[z, \Omega]) dm d\tilde{z} \frac{d\tilde{x}}{dz} d\tilde{z}. \tag{3}
\]

These number counts can be reinterpreted as a luminosity function in a cosmological model, \( \Omega \), other than the fiducial model, using the following equation,

\[
\Phi(M, \Omega) dM = \frac{1}{V} \int_0^{\chi_{\text{max}}} N(M + \mu[z, \Omega], z) dM dz \tag{4}
\]

\[
= \frac{1}{V} \int_0^{\chi_{\text{max}}} \Phi(M + \mu[z, \Omega] - \mu[z, \Omega]) \times dM \tilde{x} \frac{d\tilde{x}}{dz} d\tilde{z}. \tag{5}
\]

Here, \( z_{\text{max}} \) denotes the maximum redshift to which a galaxy can be observed in the redshift survey, given its absolute magnitude in the cosmological model \( \Omega \), and \( V \) denotes the comoving volume encompassed by the universe below this redshift. In Figure 1, we use the Schechter fit for the luminosity function provided by Blanton et al. (2003) in an \( \Omega_m = 0.3 \) model and show the residuals of the luminosity function in \( \Omega_m = 0.25 \) and \( \Omega_m = 0.35 \) models computed using the above equation. The range of cosmological models is chosen to be such that it is well within the range of cosmological constraints obtained by a number of joint analyses involving abundance, clustering and lensing measurement. We have assumed a magnitude limit in the \( r \)-band of 17.77 corresponding to the spectroscopic sample in SDSS.

Although the measurement errors on the luminosity function are large, the difference is a systematic change in the shape of the luminosity function, and can be as large as \( \sim 20\% \) at the bright end. Since the errorbars are difficult to propagate in an integral equation such as the one above, the ideal way is to change the prediction for a particular cosmological model to predict the counts in the fiducial model used to obtain the luminosity function.

2.2. Projected Clustering Measurement

For a flat \( \Lambda \)CDM model, the projected and the line-of-sight comoving separations between galaxies separated in redshift by a small difference \( \Delta z \) is given by,

\[
r_p = \chi(z_{\text{eff}}) \theta; \quad \pi = \frac{c}{H_0 E(z_{\text{eff}})} \Delta z, \tag{6}
\]

respectively, where \( \chi(z_{\text{eff}}) \) is the comoving distance to the effective redshift \( z_{\text{eff}} \), \( \theta \) denotes the angular separation between the galaxies, \( H_0 \) is the Hubble constant and \( E(z) \) is the expansion function. We have ignored the finite redshift width of the galaxy sample and assumed an effective redshift to convert the angular positions and redshift into distances. These equations can then be used to count the number of pairs of galaxies at a given separation vector \( (r_p, \pi, \tau) \), and compare it to the number of pairs expected if the galaxies were distributed at random. The excess number of pairs over those expected in a random distribution gives the clustering signal at the effective redshift, \( \xi(r_p, \pi, z) \). The projected clustering is then obtained by integrating \( \xi(r_p, \pi, z) \) along the line-of-sight,

\[
w_p(r_p, z_{\text{eff}}) = 2 \int_0^{\pi_{\text{max}}} \xi(r_p, \pi, z_{\text{eff}}) d\pi,
\]

\[
= 2 \int_0^{\Delta z_{\text{max}}} \xi(r_p, \pi, z_{\text{eff}}) \frac{c}{H_0 E(z_{\text{eff}})} d(\Delta z). \tag{8}
\]

The changes to the luminosity of galaxies due to a change in cosmology can slightly alter which galaxies enter a volume-limited sample. In addition, there are three different ways in which the \( w_p \) measurements are affected. If a cosmology other than the fiducial is used to analyze data, then a given angular scale corresponds to a different comoving projected separation scale. This difference can be small at low redshift (see Zehavi et al. 2011; \( \sim 1\% \) due to a change in \( \Omega_m \) from 0.25 to 0.3 at \( z = 0.15 \)). As \( w_p \propto r_p^{-1} \), the change in projected separation scale roughly corresponds to a similar change in the value of \( w_p(r_p) \) when the cosmology is changed.

The second effect is due to a change in the factor \( E(z) \) as the cosmology is changed, and this changes the value of \( w_p(r_p) \) by a multiplicative constant at all scales. This effect is important, especially at higher redshift (at \( z \sim 0.5 \), the difference in the \( E(z) \) is \( 3.5\% \) between \( \Omega_m \) of 0.25 and 0.3). Such effects due to the change of transverse (and line-of-sight) scales are usually taken into account when analyzing baryon acoustic oscillations (see, e.g., Blake & Glazebrook 2003; Eisenstein et al. 2005; Percival et al. 2007; Anderson et al. 2012) and redshift space distortions (see, e.g., Ballinger et al. 1996; Tegmark et al. 2006; Blake et al. 2011).
The third effect on $w_{p}(r_{p})$ is subtle and related to the change in the integration limit in the above equation, as a given value of $\pi_{\text{max}}$ corresponds to a different value of $\Delta_{\text{max}}$. For sufficiently large values of $\pi_{\text{max}}$, as are employed in observations (typically $60 \sim 100 \ h^{-1} \ Mpc$), this effect is quite small as the value of $\xi(r_{p}, \pi)$ at large values of $\pi$ does not dominate the $w_{p}(r_{p})$ integral. Note however, that even this small difference can be easily accounted for by adopting a different $\pi_{\text{max}}$ value when computing the analytical prediction.

In Table 1, we present the ratios of the comoving distance and the expansion function for three different cosmological models, at different redshifts. The fractions $f^{\Omega_{m}=0.30}_{E(\pi)}$ and $f^{\Omega_{m}=0.30}_{E(\chi)}$ are defined in the caption, and are chosen such that they correspond to the deviations in the clustering signal expected when data is analyzed in two different cosmologies (this is approximate since $w_{p}$ is not exactly proportional to $r_{p}^{-1}$). The two effects change the clustering signal in the same direction.

It can be seen that the combination of the first two effects is small, $\sim 1\%$ differences between the $\Omega_{m} = 0.25$ and $\Omega_{m} = 0.30$ models (although they are systematically in the same direction on all scales) for low redshift ($z \sim 0.1$) analyses. At $z \sim 0.5$, the effects cause $\sim 5\%$ differences between the two cosmological models above and can be very important given the statistical errors in measurements of $w_{p}(r_{p})$ by current and upcoming large surveys.

### 2.3. Galaxy–Galaxy Lensing Measurement

The primary observable for the galaxy–galaxy lensing signal is the tangential ellipticity of background galaxies in the vicinity of foreground galaxies. The galaxy–galaxy lensing signal is often reported as the excess surface density, $\Delta \Sigma$, by averaging the tangential component of ellipticity around an ensemble of galaxies

$$\Delta \Sigma(r_{p}) = \Sigma_{\text{crit}}(z_{l}, z_{s})(e)(r_{p}),$$

where $r_{p}$ denotes the projected comoving separation $r_{p}$ between the two galaxies at the redshift of the foreground lens, and $\Sigma_{\text{crit}}(z_{l}, z_{s})$ is a cosmology-dependent factor called the critical surface density which is defined as

$$\Sigma_{\text{crit}}(z_{l}, z_{s}) = \frac{c^{2}}{4\pi G} \frac{D_{\Lambda}(z_{l})(1 + z_{l})^{-2}}{D_{\Lambda}(z_{s})D_{\Lambda}(z_{l})}. \ (10)$$

Here $D_{\Lambda}(z_{l})$, $D_{\Lambda}(z_{s})$ and $D_{\Lambda}(z_{l}, z_{s})$ are the angular diameter distances to the lens, the source, and between the lens and source, respectively, and the $(1 + z_{l})^{-2}$ factor arises from the use of comoving units.

Cosmology dependence enters the measurement of $\Delta \Sigma$ in two ways. The first one is similar to that discussed in the previous subsection. A given angular scale on the sky corresponds to different comoving projected scales in different cosmological models. Since the excess surface density is also roughly proportional to $r_{p}^{-1}$, the percentage change in $\Delta \Sigma$ is similar to the percentage in the comoving distances. The second effect leads to a change in the normalization of $\Delta \Sigma$ due to the dependence of $\Sigma_{\text{crit}}$ on the cosmological parameters and depends upon both the source and lens redshift distribution.

In Table 2, we calculate the ratios of the comoving distance and the critical surface density for three different cosmological models and for different combinations of source and lens redshift, to quantify the effect it can have on the galaxy–galaxy lensing signal. The fraction $f^{\Omega_{m}=0.30}_{\Sigma_{\text{crit}}(z_{l}, z_{s})}$ is defined as the ratio of the critical surface density in a cosmological model to that in another cosmology, i.e., $f^{\Omega_{m}=0.30}_{\Sigma_{\text{crit}}(z_{l}, z_{s})} = \Sigma_{\text{crit}}(z_{l}, z_{s}, \Omega_{m} = 0.30)/\Sigma_{\text{crit}}(z_{l}, z_{s}, \Omega_{m})$.

| Redshift | $\Omega_{m}$ | $f^{\Omega_{m}=0.30}_{E(\pi)}$ | $f^{\Omega_{m}=0.30}_{E(\chi)}$ |
|----------|-------------|-------------------------------|-------------------------------|
| 0.1      | 0.25        | 0.996                         | 0.992                         |
| 0.1      | 0.30        | 1.000                         | 1.000                         |
| 0.1      | 0.35        | 1.004                         | 1.007                         |
| 0.3      | 0.25        | 0.989                         | 0.978                         |
| 0.3      | 0.30        | 1.000                         | 1.000                         |
| 0.3      | 0.35        | 1.011                         | 1.022                         |
| 0.5      | 0.25        | 0.982                         | 0.965                         |
| 0.5      | 0.30        | 1.000                         | 1.000                         |
| 0.5      | 0.35        | 1.017                         | 1.034                         |

| Redshift | $\Omega_{m}$ | $f^{\Omega_{m}=0.30}_{E(\pi)}$ | $f^{\Omega_{m}=0.30}_{E(\chi)}$ |
|----------|-------------|-------------------------------|-------------------------------|
| 0.1      | 0.5        | 0.25                          | 0.996                         |
| 0.1      | 0.5        | 0.30                          | 1.000                         |
| 0.1      | 0.5        | 0.35                          | 1.004                         |
| 0.3      | 0.7        | 0.25                          | 0.996                         |
| 0.3      | 0.7        | 0.30                          | 1.000                         |
| 0.3      | 0.7        | 0.35                          | 1.004                         |
| 0.5      | 0.8        | 0.25                          | 0.982                         |
| 0.5      | 0.8        | 0.30                          | 1.000                         |
| 0.5      | 0.8        | 0.35                          | 1.017                         |
| 0.5      | 2.0        | 0.25                          | 0.982                         |
| 0.5      | 2.0        | 0.30                          | 1.000                         |
| 0.5      | 2.0        | 0.35                          | 1.017                         |
constant normalization shift fairly independent of the source redshift distribution. This correction can then be calculated at the median redshift of the source galaxy population and applied to the model before comparing to the data. In Figure 2, we compare the differences in $\Delta \Sigma$ at $z \sim 0.5$ expected based on the above discussion, when the fiducial cosmological model used for the measurements is changed. We find that the deviations can be of the order of $\sim 2\% - 2.5\%$ between $\Omega_m = 0.25$ and $\Omega_m = 0.30$ models. Although small compared to errors possible with existing data, it is important to note that they are systematically in the opposite direction to the clustering signal. The errors are expected to be reduced to 5% or better with upcoming surveys such as the Hyper Suprime-Cam survey\(^2\) (Miyazaki et al. 2012).

3. TESTS ON REAL DATA FOR THE PROJECTED CLUSTERING FUNCTION

We now use galaxies from the SDSS-III Baryon Oscillation Spectroscopic Survey project Data Release 9 (hereafter BOSS; Dawson et al. 2013; Ahn et al. 2012), and demonstrate, for the case of the projected clustering measurement, how well the effects mentioned in Section 2.2 capture the relevant changes to the measurement. We analyze the projected clustering using three different cosmological models and show that they differ by the amount expected from the discussion in the previous section. We choose all galaxies in the northern region of BOSS with redshifts between $z \in [0.47, 0.59]$ and $M_r > 10^{10.5} M_\odot$ where $M_r$ denotes the stellar mass calculated using the stellar population synthesis models produced by the Portsmouth group (Maraston et al. 2013). The effective redshift of the sample is $z_{\text{eff}} = 0.53$.

In the top panel of Figure 3, we show the projected clustering measured by assuming three different flat $\Lambda$CDM cosmological models with varying $\Omega_m$ while converting the angular positions and redshifts to distances. The solid circles in the lower panel denote the differences between the measured clustering signal in a given cosmological model to that in the $\Omega_m = 0.30$ model. The measurement errorbars are small enough that the differences between the cosmological models are larger than the statistical error and are systematic in nature. Fitting a constant to the (inverse variance-weighted) residuals results in $0.062 \pm 0.005 (-0.042 \pm 0.003)$ for the $\Omega_m = 0.25 (0.35)$ model.\(^3\)

Next we take the measurements in the $\Omega_m = 0.25$ model, and predict the clustering expected in the $\Omega_m = 0.30$ model as follows. To account for the first effect discussed in Section 2.2, we change the projected comoving scale of the measurement from the $\Omega_m = 0.25$ analysis to

$$r_p^{\text{corr}} = r_p(\Omega_m = 0.25) \frac{\chi(z_{\text{eff}}, \Omega_m = 0.30)}{\chi(z_{\text{eff}}, \Omega_m = 0.25)}.$$  \hfill (11)

In addition we also change the amplitude of $w_p$ such that

$$w_p^{\text{corr}} = w_p(\Omega_m = 0.25) \frac{E(z_{\text{eff}}, \Omega_m = 0.25)}{E(z_{\text{eff}}, \Omega_m = 0.30)}.$$  \hfill (12)

We also use similar corrections to the clustering measurements in the $\Omega_m = 0.35$ model to deduce the clustering measurements in the $\Omega_m = 0.30$ model. The filled triangles in the bottom panel of Figure 3 show the difference between these corrected clustering measurement and the projected clustering measurement in the $\Omega_m = 0.30$ model using filled triangles (the green (red) triangles correspond to the $\Omega_m = 0.25 (0.35)$ model corrected to that in $\Omega_m = 0.30$). We see that this recovers the clustering measurement very accurately. A constant model fit to the residuals now gives $0.004 \pm 0.005 (0.005 \pm 0.004)$ for the

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\(^2\) http://www.naoj.org/Projects/HSC/index.html

\(^3\) With the DR11 catalogs (SDSS-BOSS internal data release) the differences are even more statistically significant.
\( \Omega_m = 0.25 \) (0.35) model and the residuals no longer have either just a positive or negative sign.

Although in our case we have corrected the data for the cosmological dependence, in modeling applications it is better to account for the differences in the model itself. Errors, typically assessed using a jack-knife estimator (with regions of equal areal coverage), will not depend upon the cosmological model. But errors obtained using covariances with mock simulations populated with galaxies may require revision as well. Exploring these details is beyond the scope of this Letter.

4. SUMMARY

We have presented analytical estimates for the cosmological dependence of the galaxy luminosity function, \( \Phi(M) \), the projected clustering measurement, \( w_p(r_p) \), and the galaxy–galaxy lensing signal \( \Delta \Sigma \) obtained from a galaxy redshift survey. We showed that these measurements change in different cosmological models due to the difference in the comoving distances, \( \chi(z) \), the expansion functions, \( E(z) \), and the change to the critical surface density between the lens and source galaxies used to measure the lensing signal.

These changes are small for low redshift surveys such as SDSS-I, but given the systematic nature of the shifts, they can bias the cosmological constraints obtained from a joint analysis of \( \Phi(M) \), \( w_p(r_p) \) and \( \Delta \Sigma \). These systematic effects can be very important at higher redshifts which use these observables and for ongoing and future surveys which can measure these observables with ever-increasing precision. Performing a cosmological analysis with these observables requires one to account for the cosmological parameter dependence of the observables themselves. We have presented analytical expressions which can be used to change the predictions for a particular cosmological model to the ones in the fiducial cosmological model used for the analysis, thus allowing a fair comparison between model and data.

We tested these expressions for the specific case of the projected clustering measurement \( w_p(r_p) \) using existing data from the SDSS-BOSS survey. We analyzed these data in the context of three different flat ΛCDM cosmological models. We found that the differences in the measurements are systematic in nature and significant given the errorbars. We also found that our expressions can predict these differences correctly.

In cosmological analyses it is best to correct the predictions to account for the fiducial cosmological model used to make the measurements of \( \Phi \), \( w_p \) and \( \Delta \Sigma \). If such analyses are run without accounting for the systematic issues we highlight, one runs the risk of biasing the cosmological parameters to values close to the ones assumed in the fiducial cosmology. In future work, we plan to quantify how the recent cosmological constraints obtained using joint fits to abundance, clustering and lensing of galaxies by Cacciato et al. (2013) may be affected due to these systematic issues. We also plan to investigate the effects of these systematics on the joint analysis of clustering and lensing on large scales in Mandelbaum et al. (2013), especially for the high redshift sample.

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