Impact of Catastrophic Photometric Redshifts on Constraints on the Dark Energy Equation of State Parameter from Baryon Acoustic Oscillations and Weak Gravitational Lensing Postprint

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Abstract

We investigate the complementary effects of Baryon Acoustic Oscillations (BAO) and Weak Lensing (WL) in the presence of catastrophic photometric redshift errors, as well as the impact of catastrophic photometric redshift errors on constraining dark energy equation of state parameters. For the Large Synoptic Survey Telescope (LSST)-like survey, we construct models for catastrophic photometric redshift errors that are locally distributed in the upper left (UL) and bottom right (BR) corners of the z-zph plane, and use the Fisher Matrix to estimate their respective impacts on BAO, WL, and joint BAO+WL constraints on dark energy equation of state parameters. If the fitting model does not include the actual catastrophic photometric redshift errors, the biases caused by UL and BR catastrophic photometric redshift errors are not always of the same sign. BAO is least affected by catastrophic photometric redshift errors; for a total fraction of catastrophic photometric redshift errors of F, = 0. 02, the maximum impact is only the biases on w0 and wa caused by the UL and BR components, with a relative bias of approximately 30%. However, for WL and joint BAO+WL, the biases are typically several times larger, thus the impact of catastrophic photometric redshift errors cannot be ignored. Additionally, for WL constraints on w0, the biases from UL and BR are nearly equal in magnitude but opposite in sign, resulting in a very small overall impact. When the fitting model includes catastrophic photometric redshift errors, although the photometric redshift error distribution model gains 45 additional degrees of freedom, the complementary effects between BAO and WL remain strong for the same training set size. Under these conditions, the errors on dark energy equation of state parameters do not increase significantly. In particular, the increase in BAO constraint errors is less than 1%. WL constraint errors on w0 and wa increase by approximately 14% (UL+BR) and 6% (UL+BR), respectively, while joint BAO+WL constraint errors on w0 and wa increase by only about 5% (UL+BR)}

Full Text

The Impact of Catastrophic Photometric Redshift Errors on Constraints of Dark Energy Equation of State Parameters from Baryon Acoustic Oscillations and Weak Lensing

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Abstract

This paper investigates the impact of catastrophic photometric redshift (photo-z) errors on constraints of dark energy equation of state (EOS) parameters and examines the complementarity between baryon acoustic oscillations (BAO) and weak lensing (WL). Targeting LSST-like survey projects, we construct a localized catastrophic photo-z error distribution model in the upper-left (UL) and bottom-right (BR) regions of the $z_{\rm ph}$-z plane. Using the Fisher matrix method, we forecast the effects on dark energy EOS parameter constraints from BAO, WL, and joint BAO+WL analyses. When catastrophic photo-z errors are present but not included in the fitting model, the resulting biases from UL and BR regions are not always of the same sign. BAO suffers the least from catastrophic photo-z errors; for a total catastrophic outlier fraction of $F_t = 0.02$, the maximum impact is only about 30% of the statistical error on BAO. However, for WL and BAO+WL, the biases are typically several times larger, demonstrating that catastrophic photo-z errors cannot be ignored. Notably, for WL constraints on w_0, the biases from UL and BR regions are nearly equal in magnitude but opposite in sign, causing the total impact to be significantly reduced. When catastrophic photo-z errors are included in the fitting model, the complementarity between BAO and WL remains strong despite the addition of 45 degrees of freedom. Under these conditions, the errors on dark energy EOS parameters do not increase substantially. In particular, the constraint on w_a from BAO increases by less than 1%, while the errors on w_0 and w_a from WL increase by approximately 14% (UL+BR) and 6% (UL+BR), respectively. For BAO+WL, the errors on both w_0 and w_a increase by about 5% (UL+BR).

Keywords: cosmology; large-scale structure; gravitational lensing; galaxy surveys; dark energy

1. Introduction

Weak gravitational lensing is considered a powerful tool for probing dark energy, as it studies the properties of dark energy and other cosmological parameters by measuring the shear of distant galaxy images. Many large survey telescopes, such as LSST, Euclid, and WFIRST, employ weak lensing as an important method for dark energy detection. Since the weak lensing signal is extremely weak, extracting useful information requires measuring vast samples of galaxy redshifts. Obtaining spectroscopic redshifts for all samples is temporally impractical, necessitating the use of multi-color photometric methods to estimate redshifts. Photometric redshifts are estimated through multi-band imaging using empirical formulas [?, ?], template fitting [?], artificial neural networks [?], and other methods. What is useful for cosmology is not the redshift of each individual galaxy, but rather the redshift distribution of galaxies, which can be determined through sampling measurements of true redshifts or calibrated using cosmological methods [?]. However, uncertainties in the redshift distribution inevitably propagate to the dark energy equation of state parameters and other cosmological parameters [?, ?].

If the photometric redshift error distribution for all galaxies in a true redshift interval can be approximated by a Gaussian distribution with a mean near the true redshift, the errors on dark energy parameters can be kept within a factor of 1.5 of the spectroscopic calibration case [?]. Due to confusion of spectral line features or lack of characteristic information in certain bands, catastrophic photometric redshift errors occur, particularly when the Lyman break and Balmer break in galaxy spectral energy distributions are confused, leading to large deviations between estimated photometric redshifts and true redshifts [?]. The existence of catastrophic photo-z errors biases estimates of dark energy equation of state parameters from weak lensing [?]. For catastrophic photo-z errors, one can reduce systematic errors by removing samples with high catastrophic error probability while not significantly increasing statistical errors from sample reduction [?, ?].

Baryon acoustic oscillations in the galaxy power spectrum or correlation function contain the sound horizon at the last scattering surface, providing a standard ruler to measure the Hubble parameter $H(z)$ and angular diameter distance $D_A(z)$ as functions of redshift [?]. In multi-color imaging surveys, constraints on dark energy equation of state parameters from BAO measurements of angular diameter distance alone at multiple redshifts suffer from significant degeneracy [?]. Uncertainty in the galaxy bias factor makes it difficult to extract additional information from the galaxy angular power spectrum [?, ?]. Due to the complementarity between BAO and WL, when galaxy-WL cross-power spectra are considered, WL can help calibrate the galaxy bias factor in the absence of catastrophic photo-z errors [?]. Furthermore, galaxy angular power spectra in different photometric redshift intervals are very sensitive to photo-z error distributions, providing strong self-calibration capabilities, and joint BAO+WL can provide stronger constraints on photometric redshift bias δz [?].

This paper studies the systematic biases in dark energy equation of state parameter estimates from BAO, WL, and joint constraints when localized catastrophic photo-z errors are present but not included in the fitting model. We then explore the complementarity between BAO and WL and their constraining power on dark energy EOS parameters when catastrophic photo-z errors are included in the model.

2. Methodology

2.1 Theoretical Framework Under the Limber approximation [?, ?], the angular power spectra for galaxies and weak lensing can be written as [?]:

$$C_{XY}(\ell) = \frac{2\pi^2 c}{\ell^3} \int dz\, H(z) D_A^2(z) W_X(z) W_Y(z) \Delta^2(k,z)$$

where c is the speed of light, $H(z)$, $D_A(z)$, and $\Delta^2(k,z)$ are respectively the Hubble parameter, comoving angular diameter distance, and dimensionless matter power spectrum at redshift z. The window functions $W_X(\ell)$ are defined as:

$$W_X(z) = b(z) n_i(z) \quad \text{for } X = g$$

$$W_X(z) = \int_z^\infty dz'\, n_i(z') \frac{H(z)}{c} \frac{D_A(z')}{D_A(z)} \quad \text{for } X = \gamma$$

where g and γ represent BAO and WL respectively, $b(z)$ is the linear galaxy bias factor, and $n_i(z)$ and $\bar{n}_i$ are the true redshift distribution and galaxy count in the i-th photometric redshift bin. The binning schemes for BAO and WL can be independent. In practice, observed power spectra include shot noise $\bar{n}_i^{-1}$ for galaxies and intrinsic shape noise $\gamma_{\text{rms}}^2 \bar{n}_i^{-1}$ for weak lensing:

$$\widehat{C}_{XY}^{ij}(\ell) = C_{XY}^{ij}(\ell) + \delta_{ij} \delta_{XY} N_X^i$$

where δ_{ij} is the Kronecker delta. We use the HaloFit model [?] with baryonic corrections [?] to compute the non-linear matter power spectrum at different redshifts. For galaxy angular power spectra, $\gamma_{\text{rms}} \equiv 1$, while for weak lensing, $\gamma_{\text{rms}} \sim 0.2$.

2.2 Survey Specifications and Model Parameters Our model includes 7 cosmological parameters, 30 galaxy bias factors, 60 core photo-z error distribution parameters, and when catastrophic photo-z errors are included, an additional 45 catastrophic photo-z error distribution parameters.

Without catastrophic photo-z errors, the true redshift distribution in each photometric redshift bin is described by a Gaussian function. In the presence of catastrophic photo-z errors, an additional Gaussian function describes the catastrophic component. Assuming the survey' s photometric redshift distribution is uniform from $z_{\mathrm{ph}} = 0$ to $z_{\mathrm{ph}} = 3$, divided into $n = 30$ bins of width $\Delta z = 0.1$, the true redshift distribution for galaxies in the i-th bin can be approximated by:

$$n_i(z) = \frac{1-f_i}{\sqrt{2\pi}\sigma_{\mathrm{core,i}}} \exp\left[-\frac{(z-z_{\mathrm{core,i}})^2}{2\sigma^2_{\mathrm{core,i}}}\right] + \frac{f_i}{\sqrt{2\pi}\sigma_{\mathrm{cat,i}}} \exp\left[-\frac{(z-z_{\mathrm{cat,i}})^2}{2\sigma^2_{\mathrm{cat,i}}}\right]$$

where $z_{\mathrm{core,i}}$ and $\sigma_{\mathrm{core,i}}$ are the mean and standard deviation of the core distribution, f_i is the fraction of catastrophic outliers, and $z_{\mathrm{cat,i}}$ and $\sigma_{\mathrm{cat,i}}$ describe the catastrophic component.

For the core component, we adopt fiducial values $z_{\mathrm{core,i}} = z_i$ (the bin center) and $\sigma_{\mathrm{core,i}} = 0.05(1+z_i)$ [**?**, **?**]. The first 30 bins ($i = 0-29$) serve as BAO bins, which are merged into 6 WL bins ($i = 0-5$). The galaxy distribution and counts for WL bins are obtained from their constituent BAO bins.

Catastrophic photo-z errors occur when spectral features are confused or when spectra lack sufficient information, particularly when the Lyman break and Balmer break are confused. This leads to localized catastrophic photo-z distributions in the upper-left and bottom-right regions of the z_{ph}-z plane [**?**]. We construct models where catastrophic errors appear in these regions: the upper-left region affects the first 15 bins ($i = 0-14$) while the bottom-right region affects the last 15 bins ($i = 15-29$). For all bins with catastrophic errors, we adopt uniform fiducial parameters $z_{\mathrm{cat,i}} = 0.5$ (for UL) or $z_{\mathrm{cat,i}} = 2.5$ (for BR) and $\sigma_{\mathrm{cat,i}} = 0.2$.

The total catastrophic fraction F_t determines f_i through the relation $f_i = 3.65F_t$ when $F_t = 0.02$. The galaxy bias factor $b(z)$ is parameterized with 30 nodes (one per BAO bin), with fiducial values following $b(z) = 1+0.84z$ [**?**]. The prior errors on photo-z model parameters scale with the number of spectroscopic redshifts n_{tr} used for calibration as $\sigma_{z_{\mathrm{core,i}}} = \sigma_{\sigma_{\mathrm{core,i}}} = \frac{0.05}{\sqrt{n_{\mathrm{tr}}\times(1-f_i)}}$ and $\sigma_{f_i} = \sqrt{f_i/(n_{\mathrm{tr}}\times\bar{n}_i)}$ [**?**]. We adopt $n_{\mathrm{tr}} = 400$ and $\Delta\ln\ell = 0.5$.

Cosmological parameters and their priors are listed in Table 1 , based on Planck 2013 results [**?**]. Galaxy bias priors are 15%.

2.3 Fisher Matrix Formalism The Fisher matrix for parameters $\{p_\alpha\}$ is [**?**]:

$$F_{\alpha\beta} = \sum_{\ell} \frac{(2\ell+1)f_{\mathrm{sky}}}{2} \frac{\partial O_u(\ell)}{\partial p_\alpha} C^{-1}_{uv} \frac{\partial O_v(\ell)}{\partial p_\beta}$$

where $O_u(\ell)$ is a vector of independent observables (power spectra $P_{XY}^{ij}(\ell)$), C_{uv} is the covariance matrix, and f_{sky} is the sky coverage fraction. For Gaussian observables, $C_{uv} = P_{mr}P_{ns} + P_{ms}P_{nr}$. The parameter covariance matrix is the inverse of the Fisher matrix.

Systematic errors δO_u in observables cause parameter biases:

$$\delta p_\alpha = F_{\alpha\beta}^{-1} \sum_{u,v} \frac{\partial O_u}{\partial p_\beta} C_{uv}^{-1} \delta O_v$$

We compute marginalized errors for all parameters. To avoid dark energy clustering effects, we exclude large-scale galaxy and shear statistics [**?**]. BAO analysis requires $\ell > 0.5$ to avoid small-scale non-linear effects and baryonic physics [**?**, **?**], while WL uses $\ell < 2000$.

3. Results

3.1 Systematic Biases from Ignored Catastrophic Photo-z Errors Figure 2 [Figure 2: see original paper] shows the systematic biases on dark energy EOS parameters as a function of total catastrophic fraction F_t. When only UL or BR catastrophic errors are present, the biases on w_0 from BAO are opposite in sign but similar in magnitude. For WL constraints on w_0, the biases from UL and BR are nearly equal in magnitude but opposite in sign, reducing the total impact. BAO is least affected by catastrophic photo-z errors; for $F_t = 0.02$, the maximum impact on BAO is only about 30% of the statistical error. However, for WL and BAO+WL, biases are typically several times larger, demonstrating that catastrophic photo-z errors cannot be ignored.

Table 2 quantifies the systematic biases for $F_t = 0.02$. The relative bias $\delta p/\sigma$ can reach several times the statistical error for WL and BAO+WL.

The reason catastrophic photo-z errors affect WL more than BAO is that WL window functions are much broader than BAO window functions, especially at high redshift. Consequently, WL power spectra are more sensitive to catastrophic errors.

3.2 Constraints with Catastrophic Photo-z Errors Included in the Model When catastrophic photo-z errors are included in the fitting model, the complementarity between BAO and WL remains strong despite adding 45 degrees of freedom. Figure 3 [Figure 3: see original paper] compares constraints on galaxy bias factors and photo-z parameters with and without catastrophic errors for $F_t = 0.02$.

The constraints on galaxy bias factors b_i from BAO and BAO+WL are only significantly affected in bins with catastrophic errors, while intermediate bins remain largely unchanged. Even with catastrophic errors, joint BAO+WL still constrains galaxy bias better than BAO alone. The constraints on core photo-z parameters $z_{\text{core,i}}$ and $\sigma_{\text{core,i}}$ are slightly weakened but remain strong, particularly for WL.

Table 3 shows the dark energy EOS parameter constraints after including catastrophic photo-z errors in the model. For $F_t = 0.02$, the errors do not increase substantially. Specifically: - BAO constraints on w_a increase by <1% - WL constraints on w_0 and w_a increase by ~14% (UL+BR) and ~6% (UL+BR) - BAO+WL constraints on both w_0 and w_a increase by ~5% (UL+BR)

4. Summary and Discussion

We have constructed a localized catastrophic photo-z error distribution model in the UL and BR regions of the z_{ph}-z plane, and calculated the systematic biases on dark energy EOS parameters from BAO, WL, and joint BAO+WL when these errors are ignored. The biases from UL and BR regions can have opposite signs. BAO is least affected by catastrophic photo-z errors, while WL and BAO+WL show biases several times larger than statistical errors for $F_t = 0.02$, making catastrophic errors non-negligible.

When catastrophic photo-z errors are included in the model, BAO and WL maintain strong complementarity despite 45 additional degrees of freedom. The errors on dark energy EOS parameters increase only modestly. In particular, BAO constraints on w_a increase by <1%, WL constraints on w_0 and w_a increase by ~14% and ~6% respectively, and BAO+WL constraints increase by ~5% for both parameters.

The complementarity between BAO and WL persists because WL helps calibrate galaxy bias while different redshift bins provide strong self-calibration of photo-z errors. Even with localized catastrophic photo-z errors, this synergy remains effective, enabling robust constraints on dark energy parameters.

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Note: Figure translations are in progress. See original paper for figures.