Cross-correlating dark sirens and galaxies: measurement of $H_0$ from GWTC-3 of LIGO-Virgo-KAGRA

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We measure the Hubble constant of the Universe using spatial cross-correlation between gravitational wave (GW) sources without electromagnetic counterparts from the third GW Transient Catalog (GWTC-3), and the photometric galaxy surveys 2MPZ and WISE-SuperCOSMOS. Using the eight well-localised GW events, we obtain Hubble constant $H_0 = 68.2^{+26.0}_{-9.4}$ km/s/Mpc (median and 68.3% equal-tailed interval (ETI)) after marginalizing over the matter density and the GW bias parameters. Though the constraints are weak due to a limited number of GW sources and poor sky localization, they are not subject to assumptions regarding the GW mass distribution. By combining this measurement with the Hubble constant measurement from binary neutron star GW170817, we find a value of Hubble constant $H_0 = 67.0^{+6.3}_{-4.3}$ km/s/Mpc (median and 68.3% ETI).

Introduction – Discovery of gravitational waves (GW) [1] by the LIGO-Virgo-KAGRA (LVK) collaboration [2–7] has opened a new observational window to study the cosmos using transient sources such as binary black holes (BBHs), binary neutron stars (BNSs), and neutron star black holes (NSBHs). GW sources are uniquely accurate tracers of the luminosity distance. They can therefore be used to measure the expansion history of the Universe (Schutz [8]). This fact has earned GW sources the name standard sirens. However, one of the key ingredients required to measure the expansion history using GW sources is an independent measurement (or inference) of the GW source redshifts. In the absence of electromagnetic counterparts, a promising way to infer the GW source redshifts is through spatial cross-correlation of the GW sources with galaxies. By using the clustering redshift of the GW sources [9–11] or a 3D-cross correlation generalizing the Alcock-Paczynski effect [12–16], we can measure the cosmic expansion history after marginalizing over the GW bias parameters. Apart from cross-correlation techniques, statistical host identification [8, 17–26] and GW mass distribution [27–34] can also be used to infer redshifts for BBHs. However, the mass distribution of the BBHs can have intrinsic redshift dependence that influences parameter estimation, if the full mass distribution gets affected [32, 34].

LVK dark standard sirens have been used to measure the expansion history using O1+O2 data [23] and O1+O2+O3 data [35], in tandem with GLADE [36] and GLADE+ [37] for statistical host identification. The latest LVK measurement yields $H_0 = 68^{+8}_{-8}$ km/s/Mpc (68.3% highest density interval (HDI)) after combining with the bright siren GW170817 [35]. Other independent measurements of $H_0$ using statistical host identification have also been performed on the GW data [38, 39].

In this paper, we make the first measurement of the Hubble constant $H_0$ using the cross-correlation between the GWTC-3 catalog of the LVK collaboration [40] and the photometric galaxy surveys 2MPZ [41] and WISE-SuperCOSMOS (WSC) [42]. Though currently we cannot detect clustering between GW sources and galaxies due to the limited number of GW sources and poor sky localization error, this is the first proof of principle of this technique on data. The current measurement is limited by the lack of high redshift galaxies and the number of well localised GW sources. The statistical power in the cross-correlation technique with limited number of sources having poor sky localization error will be similar to (but not worse than) the statistical host identification technique. However, the cross-correlation measurement does not depend on assumptions about the GW source population, and provides an independent technique to infer the value of the Hubble constant.

Method – The compact objects of both astrophysical and primordial origin will exhibit spatial correlation with galaxies due to the underlying distribution of dark matter. This spatial correlation can be used to infer the clustering redshift of the dark standard sirens, by cross-correlating with photometric (or spectroscopic) galaxy

1 We have not used DeCALS [43] in this analysis, as discussed later
We estimate the cosmological parameters, Hubble constant $H_0$ and matter density $\Omega_m$, along with the GW bias parameter $b_{GW}(z) = b_{GW}(1 + z)^\alpha$ using a Bayesian framework.\footnote{\cite{14, 16}} The posterior on the parameters given the GW data $\theta_{GW}$ with $N_{GW}$ sources and galaxy data $\mathbf{d}_g$ with photometric redshifts $z_c$ can be written, after marginalizing over the nuisance parameters $\Theta_n \in \{b_{GW}, \alpha\}$, as \cite{14, 16}

$$
P(\Theta_n | \theta_{GW}, \mathbf{d}_g, z_c) \propto \iint d\Theta_n dz \prod_{i=1}^{N_{GW}} \Pi(z) \Pi(\Theta_n) \Pi(\Theta_c) \times \mathcal{P}(\theta_{GW} | \{C_{\ell}^{gg}(z_c)\}, \Theta_n, \mathbf{d}_g(z_c)) \times \mathcal{P}(\mathbf{d}_g(z_c) | \{C_{\ell}^{gg}(z_c)\}) \mathcal{P}(z_c) \times \mathcal{P}((\delta \ell_i)_{GW} | z, \Theta_c, \{\hat{\theta}, \hat{\phi}\}_{GW}),$$

where the likelihood $\mathcal{P}(\theta_{GW} | \{C_{\ell}^{gg}(z_c)\}, \Theta_n, \mathbf{d}_g(z_c))$ is written as

$$
P(\theta_{GW} | \{C_{\ell}^{gg}(z_c)\}, \Theta_n, \mathbf{d}_g(z_c)) \propto \exp \left( - 0.5 \sum_{\ell, \ell'} \sum_{\ell_b, \ell'_b} D(\ell_b, \ell'_b) \Sigma^{-1}_{C_{\ell_b}^{XY} C_{\ell'_b}^{XY}} D(\ell_b, \ell'_b) \right),$$

Here, $\ell_{\max}$ denotes the maximum value of the multipoles that can be explored (which depends on the sky localization error) and $D(\ell, z_c) = \delta_{GW}^\ell - C_{\ell}^{gg}(z_c)$. The angular cross-correlation power spectrum $C_{\ell}^{gg}(z_c)$ is obtained from cross-correlating GW sources detected above a network matched filtering SNR with galaxy catalogs $\mathbf{d}_g(z_c)$. The theoretical angular cross-power spectrum is written in terms of the galaxy auto-power spectrum $C_{\ell}^{gg}(z_c)$, the galaxy bias $b_g(z_c)$ and GW bias $b_{GW}(z_c)$ as $C_{\ell}^{GW \cdot g}(z_c) = b_{GW}(z_c) b_g(z_c) C_{\ell}^{gg}(z_c)$. The term $\mathcal{P}(\mathbf{d}_g(z_c) | \{C_{\ell}^{gg}(z_c)\})$ denotes the galaxy density field given the auto-power spectrum $C_{\ell}^{gg}(z_c)$, and $\mathcal{P}(z_c)$ is the probability distribution of true redshifts within $z_c$, capturing the photometric redshift error on the galaxies. The likelihood on the luminosity distance given the cosmological parameters $\Theta_c$ and redshift is denoted by $\mathcal{P}((\delta \ell_i)_{GW} | z, \Theta_c, \{\hat{\theta}, \hat{\phi}\}_{GW})$, and the prior on the redshift, cosmological parameters, and nuisance parameters are denoted by $\Pi(\ell_b, \Pi(\Theta_c)$, and $\Pi(\Theta_n)$ respectively.

**GW catalog and selection function**: In this analysis, we use the publicly available GW catalog GWTC-3 detected by the LVK collaboration \cite{40}. As the most constraining estimations of cosmological parameters can be made from sources with high matched filtering SNR, we select samples from GWTC-3 with SNR $\geq 11$. Also,\footnote{\cite{14, 16} give a detailed derivation of the Bayesian framework. The framework is written for a spectroscopic redshift survey, so an additional term to include to error on the redshift is included.}
the cross-correlation technique is most effective for sources with better sky localization error, we further select sources with sky localization error $\Delta \Omega \leq 30$ sq. deg at 68.3% CI. These two selections lead to a total of eight GW events, namely GW170818, GW190412, GW190814, GW190701, GW190720, GW200129, GW200224, GW200311, and GW200720.

Galaxy catalog and selection function: We use galaxies from the 2MASS Photometric Redshift catalog [2MPZ, Fig. 2; 41] and WISE cross SuperCOSMOS Photometric Redshift catalog [WSC, Fig. 2; 42]. 2MPZ is derived from the all-sky 2MASS near-infrared extended source catalog (XSC) [47, 48], cross-matched to the infrared AllWISE [49] and optical SuperCOSMOS catalogs [50–53]. WSC is constructed in a similar way, but cross-matching AllWISE and SuperCOSMOS only. For WSC, we further apply a color cut of $W1 > W2 > 0.2$ to the publicly available sample to reduce stellar contamination and increase uniformity [54]. The galaxy samples are further described and validated in [55], including the impact of changing the selection criteria.

The choice of mask for the 2MPZ [41] and WSC [42] galaxy surveys left nearly 65% of the sky. At higher redshift (and with lower stellar contamination than WSC), DeCALS [43] covers about 50% of the sky area. Although

4 The details of both these catalogs can be found in [41] and [42].

5 The details for the construction of the mask are mentioned in the Appendix.

The redshift distributions of 2MPZ and WSC are shown in Fig. 3 in orange and blue respectively. At $z < 0.1$ we use 2MPZ despite its lower number density, as it has more precise photometric redshifts and far less stellar contamination. For $z > 0.1$, we use WSC exclusively. At $0.3 < z < 0.4$, WSC clustering is shot noise dominated at $\ell > 60$, and is shot noise dominated at all $\ell$ for $z > 0.4$. We still measure galaxy clustering at $0.4 < z < 0.5$, albeit with increased errors (total SNR $\sim 4.7$, after subtracting shot noise, over the relevant scales $10 < \ell < 40$), but exclude $z > 0.5$ where there are very few WSC galaxies. For both surveys, photometric redshifts are trained using the ANNz algorithm [56], yielding typical redshift errors $\sigma_z = 0.015$ for 2MPZ and $\sigma_z/(1+z) = 0.033$ for WSC.

Results - We have adopted the following uniform prior ranges: $\Pi(H_0) = U[20, 120]$ km/s/Mpc, $\Pi(\Omega_m) = U[0.1, 0.4]$, $\Pi(b_{GW}) = U[0.1, 1]$, and $\Pi(\alpha) = U[-2, 2]$. We use a redshift bin-width of $\Delta z = 0.1$ which is nearly three times the WSC photo-z error. For the cross-correlation we include only the lower multipoles $\ell \leq 30$ and consider different choices of bins $\Delta \ell = 5, 10, 15$ in the analysis. We do not use the first $\ell$-bin in the analysis to minimize low-$\ell$ contaminations.

From the auto-power spectrum, we infer the galaxy bias $b_g(z)$ by fitting a simple linear bias times the non-linear “Halofit” matter power spectrum model [57]. We use the NaMaster code [58, 59] to measure pseudo-$C_\ell$ for each redshift slice, applying a $C_1$ apodization [60] to the galaxy mask. For WSC, we additionally deproject the Schlegel-Finkbeiner-Davis [61] dust extinction map and a stellar density map from Gaia [62] to reduce the impact of contamination, following [63]. We fit the one-parameter bias model to the data in the range $10 < \ell < 40$, with shot noise fixed. For WSC, we additionally allow for systematic variations in the number density from variations in the zero point between SuperCOSMOS plates. We add a template to the model.

FIG. 2: The sky map along with mask (gray) in equatorial coordinates of 2MPZ (top) and WSC (bottom).

FIG. 3: The redshift distribution of the 2MPZ (in orange) and WSC (in blue) galaxies. The shaded region shows the redshift range that is shot noise dominated.
$C_{\ell}^{\text{plate}} = A \exp\left[-2\left(\theta_{\text{plate}}\right)^2/12\right]$, where $\theta_{\text{plate}}$ is the plate scale, 5" [63]. Finally, we fix the shot noise to the inverse of the angular number density (in steradians) except for the 0.4 < $z$ < 0.5 bin, where we adjust it downwards by 5% to match the high-$\ell$ power of $C_{\ell}^{\text{gw}}$. For the other bins, we check that $1/\bar{n}_g$ matches the high-$\ell$ power in $C_{\ell}^{\text{gw}}$, and the discrepancies are small compared to the clustering amplitude at 10 < $\ell$ < 40.

To model the redshift distribution, we convolve the observed photometric redshift distribution with a Gaussian for 2MPZ [64] and a generalized Lorentzian for WSC. $P(\delta z) \propto \left(1 + \frac{(\delta z)^2}{\sigma^2}\right)^{-a}$ [65]. The width evolves as a function of redshift, for the Gaussian following $\sigma = 0.027 \tanh\left(-20.78z_p^2 + 7.76z_p + 0.05\right)/(1 + z_p)$, i.e. increasing from 0.0013 at $z_p = 0$ to 0.013 at $z_p = 0.1$; and for the Lorentzian, $a(z_c) = -4z_c + 3$ and $s(z_c) = 0.04z_c + 0.02$, where $z_c$ is the midpoint of each redshift bin. Other choices for the redshift error (e.g. redshift-independent modified Lorentzian for 2MPZ in [41] and [65]) yield very similar results.

We then use the inferred galaxy auto power spectrum to model the cross-power spectrum between the GW sources and galaxy as $C_{\ell}^{\text{gw}}(z) = b_{gw}(z)/b_g(z)C_{\ell}^{\text{gg}}(z)$. On the GW side, we construct three GW maps from the selected GW samples composed of Set-1 (GW190814), Set-2 (GW170818, GW1901412, GW190720, GW2001129, GW200311, GW200311, GW201306, GW200224, 222234). These maps are constructed on the basis of their luminosity distance distribution. Sources with a similar maximum value of the posterior distribution are combined to enhance the cross-correlation signal. However, due to fewer sources, the shot noise for GW sources is very large compared to the galaxies (by nearly 4-6 orders of magnitude depending on the redshift bin). So, the GW auto-correlation signal is completely dominated by shot noise.

The joint estimation of the Hubble constant along with the matter density and GW bias parameters are shown in Fig. 4. Constraints on the Hubble constant are bi-modal, with the median value $H_0 = 68.2^{+26.0}_{-0.2}$ km/s/Mpc (the upper and the lower limit indicates the 68.3% equal-tailed interval (ETI)). At the lower end of the $H_0$ constraints, the constraints arise from the absence of the angular cross-correlation signal between the GW sources and the galaxies in the first $z$-bin. Due to the limited number of GW sources, we are not able to detect the cross-correlation signal with galaxies (see Fig. 6 in the appendix for further details.). The parameter constraints are driven by the structure of the cross-correlation signal and its covariance for different redshifts. Also, there are few galaxies at high redshift and the galaxy clustering signal is shot noise-dominated there. As a result, the galaxy-GW source cross-correlation does not add any additional information at high redshift. This leads to weak constraints at high $H_0$ and is one of the major sources of uncertainty. Particularly for Set-3, the constraints at the high $H_0 > 90$ km/s/Mpc are affected due unavailability of catalog above $z = 0.5$. Along with this, the uncertainties on the galaxies’ photometric redshifts and GW luminosity distance, and the limited number of sources, play a crucial role in the weak constraints. The value of the matter density $\Omega_m$ and bias parameter $b_{GW}(z)$ are not constrained. The estimated parameters obtained for different values of the bin width are consistent with each other. For large choices of the $\ell$-bin ($\Delta \ell \geq 10$), we are able to mitigate the effect from off-diagonal terms. The $\Delta \ell = 5$ case shows a stronger bi-modal distribution. This also implies any systematic error associated with the covariance estimation is not causing any major systematic error in the inferred value of the Hubble constant for $\Delta \ell \geq 10$.

By combining the bright standard siren measurement from GW170817 with a better measurement of peculiar velocity [66], we show the corresponding posterior on $H_0$ in Fig. 5 with the median value of $H_0 = 67.0^{+6.3}_{-3.8}$ km/s/Mpc (68.3% ETI). This provides tighter constraints in the value of the Hubble constant than previous measurements. In Fig. 5 we compare the GW measurements of $H_0$ with the measurements from Planck, $H_0 = 67.4^{+0.5}_{-0.5}$ km/s/Mpc [67] and with the measurement of $H_0 = 73.04^{+1.05}_{-1.05}$ km/s/Mpc from SH0ES [68]. The current measurements from the dark sires are not sufficiently constraining yet to resolve the tension in the value of $H_0$ [72, 73]. Though the systematic uncertainties in our measurement of $H_0$ are smaller than the statistical uncertainties, in future with more GW sources and better galaxy catalog, we will be able to better assess the influence of any systematic uncertainties.

This measurement of the expansion history does not depend directly on the choice of GW mass distribution nor on whether the mass distribution follows a power-law mass distribution or a power-law + Gaussian peak model [74]. It only depends on the maximum allowed mass of individual BHs. This is primarily because the maximum mass of the BHs determines the maximum luminosity distance up to which a source can be detected from a given detector sensitivity. This luminosity distance threshold, in combination with the allowed priors on the cosmological parameters, sets the maximum redshift in the prior on GW source redshift out to which one needs to explore the cross-correlation signal. However, with the currently existing galaxy surveys, we are not able to go beyond $z = 0.5$ due to limited sky coverage and the limited redshift reach of the galaxy catalogs.

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6 The ACT and WMAP measurement is $H_0 = 67.6^{+1.1}_{-1.1}$ km/s/Mpc [69]. The measurement using TRGB as a calibrator is $H_0 = 69.8^{+0.6}_{-1.6}$ km/s/Mpc [70]. The strong lensing measurement from H0LICOW is $H_0 = 73.3^{+1.8}_{-1.8}$ km/s/Mpc [72].
The GW bias parameters encode information about the GW source population and their connection to galaxies. Hence we marginalize over the GW bias parameters to infer cosmological parameters correctly and mitigate population assumptions. At large angular scales ($\ell < 30$), the GW bias parameter is expected to follow the dark matter distribution in the linear regime, and will not exhibit scale dependence. So, in this analysis, we have not considered any scale dependence in the GW bias parameter.

Even though this is the first application of the cross-correlation technique on GW data, the measurements of $H_0$ presented in this work are from a low number of GW sources. As a result, the clustering of the GW sources is not measured with any statistical significance. So, the estimates of $H_0$ presented in this work are weak and subject to systematic uncertainties associated with small number statistics. To test the robustness of our results, we have checked the following aspects, (i) randomly varied the galaxy bias parameter within their error bars, (ii) enhanced the covariance matrix by a factor of four, (iii) changed the cosmological parameters such as $S_8 \equiv \sigma_8 \sqrt{\Omega_m}$ that is used to fit the galaxy power spectrum $C_{\ell}^{gg}$ from $S_8 = 0.832$ (Planck-2018 [75]) to a lower value $S_8 = 0.75$ as indicated by the KiDS Collaboration [76], (iv) changed the value of $H_0 = 67$ km/s/Mpc to $H_0 = 74$ km/s/Mpc [77] to estimate the galaxy bias parameters, (v) changed the galaxy sample selection by additionally removing WSC sources with a low probability of being galaxies using the SVM catalog of [78], requiring $p_{gal} > 0.67$, and (vi) changed the redshift bin width $\Delta z$ to 0.05 which is comparable to the photo-z errors. The posterior on $H_0$ did not show any significant variation for (i)–(v) cases. For the scenario (vi), the $H_0$ posterior show some variation and 68% ETI gets bigger than the estimates presented with $\Delta z = 0.1$. This is because the galaxy redshift kernels begin to overlap due to photo-z errors, violating our assumption that the GW cross-correlations in neighboring bins are uncorrelated.

The measurement in this work agrees with the dark siren measurement of $H_0 = 67^{+12}_{-13}$ km/s/Mpc (68.3% HDI) by the LVK collaboration [35]. Though the current constraints on $H_0$ from LVK are driven by population assumptions, the MAP value of the distribution agrees with this measurement. This is an independent validation of the LVK population assumptions. The constraints on the higher value of $H_0$ from the LVK analysis arise from the empty catalog component (which is driven by the population assumption). So, the upper limit on $H_0$ is looser for the cross-correlation technique than for the LVK analysis. However, at lower values of $H_0$, a tighter constraint is obtained.

**Conclusion and future outlook** – We present the first measurement of the Hubble constant $H_0$ from dark standard sirens using the cross-correlation technique. The cross-correlation technique uses the spatial clustering of GW sources with galaxies and includes information beyond statistical host identification. With the best eight sources available from GWTC-3, we obtain a median value of Hubble constant $H_0 = 68.2^{+6.3}_{-6.2}$ km/s/Mpc (68.3% ETI). Due to the limited number of GW sources and absence of galaxy samples at high redshift, the cross-correlation signal is not detected, leading to only a mild improvement from the previous constraints using galaxy catalog [35]. In the future, with the availability of z $< 0.8$ spectroscopic galaxy catalogs such as DESI [79] and SPHEREx [80] (supplemented by z $> 0.8$ spectroscopy from Euclid [81] and photometric redshifts from...
Vera Rubin Observatory [82]), cross-correlation of the GW sources with galaxies will be a powerful technique to measure the expansion history [12, 14, 16] and testing the general theory of relativity [15, 83].

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Cross-correlation signal between GW sources and galaxies

The cross-correlation between the GW sources and galaxies are dominated by poor number statistics and we do not measure any cross-correlation clustering signal with statistical significance. We show the measured band average cross-correlation signal $\hat{C}_{GWg}$ as a function of redshift in Fig. 6 for $\Delta \ell = 15$ with the three GW maps constructed from the eight events. The value of maximum multipole $\ell_{\text{max}} = 30$ is chosen to take into account the poor sky localization error of the GW sources for sources with sky localization error $\Delta \Omega \leq 30$ sq. deg. The diagonal error bars are shown on the measured values. The band average signal shows a signal that is consistent with zero at all the redshift bins. The constraints on the clustering signal at low redshift $z$ for all the three cases drives the constraints on the lower value of $H_0 \leq 50$ km/s/Mpc. For the higher redshift bins, a non-zero mean value causes a non-zero posterior distribution on $H_0$ which is different from the prior (taken as $H_0[20, 120]$ km/s/Mpc. This indicates that the constraints are weak and are affected by the systematic associated with the non-detection of the cross-correlation signal. At high redshift ($z > 0.5$) the absence of sufficient galaxies leads to an abrupt cut in the galaxy distribution and provides no information on higher values of $H_0$. Due to the absence of detection of the clustering signal, the statistical power of measuring $H_0$ is similar to the statistical host identification technique.

**FIG. 6:** The band average cross-correlation power spectrum between GW sources and galaxies with a $\Delta \ell = 15$ bin-width is shown for three different maps of the GW sources Set-1 (GW190814), Set-2 (GW170818, GW1901412, GW190720, GW2001129, GW200224, 222234) composed from the selected eight events, as a function of the median value of the redshift bin.

Construction of galaxy mask for 2MPZ and WSC

The galaxy masks were carefully constructed to remove areas with large numbers of stars or other systematics that could affect galaxy clustering, either by direct stellar contamination or by correlations, e.g. suppressed galaxy density in regions of high stellar density or extinction. We follow [64] to construct the 2MPZ mask, starting by masking low Galactic latitudes ($|b| < 10^\circ$, areas of high galactic extinction $(E(B-V) > 0.3$ from [61], and areas of high stellar density as estimated from the 2MASS.
Point Source Catalog \((\log n_{\text{star}} > 3.5)^8\). We further include manual cutouts around the LMC and SMC, excluding \(275.47 < \text{RA} < 285.47\) and \(-37.89 < \text{DEC} < -27.89\), and \(300.81 < \text{RA} < 304.81\) and \(-46.33 < \text{DEC} < -42.33\). Finally, we mask additional areas with low completeness in 2MPZ, determined by comparing the number counts of 2MPZ sources and 2MASS XSC sources (with \(K_s < 13.9\)) in NSIDE=64 HEALPix. We remove pixels with \(< 85\%\) completeness, mostly corresponding to areas of lower depth around bright stars. We test variations in the masking procedure (i.e. additionally multiplying by the WSC mask, following [94], or changing the completeness threshold to \(80\%\) or \(90\%\)) and find minimal changes in results.

For WSC, we follow the masking procedure of [54]. We start with the mask distributed with the WSC data release [42]. We additionally mask regions with high extinction \((E(B-V) > 0.10)\) and high stellar density (density of stars from GAIA greater than 7 times the mean). We additionally test several variations in the masking procedure, adding an additional mask at low Galactic latitudes following [95]; adding a WISE bright stars mask [96]; and adding a mask of regions in WISE with high moon contamination, as determined by HEALPix pixels in which GLADE+ [37] is incomplete compared to WSC. We also test variations in the sample-selection procedure, i.e. additionally using the SVM catalog of [78] to restrict to likely galaxies [95, 97]. We find that these variations generally lead to a scale-independent shift in the amplitude of \(C_\ell^{gg}\), either corresponding to a change in galaxy bias due to differing populations, or a change in the stellar contamination fraction, which is entirely degenerate with bias at \(\ell > 10\) where the stellar power spectrum is small. In this regime, the effect of changing stellar contamination is degenerate with bias in both the galaxy auto spectrum and the galaxy cross-spectrum with GW sources, so it will cause systematic errors in our modeling.

We assume that the galaxy bias is redshift-independent in each bin, and obtain best-fit values of \(b_g(z_c=0.05) = 1.18, b_g(z_c=0.15) = 0.66, b_g(z_c=0.25) = 1.35, b_g(z_c=0.35) = 1.76,\) and \(b_g(z_c=0.45) = 2.33\). The very low value of \(b_g\) in the second bin is driven by the SuperCOSMOS plate template, which is degenerate with the cosmological contribution due to the limited multipole range considered \((10 < \ell < 40)\).

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8 https://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec4_5c.html