Gravitational Wave mergers 
as tracers of Large Scale Structures

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Abstract. Clustering measurements of Gravitational Wave (GW) mergers in Luminosity Distance Space can be used in the future as a powerful tool for Cosmology. We consider tomographic measurements of the Angular Power Spectrum of mergers both in an Einstein Telescope-like survey and in some more advanced scenarios (more sources, better distance measurements). We produce Fisher forecasts both for cosmological (matter and dark energy) and for merger bias parameters. Our fiducial model for the number distribution and bias of GW events is based on results from hydrodynamical simulations. The cosmological parameter forecasts with Einstein Telescope are less powerful than those achievable in the near future via galaxy clustering observations with, e.g., Euclid. However, in the more advanced scenarios we see significant improvements. Regardless of the specific constraining power of different experiments, many aspects make this type of analysis interesting anyway. For example, compact binary mergers detected by Einstein Telescope will extend up to very high redshifts. Furthermore, Luminosity Distance Space Distortions in the GW analysis have a different structure with respect to Redshift-Space Distortions in galaxy catalogues. Finally, measurements of the bias of GW mergers can provide useful insight into their physical nature and properties.
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1 Introduction

The importance of the recent discovery of Gravitational Waves (GW) produced by Black Hole (BH) and Neutron Star (NS) mergers cannot be overemphasized (important achievements in this new research field are described e.g., in [1–3, 6]). It has opened a new window in our understanding of the Universe, with a huge future discovery potential in many different areas of Astronomy. If we consider the field of Cosmology, one of the most investigated applications is the use of GW events as standard sirens, to measure cosmological distances and the Hubble parameter without the calibration issues which arise in traditional approaches. This has gained even further interest in recent times, in light of the more and more debated
discrepancy between measurements of the Hubble parameter, coming from high and low-redshift cosmological probes (see e.g., [3, 12, 40]). One caveat is that this methodology requires spectroscopic follow-ups, electromagnetic counterparts or cross-correlation of the GW signal with external galaxy surveys, in order to determine redshifts of the GW events.

A logical question therefore arises, namely whether we can extract useful cosmological information from future GW observations, without any additional redshift information. Considering that future GW experiments, such as Einstein Telescope (ET)\(^1\) or DECIGO\(^2\), will detect hundreds of thousand or millions of events, an interesting possibility is that of using GW mergers as tracers of Large Scale Structures (LSS), in essentially the same way as done with galaxies in big cosmological surveys. This does not necessarily require knowledge of redshifts, since luminosity distances – which are directly measured – can be used as radial coordinates. Using luminosity distances introduces also another layer of complementarity with galaxy surveys, since distortions of the merger distribution in Luminosity Distance Space behaves differently from distortions of the galaxy distribution in Redshift Space.

It is also interesting to point out that statistical studies of the spatial distribution of GW events allow us to characterize their clustering properties, with respect to the underlying Dark Matter (DM) distribution, i.e., their cosmological bias. From an observational point of view, studies of the spatial distribution of mergers have already been carried on in [33, 42], where it was shown that GW produced by binary BH mergers are anisotropically distributed. Attempts at measuring their correlation function and power spectrum are also ongoing, see e.g. [41]. Modeling merger bias is important when seeking cosmological information, since in this case bias parameters need to be marginalized out in the analysis. Beyond this aspect, bias measurements could also directly provide interesting information on the physical nature of the different mergers. Such approach is for example explored in [10, 36, 38]. In those works, merger bias is studied via cross-correlation between galaxy and GW surveys, rather than by relying on GW experiments alone. An approach to measuring GW bias, which relies solely on source-location posteriors, has been instead proposed in [45]. While we were in the final stages of this work, a new method to precisely infer redshifts of mergers and to estimate cosmological and bias parameters, without identifying their host galaxy, was also discussed in [30]; this approach extends the technique originally developed in [37] for Supernovae catalogues.

The possibility of building surveys of the spatial distribution of GW mergers – and use them for cosmological applications – without relying on external data, but working directly in Luminosity Distance Space, was instead originally pointed out in [32, 46]. In this work we go beyond these preliminary studies by systematically exploring this approach both for an ET-like survey and for more futuristic scenarios. We produce detailed Fisher forecasts for cosmological parameters (matter and dark energy parameters) in all different cases, and in doing so we do not rely on simplified analytical assumptions. In particular, we use the results from [7, 8] to model the expected density of mergers in the survey and to characterize their fiducial bias parameters via a simulation-based Halo Occupation Distribution (HOD) approach. The work from [7, 8] combines galaxy catalogs from hydrodynamical cosmological simulations together with the results of population synthesis models. In this way, the merger rates are computed considering galaxy and binary stellar evolution in a self-consistent way.

As mentioned above, a potentially interesting application is that of focusing on the bias parameters and trying to use them to extract information on type and properties of the

\(^1\)http://www.et-gw.eu
\(^2\)https://decigo.jp/index_E.html
mergers. We will therefore also provide specific forecasts on bias, after marginalizing over cosmological parameters (with and without priors from external cosmological surveys).

The paper is structured as follows: in Sec. 2 we compare (angular) merger and galaxy surveys, discussing in particular the use of luminosity distances as position indicators and the related Luminosity Distance Space Distortions; in Sec. 3 we study the number distribution of events and describe our method to produce a fiducial model for merger bias; in Sec. 4 we provide details on our Fisher matrix implementation; in Sec. 5 we illustrate our results. We then draw our conclusions in Sec. 6.

2 Luminosity Distance Space

This work aims at understanding how well future surveys of GW mergers will be able to constrain either Cosmology or the statistical properties of their distribution (let us note here that we focus on merger clustering in this work, but lensing studies are of course also possible and interesting, see e.g. [29]). Only GW events caused by the merger of compact binaries are considered in our current analysis, i.e. systems formed by two Neutron Stars, two stellar Black Holes or one Black Hole and one Neutron Star. The approach we consider consists in studying the spatial clustering of mergers on large scales using their power spectrum, pretty much in the same way as done for galaxy surveys (e.g. [24]), despite the different astrophysical properties of the tracers.

The main difference between galaxy and merger surveys lies in the fact that for the former we measure redshifts, whereas for the latter we have direct access only to luminosity distances, which can be extracted by combining information on the strain of the gravitational signal and its frequency. Even if the redshift associated with the GW event could be extracted from external data-sets, one of our goals in this work is to rely only on GW measurements.

The use of $D_L$ instead of $z$ in mapping the source tomographic distribution requires the introduction of some corrections, which are described in Sec. 2.1. Once these are considered, the study of the power spectrum in Luminosity Distance Space (LDS) results to be completely analogous to the standard one in Redshift Space (RS). To keep the notation more familiar to the reader and more similar to the one used in LSS analysis, quantities in this work are generally expressed through their $z$-dependence, except when the $D_L$-dependence must be made strictly explicit. Remember however that, whenever we report cosmological observables as $z$-dependent in our notation, this implies a further $z(D_L)$ dependence, computed through

$$D_L = \frac{\chi(a)}{a} = (1 + z) \int_0^z \frac{c}{H(z)} ,$$

where $\chi(a)$ is the comoving distance, $a$ is the scale factor, $c$ is the speed of light and $H(z)$ is the Hubble parameter. Throughout this paper, whenever an explicit evaluation of eq. (2.1) is required, we assume, if not differently specified, the fiducial cosmological parameters measured by Planck 2018 [13] and reported in Tab. 5 in Appendix B.

2.1 Luminosity Distance Space Distortions

When studying the Universe in RS, peculiar velocities alter the observed position in the sky, generating Redshift-Space Distortions (RSD, see e.g. [11]). Since in this work the mapping is done in LDS, we need to consider instead the analogous effect of Luminosity Distance Space Distortions (LDSD). In this Section, we do this by working in plane parallel approximation and we discuss in detail the derivation of a luminosity distance analogous of the Kaiser formula;
our final result reproduces the formula originally shown in [46]. Before proceeding with the discussion, let us note that future GW experiments will cover a large fraction of the sky; therefore, for future high precision analyses, we should actually also take into account wide-angle contributions to $D_L$, due to volume, velocity and ISW-like effects. This will particularly matter for advanced experiments with very low instrumental error in the determination of distances, such as e.g., DECIGO (see [9]). The plane parallel approximation is however fully adequate for the accuracy requirements of the Fisher analysis we carry on here (which is also mostly focused on an ET-like survey, where instrumental errors tend to dominate over other effects in affecting measurements of $D_L$).

The way peculiar velocities affect the observed position $D_{\text{obs}}^L$ in LDS depends both on the change in the observed position and on the relativistic light aberration. A first-order derivation ([34, 35], see also [23]) leads to the expression

$$D_{\text{obs}}^L = \bar{D}_L (1 + 2 \bar{v}_e \cdot \hat{n}),$$

where $\bar{D}_L$ is the luminosity distance in the unperturbed background, $\bar{v}_e$ is the peculiar velocity of the emitting source and $\hat{n}$ is the Line of Sight (LoS) direction.

As mentioned above, eq. (2.2) is used in [46] to describe the LDSD in a flat Universe, adopting the plane-parallel approximation, namely:

$$\bar{v}_e \cdot \hat{n} = \mu v_e.$$

In the previous equation, $\mu$ is the cosine of the angle between the LoS direction and the peculiar velocity of the source. Background coordinates in real space are associated to coordinates in LDS by means of eq. (2.1), leading to $\chi(D_{\text{obs}}^L) = aD_{\text{obs}}^L = a\bar{D}_L + a\delta D_L$. Considering eq. (2.2) and replacing the approximation from eq. (2.3), we get

$$\chi(D_{\text{obs}}^L) = a\bar{D}_L (1 + 2 \mu v_e) = \chi(\bar{D}_L)(1 + 2 \mu v_e).$$

Therefore, $\delta D_L = 2a\bar{D}_L \mu v_e$. Eq. (2.4) can be rewritten as

$$\chi(D_{\text{obs}}^L) = \chi(\bar{D}_L + \delta D_L) = \chi(\bar{D}_L) + \left. \frac{\partial \chi(D_{\text{obs}}^L)}{\partial D_{\text{obs}}^L} \right|_{\bar{D}_L} \delta D_L. \tag{2.5}$$

Writing $\delta D_L$ explicitly and considering that $\delta \chi/\delta z = 1/H(z)$ in a spatially flat Universe, eq. (2.5) becomes

$$\chi(D_{\text{obs}}^L) = \chi(\bar{D}_L) + \frac{1}{H(z)} \left( \frac{\partial D_{\text{obs}}^L}{\partial z} \right)^{-1} \left|_{\bar{D}_L} \right. 2\mu v_e a \bar{D}_L$$

$$= \chi(\bar{D}_L) + \left[ \frac{2\bar{D}_L}{1+z} \left( \frac{\partial \bar{D}_L}{\partial z} \right)^{-1} \right] \bar{v}_e \cdot \hat{n} \frac{\bar{D}_L}{H(z)}. \tag{2.6}$$

Eq. (2.6) is identical in structure to the standard Kaiser formula in RS [21]. The only difference between the two is the pre-factor $f_{D_L}$,

$$f_{D_L} = \frac{2\bar{D}_L}{1+z} \left( \frac{\partial \bar{D}_L}{\partial z} \right)^{-1}, \tag{2.7}$$

which was originally pointed out in [46]. This factor depends on the distance from the observer, and makes LDSD larger than RSD at $z \gtrsim 1.7$ and smaller than RSD at $z \lesssim 1.7$;
Figure 1. $f_{DL}$ factor calculated in eq. (2.7) assuming the fiducial cosmology (see Tab. 5). The lines indicate the point in which LDSD are equivalent to RSD, that is $z \in [1.6, 1.7]$. Below this value, LDSD are smaller than RSD and $f_{DL}$ varies quite fast. Differently, over it LDSD start taking over RSD while $f_{DL}$ tends to become constant.

due to this prefactor, LDSD are also vanishing as $z \to 0$, as Fig. 1 shows. Note that $f_{DL}$ depends on Cosmology; in this work, Planck 2018 results [13] are assumed as fiducial values for the cosmological parameters (see Tab. 5).

Eq. (2.6) can be used to study LDSD in Fourier space, as done for RSD. Let us briefly review the standard procedure. The observed overdensity is computed through eq. (2.6) and Fourier transformed (note that, in the transform, the source redshift $\bar{z}$ is fixed, when considering the spatial distribution of the velocities. The background $\bar{D}_L$ therefore depends only on $\bar{z}$ and not on the LoS direction $\hat{n}$).

We then use the continuity equation:

$$\frac{d\delta_k(\eta)}{d\eta} + i k v_k(\eta) = 0 ,$$

where $\eta$ is the conformal time, and use it to express the velocity as

$$v_k(\eta) = \frac{i}{k} \frac{d\delta_k(\eta)}{d\eta} = \frac{i}{k \bar{D}_1(\eta)} \left[ \frac{\delta_k(\eta) D_1(\eta)}{D_1(\eta)} \right] = \frac{i \delta_k(\eta)}{k \bar{D}_1(\eta)} \frac{dD_1(\eta)}{d\eta} .$$

In eq. (2.9), the last equality descends from $\delta_k(\eta)/D_1(\eta) \sim$ cost, $D_1(\eta)$ being the growth factor. The dimensionless growth rate is then defined as

$$f = \frac{a}{D_1} \frac{dD_1}{da} = \frac{a}{D_1} \frac{1}{a^2 H} \frac{dD_1}{d\eta} = \frac{1}{aH \bar{D}_1} \frac{dD_1}{d\eta} ,$$

where the $\eta$ dependence is omitted for clarity. Therefore, eq. (2.9) is rearranged as

$$v_k = \frac{i aH \delta_k}{k} .$$

Moving to LDS, the factor $f$ as reported in eq. (2.10) has now to be converted into $f_1 = f \cdot f_{DL}$, with $f_{DL}$ from eq. (2.7).
2.2 Numerical implementation

Sec. 2.1 shows that LDSD, in the plane-parallel approximation, can be formally treated as done for RSD, once the factor $f_{DL}$ from eq. (2.7) is properly inserted. Consequently, such factor enters the Angular Power Spectrum (APS) computation. The density contrast of the sources can be written as (see e.g. [11])

$$\delta_N = \delta_N - \frac{1}{H} \hat{n} \cdot \nabla (\vec{v}_e \cdot \hat{n}) + A(\vec{v}_e \cdot \hat{n}) + (2 - 5s)\kappa + \ldots,$$  \hfill (2.12)

where the first term is the proper number density contrast at the source, the second represents the (R/LD)SD, the third is due to the Doppler effect and the last one is due to lensing. Other observational effects are neglected in this expression but can be found in [11]. By Fourier transforming eq. (2.12), the theoretical transfer function $\Delta_{N}(z,k)$ is obtained. The observational transfer function $\Delta_{WN,l}(z,k)$ is then computed: it accounts for the redshift dependence of the source distribution $p(z)$ and for a suitable weight in each observed redshift bin provided by the Window function $W(z_i, z)$ (see Sec. 4.1 and e.g. [15] for details).

When we compute the transfer function in LDS, each term including $v_k$ in $\Delta_{N}(z,k)$ inherits the factor $f_{DL}$ from eq. (2.7). Therefore, such modifications are inserted in the terms describing the Space Distortions, the density evolution and the Doppler effect. Following [11], these are:

$$RSD \sim kv_k j''(k\chi) \rightarrow LDSD \sim f_{DL} kv_k j''(k\chi),$$
$$RS \text{ evolution } \sim v_k j''(k\chi) \rightarrow LDS \text{ evolution } \sim f_{DL} v_k j''(k\chi),$$
$$RS \text{ Doppler } \sim v_k j''(k\chi) \rightarrow LDS \text{ Doppler } \sim f_{DL} v_k j''(k\chi).$$  \hfill (2.13)

In this work, the APS is computed using the public code CAMB$^3$, introduced in [25]. When calculating the APS in RSD, the code relies on the integrated version of the expressions in eq. (2.13), which all depend on the Spherical Bessel function $j_l(k\chi)$ and not on its derivatives.

The conversion to LDS is simple if we consider a sufficiently fine distance binning of the data, when we compute the APS. In this case, without loss of accuracy, we can neglect the dependence of $f_{DL}$ on $\chi$, inside any given bin. By doing so, CAMB built-in expressions are simply multiplied by $f_{DL}$, which is computed through eq. (2.7) in the centre of the bin.

3 Source properties

If we want to study the clustering of GW merger events, both their number distribution in redshift and their bias with respect to the underlying smooth DM distribution need to be modelled. To this purpose, we rely on simulations from [7, 8]. These combine the galaxy catalogue from the EAGLE simulation [39] with the stellar population synthesis code MOBSE [18] to get the number distribution of mergers from Double Neutron Stars (DNS), Double Black Holes (DBH) and Black Hole Neutron Star (BHNS) systems.$^4$ These distributions depend on the redshift $z$ and the stellar mass of the host galaxy $M_*$; other dependencies (such as Star Formation Rate or metallicity) are neglected in this work. Moreover, the full distributions are processed to include observational effects from ET. More details about the simulations and the ET selection function are provided in Appendix A.

$^3$https://github.com/cmbant/CAMB

$^4$In this work, when talking about distributions, binary mergers or GW events are considered interchangeably, since the former triggers the latter. The distributions are ET selected, unless specified otherwise.
3.1 Number distribution

Simulations are run in a box having a comoving side $\ell = 25\text{Mpc}$, which is evolved across cosmic time. Even if the box is small, for our purposes this does not generate sample variance-related problems. We checked this by comparing relevant results for our analysis with similar figures obtained from a simulated box with size $\ell' = 100\text{Mpc}$ and verifying their stability. The simulation is divided into 22 redshift snapshots, in which the number distributions of both galaxies and (DNS, DBH, BHNS) mergers are calculated. Note that each $z$-snapshot actually corresponds to an interval $[z - \delta z, z + \delta z] = T^{SIM}$. The center of each snapshot and the associated interval are reported in Tab. 2 in Appendix A, in units of time.

The number distribution of mergers inside the box depends not only on redshift but also on the stellar mass of the host galaxy, $M_*$: the latter is divided into 15 bins, which are reported in Tab. 3 in Appendix A. Since we consider a blind survey, marginalized over $M_*$, GW from different mergers ($m =$ DNS, DBH, BHNS) and from different $M_*$ bins can not be distinguished. The overall distribution is

$$N^{SIM}(z) = \sum_{bin} \sum_m \langle N^{SIM}_m(z) | M^{bin}_* \rangle. \quad (3.1)$$

$N^{SIM}(z)$ indicates the number of binaries that merge inside the box of comoving volume $V^{SIM}$ in a given time interval $T^{SIM}(z)$ (see Tab. 2). Therefore, the merger rate of these events is $N^{SIM}(z)/T^{SIM}(z)$. This can be transformed into a detection rate by converting time intervals from the source to the observer rest frame. The conversion factor is

$$\frac{dt^{SIM}}{dt^{OBS}} = \frac{1}{1 + z}. \quad (3.2)$$

Therefore, we get

$$N(z) = T^{OBS} \frac{N^{SIM}(z)}{T^{SIM}(z)} \frac{dt^{SIM}}{dt^{OBS}} = T^{OBS} \frac{N^{SIM}(z)}{T^{SIM}(z)} \frac{1}{1 + z}, \quad (3.3)$$

where $T^{OBS}$ is the survey duration expressed in years. Here, a 3yr observation run is assumed.

The final step is to convert the merger number distribution into the number density of observed mergers per unit redshift and solid angle: $dN/dzd\Omega$. The solid angle $\Delta\Omega$ under which we see the surface delimiting the simulation box, at a given redshift $z$, is

$$\Delta\Omega = \left(\frac{D_L(z)}{\ell (1 + z)^2}\right)^2, \quad (3.4)$$

where $\ell$ is the length of the simulation box side, specified earlier. This leads to the following formula for the merger number density:

$$\frac{dN}{dzd\Omega} = N(z) \frac{c}{\ell H(z)} \left(\frac{D_L(z)}{\ell (1 + z)^2}\right)^2, \quad (3.5)$$

where $\ell$ is the length of the simulation box side. The value of $dN/dzd\Omega$ is computed in the 22 snapshots of the simulation. An interpolation is then performed to the skewed Gaussian

$$\frac{dN}{dzd\Omega} = 2 \left[A \exp\left(-\frac{(z - \bar{z})^2}{2 \sigma^2}\right)\right] \left[\frac{1}{2} \left(1 + \text{erf}\left(\frac{\alpha(z - \bar{z})}{\sigma^2\sqrt{2}}\right)\right)\right], \quad (3.6)$$

where $A = 10^{3.46}$, $\bar{z} = 0.23$, $\sigma^2 = 1.16$, $\alpha = 6.59$. Fig. 2 shows the observed number density.
Figure 2. Observed merger number distribution $dN/dzd\Omega$ obtained as Sec. 3.1 describes. The observational run is assumed to be performed with ET and to last 3 yr. The total number of sources integrated in $dz$ and $d\Omega$ is, in this case, $\sim 10^{4.99}$.

3.2 Bias computation

The method used to get the merger bias is based on the HOD approach. This is commonly used to compute the bias of a particular kind of galaxies depending on the probability that a certain number of them form inside a DM halo having mass $M_h$ (see e.g. [14]). Since mergers take place inside galaxies, an extra layer is added in the computation to link the merger distribution properties to the galaxy distribution (and consequently to DM, via galaxy bias).

Specifically, merger bias is computed as

$$b_m(z) = \int_{M_{\min}}^{M_{\max}} dM_z n_g(z, M_z) b_g(z, M_z) \frac{\langle N_m(z)|M_z\rangle}{n_m(z)} . \quad (3.7)$$

The merger HOD $\langle N_m(z)|M_z\rangle$ is extracted from the simulations described in Sec. 3.1; it is used to compute the merger number density as

$$n_m(z) = \int_{M_{\min}}^{M_{\max}} dM_z n_g(z, M_z) \langle N_m(z)|M_z\rangle . \quad (3.8)$$

As for the other quantities in eq. (3.7), $n_g(z, M_z) = \int_{M_{\min}}^{+\infty} dM_h n_h(z, M_h) \langle N_g(M_z)|M_h\rangle$ is the mean number density of galaxies having stellar mass $M_z$, while $b_g(z, M_z)$ is their bias, again computed through a standard HOD procedure as

$$b_g(z, M_z) = \int_{M_{h_{\min}}}^{+\infty} dM_h n_h(z, M_h) b_h(z, M_h) \frac{\langle N_g(M_z)|M_h\rangle}{n_g(z, M_z)} . \quad (3.9)$$

In eq. (3.9), $\langle N_g(M_z)|M_h\rangle$ is the galaxy HOD, i.e. the number of galaxies of stellar mass $M_z$ formed inside a halo with given mass $M_h$. The minimum mass $M_{h_{\min}}$ required from a halo
to form galaxies of such stellar mass, is a free parameter; the procedure we adopt to find its value is described in Sec. 3.2.1. Instead, \( n_h(z, M_h) = d\rho_h/dM_h \) is the halo mass function and \( b_h(M_h, z) \) is the halo bias. In this work, we adopt the Tinker et al. prescription [44] for the halo mass function, and compute the bias as

\[
b_h(z, M_h) = 1 + \frac{1}{\sqrt{a}} \left[ \sqrt{a} \nu + \sqrt{ab} (\nu^2)^{1-c} - \frac{(\nu^2)^c}{(a^2)^c + b(1-c)(1-c/2)} \right],
\]

where \( \nu = \delta_c/\sigma(z, M_h) \) is computed using the critical density for spherical collapse \( \delta_c \) and the mass variance \( \sigma(z, M_h) \).\(^5\) The other parameters are set as \( a = 0.707 \), \( b = 0.5 \), \( c = 0.6 \), \( M_h^{\min} = 10^8 \, h^{-1} M_\odot \), \( M_h^{\max} = 10^{19} \, h^{-1} M_\odot \).

We note here that we have chosen an HOD-based approach to compute biases for two main reasons. On one side, it is simple but at the same time sufficiently accurate for a Fisher matrix analysis, such as the one carried on in this work. On the other side, it allows for a semi-analytical description of the bias of mergers, which can be useful for general purposes. In future investigations, the bias and power spectrum of mergers will be directly measured from simulations.

### 3.2.1 Galaxy HOD and bias

In this Section, we provide more technical details on the procedure adopted to compute the galaxy bias, as a function of \( M_\star \) and \( z \). Firstly, the Stellar Mass Function (SMF) \( \Phi(z, M_\star) = dN/dVdM_\star \) is defined as the number of galaxies per unit comoving volume and unit stellar mass by interpolating the data extracted from the EAGLE simulation (e.g. see [8]) in the 22 redshift snapshots reported in Tab. 2.

Using the SMF, the galaxy number density is computed in each redshift snapshot per each stellar mass bin (see Tab. 3). This is done through

\[
n_g(z) = h^3 \int_{M_\star^{\min}}^{M_\star^{max}} \Phi(z, M_\star) dM_\star. \tag{3.11}
\]

The SMF is then compared with the HOD \( \langle N_g(M_\star) | M_h \rangle \) to set the value of \( M_h^{\min, *} \). In this work, the EAGLE HOD defined in [8] is used, that is

\[
\langle N_g | M_h \rangle = \langle N_g^{\text{central}} \rangle + \langle N_g^{\text{satellites}} \rangle
\]

\[
= \left[ 1 + \text{erf} \left( \frac{\log(M_h) - \log(M_h^{\min})}{\sigma_{\log(M_h)}} \right) \right] + \begin{cases} 
M_h - M_h^{\text{cut}} & \text{if } \frac{M_h - M_h^{\text{cut}}}{M_h^{\text{cut}}/M_{h,1}} \geq 0, \\
0 & \text{otherwise}
\end{cases}
\]

The parameters \( \sigma_{\log(M_h)} = 0.318 \), \( M_h^{\text{cut}} = 10^{11.90} \), \( \alpha = 1.17 \) are fixed, while \( M_{h,1} = 14.25 \cdot 10^{13.32} - M_h^{\text{cut}} \). Following [22], the value of \( M_h^{\min} = M_h^{\min, *} \) is fixed in each stellar mass bin, through the minimization of

\[
\Delta n_g = h^3 \int_{M_h^{\min}}^{M_h^{max}} \Phi(z, M_\star) dM_\star - \int_{M_h^{\min, *}}^{M_h^{max}} \langle N_g | M_h \rangle \ n_h(z, M_h) \ dM_h. \tag{3.13}
\]

\(^5\)We acknowledge use of the python library hmf [31] to compute the halo mass function and bias related quantities, such as the mass variance \( \sigma(z, M_h) \).
Figure 3. Galaxy bias depending on $z$, obtained through integration over $M_*$, as explained in the text. The dots are the values calculated in the 22 snapshots of the the 25Mpc box simulation, while the line is the interpolation made through $b_g(z) = a_0 + a_1 z + a_2 z^2 + a_3 z^3$.

At this point, both $n_g(z, M_*)$, described in the previous Section, and the value of $b_g(z, M_*)$ can be calculated in each stellar mass bin. The latter is computed as eq. (3.9) suggests. Moreover, the galaxy bias $b_g(z)$ can be obtained by integrating over $M_*$. This is shown in Fig. 3, together with the polynomial interpolation:

$$b_g(z) = a_0 + a_1 z + a_2 z^2 + a_3 z^3,$$

where $a_0 = 1.48$, $a_1 = 0.3$, $a_2 = -0.02$, $a_3 = 0.03$.

3.2.2 Merger bias

All ingredients are now available to compute the bias of mergers, following the prescription of eq. (3.7), where the values of $n_g(z, M_*)$ and $b_g(z, M_*)$ are obtained as described in Sec. 3.2.1, while $\langle N_m(z)|M_* \rangle$ is derived from simulations as outlined in Sec. 3.1; finally, the merger number distribution $n_m(z)$ is calculated according to eq. (3.8). As Fig. 4 shows, the bias of the mergers is well described by a linear dependence on redshift:

$$b_m(z) = mz + q,$$

where $m = 0.69$, $q = 1.68$.

A linear merger bias is actually often assumed in the few studies on the subject, which are currently in the literature (see e.g. [10]). In this work, we have not made any initial assumption, but we have instead explicitly worked out and justified such linear behaviour through the standard HOD approach, starting from astrophysically motivated simulations of the merger distribution.

4 Forecasts

Future surveys will measure the distribution of the mergers depending on both their luminosity distance and their sky position. As mentioned earlier, through these data we will be able to constrain both cosmological and merger bias parameters, without relying on any external
measurement. In this work, we forecast the constraining power of a future ET-like experiment and of a more futuristic setting, using the Fisher formalism applied to the APS of the mergers.

4.1 Angular Power Spectrum

The APS is defined as the harmonic transform of the correlation function between observed sources and it is linked to the primordial 3D power spectrum $P_{\text{pr}}(k)$ through the standard formula

$$C_l(z_i, z_j) = 4\pi \int d\ln k \ \Delta_{N,l}^W(z_i, k) \Delta_{N,l}^W(z_j, k) \ P_{\text{pr}}(k) ,$$

where $(z_i, z_j)$ are the central points of the redshift bins in which the APS is calculated, while $\Delta_{N,l}^W(z_i, k)$ are the observed transfer functions in such bins, already mentioned in Sec. 2.2. These are defined as

$$\Delta_{N,l}^W(z_i, k) = \int_{z_{\text{min}}}^{z_{\text{max}}} dz \ p(z) \ W(z_i, z) \ \Delta_l(z, k) ,$$

where $W(z_i, z)$ is the Window function considered in the redshift bin centered in $z_i$, and $p(z)$ is the background source distribution per redshift and solid angle. This is proportional to $dN/dzd\Omega$ but it is normalized in the bin through $\int dz \ p(z) W(z_i, z) = 1$. The full expression of the theoretical transfer function $\Delta_l(z, k)$ can be found e.g. in [11].

The computation of the merger distribution $dN/dzd\Omega$ and of the merger bias $b_m(z)$ is discussed in Sec. 3.1 and Sec. 3.2: eq. (3.6) and eq. (3.15) are implemented in CAMB – together with the LDSD modifications described in Sec. 2.2 and computed using the factor $f_{DL}$ defined in eq. (2.7) – to numerically compute the required APS.

4.1.1 Bin definition

To study the APS, a binning in $D_L$ is defined and converted into $z(D_L)$, after choosing fiducial values for the cosmological parameters (see Tab. 5).
The amplitude of the $D_L$ bins is chosen to reproduce the predicted ET uncertainty in measuring luminosity distances. We assume it to be

$$\frac{\Delta D_L}{D_L} = 10\%.$$  \hfill (4.3)

As [9] shows, this assumption is actually pessimistic at low redshift. However, we verified that further reducing the size of the low-$z$ bins tends to introduce numerical instabilities, without on the other hand producing significant improvements in the final error predictions. We verify that the factor $f_{D_L}$ introduced in Sec. 2.2 has little variation inside each one of these bins: $\Delta f_{D_L} \big|_{D_L} \lesssim 0.1 f_{D_L} \big|_{D_L_{\text{min}}}$. The approximation $f_{D_L} \simeq \text{cost}$ in a given bin is therefore completely reasonable.

In order to analyze more optimistic and more futuristic configurations, we consider also the case

$$\frac{\Delta D_L}{D_L} = \begin{cases} 10\% & \text{if } z < 2 \\ 3\% & \text{if } z \geq 2 \end{cases}.$$  \hfill (4.4)

While being still conservative at low distances, this configuration significantly increases the accuracy of the $D_L$ measurement at high distances. This can be compared to a DECIGO-like survey (see e.g. [9]), in which the closer events are binned together. However, note that DECIGO not only will obtain more accurate $D_L$ measurements, but also observe more sources than ET. In order to further study the effect of increasing the number of observed events, we consider a rescaling of the ET source distribution, which has been derived in eq. (3.6); we refer the reader to the discussion in Sec. 5.1 for more details.

In both the ET-like and the futuristic cases, we set a lower distance bound at $D_{L\text{min}} \simeq 476 \text{ Mpc}$, which corresponds to $z_{\text{min}} = 0.1$ in the fiducial cosmology (see Tab. 5). This lower limit is chosen to stabilize the number of bins at low redshift, without any loss of cosmological information. The highest redshift bin is chosen by considering the merger distribution, shown in Fig. 2: since we have $dN/dzd\Omega \simeq 0$ at $z \simeq 5$, we take $D_{L\text{max}} \simeq 47749 \text{ Mpc}$, corresponding to $z_{\text{max}} \simeq 5$ in the fiducial cosmology (Tab. 5). The $D_L$ bins obtained are reported in Appendix B in Tab. 6 and 7 respectively, for the ET-like and DECIGO-like surveys.

To compute the APS, a Gaussian Window function is used in each bin. This is centered in $z_i = (z_{i \text{min}} + z_{i \text{max}})/2$, with variance $\sigma = (z_{i \text{max}} - z_{i \text{min}})/2$. Fig. 5 compares the merger distribution from eq. (3.6), with the Gaussian Window functions in the bins from Tab. 6.

4.2 Fisher matrix formalism

The Fisher matrix for the APS is defined as

$$F_{\alpha\beta} = \sum_{l_{\text{min}}}^{l_{\text{max}}} \frac{2l+1}{2} f_{\text{sky}} \sum_{D_L, D_L'} \left[ (\partial_\alpha C_{ij}^l) \Gamma_{l_i}^{-1} (\partial_\beta C_{ij}^l) \Gamma_{l_i}^{-1} \right],$$  \hfill (4.5)

where $C_l$ is the APS matrix, in which $C_{ij}^l = C_l(z_i, z_j)$ from eq. (4.1). The derivatives are computed with respect to the parameters of interest

$$\Theta = [H_0, \Omega_c h^2, w_0, w_a, b_0, \ldots b_n],$$  \hfill (4.6)

where $b_0, \ldots b_n$ are the bias parameters, defined inside each of the $D_L$ bins. The fiducial values of the cosmological parameters are reported in Tab. 5, while for each bias parameter the fiducial is found through eq. (3.15), in the central point $z_i$ of the associated bin.
Figure 5. Merger distribution compared with the Window functions computed in the different $z$ bins of the ET-like survey. These are computed converting the $D_L$ bins described in Sec. 4.1 and reported in Tab. 6 through the fiducial cosmology described in Tab. 5.

We approximate the derivatives by finite differences, through the 3-point method, with the choice $\Theta_\alpha = \Theta_{\alpha}^{fid} \pm 10^{-4} \Theta_{\alpha}^{fid}$, where $\Theta_{\alpha}^{fid}$ is the fiducial value of the parameter $\Theta_\alpha$. The APS $C_l(z_i, z_j)$ is computed by CAMB, using $z$ as independent variable. Since our bins are initially defined in LDS, there is a dependence on cosmology in the conversion from $D_L$ to $z$, which is implicitly accounted for in the numerical derivatives.

The term $\Gamma_{l,ij}$ in eq. (4.5) is defined as

$$\Gamma_{l,ij} = C_{ij}^l + N_{ij}^l,$$

$N_{ij}^l$ being the noise contribution in the bins. The amplitude of the bins defines the observational uncertainty in the determination of $D_L$, while the contribution to $N_{ij}^l$ is due to shot noise. Therefore we have

$$N_{ij}^l = \delta_{ij} \bar{N}_{i,j}^{-1} = \delta_{ij} \left[ \int_{z_{i,j}^{\min}}^{z_{i,j}^{\max}} \frac{dN}{dzd\Omega} \bar{W}(z_{i,j}, z) \, dz \right]^{-1},$$

where $\bar{W}(z_{i,j}, z) = W(z_{i,j}, z)/(\sigma \sqrt{2\pi})$ and $W(z_{i,j}, z)$ is the Gaussian Window function.

In eq. (4.5), $f_{sky}$ is the observed fraction of the sky – assumed in this work to be 1 – while $l_{\min}$ and $l_{\max}$ define respectively the largest and smallest scale in the analysis. We choose $l_{\min} = 2\pi/\theta = 2$ (where $\theta = \pi$ is the largest observed angular scale) and

$$l_{\max}(z_{i,j}) = \min_{i,j} [k_{nl}^0 \chi(z_{i,j})(1 + z_{i,j})^{2/(2+ns)}],$$

where $\chi(z_{i,j})$ is the comoving distance computed in the central point of the bin and $n_s$ is the primordial spectral index. The quantity $k_{nl}^0$ is the cut-off scale in the analysis, at which non-linear effects are considered too large to be properly accounted for in our approach, at $z = 0$. We consider two prescriptions for this value. In the more optimistic one, we rely on the accuracy of the halofit model, which is used in CAMB to compute the non-linear power spectrum; therefore we include scales up to $k_{nl}^0 = 0.4 \, \text{hMpc}^{-1}$ (see [43]). In the more conservative one, we stick to linear scales and choose $k_{nl}^0 = 0.1 \, \text{hMpc}^{-1}$. The values of $l_{\max}$, used for the auto APS in each bin are reported in Tab. 6 and Tab. 7.
Table 1. Forecasted 1σ marginalized errors for the cosmological parameters in the different scenarios. The first two lines assume the ET specifications described in the main text, but differ in $k_{nl}^0$. The third line maintains the ET uncertainty on the $D_L$ measurement (defined by the amplitude of the bins) but uses a re-scaled distribution with a higher number of sources. In the fourth and fifth line, the $D_L$ measurement error is improved with respect to the baseline ET-configuration, while the number of sources is either kept at $N = 10^5$ or increased via rescaling of their distribution to $N = 10^7$. Run A uses $\Theta = [H_0, \Omega_c h^2, w_0, w_a]$; run B and run C instead use $\Theta = [H_0, \Omega_c h^2, w_0, w_a, b_0...b_n]$. In all the cases, for $H_0$ the Planck prior [13] is assumed, while for the other cosmological parameters, run A and B assume uniform prior, while run C uses Planck priors [13] as well (see Tab. 5).

| $D_L$ error | Parameter | run A | run B | run C |
|-------------|-----------|-------|-------|-------|
| ET-like survey | $\Omega_c h^2$ | 0.0182 | 0.0449 | 0.0267 |
| $k_{nl}^0 = 0.1$ hMpc$^{-1}$ | $w_0$ | 0.5910 | 0.9627 | 0.6048 |
| | $w_a$ | 2.1810 | 3.9510 | 1.2711 |
| ET-like survey | $\Omega_c h^2$ | 0.0081 | 0.0252 | 0.0148 |
| $k_{nl}^0 = 0.4$ hMpc$^{-1}$ | $w_0$ | 0.1628 | 0.3026 | 0.1995 |
| | $w_a$ | 0.7805 | 2.0134 | 1.1187 |
| ET-like survey | $\Omega_c h^2$ | 0.0092 | 0.0248 | 0.0178 |
| $k_{nl}^0 = 0.1$ hMpc$^{-1}$ | $w_0$ | 0.3478 | 0.5321 | 0.3968 |
| | $w_a$ | 1.2392 | 2.9223 | 1.2223 |
| High precision distances | $\Omega_c h^2$ | 0.0089 | 0.0234 | 0.0175 |
| $k_{nl}^0 = 0.1$ hMpc$^{-1}$ | $w_0$ | 0.3364 | 0.4967 | 0.3845 |
| | $w_a$ | 1.1985 | 2.7630 | 1.2100 |
| High precision distances | $\Omega_c h^2$ | 0.0030 | 0.0055 | 0.0053 |
| $k_{nl}^0 = 0.1$ hMpc$^{-1}$ | $w_0$ | 0.1079 | 0.1739 | 0.1656 |
| | $w_a$ | 0.3516 | 0.7293 | 0.6411 |

5 Results

This Section reports the results of our Fisher analysis. The details of the GW survey considered are shown in Appendix B in Tab. 4. Forecasts are derived for the different scenarios described in Sec. 4.1.1. For each of them, three different configurations are assumed; in each run the parameter $H_0$ is marginalized out, assuming Planck 2018 results as a prior [13]. This marginalization is always carried out because data in luminosity distance space display poor constraining power on $H_0$, which appears as an overall normalization parameter after differentiating the $z(D_L)$ $H_0$-dependence, leading to degeneracies (in similar fashion as it happens e.g. in Supernovae Ia analyses). In "run A", we fix merger bias parameters to their fiducial values and derive constraints for the remaining cosmological parameters, with a flat prior on them. In "run B" we consider the full set of parameters, including bias ones, and again take flat priors on all parameters, except $H_0$. In "run C", we set Planck 2018 priors [13] on all cosmological parameters (to maximize constraining power in the study of merger bias). Summarizing:

run A: $\Theta = [H_0, \Omega_c h^2, w_0, w_a]$, uniform prior on $[\Omega_c h^2, w_0, w_a]$; Planck prior on $H_0$;
run B: $\Theta = [H_0, \Omega_c h^2, w_0, w_a, b_0...b_n]$, uniform prior on $[\Omega_c h^2, w_0, w_a]$; Planck prior on $H_0$;
run C: $\Theta = [H_0, \Omega_c h^2, w_0, w_a, b_0...b_n]$, Planck prior on all the cosmological parameters.
Figure 6. Confidence 1σ ellipses obtained for the ET-like survey in run B, for each couple of cosmological parameters $(\Theta_\alpha, \Theta_\beta)$ described in Tab. 1. The plots for $(\Theta_\alpha, \Theta_\alpha)$ show the posterior distributions obtained. The blue line shows the results obtained setting $k_{\text{nl}}^0 = 0.4 \, h\text{Mpc}^{-1}$, while the red line refers to $k_{\text{nl}}^0 = 0.1 \, h\text{Mpc}^{-1}$.

5.1 Cosmological parameter constraints

In Tab. 1, we report the marginalized 1σ errors computed for each of the cosmological parameters $[\Omega, k^2, w_0, w_a]$. The ET-like results, with either the conservative or the optimistic $k_{\text{nl}}^0$ cut-offs, is reported in the first two rows of the Table, whereas the remaining entries consider more futuristic cases. For the futuristic scenarios, we considered three improvements, all of which computed in the conservative $k_{\text{nl}}^0$ case. First of all, in the third row, we account for the effects of having a higher density of observed mergers, by rescaling the model in eq. (3.6) to get a total number of sources $\simeq 10^7$. This latter case is similar to the one studied in [10], where a combination of one ET-like detector and two Cosmic Explorer is considered. Second of all, we analyze a situation in which distances are measured with higher precision than in the ET analysis (as in the futuristic case described in Sec. 4.1.1), but we keep the number of sources unchanged with respect to the ET-like case. Results for this case are reported in the fourth row. Finally, the fifth row considers the same high precision configuration pushing the observed sources to $\simeq 10^7$.

The run B results are used to compute the confidence ellipses in Fig. 6, which refer to the ET-like configuration. If $H_0$ was not marginalized, its forecasted 1σ error for the ET-like case assuming $k_{\text{nl}}^0 = 0.4 \, h\text{Mpc}^{-1}$, would be 3.2796 in run A, 3.5568 in run B (both assuming uniform prior) and 1.4152 in run C (assuming Planck prior [13]).

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https://cosmicexplorer.org/
Figure 7. Fiducial bias with error, forecasted through the Fisher matrix analysis in run C for both the cases of ET-like survey with $k_{nl}^0 = 0.4 \ h\text{Mpc}^{-1}$ (blue line) and $k_{nl}^0 = 0.1 \ h\text{Mpc}^{-1}$ (red line). Each point indicates the central $z_i$ of the bins in Tab. 6. To build this plot, only the bins for which $[\sigma_b/b](z_i) < 0.3$ have been considered, that is $z < 2.65$ (see Tab. 8 and Tab. 9).

For the ET-like forecasts in the strictly linear regime ($k_{nl}^0 = 0.1 \ h\text{Mpc}^{-1}$), our results show that we can achieve error bars on $\Omega_c h^2$ and $w_0$ which are worse, but not far from those expected via galaxy clustering analysis in the near future (using for example the Euclid catalogue). For $w_a$ we instead find error bars which are about 5-6 times worse than those expected with Euclid. We verify that these expectations change only marginally (by a few percent) if we take a non-informative prior on $H_0$. Of course, optimistically pushing the analysis into more non-linear scales significantly improves these figures. Likewise, much tighter constraints can be achieved with the improved settings (i.e., higher precision in the determination of distances, higher number of sources, or both, compared to the baseline ET-case).

Regardless of its actual constraining power in different regimes, we argue anyway that the main interest of this type of analysis lies in the complementarity between merger and galaxy surveys. We have pointed out since the beginning that Gravitational Wave surveys are in Luminosity Distance Space and we have shown that Luminosity Distance Space Distortions behave differently from Redshift-Space Distortions. Moreover, GW surveys provide information up to very high redshift. This means larger volumes than many forthcoming optical galaxy surveys. It also allows pushing the tomographic analysis up to small scales for high-$z$ shells, while staying in the linear or quasi-linear regime. Constraints on other interesting parameters, which we have not considered here, such as primordial non-Gaussian ($f_{NL}$) amplitudes, generally significantly benefit from large survey volumes at high redshift; we will investigate this further in the future.

Another crucial opportunity offered by merger surveys, which we have already mentioned, is of course that of marginalizing over cosmological parameters and focusing instead on the study of merger bias. This is explored further in Sec. 5.2.
Figure 8. Bias errors in run C in the case of ET-like survey with $k_{nl}^0 = 0.4$ hMpc$^{-1}$. In the upper panel, the blue dots represent the errors $\sigma_b$ in the bins in Tab. 6, while the dashed line is computed through $\sigma_b(z) = a_0 + a_1 z + a_2 z^2 + a_3 z^3 + a_4 z^4$, where the parameters are $a_0 = 0.0803$, $a_1 = -0.4396$, $a_2 = 0.9741$, $a_3 = -0.6687$, $a_4 = 0.1481$. The lower panel shows instead the relative error, $|\sigma_b/b|(z)$; the interpolation here is $|\sigma_b/b|(z) = a_0 + a_1 z + a_2 z^2 + a_3 z^3 + a_4 z^4$, where $a_0 = 0.0349$, $a_1 = -0.1574$, $a_2 = 0.3384$, $a_3 = -0.2271$, $a_4 = 0.0489$. In both plots, only the points for which $|\sigma_b/b|(z_i) < 0.3$ are considered, that is $z < 2.65$ (see Tab. 8).

5.2 Bias parameter constraints

We focus now on merger bias parameters. Since the focus is on merger properties here, rather than on Cosmology, it is appropriate and useful to include stringent cosmological priors from e.g. CMB surveys such as Planck. Therefore, in Appendix B in Tab. 8 and 9, we focus on results from run C (Planck cosmological priors [13]); they are obtained considering the ET-like survey respectively with $k_{nl}^0 = 0.4$ hMpc$^{-1}$ and $k_{nl}^0 = 0.1$ hMpc$^{-1}$. For both these cases, Fig. 7 shows both the fiducial values and error bars, $b(z_i) \pm \sigma_b(z)$, obtained in run C, adopting the model described in eq. (3.15).

To verify whether our method also allows constraining merger bias without any cosmological assumption, we consider a new configuration, in which uniform priors are assumed on all the cosmological parameters (i.e., with a flat prior now also on $H_0$). Tab. 8 and Tab. 9
Figure 9. Upper panel: comparison between the overall bias obtained in Sec. 3.2 (blue line, the errorbars showed are the same as in Fig. 7) and the bias obtained separately for the different sources DNS, DBH, BHNS. Their bias models are obtained by splitting eq. (3.7) into three different contributions, i.e. considering $\langle N_m(z)|M_\ast \rangle$ separately for $m = DNS$ (red line), BHNS (orange line), DBH (purple line). Lower panel: source distributions. As the upper plot also shows, only DNS bias can be significantly distinguished from the overall model.

Note that each bias parameter refers to one of the $D_L$ bins reported in Tab. 6: its fiducial value is computed using eq. (3.15) in the central point $z_i$. The absolute and relative bias errors, as a function of $z$, are displayed in Fig. 8. We conclude that merger bias should be detected by ET at high significance ($\gtrsim 10\sigma$), all the way up to $z \sim 2$, even in the most conservative $k_{nl}^0 = 0.1 h\text{Mpc}^{-1}$ case.

Having this kind of measurement opens up new interesting prospects. For example, it would be interesting to consider different types of GW sources separately, to understand...
whether their different bias models could be distinguished from one another. One possible application for this involves the study of Primordial Black Holes (PBH). Since PBH form before galaxies, their bias – and therefore the bias of their mergers – should be different from those calculated in Sec. 3.2.2. Therefore, the study of the APS from future GW surveys, particularly to understand their dependence on bias parameters, could help shedding light on the existence of PBH or on the properties of their distribution. Even in a more standard scenario, simply comparing the actual measured bias of compact binary mergers to predictions from theory and simulations would clearly already be of interest. As a quick illustrative example, in Fig. 9 we show the bias $b_m(z)$, computed separately for the different populations of mergers considered in this work. If we compare the single-population curves with the overall blind prediction for all events combined (which we use in the actual Fisher analysis), we see that the bias curve expected from DNS mergers alone would be in principle observationally distinguishable from the rest. This behaviour arises from the significantly different redshift dependence of the observed DNS source density curve, with respect to the other two, as predicted in our model and displayed in Fig. 9. We plan to analyze more ideas and applications of this kind in future studies.

6 Conclusions

In this work, we have discussed the possibility of using clustering properties of GW from mergers in Luminosity Distance Space as a tool for Cosmology. This will be possible with the next generation GW experiments, such as ET and DECIGO, which will detect $\sim 10^5$, or more, merger events. In our study, we have mostly focused on tomographic measurements of the Angular Power Spectrum of the mergers for an ET-like survey, but we have also considered more futuristic configurations, allowing both for a higher number of sources and for a better distance measurement (roughly reproducing expectations for a DECIGO-like survey). We have produced Fisher matrix forecasts both for cosmological parameters (matter and dark energy) and for the bias parameters of mergers, forecasting the latter with and without cosmological priors from external data sets (e.g., constraints on Cosmology from Planck).

We have concentrated our attention on mergers of compact binaries and we have predicted both their fiducial number density and bias starting from the astrophysically motivated results of [7, 8], which combine hydrodynamical cosmological simulations with population synthesis models. Our bias model was built using a Halo Occupation Distribution approach.

Our final expected constraints on cosmological parameters are less powerful than those achievable in the near future via galaxy clustering studies. This was essentially foreseeable, in light of the smaller number of tracers which we expect for ET, compared to, e.g., Euclid. It must however be noticed that the large volumes and high redshifts probed with GW mergers partially compensate for this issue, and still lead to interesting results for some parameters, such as, e.g., $\Omega_m h^2$ or $w_0$. Of course, if we instead consider experiments such as DECIGO – which will detect a larger number of events than ET with high precision determination of distances – or a longer observation time for ET itself, the cosmological forecasts significantly improve and lead to potentially tight constraints.

Regardless of the exact expected constraints and of the survey under study, the main point of interest of this approach relies anyway in the complementarity between GW and galaxy survey analyses. As already mentioned above, compact binary mergers detected by ET will extend up to very high redshifts, where electromagnetic counterparts are not available. Furthermore, Luminosity Distance Space Distortions – which have to be considered in the
GW analysis – have a different structure with respect to Redshift-Space Distortions in galaxy catalogues, (LDSD tend to vanish at low redshifts).

Finally, besides focusing on cosmological parameters, we have also explicitly shown how the approach investigated in this work will allow us to measure the bias of GW mergers at high statistical significance, over a large redshift range. This in turn can provide interesting information about the physical nature and properties of mergers themselves. This, and other interesting applications will be the object of further investigation in the future.
A Simulations

The catalogs of binary compact object mergers adopted here come from [7, 8]. These were obtained by seeding the EAGLE cosmological simulation [39] with binary compact objects from population-synthesis simulations [17, 26]. In particular, binary compact objects are randomly associated with stellar particles in the cosmological simulation based on the formation time, metallicity and total initial mass of each stellar particle [27]. Thanks to this algorithm, we self-consistently take into account the properties of the stellar progenitors of each binary compact object, as well as the delay time between formation and merger of the binary.

The initial population-synthesis simulations were run with MOBSE [18]. MOBSE exploits i) fitting formulas to describe the evolution of stellar properties as a function of metallicity and stellar mass (e.g. radii and luminosity, [20]), ii) up-to-date models for stellar-wind mass loss [18], iii) state-of-the-art prescriptions for core-collapse [16] and pair-instability supernovae [28], and iv) a formalism for binary-evolution processes [19]. The mass function and local merger rate density of binary compact objects obtained with MOBSE are in agreement with the results from the first and second observing runs of Advanced LIGO and Virgo [4, 5]. We refer to [17] and to [7] for more detail on the population-synthesis and cosmological simulations, respectively.

A.1 Snapshots

Table 2. Time intervals associated with the redshift snapshots. Here 23 snapshots are defined, while Sec. 3 refers to 22 of them: this is because the mergers in $z = 2.22 \cdot 10^{-16}$ and $z = 0.1$ are considered together. When performing eq. (3.3) in the combined snapshot, the average value of $T_{\text{SIM}}$ is used.

| $z$              | $T_{\text{SIM}}$ [Gyr] | $z$              | $T_{\text{SIM}}$ [Gyr] | $z$              | $T_{\text{SIM}}$ [Gyr] |
|------------------|------------------------|------------------|------------------------|------------------|------------------------|
| $2.22 \cdot 10^{-16}$ | 0.676                  | 0.86             | 0.634                  | 3.02             | 0.429                  |
| 0.10             | 1.161                  | 1.00             | 0.757                  | 3.53             | 0.294                  |
| 0.18             | 0.947                  | 1.26             | 0.770                  | 3.98             | 0.223                  |
| 0.27             | 0.902                  | 1.49             | 0.596                  | 4.49             | 0.194                  |
| 0.37             | 0.987                  | 1.74             | 0.525                  | 5.04             | 0.150                  |
| 0.50             | 0.930                  | 2.00             | 0.409                  | 5.49             | 0.113                  |
| 0.61             | 0.737                  | 2.24             | 0.312                  | 6.00             | 0.145                  |
| 0.73             | 0.685                  | 2.48             | 0.402                  |                 |                        |

A.2 Stellar mass bins

Table 3. Bins in which the stellar mass of the merger host galaxies are divided. The boundaries are expressed as the decimal logarithm of the mass, which is expressed in solar mass $M_{\odot}$ units.

| $[\log M_{*}^{\text{low}}, \log M_{*}^{\text{high}}]$ | $[\log M_{*}^{\text{low}}, \log M_{*}^{\text{high}}]$ | $[\log M_{*}^{\text{low}}, \log M_{*}^{\text{high}}]$ |
|-----------------------------------------------------|-----------------------------------------------------|-----------------------------------------------------|
| [7, 7.33]                                           | [7.33, 7.67]                                        | [7.67, 8]                                           |
| [8, 8.33]                                           | [8.33, 8.67]                                        | [8.67, 9]                                           |
| [9, 9.33]                                           | [9.33, 9.67]                                        | [9.67, 10]                                          |
| [10, 10.33]                                         | [10.33, 10.67]                                      | [10.67, 11]                                         |
| [11, 11.33]                                         | [11.33, 11.67]                                      | [11.67, 12]                                         |
B Angular Power Spectrum and Fisher computation

This appendix reports information on the setting used to compute the APS and the forecasts.

B.1 Survey setting

Table 4. Survey details assumed to forecast the cosmological and astrophysical constraints from GW events. Details can be found in Sec. 2.2, 4.1 and 4.2.

| Survey setting       | Sources: | \(\Delta D_L/D_L = 10\%\)  |
|----------------------|----------|-----------------------------|
| 3yr ET-like survey   | \(f_{\text{sky}} = 1\) \(z_{\text{min}} = 0.1\) | \(z_{\text{max}} = 5\) |
| 3yr ET-like survey   | \(f_{\text{sky}} = 1\) \(z_{\text{min}} = 0.1\) | \(z_{\text{max}} = 5\) |
| High precision distances | \(f_{\text{sky}} = 1\) \(z_{\text{min}} = 0.1\) | \(z_{\text{max}} = 5\) |
| High precision distances | \(f_{\text{sky}} = 1\) \(z_{\text{min}} = 0.1\) | \(z_{\text{max}} = 5\) |

B.2 Fiducial Cosmology

Table 5. Fiducial values of the cosmological parameters used to calculate the APS in CAMB; they are all taken from Planck 2018 [13], except for \(s\). This is the magnitude bias and its value is set through \(5s – 2 = 0\) to have no magnification. The parameters which are associated with an error (68% limit) are the ones used in Sec. 4.2 to compute the Fisher matrix. The values in the first, third and fourth lines are taken from TT,TE,EE+lowE+lensing+BAO data. The values in the second line are compatible with the \(\Lambda\)CDM model in a spatially flat Universe; in particular, the errors for the DE EoS parameters \(w_0\) and \(w_a\) have been estimated by symmetrizing the ones provided by Planck+SNe+BAO data.

| Fiducial Cosmology | \(H_0 = 67.66 \pm 0.42\) | \(\Omega \Lambda h^2 = 0.11933 \pm 0.00091\) | \(\Omega_b h^2 = 0.02242\) |
|--------------------|--------------------------|---------------------------------|------------------|
| \(\Omega_k = 0.0\) | \(w_0 = -1 \pm 0.13\) | \(n_s = 0.9665\) | \(w_a = 0 \pm 0.55\) |
| \(A = 2.105 \cdot 10^{-9}\) | \(Y_{He} = 0.242\) | \(T_{\text{CMB}} = 2.7255\) | \(\tau = 0.0561\) |
| \(N_{\text{eff}} = 2.99\) | \(\Delta z_{\text{rei}} = 0.5\) | \(\Omega_{\nu}h^2 = 0.00064\) | \(s = 0.4\) |
B.3 Distance bins

Table 6: Luminosity distance bins in which the APS is computed for the ET-like survey. The associated central redshifts \( z_i \) are computed in the fiducial cosmology (Tab. 5). The 47 bins are obtained setting \( \Delta D_L/D_L = 10\% \), \( z^{\text{min}}_i = 0.1 \), \( z^{\text{max}}_i \simeq 5 \) (see Sec. 4.1.1). The table shows for each bin the maximum multipoles \( l_{\text{max}} \) and \( l_{\text{lin}}^{\text{max}} \) computed through eq. (4.8) in \( z_i \), assuming respectively \( k^0_{nl} = 0.4 \, \text{hMpc}^{-1} \) and \( k^0_{nl} = 0.1 \, \text{hMpc}^{-1} \); in the last bin, \( l_{\text{max}} \) and \( l_{\text{lin}}^{\text{max}} \) are computed respect to \( z_i = 5 \). For details see Sec. 4.1.

| \( D_L \) bins [Mpc] | \( z_i \) | \( l_{\text{max}} \) | \( l_{\text{lin}}^{\text{max}} \) | \( D_L \) bins [Mpc] | \( z_i \) | \( l_{\text{max}} \) | \( l_{\text{lin}}^{\text{max}} \) |
|----------------------|----------|-----------------|-----------------|----------------------|----------|-----------------|-----------------|
| [475.73, 525.81]     | 0.10     | 124             | 31              | [525.81, 581.16]     | 0.12     | 150             | 37              |
| [581.16, 642.33]     | 0.13     | 164             | 41              | [642.33, 709.94]     | 0.14     | 177             | 44              |
| [709.94, 784.67]     | 0.15     | 190             | 47              | [784.67, 867.27]     | 0.17     | 217             | 54              |
| [867.27, 958.56]     | 0.18     | 230             | 57              | [958.56, 1059.46]    | 0.20     | 258             | 64              |
| [1059.46, 1170.99]   | 0.22     | 285             | 71              | [1170.99, 1294.25]   | 0.24     | 313             | 78              |
| [1294.25, 1430.49]   | 0.26     | 341             | 85              | [1430.49, 1581.06]   | 0.28     | 369             | 92              |
| [1581.06, 1747.49]   | 0.31     | 412             | 103             | [1747.49, 1931.44]   | 0.34     | 455             | 113             |
| [1931.44, 2134.75]   | 0.37     | 499             | 124             | [2134.75, 2359.46]   | 0.40     | 543             | 135             |
| [2359.46, 2607.82]   | 0.44     | 602             | 150             | [2607.82, 2882.33]   | 0.47     | 647             | 161             |
| [2882.33, 3185.73]   | 0.51     | 707             | 176             | [3185.73, 3521.07]   | 0.56     | 783             | 195             |
| [3521.07, 3891.71]   | 0.61     | 859             | 214             | [3891.71, 4301.36]   | 0.66     | 936             | 234             |
| [4301.36, 4754.14]   | 0.72     | 1209            | 257             | [4754.14, 5254.57]   | 0.78     | 1122            | 280             |
| [5254.57, 5807.68]   | 0.85     | 1232            | 308             | [5807.68, 6419.02]   | 0.92     | 1341            | 335             |
| [6419.02, 7094.71]   | 1.00     | 1467            | 366             | [7094.71, 7841.52]   | 1.08     | 1592            | 398             |
| [7841.52, 8666.94]   | 1.17     | 1734            | 433             | [8666.94, 9579.25]   | 1.27     | 1890            | 472             |
| [9579.25, 10587.59]  | 1.38     | 2062            | 515             | [10587.59, 11702.08] | 1.49     | 2233            | 558             |
| [11702.08, 12933.87] | 1.62     | 2435            | 608             | [12933.87, 14295.33] | 1.76     | 2650            | 662             |
| [14295.33, 15800.11] | 1.91     | 2879            | 719             | [15800.11, 17463.27] | 2.07     | 3121            | 780             |
| [17463.27, 19301.51] | 2.25     | 3391            | 847             | [19301.51, 21333.25] | 2.44     | 3673            | 918             |
| [21333.25, 23578.86] | 2.65     | 3982            | 995             | [23578.86, 26060.84] | 2.88     | 4315            | 1078            |
| [26060.84, 28804.09] | 3.13     | 4673            | 1168            | [28804.09, 31836.1]  | 3.41     | 5067            | 1266            |
| [31836.1, 35187.27]  | 3.70     | 5470            | 1367            | [35187.27, 38891.19] | 4.03     | 5921            | 1480            |
| [38891.19, 42985.0]  | 4.39     | 6405            | 1601            | [42985.0, 47509.74]  | 4.78     | 6921            | 1730            |
| [47509.74, 52510.76] | 5.20     | 7208            | 1802            |
Table 7: Luminosity distance bins in which the APS is computed for the futuristic DECIGO-like configuration. The associated central redshifts \( z_i \) are computed in the fiducial cosmology (Tab. 5). The 70 bins are obtained setting \( \Delta D_L / D_L = 10\% \) if \( z < 2 \) and \( 3\% \) if \( z \geq 2 \), \( z_{\min} = 0.1 \), \( z_{\max} \approx 5 \) (see Sec. 4.1.1). The table shows for each bin the maximum multipoles \( l_{\text{max}}^\text{lin} \) computed through eq. (4.8) in \( z_i \), assuming \( k_0^D = 0.1 \) hMpc\(^{-1}\). For details see Sec. 4.1.

| \( D_L \) bins [Mpc] | \( z_i \) | \( l_{\text{max}}^\text{lin} \) | \( D_L \) bins [Mpc] | \( z_i \) | \( l_{\text{max}}^\text{lin} \) |
|----------------------|-----------|-----------------|----------------------|-----------|-----------------|
| [475.73, 525.81]     | 0.10      | 31              | [525.81, 581.16]     | 0.12      | 37              |
| [581.16, 642.33]     | 0.13      | 41              | [642.33, 709.94]     | 0.14      | 44              |
| [709.94, 784.67]     | 0.15      | 47              | [784.67, 867.27]     | 0.17      | 54              |
| [867.27, 958.56]     | 0.18      | 57              | [958.56, 1059.46]    | 0.20      | 64              |
| [1059.46, 1170.99]   | 0.22      | 71              | [1170.99, 1294.25]   | 0.24      | 78              |
| [1294.25, 1430.49]   | 0.26      | 85              | [1430.49, 1581.06]   | 0.28      | 92              |
| [1581.06, 1747.49]   | 0.31      | 103             | [1747.49, 1931.44]   | 0.34      | 113             |
| [1931.44, 2134.75]   | 0.37      | 124             | [2134.75, 2359.46]   | 0.40      | 135             |
| 2359.46, 2607.82     | 0.44      | 150             | 2607.82, 2882.33     | 0.47      | 161             |
| 2882.33, 3185.73     | 0.51      | 176             | 3185.73, 3521.07     | 0.56      | 195             |
| 3521.07, 3891.71     | 0.61      | 214             | 3891.71, 4301.36     | 0.66      | 234             |
| 4301.36, 4754.14     | 0.72      | 257             | 4754.14, 5254.57     | 0.78      | 280             |
| 5254.57, 5807.68     | 0.85      | 308             | 5807.68, 6419.02     | 0.92      | 335             |
| 6419.02, 7094.71     | 1.00      | 366             | 7094.71, 7841.52     | 1.08      | 398             |
| 7841.52, 8666.94     | 1.17      | 433             | 8666.94, 9579.25     | 1.27      | 472             |
| 9579.25, 10587.59    | 1.38      | 515             | 10587.59, 11702.08   | 1.49      | 558             |
| 11702.08, 12933.87   | 1.62      | 608             | 12933.87, 14295.33   | 1.76      | 662             |
| 14295.33, 15800.11   | 1.91      | 719             | 15800.11, 17463.27   | 2.07      | 780             |
| 17463.27, 17995.15   | 2.18      | 821             | 17995.15, 18543.23   | 2.24      | 844             |
| 18543.23, 19107.99   | 2.29      | 862             | 19107.99, 19689.96   | 2.35      | 885             |
| 19689.96, 20289.66   | 2.41      | 907             | 20289.66, 20907.62   | 2.47      | 929             |
| 20907.62, 21544.4    | 2.53      | 951             | 21544.4, 22000.57    | 2.59      | 973             |
| 22000.57, 22876.73   | 2.66      | 999             | 22876.73, 23573.48   | 2.73      | 1024            |
| 23573.48, 24291.46   | 2.80      | 1050            | 24291.46, 25031.3    | 2.87      | 1075            |
| 25031.3, 25793.68    | 2.94      | 1100            | 25793.68, 26579.27   | 3.01      | 1125            |
| 26579.27, 27388.79   | 3.09      | 1154            | 27388.79, 28222.97   | 3.17      | 1182            |
| 28222.97, 29082.55   | 3.25      | 1210            | 29082.55, 29968.31   | 3.33      | 1238            |
| 29968.31, 30881.05   | 3.42      | 1270            | 30881.05, 31821.59   | 3.50      | 1298            |
| 31821.59, 32790.78   | 3.59      | 1329            | 32790.78, 33789.48   | 3.68      | 1360            |
| 33789.48, 34818.6    | 3.78      | 1395            | 34818.6, 35879.07    | 3.87      | 1425            |
| 35879.07, 36971.83   | 3.97      | 1460            | 36971.83, 38097.88   | 4.08      | 1497            |
| 38097.88, 39258.22   | 4.18      | 1531            | 39258.22, 40453.9    | 4.29      | 1568            |
| 40453.9, 41686.0     | 4.40      | 1604            | 41686.0, 42955.62    | 4.51      | 1641            |
| 42955.62, 44263.92   | 4.63      | 1681            | 44263.92, 45612.06   | 4.75      | 1720            |
| 45612.06, 47001.26   | 4.87      | 1759            | 47001.26, 48432.77   | 5.00      | 1802            |
B.4 Bias errors

Table 8: ET-like survey with $k_{nl}^0 = 0.4 \ h\text{Mpc}^{-1}$. For each bin from Tab. 6, the central $z_i$ is indicated, together with the fiducial bias computed through eq. (3.15). $1\sigma$ marginalized errors and relative errors $[\sigma_b/b](z_i)$ are shown both for run C and run D (see Sec. 5.2).

| $z_i$ | $b(z_i)$ | $\sigma_b$ run C | $\sigma_b$ run D | $[\sigma_b/b](z_i)$ run C | $[\sigma_b/b](z_i)$ run D |
|---|---|---|---|---|---|
| 0.10 | 1.7490 | 0.0437 | 0.0476 | 0.0250 | 0.0272 |
| 0.12 | 1.7628 | 0.0377 | 0.0429 | 0.0214 | 0.0243 |
| 0.13 | 1.7697 | 0.0334 | 0.0397 | 0.0189 | 0.0224 |
| 0.14 | 1.7766 | 0.0306 | 0.0378 | 0.0172 | 0.0213 |
| 0.15 | 1.7835 | 0.0288 | 0.0361 | 0.0161 | 0.0202 |
| 0.17 | 1.7973 | 0.0276 | 0.0347 | 0.0154 | 0.0193 |
| 0.18 | 1.8042 | 0.0269 | 0.0338 | 0.0149 | 0.0187 |
| 0.20 | 1.8180 | 0.0265 | 0.0328 | 0.0146 | 0.0180 |
| 0.22 | 1.8318 | 0.0263 | 0.0320 | 0.0144 | 0.0175 |
| 0.24 | 1.8456 | 0.0261 | 0.0311 | 0.0141 | 0.0169 |
| 0.26 | 1.8594 | 0.0260 | 0.0302 | 0.0140 | 0.0162 |
| 0.28 | 1.8732 | 0.0260 | 0.0296 | 0.0139 | 0.0158 |
| 0.31 | 1.8939 | 0.0262 | 0.0292 | 0.0138 | 0.0154 |
| 0.34 | 1.9146 | 0.0266 | 0.0289 | 0.0139 | 0.0151 |
| 0.37 | 1.9353 | 0.0271 | 0.0290 | 0.0140 | 0.0150 |
| 0.40 | 1.9560 | 0.0279 | 0.0295 | 0.0143 | 0.0151 |
| 0.44 | 1.9836 | 0.0288 | 0.0299 | 0.0145 | 0.0151 |
| 0.47 | 2.0043 | 0.0294 | 0.0302 | 0.0147 | 0.0151 |
| 0.51 | 2.0319 | 0.0314 | 0.0320 | 0.0155 | 0.0157 |
| 0.56 | 2.0664 | 0.0339 | 0.0348 | 0.0164 | 0.0168 |
| 0.61 | 2.1009 | 0.0419 | 0.0431 | 0.0199 | 0.0205 |
| 0.66 | 2.1354 | 0.0457 | 0.0462 | 0.0214 | 0.0216 |
| 0.72 | 2.1768 | 0.0504 | 0.0506 | 0.0232 | 0.0232 |
| 0.78 | 2.2182 | 0.0566 | 0.0566 | 0.0255 | 0.0255 |
| 0.85 | 2.2665 | 0.0645 | 0.0645 | 0.0285 | 0.0285 |
| 0.92 | 2.3148 | 0.0746 | 0.0746 | 0.0322 | 0.0322 |
| 1.00 | 2.3700 | 0.0878 | 0.0878 | 0.0370 | 0.0370 |
| 1.08 | 2.4252 | 0.1044 | 0.1045 | 0.0430 | 0.0431 |
| 1.17 | 2.4873 | 0.1210 | 0.1212 | 0.0486 | 0.0487 |
| 1.27 | 2.5563 | 0.1204 | 0.1210 | 0.0471 | 0.0473 |
| 1.38 | 2.6322 | 0.0932 | 0.0942 | 0.0354 | 0.0358 |
| 1.49 | 2.7081 | 0.0914 | 0.0916 | 0.0338 | 0.0338 |
| 1.62 | 2.7978 | 0.1922 | 0.1995 | 0.0687 | 0.0713 |
| 1.76 | 2.8944 | 0.0542 | 0.0548 | 0.0187 | 0.0189 |
| 1.91 | 2.9979 | 0.0803 | 0.0804 | 0.0268 | 0.0268 |
| 2.07 | 3.1083 | 0.1283 | 0.1283 | 0.0413 | 0.0413 |
| 2.25 | 3.2325 | 0.2086 | 0.2086 | 0.0645 | 0.0645 |
| 2.44 | 3.3636 | 0.3502 | 0.3502 | 0.1041 | 0.1041 |
| 2.65 | 3.5085 | 0.6165 | 0.6166 | 0.1757 | 0.1757 |
| 2.88 | 3.6672 | 1.1562 | 1.1562 | 0.3153 | 0.3153 |

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| $z_i$ | $b(z_i)$ | $\sigma_b$ run C | $\sigma_b$ run D | $\sigma_b \,(b(z_i))$ run C | $\sigma_b \,(b(z_i))$ run D |
|------|---------|-----------------|-----------------|----------------|----------------|
| 3.13 | 3.8397  | 2.3469          | 2.3469          | 0.6112        | 0.6112        |
| 3.41 | 4.0329  | 5.2523          | 5.2523          | 1.3024        | 1.3024        |
| 3.7  | 4.233   | 13.2081         | 13.2081         | 3.1203        | 3.1203        |
| 4.03 | 4.607   | 38.032          | 38.032          | 8.5260        | 8.5260        |
| 4.39 | 4.7091  | 114.14          | 114.14          | 24.239        | 24.239        |
| 4.78 | 4.9782  | 56.854          | 56.854          | 11.421        | 11.421        |
| 5.20 | 5.2680  | 12.502          | 12.502          | 2.3732        | 2.3732        |

**Figure 10.** Bias forecasted errors obtained through run C (blue dots, uniform prior on cosmology) and run D (green dots, Planck 2018 [13] prior on cosmology); the ET-like survey with $k_{nl}^0 = 0.4 \, h\text{Mpc}^{-1}$ is assumed. This plot shows only low $z$, where the difference between the results of the runs is not negligible (see Tab. 8).

**Table 9:** ET-like survey with $k_{nl}^0 = 0.1 \, h\text{Mpc}^{-1}$. For each bin from Tab. 6, the central $z_i$ is indicated, together with the fiducial bias computed here through eq. (3.15). 1σ marginalized errors and relative errors $|\sigma_b/b|(z_i)$ are shown both for run C and run D (see Sec. 5.2).

| $z_i$ | $b(z_i)$ | $\sigma_b$ run C | $\sigma_b$ run D | $\sigma_b \,(b(z_i))$ run C | $\sigma_b \,(b(z_i))$ run D |
|------|---------|-----------------|-----------------|----------------|----------------|
| 0.10 | 1.7490  | 0.0820          | 0.0954          | 0.0469        | 0.0545        |
| 0.12 | 1.7628  | 0.0726          | 0.0897          | 0.0412        | 0.0509        |
| 0.13 | 1.7697  | 0.0636          | 0.0853          | 0.0359        | 0.0482        |
| 0.14 | 1.7766  | 0.0571          | 0.0818          | 0.0321        | 0.0460        |
| 0.15 | 1.7835  | 0.0528          | 0.0785          | 0.0296        | 0.0440        |
| 0.17 | 1.7973  | 0.0502          | 0.0751          | 0.0279        | 0.0418        |
| 0.18 | 1.8042  | 0.0487          | 0.0718          | 0.0270        | 0.0398        |
| 0.20 | 1.8180  | 0.0480          | 0.0688          | 0.0264        | 0.0378        |
| $z_i$ | $b(z_i)$ | $\sigma_b$ run C | $\sigma_b$ run D | $[\sigma_b/b](z_i)$ run C | $[\sigma_b/b](z_i)$ run D |
|------|----------|-----------------|-----------------|-----------------|-----------------|
| 0.22 | 1.8318   | 0.0476          | 0.0658          | 0.0260          | 0.0359          |
| 0.24 | 1.8456   | 0.0475          | 0.0628          | 0.0257          | 0.0340          |
| 0.26 | 1.8594   | 0.0476          | 0.0602          | 0.0256          | 0.0324          |
| 0.28 | 1.8732   | 0.0478          | 0.0578          | 0.0255          | 0.0309          |
| 0.31 | 1.8939   | 0.0483          | 0.0559          | 0.0255          | 0.0295          |
| 0.34 | 1.9146   | 0.0490          | 0.0546          | 0.0256          | 0.0285          |
| 0.37 | 1.9353   | 0.0503          | 0.0540          | 0.0260          | 0.0279          |
| 0.40 | 1.9560   | 0.0520          | 0.0544          | 0.0266          | 0.0278          |
| 0.44 | 1.9836   | 0.0543          | 0.0559          | 0.0274          | 0.0282          |
| 0.47 | 2.0043   | 0.0566          | 0.0574          | 0.0282          | 0.0286          |
| 0.51 | 2.0319   | 0.0613          | 0.0620          | 0.0302          | 0.0305          |
| 0.56 | 2.0664   | 0.0674          | 0.0686          | 0.0326          | 0.0332          |
| 0.61 | 2.1009   | 0.0853          | 0.0854          | 0.0406          | 0.0406          |
| 0.66 | 2.1354   | 0.0965          | 0.0966          | 0.0452          | 0.0452          |
| 0.72 | 2.1768   | 0.1105          | 0.1108          | 0.0508          | 0.0509          |
| 0.78 | 2.2182   | 0.1296          | 0.1297          | 0.0584          | 0.0585          |
| 0.85 | 2.2665   | 0.1548          | 0.1548          | 0.0683          | 0.0683          |
| 0.92 | 2.3148   | 0.1880          | 0.1880          | 0.0812          | 0.0812          |
| 1.00 | 2.3700   | 0.2294          | 0.2297          | 0.0968          | 0.0969          |
| 1.08 | 2.4252   | 0.2664          | 0.2694          | 0.1098          | 0.1111          |
| 1.17 | 2.4873   | 0.2563          | 0.2716          | 0.1030          | 0.1092          |
| 1.27 | 2.5563   | 0.1939          | 0.2185          | 0.0759          | 0.0855          |
| 1.38 | 2.6322   | 0.1387          | 0.1538          | 0.0527          | 0.0584          |
| 1.49 | 2.7081   | 0.1704          | 0.1731          | 0.0629          | 0.0639          |
| 1.62 | 2.7978   | 0.4104          | 0.4757          | 0.1467          | 0.1700          |
| 1.76 | 2.8944   | 0.0995          | 0.1209          | 0.0344          | 0.0418          |
| 1.91 | 2.9979   | 0.1263          | 0.1358          | 0.0421          | 0.0453          |
| 2.07 | 3.1083   | 0.1927          | 0.1970          | 0.0620          | 0.0634          |
| 2.25 | 3.2325   | 0.3125          | 0.3144          | 0.0967          | 0.0973          |
| 2.44 | 3.3636   | 0.5321          | 0.5330          | 0.1582          | 0.1585          |
| 2.65 | 3.5085   | 0.9568          | 0.9572          | 0.2727          | 0.2728          |
| 2.88 | 3.6672   | 1.8356          | 1.8358          | 0.5005          | 0.5006          |
| 3.13 | 3.8397   | 3.8033          | 3.8033          | 0.9905          | 0.9905          |
| 3.41 | 4.0329   | 8.6396          | 8.6396          | 2.1423          | 2.1423          |
| 3.70 | 4.2330   | 21.835          | 21.835          | 5.1583          | 5.1583          |
| 4.03 | 4.4607   | 62.045          | 62.045          | 13.909          | 13.909          |
| 4.39 | 4.7091   | 155.72          | 155.72          | 33.069          | 33.069          |
| 4.78 | 4.9782   | 56.348          | 56.348          | 11.319          | 11.319          |
| 5.20 | 5.2680   | 12.280          | 12.280          | 2.3311          | 2.3311          |
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Bibliography

[1] B. P. Abbott et al. Observation of Gravitational Waves from a Binary Black Hole Merger. *Phys. Rev. Lett.*, 116, 2016. doi: 10.1103/PhysRevLett.116.061102.

[2] B. P. Abbott et al. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Phys. Rev. Lett.*, 119, 2017. doi: 10.1103/PhysRevLett.119.161101.

[3] B.P. Abbott et al. A gravitational-wave standard siren measurement of the Hubble constant. *Nature*, 551, 2017. doi: 10.1038/nature24471.

[4] B.P. Abbott et al. GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs. *Physical Review X*, 9(3), 2019. doi: 10.1103/PhysRevX.9.031040.

[5] B.P. Abbott et al. Binary Black Hole Population Properties Inferred from the First and Second Observing Runs of Advanced LIGO and Advanced Virgo. *Astrophysical Journal, Letters*, 882 (2), 2019. doi: 10.3847/2041-8213/ab3800.

[6] R. Abbott et al. GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object. *The Astrophysical Journal*, 896(2), 2020. doi: 10.3847/2041-8213/ab960f.

[7] M. C. Artale et al. Mass and star formation rate of the host galaxies of compact binary mergers across cosmic time. *Monthly Notices of the RAS*, 491, 2020. doi: 10.1093/mnras/stz3190.

[8] M.C. Artale et al. The impact of assembly bias on the halo occupation in hydrodynamical simulations. *Monthly Notices of the Royal Astronomical Society*, 480(3), 2018. doi: 10.1093/mnras/sty2110.

[9] D. Bertacca et al. Cosmological perturbation effects on gravitational-wave luminosity distance estimates. *Physics of the Dark Universe*, 20, 2018. doi: 10.1016/j.dark.2018.03.001.

[10] F. Calore et al. Cross-correlating galaxy catalogs and gravitational waves: a tomographic approach, 2020.

[11] A. Challinor and A. Lewis. Linear power spectrum of observed source number counts. *Phys. Rev. D*, 84(4), 2011. doi: 10.1103/PhysRevD.84.043516.

[12] H.Y. Chen, M. Fishbach, and D. E. H. A two per cent Hubble constant measurement from standard sirens within five years. *Nature*, 562(7728), 2018. doi: 10.1038/s41586-018-0606-0.

[13] Planck Collaboration. *Planck 2018 results. VI. Cosmological parameters*. arXiv:1807.06209, 2018.
[14] A. Cooray and R. Sheth. *Halo models of large scale structure*. Physics Reports, 372(1), 2002. doi: 10.1016/S0370-1573(02)00276-4.

[15] J. Fonseca et al. *Constraints on the growth rate using the observed galaxy power spectrum*. Journal of Cosmology and Astroparticle Physics, 2019(12), 2019. doi: 10.1088/1475-7516/2019/12/028.

[16] C. L. Fryer et al. *Compact Remnant Mass Function: Dependence on the Explosion Mechanism and Metallicity*. Astrophysical Journal, 749(1), 2012. doi: 10.1088/0004-637X/749/1/91.

[17] N. Giacobbo and M. Mapelli. *The progenitors of compact-object binaries: impact of metallicity, common envelope and natal kicks*. Monthly Notices of the RAS, 480, 2018. doi: 10.1093/mnras/sty1990.

[18] N. Giacobbo, M. Mapelli, and M. Spera. *Merging black hole binaries: the effects of progenitor’s metallicity, mass-loss rate and Eddington factor*. Monthly Notices of the RAS, 474, 2018. doi: 10.1093/mnras/stx2933.

[19] J. R. Hurley et al. *Evolution of binary stars and the effect of tides on binary populations*. Monthly Notices of the RAS, 329(4), 2002. doi: 10.1046/j.1365-8711.2002.05038.x.

[20] J. R. Hurley et al. *Comprehensive analytic formulae for stellar evolution as a function of mass and metallicity*. Monthly Notices of the RAS, 315(3), 2000. doi: 10.1046/j.1365-8711.2000.03426.x.

[21] N. Kaiser. *Clustering in real space and in redshift space*. Monthly Notices of the Royal Astronomical Society, 227(1), 1987. doi: 10.1093/mnras/227.1.1.

[22] D. Karagiannis et al. *Constraining primordial non-Gaussianity with bispectrum and power spectrum from upcoming optical and radio surveys*. Monthly Notices of the Royal Astronomical Society, 478(1), 2018. doi: 10.1093/mnras/stx2123.

[23] H. Lam and P.B. Greene. *Correlated fluctuations in luminosity distance and the importance of peculiar motion in supernova surveys*. Phys. Rev. D, 73, 2006. doi: 10.1103/PhysRevD.73.123526.

[24] R. Laureijs et al. *Euclid Definition Study Report*. arXiv:1110.3193, 2011.

[25] A. Lewis and S. Bridle. *Cosmological parameters from CMB and other data: A Monte Carlo approach*. Physical Review D, 66, 2002. doi: 10.1103/PhysRevD.66.103511.

[26] M. Mapelli and N. Giacobbo. *The cosmic merger rate of neutron stars and black holes*. Monthly Notices of the RAS, 479(4), 2018. doi: 10.1093/mnras/sty1613.

[27] M. Mapelli et al. *The cosmic merger rate of stellar black hole binaries from the Illustris simulation*. Monthly Notices of the RAS, 472(2), 2017. doi: 10.1093/mnras/stx2123.

[28] M. Mapelli et al. *Impact of the Rotation and Compactness of Progenitors on the Mass of Black Holes*. Astrophysical Journal, 888(2), 2020. doi: 10.3847/1538-4357/ab584d.

[29] S. Mukherjee et al. *Multimessenger tests of gravity with weakly lensed gravitational waves*. Physical Review D, 101(10), 2020. doi: 10.1103/physrevd.101.103509.

[30] S. Mukherjee et al. *Accurate and precision Cosmology with redshift unknown gravitational wave sources*, 2020.

[31] S.G. Murray et al. *HMFcalc: An online tool for calculating dark matter halo mass functions*. Astronomy and Computing, 3, 2013. doi: 10.1016/S0370-1573(02)00276-4.

[32] T. Namikawa, A. Nishizawa, and A. Taruya. *Anisotropies of Gravitational-Wave Standard Sirens as a New Cosmological Probe without Redshift Information*. Physical Review Letters, 116(12), Mar 2016. doi: 10.1103/physrevlett.116.121302.

[33] E. Payne et al. *Searching for anisotropy in the distribution of binary black hole mergers*, 2020.
[34] T. Pyne and M. Birkinshaw. The luminosity distance in perturbed FLRW space. *Monthly Notices of the Royal Astronomical Society*, 348, 2004. doi: 10.1111/j.1365-2966.2004.07362.x.

[35] T. Pyne and Birkinshaw. Beyond the thin lens approximation. *Astrophysical Journal*, 458, 1996. doi: 10.1086/176791.

[36] A. Raccanelli et al. Determining the progenitors of merging black-hole binaries. *Physical Review D*, 94(2), 2016. doi: 10.1103/physrevd.94.023516.

[37] Mukherjee S. and Wandelt B.D. Beyond the classical distance-redshift test: cross-correlating redshift-free standard candles and sirens with redshift surveys, 2018.

[38] G. Scelfo et al. GW×LSS: chasing the progenitors of merging binary black holes. *Journal of Cosmology and Astroparticle Physics*, 2018(09), 2018. doi: 10.1088/1475-7516/2018/09/039.

[39] J. Schaye et al. The EAGLE project: simulating the evolution and assembly of galaxies and their environments. *Monthly Notices of the RAS*, 446, 2015. doi: 10.1093/mnras/stu2058.

[40] B. F. Schutz. Determining the Hubble constant from gravitational wave observations. *Nature*, 323, 1986. doi: 10.1038/323310a0.

[41] B. Sharan et al. Measuring angular N-point correlations of binary black-hole merger gravitational-wave events with hierarchical Bayesian inference, 2020.

[42] R. Stiskalek et al. Are stellar mass binary black hole mergers isotropically distributed?, 2020.

[43] R. Takahashi et al. Revising the halofit model for the non linear power spectrum. *The Astrophysical Journal*, 761, 2012. doi: 10.1088/0004-637x/761/2/152.

[44] J.L. Tinker et al. Toward a Halo Mass Function for Precision Cosmology: The Limits of Universality. *The Astrophysical Journal*, 688(2), 2008. doi: 10.1086/591439.

[45] A. Vijaykumar et al. Probing the large scale structure using gravitational-wave observations of binary black holes, 2020.

[46] P. Zhang. The large scale structure in the 3D luminosity-distance space and its cosmological applications. arXiv:1810.11915, 2018.