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# Probing Cosmology with Baryon Acoustic Oscillations using Gravitational Waves

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## ABSTRACT

The third-generation (3G) GW detectors such as the Einstein telescope (ET) or Cosmic Explorer (CE) are expected to play an important role in cosmology. With the help of 3G detectors, we will be able to probe the large-scale structure (LSS) features such as baryon acoustic oscillations (BAO), galaxy bias, etc. We explore the possibility to do precision cosmology, with the 3G GW detectors by measuring the angular BAO scale using localization volumes of compact binary merger events. The BAO are the imprints of the early Universe on the distribution of matter and it provides a standard scale which can be treated as a cosmic ruler. Through simulations, we show that with a 3G detector network, by probing the angular BAO scale using purely GW observations, we can constrain the Hubble constant for the standard model of cosmology ($\Lambda$CDM) with 90% credible regions as $H_0 = 64.01^{+15.25}_{-14.47}$. When combined with BAO measurements from galaxy surveys, we show that it can be used to constrain various models of cosmology such as parametrized models for dark energy equations of state.

*Keywords:* gravitational waves — cosmology —binary neutron stars — third generation detectors

## 1. INTRODUCTION

In the last few years, the detection of gravitational waves (GW) from the merger of compact objects have become a routine (Abbott et al. 2016, 2017a) and results into detailed catalogs of gravitational wave mergers (Abbott et al. 2021b; Nitz et al. 2021). The growth of the catalogs enabled us to probe various aspects of science, to list a few: i) inferring the population properties, such as the mass, spin and redshift distribution of the compact binaries (Abbott et al. 2021c), ii) testing the validity of general relativity (Abbott et al. 2021d), iii) constraining the equation of state and radii of neutron stars (Abbott et al. 2018a; Capano et al. 2020), iv) constraining the cosmic expansion history and inferring the value of the Hubble parameter (Abbott et al. 2021e), etc.

The idea of probing cosmology with GWs is not only exciting but also timely as there exists a tension between the value of the Hubble constant $H_0$ measured from low redshift data such as supernovae (SNe) (Riess et al. 2019) and the data from surveys from the high redshift such as cosmic microwave background (CMB) (Aghanim et al. 2020). For example, the value of $H_0$ as obtained from Planck 2018 results indicate $H_0 = 67.04 \pm 0.5$ km s$^{-1}$ Mpc$^{-1}$ (Aghanim et al. 2020), while the inferred value from the low redshift probes such as SNIa yields $H_0 = 74.03 \pm 1.42$ km s$^{-1}$ Mpc$^{-1}$ (Riess et al. 2019). A recent measurement of the local value of $H_0$ from the Hubble Space Telescope (HST) and SHOES team provides constraint on the $H_0$ with $\sim$ 1 km s$^{-1}$ Mpc$^{-1}$ uncertainty as $H_0 = 73.30 \pm 1.04$ km s$^{-1}$ Mpc$^{-1}$, which implies a $5\sigma$ difference with the value predicted by *Planck2018* measurements(Riess et al. 2021). All these measurements assume the standard model of cosmology known as $\Lambda$CDM model.

The very first detection of GWs from the merger of a binary neutron star (BNS) (Abbott et al. 2017a) was accompanied by observations from various electromagnetic (EM) telescopes (Abbott et al. 2017b,c), which made it possible to put the very first constraints on the value of the Hubble constant from GW observations (Abbott et al. 2017d). Since then, binary black hole (BBH) merger events have also been used to put constraints on the Hubble parameter, by cross-correlating their localization volumes with the galaxy catalogs (Abbott et al. 2021a). The degeneracy between the mass and redshift of observed BBH mergers was also explored along with the population models to put constraints on the value of $H_0$ (Mastrogiovanni et al. 2021). The recent

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estimates of the $H_0$ from recent GWTC-3 catalog with 68% CL indicates $H_0 = 68^{+8}_{-6}$ km s$^{-1}$ Mpc$^{-1}$ (Abbott et al. 2021e). Though the uncertainties on the value of $H_0$ measured from the GW observations is not at the level of resolving Hubble tension right now, we expect that in the near future, with more GW observations and improvements in the detector sensitivity, we can resolve this tension.

The current generation of detectors such as LIGO-Hanford, LIGO-Livingston (Aasi et al. 2015), Virgo (Acernese et al. 2015), and KAGRA (Akutsu et al. 2021) are set to undergo upgrades in various stages in upcoming years (Abbott et al. 2018b), and new detectors such as LIGO-India (Saleem et al. 2022) are expected to join the global detector network at some point in the future. Thanks to these network improvements, the source localization is expected to improve a lot (Fairhurst 2014). Furthermore, the proposed third-generation (3G) ground-based detectors such as Cosmic Explorer (CE) (Reitze et al. 2019a,b) and the Einstein telescope (ET) (Sathyaprakash et al. 2012) which are expected to be operational sometime during the next decade. These detectors will be able to probe the Universe up to very high redshifts ($z \sim 10$) and will be able to detect thousands of GW merger events per year (Mills et al. 2018). Many of these GW mergers (at lower redshifts) are expected to be localized within a square degree and so that the spatial distribution of the localization volumes of well-localized mergers can be used to probe the large-scale structure (LSS) of the Universe, *e.g.* by measuring the galaxy bias (Vijaykumar et al. 2020), or by detecting the baryon acoustic oscillations (BAO) peak (Kumar et al. 2021), solely from the GW observations. The evolution of the galaxy bias as a function of redshift can be used to do precision cosmology with GW merger events (Mukherjee et al. 2021).

In this work, we explore another aspect of probing cosmology with 3G GW detectors through the LSS. We show that by detecting the angular BAO peak using localization volumes of mergers with 3G GW detector network, we can put independent constraints on the value of $H_0$. Moreover, by combining these results with the BAO measurements from the galaxy surveys, not only more stringent constraints on the cosmological parameters can be put, but the data can also be used to distinguish various cosmological models, e.g. models with a phenomenological parametrization of the dark energy (DE) equation of state.

The structure of this paper is as follows. In section 2, we outline the existing methods to probe cosmology using the current and next generation of GW detectors. We also lay down the methodology to use the BAO measurements with GW merger events, to constrain cosmological models. In section 3, we use simulated data to apply these methods to constraint dark energy (DE) models. We use three parametrized DE models along with the standard ΛCDM model. In section 4, we summarize the results.

## 2. COSMOLOGY WITH GRAVITATIONAL WAVES

The data from various cosmological surveys indicate that at present, the major constituents of the Universe are dark energy, dark matter, and baryonic matter (Aghanim et al. 2020). One of the simplest models which describe the Universe is the so-called ΛCDM model, which interprets the dark energy component of the Universe in terms of the presence of a cosmological constant Λ term in the Einstein equations, along with cold dark matter (CDM), and the baryonic matter which represents all visible matter in the Universe.

The data from GW detectors consists of a time series $s(t)$ which contains noise $n(t)$ and might contain a GW signal $h(t)$. The GW signal from the merger of two compact objects is modelled as a function of the intrinsic parameters such as individual masses and spins, as well as extrinsic parameters such as the luminosity distance ($D_L$), the inclination angle of the binary with respect to the line of sight, the sky localization (right ascension and declination angles), etc. The localization volumes estimated for a GW event provide a posterior distribution on sky location (RA, dec) and $D_L$. If, somehow, we can estimate the redshift ($z$) of the GW event independently (Holz & Hughes 2005; Dalal et al. 2006; Nissanke et al. 2013), then using the $D_L - z$ relation from the so-called Hubble equation, we can put constraints on the parameters of the cosmological model, such as the Hubble parameter ($H_0$), the density parameter corresponding to the matter component ($\Omega_{m0}$), etc. The first detection of gravitational waves from the merger of binary neutron stars, known as GW170817 (Abbott et al. 2017a) provided one such opportunity. The electromagnetic (EM) afterglow of GW170817, measured by various telescopes across the globe. It provided the constraints on $H_0$ using a GW event for the first time (Abbott et al. 2017d). Since then, various schemes have been used to probe cosmology by GW observations. For binary black holes (BBH) merger events, the localization posteriors can be cross-correlated with the galaxy catalogs to put constraints on $H_0$ (Abbott et al. 2021a). Other methods exploit the degeneracy between the inferred component masses from GW events and their redshift by putting combined constraints on $H_0$ and on the population parameters (Mastrogiovanni et al. 2021).

### 2.1. *Baryon Acoustic Oscillations*

Baryon acoustic oscillations (BAO) are imprints on the distribution of matter from the very early universe. In the standard model of cosmology, the evolution of the Universe is described through three major phases where the dominant component is radiation, matter, and dark energy respectively. In the very early time, the Universe is assumed to have gone through a period of rapid accelerated expansion, known as inflation, resulting in an extremely homogeneous Universe (Baumann 2011). After this period, the Universe enters what is known as the radiation-dominated era, when the temperature of the Universe was very high, so that the protons and electrons could not form a stable hydrogen atom. The Universe was dominated by dark matter, and a hot plasma soup of electrons, protons, and photons. The small perturbations of Gaussian nature in the very early universe acted as seeds for inhomogeneities and those perturbations grew with time. The competing forces between gravity and electromagnetic radiation pressure in the fluid generated the perturbations which acts as sound waves in the hot plasma. After about 380,000 years from the big bang, when the temperature of the Universe dropped to a level such that the electrons and protons could combine to form hydrogen atoms, the photons are set free stream, known as CMB, and the sound waves were frozen. These features have been preserved in the distribution of matter as the Universe evolved. These imprints are called Baryon acoustic oscillations (BAO) (Bassett & Hlozek 2009; Weinberg et al. 2013) and can be seen in the two-point correlation function (2PCF) estimated from the distribution of galaxies (Eisenstein et al. 2005). The acoustic scale $r_s$ corresponds to the radius the sound waves traversed before they become frozen. The first confident detection of this BAO feature with $3.4\sigma$ certainty was reported by the Sloan Digital Sky Survey (SDSS) data release 3 (Eisenstein et al. 2005) by measuring 2PCF of the luminous red galaxies. The acoustic scale $r_s$ can be used to probe the cosmology as it provides a standard ruler.

### 2.2. *Cosmology using the Large-Scale Structures of the Universe*

The large-scale structures (LSS) (greater than $\mathcal{O}(10$ Mpc$)$) of the Universe can be studied by probing the distribution of matter, such as in the galaxy surveys, using the 2PCF $\xi(r)$, which is related to the excess probability $\delta P$ with respect to the expected random distribution, of finding a pair of galaxies separated by a distance $r$,

$$\delta P(r) = n[1 + \xi(r)]dV, \tag{1}$$

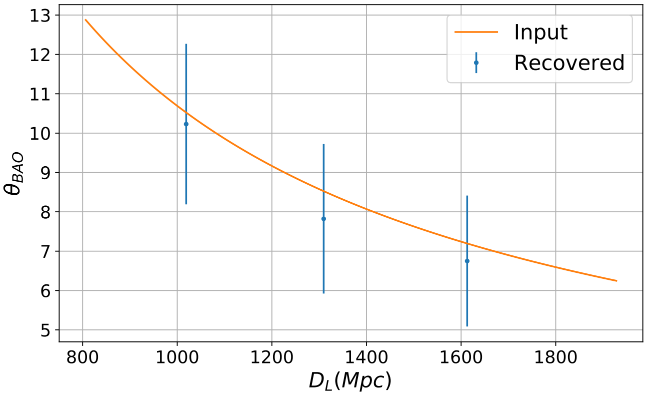

**Figure 1.** The recovery of the BAO angular scale $\theta_{BAO}$ with BNS merger events (for a 3G detector network) centered around different values of $D_L$ in shells of about $\sim 150h^{-1}$ Mpc. The solid continuous curve represent the relation between $\theta_{BAO}$ and luminosity distance $D_L$ to the shell for $\Lambda$CDM model used in simulations using parameters from Planck results (Aghanim et al. 2020)

where $n$ is the average number of galaxies per unit volume and $dV$ is the infinitesimal volume or volume element around a galaxy. The 2PCF $\xi(r)$ can be estimated from the matter overdensity field $\delta(\mathbf{x}) := \rho(\mathbf{x})/\overline{\rho} - 1$, where $\rho(\mathbf{x})$ is the local matter density at position $\mathbf{x}$ and $\overline{\rho}$ is the average matter density of the Universe, as

$$\xi(r) = \langle\, \delta(\mathbf{x})\delta(\mathbf{y})\,\rangle\,, \tag{2}$$

where the operation $\langle\cdot\rangle$ represents the ensemble average over a large volume compared to the scales we are probing. An important assumption here is the statistical homogeneity and isotropy of the Universe. Due to these assumptions, the correlation function $\xi$ depends only on the magnitude of the seperation between points $\mathbf{x}$ and $\mathbf{y}$, $r = |\mathbf{x} - \mathbf{y}|$. In general, $\xi(r)$ also evolves with the redshift, but if one restricts the analysis to a given redshift bin, the correlation function in that redshift bin can be assumed to be constant. Since the dark matter is more abundant than the baryonic matter (which constitutes the 'visible' galaxies, and intergalactic medium), the galaxies are expected to follow the gravitational potential well due to dark matter and to a good approximation, at large scales the 2PCF of galaxies $\xi_{gal}(r)$ will be related to the dark matter 2PCF $\xi_{DM}(r)$ via a factor $b_{gal}$ called 'galaxy bias' as $\xi_{gal}(r) = b_{gal}^2\,\xi_{DM}(r)$. In general, this bias can also be scale- and redshift-dependent (Coles & Erdogdu 2007).

Apart from the galaxy bias, the 2PCF is also used to detect other LSS features, such as the baryon acoustic oscillations, from the distribution of matter. As the acoustic scale $r_s$ can be considered a standard ruler, detecting the BAO peak at different redshifts provides an

**Table 1.** The list of parametrized dark energy models considered in this work. These models are valid at low redshift where the radiation component ($\Omega_{r0}$) can be neglected.

| S. No. | Model | Hubble Equation | parameters |
|---|---|---|---|
| 1. | $\Lambda$CDM | $h(z) = \sqrt{\Omega_{m_0}(1+z)^3 + 1 - \Omega_{m0}}$ | $\Omega_{m0}, h$ |
| 2. | $w$CDM | $h(z) = \sqrt{\Omega_{m_0}(1+z)^3 + (1-\Omega_{m0})(1+z)^{-3(1+w)}}$ | $\Omega_{m0}, h, w$ |
| 3. | $w_0 w_a$CDM | $h(z) = \sqrt{\Omega_{m0}(1+z)^3 + (1-\Omega_{m0})(1+z)^{3(1+w_0+w_a)} \exp\left(-\frac{3w_a z}{1+z}\right)}$ | $\Omega_{m0}, h, w_0, w_a$ |

independent method to probe the cosmological parameters. Instead of using the three-dimensional correlation function $\xi(r)$, one can also use the two-point angular correlation function (2PACF) $\omega(\theta)$ by considering the galaxies in different redshift bins and projecting them along the shell, keeping in mind that the shell should not be too thick so that the linear power spectrum $P(k,z)$ does not vary much along the redshift, i.e., $P(k,z) \sim P(k)$ for $z \in [z-dz/2, z+dz/2]$. The acoustic scale $r_s$ is related to the angular scale $\theta_{BAO}$ and to the angular diameter distance $D_A$ as,

$$\theta_{BAO}(z) = \frac{r_s}{(1+z)D_A(z)} \tag{3}$$

By estimating the angular scale $\theta_{BAO}(z)$ at a given redshift $z$, one can use the above relation to put constraints on the cosmological parameters which are embedded in the Hubble equation while calculating the angular diameter distance,

$$D_A(z;\Theta) = \frac{c}{H_0}\frac{1}{1+z}\int_0^z \frac{dz'}{h(z';\Theta)} \tag{4}$$

where $h(z;\Theta)$ is the normalized Hubble equation with parameters $\Theta$ which depends on the cosmological model. For example, the normalized Hubble equation (at nearby redshifts) for the spatially flat $\Lambda$CDM model is,

$$h(z) = \sqrt{\Omega_m^0(1+z)^3 + 1 - \Omega_m^0}, \tag{5}$$

where $\Omega_m^0 = 3H_0^2\rho_m/(8\pi G)$ is called density parameter for matter (which includes dark matter as well as baryonic matter) at present ($z = 0$). We make use of the spatial curvature being zero and the density parameter for radiation $\Omega_r$ for small redshifts being negligible, i.e. $\Omega_{r0} \sim 0$, in using the relation $\Omega_{m0} + \Omega_{\Lambda 0} = 1$ to replace $\Omega_{\Lambda 0}$ by $1 - \Omega_{m0}$.

### 2.3. *Probing the Large Scale Structures with Gravitational Waves*

As we expect the 3G detector network to provide a large number of well localized GW merger events, the natural question arises: can we extend the same methods, as used for galaxies, to probe LSS with distribution of GW observations using their localization volumes? Recent studies have shown that by cross-correlating localization volumes with galaxy catalogs, the LSS features such as galaxy bias can be probed (Mukherjee et al. 2021). In this study, we are interested in probing LSS purely with GW observations without cross correlating with galaxy catalogs.

The challenges in probing LSS with just GW observations are twofold: i) the localization volumes obtained from the posteriors of GW events are very wide ($\mathcal{O}(10) - \mathcal{O}(100)$ Mpc for $D_L$ and $\mathcal{O}(1) - \mathcal{O}(10)$ degrees for the sky localization), which washes away most of the features in LSS, and ii) the number of events which can be detected by current generation GW detectors are not enough to probe the LSS. However, with the planned third generation (3G) GW detectors such as the Einstein telescope (ET) or Cosmic Explorer (CE), which are not only expected to have an order of magnitude better sensitivity compared to current detectors, but are also expected to be more sensitive at low frequencies. This will allow the 3G detector network to detect enough events with precise enough localization volume to make it possible to probe LSS purely with GW events. It has been shown that with the 3G detector network, with the 5-10 years of observation time, it is possible to probe the galaxy bias solely from the GW events (Vijaykumar et al. 2020). Using the nearby BNS localization volumes, with 2PACF, the angular BAO scale $\theta_{BAO}$ can also be probed with the help of 3G detector network (Kumar et al. 2021).

The detection of angular BAO scale $\theta_{BAO}$ at different redshifts from the GW localization volumes can be used as another cosmological probe. However, when there are no EM counterparts (which is the case with majority of

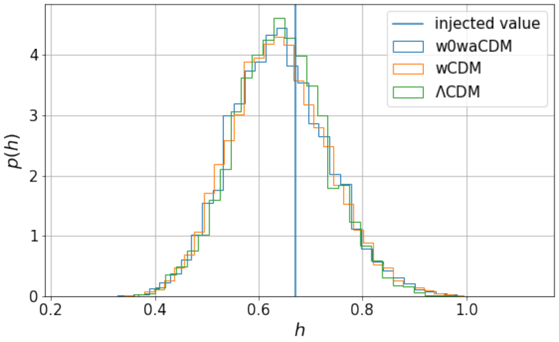

**Figure 2.** The 1D marginalized posterior distribution of Hubble parameter $H_0 = 100h\ kms^{-1}Mpc^{-1}$ using the angular BAO scale measurements $\theta_{BAO}$ from simulated GW events with 3G detector network in three shells centred at $D_L = \sim 1000$ Mpc, 1300 Mpc, and 1600 Mpc. The three cosmological models used here are described in table 1.

GW events), we will, in general, not have the redshift information. In order to probe the cosmology, we divide the GW localization volumes into shells of luminosity distance $D_L$, project them in the shell and calculate 2PACF, which gives us $\theta_{BAO}$ for each $D_L$. Here $D_L$ is estimated at the centre of each bin. The detailed method to detect angular BAO scale from localization volumes is described in (Kumar et al. 2021).

## 3. SIMULATIONS AND RESULTS

In the Bayesian framework, the posterior probability distribution $p(\Theta|d, I)$ parameters $\Theta$ given the data $d$, and any prior information $I$ is described as,

$$p(\Theta|d, I) = \frac{\mathcal{L}(d|\Theta, I)\pi(\Theta|I)}{p(d|I)}, \tag{6}$$

where $\mathcal{L}(d|\Theta, I)$ is the likelihood function which represents the probability of the data given the parameters $\Theta$ of the model. $\pi(\Theta|I)$ is the prior probability distribution on the parameters, and $p(d|I)$ is called the 'Bayesian evidence' or marginalized likelihood which acts as the normalization factor for the posterior distribution. We use the the BAO measurements in different shells $\theta_{BAO}(D_L)$ as the data and use the define the likelihood function as,

$$\mathcal{L}(\Theta) \propto \exp\left(-\frac{1}{2}\sum_i \frac{(\theta_{BAO,i} - \theta_{BAO}(\Theta))^2}{\sigma_i^2}\right), \tag{7}$$

where $\Theta$ are the parameters describing cosmological model. $\theta_{BAO,i}$ is the estimated angular BAO scale in the $i$-th shell. $\sigma_i$ is the error associated with the measurement of BAO peak in $i$-th shell. We make use of the simulations done in Kumar et al. (2021). In figure 1, we show the the recovery of the angular BAO scale at different shells centred around $D_L \sim 1010\ Mpc$, $1310\ Mpc, and\ 1620\ Mpc$. We use these measurements of angular BAO scale $\theta_{BAO}$ as the input data.

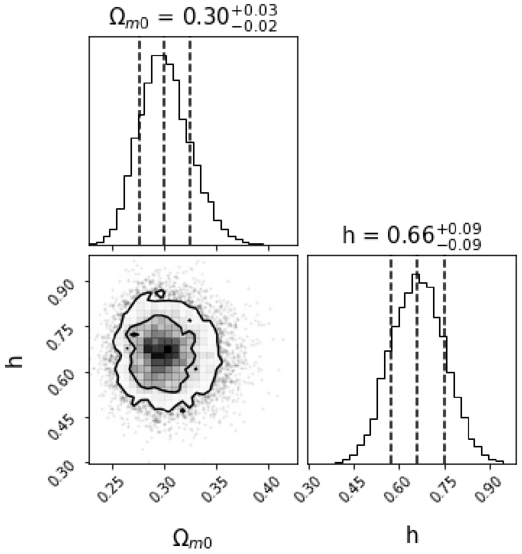

**Figure 3.** The combined constraints on the ΛCDM model with BAO measurements from GW localization volumes (from simulations) and CMB/BAO constraints from the galaxy surveys. On the marginalized 1D posteriors, we show 68% bounds with median value. For 2D contours, we show 60% and 90% regions.

We use standard ΛCDM model as reference model in our simulations. Other phenomenological dark energy models as described in table 1 are also considered, namely $w$CDM model and CPL parametrization $w_0w_a$CDM model (Chevallier & Polarski 2001). We make use of the publicly available implementation of nested sampling based sampler DYNESTY (Speagle 2020) for parameter estimation. We use uniform prior on all the parameters in ranges $\Omega_{m0} \in [0.05, 0.95]$, $h \in [0.2, 1.5]$, $w, w_0 \in [-2, 0]$, and $w_a \in [-3, 3]$. We also use uniform priors on the redshift measurements $z_{1,2,3} \in [0.1, 0.4]$ for the three $D_L$ shells we used in our analysis. We fix the acoustic length scale $r_s$ for $\theta_{BAO}$ measurements from GW data assuming it will be provided as an input from other surveys.

In figure 2, we show the recovery of the Hubble parameter for different models. With just GW data, it is possible to put constraints only on the $H_0$ because of the degeneracy between redshift and other parameters. the inferred value of $H_0$ $(90\%CL)$ for different models considered here are: i) ΛCDM model: $H_0 = 64.01^{+15.25}_{-14.47}$ km s$^{-1}$ Mpc$^{-1}$, ii) $w$CDM model:

$H_0 = 63.60^{+16.87}_{-14.52}$ km s$^{-1}$ Mpc$^{-1}$, and iii) $w_0w_a$CDM model: $H_0 = 63.67^{+17.34}_{-14.73}$ km s$^{-1}$ Mpc$^{-1}$.

We also explore the possibility to do precision cosmology by combining the BAO data from the galaxy surveys. Although we expect to have much better measurements of BAO scale from the future galaxy surveys contemporary (or prior) to 3G detector network, in this study, we consider the BAO constraints from various measurements on the angular scales of BAO oscillations as measured by SDSS survey(Ross et al. 2015), 6DF Galaxy survey (Beutler et al. 2011), and the Wiggle-z survey. The covariance matrix between different redshift is taken from (Giostri et al. 2012).

In figures 3,4, and 5, we show the combined constraints on the parameters of the models ΛCDM, $w$CDM, and $w_0w_a$CDM respectively. By combining the BAO measurements from GW events with that from the galaxy surveys, we can not only constrain cosmological parameters other than the $H_0$, we can also do the model comparison between various DE parametrization. Although, as an example, we show here only selected DE parametrization models, this can also be applied to distinguish between ΛCDM model and other modified gravity models which differ from the standard Einstein's gravity model such as scalar-tensor theories, f(R) gravity, etc.

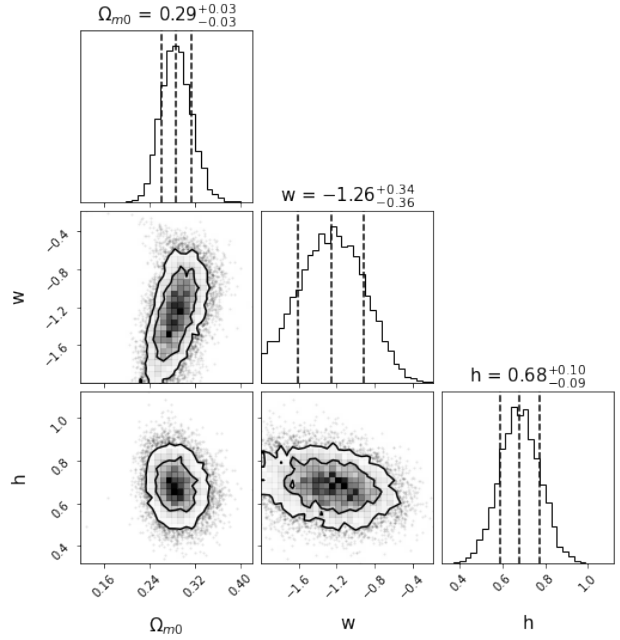

**Figure 4.** The combined constraints on the $w$CDM model with BAO measurements from GW localization volumes (from simulations) and CMB/BAO constraints from the galaxy surveys. On the marginalized 1D posteriors, we show 68% bounds with median value. For 2D contours, we show 60% and 90% regions.

## 4. SUMMARY

The future of GW cosmology looks bright as the growing catalog of GW mergers offers us various possibilities to independently probe the the Universe. The independent probes offers us not only better constraints on the cosmological parameters when combining the data, they also provide opportunities to resolve the possible tension between various data sets such as so called Hubble tension between current CMB data at high redshift and SNe data which probe the Universe at low redshifts. With current catalog of GW events, the localization volumes (from BBHs) can be used with galaxy catalogs by cross correlating them to constrain the Hubble constant $H_0$. In case of BNS events which have electromagnetic counterparts (GW170817), more stringent constraints on $H_0$ can be put because of more precise redshift information. In future, we expect these constraints to become stringent with more GW merger observations with hope to detect EM counterparts for a small fraction of events (such as nearby BNS/NSBH mergers).

The third generation of GW detectors such as ET and CE are expected to be order of magnitude more sensitive than current generation detectors, and will be able to probe lower frequencies. It will enable them to detect thousands of GW mergers with precise enough localization to probe the large scale structures of the Universe using their localization volumes, assuming that the GW merger distribution follow the matter distribution of the Universe. We can probe the LSS features such as galaxy bias, and BAO peak by measuring the 2PCF from the localization volumes. In this study we show that by tracing the angular BAO scale $\theta_{BAO}$ at various redshifts, we can put constraints on the cosmological parameters such as the Hubble constant $H_0$ with 90% credible intervals $H_0 = 64.01^{+15.25}_{-14.47}$. We make use of the fact that the BAO scale can act as the standard ruler for cosmology. By combining this with current constraints on BAO/CMB from various surveys, we show that we can also use to constrain various models of cosmology such as different parametrization of dark energy models.

Although, this is not a unique method to put constraints on cosmological parameters as more stringent constraints can be provided by the data from other cosmological surveys for example CMB, type Ia supernovae, etc. It will still provide an independent probe to cosmology which can be combined with the available data from contemporary surveys to put tighter constraints and in best case, help in resolving the tension between the competing data sets, if any. The results presented assumes

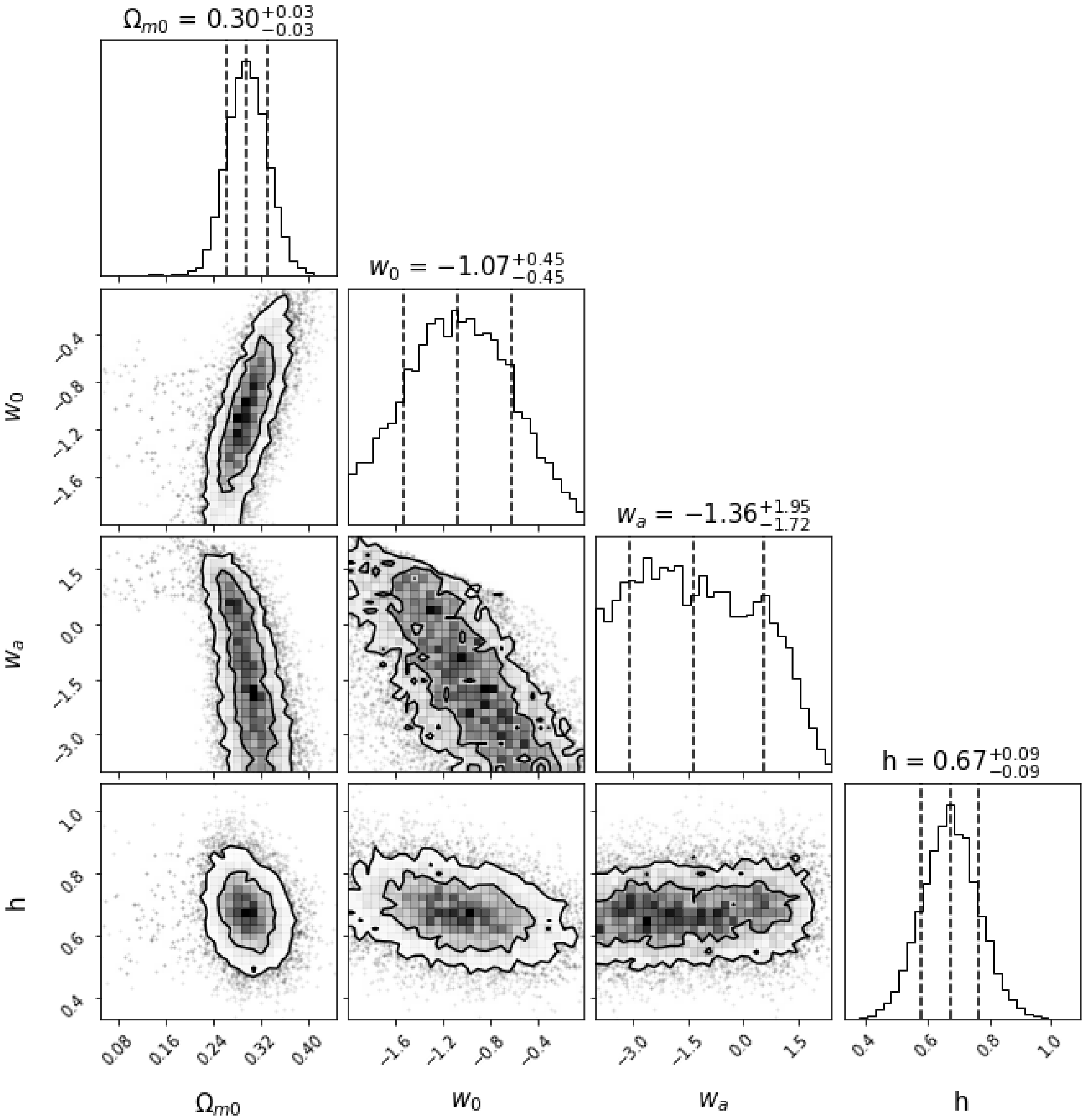

**Figure 5.** The combined constraints on the $w_0 w_a$CDM model with BAO measurements from GW localization volumes (from simulations) and CMB/BAO constraints from the galaxy surveys. On the marginalized 1D posteriors, we show 68% bounds with median value. For 2D contours, we show 60% and 90% regions.

that the a 3G detector network will be operational and assumes the current rate estimates.

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