Cosmology with Gravitational Wave/Fast Radio Burst Associations

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Abstract

Recently, some theoretical models predicted that a small fraction of fast radio bursts (FRBs) could be associated with gravitational waves (GWs). In this Letter, we discuss the possibility of using GW/FRB association systems, if they are commonly detected in the future, as a complementary cosmic probe. We propose that upgraded standard sirens can be constructed from the joint measurements of luminosity distances $D_L$ derived from GWs and dispersion measures $\text{DM}_{\text{ICM}}$ derived from FRBs (i.e., the combination $D_L \cdot \text{DM}_{\text{ICM}}$). Moreover, unlike the traditional standard-siren approach (i.e., the $D_L$ method) and the $\text{DM}_{\text{ICM}}$ method that rely on the optimization of the Hubble constant $H_0$, this $D_L \cdot \text{DM}_{\text{ICM}}$ method has the advantage of being independent of $H_0$. Through Monte Carlo simulations, we prove that the $D_L \cdot \text{DM}_{\text{ICM}}$ method is more effective for constraining cosmological parameters than $D_L$ or $\text{DM}_{\text{ICM}}$ separately, and that it enables us to achieve accurate multimessenger cosmology from approximately 100 GW/FRB systems. Additionally, even if GW/FRB associations do not exist, the methodology developed here can still be applied to those GWs and FRBs that occur at the same redshifts.

Key words: cosmological parameters – gravitational waves – intergalactic medium

1. Introduction

With the rapid development of modern astronomical technology, cosmological research has entered into the age of precision. Cosmological parameters can now be inferred precisely from the observations of various electromagnetic (EM) waves, such as cosmic microwave background anisotropies (Hinshaw et al. 2013; Planck Collaboration et al. 2016), Type Ia supernovae (Perlmutter et al. 1998; Riess et al. 1998), baryon acoustic oscillations (Beutler et al. 2011; Anderson et al. 2012), and so on.

In addition to the traditional EM methods, the observation of gravitational waves (GWs) also provides an alternative probe for cosmological studies. Due to the fact that the waveform signal of GWs from inspiralling and merging compact binaries encodes luminosity distance ($D_L$) information, GWs can be considered as standard sirens (Schutz 1986). The greatest advantage of GW standard sirens is that the distance calibration is independent of any other cosmic distance ladders (i.e., it is self-calibrating). Thus, detections of GW together with their EM counterparts providing source redshifts, could give the $D_L$–$\zeta$ relation for measuring cosmic expansion (Holz & Hughes 2005; Zhao et al. 2011). In particular, GW signals from binary neutron stars (NSs) or black hole (BH)–NS mergers are promising for conducting cosmography, as these merging systems are expected to be accompanied by some detectable EM signals, e.g., fast radio bursts (FRBs), short gamma-ray bursts (GRBs), or kilonovae/merger novae (see Fernández & Metzger 2016 for a review). In the past, several works have discussed the possibility of GWs as standard sirens and showed that with hundreds of simulated GW events they can determine the cosmological parameters with accuracies comparable to traditional probes (e.g., Holz & Hughes 2005; Zhao et al. 2011; Del Pozzo 2012; Cai & Yang 2017; Del Pozzo et al. 2017). Very recently, the coincident detection of the GW event GW170817 with EM counterparts (e.g., a GRB 170817A, or a macronova) from a binary NS merger has formally opened the new era of multimessenger astronomy (Abbott et al. 2017a; Coulter et al. 2017; Goldstein et al. 2017; Savchenko et al. 2017). Using this first truly GW/EM association, Abbott et al. (2017b) performed a standard-siren measurement of the Hubble constant $H_0$.

On the other hand, FRBs are a new mysterious class of millisecond-duration radio transients (Lorimer et al. 2007; Thornton et al. 2013). These objects have anomalously large dispersion measures (DMs), suggesting a cosmological origin for FRBs. The DM is defined as the integral of the electron number density along the propagation path from the source to the observer. Because the observed DMs of FRBs contain important information on the cosmological distance that they have traveled, one may combine the DM and $\zeta$ information to probe cosmology if more FRBs with known redshifts can be detected (Deng & Zhang 2014; Gao et al. 2014; Zheng et al. 2014; Zhou et al. 2014; Yang & Zhang 2016; Walters et al. 2018).

Regarding their physical origins, some studies suggested that mergers of double NSs (Totani 2013; Wang et al. 2016; Yamasaki et al. 2017), of BH–NS (Mingarelli et al. 2015), or even of charged BHs (Zhang 2016), could be responsible for FRBs. Particularly, Wang et al. (2016) showed that an FRB could originate from the magnetic interaction between binary NSs during their final inspiral within the framework of the unipolar inductor model. The NS–NS merger has been recently confirmed as the progenitor system of GW170817 and GRB 170817A (Abbott et al. 2017a; Goldstein et al. 2017; Savchenko et al. 2017). If FRBs can indeed be interpreted using the NS–NS merger model, one could detect possible associations of FRBs with short GRBs and GW events in the future (Wang et al. 2016). Alternatively, Zhang (2016) proposed that if at least one of the two merging BHs carries a certain amount of charge, the inspiral process would drive a global magnetic dipole. The rapid evolution of the magnetic moment of the BH–BH system would lead to a magnetospheric outflow with an increasing wind power, which may produce an FRB and even a short GRB, depending upon the value of the charge. The detection of an FRB associated with gravitational waves provides a new tool for constraining cosmological parameters.
with future NS–NS (or BH–BH) merger GW events would verify the NS–NS (or BH–BH) merger model.

In this Letter, we show that if such GW/FRB association systems are commonly detected in the future, “upgraded standard sirens” could be constructed from the combination of $D_L$ derived from GWs and DM derived from FRBs, independent of the Hubble constant $H_0$. We explore its use to constrain the cosmological parameters in view of the large samples of GWs and FRBs found in third-generation GW interferometric detectors such as the Einstein Telescope (ET) and the upcoming radio transient surveys such as the Square Kilometer Array.

2. GW/FRB Associations as Upgraded Standard Sirens

2.1. Luminosity Distances from GWs

Third-generation GW ground-based detectors such as the ET, with ultra-high sensitivity, would significantly improve the detection rate of the GW events. The ET is designed to be 10 times more sensitive than the current advanced laser interferometric detectors, covering the frequency range of $1\times10^4$ Hz. It has three interferometers with 10 km arm lengths and 60° opening angles, arranged in an equilateral triangle. Here, we present an overview of using GWs as standard sirens in the potential ET observations (see also Cai et al. 2017 for a recent review). Throughout we use units $G = c = 1$.

The amplitude of the GW depends upon the chirp mass and the luminosity distance $D_L$. Because the chirp mass can already be obtained from GW signal’s phasing, $D_L$ can be extracted from the amplitude of waveform. In the transverse-traceless gauge, the strain $h(t)$ is the linear combination of the two components of the GW’s tensor (i.e., $h_+$ and $h_\times$),

$$h(t) = F_+(\theta, \phi, \psi) h_+(t) + F_\times(\theta, \phi, \psi) h_\times(t),$$

where $F_+$ and $F_\times$ are the beam-pattern functions, $(\theta, \phi)$ are angles describing the location of the source relative to the detector, and $\psi$ denotes the polarization angle. The corresponding antenna pattern functions of one of the interferometers in the ET are (Zhao et al. 2011)

$$F_+^{(1)}(\theta, \phi, \psi) = \frac{\sqrt{3}}{2} \left[ \frac{1}{2} (1 + \cos^2(\theta)) \cos(2\phi) \cos(2\psi) - \cos(\theta) \sin(2\phi) \sin(2\psi) \right],$$

$$F_\times^{(1)}(\theta, \phi, \psi) = \frac{\sqrt{3}}{2} \left[ \frac{1}{2} (1 + \cos^2(\theta)) \cos(2\phi) \sin(2\psi) + \cos(\theta) \sin(2\phi) \cos(2\psi) \right].$$

The other two interferometers’ antenna pattern functions can be derived from Equation (2), as the interferometers have 60° with each other. That is to say, $F_+^{(2)}(\theta, \phi, \psi) = F_\times^{(1)}(\theta, \phi + 2\pi/3, \psi)$ and $F_\times^{(2)}(\theta, \phi, \psi) = F_+^{(1)}(\theta, \phi + 4\pi/3, \psi)$.

In this Letter, we focus on the GW signals produced by the merger of binary systems. Considering a merging binary with component masses $m_1$ and $m_2$, the chirp mass is defined to be $M_c = M_1^{\eta/3}$, where $M = m_1 + m_2$ is the total mass, and $\eta = m_1 m_2 / M^2$ represents the symmetric mass ratio. For a GW source located at cosmological distance with redshift $z$, the observed chirp mass is given by $M_{c,\text{obs}} = (1 + z) M_{c,\text{phys}}$. Below, $M_c$ always refers to the observed chirp mass.

Following Sathyaprakash & Schutz (2009) and Zhao et al. (2011), we apply the stationary phase approximation to calculate the Fourier transform $\mathcal{H}(f)$ of the time domain waveform $h(t)$,

$$\mathcal{H}(f) = A f^{-7/6} \exp \left\{ i (2 \pi ft_0 - \pi/4 + 2\psi(f/2) - \varphi_{20}) \right\},$$

where the constant $t_0$ is the epoch of the merger. The definitions of the functions $\psi$ and $\varphi_{20}$ are presented in Zhao et al. (2011).

The Fourier amplitude $A$ is given by

$$A = \frac{1}{D_L} \sqrt{\frac{F_+^2 + 4 F_\times^2}{(1 + \cos^2(\theta))^2} + 4 F_\times^2 \cos^2(\theta)} \times \sqrt{\frac{8\pi/96 \pi^{-7/6} M_c^{5/6}}},$$

where $\psi$ denotes the angle of inclination of the binary’s orbital angular momentum with the line of sight, and

$$D_L(z) = \frac{1 + z}{H_0} \int_0^z \frac{dz}{\sqrt{\Omega_m(1 + z)^3 + (1 - \Omega_m)(1 + z)^{3(1+w)}}},$$

is the theoretical luminosity distance in the wCDM model. Note that averaging the Fisher matrix over the inclination $\psi$ and the polarization $\psi$ with the constraint $\psi < 20°$ is approximately equivalent to taking $\psi = 0$. Therefore, we only consider the simplified case of $\psi = 0$, and $A$ is independent of the polarization angle $\psi$ (Cai & Yang 2017).

Given the waveform of GWs, we can compute the signal-to-noise ratio (S/N) of the GW detection. The combined S/N for the network of three independent ET interferometers is

$$\rho = \sqrt{\sum_{i=1}^3 \langle \mathcal{H}^{(i)}, \mathcal{H}^{(i)} \rangle},$$

where the inner product is defined as

$$\langle a, b \rangle = 4 \int_{f_{\text{lower}}}^{f_{\text{upper}}} \frac{\tilde{a}(f) \tilde{b}^*(f) + \tilde{a}^*(f) \tilde{b}(f)}{2 S_b(f)} \, df,$$

where the superscript “*” stands for the Fourier transform of the corresponding function and $S_b(f)$ is the one-side noise power spectral density. We take the ET’s $S_b(f)$ to be the same as in Zhao et al. (2011). The upper cutoff frequency is assumed to be $f_{\text{upper}} = 2 f_{\text{LSO}}$, where $f_{\text{LSO}} = 1/(6^{3/2} \pi M_{\text{obs}})$ corresponds to the orbit frequency at the last stable orbit, and $M_{\text{obs}} = (1 + z) M_{\text{phys}}$ is the observed total mass (Zhao et al. 2011). The lower cutoff frequency $f_{\text{lower}}$ is fixed to be 1 Hz. The signal is identified as a GW event only when the ET interferometers have a network S/N of $\rho > 8.0$.

Using the Fisher information matrix, we can estimate the instrumental uncertainty on the measurement of $D_L$, which can be expressed as (Zhao et al. 2011)

$$\sigma_{D_L}^{\text{inst}} \approx \sqrt{\partial \mathcal{H} / \partial D_L \cdot \partial \mathcal{H} / \partial D_L}.$$
estimate of the error on $D_L$, i.e.,

$$\sigma_{D_L}^{\text{inst}} \approx \frac{2D_L}{\rho}.$$  \hspace{1cm} (9)

We also add an additional error $\sigma_{D_L}^{\text{ext}} / D_L = 0.05z$ caused by the weak lensing. Thus, the total error on $D_L$ is given by

$$\sigma_{D_L} = \sqrt{\left(\frac{2D_L}{\rho}\right)^2 + (0.05zD_L)^2}.$$  \hspace{1cm} (10)

2.2. DMs from FRBs

In principle, the observed DM of an FRB ($\text{DM}_{\text{obs}}$; Deng & Zhang 2014; Gao et al. 2014; Yang & Zhang 2016)

$$\text{DM}_{\text{obs}} = \text{DM}_{\text{MW}} + \text{DM}_{\text{IGM}} + \frac{\text{DM}_{\text{HG}}}{1 + z}$$  \hspace{1cm} (11)

has contributions from the Milky Way (MW; $\text{DM}_{\text{MW}}$), intergalactic medium (IGM; $\text{DM}_{\text{IGM}}$), and FRB host galaxy (HG; $\text{DM}_{\text{HG}}$), respectively. Note that for a GRB-associated FRB, $\text{DM}_{\text{HG}}$ has contributions from the host galaxy and the GRB blastwave. Among these terms, $\text{DM}_{\text{IGM}}$ is the relevant one for cosmological studies. Considering local inhomogeneity of the IGM, we define the average DM of the IGM, which can be written as (Deng & Zhang 2014)

$$\langle \text{DM}_{\text{IGM}} \rangle = \frac{3H_0\rho_b f_{\text{IGM}}}{8\pi m_p} \int_0^z \frac{\chi(z)(1+z)dz}{\sqrt{\Omega_m(1+z)^3 + (1 - \Omega_m)(1+z)^{3(1+w)}}},$$  \hspace{1cm} (12)

where $f_{\text{IGM}}$ is the fraction of baryon mass in the IGM, $\Omega_b$ is the current baryon mass fraction of the universe, $\chi(z) = (3/4)y_1\chi_{\text{e,H}}(z) + (1/8)y_2\chi_{\text{e,He}}(z)$, $y_1 \sim 1$ and $y_2 \sim 4 - 3y_1 \sim 1$ are the hydrogen (H) and helium (He) mass fractions normalized to 3/4 and 1/4, respectively, and $\chi_{\text{e,H}}(z)$ and $\chi_{\text{e,He}}(z)$ are the ionization fractions for H and He, respectively. As H and He are fully ionized at $z < 6$ and at $z < 2$ separately (Fan et al. 2006; McQuinn et al. 2009), it is reasonable to take $\chi_{e,H}(z) = \chi_{e,He}(z) = 1$ for nearby FRBs ($z < 2$). One then has $\chi(z) \approx 7/8$.

As long as $\text{DM}_{\text{obs}}$, $\text{DM}_{\text{MW}}$, and $\text{DM}_{\text{HG}}$ can be precisely determined, one can infer the value of $\langle \text{DM}_{\text{IGM}} \rangle$ (see Equation (11)). Then, we can calculate the total uncertainty of $\langle \text{DM}_{\text{IGM}} \rangle$ using the expression

$$\sigma_{\langle \text{DM}_{\text{IGM}} \rangle} = \sqrt{\sigma_{\text{obs}}^2 + \sigma_{\text{MW}}^2 + \sigma_{\text{IGM}}^2 + \left(\frac{\sigma_{\text{HG}}}{1+z}\right)^2}.$$  \hspace{1cm} (13)

Following Gao et al. (2014), we investigate different contributions of the relevant uncertainties in Equation (13) below.

Up to FRB 180311, a total of 33 FRBs have been detected (Petroff et al. 2016). The measurements of $\text{DM}_{\text{obs}}$ and the corresponding uncertainties for these 33 FRBs are available in the FRB catalog. Here, we adopt an average of these values as the uncertainty of $\text{DM}_{\text{obs}}$, i.e., $\sigma_{\text{obs}} = 1.5 \text{ pc cm}^{-3}$. With the ATNF pulsar catalog (Manchester et al. 2005),\footnote{http://frbcat.org/} we find that the average uncertainty of $\text{DM}_{\text{MW}}$ for high Galactic latitude ($|b| > 10^\circ$) sources is about 10 pc cm$^{-3}$, and we adopt this value as $\sigma_{\text{MW}}$. To be conservative, we associate an uncertainty of $\sigma_{\text{IGM}} = 100 \text{ pc cm}^{-3}$ to $\text{DM}_{\text{IGM}}$, as Yang & Zhang (2016) did in their treatment, with the hope that such a large uncertainty could account for the IGM inhomogeneity effect. On the basis of the DM uncertainty of the MW, one may deduce that the uncertainty of $\text{DM}_{\text{HG}}$ could be from tens to hundreds of pc cm$^{-3}$. In addition, Gao et al. (2014) showed that the resulting constraints on cosmological parameters are not very sensitive to the value of $\sigma_{\text{HG}}$, because $\sigma_{\text{HG}}$ becomes less significant at high redshifts due to the $(1+z)$ factor. Here we adopt $\sigma_{\text{HG}} = 30 \text{ pc cm}^{-3}$.

2.3. The Combination of $D_L$ and DM

If FRBs are confirmed to be associated with GW events, the combination of $D_L$ measurements of GWs and DM measurements of FRBs could provide upgraded standard sirens to study cosmology. From Equations (5) and (12), we can see that the Hubble constant $H_0$ cancels out when we multiply $D_L$ by $\text{DM}_{\text{IGM}}$, so the constraints on the cosmological parameters from the product $D_L \cdot \text{DM}_{\text{IGM}}$ are independent of the Hubble constant. With the combination of $D_L \cdot \text{DM}_{\text{IGM}}$, the propagated error $\sigma_{D_L,\text{DM}}$ in $D_L \cdot \text{DM}_{\text{IGM}}$ is

$$\sigma_{D_L,\text{DM}} = \left[\langle (\text{DM}_{\text{IGM}} - \sigma_{\text{DM}_{\text{IGM}}}^2 + (D_L - \sigma_{D_L})^2) \right]^{1/2}.$$  \hspace{1cm} (14)

In Figure 1, we illustrate the three quantities ($D_L$, $\text{DM}_{\text{IGM}}$, and $D_L \cdot \text{DM}_{\text{IGM}}$) as a function of the redshift $z$ in the flat cold dark matter (CDM) model. To show the sensitivity of the three functions to the cosmological parameter $\Omega_m$, we plot them for five cases of a flat universe with $\Omega_m = 0.1, 0.3, 0.5, 0.7$, and 0.9, relative to an Einstein–de Sitter universe ($\Omega_m = 1, \Omega_\Lambda = 0$). It is clearly seen that the $D_L \cdot \text{DM}_{\text{IGM}}$ curves have a wider separation than the $D_L$ or $\text{DM}_{\text{IGM}}$ curves, which allows for a better discrimination among different cosmological models. Meanwhile, the sensitivity increases with the redshift, thus, it is especially significant for the $D_L \cdot \text{DM}_{\text{IGM}}$ method with regard to the study of high-redshift associations.

2.4. Redshifts from EM Counterparts

Measuring the source redshift is crucial when using the GW/FRB association as the upgraded standard siren. Several methods have been suggested to obtain the redshift associated to a GW event, such as the galaxy catalog (Schutz 1986), NS mass distribution (Marković 1993; Taylor et al. 2012), and the tidal deformation of NSs (Messenger & Read 2012). In this Letter, we adopt the widely used method of identifying an EM counterpart of the GW event to obtain the source redshift (Nissanke et al. 2010; Sathyaprakash et al. 2010; Zhao et al. 2011). An EM counterpart like the GRB or the kilonova can provide redshift information if the host galaxy of the event can be pinpointed. The redshift can also be measured from the absorption lines of the GRB afterglows.

3. Monte Carlo Simulations

To explore the cosmological constraint ability by future joint measurements of luminosity distance $D_L$ and DM, we perform Monte Carlo simulations on GW/FRB systems. Here we adopt the cosmological parameters of the fiducial flat ΛCDM model derived from Planck 2015 data: $H_0 = 67.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.308$, $\Omega_\Lambda = 0.692$, and $\Omega_b = 0.049$ (Planck Collaboration et al. 2016). For the fraction of baryon mass in the IGM, we take

\hspace{1cm}
$f_{\text{IGM}} = 0.83$ (Fukugita et al. 1998; Shull et al. 2012; Deng & Zhang 2014). If compact binaries are NS–NS binaries or NS–BH binaries, it is believed that the source redshift can be obtained from an EM counterpart that occurs coincidentally with the GW event (Nissanke et al. 2010; Sathyaprakash et al. 2010; Zhao et al. 2011). Moreover, Wang et al. (2016) proposed that possible GW/FRB associations could be detected within the framework of the NS–NS merger model. Therefore, we consider the mergers of binary NS systems as the sources of GWs and FRBs. Following Zhao et al. (2011) and Cai & Yang (2017), the redshift distribution of the sources takes the form

$$P(z) \propto \frac{4\pi D_{C}^{2}(z) R(z)}{H(z)(1 + z)^{3}},$$  \hspace{1cm} (15)

where $D_{C}(z) = \int_{0}^{z} 1/H(z) \, dz$ is the comoving distance, and $R(z)$ denotes the time evolution of the merger rate and takes the form (Schneider et al. 2001; Cutler & Holz 2009; Cai & Yang 2017)

$$R(z) = \begin{cases} 1 + 2z, & z \leq 1 \\ \frac{3}{5}(5 - z), & 1 < z < 5 \\ 0, & z \geq 5. \end{cases}$$  \hspace{1cm} (16)

In our simulations, the redshifts of source $z$ are randomly generated from the redshift probability distribution function (Equation (15)). As the ET would be able to detect binary NS inspirals up to redshifts of $z \sim 2$, the range of the source redshift $z$ for our analysis is from 0 to 2. With the mock $z$, we infer the fiducial values of $D_{C}^{\text{fid}}$ and $D_{\text{IGM}}^{\text{fid}}$ from Equations (5) and (12), respectively. The mass of each NS and the position angle $\theta$ are uniformly distributed in the two parameter intervals: [1, 2] $M_{2}$, and $[0, \pi]$, respectively.\(^6\) We then calculate the combined $S/N$ of each set of the random sample using Equation (6), and confirm that the simulated signal is a GW detection if $\rho > 8.0$. For every confirmed detection, we add the deviations in Equations (10) and (13) to the fiducial values of $D_{L}^{\text{fid}}$ and $D_{\text{IGM}}^{\text{fid}}$, respectively. That is, we sample the $D_{L}^{\text{mock}}$ (or $D_{\text{IGM}}^{\text{mock}}$) measurement according to the Gaussian distribution

$$D_{L}^{\text{mock}} = N(D_{L}^{\text{fid}}, \sigma_{D_{L}}) \quad \text{and} \quad D_{\text{IGM}}^{\text{mock}} = N(D_{\text{IGM}}^{\text{fid}}, \sigma_{D_{\text{IGM}}}).$$

The inferred event rate density of NS–NS mergers from the detection of GW170817 is $\sim 1100^{+2500}_{-910}$ Gpc$^{-3}$ yr$^{-1}$ (Abbott et al. 2017a). The event rate density of FRBs may be estimated as (Zhang 2016)

$$\rho_{\text{FRB}} = \frac{3.65\tilde{N}_{\text{FRB}}}{(4\pi/3)D_{s}^{3}} \simeq (1.4 \times 10^{3}$ Gpc$^{-3}$ yr$^{-1})$$

$$\times \left(\frac{D_{s}}{3.4 \text{ Gpc}}\right)^{-3} \left(\frac{\tilde{N}_{\text{FRB}}}{10^{3}}\right),$$

where $D_{s}$ is the comoving distance of the FRB normalized to 3.4 Gpc ($z = 1$), and $\tilde{N}_{\text{FRB}}$ denotes the daily all-sky FRB rate that is normalized to $10^{3}$. One can see that the FRB rate is consistent with the NS–NS merger rate. The expected detection rates of NS–NS and BH–NS per year for the ET\(^7\) are about the order $10^{3–10^{7}}$. Taking the detection rate in the middle rang $O(10^{5})$, and assuming that only a small fraction ($\sim 10^{-3}$) of GW/FRB systems could be detected, we can expect to detect $O(10^{5})$ such systems per year. Thus, we simulate a population of 100 GW/FRB systems.

An example of 100 simulated GW/FRB systems from the fiducial model is shown in Figure 2. For a set of 100 simulated data points, the likelihood for the cosmological parameters can be determined by the minimum $\chi^{2}$ statistic, i.e.,

$$\chi^{2}(p) = \sum_{i} \frac{[D_{L}^{\text{mea}} \cdot D_{\text{IGM}}^{\text{mea}} - D_{L}^{\text{th}}(p) \cdot D_{\text{IGM}}^{\text{th}}(p)]^{2}}{\sigma_{D_{L}, D_{\text{IGM}}}^{2}},$$  \hspace{1cm} (17)

\(^6\) We do not need to consider the other two angles $\phi$ and $\psi$, as the $S/N$ is independent of them.

\(^7\) The Einstein Telescope Project, https://www.et.gw.eu.
In $w$CDM, the equation-of-state of dark energy, $w$, is constant, and there are three free parameters: $\Omega_m$, $w$, and $H_0$. It should be underlined that the $D_L \cdot DM_{IGM}$ method (the product of Equations 5 and 12) can be used to test cosmological models in a rather unique way because, unlike the other two methods ($D_L$ or $DM_{IGM}$) that rely on the optimization of the Hubble constant $H_0$, this particular analysis is completely independent of $H_0$. For the $D_L$ and $DM_{IGM}$ methods, we let $\Omega_m$, and $w$ be free parameters while either fixing or marginalizing over $H_0$.

We first marginalize $H_0$ in the $w$CDM model to find the confidence levels in the $\Omega_m - w$ plane. The constraint results (solid lines) from three different methods ($D_L \cdot DM_{IGM}$ and $D_L \cdot DM_{IGM}$) are illustrated in Figure 3. One can see from these solid contours that the $D_L \cdot DM_{IGM}$ method gives much tighter constraints on both cosmological parameters than the other two methods as we expected. In both the traditional standard-siren approach (i.e., the $D_L$ method) and the $DM_{IGM}$ method, we need a much larger sample to increase the significance of the constraints. By contrast, future observations of GWs and their FRB counterparts will enable us to achieve precise cosmography from around 100 such systems. All in all, upgraded standard sirens could be constructed if GW/FRB association systems are commonly detected in the future.

To show the importance of $H_0$ in the $D_L$ and $DM_{IGM}$ methods, we also present the case of fixing $H_0 = 67.8$ km s$^{-1}$ Mpc$^{-1}$. As shown by the dashed contours in Figures 3(a) and (b), the constraints on cosmological parameters can be significantly improved when $H_0$ is fixed. Even if the prior value of $H_0$ is adopted, however, the constraints obtained from the methods of $D_L$ and $DM_{IGM}$ are still not better than that of the $D_L \cdot DM_{IGM}$ method (Figure 3(c)). Therefore, we can conclude that the cosmological constraint ability of the methods of $D_L$ and $DM_{IGM}$ are restricted by the fact that they both explicitly depend on $H_0$, while the $D_L \cdot DM_{IGM}$ method has the advantage of being independent of $H_0$.

To better represent how effective this $D_L \cdot DM_{IGM}$ method might be with a certain number of coincident detections, in Figure 4 we plot the best-fit dark matter density parameter $\Omega_m$...
and 1σ confidence level in the flat ΛCDM model as a function of the number of GW/FRB associations (analogous to Figure 5 of Del Pozzo 2012). The 1σ confidence level constraint on Ωm from Planck temperature data and Planck lensing combined results (blue shaded area; Planck Collaboration et al. 2016) is also plotted for comparison. One can see from this figure that with about 100 GW/FRB associations we can constrain Ωm with an accuracy comparable to Planck data.

4. Summary and Discussion

In this Letter, we propose that if GW/FRB associations are confirmed to commonly exist, upgraded standard sirens can be constructed from the joint measurements of luminosity distances DL derived from GWs and dispersion measures DMIGM derived from FRBs. Moreover, the combination of DL and DMIGM (i.e., the DL · DMIGM method) can be used to differentiate cosmological models in a rather unique way because, unlike the traditional standard-siren approach (i.e., the DL method) and the DMIGM method that rely on the optimization of the Hubble constant H0, this particular analysis is completely independent of H0. Through Monte Carlo simulations, we prove that this DL · DMIGM method is able to constrain the cosmological parameters more strongly than DL or DMIGM separately. With the help of the DL · DMIGM method, precise multimessenger cosmology can be achieved from around 100 GW/FRB systems.

Thanks to the high sensitivity, the planned third-generation GW detectors, such as the ET, could detect about 105–106 NS–NS and BH–NS merger GW events per year. Although a considerable catalog of GW events would be obtained, the measurements of GW/FRB association systems suggested by our method may not be easy in practice. To be specific, GW/FRB systems could serve as a viable cosmic probe only in the optimistic case that satisfying (i) GWs and FRBs are confirmed to have the same progenitor system; (ii) the coincident detections of GW events with FRBs can be accomplished by the collaboration of the GW interferometer detectors and the radio transient surveys; (iii) the source redshifts can be identified; (iv) an overall statistical error from the contribution of DMIGM, DMGW, and DMIGM is smaller than the systematic uncertainty σIGM in modeling and inferring the dispersion measure DMIGM of the intergalactic plasma, and σIGM is not too big. If some of these requirements are not met, using GW/FRB systems as upgraded standard sirens would be challenged. Although in this Letter we only discuss FRBs, the methodology developed here is also applicable for any other kind of cosmological radio transients that occur simultaneously with GWs (if there are any) to constrain the cosmological parameters and the equation of state of dark energy with high accuracy. On the other hand, even if FRBs are not associated with GWs, our method is still applicable for those GWs and FRBs that occur at the same redshifts.

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\[8\] If it turns out that the statistical error could become larger than σIGM, the accuracy of our results would be reduced dramatically.