

Breaking the baryon density-Hubble constant degeneracy in fast radio burst applications with associated gravitational waves

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Fast radio bursts (FRBs) are a unique probe of the cosmos, owing to dispersion caused by free electrons in the intergalactic medium. Two of the main quantities of interest are degenerate: the density of matter $\Omega_b f_d$ outside of galaxies and the Hubble constant H_0 . Here, we present a new possibility of breaking the degeneracy without invoking early-Universe priors on Ω_b . Assuming some FRBs originate in compact object mergers, the combination of dispersion and luminosity distance from the gravitational wave (GW) can be used to measure $\Omega_b h^2 f_d$ (where h is the dimensionless Hubble constant). We show that this measurement can be combined with the abundant FRBs that have a redshift measurement. This combination breaks the degeneracy with the Hubble constant. We develop a Bayesian framework and forecast that third-generation GW detectors are required to obtain meaningful constraints. We forecast that 1 year of Einstein Telescope operations can constrain H_0 to $\pm 6 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_b h^2 f_d$ to $^{+0.0015}_{-0.0016}$ (68% credible interval). The method can also be used with luminosity distances obtained through other means than GWs.

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I. INTRODUCTION

The disagreement between measurements of the local expansion rate of the Universe and the Hubble constant inferred from early-Universe probes is known as the Hubble tension and poses one of the biggest problems to the standard cosmological model [1,2] (see [3,4] for recent reviews). Because systematics are the leading-order uncertainties, independent probes are essential to judge the significance of the disagreement. One such proposed probe are fast radio bursts (FRBs). The dispersion measure (DM) of FRBs is the integrated column density of electrons along their path. As such, it is a proxy for distance that can be compared with the FRBs' host galaxy redshift (z). The relation depends on the geometry of the Universe and hence can be used to infer cosmological parameters. However, the DM- z relation depends on the combination $\Omega_b f_d H_0$, with Ω_b being the density parameter for baryons and f_d being the fraction of diffuse baryons in the intergalactic

medium and in galaxy halos. Macquart *et al.* [5] constrained $\Omega_b h$ using a fixed f_d from taking the remainder of a census of baryons in galaxies, where we write $h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. James *et al.* [6] broke the degeneracy further by assuming $\Omega_b h^2 = 0.02242$ from the *Planck* Collaboration [7]. In this paper, we propose a new method to measure $\Omega_b h^2 f_d$ using a subset of FRBs, proposed to be associated with gravitational waves (GWs).

The merger of two neutron stars (NSs) or of an NS with a black hole (BH) could potentially produce a GW and an FRB. Although NSs are now the favored progenitor for the majority of the FRB population [8,9], mergers could still cause a fraction of FRBs. The volumetric binary NS (BNS) merger rate of $10\text{--}1700 \text{ Gpc}^{-3} \text{ yr}^{-1}$ [10] allows them to account for $\sim 2\%$ of the observed FRBs, which have a rate of $7.3^{+8.8}_{-3.8} \times 10^4 \text{ bursts Gpc}^{-3} \text{ yr}^{-1}$ above an energy of 10^{39} erg (not corrected for beaming) [11]. The accounted fraction could be higher if the coalescence or the merger product produce more than one FRB. Theoretically, FRBs have been suggested to arise from NS mergers in over four different ways (see [12] for a comprehensive review). The interactions of magnetic fields before the merger might result in an FRB [13,14]. A jet that is launched during the merger could interact with the surrounding medium and produce an FRB [15]. The NS resulting from the merger might emit FRBs in any way that has been suggested for NSs. Finally, the newly formed NS can collapse into a BH

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if its mass exceeds a certain threshold. When this happens, its whole magnetic field snaps and recombines, which might result in an FRB [16]. Additionally, NS-BH mergers have been proposed as an FRB source through the interaction of the BH with the NS magnetic field [17–19].

Several observational studies have been conducted to search for associated GW-FRB events. Rowlinson and Anderson [20] put constraints on FRB counterparts of GRB 150424A with triggered observations of the Murchison Widefield Array [MWA [21]]. Moroianu *et al.* [22] reported a tentative association between GW190425 and FRB 190425A. Panther *et al.* [23] also identified the most probable host of FRB 190425A to be the galaxy UGC10667 with 80% confidence. However, Bhardwaj *et al.* [24] reestimated the GW parameters under the assumption that UGC10667 is the host. They argued that an FRB could not pass through the ejecta of a merger after only 2.5 hours without noticeable attenuation. They further inferred a viewing angle of $>30^\circ$ on the system, disfavoring the FRB emission in our direction. Additionally, Radice *et al.* [25] argued that at the location and distance of FRB 190425A, a kilonova would have been observed. Most recently, Rowlinson *et al.* [26] reported a tentative association of GRB 201006A with an FRB found with the Low-Frequency Array [27]. However in summary, no sufficiently significant association has yet been made that would allow establishing a definitive connection between GWs and FRBs.

Like classical probes, BNS mergers as standard sirens can be used to measure H_0 . Here, the luminosity distance obtained from the chirp is compared with the redshift of the host galaxy. In this way, Abbott *et al.* [28] obtained $H_0 = 70^{+12}_{-8} \text{ km s}^{-1} \text{ Mpc}^{-1}$ from GW170817. The campaign around GW170817 benefited from the fortunate circumstance that the event happened at a relatively close distance of only 40 Mpc ($z = 0.01$) [29]. Gradual improvements of GW experiments and, eventually, the third-generation detectors Einstein Telescope and Cosmic Explorer [30,31] will detect GWs to greater distances. This will pose challenges for multifrequency follow-up campaigns similar to those conducted to find GW170817. It comes as a convenient advantage that most telescopes used for FRB searches come with a large field of view. For example, the Australian Square Kilometre Array Pathfinder has a 30° field of view and could almost cover the 31-deg^2 initial LIGO-Virgo localization region of GW170817 in a single pointing. Should BNS mergers emit FRBs, these could lead to future multimessenger follow-up.

Wei *et al.* [32] developed a method (largely based on [33]) to use luminosity distances, D_L , from GW-FRB associations together with DMs and redshifts to measure Ω_m and w in a w CDM cosmology. Li *et al.* [34] proposed employing the ratio D_L/DM [33] to measure f_d using a minimum χ^2 statistic. Lemos *et al.* [35] proposed combining DMs with the D_L 's of supernovae at the same redshifts to measure f_d .

Motivated by the tentative associations with unclear hosts, and since there will always be FRBs whose redshifts cannot be obtained [36,37], we develop a new method to use GW-FRB associations that does not require a redshift. We derive the full solution for the DM- D_L relation by inverting $D_L(z)$. We only use the DM and D_L of a subpopulation of FRBs and combine it with normal FRBs with measured redshifts. This combination breaks the degeneracy in the DM- z relation and yields H_0 and $\Omega_b h^2 f_d$ separately.

II. METHODS

The method we propose is based on the measurement of the DM from the FRB and luminosity distance, D_L , derived from the GW. Both quantities are imprecise distance measurements. The leading uncertainty in D_L comes from the degeneracy with the inclination angle of the merger system. The reason is that the signal from a farther, face-on merger system can have a very similar shape as a closer but more edge-on system. The measured dispersion is a composite of contributions from the host galaxy DM_{host} , the diffuse cosmic plasma in the intergalactic medium and the circumgalactic medium of intervening galaxies DM_{cosm} , and the Milky Way DM_{MW} , including its halo [38]:

$$\text{DM} = \text{DM}_{\text{MW}} + \text{DM}_{\text{cosm}} + \frac{\text{DM}_{\text{host}}}{1+z}. \quad (1)$$

The distance of the FRB can be estimated using the sight line-averaged $\langle \text{DM}_{\text{cosm}} \rangle(z)$. The leading uncertainties in DM stem from sight line-to-sight line variations in the baryon density (e.g., how many filaments are intersected) and from the uncertain DM_{host} . We marginalize over the probability distribution functions of D_L and DM_{cosm} in a Bayesian framework. But first, we derive the sight line-averaged $\langle \text{DM}_{\text{cosm}} \rangle(D_L)$.

A. The DM- D_L relation

We assume a flat Λ -cold-dark-matter (Λ CDM) universe where the redshift-dependent Hubble parameter is given by the Friedmann equation (e.g., [39]) in the form

$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}, \quad (2)$$

where H_0 is the Hubble constant, $\Omega_m = \frac{\rho_m}{\rho_0}$ is the present-day matter density in terms of the critical density $\rho_0 = \frac{3H_0^2}{8\pi G}$ with the gravitational constant G , and $\Omega_\Lambda = \frac{\rho_\Lambda}{\rho_0}$ is the dark energy density, which can be expressed in terms of the cosmological constant Λ as $\rho_\Lambda = \Lambda c^2/(8\pi G)$. The luminosity distance for a source at redshift z follows as

$$D_L(z) = (1+z) \frac{c}{H_0} \int_0^z \frac{1}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} dz'. \quad (3)$$

The average of DM_{cosm} over many sight lines is given as [38,40,41]

$$\langle \text{DM}_{\text{cosm}} \rangle(z) = \frac{3c}{8\pi G m_p} \Omega_b H_0 \int_0^z \frac{(1+z') f_d(z') \chi(z')}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} dz', \quad (4)$$

where m_p is the proton mass and $\chi(z)$ is the ionization fraction at a given redshift, which can be expressed in terms of the ionization fractions of hydrogen and helium $\chi(z) = \frac{3}{4}\chi_H(z) + \frac{1}{8}\chi_{\text{He}}(z)$. In this work, we consider only low- z FRBs, so we assume hydrogen and helium to be fully ionized, i.e., $\chi_H(z) = \chi_{\text{He}}(z) = 1$, and we assume f_d is constant. Equation (4) then becomes

$$\langle \text{DM}_{\text{cosm}} \rangle(z) = \frac{3c}{8\pi G m_p} \frac{7}{8} \Omega_b f_d H_0 \times \int_0^z \frac{1+z'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} dz'. \quad (5)$$

This famous DM- z relation depends on the product $\Omega_b f_d H_0$, such that these quantities cannot be inferred individually. This degeneracy can only be broken with additional constraints, e.g., from measurements of the cosmic microwave background.

If only DM and D_L are available, while z is not directly measurable, we can invert $D_L(z)$ to obtain $\langle \text{DM}_{\text{cosm}} \rangle(D_L)$. The inversion of $D_L(z)$ can only be done numerically, but this does not hinder us from using the relationship. We refer to the inverted function as $z(D_L)$ and write

$$\langle \text{DM}_{\text{cosm}} \rangle(D_L) = \langle \text{DM}_{\text{cosm}} \rangle(z(D_L)). \quad (6)$$

The Taylor approximation can be done analytically; the first-order term is

$$\langle \text{DM}_{\text{cosm}} \rangle(D_L) \approx \frac{3}{8\pi G m_p} \frac{7}{8} \Omega_b f_d H_0^2 D_L. \quad (7)$$

Interestingly, this equation is proportional to $\Omega_b f_d H_0^2$, while the classic DM- z relation has a proportionality to $\Omega_b f_d H_0$. Combining the DM- D_L relation with the DM- z relation, i.e., GW-FRB associations with independent FRBs that have a measured redshift, we can break the degeneracy between $\Omega_b f_d$ and H_0 .

Figure 1 illustrates the curves along which perfectly measured relations would still allow parameters to be free. If the DM- z and DM- D_L relations are both measured, only the intersection of the two relations is allowed and the degeneracy is broken. The degeneracy can also be broken by using only the DM- D_L relation with FRBs at different redshift. The reason is the deviation of the full solution from the linear relation. Due to large uncertainties in single

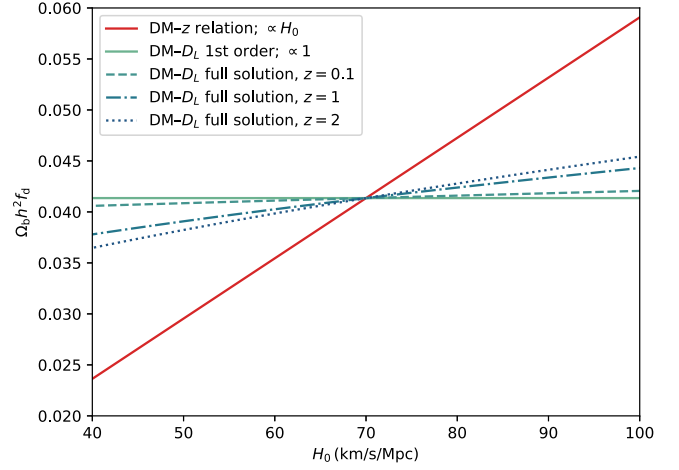


FIG. 1. Curves along which parameters are degenerate in different methods. Measuring both relations breaks the degeneracy by allowing only the intersection of the two curves.

measurements, this variation will only give useful constraints long after the combination with the DM- z relation.

B. Bayesian framework

To utilize the derived relation and combine it with other FRB data, we use a Bayesian framework. From Bayes' rule (see, e.g., [42] for an introduction), the posterior probability distribution is proportional to the product of the likelihood and the prior probability:

$$\begin{aligned} p(\Omega_b h^2 f_d, H_0 | \text{DM}, D_L) \\ \propto p(\text{DM}, D_L | \Omega_b h^2 f_d, H_0) p(\Omega_b h^2 f_d, H_0) \\ = \prod_i p(\text{DM}_i, D_{Li} | \Omega_b h^2 f_d, H_0) p(\Omega_b h^2 f_d, H_0), \end{aligned} \quad (8)$$

where i goes over all FRBs.

In this exploratory work, we restrict ourselves to the two free parameters $\Omega_b h^2 f_d$ and H_0 , but additional parameters should be left free in further studies. We assume that the Milky Way contribution can be subtracted from the measured DM with sufficient precision, such that we can use the resulting excess $\text{DM}_{\text{exc}} = \text{DM} - \text{DM}_{\text{MW}} = \text{DM}_{\text{cosm}} + \text{DM}_{\text{host}}/(1+z)$.

We follow Macquart *et al.* [5] in the likelihood definitions of DM_{cosm} and DM_{host} . We describe DM_{host} by a log-normal probability distribution function (PDF) in the formulation of Jahns-Schindler *et al.* [37] with median DM_0 and the standard deviation σ_{host} of the DM's base 10 logarithm, i.e.,

$$\begin{aligned} p_{\text{host}}(\text{DM}_{\text{host}} | \text{DM}_0, \sigma_{\text{host}}) \\ = \frac{\log_{10}(e)}{\text{DM}_{\text{host}} \sigma_{\text{host}} \sqrt{2\pi}} \times \exp \left(-\frac{(\log_{10} \text{DM}_{\text{host}} - \log_{10} \text{DM}_0)^2}{2\sigma_{\text{host}}^2} \right). \end{aligned} \quad (9)$$

We describe the PDF of DM_{cosm} for a given D_L in terms of $\Delta = \frac{\text{DM}_{\text{cosm}}}{(\text{DM}_{\text{cosm}}/z(D_L))}$ and with the fluctuation parameter F as

$$p_{\text{cosm}}(\text{DM}_{\text{cosm}}|D_L, \Omega_b h^2 f_d, H_0, F) = \frac{A\Delta^{-3}}{\text{DM}_{\text{cosm}}} \exp\left(-\frac{(\Delta^{-3} - C_0)^2}{18\sigma^2}\right), \quad (10)$$

where $\sigma = F/\sqrt{z(D_L)}$, A is the normalization constant, and C_0 is fixed by the condition $\langle\Delta\rangle = 1$. For the assumed flat universe, the normalization can be calculated analytically and is given in Appendix A.

$$\begin{aligned} p(\text{DM}_i, D_{Li}|\Omega_b h^2 f_d, H_0) p(\Omega_b h^2 f_d, H_0) &= \int dD_L \int_0^{\text{DM}_{\text{exc}}} d\text{DM}_{\text{cosm}} p(\text{DM}_{\text{cosm}}, D_L|\Omega_b h^2 f_d, H_0) p(\Omega_b h^2 f_d, H_0) \\ &= \int dD_L \int_0^{\text{DM}_{\text{exc}}} d\text{DM}_{\text{cosm}} p_{\text{cosm}}(\text{DM}_{\text{cosm}}|D_L, \Omega_b h^2 f_d, H_0, F) p_{\text{host}}(\text{DM}_{\text{exc}} - \text{DM}_{\text{cosm}}|\text{DM}_0, \sigma_{\text{host}}) \\ &\quad \times p_{H_0}(H_0|\Omega_b h^2 f_d) p(D_L) p(\Omega_b h^2 f_d), \end{aligned} \quad (11)$$

where F is fixed but can be marginalized over in future work, and DM_0 and σ_{host} are fixed at first but will be left free later.

III. FORECASTS

Now, we simulate a population of GW-FRB events to forecast the potential of this method. We explore the posterior distribution using Markov chain Monte Carlo simulations using the EMCEE package [43].

We make three forecasts. One resembles future detections of current GW detectors and one the next-generation GW detectors assuming the specifications of the proposed Einstein Telescope. The third run is similar to the second but treats the parameters of the DM_{host} distribution as unknowns. We combine the first forecast with the current constraints from FRBs and the second and third with the projected constraints of future FRBs. Detections with current GW detectors will mainly stem from observing run O5 of the international GW network, which is planned for 2027–2030 [44]. The Einstein Telescope is planned to start operations in 2035 [45].

A. Current-generation GW detectors

We simulate 10 FRBs with GW counterparts. The true number is very uncertain. Kiendrebeogo *et al.* [46] predicted the number of BNS mergers in O5 to be 86_{-59}^{+171} or $180_{-100}^{+220} \text{ yr}^{-1}$ (uncertainties are the 5% and 95% quantiles), for two different population models. Additionally, it is uncertain how many of them could emit a detectable FRB.

For simplicity, we place all events at a fixed redshift $z = 0.1$. This is conservative in comparison with the forecasted (Table 4 in [46]) median luminosity distances of 619_{-19}^{+15} and $738_{-25}^{+30} \text{ Mpc}$ ($z = 0.127$ and 0.150 , respectively), and uncertainties are again the 5% and 95% quantiles), because a higher median redshift means a

Because $\text{DM}_{\text{host}} = (\text{DM}_{\text{exc}} - \text{DM}_{\text{cosm}}) \times (1 + z)$, the above equations still leave some freedom for either DM_{cosm} or DM_{host} . Therefore, we use a flat prior for DM_{cosm} between 0 and DM_{exc} and marginalize over it. Additionally, D_L is not an exact measurement but described by a posterior distribution resulting from the GW analysis. When simulating data, we assume that the uncertainty of D_L follows a normal distribution. Finally, we incorporate the constraints on $\Omega_b H_0 f_d$ from FRBs with redshifts (and without GWs) as a prior in the form $p_{H_0}(H_0|\Omega_b h^2 f_d)$ and put a flat prior distribution for $\Omega_b h^2 f_d$. Collecting everything in Eq. (8) and integrating over D_L and DM_{exc} yields

higher cosmological signal relative to the uncertain contributions.

We assume a 1σ Gaussian D_L uncertainty of 40%, which is the median of presently detected GW events [47]. With this uncertainty, we draw the D_L mock measurements around the value corresponding to $z = 0.1$. In the inference, we consider it in the form of a normal likelihood for D_L . To draw DM, we use Eqs. (9), (10), and (1). We summarize all parameters in Tables I and II.

As a prior from the “classic” FRB- z method, we use the current constraints on $\Omega_b f_d H_0$ (which might significantly improve in the next years). Specifically, we use the constraints from mostly localized FRBs from [6], as detailed in Appendix B.

B. Einstein Telescope

To forecast the potential for the next generation of GW detectors, we adhere to the forecasts for the Einstein

TABLE I. Parameters used for our simulations and prior distributions used in the inference. Brackets denote the limits of flat distributions and $\mathcal{N}(\mu, \sigma)$ denotes the normal distribution.

Parameter	Simulation value
F	0.32
σ_{host}	0.57
Cosmology	Flat Λ CDM
H_0	$73 \text{ km s}^{-1} \text{ Mpc}^{-1}$
Ω_m	0.3
Prior	
H_0	$[10, 150] \text{ km s}^{-1} \text{ Mpc}^{-1}$
$\Omega_b h^2 f_d$	$[0, 1]$
DM_{cosm}	$[0, \text{DM}_{\text{exc}}]$
D_L	$\mathcal{N}(D_L(z), \sigma_{D_L})$

TABLE II. Parameters and distributions that are different between the different runs.

Parameter	LIGO + Virgo + KAGRA	Einstein Telescope	Einstein Telescope free host DM parameters
Number	10	20, 100	20, 100
z	0.1	0.1, 0.2	$\mathcal{N}^+(0.1, 0.1), \mathcal{N}^+(0.2, 0.2)$
σ_{D_L}/D_L	0.4	0.1, 0.2	0.1, 0.2
DM_0	$170 \text{ cm}^{-3} \text{ pc}$	$170 \text{ cm}^{-3} \text{ pc}$	$100 \text{ cm}^{-3} \text{ pc}$
FRB- z prior	James <i>et al.</i> [6]	$\mathcal{N}(73 \text{ km s}^{-1} \text{ Mpc}^{-1}, 0.8 \text{ km s}^{-1} \text{ Mpc}^{-1})$	

⁺ $\mathcal{N}^+$ is the truncated normal distribution, truncated at 0 to give only positive values.

Telescope of Iacovelli *et al.* [48]. They predicted about 20 out of their $\sim 10\,000$ annual detections to have a relative uncertainty in the luminosity distance below 10% and about 100 below 20%. As conservative values, we pick 10% and 20% and the estimated median redshifts of 0.1 and 0.2, respectively.

As the FRB- z prior, we assume a normally distributed PDF for H_0 . James *et al.* [6] predicted an H_0 uncertainty of about $2.45 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for 100 FRBs. We extrapolate this value to ~ 1000 FRBs through $2.45/\sqrt{10} \approx 0.8$. The actual number of localized FRBs will likely be higher by the time of the Einstein Telescope, but systematics are going to start dominating the uncertainties.

C. Leaving the host DM free

So far, we have assumed that DM_{host} in the GW-FRB population has the same distribution as DM_{host} of the

general FRB population, which is unlikely if the progenitors are different. The FRBs coming from mergers could, e.g., come from an older stellar population, which would also imply a lower DM_{host} compared with an FRB population of young magnetars. This requires a separate inference of DM_{host} for the GW-FRB population.

We model DM_{host} as a log-normal distribution with parameters DM_0 and σ_{host} and leave them as free parameters in our inference. As input values, we take $DM_0 = 100 \text{ cm}^{-3} \text{ pc}$ and $\sigma_{\text{host}} = 0.57$. Because of the dependency on z in Eq. (1), a realistic spread in z would now help in constraining the DM_{host} parameters and give more realistic forecasts. We therefore distribute the sources in z . We choose a normal distribution requiring values to be positive, with 20 FRBs with $z \sim \mathcal{N}(0.1, 0.1)$ and 100 FRBs with $z \sim \mathcal{N}(0.2, 0.2)$. This choice is motivated again by Fig. 15 of [48].

D. Results

We apply the Bayesian inference to the three simulated data sets. The results are shown in Figs. 2–4.

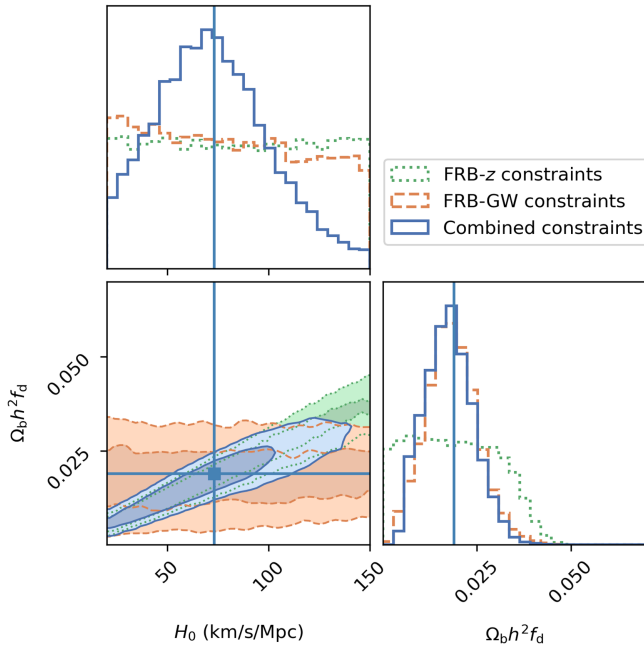


FIG. 2. Posterior distribution when using ten simulated FRB-GW events. The prior distribution p_{H_0} derived from the DM- z relation [6] is also shown, as well as the posterior distribution without using this prior. Contours show the 68% and 95% confidence regions. Panels above and to the right of the plot show the posteriors when marginalizing over one of the variables. Blue lines mark the input values.

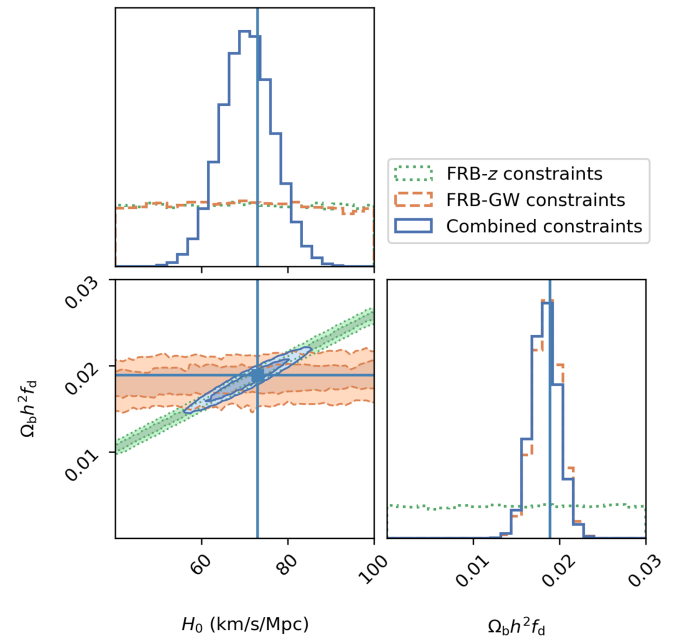


FIG. 3. Same as Fig. 2 but for 120 simulated FRB-GW events as specified in Table I.

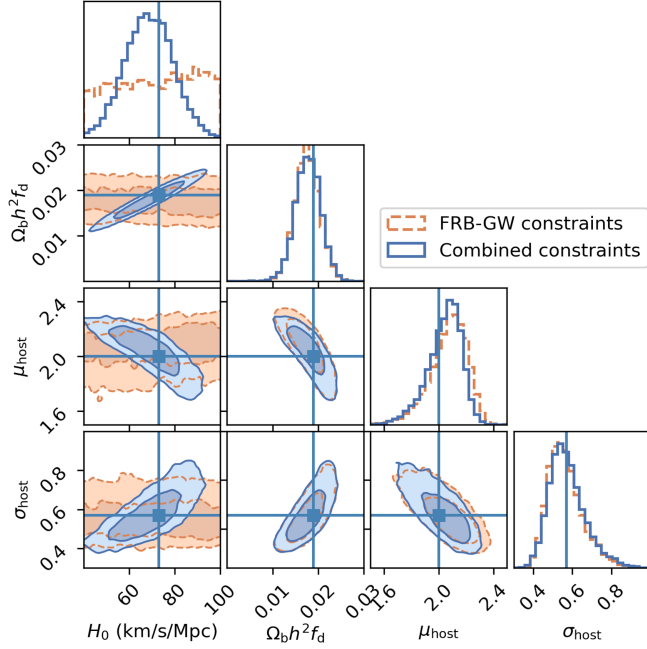


FIG. 4. Same as Fig. 3 but treating the host parameters DM_0 and σ_{host} as unknown. The source redshifts are now distributed. The parameter $\mu_{\text{host}} = \log_{10} DM_0$.

The ten simulated FRB-GW events at $z = 0.1$ cannot constrain the parameter space much beyond the prior distribution. The reason is likely the large scatter in DM and D_L . Particularly at such low redshifts of only $z = 0.1$, the median of DM_{host} is larger than the median of DM_{cosm} .

The 120 simulated FRB-GW events at $z = 0.1$ and 0.2 show meaningful constraints. The resulting parameters are $H_0 = 71 \pm 6 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_b h^2 f_d = 1.83^{+0.15}_{-0.16} \times 10^{-2}$ with 68% credibility, an 8.6% and 8.5% relative uncertainty, respectively.

The case with free DM_0 and σ_{host} gives $\sigma_{H_0} = {}^{+7}_{-7}$ and $\sigma_{\Omega_b h^2 f_d} = {}^{+0.19}_{-0.17} \times 10^{-2}$, a small increase with respect to the previous case where the parameters were fixed.

IV. DISCUSSION

A. Comparison with other probes

The constraints on H_0 we forecast for 120 events are tighter than the current constraints from FRB DM- z measurements with cosmic microwave background priors on $\Omega_b h^2$, which yield an uncertainty of $\sigma_{H_0} = {}^{+22}_{-12} \text{ km s}^{-1} \text{ Mpc}^{-1}$ (90% credible [6]). Compared with the assumed future constraints of $\sigma_{H_0} = 0.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$, we are losing a factor 7.5 in precision, the price we pay for independence from early-Universe measurements.

Compared with current measurements, the predictions exceed some less-precise, current probes like GWs [$H_0 = 69^{+16}_{-8} \text{ km s}^{-1} \text{ Mpc}^{-1}$ (68% credible) [49]], but we would have to accumulate several years of data to reach the current precision of, e.g., type Ia supernovae calibrated

with Cepheids and parallax measurements ($73.04 \pm 1.04 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [1]) or baryonic acoustic oscillations ($68.52 \pm 0.62 \text{ km s}^{-1} \text{ Mpc}^{-1}$ [2]). In the end, how well we can understand the systematics in FRB DMs will be decisive.

B. Reviewing assumptions

The assumptions of the forecast were conservative in several ways. The assumed distribution of DM_{host} from [6] given by $DM_0 = 170^{+59}_{-47} \text{ cm}^{-3} \text{ pc}$ (all uncertainties in this discussion are 68% credible) and $\sigma_{\text{host}} = 0.57^{+0.13}_{-0.09}$ is high in comparison with the results of other studies. Shin *et al.* [11], for example, found $DM_0 = 84^{+69}_{-49} \text{ cm}^{-3} \text{ pc}$ and $\sigma_{\text{host}} = 0.41^{+0.21}_{-0.20}$. This would result in a much narrower PDF of DM_{host} and in turn much narrower posterior distributions.

Our assumption of vanishing DM_{MW} is not always warranted. The halo contribution is known with an uncertainty of $\sim 10 \text{ cm}^{-3} \text{ pc}$, which is certainly much smaller than the uncertainty of DM_{host} and can be absorbed by it. Ideally, it is modeled separately as, e.g., Hoffmann *et al.* [50] did with $DM_{\text{MW}} \sim \mathcal{N}(50 \text{ cm}^{-3} \text{ pc}, 15 \text{ cm}^{-3} \text{ pc})$. In particular, at low galactic latitudes, model uncertainties in the MW interstellar medium can be larger than the halo uncertainty, and one problem is that the uncertainties themselves are not very well known [51]. The effects from an incorrectly estimated DM_{MW} can be estimated using the approximation $DM_{\text{cosm}} \approx z \times 1000 \text{ cm}^{-3} \text{ pc}$. Generally, an underestimated DM_{MW} will produce estimates of $\Omega_b h^2 f_d$ and H_0 that are too high. This potential bias is shared with all FRBs and is therefore one of the primary goals that will be addressed with close-by FRBs.

The uncertainty in each DM_{cosm} could be reduced by detailed optical follow-up. By taking spectra of galaxies close to the sight line, one can attribute a part of the DM to their halo and identify filaments or galaxy clusters along the sight line [52–54].

Although we derive it in the context of a GW-FRB association, the method presented in this paper only requires a luminosity distance measurement of any kind in combination with the DM of an FRB.

C. Preferred direction of FRB emission

In this work, we implicitly assume that the emission direction of the FRB is independent of the inclination of the merger system with respect to the observer. If instead there is a preferred direction, the chances of the simultaneous detection of FRBs and GWs are affected, and the D_L inference can be biased. If FRBs are preferentially emitted towards the poles but isotropic emission is assumed, the inferred D_L is lower than the real value, resulting in $\Omega_b h^2 f_d$ and H_0 being biased high.

Some models for FRB emission from BNS mergers favor a direction, but often the direction is not explicitly discussed or not predicted. In models where the FRB emerges from the jet [15,55,56] or the GW itself [57,58],

the direction of the rotational axis is preferred. In models with pulsar-like emission (e.g., [59]), the direction of the pulsar magnetic field is preferred, which is expected to align with the system's rotational axis during inspiral [60,61]; yet more complex magnetic fields might allow emission in other directions. Ultimately, it is unclear which models can produce FRBs.

To find the correct prior, the beaming direction of the FRB with respect to the merger axis needs to be studied. One possibility is to compare the FRB brightness with the brightness of other electromagnetic counterparts, e.g., x-rays and gamma rays.

D. Future detectors not considered here

Apart from the Einstein Telescope considered here, additional 2.5 and third-generation GW detectors are being planned. The Cosmic Explorer [31] is planned to start operations in 2035. Iacovelli *et al.* [48] predicted the BNS merger rates to increase from 910 to 160 000 per year for the Einstein Telescope alone to 3800 to 650 000 per year for the combination of the Einstein Telescope and Cosmic Explorer. The precision in the luminosity measurements will also increase and therefore the number of events with a <10% uncertainty will increase from ~ 20 to ~ 2000 .

In terms of FRB detections, the most suitable telescopes will be ones with a very wide field of view, like the Bustling Universe Radio Survey Telescope in Taiwan [62].

E. Mergers with redshift measurements

In this work, we explicitly assume events without measured redshifts. If the redshift is measured, the D_L - z relation could provide the H_0 measurement to directly break the degeneracy in the DM- z relation. It would be straightforward to extend our Bayesian framework to include the redshift.

However, when assuming perfectly known redshifts, the likelihoods of DM and D_L factorize and become independent. This method would therefore be similar to combining the FRB data with some external H_0 measurements. The joint analysis of D_L , DM, and z will be favorable when additional cosmological parameters are considered or when the redshift uncertainty from peculiar velocities becomes relevant, which is often the case at low redshifts.

Previous works mentioned in the Introduction suggested other methods to use the three measurements of D_L , DM, and z . Gao *et al.* [33] proposed $D_L(z)/\langle \text{DM}_{\text{cosm}} \rangle(z)$ as a probe of the scatter in DM_{cosm} and the evolution in the scatter with redshift. They argued that the division makes it less dependent on cosmological parameters because the integrals in Eqs. (3) and (5) almost cancel out. Wei *et al.* [32] suggested to instead use the product $D_L \times \langle \text{DM}_{\text{cosm}} \rangle(z)$, which is independent of H_0 , to measure Ω_m and w in the w CDM model. Li *et al.* [34] again used the ratio $D_L/\langle \text{DM}_{\text{cosm}} \rangle(z)$ but with the aim of measuring f_d , similar to this study.

At several points in these papers, it was claimed that z and D_L can be used interchangeably and it was sometimes not clear which one was used in their mock observations. However, this is not true as calculating, e.g., D_L from z depends on cosmology, so if only z is measured, the DM- z relation needs to be used and vice versa.

Furthermore, all of these methods take the product or ratios of the measurements, discarding information from the individual values. Their advantages of being less dependent on H_0 or other cosmological parameters will also be there in a Bayesian framework. Therefore, and because it is more flexible and clear, our Bayesian framework should generally be advantageous.

V. CONCLUSION

We developed and tested a new method to use FRBs with an associated luminosity distance measurement as a cosmological tool. This luminosity distance could most likely come from a GW counterpart if FRBs arise during a BNS merger. The DM- D_L measurements allow inferring $\Omega_b h^2 f_d$ and H_0 when combined with independent DM- z measurements from localized FRBs. The combination of measurements breaks the degeneracy between $\Omega_b h^2 f_d$ and H_0 that each measurement would have individually, without using external priors from cosmic microwave background or supernovae measurements. We developed a Bayesian framework to use the DM and D_L measurements and combine them with the existing DM- z measurements. We found that third-generation GW detectors, like the Einstein Telescope and Cosmic Explorer, are required to obtain meaningful constraints. According to our simulations, 120 events could constrain H_0 and $\Omega_b h^2 f_d$ to $\pm 6 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $^{+0.15}_{-0.16} \times 10^{-2}$, respectively. When assuming that the DM_{host} of FRBs that are associated with GWs is distributed differently than DM_{host} of the general FRB population, we obtained uncertainties of $^{+8}_{-8}$ and $^{+0.21}_{-0.20} \times 10^{-2}$ for H_0 and $\Omega_b h^2 f_d$, respectively.

The simulation and inference code used in this article are available at <https://github.com/Joscha/DMDLInference>.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [63].

APPENDIX A: NUMERICAL SIMPLIFICATION

As we assume a flat cosmology, we speed up our numerical calculations by using the analytic solutions of the two integrals in Eqs. (3) and (5). These integrals can be calculated as

$$\int_0^z \frac{1}{\sqrt{\Omega_m(z+z')^3 + \Omega_\Lambda}} dz = \frac{z+1}{\sqrt{\Omega_\Lambda}} {}_2F_1\left(\frac{1}{3}, \frac{1}{2}; \frac{4}{3}; -\frac{\Omega_m(1+z)^3}{\Omega_\Lambda}\right) \Big|_0^z \quad \text{and} \quad (\text{A1})$$

$$\int_0^z \frac{1+z}{\sqrt{\Omega_m(z+z')^3 + \Omega_\Lambda}} dz = \frac{(z+1)^2}{2\sqrt{\Omega_\Lambda}} {}_2F_1\left(\frac{1}{2}, \frac{2}{3}; \frac{5}{3}; -\frac{\Omega_m(1+z)^3}{\Omega_\Lambda}\right) \Big|_0^z, \quad (\text{A2})$$

where ${}_2F_1$ is the Gaussian hypergeometric function.

The normalization for Eq. (10) is

$$A = 3(12\sigma)^{1/3} \left[3\Gamma\left(\frac{1}{3}\right) \sigma {}_1F_1\left(\frac{1}{6}, \frac{1}{2}; -\frac{1}{2}\left(\frac{C_0}{3\sigma}\right)^2\right) + \sqrt{2}\Gamma\left(\frac{5}{6}\right) C_0 {}_1F_1\left(\frac{2}{3}, \frac{3}{2}; -\frac{1}{2}\left(\frac{C_0}{3\sigma}\right)^2\right) \right]^{-1}, \quad (\text{A3})$$

where Γ is the gamma function and ${}_1F_1$ is the generalized hypergeometric function.

APPENDIX B: OBTAINING THE PRIOR FOR $\Omega_b h^2 f_d$

Here, we give the details on how we obtain the prior from current FRB- z constraints. Since James *et al.* [6] used priors on $\Omega_b h^2 f_d$ to constrain H_0 , but we want to leave it as a free parameter, we have to exclude their prior again. We read the PDF of H_0 from their Fig. 6 using WebPlotDigitizer [64], as the data are not published. James *et al.* [6] fixed $\Omega_b h^2 = 0.02242$ using big bang nucleosynthesis theory and cosmic microwave background measurements [7]. They further used $f_d(z=0) = 0.844$ with an evolving $f_d(z)$. As we have no possibility to account for the evolution, we have to assume that it did not have a big influence on their result, which is reasonable given the mostly low- z FRBs. Hence, we fix $f_d = 0.844$ and obtain a constant C that allows us to reverse their assumptions:

$$C = \Omega_b h^2 f_d = 0.02242 \times 0.844. \quad (\text{B1})$$

We then transform the PDF reported for H_0 , which we label as $p_J(H_0)$, to account for the change of variables,

$$p_{H_0}(H_0|\Omega_b h^2 f_d) = \frac{C}{\Omega_b h^2 f_d} p_J\left(\frac{C}{\Omega_b h^2 f_d} H_0\right). \quad (\text{B2})$$

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