Constraining the evolution of the baryon fraction in the IGM with FRB and $H(z)$ data

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Abstract. Extragalactic dispersion measures (DMs) obtained from observations of fast radio bursts (FRBs) are an excellent tool for probing intergalactic medium (IGM) and for conducting cosmography. However, the DM contribution from the IGM ($\text{DM}_{\text{IGM}}$) depends on the fraction of baryon mass in the IGM, $f_{\text{IGM}}$, which is not properly constrained. As $f_{\text{IGM}}(z)$ is geometrically related to the Hubble parameter $H(z)$ and $\text{DM}_{\text{IGM}}(z)$, here we propose that combining two independent measurements of FRBs and $H(z)$ in similar redshift ranges provides a novel and cosmology-free method to constrain the evolution of $f_{\text{IGM}}(z)$. Under the assumption that $f_{\text{IGM}}$ is evolving with redshift in a functional form, we forecast that the evolution of $f_{\text{IGM}}(z)$ can be well inferred in a combined analysis of $\sim 3000 \text{ DM}_{\text{IGM}}(z)$ derived from FRBs and $\sim 50 H(z)$ derived from the Hubble parameter data. Though the efficiency of our method is not as good as that of the other model-independent method involving the joint measurements of DM and luminosity distance of FRBs, our method offers a new model-independent way to constrain $f_{\text{IGM}}(z)$.

Keywords: intergalactic media, baryon asymmetry

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1 Introduction

Fast radio bursts (FRBs) are a mysterious class of millisecond-duration radio transients, all with dispersion measures (DMs) in excess of Galactic expectations, signaling an extragalactic or even a cosmological origin [1–4]. The localization of the repeating event FRB 121102 at $z = 0.19$ confirmed the cosmological origin of at least this source [5–9]. Very recently, the host galaxies and distances of non-repeating FRBs have been identified as well. Ref. [10] reported the interferometric localization of the non-repeating burst FRB 180924 to a position 4 kpc from the center of an early-type spiral galaxy at a cosmological redshift of 0.3214. Similarly, ref. [11] reported the localization of FRB 190523 to a few-arcsecond region containing a massive galaxy at redshift 0.66. If lots of FRBs with known redshifts are detected, the combined DM and $z$ information of these events can be used to measure the baryon number density of the universe [12, 13], find circumgalactic baryons [14–17], probe the reionization history of the universe [12, 18], constrain cosmological parameters [19–23], test the weak equivalence principle [24, 25], constrain the rest mass of the photon [26–29], determine the cosmic proper distance [30], and probe compact dark matter [31, 32] or measure Hubble constant and cosmic curvature [33] through gravitational lensing.

However, one issue that stand out for restricting the cosmological applications of FRBs is the strong degeneracy between cosmological parameters and the fraction of baryon mass in the intergalactic medium (IGM), $f_{\mathrm{IGM}}$. Moreover, $f_{\mathrm{IGM}}$ is a poorly known parameter. The baryon distribution of the universe has been an important subject of study for a long time. Ref. [34] presented an estimate of the global budget of baryons in all states based on all relevant information they had been able to marshal. They showed that stars and their remnants comprise only about 17% of the baryons. Although many other researches on the baryon distribution through numerical simulations [35–37] or observations [16, 38–40] have been performed, the baryon fraction in the IGM, $f_{\mathrm{IGM}}$, is still not well constrained. Numerical simulations suggested that at $z \geq 1.5$, $\sim 90\%$ of the baryons produced by the Big Bang are contained within the IGM (i.e., $f_{\mathrm{IGM}} \approx 0.9$), with only $\sim 10\%$ in galaxies, galaxy clusters or possibly locked up in compact stars [37]. While $18 \pm 4\%$ of the baryons are found to exist in galaxies, circumgalactic medium, intercluster medium, and cold neutral gas at redshifts $z \leq 0.4$ [39], and then we have $f_{\mathrm{IGM}} \approx 0.82$. Indeed, the slowly evolving $f_{\mathrm{IGM}}$ at low redshifts is also a big challenge for the cosmological applications of FRBs.

Recently, ref. [41] proposed that a nearly cosmology-free estimation for the fraction of baryons in the IGM can be achieved by using a putative sample of FRBs with the measurements of both DM and luminosity distance $d_L$. In principle, within the framework of the
standard ΛCDM model, $f_{\text{IGM}}$ can be directly estimated by using the usual DM–z way. However, the ΛCDM model currently faces the so-called Hubble constant tension problem, which is the $4\sigma$ discrepancy between the expansion rate directly determined from local distance measurements [42] and the one obtained in the context of the ΛCDM model from high-redshift cosmic microwave background radiation data [43]. Moreover, the ΛCDM model presents some puzzles for theorists, such as the nature of dark matter and dark energy as well as fine-tuning and coincidence problems [44, 45]. In order to alleviate these problems, numerous alternative models have been proposed. This scenario makes clear that cosmology-independent measurements of cosmological quantities are fundamental importance for a proper evaluation of the possibilities. In other words, any model-independent methods for estimating $f_{\text{IGM}}$ are worthy of consideration.

In this paper, we propose a new geometric and cosmology-free method to constrain the evolution of $f_{\text{IGM}}(z)$ by combining two independent measurements of the Hubble parameter $H(z)$ and the dispersion measure $\text{DM}(z)$. For $H(z)$ data, it can be obtained from differential ages of galaxies [46–48] and from radial baryon acoustic oscillation data [49–51]. As for $\text{DM}(z)$ data, we use the large FRB sample. The rest of the paper is arranged as follows. In section 2, we introduce the model-independent method used to determine $f_{\text{IGM}}(z)$. In section 3, we test the validity and efficiency of our new method using Monte Carlo simulations. Finally, a brief summary and discussion are drawn in section 4.

2 Model-independent method for determining $f_{\text{IGM}}(z)$

The observed DM of an FRB consists of several components:

$$\text{DM}_{\text{obs}} = \text{DM}_{\text{MW}} + \text{DM}_{\text{IGM}} + \frac{\text{DM}_{\text{host}}}{1+z},$$

where $\text{DM}_{\text{MW}}$, $\text{DM}_{\text{IGM}}$, and $\text{DM}_{\text{host}}$ represent the DM contributions from the Milky Way, the IGM, and the FRB host galaxy (including the host galaxy interstellar medium and the near-source plasma), respectively. The cosmological redshift factor, $1+z$, converts the DM measured by the rest-frame observer to that of the Earth observer [12, 52]. The average $\text{DM}_{\text{IGM}}$ caused by the inhomogeneous IGM can be estimated as

$$\langle \text{DM}_{\text{IGM}}(z) \rangle = \frac{3c\Omega_b H_0^2}{8\pi G m_p} \int_0^z \frac{(1+z') f_{\text{IGM}}(z') \chi(z')}{H(z')} dz',$$

where $\Omega_b$ is the present-day baryon density parameter of the universe, $f_{\text{IGM}}(z)$ is the fraction of baryons in the IGM, $H(z) = H_0[\Omega_m(1+z)^3 + (1 - \Omega_m)(1+z)^{3(1+w_0)})^{1/2}$ is the Hubble parameter at redshift $z$ in the wCDM model, and

$$\chi(z) = Y_H \chi_{e,H}(z) + \frac{1}{2} Y_{He} \chi_{e,He}(z)$$

is the free electron number fraction per baryon, with $Y_H = 3/4$ and $Y_{He} = 1/4$ denoting the mass fractions of hydrogen and helium, respectively, and $\chi_{e,H}(z)$ and $\chi_{e,He}(z)$ denoting the ionization fractions of hydrogen and helium, respectively. As both hydrogen and helium are fully ionized at $z < 3$ [37, 53–55], it is reasonable to take $\chi_{e,H}(z) = \chi_{e,He}(z) = 1$ for nearby FRBs. One then has $\chi(z) \simeq 7/8$. Different from previous studies [12, 52, 56], we call equation (2.2) the “average DM$_{\text{IGM}}$” since the IGM is considered to be inhomogeneous and large fluctuation of individual line of sight is expected [14].
In order to extract $\text{DM}_{\text{IGM}}$ of an FRB, one needs to know $\text{DM}_{\text{MW}}$ and $\text{DM}_{\text{host}}$. For a well-localized FRB, $\text{DM}_{\text{MW}}$ can be well derived based on the Galactic electron density models of ref. [57] or ref. [58]. However, it is difficult to derive $\text{DM}_{\text{host}}$ from an individual FRB, because it depends on the type of the host galaxy, the relative orientations of the FRB host and source, and the near-source plasma [59]. Ref. [60] modeled the FRB host DM contribution as a function of redshift by assuming that the rest-frame $\text{DM}_{\text{host}}$ distribution accommodates the evolution of star formation history, i.e., $\text{DM}_{\text{host}}(z) = \text{DM}_{\text{host},0}\sqrt{\frac{\text{SFR}(z)}{\text{SFR}(0)}}$, where $\text{DM}_{\text{host},0}$ is the present value of $\text{DM}_{\text{host}}(z = 0)$ and $\text{SFR}(z) = 0.0157 + 0.118z_{1+0.23}^{-1 + 1.66} \text{M}_ \odot \text{yr}^{-1} \text{Mpc}^{-3}$ is the adopted star formation rate [61, 62]. In addition, while $\text{DM}_{\text{IGM}}$ increases with redshift, $\text{DM}_{\text{host}}$ becomes less significant at high redshifts due to the $(1 + z)$ factor. Therefore, we can roughly subtract $\text{DM}_{\text{host}}$ from $\text{DM}_{\text{obs}}$ and leave its uncertainty $\langle \sigma_{\text{host}} = \sigma_{\text{host},0}\sqrt{\frac{\text{SFR}(z)}{\text{SFR}(0)}} \rangle$ into the total uncertainty $\sigma_{\text{tot}}$, which is the uncertainty of $\text{DM}_{\text{IGM}}$ extracted from $\text{DM}_{\text{obs}}$. It has

$$
\sigma_{\text{tot}} = \left[ \sigma_{\text{obs}}^2 + \sigma_{\text{MW}}^2 + \sigma_{\text{IGM}}^2 + \left( \frac{\sigma_{\text{host}}}{1 + z} \right)^2 \right]^{1/2}.
$$

Based on current observations compiled in the FRB catalog (see ref. [4] and references therein), we adopt an average value $\sigma_{\text{obs}} = 1.5 \text{ pc cm}^{-3}$ as the uncertainty of $\text{DM}_{\text{obs}}$. For high Galactic latitude ($|b| > 10^\circ$) sources, the average uncertainty of $\text{DM}_{\text{MW}}$ is about 10 pc cm$^{-3}$ [63]. As pointed out in ref. [14], for individual FRBs, the detected $\text{DM}_{\text{IGM}}(z)$ may deviate significantly from $\langle \text{DM}_{\text{IGM}} \rangle(z)$ given in equation (2.2). The sightline-to-sightline scatter in $\text{DM}_{\text{IGM}}(z)$ is related to the profile models characterizing the inhomogeneity of the baryon matter in the IGM (see figure 1 of ref. [14]). Here we associate the standard deviation $\sigma_{\text{IGM}}(z)$ derived from the simulations of ref. [14] to $\langle \text{DM}_{\text{IGM}} \rangle(z)$. Due to the effects of inhomogeneities, the ratio $\sigma_{\text{IGM}}/\langle \text{DM}_{\text{IGM}} \rangle$ is very large. Fortunately, if there are enough FRBs from different sightlines but in a narrow redshift bin, their weighted average $\overline{\text{DM}}_{\text{IGM}}(z)$ would be a reasonable approximation of $\langle \text{DM}_{\text{IGM}} \rangle(z)$ [20]. We thus use the data-binning procedure to estimate the derivative $\overline{\text{DM}}_{\text{IGM}}'(z)$ (more on this below). Following ref. [41], we take $\sigma_{\text{host},0} = 30 \text{ pc cm}^{-3}$ as the uncertainty of $\text{DM}_{\text{host},0}$.

Differentiating equation (2.2), we can obtain an expression for the fraction of baryon mass in the IGM:

$$
\tilde{f}_{\text{IGM}}(z) = \frac{H(z)\overline{\text{DM}}_{\text{IGM}}'(z)}{A(1 + z)},
$$

where $A = \frac{21 \cdot 3 \cdot H_0^2}{6 \pi G \rho_{\text{mp}}}$ and $\overline{\text{DM}}_{\text{IGM}}'(z) = d\text{DM}_{\text{IGM}}(z)/dz$ denotes the first derivative with respect to redshift $z$. As suggested in equation (2.5) that the baryon fraction in the IGM, $\tilde{f}_{\text{IGM}}(z)$, can be cosmological-model-independently determined by combining the Hubble expansion rate $H(z)$ and DM measurements. Remarkably, this estimation achieves the evolution of $\tilde{f}_{\text{IGM}}(z)$ from these measurements at any single redshift.

## 3 Simulations and results

In this section, we perform Monte Carlo simulations to test the efficiency of our new model-independent method. Here we adopt the fiducial flat $\Lambda$CDM model with the cosmological parameters derived from the latest Planck data ($H_0 = 67.36 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.315$, and $\Omega_b = 0.0493$) [43]. In order to determine the baryon fraction in the IGM, $\tilde{f}_{\text{IGM}}$, at different
redshifts, one needs to combine two independent measurements of the Hubble parameter $H(z)$ and the dispersion measure $\text{DM}_{\text{IGM}}(z)$ (or the derivative of $\text{DM}_{\text{IGM}}(z)$).

Firstly, we simulate $\text{DM}_{\text{IGM}}(z)$ data of future FRBs. In previous studies, $f_{\text{IGM}}$ is often assumed to be a constant. But in reality, as massive halos become less abundant in the early universe, $f_{\text{IGM}}$ should grow with redshift $[14]$. In our simulations, we parameterize $f_{\text{IGM}}$ as a mildly increasing function of redshift, $f_{\text{IGM}}(z) = f_{\text{IGM},0} + \alpha z/(1+z)$, as ref. $[41]$ did in their treatment. The estimated values of $f_{\text{IGM}}$ are 0.82 and 0.9 at $z \leq 0.4$ and $z \geq 1.5$, respectively $[37, 39]$. Substituting $f_{\text{IGM}}(z = 0.4) = 0.82$ and $f_{\text{IGM}}(z = 1.5) = 0.9$ into the parameterized $f_{\text{IGM}}(z)$ function, one then has $f_{\text{IGM}}(z) = 0.747 + 0.255 z/(1+z)$. Thus, we take $f_{\text{IGM},0} = 0.747$ and $\alpha = 0.255$ as the fiducial values for DM simulations. The redshift distribution of FRBs is assumed as $P(z) \propto z e^{-z}$ in the redshift range $0 < z < 3$, which is a phenomenological model for the redshift distribution of gamma-ray bursts (GRBs) $[20, 64]$. With the mock $z$, we infer the fiducial value of $\text{DM}_{\text{IGM}}^{\text{fid}}$ from equation (2.2). We then add the deviation $\sigma_{\text{tot}}$ in equation (2.4) to the fiducial value of $\text{DM}_{\text{IGM}}^{\text{fid}}$. That is, the simulated DM, $\text{DM}_{\text{IGM}}^{\text{sim}}$, is sampled from the normal distribution $\text{DM}_{\text{IGM}}^{\text{sim}} = N(\text{DM}_{\text{IGM}}^{\text{fid}}, \sigma_{\text{tot}})$. Thanks to the high event rate ($\sim 10^4 \text{sky}^{-1} \text{day}^{-1}$) $[2, 65]$, FRBs are expected to be detected in the tens of thousands by the upcoming Canadian Hydrogen Intensity Mapping Experiment (CHIME) $[66]$ and Hydrogen Intensity and Real-time Analysis experiment (HIRAX) $[67]$ radio arrays. We first run a simulation with 3000 mock FRBs probably detected with CHIME or HIRAX in a few years. Panel (a) of figure 1 shows an example of 3000 simulated $\text{DM}_{\text{IGM}}(z)$ data.

By the time we have a few thousands of FRBs, there might be more $H(z)$ measurements from different observables, such as the Baryon Oscillation Spectroscopic Survey, the proposed Sandage-Loeb observational plan $[68–70]$, and the Atacama Cosmology Telescope. Especially, the Atacama Cosmology Telescope might be able to identify $\sim 2000$ passively evolving galaxies up to $z \approx 1.5$ via the Sunyaev-Zel’dovich effect, and their spectra could be analyzed to yield age determinations that would obtain $\sim 1000 H(z)$ measurements $[47]$. But it is difficult to figure out how many $H(z)$ measurements will actually be yielded by the time that 3000 FRBs are detected. Since the number of currently observational $H(z)$ data is around 40 (see $[71]$ and references therein), we conservatively assume that there will be 50 $H(z)$ data points when we have 3000 FRBs, the redshifts of which are chosen equally within the range $0.1 \leq z \leq 2.1$. The uncertainties of current $H(z)$ measurements are in the region confined by two straight lines $\sigma_+ = 16.87 z + 10.48$ and $\sigma_- = 4.41 z + 7.25$ from above to below, respectively $[72]$. If we believe that future observations of $H(z)$ would also have uncertainties at this level, we can draw their uncertainties $\sigma_H(z)$ from the Gaussian distribution $N(\sigma_0(z), \epsilon(z))$, where $\sigma_0(z) = (\sigma_+ + \sigma_-)/2$ is the mean uncertainty and $\epsilon(z) = (\sigma_+ - \sigma_-)/4$ is chosen so that the probability of $\sigma_H(z)$ falling within the confined area is 95.4% $[72]$. With the fiducial value of $H^{\text{fid}}(z)$ inferred from the flat $\Lambda$CDM model, we sample the simulated Hubble parameter, $H^{\text{sim}}(z)$, according to the Gaussian distribution $H^{\text{sim}}(z) = N(H^{\text{fid}}(z), \sigma_H(z))$. An example of 50 simulated $H(z)$ data (green circles) is presented in figure 1(b).

The remaining issue is to reasonably estimate the derivative of $\text{DM}_{\text{IGM}}(z)$ with respect to $z$, $\text{DM}'_{\text{IGM}}(z)$, from the mock FRB data. In order to maximize the use of all available mock data, we take the following data-binning procedure to estimate $\text{DM}_{\text{IGM}}(z)$ and then to determine $f_{\text{IGM}}(z)$ $[73]$. We split the redshift interval into five bins delimited by the following redshifts: $z = \{0.1, 0.5, 0.9, 1.3, 1.7, 2.1\}$. This choice was made for two main reasons. First,

\[^1\text{http://www.sdss3.org/surveys/boss.php.}\]
\[^2\text{http://www.physics.princeton.edu/act/index.html.}\]
such a large uncertainty of $\Delta \text{DM}_{\text{IGM}}(z)$, $\sigma_{\text{tot}}$ (see figure 1(a)), is a serious challenge for using FRBs as a cosmic probe, but it is feasible by using the weighted average $\overline{\Delta \text{DM}_{\text{IGM}}}(z)$ when there are sufficient FRBs in a narrow redshift bin. Second, we do not want to have redshift bins that are too large, in order for the assumption that $\Delta \text{DM}_{\text{IGM}}(z)$ and $H(z)$ be constant inside each bin to be still reasonable. The resulting bins are listed in table 1. In each bin, we then calculate the weighted average of all available $H(z)$ through

$$\overline{H}(z) = \frac{\sum_i H(z_i)/\sigma_{H,i}^2}{\sum_i 1/\sigma_{H,i}^2}.$$  

(3.1) 

The corresponding uncertainty on $\overline{H}(z)$ can be obtained from

$$\sigma_{\overline{H}(z)}^2 = \frac{1}{\sum_i 1/\sigma_{H,i}^2}.$$  

(3.2) 

---

**Figure 1.** Example of the simulations for the case of 3000 simulated FRBs and 50 simulated $H(z)$ data. Panel (a) shows 3000 mock $\Delta \text{DM}_{\text{IGM}}$ data (green circles) and the theoretical $\Delta \text{DM}_{\text{IGM}}(z)$ function (dashed line). Panel (b) shows 50 mock $H(z)$ data (green circles), five binned mock $H(z)$ data (blue dots), and the theoretical $H(z)$ function (dashed line). Panels (c) and (d) show the final constraints on $\Delta \text{DM}_{\text{IGM}}$ and $f_{\text{IGM}}$ at different redshifts (blue dots) derived from these mock data with the binning method, respectively. The theoretical $\Delta \text{DM}_{\text{IGM}}(z)$ and $f_{\text{IGM}}(z)$ functions (dashed lines) are also displayed for comparison. Horizontal error bars in Panels (b), (c), and (d) correspond to the ranges of each redshift bin.
bins, taking (see figures 1(b) and 1(c)), the precision of the derived dots) are well consistent with theoretical functions (dashed lines). This suggests that the mean square of uncertainties. The final constraints on DM avoid the randomness of simulation, we repeat the simulation process 1000 times for each FRB redshifts of the corresponding sub-bins, each sub-bin, obtaining this binning. To compute the derivative DM, we adopt the following formula as its discrete approximation:

\[
\text{DM}'(\bar{z}) \approx \frac{\text{DM}(\bar{z} + \Delta z) - \text{DM}(\bar{z})}{\Delta z},
\]

(3.3)

In order to apply this formula to our FRB data, we divide each bin into two equal sub-bins, taking \( \bar{z}_H \) as the splitting point. We then compute the weighted average \( \overline{\text{DM}} \) in each sub-bin, obtaining \( \overline{\text{DM}}_\text{left} \) and \( \overline{\text{DM}}_\text{right} \). We assign \( \overline{\text{DM}}_\text{left} \) and \( \overline{\text{DM}}_\text{right} \) to the average redshifts of the corresponding sub-bins, \( \bar{z}_\text{left} \) and \( \bar{z}_\text{right} \), and finally compute the approximated derivative as

\[
\text{DM}'(\bar{z}) = \frac{\overline{\text{DM}}_\text{right} - \overline{\text{DM}}_\text{left}}{\bar{z}_\text{right} - \bar{z}_\text{left}}.
\]

(3.4)

Having obtained \( \overline{\text{H}}(\bar{z}) \) and \( \text{DM}'(\bar{z}) \), we can finally compute \( f(\bar{z}) \) at each redshift \( \bar{z} \) through equation (2.5), where, as already said, \( \text{DM}(\bar{z}) \) are computed from FRB data as explained above and \( \overline{\text{H}}(\bar{z}) \) come from Hubble parameter measurements. To avoid the randomness of simulation, we repeat the simulation process 1000 times for each FRB + \( H(z) \) data sets and draw the means of DM and \( f(\bar{z}) \) as well as their corresponding root mean square of uncertainties. The final constraints on DM and \( f(\bar{z}) \) (blue dots) together with their 1σ error bars are displayed in panels (c) and (d) of figure 1, respectively. Because of the poor quality of mock data at higher redshifts, the errors become larger. For a comparison, we also give the theoretical DM and \( f(\bar{z}) \) (functions (dashed lines) in panels (c) and (d) of figure 1, respectively. It is found that the final derived DM and \( f(\bar{z}) \) data (blue dots) are well consistent with theoretical functions (dashed lines). This suggests that the discrete DM and \( f(\bar{z}) \) data derived from mock FRB + \( H(z) \) data with the binning method are reliable. Additionally, we find that, from 3000 simulated FRBs and 50 simulated \( H(z) \) data points, the unbiased constraints on the fraction of baryon mass in IGM at different redshifts are \( f(\bar{z} = 0.3) = 0.808 \pm 0.076, f(\bar{z} = 0.7) = 0.852 \pm 0.089, f(\bar{z} = 1.1) = 0.893 \pm 0.109, f(\bar{z} = 1.5) = 0.896 \pm 0.131, \) and \( f(\bar{z} = 1.9) = 0.911 \pm 0.151, \) respectively.

The mean relative error of these five \( f(\bar{z}) \) data is \( \langle \sigma_{\text{DM}}/f(\bar{z}) \rangle \approx 12.6\%. \) Note that as the relative errors of DM are much larger than those of \( H(z) \) at the same redshifts (see figures 1(b) and 1(c)), the precision of the derived \( f(\bar{z}) \) is strongly dominated by

| Bins | \( z_{\text{min}} \) | \( z_{\text{max}} \) | \( \bar{z} \) | \( f_{\text{IGM}}(\bar{z}) \) | \( f_{\text{IGM}}(\bar{z}) \) | \( f_{\text{IGM}}(\bar{z}) \) |
|------|-------------|-------------|-----|-----------------|-----------------|-----------------|
| 1    | 0.1         | 0.5         | 0.3 | 0.808 ± 0.076   | 0.808 ± 0.054   | 0.807 ± 0.038   |
| 2    | 0.5         | 0.9         | 0.7 | 0.852 ± 0.089   | 0.852 ± 0.064   | 0.851 ± 0.045   |
| 3    | 0.9         | 1.3         | 1.1 | 0.893 ± 0.109   | 0.892 ± 0.077   | 0.891 ± 0.054   |
| 4    | 1.3         | 1.7         | 1.5 | 0.896 ± 0.131   | 0.896 ± 0.091   | 0.896 ± 0.064   |
| 5    | 1.7         | 2.1         | 1.9 | 0.911 ± 0.151   | 0.911 ± 0.107   | 0.911 ± 0.076   |

Note: \( z_{\text{min}} \) and \( z_{\text{max}} \) correspond to the left and right edges of each redshift bin, respectively. \( \bar{z} \) represents the mean redshift of the bin.

Table 1. Model-independent Estimates of the Fraction of Baryon Mass in the IGM from FRB and \( H(z) \) data. Note: \( z_{\text{min}} \) and \( z_{\text{max}} \) correspond to the left and right edges of each redshift bin, respectively. \( \bar{z} \) represents the mean redshift of the bin.

We assign these values to the mean redshifts of different \( H(z) \) that contained in each bin, i.e., \( \bar{z}_H = \{0.3, 0.7, 1.1, 1.5, 1.9\} \). In figure 1(b) we show \( \overline{H}(\bar{z}_H) \) (blue dots) obtained with this binning. To compute the derivative DM, we adopt the following formula as its discrete approximation:

\[
\text{DM}'(\bar{z}) \approx \frac{\text{DM}(\bar{z} + \Delta z) - \text{DM}(\bar{z})}{\Delta z}.
\]

(3.3)
the uncertainty of $\Delta M_{\text{IGM}}(z_H)$. That is, the chosen number of $H(z)$ measurements has little impact on our results.

At this point, it is interesting to compare our forecast result with the other model-independent method. Ref. [41] showed that a cosmology-independent estimate of the value of $f_{\text{IGM}}$ at $z = 1.5$ with a $\sim 14.0\%$ uncertainty can be obtained by using 500 FRBs with the measurements of both DM and $d_L$ (i.e., the $d_L/DM$ method). The relative uncertainty on the determined $f_{\text{IGM}}(z = 1.5)$ is at the level of $\sigma_{f_{\text{IGM}}}/f_{\text{IGM}} \simeq 14.6\%$ using 3000 FRBs with our new method, which is almost as well as that of using 500 FRBs with the $d_L/DM$ method. Though our method needs six times the number of FRBs to achieve the same precision, the joint measurements of DM and $d_L$ suggested by the $d_L/DM$ method may not be easy in practice. It is not clear what fraction of FRBs will actually satisfy the joint measurements. Most importantly, our method provides a new cosmology-independent way to constrain $f_{\text{IGM}}(z)$.

To better represent how effective our method might be with more FRB and $H(z)$ measurements, we also carry out a similar analysis by considering the case of 6000 simulated FRBs and 100 simulated $H(z)$ data. Simulations for $DM_{\text{IGM}}$ and $H(z)$ are shown in panels (a) and (b) of figure 2, respectively. The final constraints on $DM'_{\text{IGM}}$ and $f_{\text{IGM}}$ at different redshifts derived from these mock data with the binning method are presented in panels (c) and (d) of figure 2, respectively. The mean relative error of $f_{\text{IGM}}$ in five bins is $\sim 8.9\%$. Finally, we investigate the case of 12000 simulated FRBs and 200 simulated $H(z)$ data. Simulations for $DM_{\text{IGM}}$ and $H(z)$ are shown in panels (a) and (b) of figure 3, respectively. Corresponding constraints on $DM'_{\text{IGM}}$ and $f_{\text{IGM}}$ are presented in panels (c) and (d) of figure 3, respectively. The mean relative error of $f_{\text{IGM}}$ is $\sim 6.3\%$. The resulting constraints on the evolution of $f_{\text{IGM}}$ for different FRB + $H(z)$ cases are summarized in table 1. As expected, the uncertainty of $f_{\text{IGM}}$ is gradually reduced with the increasing number of FRBs and $H(z)$. These results imply that the evolution of $f_{\text{IGM}}$ can be unbiasedly inferred in a model-independent manner when $\sim O(10^3)$ FRBs are detected.

To understand how the quality of simulated data affects the constraints, we perform parallel comparative analyses of the mock data sets by reducing the original errors by a factor of 0.5 and 0.25, respectively. We also assume that $N_{\text{FRB}} = 3000$ and $N_{H(z)} = 50$. For the analysis with a half of the errors, as shown in table 2 and the left panel of figure 4, we obtain $\sigma_{f_{\text{IGM}}}/f_{\text{IGM}} \simeq 6.4\%$. For the case with a quarter of the errors, as shown in table 2 and the right panel of figure 4, we obtain $\sigma_{f_{\text{IGM}}}/f_{\text{IGM}} \simeq 3.3\%$. One can see that the precision of $f_{\text{IGM}}$ can be significantly improved with the increasing quality of FRBs and $H(z)$. Additionally, increasing the quality of future FRB and $H(z)$ data is more important than increasing their quantity.

In all the above simulations, we assume that the redshift distribution of FRBs satisfies $P(z) \propto z e^{-z}$ [20, 64], a phenomenological model for GRB redshift distribution. While the redshift distribution of $H(z)$ measurements is assumed to be uniform. Since the precision of the derived $f_{\text{IGM}}(z)$ is mainly dominated by the uncertainty of $\Delta M'_{\text{IGM}}(z)$, different $z$ distributions of $H(z)$ measurements would not affect the scatter of $f_{\text{IGM}}(z)$, but FRB redshift distribution might be. The true $z$ distribution of FRBs depends on the corresponding progenitor system(s) of FRBs, which can take different empirical formulae (e.g., for the $z$ distributions tracing the history of star formation or mergers of double compact stars, see approximate analytical forms in ref. [74]). In order to test how the $z$ distribution of FRBs affects our results, we perform simulations with two different progenitor models. We also assume that $N_{\text{FRB}} = 3000$ and $N_{H(z)} = 50$ with the original errors. For
Figure 2. Same as figure 1, but for the case of 6000 simulated FRBs and 100 simulated $H(z)$ data.

Table 2. $f_{IGM}(z)$ estimations obtained from the mock data sets of 3000 FRBs and 50 $H(z)$ but with an increase in their quality.

| Bins | $z_{min}$ | $z_{max}$ | $\bar{z}$ | $f_{IGM}(z)$ with Errors Reduced by 50% | $f_{IGM}(z)$ with Errors Reduced by 75% |
|------|----------|----------|----------|-------------------------------------|-------------------------------------|
| 1    | 0.1      | 0.5      | 0.3      | 0.808 ± 0.038                       | 0.808 ± 0.020                       |
| 2    | 0.5      | 0.9      | 0.7      | 0.851 ± 0.045                       | 0.851 ± 0.024                       |
| 3    | 0.9      | 1.3      | 1.1      | 0.892 ± 0.055                       | 0.892 ± 0.029                       |
| 4    | 1.3      | 1.7      | 1.5      | 0.896 ± 0.066                       | 0.896 ± 0.034                       |
| 5    | 1.7      | 2.1      | 1.9      | 0.911 ± 0.076                       | 0.911 ± 0.039                       |
|      |          |          |          | $\langle \sigma_{f_{IGM}/f_{GM}} \rangle$ 6.4% | $\langle \sigma_{f_{IGM}/f_{GM}} \rangle$ 3.3% |

Table 2. $f_{IGM}(z)$ estimations obtained from the mock data sets of 3000 FRBs and 50 $H(z)$ but with an increase in their quality.

the $z$ distribution tracing star formation, we adopt the approximate analytical model derived by ref. [75]: $P(z) = [ (1 + z)^{3.4\eta} + (\frac{1+z}{5000})^{-0.3\eta} + (\frac{1+z}{9})^{-3.5\eta} ]^{1/\eta}$, where $\eta = -10$. As shown in table 3 and the left panel of figure 5, now we obtain $\langle \sigma_{f_{GM}/f_{GM}} \rangle \approx 13.7\%$. For the $z$ distribution tracing compact star mergers, we adopt the analytical model $P(z) =$
\[ (1 + z)^5.0\eta + \left(\frac{1 + z}{1.17}\right)^{0.87\eta} + \left(\frac{1 + z}{1.05}\right)^{-8.0\eta} + \left(\frac{1 + z}{1.05}\right)^{-20.5\eta}\]^{1/\eta}, \text{where } \eta = -2 \ [76]. \ As shown in table 3 and the right panel of figure 5, now we obtain \( \langle \sigma_{f_{\text{IGM}}} / f_{\text{IGM}} \rangle \simeq 12.3\% \). By comparing these constraints with those obtained from the phenomenological GRB model (see figure 1(d)), we can conclude that the explicit form of \( z \) distribution does not affect the global shape of the \( f_{\text{IGM}} - z \) plot we are modeling, but affects the scatter of \( f_{\text{IGM}}(z) \) to some extent.

### 4 Summary and discussion

The measured DM and \( z \) of FRBs have been applied to study cosmology, but one happens to encounter the strong degeneracy between cosmological parameters and the very uncertain baryon fraction in the IGM, \( f_{\text{IGM}} \). In this paper, we propose that combining the FRB and Hubble parameter \( H(z) \) data in similar redshift ranges offers a new model-independent way to constrain the evolution of \( f_{\text{IGM}}(z) \). Based on the DM_{\text{IGM}}(z) data derived from FRBs, we use the data-binning technique to estimate the derivative of DM_{\text{IGM}}(z) with respect to \( z, \) DM'_{\text{IGM}}(z). By combining \( H(z) \) and DM'_{\text{IGM}}(z) at the same redshifts, we can directly determine \( f_{\text{IGM}}(z) \). Through Monte Carlo simulations, we prove that the evolution of \( f_{\text{IGM}}(z) \) can be well inferred from a sample of FRBs using our method.
Figure 4. $f_{IGM}(z)$ estimations obtained from the mock data sets of 3000 FRBs and 50 $H(z)$, but with a half of (left panel) and a quarter of (right panel) the original errors, respectively.

| Bins | $z_{min}$ | $z_{max}$ | $\bar{z}$ | star formation $f_{IGM}(z)$ | compact star mergers $f_{IGM}(z)$ |
|------|-----------|-----------|-----------|-------------------------------|----------------------------------|
| 1    | 0.1       | 0.5       | 0.3       | $0.811 \pm 0.107$            | $0.810 \pm 0.089$                |
| 2    | 0.5       | 0.9       | 0.7       | $0.852 \pm 0.109$            | $0.852 \pm 0.098$                |
| 3    | 0.9       | 1.3       | 1.1       | $0.892 \pm 0.113$            | $0.893 \pm 0.107$                |
| 4    | 1.3       | 1.7       | 1.5       | $0.897 \pm 0.128$            | $0.895 \pm 0.114$                |
| 5    | 1.7       | 2.1       | 1.9       | $0.911 \pm 0.143$            | $0.912 \pm 0.129$                |
|      |           |           |           | $\langle \sigma_{f_{IGM}} / f_{IGM} \rangle$ | 13.7%                            |

Table 3. $f_{IGM}(z)$ estimations obtained from the mock data sets of 3000 FRBs and 50 $H(z)$ but with different redshift distributions of FRBs.

The key issue in the idea of constraining $f_{IGM}(z)$, however, is measuring the redshifts of a large sample of FRBs. Essentially, the redshifts of FRBs can be measured by identifying their host galaxies or counterparts in other electromagnetic wavelengths. With the help of very-long-baseline interferometry observations, one may precisely localize their host galaxies, especially for dedicated observations on the repeating FRBs. By promptly performing multi-wavelength follow-up observations after the FRB trigger, one may catch the associated gamma-ray bursts [77] or any other bright counterparts [6, 78–80]. It is encouraging that the upcoming CHIME and HIRAX radio arrays could detect $\sim 10^4$ FRBs per year [66, 67]. In the next few years, a large sample of FRBs with redshift measurements may become available, so the model-independent analysis of $f_{IGM}(z)$ proposed here may be carried out.

As described above, given a cosmological model, one can directly obtain estimates of $f_{IGM}(z)$ by using the usual DM–$z$ way. To investigate the importance of developing cosmology-free estimators, we also run the usual DM–$z$ method to constrain $f_{IGM}(z)$. We allow the parameters $f_{IGM,0}$ and $\alpha$ of the parameterized $f_{IGM}(z)$ function to be free along with the matter energy density $\Omega_m$ and the dark energy equation-of-state $w_0$ in the $w$CDM
model, and optimize these four free parameters by minimizing the \( \chi^2 \) statistic, i.e.,

\[
\chi^2_{\text{tot}} = \chi^2_{\text{DM}} + \chi^2_{H},
\]

where

\[
\chi^2_{\text{DM}}(\mathbf{p}_1, \mathbf{p}_2) = \sum_i \left[ \frac{\text{DM}^\text{sim}_{\text{IGM}}(z_i) - \text{DM}^\text{wCDM}_{\text{IGM}}(z_i; \mathbf{p}_1, \mathbf{p}_2)}{\sigma_{\text{tot},i}} \right]^2
\]

and

\[
\chi^2_{H}(\mathbf{p}_2) = \sum_i \left[ \frac{H^\text{sim}(z_i) - H^{w\text{CDM}}(z_i; \mathbf{p}_2)}{\sigma_{H,i}} \right]^2.
\]

Here \( \mathbf{p}_1 = \{f_{\text{IGM},0}, \alpha\} \) and \( \mathbf{p}_2 = \{\Omega_m, w_0\} \) stand for the parameters of the parameterized \( f_{\text{IGM}}(z) \) function and of the cosmological model, respectively. \( \text{DM}^\text{wCDM}_{\text{IGM}}(z) \) and \( H^{w\text{CDM}}(z) \) denote the theoretical values calculated from the concerning parameters, \( \text{DM}^\text{sim}_{\text{IGM}}(z) \) and \( H^\text{sim}(z) \) are the simulated data as explained earlier in section 3, and \( \sigma_{\text{tot}} \) and \( \sigma_H \) correspond to the original errors of \( \text{DM}^\text{sim}_{\text{IGM}}(z) \) and \( H^\text{sim}(z) \), respectively. Here the redshift distribution of FRBs is assumed to be the phenomenological model for GRB redshift distribution. To ensure the final constraints are unbiased, we also repeat the simulation process 1000 times for each FRB + \( H(z) \) data set using different noise seeds. In the left panel of figure 6, we display the confidence regions of \( f_{\text{IGM},0}, \alpha, \Omega_m, w_0 \) in the \( w\text{CDM} \) model determined with the usual \( \text{DM} - z \) (model-dependent) method for 3000 simulated FRBs + 50 simulated \( H(z) \) data. The contours show that at the 1\( \sigma \) confidence level, the best fits are \( f_{\text{IGM},0} = 0.739^{+0.044}_{-0.047}, \alpha = 0.286^{+0.106}_{-0.104}, \Omega_m = 0.325^{+0.041}_{-0.041}, w_0 = -1.041^{+0.211}_{-0.367} \). With the constraint results of \( f_{\text{IGM},0} \) and \( \alpha \), the derived \( f_{\text{IGM}}(z) \) function (solid line) with 1\( \sigma \) confidence region (shaded area) is plotted in the right panel of figure 6, where we also present the \( f_{\text{IGM}}(z) \) constraints at different redshifts (blue dots) derived from our model-independent method for the case of 3000 simulated FRBs and 50 simulated \( H(z) \) data for the sake of comparison. One can see that the derived constraints on \( f_{\text{IGM}}(z) \) from our model-independent method are somewhat

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**Figure 5.** \( f_{\text{IGM}}(z) \) estimations obtained from the mock data sets of 3000 FRBs and 50 \( H(z) \), but with the redshift distributions of FRBs tracing star formation (left panel) and compact star mergers (right panel), respectively.
weaker than those of the usual DM–z method. But it is worth pointing out that the $f_{\text{IGM}}(z)$ constraints obtained from the usual DM–z method would become worse when considering the evolution of the dark energy equation-of-state. What’s more, the constraints on the evolving $f_{\text{IGM}}(z)$ with our method are more robust and widely applicable, as they do not depend on the cosmological model.

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