Search for the correlations between host properties and $\text{DM}_{\text{host}}$ of fast radio bursts: constraints on the baryon mass fraction in IGM

Hai-Nan Lin$^{1,1)}$  Xin Li$^1$  Li Tang$^2$

$^1$ Department of Physics, Chongqing University, Chongqing 401331, China
$^2$ Department of Math and Physics, Mianyang Normal University, Mianyang 621000, China

Abstract: The application of fast radio bursts (FRBs) as probes to investigate astrophysics and cosmology requires the proper modelling of the dispersion measures of Milky Way ($\text{DM}_{\text{MW}}$) and host galaxy ($\text{DM}_{\text{host}}$). $\text{DM}_{\text{MW}}$ can be estimated using the Milky Way electron models, such as NE2001 model and YMW16 model. However, $\text{DM}_{\text{host}}$ is hard to model due to limited information on the local environment of FRBs. In this paper, using 17 well-localized FRBs, we search for the possible correlations between $\text{DM}_{\text{host}}$ and the properties of host galaxies, such as the redshift, the stellar mass, the star-formation rate, the age of galaxy, the offset of FRB site from galactic center, and the half-light radius. We find no strong correlation between $\text{DM}_{\text{host}}$ and any of the host property. Assuming that $\text{DM}_{\text{host}}$ is a constant for all host galaxies, we constrain the fraction of baryon mass in the intergalactic medium today to be $f_{\text{IGM},0} = 0.78^{+0.15}_{-0.19}$. If we model $\text{DM}_{\text{host}}$ as a log-normal distribution, however, we obtain a larger value, $f_{\text{IGM},0} = 0.83^{+0.12}_{-0.17}$. Based on the limited number of FRBs, no strong evidence for the redshift evolution of $f_{\text{IGM}}$ is found.

Key words: fast radio bursts – intergalactic medium – cosmological parameters

PACS: 98.54.Gr, 98.58.-w, 98.80.-k

1 Introduction

Fast radio bursts (FRBs) are short-duration and luminous radio transients happening in the Universe, see e.g. Refs. [1–4] for recent review. In 2007, Lorimer et al. [5] reanalyzed the archive data of the Parkes 64-m telescope recorded in 2001, and found an extraordinary radio pulse, which is now named FRB 010724. This phenomenon is for long time not attracted much attention until four other bursts were discovered several years later [6]. Thereafter, FRBs have attracted great interests within the astronomy community. The observed dispersion measures (DM) of most FRBs significantly exceed the contribution from the Milky Way, hinting that they occur at cosmological distance. The cosmological origin was further confirmed as the identification of host galaxy and the direct measurement of redshift [7–9]. There are in general two kinds of FRBs, i.e., the repeaters and non-repeaters. Most of the repeating sources found by the Canadian Hydrogen Intensity Mapping Experiment (CHIME) telescope only repeated two or three times for each source [10]. There is one exception, FRB 121102, from which thousands of bursts have been observed by different telescopes [11–16]. Statistical analysis of FRB 121102 shows that the burst energies and waiting times follow the power-law distribution [17, 19], hinting that the explosion of repeating FRBs may be a self-organized criticality process. Further analysis shows that the bursts of FRB 121102 can be more well fitted by the bent power-law and are scale-invariant [20], implying that there are some similarities between FRBs and soft gamma repeaters (SGRs) [21, 22]. As the FAST telescope extensively increases the bursts from FRB 121102, a bimodal burst energy distribution is found [16]. Repeating FRBs usually have no regular period, but the CHIME/FRB Collaboration [23] found an unexpected long period of 16.35 days with an approximately 4-day active window in FRB 180916.J0158+65. The physical mechanism of FRBs is still under extensive debate. Several theoretical models have been proposed to explain the explosion of FRBs [24–32]. The most popular models involve one or two compact objects such as neutron star and magnetar in the central of FRB source. The recently discovered burst FRB200428, which was associated with a Galactic magnetar, strongly supports the magnetar origin of at least some FRBs [33, 34].

FRBs are very luminous and they are expected to be detectable in the most ideal case up to redshift $z \sim 15$ for sensitive radio telescopes such as the Five-hundred-meter Aperture Spherical radio Telescope [35]. There-
fore, FRBs could be used as probes to study the high-redshift cosmology. For example, Munoz et al. [36] pointed out that the strongly lensed FRBs can be used to probe the compact dark matter in the Universe. Yu & Wang [37] showed that FRBs can be used to measure the cosmic proper distance. Li et al. [38] proposed that the strongly lensed repeating FRBs can tightly constrain the Hubble constant and cosmic curvature. Walters et al. [39] showed that FRBs can be used to constrain the baryon matter density. Li et al. [40, 41] showed that FRBs can be used to constrain the fraction of baryon mass in the intergalactic medium (IGM). Xu & Zhang [42] proposed that FRBs can be used to probe the intergalactic turbulence. Wu et al. [43] proposed that FRBs can be used to model-independently measure the Hubble parameter. Qiang et al. [44] showed that FRBs can be used to test the possible cosmic anisotropy. Pagano & Fronenberg [45] pointed out that the highly dispersed FRBs can be used to constrain the epoch of cosmic reionization. Pearson et al. [46] showed that strongly lensed repeating FRBs can be used as the probes to search for gravitational waves. In addition, FRBs can be used as the probes to test the fundamental physics, such as constraining the Lorentz invariance violation, the weak equivalent principle and the photon mass [47–51].

The applications of FRBs as the probes to investigate the Universe often involve the observation of dispersion measure (DM, see the next section for detail), which depends on the electron distribution alone the line of sight. The total DM of an extragalactic FRB consists of three parts: the Milky Way interstellar medium (ISM), the Milky Way halo, the IGM and the host galaxy. The electron distribution in the Milky Way ISM has been modelled from pulsar observation, for example, the TC93 model [52], NE2001 model [53], YMW16 model [54], and so on. The DM of Milky Way halo can be reasonably estimated [55]. Therefore, the DM contributed by the Milky Way can be subtracted from the total DM. The IGM contribution is proportional to the electron density in IGM, which depends on the density and ionization rate of baryon matter in IGM. It is this part that contains the information of Universe and can be used to investigate the cosmology. The difficulty is the that the host galaxy contribution to DM is hard to model. This is because, although there are some observations [56–58], we still have poor knowledge on the local environment of majority of FRBs. Several factors may affect the DM of host galaxy, such as the galaxy type, the inclination angle of host galaxy, the mass of host galaxy, the star-formation rate, the offset of FRB site from galactic center, just to name a few. FRBs have been observed in different types of galaxies, and there is no unique way to model the DM of host galaxy. For example, Xu & Han [59] modelled the DM of host galaxy by assuming that the host galaxies are similar to the Milky Way or M31. Luo et al. [60] assumed that the distribution of DM of host galaxy follows the star-formation rate (SFR). Because there is a lack of direct measurement on the DM of host galaxy, reasonably extracting it from observation is of great importance. Yang & Zhang [61] pointed out that the average DM of host galaxy can be obtained statistically from a large sample of FRBs with redshift measurements. However, this method requires the reconstruction of the first order derivative curves from discrete data points, which will introduce large uncertainty.

Up to now, hundreds of FRBs are reported [62–63]. However, there are only 19 well-localized FRBs (except for the Galactic FRB200428) which have direct identification of host galaxies [64]. All of the 19 well-localized FRBs have direct measurement of redshift (either spectroscopic redshift or photometric redshift), which falls in the redshift range \( z \in (0.0039, 0.66) \). The properties of the host galaxies, such as the stellar mass, the age of galaxy, the SFR, the half-light radius, and so on, have been observed in detail by follow-up observations. In this paper, based on the well-localized FRBs, we investigate the DM of host galaxy statistically. The rest parts of this paper are arranged as follows: In Section 2, we search for the possible correlations between DM_{host} and the host galaxy properties. In Section 3, assuming a constant value of DM_{host}, we use the well-localized FRBs to constrain the fraction of baryon mass in IGM. Finally, discussions and conclusions are given in Section 4.

### 2 The DM of host galaxy

The propagation of electromagnetic waves in cold plasma leads to the frequency-dependent group velocity of light. Therefore, photons with different energy traveling the same distance cost different time. This plasma effect, although is tiny, can be detectable if cumulated at cosmological distance. The time delay between low- and high-energy photons propagating from a distant source to earth is proportional to a quantity called dispersion measure (DM), which is the integral of electron density along the photon path [64]. The plasma effect is negligible for the visible light, but it is important for the radio waves in e.g. FRBs. The DM of an FRB can be obtained from the time-resolved spectrum. The observed DM of an extragalactic FRB consists of three parts: the contributions from Milky Way, intergalactic medium (IGM) and host galaxy [65–66].

\[
DM_{\text{obs}} = DM_{\text{MW}} + DM_{\text{IGM}} + \frac{DM_{\text{host}}}{1 + z},
\]  

*The FRB Host Database [http://frbhosts.org/](http://frbhosts.org/)*
where \( DM_{\text{host}} \) is the DM of host galaxy in the source frame, \( z \) is the redshift of host galaxy, and the factor \( 1 + z \) accounts for the cosmic dilation.

The DM of Milky Way can be divided into two components: the contributions from Milky Way interstellar medium (ISM) and Milky Way halo \[^{55}\].

\[
DM_{\text{MW}} = DM_{\text{MW, ISM}} + DM_{\text{MW, halo}}. \tag{2}
\]

Given the sky position of an FRB, \( DM_{\text{MW, ISM}} \) can be well constrained by modelling the electron distribution in the Milky Way ISM from pulsar observations, such as the NE2001 model \[^{53}\] and the YMW16 model \[^{54}\]. The Milky Way halo contribution is not well constrained yet, but it is expected to be in the range 50–100 pc cm\(^{-3}\) \[^{55}\].

The DM of IGM, assuming that both hydrogen and helium are fully ionized, can be written as \[^{65, 67}\]

\[
DM_{\text{IGM}}(z) = \frac{21cH_0\rho_0}{64\pi G m_p} \int_0^z \frac{f_{\text{IGM}}(z)(1+z)}{\sqrt{\Omega_m(1+z)^3+\Omega_{\Lambda}}} dz, \tag{3}
\]

where \( m_p \) is the proton mass, \( f_{\text{IGM}}(z) \) is the fraction of baryon mass in IGM, \( H_0 \) is the Hubble constant, \( G \) is the Newtonian gravitational constant, \( \Omega_m \) is the normalized baryon matter density, \( \Omega_m \) and \( \Omega_{\Lambda} \) are the normalized densities of matter (includes baryon matter and dark matter) and dark energy at present day, respectively. Note that equation (3) should be interpreted as the mean contribution from IGM. The actual value would deviate from equation (3) causing by e.g. the fluctuation of baryon matter, the incomplete ionization of hydrogen or helium, etc.

The DM of host galaxy is difficult to model due to the lack of observation on the local environment of FRB sources. However, given that the DM of Milky Way is modeled, and the DM of IGM is predicted by a specific cosmological model, we can invert equation (1) to obtain the DM of host galaxy,

\[
DM_{\text{host}} = (1 + z)(DM_{\text{obs}} - DM_{\text{MW}} - DM_{\text{IGM}}). \tag{4}
\]

The uncertainties of \( DM_{\text{host}} \) can be calculated using the standard error propagation formula,

\[
\sigma_{\text{host}} = (1+z)\sqrt{\sigma_{\text{obs}}^2 + \sigma_{\text{MW}}^2 + \sigma_{\text{IGM}}^2}, \tag{5}
\]

where the uncertainty on \( DM_{\text{MW}} \) is propagated from the uncertainties on \( DM_{\text{MW, ISM}} \) and \( DM_{\text{MW, halo}} \),

\[
\sigma_{\text{MW}} = \sqrt{\sigma_{\text{MW, ISM}}^2 + \sigma_{\text{MW, halo}}^2}. \tag{6}
\]

Note that the DM contribution from host galaxy also consists of ISM and halo parts. Without other observations, these two parts are completely degenerated. Therefore, we don’t distinguish them and treat them as a whole.

So far there are in total 19 extragalactic FRBs that are well localized and host identified. Among the 19 FRBs, we omit FRB20200120E and FRB20190614D. The repeating burst FRB20200120E is localized to the direction of M81, and its redshift is measured to be \(-0.0001 \[^{66}\]. This burst is very close to the Milky Way and the peculiar velocity dominates over the Hubble flow, so it is inappropriate to be used to study the cosmology. The non-repeating burst FRB20190614D has a photometric redshift \( z \approx 0.6 \[^{69}\], but there is a lack of detailed observation on the host galaxy. Therefore, we only consider the rest 17 FRBs, whose properties are listed in Table 1. Among these 17 FRBs, 6 bursts are repeating and 11 bursts are non-repeating. All the FRBs have well-measured sky position (RA, Dec), the observed dispersion measure (\( DM_{\text{obs}} \)), the spectroscopic redshift (\( z \)), the stellar mass of host galaxy (\( M_\star \)), the star formation rate (SFR), the mass-weighted age of host galaxy (Age), the offset of FRB site from galactic center (Offset), and the half-light radius of host galaxy (\( R_{\text{eff}} \)). We calculate the DM of the Milky Way ISM using two different models, i.e. the NE2001 model and YMW16 model, and list the results in the fifth and sixth columns of Table 1 respectively.

Figure 1 shows the sky positions of 17 FRBs in the Galactic coordinates. The repeaters and non-repeaters are denoted in red and blue dots, respectively. Four repeaters (FRB20121102A, FRB20180301A, FRB20180916B and FRB20201124A) locate at low Galactic latitudes, so the Milky Way ISM contribution to DM is very large (see Table 1). The rest 13 bursts locate at high Galactic latitudes (|\( b \)| > 30°), hence the Milky Way ISM contribution to DM is relatively small, with the mean values \( DM_{\text{MW, ISM}} \approx 42 \) and 32 pc cm\(^{-3}\) for NE2001 model and YMW16 model, respectively. Three bursts (FRB20190102C, FRB20190611B and FRB20190711A) have very close sky orientation, hence their Milky Way ISM contributions to DM are similar with each other. We note that \( DM_{\text{MW, ISM}} \) strongly depends on the Milky Way electron models, especially for low-latitude FRBs. At low Galactic latitude, the YMW16 model predicts a much larger value of \( DM_{\text{MW, ISM}} \) than the NE2001 model.

We calculate the DM of host galaxy, \( DM_{\text{host}} \), by subtracting \( DM_{\text{MW}} \) (including Milky Way ISM and halo contributions) and \( DM_{\text{IGM}} \) from the observed \( DM_{\text{obs}} \) according to equation (1). The \( DM_{\text{IGM}} \) term is calculated according to equation (3) using the Planck 2018 parameters, \( H_0 = 67.4 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_m = 0.315 \), \( \Omega_{\Lambda} = 0.685 \).
Table 1. The properties of host galaxies of 17 well-localized FRBs.

| FRBs     | RA     | Dec    | DM_{obs} | NE2001 | YMW16 | z    | M_{s}  | SFR  | Age  | Offset | Repe   | References |
|----------|--------|--------|----------|---------|--------|------|--------|------|-------|--------|---------|------------|
|          | [°]    | [°]    | [pc cm^{-3}] | [pc cm^{-3}] | [pc cm^{-3}] |   | [10^{5}M_{\odot}] | [M_{\odot}/yr] | [Myr] | [kpc] | [kpc] |          |            |
| 20121102A | 82.99  | 33.15  | 557.00   | 157.60  | 287.62 | 0.1927| 0.14±0.07 | 0.15±0.04 | 257.7 | 0.8±0.1 | 2.05±0.11| Yes | [8, 9, 11, 55, 70] |
| 20180301A | 93.23  | 4.67   | 536.00   | 136.53  | 263.16 | 0.3305| 2.30±0.60 | 1.93±0.58 | 607.2 | 10.8±3.0| 5.80±0.20| Yes | [71] |
| 20180916B | 29.50  | 65.72  | 348.80   | 168.73  | 319.42 | 0.0337| 2.15±0.33 | 0.96±0.02 | 154.9 | 5.5±0.0 | 3.57±0.36| Yes | [57, 58, 12, 74] |
| 20180924B | 326.11 | −40.90 | 362.16   | 41.45   | 27.28  | 0.3214| 13.20±5.10 | 0.88±0.26 | 383.4 | 3.4±0.8 | 2.75±0.10| No | [71, 55, 54, 74] |
| 20181030A | 158.60 | 73.76  | 103.50   | 40.16   | 32.72  | 0.0039| 5.80±1.80 | 0.36±0.10 | 4800.0 | −       | −       | 2.60±0.00| Yes | [75] |
| 20181112A | 327.35 | −52.97 | 589.00   | 41.98   | 28.65  | 0.4755| 3.98±2.02 | 0.37±0.11 | 572.4 | 1.7±1.9 | 7.19±1.7 | No | [55, 76, 79] |
| 20190102C | 322.42 | −79.48 | 364.55   | 56.22   | 42.70  | 0.2913| 3.39±1.02 | 0.86±0.26 | 55.6  | 2.3±4.5 | 5.00±0.15| No | [55, 57, 58, 76, 77] |
| 20190525A | 207.06 | 72.47  | 760.80   | 36.74   | 29.75  | 0.6600| 61.20±40.10 | 0.09±0.00 | 685.9 | 27.2±22.6| 3.28±0.18| No | [55, 80] |
| 20190608B | 334.02 | −7.90  | 340.05   | 37.81   | 26.44  | 0.1178| 11.60±2.80 | 0.69±0.21 | 383.4 | 6.5±0.8 | 7.37±0.07| No | [55, 58, 76, 77] |
| 20190611B | 320.74 | −79.40 | 320.63   | 56.60   | 43.04  | 0.3778| 0.75±0.53 | 0.27±0.08 | 11.7±5.8| 2.15±0.11| No | [55, 58, 77] |
| 20190711A | 329.42 | −80.36 | 592.60   | 55.37   | 42.06  | 0.5217| 0.81±0.29 | 0.42±0.12 | 607.2 | 3.2±2.1 | 2.94±0.17| Yes | [55, 57, 58, 77] |
| 20190714A | 183.98 | −13.02 | 504.13   | 38.00   | 30.94  | 0.2365| 14.20±5.50 | 0.65±0.20 | 1593.2 | 2.7±1.8 | 3.94±0.05| No | [57, 58] |
| 20191001A | 323.35 | −54.75 | 507.90   | 44.22   | 30.67  | 0.2340| 46.40±18.80 | 8.06±2.42 | 639.7 | 11.1±0.8 | 5.55±0.03| No | [71, 55, 58] |
| 20191228A | 344.43 | −29.59 | 297.50   | 33.75   | 19.67  | 0.2432| 5.40±6.00 | 0.03±0.01 | 5.7±3.3 | 1.78±0.06| No | [71] |
| 20200430A | 229.71 | 12.38  | 380.25   | 27.35   | 26.33  | 0.1608| 2.10±1.10 | 0.26±0.08 | 689.5 | 1.7±2.2 | 1.64±0.53| No | [55, 71] |
| 20200906A | 53.50  | −14.08 | 577.80   | 36.19   | 38.37  | 0.3688| 13.30±3.70 | 0.48±0.14 | 1150.7 | 5.9±2.0 | 7.58±0.06| No | [71] |
| 20201124A | 77.01  | 26.06  | 413.52   | 126.49  | 204.74 | 0.0979| 16.00±1.00 | 2.12±0.49 | 5000.0 | 1.3±0.1 | −       | Yes | [82, 51] |

Figure 1. The sky positions of 17 well-localized FRBs in the Galactic coordinates. The repeaters and non-repeaters are denoted in red and blue dots, respectively. The red-dashed line is the Equatorial plane.
and \( \Omega_{\text{DM}} = 0.0493 \). The fraction of baryon mass is assumed to be a constant, \( f_{\text{IGM}} = 0.84 \). The uncertainty of \( \Delta M_{\text{host}} \) is calculated using equation (5). The \( \Delta M_{\text{host}} \) can be tightly constrained by observing the time-resolved spectra of FRBs. According to the FRB catalog (62), the average uncertainty on \( \Delta M_{\text{obs}} \) is only \( \sim 1.5 \) pc cm\(^{-3}\). Both the NE2001 model and YMW16 model do not provide the uncertainty on \( M_{\text{MW,ISM}} \). Since these two models predict different values of \( M_{\text{MW,ISM}} \), we take \( \sigma_{\text{MW,ISM}} \) as the absolute value of the difference of \( M_{\text{MW,ISM}} \) calculated using these two models. This ensures that two models give consistent results within \( 1\sigma \) uncertainty. For FRBs at high Galactic latitude (\(|b| > 10^\circ\)), the value of \( \sigma_{\text{MW,ISM}} \) is about 10 pc cm\(^{-3}\), while for low-latitude (\(|b| < 10^\circ\)) FRBs it is at the order of magnitude 100 pc cm\(^{-3}\). The Milky Way halo contribution is assumed to be \( M_{\text{MW,halo}} = 50 \) pc cm\(^{-3}\) (55), and we add 50% uncertainty on it. The \( \Delta M_{\text{IGM}} \) term has large uncertainty due to the density fluctuation in the large-scale structure (58). Cosmological simulations show that the uncertainty on \( \Delta M_{\text{IGM}} \) increases with redshift (57). Here we use the \( \sigma_{\text{IGM}}(z) \) relation given in Ref. [40] to calculate the uncertainty.

In Figure 2, we plot the correlations between \( \Delta M_{\text{host}} \) and the properties of host galaxies. In all subfigures, the vertical axes are \( \Delta M_{\text{host}} \), and the horizontal axes are the redshift, the stellar mass, the SFR, the mass-weighted age, the offset from galactic center, and the half-light radius, respectively. In Table 2, we list the Spearman’s correlation coefficients \( \rho \) of six correlations [58]. In general, \( |\rho| < 0.3 \), \( 0.3 < |\rho| < 0.7 \) and \( |\rho| > 0.7 \) imply that the correlation is weak, moderate and strong, respectively. From Table 2, we see that there is no strong correlation between \( \Delta M_{\text{host}} \) and any of the host galaxy parameters, neither in NE2001 model nor in YMW16 model. From the upper-left panel of Figure 2, we note that \( \Delta M_{\text{host}} \) of the first 8 FRBs at \( z < 0.24 \) is strongly linearly correlated with redshift. The Spearman’s correlation coefficients are 1.0 and 0.8 for NE2001 model and YMW16 model, respectively. The positive \( \Delta M_{\text{host}} - z \) correlation means that high-redshift FRBs generally have larger host DM than low-redshift FRBs, which may imply that high-redshift galaxies have richer diffuse gas than low-redshift galaxies. Due to the small FRB sample and large uncertainty, it’s unclear if the \( \Delta M_{\text{host}} - z \) correlation is intrinsic or not. For high-redshift FRBs (\( z > 0.24 \)), however, the correlation disappears. Therefore, we suspect that the linear \( \Delta M_{\text{host}} - z \) correlation at \( z < 0.24 \) may be happened by chance. From Table 2, we note that there is a moderate correlation between \( \Delta M_{\text{host}} \) and the stellar mass of host galaxy. The positive \( \Delta M_{\text{host}} - M_* \) correlation implies that a more massive galaxy usually contributes a larger \( \Delta M_{\text{host}} \). This is because more massive galaxies in general contain more diffuse gas. In addition, some other factors such as the age of host galaxy may also moderately affect \( \Delta M_{\text{host}} \). A larger FRB sample is required to confirm or falsify the \( \Delta M_{\text{host}} - M_* \) correlation.

The central value of \( \Delta M_{\text{host}} \) of FRB20190611B (galactic latitude \( b = -33.6^\circ \), redshift \( z = 0.3778 \)) is somehow negative in both NE2001 model and YMW16 model, which implies that \( M_{\text{MW,ISM}} \) and/or \( \Delta M_{\text{IGM}} \) for this burst are/is overestimated. Since the \( \Delta M_{\text{MW,ISM}} \) values of FRB 190611 calculated from both models are consistent with that of other FRBs located at the similar directions (such as FRB20190102C and FRB 20190711A), the most possibility is that \( M_{\text{MW,ISM}} \) is accurate while \( \Delta M_{\text{IGM}} \) is overestimated. The overestimation of \( \Delta M_{\text{IGM}} \) may be caused by matter fluctuation. For FRB20180301A (\( b = -5.8^\circ \), \( z = 0.3305 \)) and FRB20180916B (\( b = 4.0^\circ \), \( z = 0.0337 \)), the central values of \( \Delta M_{\text{host}} \) calculated from YMW16 model are negative. This is because the YMW16 model may overestimate the Milky Way ISM contribution at low Galactic latitude (59). Excluding the unphysical negative values, the mean and standard deviation of \( \Delta M_{\text{host}} \) are (\( \Delta M_{\text{host}}, \sigma_{\Delta M_{\text{host}}} \)) = (131.6, 92.0) pc cm\(^{-3}\) for NE2001 model, and (\( \Delta M_{\text{host}}, \sigma_{\Delta M_{\text{host}}} \)) = (120.1, 96.3) pc cm\(^{-3}\) for YMW16 model.

3 Constraints on the fraction of baryon mass

The DM of IGM in equation (3) contains the information of cosmology, thus can be used to study the Universe. In this section we use the well-localized FRBs to constrain the fraction of baryon mass in IGM, i.e. the parameter \( f_{\text{IGM}}(z) \). To test if \( f_{\text{IGM}} \) is redshift-dependent or not, we follow Li et al. [40] and parameterize it as a slowly evolving function of redshift,

\[
f_{\text{IGM}} = f_{\text{IGM,0}} \left(1 + \frac{\alpha z}{1+z}\right),
\]

where \( f_{\text{IGM,0}} \) is the fraction of baryon mass in the IGM at present day, and \( \alpha \) is a constant.

In the previous section, we have shown that there is no strong correlation between \( \Delta M_{\text{host}} \) and any of the host galaxy parameters. Therefore, there is no reason to parameterize \( \Delta M_{\text{host}} \) as a function of one or some of the host galaxy parameters. The simplest and most straightforward assumption is that \( \Delta M_{\text{host}} \) is a constant. We introduce an uncertainty term \( \sigma_{\Delta M_{\text{host}}} \) to account for the possible deviation from the constant. The value of \( \sigma_{\Delta M_{\text{host}}} \) is fixed to be the standard deviation of \( \Delta M_{\text{host}} \) obtained in the previous section, i.e. \( \sigma_{\Delta M_{\text{host}}} = 92.0 \) and 96.3 pc cm\(^{-3}\) in NE2001 model and YMW16 model, respectively. This choice of \( \sigma_{\Delta M_{\text{host}}} \), rather than the value calculated from equation (5), avoids double bias caused by the large uncertainty of \( \Delta M_{\text{IGM}} \).
Figure 2. The correlations between DM$_{\text{host}}$ and the properties of host galaxy. The DM of the Milky Way is calculated using two different electron models, i.e. the NE2001 model (red diamonds) and the YMW16 model (black circles).
By fitting the observed DM to the theoretical prediction, the cosmological parameters can be constrained. The likelihood function is given by

\[ \mathcal{L}(\text{Data}|\theta) = \prod_{i=1}^{N} \frac{1}{\sqrt{2\pi} \sigma_{\text{total}}} \exp \left( -\frac{1}{2} \chi^2 \right), \]  

where \( \theta \) is the set of free parameters and ‘Data’ represents the FRB sample, and

\[ \chi^2 = \left[ \frac{\text{DM}_{\text{obs}} - \text{DM}_{\text{MW}} - \text{DM}_{\text{IGM}} - \text{DM}_{\text{host}}}{\sigma_{\text{total}}} \right]^2, \]  

where \( \text{DM}_{\text{IGM}} \) is calculated from equation [3], and the total uncertainty is given by [40]

\[ \sigma_{\text{total}} = \sqrt{\sigma^2_{\text{obs}} + \sigma^2_{\text{MW}} + \sigma^2_{\text{IGM}} + \sigma^2_{\text{DM}_{\text{host}}}/(1+z)^2}. \]  

The posterior probability density functions (PDFs) of the parameters are given by

\[ P(\theta|\text{Data}) \propto \mathcal{L}(\text{Data}|\theta) P_0(\theta), \]  

where \( P_0(\theta) \) is the prior of the parameters.

We calculate the posterior PDFs of the parameters using the publicly available python package emcee[11]. Note that \( f_{\text{IGM}} \) is completely degenerated with the Hubble constant \( H_0 \) and the baryon density \( \Omega_b \), hence we fix the latter two parameters to the Planck 2018 values, i.e. \( H_0 = 67.4 \text{ km s}^{-1} \text{ Mpc}^{-1} \) and \( \Omega_b = 0.0493 \) [55]. In addition, \( \Omega_m \) and \( \Omega_\Lambda \) depict the background Universe and they have been tightly constrained by the Planck data. Therefore, we also fix them to the Planck 2018 values, namely, \( \Omega_m = 0.315 \) and \( \Omega_\Lambda = 0.685 \) [55]. This leaves behind three free parameters \( (f_{\text{IGM}}, \alpha, \text{DM}_{\text{host}}) \). We use a flat prior on all the free parameters: \( f_{\text{IGM},0} \in \mathcal{U}(0,1), \alpha \in \mathcal{U}(-2,2) \) and \( \text{DM}_{\text{host}} \in \mathcal{U}(0,300) \text{ pc cm}^{-3} \).

The best-fitting parameters \( (f_{\text{IGM},0}, \alpha, \text{DM}_{\text{host}}) \) are listed in Table 3 and the marginalized posterior PDFs and 2-dimensional marginalized confidence contours of the parameter space are plotted in Figure 3. FRBs with negative DM values are excluded in the fitting. For NE2001 model, we obtain \( f_{\text{IGM},0} = 0.78^{+0.15}_{-0.19}, \alpha = 0.20^{+1.13}_{-1.10} \) and \( \text{DM}_{\text{host}} = 141.3^{+29.8}_{-55.8} \text{ pc cm}^{-3} \), where the uncertainties are given at \( 1\sigma \) confidence level. For YMW16 model, we obtain \( f_{\text{IGM},0} = 0.78^{+0.15}_{-0.19}, \alpha = 0.29^{+1.10}_{-1.18} \) and \( \text{DM}_{\text{host}} = 135.8^{+65.4}_{-60.4} \text{ pc cm}^{-3} \). In both models, \( f_{\text{IGM},0} \) and \( \text{DM}_{\text{host}} \) can be tightly constrained. Although the constraint on \( \alpha \) is loose, the best-fitting \( \alpha \) prefers a positive value, which is consistent with the requirement that \( f_{\text{IGM}} \) mildly increases with redshift [10] [87]. The two Milky Way electron models give very consistent results within \( 1\sigma \) uncertainty, which is because high-latitude FRBs have much larger weights than low-latitude FRBs in the fitting, while both models give consistent DM values for high-latitude FRBs. Based on the limited number of FRBs and large uncertainty, there is no evidence for the redshift evolution of baryon mass fraction in IGM.

In fact, \( \text{DM}_{\text{host}} \) can vary significantly from burst to burst. Hence it is not a good approximation to assume a constant \( \text{DM}_{\text{host}} \). A more reasonable way to deal with \( \text{DM}_{\text{host}} \) is to model it as a probability distribution and marginalize over the free parameters. It is shown that \( \text{DM}_{\text{host}} \) can be fitted with log-normal distribution from theory and cosmological simulations [56] [72] [88]. Therefore, instead of assuming a constant \( \text{DM}_{\text{host}} \), we model it as a log-normal distribution centered at \( \text{DM}_{\text{host}} \) and refit the data. This is equivalent to use a log-normal prior on the parameter \( \text{DM}_{\text{host}} \) in the MCMC fitting. The best-fitting results are listed in Table 4. The marginalized posterior PDFs and 2-dimensional marginalized confidence contours of the parameter space are plotted in Figure 4. The best-fitting curves to the extragalactic DM \( (\text{DM}_e = \text{DM}_{\text{obs}} - \text{DM}_{\text{MW}} = \text{DM}_{\text{IGM}} + \text{DM}_{\text{host}})/(1+z) \) for NE2001 model and YMW16 model are plotted in the left and right panels of Figure 5, respectively. Using log-normal prior, we obtain a larger \( f_{\text{IGM}} \) value (0.83 vs. 0.78) and a smaller \( \text{DM}_{\text{host}} \) (~100 vs. ~140 pc cm\(^{-3}\)) than using flat prior. Using log-normal prior, the best-fitting \( f_{\text{IGM}} \) is more consistent with the fiducial value (0.84). This confirms that assuming a log-normal distribution on \( \text{DM}_{\text{host}} \) is more reasonable than assuming a constant value.

### 4 Discussion and Conclusions

In this paper, we investigated the host galaxy DM using the well-localized FRBs. We tested the possible correlations between \( \text{DM}_{\text{host}} \) and six properties of host galaxies: the redshift, the stellar mass, the star-formation rate, the age of galaxy, the offset of FRB site from galactic center, and the half-light radius. We found that there is no strong correlation between \( \text{DM}_{\text{host}} \) and any of the parameters. Luo et al. [60] pointed out that \( \text{DM}_{\text{host}} \) is proportional to the square-root of the SFR of host galaxy. However, we found no cor-
Table 3. The best-fitting parameters ($f_{IGM,0}, \alpha, DM_{host}$) by assuming a constant $DM_{host}$.

|        | $f_{IGM,0}$ | $\alpha$ | $DM_{host}$ [pc cm$^{-3}$] |
|--------|-------------|-----------|----------------------------|
| NE2001 | 0.78$^{+0.15}_{-0.19}$ | 0.20$^{+1.15}_{-1.14}$ | 141.3$^{+59.8}_{-55.8}$   |
| YMW16  | 0.78$^{+0.15}_{-0.19}$ | 0.29$^{+1.10}_{-1.18}$ | 135.8$^{+65.6}_{-60.4}$   |

Figure 3. The posterior PDFs and confidence contours on the free parameters ($f_{IGM,0}, \alpha, DM_{host}$) by assuming a constant $DM_{host}$. Left panel: NE2001 model; right panel: YMW16 model.

Table 4. The best-fitting parameters ($f_{IGM,0}, \alpha, DM_{host}$) by assuming a log-normal distribution on $DM_{host}$.

|        | $f_{IGM,0}$ | $\alpha$ | $DM_{host}$ [pc cm$^{-3}$] |
|--------|-------------|-----------|----------------------------|
| NE2001 | 0.83$^{+0.12}_{-0.17}$ | 0.36$^{+1.02}_{-1.13}$ | 107.7$^{+65.3}_{-62.9}$  |
| YMW16  | 0.83$^{+0.12}_{-0.17}$ | 0.44$^{+1.00}_{-1.15}$ | 94.0$^{+69.0}_{-59.1}$   |
Figure 4. The posterior PDFs and confidence contours on the free parameters ($f_{IGM,0}, \alpha, DM_{host}$) by assuming a log-normal distribution on $DM_{host}$. Left panel: NE2001 model; right panel: YMW16 model.

Figure 5. The best-fitting curves to the extragalactic DM for NE2001 model (left) and YMW16 model (right). Black dots with 1σ error bars are the data points, red and blue lines are the best-fitting curves assuming flat prior and log-normal prior on $DM_{host}$, respectively.
The host of FRB20190101A is an active galaxy, with SFR = 8.06 ± 2.42 $M_\odot$ yr$^{-1}$. For the rest 16 FRBs, the SFRs of host galaxies are small (SFR \lesssim 2 $M_\odot$ yr$^{-1}$). There is a big gap in the SFR range 2 \sim 8 $M_\odot$ yr$^{-1}$. We can’t exclude the possible existence of correlation between DM$_{host}$ and SFR if FRB sample is enlarged in the future.

The FRB sample contains host galaxies of very different properties. For example, the galaxy types vary from burst to burst, the stellar masses of host galaxies span a wide range from 10$^8$ $M_\odot$ to 10$^{11}$ $M_\odot$, and the galaxy ages range from decades Myr to thousands Myr. Since the available FRB sample is very small, we have to combine all the FRBs together to study the correlations. When studying the correlation between host DM and other properties (such as DM$_{host}$ − $\sigma$ correlation), it is better to choose FRBs whose other properties (such as galaxy type, stellar mass, SFR, etc.) are similar. Only in this way can we make a fair comparison. However, due to the small FRB sample, we can’t do this at present. An alternative way is to study the multi-dimensional correlations. But this also requires a large FRB sample. Thus multi-dimensional correlations are not considered here. But this also requires a large FRB sample. Thus multi-dimensional correlations are not considered here. If the host galaxy is a spiral galaxy, one of the main factors that may affect DM$_{host}$ is the inclination angle. A edge-on galaxy is expected to contribute a larger value of DM$_{host}$ than a face-on galaxy. Unfortunately, except for FRB20190608B \cite{56}, the rest FRBs have no observation on inclination angle.

The DM$_{host}$ values obtained by subtracting the contributions of MW and IGM from the observed DM have large uncertainty. The uncertainty on DM$_{host}$ is dominated by the uncertainty on DM$_{IGM}$. For low-latitude FRBs, the DM$_{MW, ISM}$ term also introduces a large uncertainty. Because both Milky Way electron models do not provide the uncertainty of DM$_{MW, ISM}$ directly, we just simply adopt the difference of DM$_{MW, ISM}$ values calculated from two electron models as $\sigma_{MW, ISM}$. This is reasonable for high-latitude FRBs, since both electron density models give consistent DM$_{MW, ISM}$ values. For low-latitude FRBs, however, YMW16 model gives a much higher value of DM$_{MW, ISM}$ than NE2001 model. Koch Ocker et al. \cite{90} pointed out that YMW16 model may overestimate DM$_{MW, ISM}$ at low latitude. With more Galactic plane pulsars discovered by e.g. the FAST telescope \cite{91}, DM$_{MW, ISM}$ at low latitude is expected to be modeled more accurately in the future. In addition, FRB source may also contribute a non negligible DM value, thus introduces additional uncertainty. However, without independent observations, the FRB source contribu-}

relation between them in the 17 well-localized FRBs. The host of FRB20191001A is an active galaxy, with SFR = 8.06 ± 2.42 $M_\odot$ yr$^{-1}$. For the rest 16 FRBs, the SFRs of host galaxies are small (SFR \lesssim 2 $M_\odot$ yr$^{-1}$). There is a big gap in the SFR range 2 \sim 8 $M_\odot$ yr$^{-1}$. We can’t exclude the possible existence of correlation between DM$_{host}$ and SFR if FRB sample is enlarged in the future.

The FRB sample contains host galaxies of very different properties. For example, the galaxy types vary from burst to burst, the stellar masses of host galaxies span a wide range from 10$^8$ $M_\odot$ to 10$^{11}$ $M_\odot$, and the galaxy ages range from decades Myr to thousands Myr. Since the available FRB sample is very small, we have to combine all the FRBs together to study the correlations. When studying the correlation between host DM and other properties (such as DM$_{host}$ − $\sigma$ correlation), it is better to choose FRBs whose other properties (such as galaxy type, stellar mass, SFR, etc.) are similar. Only in this way can we make a fair comparison. However, due to the small FRB sample, we can’t do this at present. An alternative way is to study the multi-dimensional correlations. But this also requires a large FRB sample. Thus multi-dimensional correlations are not considered here. If the host galaxy is a spiral galaxy, one of the main factors that may affect DM$_{host}$ is the inclination angle. A edge-on galaxy is expected to contribute a larger value of DM$_{host}$ than a face-on galaxy. Unfortunately, except for FRB20190608B \cite{56}, the rest FRBs have no observation on inclination angle.

The DM$_{host}$ values obtained by subtracting the contributions of MW and IGM from the observed DM have large uncertainty. The uncertainty on DM$_{host}$ is dominated by the uncertainty on DM$_{IGM}$. For low-latitude FRBs, the DM$_{MW, ISM}$ term also introduces a large uncertainty. Because both Milky Way electron models do not provide the uncertainty of DM$_{MW, ISM}$ directly, we just simply adopt the difference of DM$_{MW, ISM}$ values calculated from two electron models as $\sigma_{MW, ISM}$. This is reasonable for high-latitude FRBs, since both electron density models give consistent DM$_{MW, ISM}$ values. For low-latitude FRBs, however, YMW16 model gives a much higher value of DM$_{MW, ISM}$ than NE2001 model. Koch Ocker et al. \cite{90} pointed out that YMW16 model may overestimate DM$_{MW, ISM}$ at low latitude. With more Galactic plane pulsars discovered by e.g. the FAST telescope \cite{91}, DM$_{MW, ISM}$ at low latitude is expected to be modeled more accurately in the future. In addition, FRB source may also contribute a non negligible DM value, thus introduces additional uncertainty. However, without independent observations, the FRB source contribu-
75 K. W. Bannister, et al., A single fast radio burst localized to a massive galaxy at cosmological distance. arXiv:1906.11476 doi:10.1126/science.aau5903
76 S. Bhandari, et al., The host galaxies and progenitors of Fast Radio Bursts localized with the Australian Square Kilometre Array Pathfinder, Astrophys. J. Lett. 895 (2) (2020) L37. arXiv:2005.13160 doi:10.3847/2041-8213/ab672e
77 C. K. Day, et al., High time resolution and polarization properties of ASKAP-localized fast radio bursts, Mon. Not. Roy. Astron. Soc. 497 (3) (2020) 3335–3350. arXiv:2005.13162 doi:10.1093/mnras/staa2138
78 M. Bhardwaj, et al., A Local Universe Host for the Repetitive Fast Radio Burst FRB 20181030A arXiv:2108.12122 doi:10.3847/2041-8213/ac223b
79 J. X. Prochaska, J.-P. Macquart, M. McQuinn, S. Simha, R. M. Shannon, C. K. Day, L. Marnoch, S. Ryder, A. Deller, K. W. Bannister, S. Bhandari, R. Bordoloi, J. Bunton, H. Cho, C. Flynn, E. K. Mahony, C. Phillips, H. Qiu, N. Tejos, The low density and magnetization of a massive galaxy halo exposed by a fast radio burst, Science 366 (6462) (2019) 231–234. arXiv:1909.11681 doi:10.1126/science.aay0073
80 V. Ravi, et al., A fast radio burst localized to a massive galaxy, Nature 572 (7769) (2019) 352–354. arXiv:1907.01542 doi:10.1038/s41586-019-1389-7
81 S. Bhandari, et al., Limits on Precursor and Afterglow Radio Emission from a Fast Radio Burst in a Star-forming Galaxy, Astrophys. J. Lett. 901 (2) (2020) L20. arXiv:2008.12488 doi:10.3847/2041-8213/ac242b
82 W.-f. Fong, et al., Chronicling the Host Galaxy Properties of the Remarkable Repeating FRB 20201124A arXiv:2106.11993 doi:10.3847/2041-8213/ac242b
83 V. Ravi, C. J. Law, D. Li, K. Aggarwal, S. Burke-Spolaor, L. Connor, T. J. W. Lazio, D. Simon, J. Somalwar, S. P. Tendulkar, The host galaxy and persistent radio counterpart of FRB 20201124A arXiv:2105.09719
84 L. Piro, et al., The Fast Radio Burst FRB 20201124A in a star forming region: constraints to the progenitor and multiwavelength counterpart arXiv:2107.14339
85 N. Aghanim, et al., Planck 2018 results. VI. Cosmological parameters, Astron. Astrophys. 641 (2020) A6. arXiv:1807.06209 doi:10.1051/0004-6361/201833910
86 N. Pol, M. T. Lam, M. A. McLaughlin, T. J. W. Lazio, J. M. Cordes, Estimates of Fast Radio Burst Dispersion Measures from Cosmological Simulations, Astrophys. J. 886 (2019) 135. arXiv:1903.07630 doi:10.3847/1538-4357/ab4c2f
87 M. McQuinn, Locating the "missing" baryons with extragalactic dispersion measure estimates, Astrophys. J. Lett. 780 (2014) L33. arXiv:1309.4461 doi:10.1088/2041-8205/780/2/L33
88 C. Spearman, The proof and measurement of association between two things, American Journal of Psychology 15 (1) (1904) 72. doi:10.2307/1412159
89 A. Haldun, User’s guide to correlation coefficients, Turkish Journal of Emergency Medicine 18 (2018) 91. doi:10.1016/j.tjem.2018.08.001
90 S. Koch Ocker, J. M. Cordes, S. Chatterjee, Constraining Galaxy Halos from the Dispersion and Scattering of Fast Radio Bursts and Pulsars, Astrophys. J. 911 (2021) 102. arXiv:2101.04784 doi:10.3847/1538-4357/abeb6e
91 D. Foreman-Mackey, D. W. Hogg, D. Lang, J. Goodman, emcee: The MCMC Hammer, Publ. Astron. Soc. Pac. 125 (2013) 306–312. arXiv:1202.3665 doi:10.1086/670067
92 M. Jaroszynski, FRBs: the Dispersion Measure of Host Galaxies, Acta Astron. 70 (2) (2020) 87–100. arXiv:2008.04634 doi:10.32023/0001-5237/70.2.1
93 G. Q. Zhang, H. Yu, J. H. He, F. Y. Wang, Dispersion measures of fast radio burst host galaxies derived from IllustrisTNG simulation, Astrophys. J. 900 (2) (2020) 170. arXiv:2007.13955 doi:10.3847/1538-4357/aba4a
94 J. L. Han, et al., The FAST Galactic Plane Pulsar Snapshot survey: I. Project design and pulsar discoveries, Res. Astron. Astrophys. 21 (2021) 107. arXiv:2105.08680 doi:10.1088/1674-4527/21/5/107
95 M. Fukugita, C. J. Hogan, P. J. E. Peebles, The Cosmic baryon budget, Astrophys. J. 503 (1998) 518. arXiv:astro-ph/9712020 doi:10.1086/306026
96 A. G. Riess, et al., New Parallaxes of Galactic Cepheids from Spatially Scanning the Hubble Space Telescope: Implications for the Hubble Constant, Astrophys. J. 855 (2) (2018) 136. arXiv:1801.01120 doi:10.3847/1538-4357/aaadb7