Intergalactic Medium Dispersion Measures of Fast Radio Bursts Estimated from IllustrisTNG Simulation and Their Cosmological Applications

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Received 2020 August 16; revised 2020 November 25; accepted 2020 November 26; published 2021 January 6

Abstract

Fast radio bursts (FRBs) are millisecond-duration radio transients and can be used as a cosmological probe. However, the dispersion measure (DM) contributed by the intergalactic medium (IGM) is hard to distinguish from other components. In this paper, we use the IllustrisTNG simulation to realistically estimate DM_{IGM} up to z ~ 9. We find DM_{IGM} = (892 \pm 72) \text{ pc cm}^{-3} at z = 1. The probability distribution of DM_{IGM} can be well fitted by a quasi-Gaussian function with a long tail. The tail is caused by structures along the line of sight in the IGM. Subtracting DM contributions from the Milky Way and host galaxy for localized FRBs, the DM_{IGM} value is close to that given by the derived DM_{IGM} relation. We also show the ability to constrain the cosmic reionization history with DM_{IGM} of high-redshift FRBs in the IllustrisTNG universe. The derived DM_{IGM} relation at high redshifts can be well fitted by a tanh reionization model with the reionization redshift z = 5.95, which is compatible with the reionization model used by the IllustrisTNG simulation. DM_{IGM} of high-redshift FRBs also provides an independent way to measure the optical depth of the cosmic microwave background. Our result can be used to derive the pseudo-redshifts of nonlocalized FRBs for DM_{IGM} < 4000 \text{ pc cm}^{-3}.

Unified Astronomy Thesaurus concepts: Radio transient sources (2008); Intergalactic medium (813); Reionization (1383); Radio bursts (1339)

1. Introduction

Fast radio bursts (FRBs) are millisecond luminous radio pulses with large dispersion measures (DMs), well in excess of the Milky Way contribution. More than 100 FRBs have been reported since Lorimer et al. (2007) found the first one from archival data. Only 13 of them have been localized (Chatterjee et al. 2017; Bannister et al. 2019; Prochaska et al. 2019; Ravi et al. 2019; Macquart et al. 2020; Marcote et al. 2020). Apparently, FRBs can be divided into two types, repeating and non-repeating, and the properties of their host galaxies may be different.

The DM is defined as the column density of free electrons along a given line of sight (LoS). The observed DM is usually divided into several parts:

\[
DM = DM_{MW} + DM_{halo} + DM_{IGM} + \frac{DM_{host} + DM_{source}}{1 + z}.
\]

(1)

In the above equation, DM_{MW} is the contribution of the interstellar medium in the Milky Way, which can be derived from the NE2001 model of the Galactic free electron density (Cordes & Lazio 2002) or the YMW model (Yao et al. 2017). DM_{halo} is contributed by the free electrons in the Galactic halo. Prochaska & Zheng (2019) found that DM_{halo} is between 50 and 80 pc cm\(^{-3}\). Recently, Yamasaki & Totani (2020) estimated that the mean DM_{halo} is 43 pc cm\(^{-3}\), with a full range of 30–425 pc cm\(^{-3}\). Zhang et al. (2020) derived distributions of the host contribution DM_{host} of repeating and non-repeating FRBs with the IllustrisTNG simulation. They found that the distributions of DM_{host} can be well fitted by a log-normal function. For non-repeating FRBs, the median of DM_{host} is about 30–70 pc cm\(^{-3}\) in the redshift range z = 0.1–1.5. DM_{source} depends on the central engine of FRBs. If an FRB is generated by a merger of binary neutron stars (Wang et al. 2016; Zhang 2020), the value of DM_{source} is small (Wang et al. 2020; Zhao et al. 2020).

The DM contributed by the intergalactic medium (IGM) is an important cosmological probe (Gao et al. 2014; Zhou et al. 2014; Muñoz et al. 2016; Yu & Wang 2017; Wang & Wang 2018; Walters et al. 2018; Jaroszynski 2019; Li et al. 2019; Wei et al. 2019; Wu et al. 2020; Zhao et al. 2020). By assuming the cosmic reionization history, the value of DM_{IGM} can be derived theoretically (Ioka 2003; Inoue 2004; Deng & Zhang 2014):

\[
DM_{IGM}(z) = \frac{3c \Omega_b H_0}{8\pi G m_p} \int_0^z \frac{(1 + z') f_{IGM}(z') f_e(z') \rho(z')}{E(z')} dz',
\]

(2)

where \(E(z) = H(z)/H_0\), H(z) is the Hubble parameter, \(H_0\) is the Hubble constant, \(m_p\) is the mass of a proton, \(\Omega_b = 0.0486\) is the density of baryons, and \(f_{IGM}\) is the fraction of baryon mass in the IGM. \(f_e = Y_H X_{eH}^e(z) + \frac{1}{2} Y_{He} X_{eHe}^e(z)\), \(Y_H = 3/4\) and \(Y_{He} = 1/4\) are the mass fractions of hydrogen and helium, respectively. \(X_{eH}\) and \(X_{eHe}\) are the ionization fractions of intergalactic hydrogen and helium.

Unlike previous theoretical investigations, which use an extragalactic DM with a homogeneous universe (Ioka 2003; Inoue 2004), McQuinn (2014) considered the effect of inhomogeneity with three models for the halo gas profile of ionized baryons. Dolag et al. (2015), Pol et al. (2019), and Zhu & Feng (2020) studied DM_{IGM} with different cosmological simulations in the low-redshift (z < 2) universe. Jaroszynski (2019) used the Illustris simulation to estimate DM_{IGM} and its scatter in the \(z < 5\) universe. However, the simulation accuracy can be improved with the latest IllustrisTNG simulation. Another advantage of IllustrisTNG is that it can provide the...
electron density directly instead of converting from the dark matter particle number density to baryonic matter density like Pol et al. (2019). The complicated conversion may introduce extra uncertainties. Besides, the IllustrisTNG has a wide redshift range.

Considering these advantages, we choose the IllustrisTNG (the successor to Illustris) simulation, which possesses both high accuracy and large structures in the range $0 < z < 20$. Such a broad range of redshifts enables us to examine the prospect of constraining the cosmic reionization history with high-redshift FRBs. It also provides a chance to check whether FRBs can be a new type of standard candle besides supernovae, which is crucial for distance measurement.

In this paper, we use the IllustrisTNG simulation to study DM$_{\text{IGM}}$ and its cosmological applications, especially in the high-redshift universe. The outline is as follows. An introduction to the IllustrisTNG simulation and our method to derive DM$_{\text{IGM}}$ from the simulation are given in Section 2. We show the result in Section 3. The scenario of constraining the cosmic reionization history with FRBs is discussed in Section 4. We estimate the redshifts of nonlocalized FRBs with the DM$_{\text{IGM}}$ relation in Section 5. Conclusions are given in Section 6.

2. Methods

2.1. Data Access to IllustrisTNG

The IllustrisTNG project, a successor to Illustris, consists of three large-volume, cosmological, and gravito-magnetohydrodynamical simulations (Marinacci et al. 2018; Naiman et al. 2018; Nelson et al. 2018; Pillepich et al. 2018; Springel et al. 2018), such as TNG50, TNG100, and TNG300. The number represents the scale of simulations in units of cMpc (c for comoving, similarly hereinafter). Each simulation contains several runs with different resolutions. The final results are stored in 600 HDF5 files. According to the cosmological principle, TNG300 is the best choice for our research and TNG300-1 is chosen among the three runs for its best resolution. There are 100 snapshots at different redshifts stored in each run and each snapshot has 15,625,000,000 Voronoi gas cells in total. Each cell corresponds to a particle, and its physical parameters given by IllustrisTNG represent the whole cell. In the 100 snapshots, 20 of them are “full” and 80 are “mini,” which only lack some particle fields. We use all the full snapshots at $z < 10$ and several “mini” snapshots for better accuracy. The web-based JupyterLab Workspace and high-performance computing resources provided by IllustrisTNG are used in this work.

2.2. Dispersion of the IGM

For an FRB at $z_s$, DM$_{\text{IGM}}$ can be written as

$$\text{DM}_{\text{IGM}}(z_s) = \int_0^{z_s} n_e(z) \frac{1 + z}{1 + z} dz_{\text{prop}},$$

where $n_e(z)$ is electron density in the comoving frame and $dl_{\text{prop}}$ is the differential proper distance. Then we use the redshift differential $dz$ to express $dl_{\text{prop}}$ as

$$dl_{\text{prop}} = \frac{c}{H_0(1 + z)E(z)} dz,$$

where

$$E(z) = \sqrt{\Omega_m(1 + z)^3 + \Omega_k(1 + z)^2 + \Omega_\Lambda}.$$  

So DM$_{\text{IGM}}$ can be rewritten as

$$\text{DM}_{\text{IGM}}(z_s) = \frac{c}{H_0} \int_0^{z_s} \frac{n_e(z)}{(1 + z)^2 E(z)} dz.$$  

The cosmological parameters are taken as $\Omega_m = 0.3089$, $\Omega_\Lambda = 0.6911$, and $H_0 = 67.74$ km s$^{-1}$ Mpc$^{-1}$, which are the same as those used by the IllustrisTNG simulation (Pillepich et al. 2018).

None of the cosmological simulations provides continuous evolution of the universe—that is why snapshots exist. Therefore, Equation (6) cannot be applied directly. In practice, Jaroszynski (2019) and Pol et al. (2019) clipped and stacked the snapshots to construct the LoS. Here we solve the problem from another aspect. The basic idea is to convert the integral into a summation.

If $n_e(z_s)$ is available, $d\text{DM}_{\text{IGM}}/dz$ at a specific redshift $z_i$ ($z_i = 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.7, 1, \ldots$) can be derived from

$$\frac{d\text{DM}_{\text{IGM}}}{dz} \bigg|_{z_i} = \frac{c}{H_0(1 + z_i)^2 E(z_i)} n_e(z_i).$$

Then we use

$$\text{DM}_{\text{IGM}}(z_{i+1}) = \text{DM}_{\text{IGM}}(z_i) + \frac{1}{2} \left( \frac{d\text{DM}_{\text{IGM}}}{dz} \bigg|_{z_i} + \frac{d\text{DM}_{\text{IGM}}}{dz} \bigg|_{z_{i+1}} \right) (z_{i+1} - z_i)$$

(8)

to calculate DM$_{\text{IGM}}$ with the initial condition DM$_{\text{IGM}}(z)|_{z=0} = 0$.

The next subsection will introduce how to obtain the electron density.

2.3. Calculations of DM$_{\text{IGM}}$

IllustrisTNG snapshot data are not organized according to spatial position. In order to obtain the average electron density along a given LoS, we use a traversal method on all the 15,625,000,000 particles and find those particles belonging to the given LoS. For computational simplicity, the LoS is chosen to be parallel to the $x$-axis, which is similar to Jaroszynski (2019). Then we construct 5125 square pipes of side length $100h^{-1}$ kpc ($H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$) in each snapshot and find the particles as well as necessary parameters (including Coordinates, Density, ElectronAbundance, GFM_Metals, and Star FormationRate) in the pipes (see Figure 1). The 5125 pipes are chosen from different locations in 24 snapshots randomly and a Kolmogorov–Smirnov test shows that the sample size is representative. The electron density can be calculated from

$$n_e(z)_{\text{prop}} = \eta_eX_H\rho m_p (1 + z)^3,$$

where $\eta_e$ is the electron abundance, $X_H$ is the hydrogen mass ratio, $\rho$ is the density, and $m_p$ is mass of a hydrogen atom. The fourth parameter is the particle coordinate, which is used to select particles. The factor $(1 + z)^3$ converts the density in the simulation comoving units into the proper units.
Equation (9) cannot be used in star-forming gas because the calculation is based on the “effective” temperature of the equation of state, which is not a physical temperature. Therefore, we use the parameter $\text{Star FormationRate}$ to exclude the star-forming gas. For comparison, star-forming particles are also excluded in Dolag et al. (2015). Jaroszynski (2019) excluded gas cells belonging to halos where the dark matter density is 15 times larger than the cosmic critical density.

It is hard to get the electron density field along the LoS analytically, because it requires calculation of the boundary of all the cells. But we know the cell to which any point on an LoS belongs. We divide the pipe into 10,000 bins along the x-axis and take the coordinates of the geometric center as the representation of bins. The distances between each bin and each particle in the pipe are calculated. We choose the nearest particle of each bin and assume the bin belongs to the cell of the chosen particle. We take an average of the electron density of 10,000 bins and put it into Equation (7). As a result, 5125 values of $d\text{DM}_{\text{IGM}}/dz$ are obtained at each redshift. Ten million $d\text{DM}_{\text{IGM}}$–$z$ relations are built by randomly selected $d\text{DM}_{\text{IGM}}/dz$ from $z = 0.1$ to 9.

### 3. Result

The redshifts of snapshots besides $z = 0$ are shown in Table 1. The distributions of $\text{DM}_{\text{IGM}}$ (from 0 to $z$ similarly hereafter) at different redshifts are shown in Figure 2. The DM distributions are fitted with (McQuinn 2014; Prochaska & Zheng 2019; Macquart et al. 2020)

$$p_{\text{DM}}(\Delta) = A\Delta^{-\beta} \exp \left[ -\frac{(\Delta - \Delta_0)^2}{2\alpha^2\sigma_{\text{DM}}^2} \right], \quad \Delta > 0,$$

where $\Delta = \text{DM}_{\text{IGM}}/(\text{DM}_{\text{IGM}})$, and $\beta$ is related to the inner density profile of gas in halos. We take $\alpha = \beta = 3$, which is the same as Macquart et al. (2020). $\sigma_{\text{DM}}$ is an effective standard deviation. $C_0$, which can affect the horizontal position, is the remaining parameter to be fitted. The fitting results are shown in Table 1.

It is obvious that the asymmetrical distributions have long tails at high $\text{DM}_{\text{IGM}}$, so we choose the most probable value for analysis, which is also used by Dolag et al. (2015) and Pol et al. (2019). We find $\text{DM}_{\text{IGM}}(z = 1) = 892^{+721}_{-270}$ pc cm$^{-3}$ (errors represent 95% confidence level). Ioka (2003)

![Figure 1. A schematic diagram of the choice of LoS. There are 5125 pipes at each redshift as shown in this figure.](image-url)

| Redshifts of the Snapshots and Fitting Parameters of the $\text{DM}_{\text{IGM}}$ Distributions in Figure 2 |
|---|
| **z** | **$A$** | **$C_0$** | **$\sigma_{\text{DM}}$** |
| 0.1 | 0.04721 | 13.17 | 2.554 |
| 0.2 | 0.005693 | 1.008 | 1.118 |
| 0.3 | 0.003584 | 0.596 | 0.7043 |
| 0.4 | 0.002876 | 1.010 | 0.5158 |
| 0.5 | 0.002423 | 1.127 | 0.4306 |
| 0.7 | 0.001880 | 1.170 | 0.3595 |
| 1 | 0.001456 | 1.189 | 0.3044 |
| 1.5 | 0.001098 | 1.163 | 0.2609 |
| 2 | 0.0009672 | 1.162 | 0.2160 |
| 2.4 | 0.0009220 | 1.142 | 0.1857 |
| 3 | 0.0008968 | 1.119 | 0.1566 |
| 3.5 | 0.0008862 | 1.104 | 0.1385 |
| 4 | 0.0008826 | 1.092 | 0.1233 |
| 4.4 | 0.0008827 | 1.084 | 0.1134 |
| 5 | 0.0008834 | 1.076 | 0.1029 |
| 5.2 | 0.0008846 | 1.073 | 0.09918 |
| 5.5 | 0.0008863 | 1.070 | 0.09481 |
| 5.8 | 0.0008878 | 1.067 | 0.09072 |
| 6 | 0.0008881 | 1.066 | 0.08971 |
| 6.5 | 0.0008881 | 1.066 | 0.08960 |
| 7 | 0.0008881 | 1.066 | 0.08952 |
| 8 | 0.0008881 | 1.066 | 0.08944 |
| 9 | 0.0008881 | 1.066 | 0.08941 |

3 https://www.tng-project.org/data/docs/specifications/
and Inoue (2004) predicted DM_{IGM}(z = 1) \sim 1200 \, \text{pc cm}^{-3}.\n\nZhang (2018) predicted DM_{IGM}(z = 1) \sim 855 \pm 345 \, \text{pc cm}^{-3}.\n\nJaroszynski (2019) found DM_{IGM}(z = 1) \sim 905 \pm 115 \, \text{pc cm}^{-3} (errors represent 1σ standard deviation). Pol et al. (2019) derived DM_{IGM}(z = 1) \sim 800^{+7000}_{-1700} \, \text{pc cm}^{-3} with uniform weighting and DM_{IGM}(z = 1) \sim 960^{+350}_{-160} \, \text{pc cm}^{-3} with weighting by matter distribution (errors represent 95% confidence level). We show these DM_{IGM}-z relations in Figure 3. Our result is shown as a blue solid line with 95% confidence region (shaded blue). DM_{IGM} estimated in our work is consistent with others within the 95% confidence level including the one derived by Pol et al. (2019). The difference between Pol et al. (2019) and our result may be caused by the conversion from the dark matter number density to the free electron density in the MareNostrum Instituto de Ciencias del Espacio Onion Universe simulation. A non-negligible systematic error may arise from the different cosmological parameters used by these simulations. For example, Illustris uses the cosmological parameters from WMAP-9 measurements (Vogelsberger et al. 2014), while IllustrisTNG uses those from Planck (Planck Collaboration et al. 2016b). The DM_{host} value is adopted from Zhang et al. (2020). Based on observations of the host galaxy, Zhang et al. (2020) calculated DM_{host} of repeating and non-repeating FRBs from the IllustrisTNG simulation. They found DM_{host} = 32.97(1 + z)^{0.84} \, \text{pc cm}^{-3} for non-repeating FRBs. For FRB 190608 we adopt its DM_{host} = 137 \pm 43 \, \text{pc cm}^{-3} from observations (Chittidi et al. 2020). The DM_{MW} value is derived with the NE2001 model (Cordes & Lazio 2002). We take DM_{halo} = 50 \, \text{pc cm}^{-3} for all FRBs. The contributions from FRB sources are ignored. All the derived DM_{IGM} are compatible with our result.

4. The Scenario of Constraining the Cosmic Reionization History

High-redshift FRBs can be used to probe the cosmic reionization history and we test our expectations with the TNG300 simulation. The universe is mostly neutral and non-transparent after the recombination (Peebles 1968; Zel’dovich et al. 1969; Seager et al. 2000). The transition from a neutral universe to an ionized one is called reionization, and it is the first chance to detect the evolution of the universe after the end of the cosmic dark ages. Reionization history is a frontier and a
We take because it is hard to detect now. Usually, it is believed that the challenging area in cosmology is the redshift-symmetric case of Planck Collaboration et al. (2016a), where the offset that has been observed in FRBs, considering both hydrogen and helium and expressed as $x = 1 + f_{\text{He}} = 1 + n_{\text{He}}/n_H$. Typically $f \sim 1.08$, $y = (1 + z)^{3/2}$, $y_{\text{re}} = (1 + z_{\text{re}})^{3/2}$, and $z_{\text{re}}$ is defined as the redshift at which $x = f/2$. $\Delta y = 1.5 \sqrt{1 + z_{\text{re}}} \Delta z$ and $\Delta z$ reflects the duration of reionization. In the model of Lewis (2008), $\Delta z$ is a fixed value. It was estimated with an upper limit of 1.3 at 95% confidence level in the redshift-symmetric case of Planck Collaboration et al. (2016a). Then we calculate $n_e(z)$ from

$$n_e(z) = n_b(z) X_H x(z)$$

and

$$n_b(z) = \frac{\Omega_b \rho_{\text{crit}, 0} (1 + z)^3}{m_p},$$

where $\rho_{\text{crit}, 0}$ is the critical density of the universe. After substituting $n_e(z)$ into Equation (6), the theoretical value of $\Delta z$ in cosmic reionization model. Figure 5 gives the value of $\Delta z$ in this cosmic reionization model.
reionization process ($\Delta z = 0.05$) at $z_{ee} = 5.95$ with the \textit{tanh} model, which is also compatible with the model used by IllustrisTNG (Faucher-Giguère et al. 2009).\footnote{2011 December version, https://galaxies.northwestern.edu/uvb-fg09/} Therefore, high-redshift FRBs are promising probes of the cosmic reionization history.

Meanwhile, we calculate the optical depth $\tau(z)$ of the CMB contributed by the IGM from
\begin{equation}
\tau(z) = \int_{0}^{z} \sigma_T n_e(z')dz',
\end{equation}
where $\sigma_T = 6.25 \times 10^{-25}$ cm$^2$ is the Thompson scattering cross section. The measurement of $\tau$ changes for different instruments and we are curious whether FRBs may help. Using the electron number density derived from the TNG300 simulation, we find that the total optical depth $\tau(z > 6) = 0.037 \pm 0.004$ at the 95% confidence level. Figure 6 shows the value of $\tau(z)$ as a function of redshift from the TNG300 simulation (blue line). The ionized electron fraction drops to zero before reionization, so the optical depth saturates at high redshifts (Fialkov & Loeb 2016). The saturation value can be indicated by high-redshift FRBs, which have no connection with the CMB. The optical depth $\tau = 0.058 \pm 0.023$ (95% confidence level) from the Planck result is shown as the orange region (Planck Collaboration et al. 2016a).

Considering the uncertainties, we find that these two results are consistent with each other. Therefore, the DM of high-redshift FRBs provides an independent way to measure the optical depth of the CMB, which can tightly constrain the cosmic reionization history. However, we must state that the resolution of Planck is $12^\circ$, which is much larger than that of FRBs. Comparing the two results with different resolutions directly may be somewhat inappropriate, but there is no need to decrease the resolution of FRBs.

5. Estimating the Redshifts of Nonlocalized FRBs

As mentioned before, there are only 13 localized FRBs (Chatterjee et al. 2017; Bannister et al. 2019; Prochaska et al. 2019; Ravi et al. 2019; Macquart et al. 2020; Marcote et al. 2020), which means that the redshifts for most FRBs are unknown. Assuming that $\Delta z$ is known accurately, we check whether the redshift of an FRB can be precisely derived from the $\Delta z$ relation.

We get $24 \times 10,000,000$ DM$_{IGM}$ data points (FRBs) in total (24 snapshots and 10,000,000 combinations). We divide the data points whose $\Delta z = 0.058 \pm 0.023$ (95% confidence level) from the Planck result is shown as the orange region (Planck Collaboration et al. 2016a) into 150 bins (40 pc cm$^{-3}$ in each bin) and calculate the mean redshift of the FRBs in each bin. The $\Delta z$ relation is shown in Figure 7. The standard deviation of derived redshift is $0.74$ at the pseudo-redshift $4.61$ (DM$_{IGM} = 4000$ pc cm$^{-3}$), which means the relative error is 16.1%. The small redshift standard deviations of FRBs whose DM$_{IGM}$ is less than $4000$ pc cm$^{-3}$ show a good prospect for calculating pseudo-redshifts of nonlocalized FRBs.

We only take full snapshots at low redshifts, which means that the redshifts of our simulated FRBs are restricted to some fixed values such as 0.1, 0.2, 0.3, 0.4, 0.5, 0.7, 1, and 1.5. However, the standard deviation should not be larger when including mini snapshots because it does not change for different sampling methods. Moreover, the bin width of $40$ pc cm$^{-3}$ can be taken as the systematic error during the estimation of DM$_{halo}$, DM$_{host}$, and DM$_{source}$, which means it is
even optimistic to derive the pseudo-redshift with a “not very accurate” $\text{DM}_{\text{IGM}}$.

6. Conclusions

In this work, we derive $\text{DM}_{\text{IGM}}$ of FRBs in the redshift range $0 < z < 9$ from IllustrisTNG simulations. We obtain $\text{DM}_{\text{IGM}} = 892^{+721}_{-270} \text{ pc cm}^{-3}$ at $z = 1$. The $\text{DM}_{\text{IGM}}$ values of localized FRBs are consistent with the derived $\text{DM}_{\text{IGM}}$--$z$ relation. At high redshifts $z > 5$, we show the scenario of probing the cosmic reionization history with FRBs. The $\tanh$ reionization model is used to fit the derived $\text{DM}_{\text{IGM}}$--$z$ relation at high redshifts. We find that the reionization of the IllustrisTNG universe occurs quickly at $z = 5.95$. This reionization model is compatible with the theoretical model used by the IllustrisTNG simulation (Faucher-Giguère et al. 2009). The optical depth of the CMB is also derived from the IllustrisTNG simulation, and is consistent with that from Planck Collaboration et al. (2016b). We also derive the redshifts of nonlocalized FRBs with their $\text{DM}_{\text{IGM}}$. The standard deviation of pseudo-redshifts for nonlocalized FRBs is 16.1% for $\text{DM}_{\text{IGM}} = 4000 \text{ pc cm}^{-3}$.

The highest DM of an observed FRB is $2596.1 \pm 0.3 \text{ pc cm}^{-3}$ and its nominal redshift is 2.1 (Bhandari et al. 2018; Caleb et al. 2018). It is likely that there will be two orders of magnitude more FRBs in the next few years (Keane 2018). According to Fialkov & Loeb (2016) and Zhang (2018), FAST and SKA will be capable of detecting FRBs out to $z = 14–15$. Therefore, FRBs will be a powerful and independent probe of the universe during the EoR in addition to the hydrogen 21 cm line. The future large sample of FRBs can be used to test our result about estimating redshifts for nonlocalized FRBs. Moreover, most previous works have only considered the mean value of $\text{DM}_{\text{IGM}}$ (Equation (2)) for cosmological constraints, while its scatter (Figure 2), which can degrade the cosmological constraints, was not handled properly. Since IllustrisTNG shows a certain shape of the scatter, more authentic distributions of $\text{DM}_{\text{IGM}}$ and $\text{DM}_{\text{host}}$ can be used to test the capability of FRBs to constrain cosmological parameters such as $\Omega_m$ and $\Omega_\Lambda$.

We thank the anonymous referee for valuable comments. We thank Zhenwei Tian, Lingrui Lin, Yichen Sun, Fangzheng Shi, and Zhensong Hu for helpful discussions and thank Dylan Nelson for his theoretical and technical help. This work is supported by the National Natural Science Foundation of China (grant U1831207).

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