A Measurement of Circumgalactic Gas around Nearby Galaxies Using Fast Radio Bursts

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Abstract

The distribution of gas in the circumgalactic medium (CGM) of galaxies of all types is poorly constrained. Foreground CGMs contribute an extra amount to the dispersion measure (DM) of fast radio bursts (FRBs). We measure this DM excess for the CGMs of $10^{11}–10^{13} M_\odot$ halos using the CHIME/FRB first data release, a halo mass range that is challenging to probe in any other way. Because of the uncertainty in the FRBs’ angular coordinates, only for nearby galaxies is the localization sufficient to confidently associate them with intersecting any foreground halo. Thus we stack on galaxies within 80 Mpc, optimizing the stacking scheme to approximately minimize the stack’s variance and marginalize over uncertainties in FRB locations. The sample has 20–30 FRBs intersecting halos with masses of $10^{11}–10^{12} M_\odot$ and also of $10^{12}–10^{13} M_\odot$, and these intersections allow a marginal $1\sigma–2\sigma$ detection of the DM excess in both mass bins. The bin of $10^{11}–10^{12} M_\odot$ halos also shows a DM excess at 1–2 virial radii. By comparing data with different models for the CGM gas profile, we find that all models are favored by the data up to 2 $\sigma$ level compared to the null hypothesis of no DM excess. With 3000 more bursts from a future CHIME data release, we project a 4$\sigma$ detection of the CGM. Distinguishing between viable CGM models by stacking FRBs with CHIME-like localization would require tens of thousands of bursts.

1. Introduction

The circumgalactic medium (CGM)—the diffuse gas that sits outside galaxy disks and inside the virial radii of halos—is a crucial component in the baryonic processes in the universe. It receives inflow of the intergalactic gas, fuels star formation in galaxies, and bears the impact of galactic feedback (Naab & Ostriker 2017; Tumlinson et al. 2017). An understanding of the CGM would resolve an aspect of the “missing baryon problem,” whereby a substantial fraction of the baryons associated with halos has not been detected (Dai et al. 2010; McGaugh et al. 2010; McQuinn 2016).

Questions remain about how the CGM is distributed around galaxies and how much mass there is in the CGM (e.g., Tumlinson et al. 2017). Fast radio bursts (FRB), however, are starting to provide an unprecedented probe of the CGM, with the advent of many radio telescopes geared for this science coming online across the globe (Cordes & Chatterjee 2019; Petroff et al. 2019, 2022; Prochaska & Zheng 2019; Keating & Pen 2020). FRBs are bright (up to a few hundred jansky) transient radio pulses (typically up to a few milliseconds) of mostly extragalactic origin, and have been detected over a wide range of frequencies (100 MHz–8 GHz). As the radio waves from FRBs travel through the intervening plasma, the interaction with free electrons causes a frequency-dependent delay of their arrival time, which is proportional to the integral of the electron number density along the line of sight (with a factor of $(1+z)$ correction for cosmological lines of sight)—the dispersion measure (DM). Since most of the CGM gas is ionized, the ionized gas contributes an extra amount to the total DM along a sightline, which can be used to constrain the distribution of CGM gas (McQuinn 2014; Ravi 2019).

There are many challenges to precisely measuring the excess DM from the CGM, especially in a sample of FRBs that are not well localized. First of all, the host galaxy and local environment around the FRB can contribute from a few tens to a few hundreds of pc $cm^{-3}$ (Kulkarni et al. 2015; Connor et al. 2016; Tendulkar et al. 2017; Yang et al. 2017; Cordes et al. 2022; Niu et al. 2022). Cosmic structures can also contribute scatter at the level of hundreds of pc $cm^{-3}$ (McQuinn 2014; Macquart et al. 2020). If the redshifts of the FRB host and intervening galaxies can be measured, requiring arcsecond localizations, one can subtract the average cosmological contribution to the total DM, which significantly reduces the variance in the measurement. Previous theoretical works predict that $O(100)$ FRBs are required to put constraints on the CGM when stacking arcsecond-localized FRBs (McQuinn 2014; Ravi 2019). However, there are approximately 20 FRBs that are sufficiently well localized to date (Petroff et al. 2022), while thousands of predominantly unlabeled FRBs have been observed, with more expected in the next few years. Without arcsecond localizations, many more FRBs are required to detect an excess DM from foreground CGMs (but see Platts et al. 2020, for constraining the Milky Way DM using a small number of transients). This paper considers this case.

We expand upon the recent work of Connor & Ravi (2021) and present a measurement of the CGM of nearby galaxies using the first FRB catalog published by the Canadian Hydrogen Intensity Mapping Experiment (CHIME) FRB project (Amiri et al. 2021). CHIME is a drift scan radio telescope operating across 400–800 MHz. The first CHIME/FRB catalog contains 535 FRBs detected between 2018 July 25 and 2019 July 1, including 18 repeating ones. While the typical localization error of $0.2^\circ$ is too large for any sophisticated analysis on the CGM, nearby ($<100$ Mpc) halos that cover even larger areas on the sky ($>0.2^\circ$ $deg^2$) make it...
possible to detect the DM excess from these halo CGMs. We thus stack FRBs that intersect $10^{11} - 10^{13} M_{\odot}$ halos within two virial radii and measure the DM excess, with a flexible weighting function that considerably reduces the stack’s variance and, importantly, downweights high-DM FRBs. We show that with our weighting scheme, having 3000 more FRBs from a CHIME data release would lead to a $> 3\sigma - 4\sigma$ detection of the CGM of $10^{11} - 10^{13} M_{\odot}$ halos, a number that is easily achievable with CHIME in the next few years. This will open up a novel window for understanding the baryon physics in the universe, since other methods of studying the CGM, such as the thermal and kinetic Sunyaev–Zeldovich effect (Schaan et al. 2021) and halo X-ray emission (Chadayamurthy et al. 2022), usually probe higher-mass ($> 10^{12} - 10^{13} M_{\odot}$) halos (but see Bregman et al. 2022, for a measurement of nearby halos of Milky Way size).

We note that another interesting constraint on the DM excess of the CGM comes from the repeating FRB 20200120E, which was recently localized to a globular cluster in M81 (Kirsten et al. 2022; Nimmo et al. 2023). Since the sightline does not cross the M81 disk, the DM of this FRB puts a tight upper bound on the Milky Way halo DM and M81 halo DM. With an estimate of the Milky Way disk DM of 30–40 pc cm$^{-3}$ (Cordes & Lazio 2002; Yao et al. 2017), the sum of the two halo DMs is $\sim 50–60$ pc cm$^{-3}$. This is broadly consistent with our measured DM excess of nearby halos.

This paper is organized as follows. Section 2 first presents our galaxy catalog and FRB sample selection. Then it describes our weighting method, the estimator of the DM excess from the CGM, and the derivation of a scheme to compare data with CGM models. Section 3 presents our measured DM excess and comparison with models, and makes forecasts for a future CHIME data release.

2. Methods

2.1. FRB Selection

We use the nonrepeaters in the CHIME FRB catalog, following Connor & Ravi (2021). Since the identified repeaters might exhibit a very different DM distribution from the nonrepeaters because the repeaters are likely younger and more energetic systems, including them may add noise to our measurements of DM excess. As in Connor & Ravi (2021), we exclude FRBs of Galactic latitudes within 5° of the Galactic plane to avoid regions where the Milky Way DM is higher such that modeling errors for this contribution can be larger. This gives a total number of 453 FRBs. We have verified that our results are not sensitive to this Galactic latitude threshold. For the FRB DM we use DM values provided by the CHIME catalog that have the Milky Way disk contribution removed using the Cordes & Lazio (2002) model. We have checked that using the Yao et al. (2017) model for the Milky Way disk DM does not change our conclusions. We do not attempt to subtract the Milky Way halo DM since it is poorly constrained (Prochaska & Zheng 2019; Keating & Pen 2020; Platts et al. 2020; Cook et al. 2023; Ravi et al. 2023), but stacking should average out the fluctuations in the Milky Way halo DM, and this DM is anticipated to be similar for all sightlines.

As in Connor & Ravi (2021), we use the galaxies in the Gravitational Wave Galaxy Catalogue (GWGC, White et al. 2011). At 40 Mpc, the angular sizes of the virial radii of $10^{11}$, $10^{12}$, and $10^{13} M_{\odot}$ halos are $0'15$, $0'33$, and $0'70$ respectively, assuming $R_{\text{vir}} = 250(M/1.3 \times 10^{12} M_{\odot})^{1/3}$ kpc. We use this expression for $R_{\text{vir}}$ throughout the paper. Since the typical $1\sigma$ error of CHIME localization is 0.2, we use $10^{11} - 10^{12} M_{\odot}$ halos at 0.5–40 Mpc and $10^{12} - 10^{13} M_{\odot}$ halos at 0.5–80 Mpc for our analysis. Later on, we develop a method to account for location uncertainties when comparing CGM models. We calculate the halo masses of galaxies by converting from their stellar masses using the relation in Moster et al. (2010). To estimate the galaxy stellar mass, we adopt any of four methods depending on what photometric data are available (higher priority comes first): cross-matching with NASA–Sloan Atlas catalog (NSA, 4200 galaxies), JHK-band spectral energy distribution (SED) fitting (3400 galaxies) or K-band mass-to-light ratio (100 galaxies), Sloan Digital Sky Survey $g – r$ color (400 galaxies). For the remaining 1900 galaxies in GWGC for which we were unsuccessful at obtaining optical or infrared photometric data, we convert their $B$-band luminosities to stellar masses by calibrating a conversion relation using the other galaxies. Among the galaxies in the NSA catalog, 1800 also have JHK photometric data, for which we find that our estimates of stellar mass using JHK bands mostly lie within a factor of 3 from the NSA stellar masses. We have verified that our main conclusions do not change if we use the JHK stellar masses for these galaxies instead.

For the candidate $> 10^{11} M_{\odot}$ halos, we identify galaxy groups and remove satellite galaxies. For a given galaxy, we define it as a satellite if it lies within 1.2 $R_{\text{vir}}$ of a more massive galaxy nearby in terms of their 3D distance. We do not consider M33 as a satellite of M31. Since the distances listed in GWGC have a typical error of 20%, we also test determining a satellite using the 2D projected distance and the difference in the radial velocities. We find that our results change very little if a satellite is identified by requiring that the radial velocities differ within three times the halo circular velocity instead of using the 3D distances. Our group-finding leaves 4600 $10^{11} - 10^{12} M_{\odot}$ galaxies at 0.5–40 Mpc and 4000 $10^{12} - 10^{13} M_{\odot}$ galaxies at 0.5–80 Mpc. We also remove five FRBs that we identify as intersecting $> 10^{13} M_{\odot}$ halos at $< 1 R_{\text{vir}}$. These more massive halos give a DM excess of $> 100–200$ pc cm$^{-3}$ (Williams et al. 2023) and so may bias our estimated DM excess for the lower-mass halos if some sightlines pass through multiple halos. However, we have checked that not removing these FRBs does not affect our conclusions. The five excluded FRBs also include two that lie close to the Virgo cluster, although their DM being only 200–400 pc cm$^{-3}$ suggests that they originate in front of Virgo (Virgo should give an excess DM of order 1000 pc cm$^{-3}$, see Prochaska & Zheng 2019).

We select FRBs that intersect nearby halos out to 2 $R_{\text{vir}}$ and bin them according to their $b/R_{\text{vir}}$. Figure 1 shows the map of FRBs, with colors indicating the DM values, and locations of galaxies that have FRB intersections within 1 $R_{\text{vir}}$. Blue and red crosses represent the centers of $10^{11} - 10^{12} M_{\odot}$ and $10^{12} - 10^{13} M_{\odot}$ halos in this sample, respectively. Ellipses of corresponding colors enclose the regions of radius $1 R_{\text{vir}}$ in R.A.–decl. coordinates. The two biggest ellipses at R.A. < 50° are M31 and M33. With our selections, there are 26 FRBs

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4. Different models predict similar stellar mass–halo mass relations at $z = 0$, e.g., Figure 34 of Behroozi et al. (2019).

5. Provided by Matt Wilde.

6. We performed SED fitting using CIGALE (Boquien et al. 2019, https://cigale.lam.fr/) and find that using JHK bands alone provides more reliable stellar masses than using optical bands. A lot of galaxies do not have optical photometry, because we queried the NASA/IPAC Extragalactic Database (NASA/IPAC Extragalactic Database (NED) 2019) web service with astropy.
Figure 1. Locations of the CHIME catalog FRBs used in our analysis as well as of galaxies having FRB interaction with an impact parameter of \( b < 1 \, R_{\text{vir}} \). Dots show the position of FRBs, with colors denoting their DM. Blue and red crosses illustrate the centers of \( 10^{11} - 10^{12} \, M_\odot \) and \( 10^{12} - 10^{13} \, M_\odot \) halos, respectively. Ellipses around these halos enclose the regions of radius \( 1 \, R_{\text{vir}} \) in these angular coordinates.

### Table 1

| (1) \( b \) Range | (2) \( N_{\text{FRB}} \) \( 10^{11} - 10^{12} \, M_\odot \) | (3) \( N_{\text{FRB}} \) M33 | (4) \( N_{\text{halo}} \) \( 10^{11} - 10^{12} \) | (5) DM Excess \( 10^{11} - 10^{12} \) | (6) \( N_{\text{FRB}} \) M31 | (7) \( N_{\text{halo}} \) \( 10^{12} - 10^{13} \) | (8) DM Excess |
|-------------------|-------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \([0, 1] \, R_{\text{vir}}\) | 26 (26–31) | 6 | 24 | 71 ± 53 (18 ± 61) | 30 (28–33) | 16 | 18 | 69 ± 49 (96 ± 72) |
| \([1, 1.5] \, R_{\text{vir}}\) | 31 (28–34) | 5 | 26 | 87 ± 48 (78 ± 53) | 38 (36–42) | 22 | 18 | 4 ± 43 (6 ± 61) |
| \([1.5, 2] \, R_{\text{vir}}\) | 39 (32–40) | 9 | 32 | 41 ± 43 (35 ± 46) | 57 (49–56) | 28 | 31 | 37 ± 35 (–11 ± 46) |

Note. Columns 2–4: number of FRBs intersecting \( 10^{11} - 10^{12} \, M_\odot \) halos, number of FRBs intersecting M33, and the number of \( 10^{11} - 10^{12} \, M_\odot \) halos with FRB intersections. Numbers in parentheses indicate the 1σ range (16th and 84th percentiles) of the number of FRBs owing to localization uncertainties, calculated by perturbing FRB locations assuming Gaussian errors. Column 5: the estimated DM excess using Equation (5) and 1σ error, with numbers in parentheses denoting the results excluding M33. Columns 6–9: the same but for \( 10^{12} - 10^{13} \, M_\odot \) halos.

interacting 24 halos with masses of \( 10^{11} - 10^{12} \, M_\odot \) within \( 1 \, R_{\text{vir}} \), and 30 FRBs intersecting 18 halos with \( 10^{12} - 10^{13} \, M_\odot \), although half of these intersections are with M31. Among the FRBs selected, three pass through both low-mass and high-mass halos, giving 53 in total. Table 1 lists the numbers of FRBs and halos falling in impact parameter bins of \([0, 1] \), \([1, 1.5] \), and \([1.5, 2] \, R_{\text{vir}}\). The numbers in parentheses in this table represent the 1σ errors on these numbers owing to localization uncertainties, obtained by perturbing FRB locations assuming Gaussian errors.\(^7\) If an FRB falls into multiple radial bins owing to intersections with different halos, we only count this FRB once, grouping it with the halo it intersects at the smallest impact parameter. We have tested that counting the halo twice does not change our results.

#### 2.2. An Estimator of DM Excess

We aim to examine whether the FRBs with impact parameter \( b < 2 \, R_{\text{vir}} \) exhibit a statistically significant excess DM over the full sample of FRBs. A simple estimator for the DM excess is the mean DM of the sample minus the mean of all CHIME FRBs. However, since the number of FRBs with halo intersections is small, one or two FRBs with high DM can significantly affect the sample mean DM. For a sample size of 20, one FRB with DM = \( 2000 \, \text{pc cm}^{-3} \) contributes \( 100 \, \text{pc cm}^{-3} \) to the sample mean, and the CHIME FRBs have a high-DM tail of DM \( \gtrsim 1500 \) (see the black histogram in Figure 2; hereafter we omit the unit of DM, \( \text{pc cm}^{-3} \)). An unweighted mean is thus not an ideal estimator for the DM excess because high DM bursts add to the variance of the estimated DM excess and bias it. Therefore, instead of calculating the sample mean DM, we compute a weighted-average DM where we downweight contributions from high-DM FRBs using a flexible weighting function

\[
 w(\text{DM}) \propto \exp\left(-\frac{(\text{DM}/\alpha)^\beta}{\beta}\right),
\]

where \( \alpha \) and \( \beta \) shape how quickly the weight cuts off. Hereafter we assume that the weights are already normalized so that the sum of weights equals unity. For a subsample of FRBs intersecting CGMs, a simple statistical measure (which we will improve below) for the DM excess is

\[
 \delta \text{DM} = \sum_{i \in I} w(\text{DM}_i) \text{DM}_i - \bar{\text{DM}},
\]

where \( i \) denotes the indices of FRBs, \( I \) is the subset of \( N_{\text{DM}} \) FRBs with CGM intersections, and

\[
 \bar{\text{DM}} = \sum_{i \in \text{CHIME}} w(\text{DM}_i) \text{DM}_i
\]

is the weighted mean DM of the whole CHIME sample. This downweighting is a major difference of our work from Connor & Ravi (2021), who used uniform weighting.\(^8\) Optimizing our

\(^7\) We note that the error bars on the number of FRBs in a bin are likely asymmetric around the number calculated using the maximum likelihood localization. This occurs because some FRBs fall on the edge of halos.

\(^8\) A counterargument to downweighting is that the high-DM FRBs, which presumably originate from halos at higher redshift, should encounter more CGMs along the line of sight so can be upweighted for measuring the DM excess of the CGM. However, since we want to study the CGM of nearby halos, in principle we just need the FRBs that originate right behind these halos. High-DM FRBs that go through more CGMs will not contribute to our measurements and will only add noise to our estimates.
weighting function by minimizing the estimated DM in the two-dimensional \((\alpha, \beta)\) space allows us to detect a DM excess with added precision.

For a nonlinear weighting function, the simple estimator of the DM excess given by Equation (2) is a biased estimate of the true DM excess, which we will revise below. To see this, if we artificially add a DM excess \(\delta DM\) to an arbitrary array of DM values, we have

\[
\hat{\delta DM} = \sum_i w(\Delta M_i + \delta DM)(\Delta M_i + \delta DM) - \Delta M
\]

\[
= \sum_i w(\Delta M_i + \delta DM)(\Delta M_i + \delta DM)
\]

\[
- \sum_i w(\Delta M_i) \Delta M_i
\]

\[
= \left[ \sum_i w(\Delta M_i + \delta DM) \Delta M_i - \sum_i w(\Delta M_i) \Delta M_i \right]
\]

\[
+ \delta DM,
\]

where in each summation the weights are normalized to sum to 1. One can see that if \(\beta > 1\), \(\hat{\delta DM} < \delta DM\); if \(0 < \beta < 1\), then \(\hat{\delta DM} > \delta DM\). Only when \(\beta = 1\) do we get \(\hat{\delta DM} = \delta DM\). To correct for this offset, we thus define a bias factor

\[
f = \delta DM/\hat{\delta DM},
\]

which we find is nearly independent of the DM excess for \(\delta DM < 200\), a limit that is easily satisfied in models for the foreground CGMs of galactic halos. This independence of \(f\) is convenient as it means that the correction does not depend on the true excess. Our revised unbiased estimator for the DM excess is thus

\[
\delta DM = \delta DM/f = \left[ \sum_{i \in I} w(\Delta M_i) \Delta M_i - \Delta M \right] / f,
\]

which we will use to measure the DM excess of CHIME FRBs intersecting halos.

For self-consistency, one can easily verify that for the range of DM excess that we are interested in here \((\delta DM \lesssim 200)\) and for the \(\alpha, \beta\) ranges that we adopt for CHIME FRBs (see Section 3.1), Equation (5) gives the same DM excess estimate as iteratively solving

\[
\delta DM = \sum_{i \in I} w(\Delta M_i - \delta DM) \Delta M_i - \Delta M,
\]

where in each iteration the weights \(w(\Delta M_i - \delta DM)\) have to be normalized. If one is interested in much larger DM excess or FRBs encountering multiple halos, the correction factor \(f\) should be recalibrated according to the proper choice of the weighting function.

2.3. Goodness of Fit of CGM Models

The above gives a way of calculating a statistical average of the DM excess for FRBs intersecting CGMs. We now extend Equation (6) to allow each FRB to have a different DM excess that is predicted by some CGM models, so that we can derive a metric to compare models with the data. Suppose we are in the limit of a very large number of FRBs, although with imprecise localization so the hosts are unknown. We expect the following relation to hold for the subsample \((I)\) of FRBs that have CGM
intersections:

$$\sum_{i \in z} [DM_i - \delta DM_i] w(DM_i - \delta DM_i) = \Delta DM.$$  \hspace{1cm} (7)

Here, unlike Equation (6), $\delta DM_i = \delta DM_i (b, M)$ models the excess DM from intervening CGMs in terms of the impact parameter $b$ and halo mass $M$ of each foreground galaxy (and not necessarily just one halo despite our notation).

We aim to find the model for $\delta DM_i$ that best describes the data. We therefore define a measure for the goodness of fit

$$\xi^2 = \left\{ \frac{\sum_{i \in z} [DM_i - \delta DM_i] w(DM_i - \delta DM_i)}{\Delta DM} \right\}^2.$$  \hspace{1cm} (8)

We can also take the expectation value of $\xi^2$ by randomly sampling the same number of intersections from the full DM distribution:

$$\langle \xi^2 \rangle = \left\{ \frac{\sum_i w(DM_i) DM_i - \Delta DM}{\Delta DM} \right\}^2,$$  \hspace{1cm} (9)

where the summation goes over the desired number of FRBs $N_{DM}$. Since $\langle \xi^2 \rangle$ is like the squared variance of the sample mean DM, it scales with $N_{DM}$ as $\langle \xi^2 \rangle \propto N_{DM}^{-1}$.

Our formalism still holds when dividing the FRBs into impact parameter bins based on their $b/R_{vir}$ values, as long as there are enough FRBs in a bin. For each radial bin $j$, we can calculate the $\chi^2$ statistic by dividing $\xi^2$ by $\langle \xi^2 \rangle$ in that bin:

$$\chi_j^2 = \frac{\xi_j^2}{\langle \xi^2 \rangle_j},$$  \hspace{1cm} (10)

which is a function of the set of impact parameters $b$. Summing these over radial bins gives the total:

$$\chi^2 = \sum_j \chi_j^2.$$  \hspace{1cm} (11)

The above is the procedure without accounting for localization error. However, for some of our intersections, the localization is comparable to the halo virial radius. To take account of the localization uncertainties, we calculate the marginalized $\chi^2$ value of bin $j$:

$$\exp(-\chi_j^2/2) = \int \exp\left(-\frac{1}{2} \frac{\xi_j^2}{\langle \xi^2 \rangle_j} \langle |b| \rangle \right) P(b) \, db.$$  \hspace{1cm} (12)

The total $\chi^2$ is

$$\exp(-\chi^2/2) = \int \exp\left(-\frac{1}{2} \sum_j \frac{\xi_j^2}{\langle \xi^2 \rangle_j} \langle |b| \rangle \right) P(b) \, db.$$  \hspace{1cm} (13)

We will calculate these $\chi^2$ values for different CGM models in Section 3.3.3.

3. Results

3.1. Choice of the Weighting Function Parameters

Before we measure the DM excess from intervening CGMs using the CHIME FRB catalog, we first determine the best values of $\alpha$, $\beta$ to use in our weighting function (Equation (1)). We thus examine how much reduction in the variance of the weighted-average DM our weighting function can give. To this end, we created a mock FRB catalog of size $10^5$ that has the same DM distribution as the CHIME catalog. We then randomly sample $N_{DM}$ FRBs from this mock catalog and for each sample calculate $\delta DM$ using Equation (5) for a range of $\alpha$, $\beta$ values. We repeat this step 10,000 times and compute the standard deviation (std) of $\delta DM$ for each $\alpha$, $\beta$.

The left panel of Figure 2 shows contours of the std of $\delta DM$ as a function of $\alpha$, $\beta$, obtained by randomly sampling $N_{DM} = 20$ FRBs from the CHIME DM distribution. Twenty is chosen to roughly match the number of CHIME FRBs with halo intersections, although we find that the contours of the std of $\delta DM$ remain mostly unchanged when assuming different $N_{DM}$ such as $N_{DM} = 100$. The gray shaded region represents $\alpha$, $\beta$ values that can lead to all zero weights to machine precision, for at least one out of the 10,000 times of random sampling (so that only one FRB receives any weight). The best estimator for mean DM when sampling 20 FRBs seems to be given by values near $(\alpha, \beta) = (100, 1)$ that lead to a factor of 2.2 in the estimator std relative to uniform weighting, but such a weighting falls off exponentially above the low value of DM $\sim 100$, selecting the few sightlines with the smallest DM. Therefore, the minimum variance estimator is close to selecting the minimum DM—for many distributions the minimum value in the DM array converges faster than the mean. However, the minimum DM is only useful for our estimate of the DM excess when there is intervening CGM. If the minimum-DM FRB actually originates from a nearby halo (e.g., the low-DM FRBs in Bhardwaj et al. 2021a, 2021b) instead of intervening from further away, the minimum DM becomes problematic. We thus explore $(\alpha, \beta) = (600, 4)$ and $(400, 1)$, which—while giving substantial weight to about half of the FRBs—still give a reduction by factors of 1.6 and 2 of the standard deviation relative to an unweighted estimator, respectively, and just modestly larger variances than the minimum variance $(\alpha, \beta) = (100, 1)$ of a 2.2 reduction.\(^9\)

The black lines in the middle panels of Figure 2 illustrate the DM histogram of the CHIME FRBs, and red lines represent these weighting functions in arbitrary units. From top to bottom we use uniform weighting, $(\alpha, \beta) = (600, 4)$, and $(\alpha, \beta) = (400, 1)$. Using $(\alpha, \beta) = (600, 4)$ has a much stronger cutoff at high DM values, leading to 20%–30% of the CHIME DM distribution contributing negligibly. The right panels of Figure 2 show the histograms of $\delta DM$ by randomly sampling 20 FRBs from mocks. Blue lines illustrate the histograms, and the orange lines represent Gaussian fits to the histograms. Also quoted are the standard deviations of $\delta DM$. Since $(\alpha, \beta) = (400, 1)$ gives a slightly more skewed distribution of the weighted-mean DM with a high-value tail, by default we use $(\alpha, \beta) = (600, 4)$, but we have verified that $(\alpha, \beta) = (400, 1)$ yields very similar stacked DM excesses and conclusions.

\(^9\) The bias factor $f$ of the estimator with $(\alpha, \beta) = (600, 4)$ is 0.65, while $(400, 1)$ is unbiased.
3.2. The Measured DM Excess

Using the FRBs that intersect halos, we measure their excess DM by using the estimator given by Equation (5) with $(\alpha, \beta) = (600, 4)$. The left panel of Figure 3 shows the DM distributions of the 26 FRBs that intersect $10^{11} - 10^{12} M_\odot$ halos (blue) within 1 $R_{\text{vir}}$, and the 30 FRBs intersecting $10^{12} - 10^{13} M_\odot$ halos (red). The black line represents the DM distribution of the whole CHIME sample. The gray dashed line represents our weighting function. The middle panel shows the probability distributions of the measured DM excess, centered on the solution of Equation (5) with the std determined by randomly sampling 26 (blue line) and 30 (red line) FRBs from the CHIME DM distribution respectively. The shaded regions indicate the $1\sigma$ and $2\sigma$ bounds of the distributions. The estimated DM excess is similar for both halo ranges, and the similar number of FRBs in each group.

Figure 3. Statistics of CHIME FRBs that intersect nearby $10^{11} - 10^{12} M_\odot$ (blue) and $10^{12} - 10^{13} M_\odot$ (red) halos within 1 $R_{\text{vir}}$. Left panel: the blue and red histograms show the DM distributions of the 26 and 30 FRBs intersecting the smaller and larger halo mass bins, respectively. The black line illustrates the DM distribution of the full CHIME sample. The gray dashed line represents our weighting function in arbitrary units, which is effectively multiplied by the DM distribution to calculate the stacked DM. Middle panel: the blue and red lines represent the likelihood of our estimator $\delta N$ with $(\alpha, \beta) = (600, 4)$ for the whole CHIME sample, where the central value is our measurement—the estimator applied to the observational data—and the Gaussian probability distribution function is calculated by randomly sampling the CHIME DM distribution with 26 and 30 FRBs respectively. Shaded regions show the $1\sigma$ and $2\sigma$ bounds of the distributions. Right panel: the same as the middle panel, except that we have excluded FRBs that intersect M31 and M33, which results in 20 FRBs intersecting $10^{12} - 10^{13} M_\odot$ ones.

Since our constraints are in the ballpark of the expected DM excess of the CGM, it is possible that they already rule out some CGM models. Given a model of the CGM, the radial profile of DM around a sample of halos has a one-halo term owing to the gas surrounding these halos themselves, and also a rather flat two-halo term coming from the overlapping of gas from other halos. We use the DM radial profiles calculated using the CGMBrush algorithm (Williams et al. 2023) for our $\chi^2$ calculation. This algorithm subtracts the dark matter associated with each halo in an $N$-body simulation and then adds on different models for the size of 30. This likely leads to the $t$-test returning $p < 0.05$ in Connor & Ravi (2021).

We performed the same analysis on the DM excess of FRBs intersecting halos within impact parameters of $1-1.5 R_{\text{vir}}$ and $1.5-2 R_{\text{vir}}$. We find that the FRBs intersecting $10^{11} - 10^{12} M_\odot$ halos continue to show a DM excess at $\geq 1\sigma$ level in these more extended radial bins, while the $10^{12} - 10^{13} M_\odot$ halos no longer show a DM excess there. Figure 4 summarizes our stacking results. Dots with error bars show the measured DM excess as a function of $b/R_{\text{vir}}$ assuming constant DM excess in each radial bin. Left and right panels illustrate results for the $10^{11} - 10^{12} M_\odot$ and $10^{12} - 10^{13} M_\odot$ halos, respectively. The values of $b$ used to plot the measurements are the weighted average of $b$ in each radial bin, with the weights given by our weighting function and the DM. As a reference for the expected DM excess, this figure also shows the radial DM profiles for a model in which the CGM gas traces the Navarro–Frenk–White (NFW) profile and another where it is distributed as a top-hat model with radius of $2 R_{\text{vir}}$ (STH2). Our DM excess measurements are largely consistent with the model predictions. Both models are discussed in what follows.

3.3. Comparison with CGM Models

Since our constraints are in the ballpark of the expected DM excess of the CGM, it is possible that they already rule out some CGM models. Given a model of the CGM, the radial profile of DM around a sample of halos has a one-halo term owing to the gas surrounding these halos themselves, and also a rather flat two-halo term coming from the overlapping of gas from other halos. We use the DM radial profiles calculated using the CGMBrush algorithm (Williams et al. 2023) for our $\chi^2$ calculation. This algorithm subtracts the dark matter associated with each halo in an $N$-body simulation and then adds on different models for the
distribution of the gas associated with that halo. It assumes that gas outside halos traces the dark matter. Using these models for the DM excess, we calculate $\chi^2$ values using Equations (8) and (12) for FRBs in each of the three radial bins [0, 1], [1, 1.5], and [1.5, 2], in units of $R_{\text{vir}}$. To speed up the calculation, we restrict to using FRBs that lie within $(2R_{\text{vir}} + 3 \times 0.2')$ of galaxies, where $0.2'$ is the typical localization error of CHIME. As mentioned in Section 2.1, we count an FRB only once if it intersects multiple halos. Counting galaxy–FRB pairs instead leads to somewhat larger $\Delta \chi^2$, but with differences smaller than 1–2. To evaluate the high-dimension integral on the right-hand side of Equation (12) or Equation (13), we draw from a 2D Gaussian for the location of each FRB on the sky plane so that the draws trace $P(b)$ and sum up $10^5$ realizations for a Monte Carlo evaluation.

We perform this $\chi^2$ calculation for the STH2 model of the CGM where the gas is distributed as a top hat with radius of $2 R_{\text{vir}}$ and the NFW model. These extreme models roughly bound the DM excess predicted by the more realistic models in Williams et al. (2023). The STH2 model has only an eighth of the halo-associated baryons within $1R_{\text{vir}}$ whereas the NFW contains all of them within $1R_{\text{vir}}$. Indeed, owing to its diffuseness, we find that the STH2 DM excess is shaped at most radii by the two-halo term and not the halo profile. Figure 4 illustrates DM excess as a function of $b/R_{\text{vir}}$ predicted by the NFW (blue lines) and the STH2 (orange lines) models. These illustrative curves in the left and right panels assume halo masses of $4 \times 10^{11} M_\odot$ and $4 \times 10^{12} M_\odot$ respectively, roughly the mean of our two halo samples. Despite these two profiles having very different assumptions for the halo-associated baryons, these models give similar predictions outside $0.5 R_{\text{vir}}$, with DM differences smaller than 50 because of the large two-halo excess that depends weakly on the halo gas profiles. Our sample contains only seven and four FRBs intersecting the small and large halo mass bins with $b < 0.5 R_{\text{vir}}$ respectively. The STH2 model predicts a flat DM excess of 30–50 at $0.5–1R_{\text{vir}}$ for the $10^{11}–10^{12} M_\odot$ halos, and 50–80 for the $10^{12}–10^{13} M_\odot$ halos. The NFW model produces 30–50 pc cm$^{-3}$ higher DM excess than the STH2 model. The two-halo term is about 30–50 for both halo mass bins outside $1R_{\text{vir}}$. Because the DM differences among models are only $\lesssim 50$, we expect the $\chi^2$ values of these two models (and other models in Williams et al. 2023) to differ only at $<1\sigma$ level.

Table 2 lists the $\chi^2$ values as well as their differences, $\Delta \chi^2$, in each radial bin. It also lists the total $\chi^2$ summing over all bins. By default, we calculate $\chi^2$ by marginalizing localization errors, but we show the $\chi^2$ computed using maximum likelihood localization in parentheses (i.e., assuming $P(b)$ is a $\delta$-function at the best-fit value). Not marginalizing over localization errors generally changes the results at the $<1\sigma$ level, but in some cases the differences are somewhat larger, showing that accounting for positional errors is important. The $\Delta \chi^2$ values are calculated by subtracting $\chi^2$ of the STH2 or NFW model from that of the model with no DM excess. We have also verified that further dividing the radial bins (but keeping at least 15–20 FRBs in a bin) does not affect the $\Delta \chi^2$ values. With three radial bins we would expect total $\chi^2 \sim 3$, and the models produce a slight overfit of total $\chi^2 \sim 1.5$.

The $\chi^2$ in all radial bins of the $10^{11}–10^{12} M_\odot$ halos disfavours the model with no DM excess at $\sqrt{\Delta \chi^2} \approx 1 \sigma$ level, although the significance level drops when excluding M33. The total $\chi^2$ of NFW and STH2 models considering all bins is smaller than that of the case with no DM excess by 2–5, regardless of marginalizing over the localization uncertainties or using maximum likelihood localization. Thus the

$\chi^2$ values in individual bins.

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$^{10}$ To compute the total DM excess for an FRB for the few sightlines that have multiple intersections, we first sum up the one-halo terms from all the nearby $10^{11}–10^{12} M_\odot$ halos that this FRB can intersect along its sightline. We compute an average two-halo term using these halos and add to the total excess DM, since an FRB may intersect multiple halos at $>1R_{\text{vir}}$. It perhaps makes the most sense to take the maximum value of the two-halo terms if the intersecting halos are within several impact parameters, and to sum the two-halo terms if halos are further apart than several impact parameters. However, the exact algorithm does not affect our results by $\Delta \chi^2 > 1$.

$^{11}$ We note that technically $\chi^2 \geq \sum_{i} \chi_i^2$ with equality achieved when $P(b)$ is a delta function. This is why the total $\chi^2$ differences are larger than summing up the $\Delta \chi^2$ values in individual bins.
significant for a DM excess is preferred over no excess ranges from 1.4σ to 2.2σ. The 10^{12–13} M_{⊙} halos, on the other hand, favor a DM excess only in the [0, 1] R_{vir} bin and cannot distinguish any models for the larger impact parameter bins. The Δχ^2 values are consistent with our results in Figure 3. Finally, the χ^2 of the STH2 and NFW models are very similar, as anticipated, and so not distinguishable by the data.

### 3.4. How Many FRBs are Needed to Get a Significant Detection of DM Excess?

Thus, we have found a marginal detection of an excess DM when stacking on foreground halos, but the data set of 453 FRBs is insufficient to distinguish between realistic CGM models. Larger samples are of course required to get a more significant detection of a given DM excess of 50–100—the anticipated DM excess for the CGM of 10^{11–13} M_{⊙} halos—and this is also the difference between viable models for b < 0.5 R_{vir}. Since we currently get an error bar in DM of 50 with ∼30 intersections, we anticipate that the error bar scales with the number of intersections as σ_{DM} = 50 \sqrt{30/N_{DM}} pc cm^{-3}, where N_{DM} is the number of intersections (which was approximately 30 in our stacks).

We have also calculated the likelihood of different CGM models given the CHIME FRB data. All models are favored by the data at 1.4σ–2.2σ over a model with no DM excess, consistent with our measurements of a DM excess. We find that viable models for the CGM gas distribution produce DM differences smaller than 50 outside 0.5 R_{vir} because of the importance of the two-halo term around 10^{11–13} M_{⊙} halos. Owing to the paucity of intersections at these impact parameters, a large increase in the number of FRBs to at least 10,000 would be needed to discriminate between viable CGM model with our method that stacks on nearby galaxies.

In the next few years, our weighted stacking method will continue to be a valuable tool to detect and measure the CGM of nearby halos as more data from CHIME arrive, especially for the relatively low-mass ones as we considered here, whose CGM is hard to probe in any other way. For a different data set with a different DM distribution, one can recalibrate a weighting function suitable for the shape of the distribution and geared more toward measuring the halos of interest.
weighted stacking. In particular, the intergalactic contribution might be modeled with a reconstruction of the underlying density field (e.g., Burchett et al. 2020; Lee et al. 2022). This may be particularly useful when dealing with FRBs that originate way beyond the local universe so that they have multiple halo intersections and have large total DM (e.g., FRBs from $z > 0.1$, Lee et al. 2022), which is a regime where our weighted stacking becomes less powerful. The improved angular resolution of these surveys will also allow stacking on galaxies that are further away than in this study. Another interesting related direction is to constrain the fraction of cool ionized gas via scattering and lensing of FRBs (Prochaska et al. 2019; Vedantham & Phinney 2019).

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Software: astropy (Astropy Collaboration et al. 2013), CIGALE (Boquien et al. 2019), PATH (Aggarwal et al. 2021).

Appendix
Possibility of FRBs Originating from Nearby Halos

While we have implicitly assumed that all the FRBs used in this work should originate from halos further away than 40–80 Mpc, it is likely that some FRBs may come from nearby halos, especially low-DM (DM $\lesssim 100$) ones (Bhardwaj et al. 2021a, 2021b). Even for FRBs with DM of several hundred, it is not unlikely that they are from nearby galaxies because the host DM may well be a few hundred (Table 2 of Cordes et al. 2022).

To address this issue, we ran the Probabilistic Association of Transients to Hosts (PATH) code\(^{12}\) to determine which FRBs might originate from <80 Mpc galaxies (Aggarwal et al. 2021). PATH calculates the probability that an extragalactic transient source is associated with a candidate host galaxy using the Bayes’ rule. For each FRB, we take all <80 Mpc galaxies in GWGC that lie within three times the R.A.–decl. error bars of the FRB to be the candidates that the FRB can be associated with. Instead of using the “inverse” prior that assumes brighter galaxies have higher probabilities, we adopt a uniform prior. We assume that the distribution of FRBs around galaxies follows an exponential profile, where the size of the exponential function is given by the tabulated major and minor diameters of galaxies in GWGC. PATH then integrates over the FRB localization ellipse, and finds the galaxy with a >0.95 posterior to be the most likely host of the FRB. It does not take into account the FRB DM, however.

For the 26 (30) FRBs that we find to pass through nearby $10^{11}$–$10^{12} M_\odot$ ($10^{12}$–$10^{13} M_\odot$) halos at $<1 R_{\text{vir}}$, PATH shows that 5 (1) of them might originate from these halos themselves, but one has DM over 1000 so is unlikely to have a nearby origin. We find seven more FRBs likely associated with the intersected galaxies when focusing on $b < 2 R_{\text{vir}}$, and three FRBs may arise from halos closer to the ones they are found to intersect. We thus performed our measurement of DM excess again without these FRBs identified, and find that our main conclusions remain unchanged. The PATH code, however, is only a rough way of estimating the probability of FRBs being associated with galaxies, and much more careful visual inspection of the locations of galaxies versus the localization contours of FRBs should be done before drawing conclusions.

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\(^{12}\) https://github.com/FRBs/astopath