Measuring Dark Matter in Galaxies: The Mass Fraction within Five Effective Radii

William E. Harris1, Rhea-Silvia Remus2, Gretchen L. H. Harris3, and Iv. U. Babyt4

1 Department of Physics and Astronomy, McMaster University, Hamilton, ON L8S 4M1, Canada; harris@physics.mcmaster.ca
2 Universitäts-Sternwarte München, Scheinerstraße 1, D-81679 München, Germany
3 Department of Physics and Astronomy, Waterloo Institute for Astrophysics, University of Waterloo, Waterloo, ON N2L 3G1, Canada
4 Main Astronomical Observatory of the National Academy of Sciences of Ukraine, 27 Zabolotnoho str., Kyiv 03143, Ukraine

Received 2020 April 7; revised 2020 October 20; accepted 2020 October 21; published 2020 December 9

Abstract

Large galaxies may contain an “atmosphere” of hot interstellar X-ray gas, and the temperature and radial density profile of this gas can be used to measure the total mass of the galaxy contained within a given radius $r$. We use this technique for 102 early-type galaxies with stellar masses $M_\star > 10^{10}M_\odot$, to evaluate the mass fraction of dark matter (DM) within the fiducial radius $r = 5r_e$, denoted $f_\text{DM} = f_\text{DM}(5r_e)$. On average, these systems have a median $\overline{T_5} \approx 0.8-0.9$ with a typical galaxy-to-galaxy scatter $\pm 0.15$. Comparisons with mass estimates made through the alternative techniques of satellite dynamics (e.g., velocity distributions of globular clusters, planetary nebulae, satellite dwarfs) as well as strong lensing show encouraging consistency over the same range of stellar mass. We find that many of the disk galaxies (S0/SA0/SB0) have a significantly higher mean $f_5$ than do the pure ellipticals, by $\Delta f_5 \approx 0.1$. We suggest that this higher level may be a consequence of sparse stellar haloes and quieter histories with fewer massive episodes of feedback or mergers. Comparisons are made with the Magneticum Pathfinder suite of simulations for both normal and centrally dominant “Brightest Cluster” galaxies. Though the observed data exhibit somewhat larger scatter at a given galaxy mass than do the simulations, the mean level of DM mass fraction for all classes of galaxies is in good first-order agreement with the simulations. Finally, we find that the group galaxies with stellar masses near $M_\star \sim 10^{11}M_\odot$ have relatively more outliers at low $f_5$ than in other mass ranges, possibly the result of especially effective AGN feedback in that mass range leading to expansion of their DM halos.

Unified Astronomy Thesaurus concepts: X-ray surveys (1824); Galaxy masses (607); Baryonic dark matter (140); Galaxy dark matter halos (1880)

Supporting material: machine-readable tables

1. Introduction

The total mass and mass profile of a galaxy are fundamental tracers of its evolutionary history. However, because most of the mass of a galaxy is in the form of dark matter (DM), the mass profile must be determined indirectly through the use of visible tracers of various kinds.

The DM fraction of mass within a given radius $r$ is simply

$$f_\text{DM}(r) = 1 - \frac{M_{\text{bary}}(r)}{M_{\text{tot}}(r)},$$

where $M_{\text{bary}}$ and $M_{\text{tot}}$ denote the total baryonic mass and total gravitating mass within $r$. In most galaxies, the stellar mass is more centrally concentrated than the DM halo, therefore $f_{\text{DM}}$ should increase with $r$ (e.g., Deason et al. 2012; Tortora et al. 2014; Alabi et al. 2016, 2017). However, in addition, recent theory indicates that the ratio of baryonic mass to DM within a given radius should also depend on galaxy total mass, environment, and evolutionary history including the epochs and amounts of gas infall, merging, and feedback; see the references cited above, as well as Wojtak & Mamon (2013), Hirschmann et al. (2014), Remus et al. (2017b), D’Souza & Bell (2018), Elias et al. (2018), Lovell et al. (2018), Monachesi et al. (2019), and Tortora et al. (2019), among others. Observational measurements of $f_{\text{DM}}$ can therefore provide markers of those histories.

The radius $r$ is often normalized in units of the effective radius $r_e$ of the stellar light that encloses half the (projected 2D) total luminosity; most recent discussions (see the papers cited above) have tended to focus on $f_{\text{DM}}$ within fiducial radii of either $1r_e$ or $5r_e$. The radius of $5r_e$ encloses a large volume well outside the merger and star-forming activity often contained within the bulge and inner halo (roughly, $r \lesssim 2r_e$). At radii as large as $5r_e$ and beyond, the recent models and simulations indicate that we should expect a relatively high mean DM fraction, but perhaps with outliers at lower $f_{\text{DM}}$ that preserve the record of the most major merger, feedback, or accretion events (see Deason et al. 2012; Wojtak & Mamon 2013; Forbes et al. 2017; Remus et al. 2017b; Lovell et al. 2018).

Comparisons between theoretical models and observational data can now be done through high-resolution simulations of galaxy formation rather than simpler analytical models; and on the observational side, the amount and quality of measured mass profiles is steadily increasing. For early-type galaxies (ETGs), direct measurement of $M(r)$ has most often been done through the radial velocity distributions of satellites such as old halo stars, globular clusters (GCs), planetary nebulae (PNe), or dwarf satellite galaxies. For the Milky Way, tangential velocities (from proper motions) can be added to the mix, enabling narrower constraints on the phase-space distributions of its satellites. Many analytical methods have been developed for external galaxies, including the Projected Mass Estimator (PME), the Tracer Mass Estimator (TME), solutions of the Jeans equations, orbit libraries and made-to-measure codes, or the distribution function in phase space (see Rix et al. 1997; Wu & Tremaine 2006; de Lorenzi et al. 2007; Napolitano et al. 2009; Romanowsky et al. 2009; Watkins et al. 2010; Deason et al. 2012; Cappellari et al. 2013; Courteau et al. 2014; Alabi et al. 2017; Eadie & Juric 2019, among others).
Well-known uncertainties affecting these methods include the anisotropy of the tracer orbital distributions (since only the radial velocities of the tracers are measured), the slope of the gravitational potential, and the presence of substructure among the tracers, all of which can differ strongly and unpredictably from one target galaxy to another. In addition, at larger radii the estimated \( M(r) \) may depend heavily on small numbers of tracers that lie at the largest observed radii. These issues and others are discussed at length by Alabi et al. (2016, 2017) (hereafter denoted A16, A17) and in the other papers cited above.

High-mass galaxies (Milky Way–sized and above) may also hold significant amounts of diffuse, hot interstellar X-ray gas. Using the temperature and density distribution of this gas opens up an entirely different approach for deducing the mass profile of its host galaxy (e.g., Bahcall & Sarazin 1977; Fabricant & Gorenstein 1983; Nulsen & Bohringer 1995; Irwin & Sarazin 1996; Brighenti & Mathews 1997; Loewenstein & Mushotzky 2003; Fukazawa et al. 2006; Babyk et al. 2018; Harris et al. 2019, among many others). Such work has added substantial evidence for the presence of DM at scales ranging from individual galaxies out to their larger groups and clusters. There are now enough individual galaxies with X-ray studies in the literature to permit a new look at the pattern of DM mass fractions at radii reaching the outer halo.

Both the X-ray gas method and the tracer satellite method have uncertainties and potential biases for deriving \( M(r) \) (which represents the depth of the potential well that ultimately drives both the gas temperature and the amplitude of the satellite motions). These will be discussed further below. Perhaps the most important point to highlight, however, is that the two methods have different inbuilt biases and uncertainties and are encouragingly close to being physically independent. Comparisons between them should therefore be worthwhile. Direct comparisons of the estimates of \( M(r) \) from satellite dynamics and X-ray gas have been done for only a handful of relatively nearby, giant galaxies (e.g., Cohen & Ryzhov 1997; Côté et al. 2003; Bridges et al. 2006; Schuberth et al. 2006; Romanowsky et al. 2009; Longobardi et al. 2018, among others), all of which have rich GC and PNe populations. These detailed individual studies are extremely valuable. However, detection and characterization of large-scale trends of DM fraction with galaxy mass and morphology, and follow-up comparison with galaxy evolution modeling, require much larger observational samples.

Our present paper has two primary goals: (1) We compare measurements of the DM mass fraction \( f_{DM} \) obtained by the X-ray gas method with two other very different methods, satellite dynamics and strong lensing, using previously published data from the recent literature. (2) We assess how well these current sets of data agree with one particular suite of theoretical realizations for galaxy formation, the recent Magneticum Pathfinder simulations from which \( f_{DM} \) can be predicted (i.e., Remus et al. 2017b). Our findings are that there is now excellent first-order concordance among these simulations and the different observational methods, but interesting differences in detail show up that may be connected with the evolutionary histories as well as features of the simulations.

The outline of this paper is as follows. In Section 2, we provide background on the data for the various mass parameters. Section 3 shows the resulting \( f_{DM} \) distributions versus galaxy mass. Section 4 gives an overall discussion and comparison with selected model simulations. In Sections 5–7, we provide an overview, prospects for the next steps in this investigation, and a summary.

A distance scale \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \) is assumed throughout this discussion. For convenience, in what follows, we denote \( f_{DM}(5r_e) \) more concisely as \( f_s \). We also denote \( M_{\text{tot}}(5r_e) \), the total gravitating mass within \( 5r_e \), simply as \( M_\text{s} \). We will also refer to the enclosed masses derived from either the X-ray gas profiles or the dynamics of tracer objects (GCs, PNe, dwarf satellites) as simply the “X-ray” and “Satellite” masses in the various figures and discussion to follow.

## 2. The Data

In Harris et al. (2019) (hereafter H19), we discussed a subset of 45 galaxies for which information about both their X-ray atmospheres and their GC populations is available. These 45 comprise the galaxies that appear in both the GC system catalog of Harris et al. (2013) and the X-ray list of Babyk et al. (2018) (hereafter B18). H19 derived correlations among mass and total gravitating mass within \( 5r_e \), total stellar mass \( M_* \), GC system mass \( M_{\text{GCs}} \), and total halo (virial) mass \( M_h \) and finally the correlations of \( f_s \) with both \( M_* \) and \( M_h \). We found that almost 90% of this restricted sample fell along a consistent mean level of \( f_s = 0.83 \), with a dispersion of only \( \sigma(f_s) = 0.07 \) and a handful of outliers falling below \( f_{DM} \lesssim 0.6 \). This pattern, though still sketchy, proved to be strikingly similar to predictions from two recent hydrodynamical simulations, specifically the Magneticum Pathfinder suite (Remus et al. 2017b), and the Illustris TNG suite (Lovell et al. 2018).

The observational correlation of \( f_s \) with \( M_* \) has also recently been analyzed by A16 and A17 from their velocity measurements for GCs, combined with PNe velocities from the previous literature, as satellite tracers. In their results, 32 individual galaxies yielded \( f_s \) values that spread across almost the entire physically permitted range, from \( f_s \lesssim 0.1 \) up to nearly 1.0. Although 2/3 of these fall in the range \( f_s \sim 0.6 \sim 0.9 \), the remaining 1/3 scatter to much lower values, and no clear systematic trend with total stellar mass is seen (in particular, see Figure 2 of A17). Clearly, analyses of larger samples of galaxies are desirable.

In the present paper, we drop any restrictions on comparisons with GC/PNe satellite populations and concentrate on results from X-ray data alone. B18 provide a homogeneous set of measurements of the total X-ray radial profiles, the gas mass \( M_X \), and \( M_5 \) for 94 relatively massive galaxies nearer than \( \sim 200 \text{ Mpc} \). The great majority of these are ETGs (ellipticals or S0 disk galaxies), but the sample also includes a few late-type galaxies (LTGs) that happen to have measurable amounts of X-ray gas. They cover the full range of galaxy environments, from relatively isolated systems up to BCGs (Brightest Cluster Galaxies) and BGGs (Brightest Group Galaxies) at the centers of clusters; we will refer to those giants as “centrals” and the other galaxies as “normals.” From this list of 94, we have deleted 16 with the most uncertain measurements (see below), leaving 78 systems. We have, however, added 24 more ETGs with Chandra data newly measured through exactly the same procedures by I. V. Babyk (2020, in preparation), making a final total of 102 galaxies with measured mass distributions based on their X-ray gas content. This sample is significantly larger than the one in H19 and covers a wider mass range.

Basic parameters for this target list are given in Table 1, including: the galaxy identification; group or cluster environment; Hubble type; de Vaucouleurs T-type; location on the sky (R.A., Decl. for J2000); foreground extinction \( A_V \); distance D;
and effective radius \( r_e \). These parameters are drawn from the HyperLeda catalog, except for the environments and foreground extinctions, which are taken from NED (NASA Extragalactic Database). In cases where no entry is given for the environment, the galaxy is relatively isolated or part of a very small group. For the effective radii \( r_e \), we used optical Digitized Sky Survey (DSS) images for our own measurements, as noted in B18. We extracted 10′ × 10′ images of each galaxy and determined surface brightness profiles centered on the peak of the optical emission through a curve-of-growth technique. We obtained the background level at large radius by fitting a constant to the brightness profile, and performed numerical integration to define the total optical flux as the emission above background by 5\( \sigma \), and finally determined the uncertainties on \( r_e \) by running 1000 Monte Carlo realizations.

2.1. X-Ray Measurements

For the X-ray data, full discussions of the measurements and data reduction are given in B18 and H19, and we provide only a brief summary here. Chandra X-ray observations with \( > 10^3 \) ks exposures of the target galaxies were used to extract exposure- and background-corrected images in the 0.5–6.0 keV energy band. Point sources and other non-X-ray-gas features were detected and then removed by applying the wavdetect routine.

The radial profiles were fitted with a single \( \beta \)-model (Cavaliere & Fusco-Femiano 1978; Gorenstein et al. 1978) yielding a gas density profile

\[
\rho_g(r) = \rho_0 \left( 1 + \left( \frac{r}{r_c} \right) \right)^{-3/2},
\]

(2)

where \( \rho_0 = 2.21 \mu m_p n_0 \) is the central gas density that can be found from the emissivity profile (e.g., Ettori 2000, B18), \( n_0 \) is the central number density, and \( r_c \) is the core radius of the density profile. The index \( \beta \) refers physically to the ratio of specific energies of the stellar component to the gas (see the references cited above), but acts as a free parameter for the fit. The hot-gas mass within radius \( r \) results from integration of the gas density profile as

\[
M_X(r) = 4\pi \rho_0 \int_0^r r^2 \left( 1 + \left( \frac{r}{r_c} \right) \right)^{-3/2} \, dr.
\]

(3)

Finally, the total gravitational mass within \( r \) is calculated from the condition of hydrostatic equilibrium,

\[
M_{\text{tot}}(r) = -\frac{kT_r}{G \mu m_p} \left( \frac{d \ln \rho_g}{d \ln r} \right).
\]

(4)

The implicit assumptions of hydrostatic equilibrium and isothermality are used throughout (see B18). At large radii well outside the X-ray core \( r_c \), the expression for total mass simplifies to \( M_{\text{tot}}(r) \sim 3.3kT_r/G\mu m_p \) as long as the gas follows the \( \beta \)-model density profile.

In all cases, the gas component as we use it here refers to the hot gas within the galaxy (its X-ray “atmosphere”), and is restricted to within the fiducial radius of 5\( r_c \). It does not include any gas at larger radii, such as any cooler material, nor any intracluster medium (ICM). We note that the ICM is most strongly present in rich clusters, but most of our target galaxies are not in such environments.

As hinted above, this approach to measuring both \( M_X \) and \( M_{\text{tot}} \) has its own set of intrinsic uncertainties. For the least massive galaxies in our candidate list, the X-ray emission falls in the low-temperature regime \( kT_X \lesssim 0.5 \) keV, where the Chandra instruments are less sensitive and the luminosity \( L_X \) is also low. Departures from hydrostatic equilibrium in the inner regions of the bulge and halo, due particularly to cavities and shockwaves embedded in the gas distribution, may also be present to different degrees in different galaxies. Nonsphericity of the gas profile is not a major concern: various recent studies have shown that spherical averaging of an ellipsoidal mass profile typically introduces only small biases for global quantities such as total mass and gas fraction, in X-ray hydrostatic equilibrium studies of galaxy and cluster masses (e.g., Buote & Humphrey (2012a, 2012b) and references therein). In the case of the massive elliptical NGC 6482, Buote & Barth (2019) also found such small biases to be negligible compared to the statistical uncertainties. Buote & Humphrey (2012a) (see also Churazov et al. (2008)) showed that spherical averaging in a hydrostatic equilibrium analysis introduces zero bias in the inferred mass for any gas temperature profile. However, the baryon physics associated with assumed gas properties and uncertainties in the heating and cooling rates introduced by feedback may also be kept in mind (Fabjan et al. 2011). Considering these observational limitations, we do not include in our list those galaxies with \( kT < 0.4 \) keV and \( L_X \sim 0.4 \times 10^{40} \) erg s\(^{-1} \); that is, the lowest-temperature and lowest-luminosity systems for which the \( \beta \)-model fits and mass measurements are the weakest. Galaxies falling below those thresholds show noticeably increased scatter among the various correlations between mass, temperature, and luminosity (see B18). We do, however, include NGC 1052 and NGC 1387 (both with \( kT_x \simeq 0.45 \) keV), for which the raw data are of unusually high quality and the profiles well-determined. After these cuts, we are left with 102 target galaxies.
2.2. Stellar and Halo Masses

For the purpose of the present analysis, we have recalculated the total stellar mass \( M_* \) and halo mass \( M_h \) of each target galaxy, to update the previous values used in H19 that were drawn in turn from Harris et al. (2013) and Hudson et al. (2014). The value of \( M_* \) is determined from the total K-band and V-band luminosities of each galaxy along with mass-to-light ratios that are calibrated functions of integrated color (representing morphological type), as given by Bell et al. (2003). Specifically, these are

\[
\log(M/L_K) = -0.356 + 0.135(B - V)_0, \tag{5}
\]

\[
\log(M/L_V) = -0.778 + 1.305(B - V)_0, \tag{6}
\]

where \((B - V)_0\) is the intrinsic (dereddened) integrated color. The adopted Solar absolute magnitudes are \( M_{K,0} = 3.32, M_{V,0} = 4.82\). We adopt here the scaling for the stellar IMF defined by Chabrier (2003) and Kroupa (2002), using the offsets given in Bell et al. (2003) that are needed to convert their nominal “diet Salpeter” IMF into the Chabrier/Kroupa scale. Though empirically the two ways of defining \( M_* \) through either \( L_K \) or \( L_V \) are very consistent with one another for ETGs that are dominated by an old population with little or no recent star formation, double weight is given to the \( K \)-band estimate since it conventionally represents the total stellar mass better for most galaxies.

Calculation of halo mass \( M_h \) follows the prescriptions in Hudson et al. (2015) (see Appendix C therein). Given \( M_* \), the stellar-to-halo mass ratio SHMR is calculated with their “Default” set of functional parameters, extrapolated to redshift \( z = 0 \). With this set of adopted parameters, their expression for the SHMR (\( \sim M_*/M_h \)) simplifies to

\[
\frac{M_*}{M_h} = 0.0454 \left[ \frac{M_*}{M_\odot} \right]^{-0.43} \left[ \frac{M_h}{M_\odot} \right]^{1.07 - 1}, \tag{7}
\]

where the pivot mass is \( M_\odot = 10^{10.76} M_\odot \). This transformation is quite similar in form to other recent expressions for the SHMR (e.g., Leauthaud et al. 2012; Behroozi et al. 2013; Moster et al. 2013), and the particular version does not affect any of the conclusions discussed below. Hudson et al. (2015) implicitly use the Chabrier IMF (see Veltander et al. 2014), so no further adjustment to their mass scale is needed.

In Table 2, the compiled quantities for the observational sample of galaxies are listed, including the luminosities \((M_V, M_K)\), the predicted Sérsic index \( n \) (see below), the resulting masses \((M_*, M_K, M_5, M_h)\), and finally the DM mass fraction \( f_5 = f_{DM}(5r_\epsilon) \).

2.3. Predicted Mass Ratios from Simulations

As noted above, our observational sample of galaxies ranges from nearly isolated systems to giant central galaxies in rich environments, so it will be useful to compare the results with simulated galaxies that cover a similar range. To compare observations with theory, in this paper we concentrate particularly on galaxies from the cosmological hydrodynamical Magneticum’ Pathfinder simulations (K. Dolag et al. 2020, in preparation, but see also Hirschmann et al. 2014). This is a set of several cosmological simulation volumes (from (2688 Mpc/h)³ to (48 Mpc/h)³) with different resolutions extending from \( m_{Gas} = 2.6 \times 10^8 M_\odot/h \) to \( m_{Gas} = 7.3 \times 10^5 M_\odot/h \), performed with a modified Gadget-3 version using a WMAP7 ΩCDM cosmology (Komatsu et al. 2011) with parameters \( \sigma_8 = 0.809, h = 0.704, \Omega_m = 0.272, \Omega_k = 0.272, \Omega_b = 0.0451 \). Small changes in the cosmological parameters on the order of the difference between those used for Magneticum and those from Planck (\( \sigma_8 = 0.811; \) Planck Collaboration et al. 2020) have no significant impact on the DM fractions used in this work, as the changes are too small to noticeably change the DM halo concentration parameters; see Ragagnin et al. (2020).

Baryonic physics is included in the Magneticum simulations as subgrid physics, which are described in detail by Teklu et al. (2015). The underlying IMF used for Magneticum is a Chabrier IMF, though this does not influence the calculations of the stellar mass of the galaxies, as the IMF is only used to calculate stellar feedback and other quantities related to stellar evolution, but the stellar mass of a particle does not change once it is born. Structures are identified with a modified version of SUBFIND (Springel et al. 2001; Dolag et al. 2009). For the comparison performed in this work, we use central halo galaxies from two simulations with different resolutions:

1. For a general population of field galaxies (the “normals”), we select galaxies from Box4, which has a size of (48 Mpc/h)³ and mass resolutions for the DM, gas, and stellar particles of \( m_{DM} = 3.6 \times 10^8 M_\odot/h \), \( m_{Gas} = 7.3 \times 10^5 M_\odot/h \), and \( m_\star \approx 2 \times 10^5 M_\odot/h \). The gravitational softening length of this simulation at \( z = 0 \) is \( \epsilon_{DM} = \epsilon_{Gas} = 1.4 \text{ kpc}/h \) for DM and gas particles, and \( \epsilon_\star = 0.7 \text{ kpc}/h \) for stellar particles. To
ensure that the half-mass radii of the galaxies used in this work are well-resolved, we use a lower total stellar mass limit of $M_\ast > 2 \times 10^{10} M_\odot$, and select all central galaxies above this mass threshold. These galaxies have already been used in several publications, and for more details on their global and kinematic properties, see Teklu et al. (2015) and Schulze et al. (2018). Regarding stellar masses, sizes, and DM fractions within the half-mass radius for the spheroidal galaxies in this sample of galaxies, we refer the reader to Remus et al. (2017b) and A17. While this simulation has enough resolution to study the population of “normal” galaxies, the box size is too small to include massive galaxy clusters and thus BCGs, and it includes only a few galaxy groups with their BGGs. Therefore, to study the “BCG” counterparts, we have to use a simulation volume different from the Magneticum fielder set.

2. For the simulated sample of centrals (BCG/BGG) in this work, we select galaxies from Box2, which has a size of $(640 \text{ Mpc}/h)^3$ and mass resolutions of $m_{\text{DM}} = 6.9 \times 10^9 M_\odot/h$, $m_{\text{Gas}} = 1.4 \times 10^9 M_\odot/h$, and $m_\ast = 3.5 \times 10^7 M_\odot/h$. The gravitational softening lengths of this simulation at $z = 0$ are $\epsilon_{\text{DM}} = \epsilon_{\text{Gas}} = 3.75 \text{ kpc}/h$ and $\epsilon_\ast = 2 \text{ kpc}/h$ for DM, gas, and stellar particles, respectively. We select all central galaxies in halos with total masses $M_{\text{tot}} > 5 \times 10^{13} M_\odot$, to ensure sufficient resolution. For more details on this specific simulation and its clusters, see Remus et al. (2017a) and Lotz et al. (2019). Further properties of the centrals in this sample are discussed by Remus & Forbes (in preparation). While for this simulation the resolution is not high enough to study Milky Way–like galaxies, the BCGs are well-resolved. For both sets of simulated galaxies, the properties compared in this work are calculated in the same way. Halo masses $M_h$ are calculated as the sum of all particle masses (DM, gas, and stars) within the virial radius, with only the substructures identified by Subfind subtracted from the halo.

Determining the “real” stellar masses of the simulated galaxies is, however, more of an issue. For the observed galaxies, the stellar mass $M_\ast$ is derived from the observed luminosities, and the problem is to estimate the halo mass $M_h$ with a transformation such as the one in Equation (7). On the theory side, the problem is essentially the opposite: the halo (virial) mass is well-known from the simulations, but a way to estimate $M_\ast$ needs to be defined because the total stellar mass within the virial radius (i.e., the “real” mass) is usually not what can be observed (especially for BCGs and their ICL). Therefore, criteria need to be applied in order to mimic the observational limitations. Because we do not a priori know the definitively correct approach to this, we consider four different ways, described below, to estimate the stellar mass in order to understand how the the DM fractions may be influenced.

For each of these given stellar mass definitions, we sort the stellar particles radially and sum up their masses until half of the given $M_\ast$ is reached. The corresponding radius defines the half-mass radius $R_{1/2}$ as an analog to the observed half-light radius. Given the half-mass radius, the DM fraction within $5 R_{1/2}$ is then calculated from the particles in the simulation directly as

$$f_\ast = f_{\text{DM}}(5 R_{1/2}) = \frac{M_{\text{DM}}(5 R_{1/2})}{M_{\text{DM}}(5 R_{1/2}) + M_\ast(5 R_{1/2}) + M_{\text{Gas}}(5 R_{1/2})}. \quad (8)$$

The four different stellar mass definition are:

1. $M_1^1$: Inverting Equation (7), we calculate the stellar mass of the galaxy from the total halo mass, in a method analogous to that used for the observations to calculate the total halo mass. While this approach ensures self-consistency of both observations and simulations, we also ignore the scatter in the SHMR and subsequently we underestimate the stellar mass and therefore systematically overestimates $M_\ast$.

2. $M_2^2$: The stellar mass is calculated as all stellar particles within the virial radius, with only the substructures (as identified by Subfind) subtracted. This method is most realistic for the field galaxies. However, for the BCGs, it adds the full mass of the ICL within the virial radius to the BCG stellar mass—and therefore systematically overestimates $M_\ast$.

3. $M_3^3$: The stellar mass is calculated as 40% of the stellar mass within the virial radius, following the average stellar mass split of 40/60 between BCG and ICL as found by Remus et al. (2017a). This split between the BCG and the ICL is based on a decomposition of the stellar component into two populations according to their velocity distribution, with the ICL component having significantly larger velocities than the BCG. This is a good approximation for the BCGs, but is a poor approximation to the field galaxies where the stellar halos are far less than 60% of the full stellar body of a galaxy. For example, Merritt et al. (2016) report, for disk galaxies with $M_\ast < 1 \times 10^{11} M_\odot$ from Dragonfly, an average stellar halo fraction below 1%, and their highest fractions are still well below 10%. Similarly, Harmsen et al. (2017) find stellar halo fractions from the GHOSTS survey of only 2%–14% of the total stellar mass.

4. $M_4^4$: Following a common approach from simulations (e.g., Teklu et al. 2015; Remus et al. 2017b; Schulze et al. 2018), we assume the galaxy’s stellar body to reside well within 10% of the virial radius, and as such we calculate the stellar mass from all stars within 0.1 $R_{\text{vir}}$.

Figure 1 shows the resulting mass–size relations for the four different methods of deriving the stellar mass $M_\ast$. In this figure, we compare the four methods directly with two recent observational mass–size relations built on large samples, from the SDSS (Shen et al. 2003) and GAMA (Lange et al. 2015) surveys. All four definitions illustrated in Figure 1 provide mass–size relations that are in overall agreement with the observations (though it is also worth noting that the GAMA and SDSS relations are not in close agreement with each other). Generally, all four methods used for the simulations are closer to the GAMA results than to SDSS, though method $M_2^2$ is the closest to the SDSS values, and methods $M_3^3$ and $M_4^4$ are the closest to the GAMA survey values. Observationally, measuring the half-mass radius requires one to confront the problem that the outer stellar component of galaxies is often below the sensitivity limit of the observations and therefore the total stellar mass cannot be measured directly. Profile fitting (and extrapolation to large radii) must be used instead.

As noted above, on the theoretical side, the choice of a “best” approach from the viewpoint of the mass–radius relation is not immediately clear. Consider our method $M_1^1$ (predicting the stellar mass directly from the halo mass and the SHMR
As an example. Because the slope of the density profile changes with radius, a different (assumed) total stellar mass changes the inferred relation between half-mass radius and stellar mass. In addition, due to the large scatter in the true SHMR as predicted by simulations (e.g., Teklu et al. 2017), the scatter in the stellar mass–size relation is also increased significantly if we use an incorrect stellar mass inferred from the given SHMR.

Both the simulated and the observed mass–radius relations have significant scatter, so we cannot definitively exclude any of our four methods based on the mass–size relation alone. Generally, the scatter is largest for \( M_1^* \) because this method neglects the intrinsic scatter in the SHMR as discussed above, but the scatter (seen in Figure 1) from methods \( M_2^* \) and \( M_4^* \) is nearly as large. Method \( M_3^* \) shows the smallest scatter: the normals are cut to only 40% of their total stellar mass within the virial radius, which means that their stellar mass tends to be dominated by their bulges while the outer (disk) parts, which cause most of the scatter, are cut away. Thus, while this method works nicely for the centrals, it appears to be less appropriate for the normals.

One final obstacle for the simulations is that we need to compare the half-mass radius in 3D for the simulated galaxies to the half-light radius in projected 2D for the observed galaxies. The latter is usually calculated in an optical wave band, but it depends to some extent on mean wavelength. On the one hand, projected radii are usually smaller than the 3D radii by a factor of \( 3/4 \) for standard Sérsic galaxy profiles (Ciotti 1991). On the other hand, mass-estimated radii are smaller than light-estimated radii. As shown by Genel et al. (2018) for the IllustrisTNG project, for galaxies with stellar masses of \( \log(M_*) > 10.5 \), these two effects approximately cancel out by chance. We find a similar behavior for our Magneticum simulation sample. As projections of simulated data always require a (random) choice of orientation and additional uncertainty comes in when converting from mass to
light, we simply use $R_{1/2}$ (the 3D half-mass radii) calculated directly from the simulations without any further conversion, given that most of our galaxies have stellar masses above $\log(M_*) > 10.5$. It should also be kept in mind that the uncertainty on $R_{1/2}$ is large enough already, depending on the method used to calculate the stellar mass of the galaxies. Nevertheless, this point could be addressed in a future study in more detail.

The distribution of the theoretically predicted $f_5$ values from the simulated galaxies, for the four different ways to define $M_*$, is shown in Figure 2. Despite the very different ways in which the stellar mass is defined, the four methods show first-order agreement, with predicted $f_5$ values in the general range $\sim 0.6-0.9$. Nevertheless, a small change in half-mass–radius can lead to differences both in the range of $f_5$, and also in the relative number of objects that scatter to lower $f_5$ values. For $M_2^*$ and $M_4^*$, the difference is mostly a tiny systematic shift toward lower $f_5$, clearly showing that the stellar content of all galaxies from BCGs to field galaxies is well within 10% of the virial radius. For the other two methods, $M_1^*$ and $M_3^*$, the differences are stronger, with a much larger scatter in $f_5$. We especially see here that $M_3^*$ (which assumes that a galaxy only consists of 40% of the total stellar mass inside a halo) provides significantly different results for the cluster environments and its BCGs and the field, normal galaxies, clearly highlighting the impact of the two distinct ICL and BCG components in galaxy clusters. Method $M_4^*$, on the other hand, is the closest match to the observational method used in this work, and it is the method that leads to the largest scatter in $f_5$, especially at the low-mass end, mirroring the large scatter in the SHMR as shown by Teklu et al. (2017).

Table 3 lists the mean and the median of the $f_5$ distributions for the different methods of calculating $M_*$ for normals and centrals. In general, the BCGs have a somewhat larger DM fraction $f_5$ than the normals for all four methods. Additionally, for the BCGs, we find that the mean and the median are approximately the same, while the mean generally is slightly lower than the median for the normals. We can also clearly see that the scatter is largest for both normals and centrals if $M_1^*$ is used.

This comparison of alternatives clearly demonstrates how sensitive the actual values of $f_5$ are to the method used to define the stellar mass of a galaxy, and the resulting differences in the half-mass radius, which are directly related with each other via the stellar density profile of a given galaxy. The relative differences in the slopes of the radial stellar and DM profiles ultimately determine how the DM fractions vary as a function of $M_*$ and $R_{1/2}$. In Section 4, we will provide additional comments on the impact of the different stellar mass estimates on the resulting DM fractions and how they match up (or fail to do so) with the observations.

![Figure 2. Dark matter fraction $f_5$ within 5 times $R_{1/2}$ vs. stellar mass for the simulated galaxies, with the colors indicating the different methods to calculate the stellar mass and its half-mass radius, as described in Section 2.3. The four different symbol colors show the results for the four different ways to define $M_*$ defined and discussed in the text. Right panel shows histograms of the $f_5$ distribution for the four different methods.](image)
Considering all the arguments above, we ultimately adopt the stellar mass definition $M_*^h$ for the simulated centrals, to ensure that the ICL is subtracted properly and the scatter in the stellar mass—halo mass relation is smallest at the high-mass end. For the normals, we adopt $M_*^b$ because we assume, for the field galaxies, that any ICL component is negligible, so essentially all stellar mass really belongs to the galaxy. These will be our baselines for comparisons with the observations.

### 3. Results and Comparisons

The observational data in our study represent a wide range of galaxy morphologies, luminosities, environments, and other parameters. However, our list of targets does not make up a large enough sample (a total of little more than 100 galaxies) to do a full analysis of DM fraction versus all these parameters. For our present paper, we restrict the discussion to correlations of $f_5$ versus galaxy mass, with only secondary and very broad-brush subdivisions by morphology (early-type versus late-type) and environment (central giants versus all others). Nevertheless, the simulations also contain a wide variety of galaxy types and environments, so in a general sense they represent a sample that is comparable to the real data.

Here, we make the simple assumption that $M_{\text{bary}}(r) = M_N(r) + M_L(r)$, ignoring the presence of any cool gas (which for most ETGs is small). In most cases, the stellar mass is the dominant baryonic component regardless. Lacking homogeneous detailed light profiles for most of our individual galaxies, we make the assumption that the galaxies can be adequately described by the well-known Sérsic profile typical for ETGs. The central concentration index $n$ of the profile is found empirically to increase with either $r_e$ itself or the luminosity of the galaxy (e.g., Caon et al. 1993; Graham et al. 1996; Graham & Driver 2005; Ferrarese et al. 2006; Kormendy et al. 2009; Graham 2019, among many others). The relation between $n$ and galaxy luminosity we use here is (log $n = -0.104M_V^{1.56} - 1.56$) for galaxy total absolute magnitude $M_V$ (Kormendy et al. 2009; Graham 2019); it is closely consistent with the other studies cited above and gives predicted $n$ — values that are entirely consistent (within the large empirical scatter) with (e.g.) observed correlations of $n$ with $r_e$ or stellar mass $M_*$. These calculated values of $n$ are listed in Table 2.

We denote $q_n$ as the fraction of the total light contained within $5r_e$. In Figure 3, $q_n$ as calculated by integration of the Sérsic profile is shown versus index $n$, for fiducial radii of $r = 2, 3, 4,$ and $5r_e$ (though only $5r_e$ is relevant for the discussion to follow); by definition, $q_n = 0.5$ for $r_e$. For the classic de Vaucouleurs profile ($n = 4$), $88\%$ of the total light falls within $5r_e$, but for the largest observed $n$-values (such as apply to the very luminous, extended BCGs), $q_n$ falls to $78\%$ or less. For the galaxies with $M_V^{1.56} \lesssim -19.5$ that are in the present study, to a good approximation we have

$$q_n = 1.056 - 0.278 \log n.$$  

(9)

The DM mass fraction can then be defined as

$$f_5 = 1 - \frac{(q_nM_* + M_X)}{M_5}.$$  

(10)

The final calculated $f_5$ values are listed in the last column of Table 2. In practice, $f_5$ is insensitive to $n$ because $M_5$ dominates over $M_*$; even the simple assumption of a de Vaucouleurs profile ($n = 4$) for all galaxies would change the $f_5$ estimates in Table 2 by $\pm 0.02$ at most.

The next stages are to plot the observed distribution of $f_5$, compare with the simulated galaxies, and look for any dependencies on galaxy mass, morphological type, or environment. In Figure 4, $f_5$ as calculated from the X-ray sample of 102 galaxies is plotted versus both halo and stellar mass ($M_5, M_*$). In addition, the predicted $f_5$ values for the realizations of the Magneticum Pathfinder simulations described above (both normal galaxies and centrals) are shown for comparison. Not surprisingly, one effect of observational selection is immediately seen: the majority of the observed galaxies lie at fairly high masses, where $T_X$ and $M_X$ are larger and more securely measurable, whereas the simulated “normal” galaxies follow a luminosity function that more heavily populates the lower-mass end of the distribution regardless of how much gas they contain. For this reason, only the trends of $f_5$ versus mass or type are relevant—and not the relative numbers of galaxies in a given mass range. In general, good first-order agreement is seen between the mean level of the simulations and the observed galaxies, as well as the typical scatter. The observed galaxies, however, show excursions to both higher and lower $f_5$ levels ($\gtrsim 0.9$,
In the lowest-mass ones in the sample studied in the GHOSTS and Dragonfly surveys, some of which have very sparse stellar halos (Merritt et al. 2016; Harmesen et al. 2017). We note as well that, even within $r_e$, the halos of some moderately luminous ETGs are quite DM-dominated (Tortora et al. 2019) and thus should be even more so at $5r_e$. Interpretations from galaxy formation simulations (e.g., Elias et al. 2018; D’Souza & Bell 2018; Monachesi et al. 2019) suggest that systems in this high-$f_5$ range are likely to have had quieter evolutionary histories, with earlier and higher fractions of \textit{in situ} star formation. The Magneticum simulations for the small range are likely to have had quieter evolutionary histories, with earlier and higher fractions of \textit{in situ} star formation. The Magneticum simulations for the

$\lesssim 0.6$) that are very rarely reached in the simulated systems. Both of these extremes will be discussed below. Notably, no strong trend of $f_5$ versus galaxy mass is evident, at least in the mass range studied here.

Though both $M_h$ and $M_*$ are shown in Figure 4, they give much the same information about the distributions of DM fraction versus galaxy mass. In what follows, we will therefore show only $f_5$ versus stellar mass $M_*$, though if desired, any of the distributions against $M_h$ can be constructed from the information in Table 2.

In Figure 5 (left panel), the galaxies are separated into elliptical (E) and disk (S0/SA0/SB0) types in order to see if any obvious differences emerge versus morphology. A particularly noticeable subset consists of the $\sim$10 disk galaxies at the upper left in Figure 5 that have $f_5 \approx 0.95$; these are also the lowest-mass ones in the sample ($M_* < 5 \times 10^{10} M_\odot$). A17 found a slight trend in the opposite sense between S0 and E types, though as they point out, any trends with galaxy type or environment in their sample were obscured by the large dispersion in $f_5$ and small-sample statistics. These very DM-dominated disk galaxies are reminiscent of the disk systems studied in the GHOSTS and Dragonfly surveys, some of which have very sparse stellar halos (Merritt et al. 2016; Harmesen et al. 2017). We note as well that, even within $r_e$, the halos of some moderately luminous ETGs are quite DM-dominated (Tortora et al. 2019) and thus should be even more so at $5r_e$. Interpretations from galaxy formation simulations (e.g., Elias et al. 2018; D’Souza & Bell 2018; Monachesi et al. 2019) suggest that systems in this high-$f_5$ range are likely to have had quieter evolutionary histories, with earlier and higher fractions of \textit{in situ} star formation. The Magneticum simulations for the

“normal” suite of galaxies, however, predict very few galaxies with $f_5 > 0.9$.

Another noticeable subset consists of the four galaxies with $f_5 \lesssim 0.4$: these are NGC 499, 4697, 5044, and IC 1262. In all cases, these are ones where the estimated gas mass $M_X$ is extremely high—perhaps implausibly so. While these four objects are kept in the lists for the present, we suggest that these cases call for remeasurement of the gas mass with higher signal-to-noise observations. It is worth noting as well that the effect of errors in $M_X$ is strongly asymmetric. If $M_X$ is severely underestimated, $f_5$ would increase by only a tiny amount because $M_*$ already dominates over $M_X$ in most cases. However, if $M_X$ is overestimated, $f_5$ can decrease very significantly, as we see here for these few cases.

In this context, we note that a few of the $f_5$ values measured through satellite dynamics (A16, A17) were also found to lie at similarly low values in their papers, but once their adopted IMF scale is renormalized (see below), these move up into the normal range $f_5 \lesssim 0.5$ occupied by the majority of cases (see the discussion in the next section).

In Figure 5 (right panel), the same data are displayed but now broken out roughly by environment: BCGs or BGGs are contrasted with all others that are not the centrally dominant objects in their local environments. The BCGs/BGGs almost all have masses $M_* > 10^{11} M_\odot$. No strong difference in the $f_5$ distributions is evident between them and the normals. Apparently, central location by itself does not correlate with unusually high or low DM fraction, at least in the same mass ranges. Notably, the simulated centrals lie in very much the same $f_5$ range as their real-world counterparts, at $f_5 \approx 0.7–0.9$. The same result was found by A17 from the seven BCGs in their list.
The Astrophysical Journal, 905:28 (17pp), 2020 December 10

Harris et al.

The distributions of \( f_5 \) are shown in histogram form in Figure 6. Separate panels are used to show the two groups of simulated systems (normal or central) and two groups of X-ray observed galaxies (E-types and disk types). The difference between the E-type and disk-type systems is more evident here: the disk systems sit higher on average, and they lack the “tail” extending to lower \( f_5 \). The \( f_5 \) distributions for the E and Disk samples turns out to be statistically significant at 98% confidence, according to a KS test.

4. Discussion

In Table 4, we list some numbers that roughly characterize each sample: the sample median \( \overline{f}_5 \), the sample mean \( \langle f_5 \rangle \), and the rms dispersion \( \sigma(f_5) \), along with their uncertainties. Because the \( f_5 \) distributions are asymmetric, the median is higher than the mean, though in no case by more than \( \approx 0.1 \).

As noted above, the simulated galaxies occupy a range of \( f_5 \) that matches the observed samples to first order, though the match is best for the giant centrals. Given both the present state of development of the simulations and the measurement uncertainties for the real galaxies, it is not yet clear that systematic differences at the level of \( \Delta f_5 \approx 0.1 \) between the observations and the simulations in any part of the \( (f_5, M) \) plane can be viewed as significant. It seems quite possible that differences of this order can be the results of the basic differences in the way that \( M_5 \) in particular is calculated, but they could also originate from our choice of calculating the stellar masses from simulations, as discussed previously and as also seen from Table 3. Further discussion of these points will be made below.

4.1. Comparison with Satellite Dynamics Methods

In Figure 7, the \( f_5 \) distribution from the X-ray gas method is now compared more completely with estimates from satellite dynamics (GCs and PNe) for 32 galaxies, as listed by A17. Their adopted distances employ the same distance scale (Brodie et al. 2014) and agree closely with ours. However, their analysis assumed a mass-to-light ratio \( M/L_{K} = 1.0 \) that is roughly equivalent to a Salpeter IMF. Their adopted \( M_5 \) values have therefore been adjusted by \( -0.3 \) dex, to put them close to the Chabrier IMF that we use here. After this renormalization, the results are as shown in Figure 7 for the 102 X-ray measurements (black dots) and the 32 satellite-dynamics measurements (blue diamonds). In a strict sense, the A17 data points are upper limits to \( f_5 \), as they include only stellar mass and not gas mass in \( M_{\text{gas}}(5r_e) \); however, in most cases the difference is small because \( M_5 \) dominates (see H19). A KS test shows that the satellite-\( f_5 \) distribution is not significantly different from the X-ray sample.

The satellite-based data make an especially important contribution to filling in the mass range \( M_\odot \lesssim 10^{11}M_\odot \), where relatively few galaxies contain X-ray gas that is easily measurable. The A17 set of galaxies does not constitute a list that is entirely independent from the X-ray targets, however. There are 17 galaxies in common between the lists, for which H19 compared the \( f_5 \) and \( M_5 \) values (see their Figure 6). In Figure 8, for these 17 overlapping galaxies, the difference \( \Delta f_5(\text{X-ray-A17}) \) is plotted versus stellar mass. To make the two data sets more strictly comparable, the gas mass \( M_X \) has been removed from the X-ray measurements.

---

\( H19 \) actually compared 20 galaxies measured by both methods. However, in the present paper, a few of these were removed from our sample because of their low \( L_X \) and \( T_X \), as discussed above.
of $f_5$ before calculating $\Delta f$. At the highest masses, the agreement between the two methods is close with little scatter; at the lowest masses, the scatter increases, but the net offset $\Delta f_5$ is still consistent with zero and is independent of $M_*$. In brief, we find no serious evidence of systematic disagreement between the two methods, once both have been put onto the same IMF scale. Interestingly, the median of the 17 overlapping galaxies is $\bar{f}_5 = 0.89 \pm 0.04$, with no low-$f$ outliers.

Finally, the results from Wojtak & Mamon (2013) are added for comparison with both the X-ray and A17 data. Wojtak & Mamon used spectroscopy and photometry from the Sloan Digital Sky Survey (SDSS) to extract 3800 isolated nearby ETGs along with their satellite galaxies, to deduce the mass profiles along with $f_1, f_2,$ and $f_3$. These systems were selected such that their satellites were $\gtrsim 1.5$ magnitudes fainter than the central galaxy, and so they can be seen as fitting into the BGG category or even as “fossil groups.” Their method uses an anisotropic model for the phase-space distribution of satellites, generalized for the case where the DM halo and the tracers may follow different radial profiles. Their mean points for $f_5$ are tabulated in six bins of galaxy stellar mass and are shown in Figure 7 as the shaded region. They use the Chabrier IMF scale, and so their data need no adjustment before comparison. Just as for A17, however, their $f_5$ estimates do not include gas mass in $M_{\text{bary}}$, and so in a strict sense are (slight) upper estimates. A striking feature of the SDSS sample is the clear dip in the mean $f_5$ near $M_\star \sim 3 \times 10^{11} M_\odot$, very near the mass range where we see most of the low-$f_5$ outliers in the X-ray and satellite methods.

In Figure 9, the distribution of $f_5$ is shown for a “best” data set constructed from combination of the X-ray and satellite-dynamics methods. For the 17 galaxies in common between the A17 list ($n = 32$) and the X-ray list ($n = 102$), we take an average of the measurements, since there is no compelling physical reason to prefer one method over the other. Via this combination, we find a total of 117 galaxies: 17 measured by both methods, 15 from satellite dynamics only, and 85 from X-ray only.

4.2. Scatter and the Effects of Measurement Uncertainties

On strictly observational grounds, unphysical scatter in the estimated $f_5$ values can be generated in a variety of ways, but perhaps most importantly from measurement uncertainty in $M_\star$, the total gravitating mass within $5r_e$. In the defining relation for $f_5$ (Equation (10)), $M_\star$ is understood fairly well, except for some BCGs with extended-halo envelopes that may require multiple radial components for a fit. $M_X$ may be internally uncertain, but it is also usually small compared with $M_\star$. Thus, in most cases, the calculated uncertainty in $f_5$ is dominated by the uncertainty in $M_\star$. Any under/overestimate of $M_\star$ translates directly into under/overestimation of $f_5$. In turn, $M_\star$ is sensitive to the measured values of $\beta$, $T_X$, and $r_e$, varying in nearly direct proportion to all three.

The estimated values of $\beta$ and $T_X$, as mentioned above, depend on the properties of the fits to the X-ray data: the assumptions are that the gas is isothermal, it is in hydrostatic equilibrium, a single $\beta$-model profile is valid, and spherical symmetry applies (Equations (2)–(4) above). These assumptions differ in degree of validity from case to case (see B18). Similarly, the satellite-dynamics method for deriving $M_\star$ has its own, very different uncertainties, including the degree of substructure and correlated motions in the tracer particles, the orbital anisotropy profile, and small-number statistics (see A16, A17).

4.3. Effective Radii

One factor that is common to both X-ray and satellite methods is the uncertainty in the key quantity $r_e$, which affects all of $M_\star$, $M_X$, and $M_\text{bary}$. Though very simple in principle (the projected radius enclosing half the total stellar light), $r_e$ is
difficult to measure consistently, and different methods have a long history of internal disagreement and scatter. Graphic examples of such scatter are shown in Harris et al. (2014) (see their Figure 2), where differences as large as factors of two can be found even for nearby luminous galaxies. For the satellite-dynamics galaxy sample of A16, A17, the adopted $r_e$ values are taken largely from the ATLAS3D survey (Cappellari et al. 2013), whereas for the X-ray sample, we use the independently measured values from B18. These two lists correlate well (see Figure 3 of B18), with little or no systematic offset, but the galaxy-to-galaxy scatter is at the typical level of $\sim 30\%-40\%$.

At $f_s \simeq 0.5$, an uncertainty of 30% in $r_e$ and thus in $M_*$ will produce an asymmetric external uncertainty of $(+0.12, -0.21)$ in $f_s$ from this source alone. However, at $f_s \simeq 0.8$—a level near the mean for our current data—the resultant uncertainty range shrinks to $(+0.05, -0.11)$.

The Astrophysical Journal, 905:28 (17pp), 2020 December 10

Figure 7. Dark matter mass fraction $f_5$ for our entire sample of X-ray galaxies (black filled circles) is compared with the results from analysis of satellite dynamics (blue diamonds, from Alabi et al. 2017). Large open squares and the cyan-shaded region show the mean results from the SDSS galaxy sample studied by Wojtak & Mamon (2013).

Figure 8. Comparison of our results for $f_5$ with those from A17, for the overlapping set of 17 galaxies. Difference in $\Delta f_5$ (this work minus A17) is plotted vs. stellar mass $M_*$.

We should also consider the known systematic increase of $r_e$ with galaxy luminosity or mass. A recent compilation of optical measurements (Bender et al. 2015) is well-described over the range $-16 \lesssim M_V \lesssim -24$ by

$$\log r_e (\text{kpc}) = 0.411 - 0.256 (M_V + 20).$$

This relation is shown in the upper panel of Figure 10, along with the measured data for our list of galaxies from Table 1. The slope is equivalent to a scaling very close to $r_e \sim L^{2/3}$, which is consistent with the various versions of the fundamental plane for ETGs that relate mass, $M/L$, and scale radius (e.g., Burstein et al. 1997; Chiosi et al. 2020; Graham 2019). As is evident from Figure 10, our independent measurements of $r_e$ versus luminosity are consistent with this standard relation. They are also closely consistent with standard correlations of $r_e$ versus stellar mass $M_*$ (see the references cited above and also Lange et al. (2015), for results from the GAMA sample), within the significant galaxy-to-galaxy scatter around these relations as noted above. Within this scatter, our definitions of effective radius for both the simulated galaxies and the observations are therefore consistent.

For each galaxy in our list, we can then calculate the normalized ratio $r_e/r_0$, where $r_e$ is the measured radius and $r_0$ is the predicted value from Equation (11), given its luminosity $M_V$. In the lower panel of Figure 10, we show $f_s$ versus this normalized ratio. No major correlation is evident. A handful of objects with abnormally large ratios ($r_e/r_0 > 3$) all have $f_s > 0.8$. These few cases may be ones where the measured $r_e$ has been overestimated; if $r_e$ is too large, then 5$r_e$ will be so
large that the included halo volume will inevitably be more DM-dominated and thus $f_5$ will be larger than its true value.

The four cases with $f_5 \approx 0.4$ all have values of $(r_e/r_0) \approx 2.5$, which fall within the main scatter seen in the upper panel of Figure 10. In other words, these low $- f_5$ cases do not seem to be due to overestimates of $r_e$, which as noted above would tend to bias $f_5$ upward. Finally, there are several objects with $(r_e/r_0) < 1$ and $f_5 \approx 0.7$. Though they are not strongly anomalous in the preceding figures of $f_5$ versus mass, some of them could represent cases where $r_e$ (and thus $5r_e$) is underestimated, leading to an overestimate of $(M_{\text{sary}}/M_{\text{DM}})$ and thus a decreased $f_5$. Our tentative conclusion for this section is that at least some of the outliers in the $f_5$ distributions, on both the high and low ends, may be due to problems in the raw measurements of the galaxy effective radii.

In Tables 1 and 2, the uncertainties listed are only the internal measurement errors and do not include their external, method-dependent uncertainties, which are much harder to assess. A better way to gauge the size of these effects may be what we have done here, which is to compare two nearly independent methods for estimating the DM mass fraction. In the end, the mutual agreement is encouraging despite some anomalous cases.

5. Overview and Conclusions

Seen broadly, the simulations as shown in Figure 9 indicate that luminous galaxies can realistically lie in the range $f_5 \approx 0.6$–$0.9$, depending on the details of their merger and growth histories. High AGN activity, major mergers, and tidal stripping of the outer halo may all contribute to lowering $f_5$, but in the present data, few or no physically convincing cases fall below $f_5 \approx 0.5$, independent of mass.

Interestingly (and as also discussed in A17), the cases with $f_5 \lesssim 0.5$ predominantly fall in the relatively narrow mass range $M_e \sim 0.6$–$3 \times 10^{11} M_\odot$. Similarly, in the SDSS binned sample

Figure 9. Dark matter mass fraction $f_5$ for all measurements combined. Black filled circles represent 85 systems measured through the X-ray method alone; blue diamonds the 15 systems through satellite dynamics alone; and magenta squares the 17 systems for which both methods are averaged (see text). Shaded region with mean lines shows the results from the SDSS satellite analysis as in the previous figure. Filled-contour plots show the distribution of the simulated systems; contour levels have been logarithmically scaled for visibility.

Figure 10. Upper panel: Effective radius $r_e$ (kpc) vs. luminosity $M_V$. Solid line is not a fit to the data points: it shows the normal relation for ETGs from Bender et al. (2015), as given in the text. Lower panel: Scatter plot for $f_5$ (from Table 2) vs. normalized effective radius $(r_e/r_0)$, where $r_0$ is the expected effective radius for each galaxy’s luminosity from the normal relation (see text). Vertical line denotes $r_e = r_0$. 

The Astrophysical Journal, 905:28 (17pp), 2020 December 10 Harris et al.
of Wojtak & Mamon (2013), $f_5(\text{min}) = 0.63$ is reached at $M_\ast = 2.4 \times 10^{11} M_\odot$. This mean mass is about 3–4 times higher than the stellar mass $M_\ast \simeq 6 \times 10^{10} M_\odot$, where the SHMR reaches its peak (Equation (7) above), i.e., where the global baryonic mass fraction is maximal. As another comparison with theory, the predicted run of $f_5$ versus $M_\ast$ from the Illustris TNG simulations (Lovell et al. 2018) goes through a shallow minimum of $f_5(\text{min}) \simeq 0.75$ at $M_\ast \simeq 2 \times 10^{11} M_\odot$, an order of magnitude lower mass than we observe here.

Figure 11 shows our final comparison of theory with data. Here, we group the combined list of 117 galaxies in our study into 13 mass bins of 9 galaxies each, and the mean $f_5$ of each bin is plotted versus stellar mass. This distribution of mean points agrees well with the mean trend from the SDSS satellite data, including the shallow dip near $M_\ast \simeq 2 \times 10^{11} M_\odot$. Comparing Figures 9 and 11 suggests that this dip is not so much a downward shift of the median $f_5$ at that mass, but rather indicates the presence of a distinctly larger proportion of low–$f_5$ galaxies in that critical mass range. This same dip is not evident in the simulations, and if real, it may present an interesting challenge for future modeling.

As one more extremely interesting comparison with a very different kind of observational data, we also show the mean value of $f_5$ obtained by Oguri et al. (2014) from a sample of 161 ETGs measured via the strong-lensing technique (see their Figure 7). The list of galaxies in their compilation covers the stellar mass range from $M_\ast \simeq 2 \times 10^{10} M_\odot$ up to $5 \times 10^{11} M_\odot$, overlapping well with our X-ray and satellite samples. For stellar masses, they adopt the Salpeter IMF. When these are adjusted by $-0.3$ dex to the Chabrier/Kroupa ($M/L$) scale that we adopt here, their strong-lensing mean value becomes $\langle f_5 \rangle = 0.86 \pm 0.06$, which sits higher by about $\Delta f_5 \simeq 0.05$ than the X-ray and satellite observations and the centroid of the simulations. Despite this small offset, the mutual agreement in mean $f_5$ among the very different techniques (strong-lensing, X-ray, and satellite dynamics) is encouraging.

Finally, the choice of the definition of stellar mass $M_\ast$ used for the simulations has a clear effect on comparison with the observed DM fractions $f_5$, as first noted in Section 2 and Figure 2. For the “normal” simulated galaxies, all four ways to define $M_\ast$ place the simulated points somewhat below the observations in the same mass range, but the choice of $M_\ast^5$ (all stellar particles within the virial radius, minus substructure) gives the best overall agreement. It should also be noted, however, that in this lower-mass regime ($M_\ast \lesssim 10^{11} M_\odot$) on the observational side, the X-ray signals are the weakest and the mass estimates subject to uncertainties that are hard to assess. On the high-mass end (the “centrals” or BCGs), the best agreement comes with the choice of $M_\ast^7$ (predicting stellar mass from total halo mass via inversion of Equation (7)). Though the mean $f_5$ level for the centrals does not change much for any of the four definitions of $M_\ast$, the range of estimated stellar masses matches the observations best for $M_\ast^7$. It is perhaps also worth noting that the relative numbers of low-$f_5$ outliers are fairly similar for the different definitions.

Figure 11. Mean data points for $f_5$, grouped in bins of $M_\ast$. Black filled circles with error bars show the mean points from the total sample of 117 galaxies combining both X-ray and satellite data (see text). Shaded cyan region with mean lines shows the results from the SDSS satellite analysis as in the previous figures. Filled green diamonds show the mean points for the simulated central (BCG/BGG) galaxies, with stellar masses $M_\ast^{\text{sim}}$ defined by Equation (7). Filled red circles are the mean points for the simulated galaxies with stellar masses defined by $M_\ast^{\text{sim}}$ (including all stars) as described above. Finally, the dotted–dashed horizontal line at $f_5 = 0.86$ is the mean value obtained via the strong-lensing technique from a sample of 161 ETGs (Oguri et al. 2014).
6. Some Future Prospects

To first order, we are encouraged by the general agreement between simulations and observations (quantified in Tables 3 and 4). For the entire mass range $M_*>10^{12}M_\odot$, the mean $\langle f_s \rangle$ remains in the range 0.7–0.9, with no large systematic trend with either galaxy mass or morphology. At a finer level of detail, there remain interesting features of the distribution that may be due to measurement scatter, problems with the analytical methods (both X-ray and satellites), or genuine differences in galaxy histories. These discrepancies still need to be sorted out.

Ultimately, the choice of $5r_e$ as a fiducial radius for evaluating DM fractions remains, at the very least, a little arbitrary. In the longer term, more information and a better understanding of formation histories should come from measurements of the radial profile of $f_{DM}(r)$ for any given galaxy, from its inner halo out to the observational limits that the data permit. Different fiducial radii such as 1, 2, 3, or $5r_e$ have been used by some other authors (e.g., Deason et al. 2012; Wojtak & Mamon 2013, A16, A17), but more continuous radial profiles are within reach. These goals will be addressed in future papers, but a brief look at their potential is illustrated in Figure 12. Here, the more general DM mass fraction within 3D radius $R$ is plotted versus radius in units of the half-mass radius $R_{1/2}$ as defined previously, for all normal galaxies from the Magneticum simulations. The simulated systems define the family of (gray) curves $f_{DM}(R)$ that, in most cases, rise steeply from $\sim 1.5R_{1/2}$ and then flatten off once we are so far out in the halo that the enclosed baryonic mass is no longer changing. How far to the left or right each curve falls is a marker of its halo central concentration and the particular evolutionary history it has experienced. Fiducial curves are also shown for various NFW-type halos from Courteau & Dutton (2015). These include curves for a standard ETG as well as a late-type galaxy (LTG), along with two additional curves for these models in which the DM halo is adiabatically contracted (dotted and dashed–dotted lines). The standard (noncontracted) model halos clearly make a better match to the curves of growth for the simulated galaxies, even though several simulated halos show clear signs of at least some contraction. This spread in DM radial distribution, with most galaxies being close to NFW-like or (slightly) contracted, is in good agreement with results from the IllustrisTNG simulations, as shown by Wang et al. (2020), and also with the strong-lensing results from Oguri et al. (2014), who find that the DM halos of the galaxies in their sample are closer to NFW profiles than contracted profiles.

The cases with lower than average DM fractions ($f_s<0.6$ using stellar mass $M_*$) are plotted as blue curves. Interestingly, all of these low-$f_s$ galaxies from the Magneticum simulations have centrally expanded DM halos, as evidenced by the much flatter inner DM fraction slopes; see Figure 12. We find these expanded halos at all mass ranges, in contrast to Wang et al. (2020), who find these halos only at the low-mass end of $M_*<10^{11}M_\odot$. However, their expanded halos also have rather low DM fractions, at least within one half-mass radius. A potential explanation for the expansion of halos is strong outflows from stellar feedback (e.g., Governato et al. 2012, using Zoom simulations with Gasoline, and Dutton et al. 2016, using the NIHAO simulations) or AGN feedback.

![Figure 12](image_url)
(Peirani et al. (2017), using HorizonAGN), and feedback is most likely also the reason for the expanded halos in both Magneticum and IllustrisTNG. However, analyzing this interplay between stellar and dark component leading to contraction and expansion of DM halos is beyond the scope of this paper and will be addressed in a follow-up study.

Since contracted and expanded halos are clear signs of different dominant formation scenarios, it would be extremely helpful in deciphering individual histories to measure the amount of contraction or expansion in detail. The contracted halos raise the DM fraction dramatically at small radii but have relatively less effect at several effective radii beyond most of the baryonic matter. In contrast, the expanded halos differ strongly at larger radii. Measuring radial DM profiles (that is, the curves of growth as seen in Figure 12) from observations would be invaluable.

The observations (magenta dots in Figure 12), obviously, sample the theoretical curves at only one radius. A reanalysis of the data for a series of radii, not just 5 times (both for the X-ray and satellite techniques), would generate these curves of growth directly from the observations and would lead to a more informative confrontation with the simulations. The current list of observations at 5 times is not sufficient for strong conclusions about which model curves might be better, but it is potentially interesting to note that the median of the observed distribution indicates contracted halos instead of classical standard halos. This again points to the need to develop a more complete curve of growth, particularly at smaller radii. Similarly, for those halos with especially low fDM, we may be able to determine whether or not they are expanded halos.

7. Summary

We have used measurements of the X-ray gas that can be found in individual large galaxies for a new assessment of the mass fraction fDM = fDM(5 times) of DM within the fiducial radius of 5 times. This mass measurement technique is nearly independent of the more widely used satellite kinematics methods. The results for our sample of 102 galaxies are compared directly with theoretical predictions from the Magneticum/Pathfinder suite of simulations for both normal galaxies and centrally dominant systems (BCGs and BGGs). A summary of our findings is as follows:

1. Over the mass range of our sample of 102 galaxies (10^10 M☉ <= M* <= 10^12 M☉), we find that fDM stays at a median level near fDM ~ 0.85 and rms scatter ±0.15, nearly independent of mass.

2. The observed distribution of fDM shows substantial agreement with the simulations in the mean (high) level of fDM and the galaxy-to-galaxy scatter (see Figure 9). The observed data, however, show some individual galaxies scattering to both higher and much lower fDM values that are only rarely reached by the simulated systems. Many, though not all, of these extreme cases may be real. In general, the galaxy-to-galaxy spread in halo DM fraction points to the diverse formation pathways, including feedback, outflows and inflows, and mergers of different mass fractions, that exist for galaxies in this mass range. This diversity clearly emphasizes the importance of further combined studies from simulations and observations.

3. In our X-ray sample, the disk-type galaxies (SO/SAB/SBO) have a significantly higher dark matter fraction (median fDM ~ 0.9) than do the E-types (fDM ~ 0.8). If physically real, this difference may be an indicator of their quieter and earlier history of growth via mergers and satellite accretions, less halo expansion due to feedback, and very sparse stellar halo components.

4. Though with differences in detail, the overall pattern of fDM from the X-ray measurements generally agrees well with recent measurements from satellite dynamics (A17). The median and mean fDM levels from both X-ray and satellite methods also agree to within their uncertainties with the estimate of fDM = 0.86 ± 0.06 obtained from strong lensing and from a different sample of galaxies. To first order, there is now an encouraging concordance among three quite different methods for measuring DM mass fraction in the outer halos of large galaxies: satellite dynamics, strong lensing, and X-ray gas profiles.

5. For the central giant galaxies (BCGs or BGGs), there is good agreement between the 44 observed cases and the predicted level from the simulations. This result emphasizes the strong DM dominance within the BCGs.

6. In all subgroups of the data (E-type galaxies, disk types, BCG/BGG types, X-ray or satellite methodology), the observed internal scatter at any mass is fDM ~ 0.15, which is larger than the typical measurement uncertainty for most individual galaxies. For comparison, the internal scatter of the simulated systems is fDM ~ 0.1, which appears to be primarily because the simulations do not predict the same fractions of galaxies at extremely high or low fDM (outliers).

7. Further studies to generate more observational DM mass fraction profiles covering a much greater range in radii will be crucial for making deeper connections with the simulations.

This research has made use of data obtained from the Chandra Data Archive and the Chandra Source Catalog, as well as software provided by the Chandra X-ray Center (CXC) in the application packages CIAO, ChIPS, and Sherpa. We thank all the staff members involved in the Chandra project. We are grateful to Mike Hudson and Ian Roberts for their advice, and to Gary Mammon for transmitting the SDSS comparison data shown in the figures. W. E. H. acknowledges the financial support of NSERC. The Magneticum Pathfinder simulations were performed at the Leibniz-Rechenzentrum with CPU time assigned to the Project pr9153 and supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy—EXC-2094-390783311. Finally, we thank the anonymous referee for helpful comments and suggestions.

Software: CIAO (inc., wavedetect, Fruscione et al. 2006), Sherpa (Version 4.12.1, Freeman et al. 2001; Burke & Laurino 2020).

ORCID iDs
William E. Harris https://orcid.org/0000-0001-8762-5772
Gretchen L. H. Harris https://orcid.org/0000-0002-9451-148X
Iu. V. Babyl https://orcid.org/0000-0003-3165-9804

References
Alabi, A. B., Forbes, D. A., Romanowsky, A. J., et al. 2016, MNRAS, 460, 3838
Alabi, A. B., Forbes, D. A., Romanowsky, A. J., et al. 2017, MNRAS, 468, 3949
