HIDING IN PLAIN SIGHT: AN ABUNDANCE OF COMPACT MASSIVE SPHEROIDS IN THE LOCAL UNIVERSE

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ABSTRACT

It has been widely remarked that compact, massive, elliptical-like galaxies are abundant at high redshifts but exceedingly rare in the universe today, implying significant evolution such that their sizes at \( z \sim 2 \pm 0.6 \) have increased by factors of 3 to 6 to become today’s massive elliptical galaxies. These claims have been based on studies that measured the half-light radii of galaxies as though they are all single-component systems. Here we identify 21 spheroidal stellar systems within 90 Mpc that have half-light, major-axis radii \( R_e \lesssim 2 \text{ kpc} \), stellar masses \( 0.7 \times 10^{11} < M_\ast / M_\odot < 1.4 \times 10^{11} \), and Sérsic indices typically around a value of \( n = 2–3 \). This abundance of compact, massive spheroids in our own backyard—with a number density of \( 6.9 \times 10^{-6} \text{ Mpc}^{-3} \) (or \( 3.5 \times 10^{-3} \text{ Mpc}^{-3} \) per unit dex\(^{-1} \) in stellar mass)—and with the same physical properties as the high-redshift galaxies, had been overlooked because they are encased in stellar disks that usually result in galaxy sizes notably larger than 2 kpc. Moreover, this number density is a lower limit because it has not come from a volume-limited sample. The actual density may be closer to \( 10^{-4} \), although further work is required to confirm this. We therefore conclude that not all massive “spheroids” have undergone dramatic structural and size evolution since \( z \sim 2 \pm 0.6 \). Given that the bulges of local early-type disk galaxies are known to consist of predominantly old stars that existed at \( z \sim 2 \), it seems likely that some of the observed high-redshift spheroids did not increase in size by building (three-dimensional) triaxial envelopes as commonly advocated, and that the growth of (two-dimensional) disks has also been important over the past 9–11 billion years.

Key words: galaxies: bulges – galaxies: evolution – galaxies: formation – galaxies: fundamental parameters – galaxies: high-redshift

1. INTRODUCTION

A little over a decade ago it was advocated that the mass–size relation for massive galaxies \(( M_\ast > 0.2 \times 10^{11} h_7^2 M_\odot) \) had evolved little from \( z \sim 2.5 \) to today (Trujillo et al. 2004). However, this view was quickly challenged by Daddi et al. (2005), who had detected seven passively evolving galaxies at \( z > 1.4 \), with stellar masses \( >10^{11} h_7^2 M_\odot \), and morphologies typical of elliptical/early-type galaxies. They questioned the lack of evolution because some of their galaxies had much smaller effective half light radii than local elliptical galaxies of the same mass (see also Papovich et al. 2005). They suggested that this difference was either a real sign of galaxy size evolution or artificial because of biasing active galactic nucleus (AGN) light or morphological \( K \)-corrections due to blue cores in the high-\( z \) sample. Addressing the latter uncertainty, Kriek et al. (2006, 2008) found that nearly half of their distant massive galaxies had old stellar populations, and van Dokkum et al. (2008) subsequently showed that half of those had sizes less than \( \sim 2 \) kpc. Following Daddi et al. (2005), Trujillo et al. (2006a) reported galaxy sizes ranging from 1 to 5 kpc for 10 massive \(( >5 \times 10^{11} h_7^2 M_\odot) \) galaxies at \( 1.2 < z < 1.7 \). From this Trujillo et al. (2006a) concluded that (i) the sizes were at least a factor of 3–6 times lower than “the local counterparts” of similar mass, (ii) the structural properties of these high-\( z \) objects are therefore rapidly changing, (iii) the data disagree with a scenario where the more massive and passive galaxies are fully assembled by \( 1.2 < z < 1.7 \) (i.e., a monolithic scenario), and (iv) they suggested that a dry merger scenario (no new star formation) was responsible for the subsequent evolution of these galaxies (see also Toft et al. 2007; Trujillo et al. 2007; Zirm et al. 2007; Buitrago et al. 2008; van Dokkum et al. 2008; Damjanov et al. 2009).

While not denying the occurrence of dry mergers, nor claiming that early-type galaxies had to have formed in a monolithic collapse (for an alternative see Dekel & Burkert 2014; Zolotov et al. 2015), given the data under investigation we are questioning the universality of the above conclusions because they rest on the assumption as to what the “local counterparts” to the compact, massive high-\( z \) galaxies actually are. Popular opinion has been that these distant objects are very rare today (e.g., Cimatti et al. 2008 and references therein), with Trujillo et al. (2009) reporting a local number density of \( 10^{-7} \text{ Mpc}^{-3} \), and Taylor et al. (2010) finding none and therefore concluding that the distant spheroidal stellar systems have experienced considerable size evolution to form today’s massive elliptical galaxies. However, there are many independent lines of reasoning to think that this paradigm of early-type galaxy evolution may not be correct.

Key to much of this is that Trujillo et al. (2006a, 2007) used the sizes of \( z \sim 0.1 \) Sloan Digital Sky Survey (SDSS; York et al. 2000) early-type, i.e., elliptical and lenticular, galaxies (with Sérsic index \( n > 2.5 \)), to claim that there has been significant size, and surface-mass density, evolution of the distant spheroids (see also Taylor et al. 2010; Newman et al. 2012; McLure et al. 2013; Damjanov et al. 2014; Fang et al. 2015). In addition to early-type galaxies, there is, however, another type of spheroidal stellar system in the local universe, namely, the bulges of disk galaxies, including the lenticular galaxies. Furthermore, there has been a slowly growing realization over the past three decades that most early-type galaxies in fact consist of a bulge and a rotating...
stellar disk (e.g., Capaccioli 1987, 1990; Carter 1987; Nieto et al. 1988; D’Onofrio et al. 1995; Graham et al. 1998; Emsellem et al. 2011; Scott et al. 2014), arguing against the treatment of lenticular galaxies as single-component systems. While many of these galaxies do not have massive bulges, and some contain pseudobulges built out of disk material (Kormendy & Kennicutt 2004; see also Graham 2014 for cautionary remarks regarding their identification), our interest lies with some of the more massive lenticular and spiral galaxies that do have massive bulges. The most massive local bulges ($M_B > 2 \times 10^{11} M_\odot$) have sizes in excess of 2.5 kpc and are therefore not considered “compact”; as such they have been excluded from this study.

Here we effectively explore what evolutionary conclusion might have been drawn a decade ago for the compact massive spheroids at $z \approx 2$ if the size–mass comparison had been performed with the massive bulges of present-day early-type disk galaxies rather than with the combined bulge+disk system. In so doing, we can answer the question, Have the high-$z$ spheroidal stellar systems truly evolved to near extinction, or are they doing, we can answer the question, Have the high-$z$ spheroidal stellar systems truly evolved to near extinction, or are they perhaps hiding in plain sight around us today? While we do not deny that there has been galaxy size evolution, we are suggesting a fundamentally different formation model that presents a dramatic shift in our way of thinking about how the compact massive objects at $z = 2.0 \pm 0.6$ have actually evolved in our universe. It is such that they have not expanded 3-6 times in size, nor accreted, through dry minor mergers, a three-dimensional (3D) envelope of a similarly large dimension, to become today’s massive elliptical galaxies (e.g., Hopkins et al. 2009; Carrasco et al. 2010; Cinatti et al. 2012; Fan et al. 2013b; De et al. 2014). Instead, we advocate the view presented by Graham (2013) that they have grown two-dimensional (2D) planar disks and are thus effectively hidden today until bulge-to-disk decompositions are performed. It turns out that there are actually many reasons to favor this scenario.

There is no widely accepted solution as to how the distant objects could have grown into much larger “spheroids” by today. For instance, major dry mergers cannot account for the size evolution; they move galaxies along the mass–size relation rather than off it (e.g., Ciotti & van Albada 2001; Boylan-Kolchin et al. 2006; see also Bundy et al. 2009; Nichita et al. 2009; Nair et al. 2011). In addition, based on observations of galaxy pairs, there have been insufficient major (i.e., near-equal mass ratio) merger events to explain the removal of every distant, compact massive galaxy (e.g., Man et al. 2015; see also Shih & Stockton 2011). Similarly, there are not enough satellites observed around massive galaxies for minor mergers (e.g., Khochfar & Burkert 2006; Maller et al. 2006; Hopkins et al. 2009; Naab et al. 2009; McLure et al. 2013) to be the sole explanation (Trujillo 2013, and references therein), and even in $\Lambda$CDM simulations there are not enough satellites to have transformed all of the distant spheroids.

It is worth noting that “normal-sized” (i.e., not compact), massive elliptical-like galaxies are observed at these high redshifts, coexisting with the “compact,” massive galaxies (e.g., Trujillo et al. 2006b; Mancini et al. 2010; Newman et al. 2010; Bruce et al. 2012; Ferreras et al. 2012; Fan et al. 2013a). Furthermore, new galaxies are known to appear (e.g., Ciotti & van Albada 2001; Boylan-Kolchin et al. 2006; see also Graham 2014 for a general discussion of these findings and the growth of disks in our universe. Section 4 finishes by re-iterating our main conclusions.

2. DATA SAMPLE

Five survey papers were consulted to check for the existence of compact massive bulges in the nearby universe. Our criteria were that the stellar mass be greater than $0.7 \times 10^{11} M_\odot$ and the major-axis half-light radius be less than 2.5 kpc. The first paper we examined was Dullo & Graham (2013), which has already broached this topic, and the second was G. A. D. Savorgnan et al. (2015, in preparation), which has carefully modeled the different structural components for 66 galaxies from a sample of 75 (Graham & Scott 2013; Scott et al. 2013) having directly measured black hole masses. Building on this, we checked two samples dominated by lenticular galaxies.

Keating et al. 2014). For example, Carollo et al. 2015 detail how past quenching can transform star-forming galaxies and shift them to the early-type sequence. Known as “progenitor bias,” studies that attempt to measure the evolution of the massive quiescent galaxies (e.g., Trujillo et al. 2006b; Ryan et al. 2012; Chang et al. 2013; van der Wel et al. 2014) can suffer from sample confusion because of the emerging population onto the red sequence; such studies are effectively sampling different objects as a function of redshift.

In mid-2011, Graham (2013; see also Driver et al. 2013) suggested that some of the distant objects are likely to be the bulges of today’s massive early-type disk galaxies. Indeed, Graham showed that the distant compact massive objects and massive local bulges occupy the same region in the size–mass and size–density diagram. Dullo & Graham (2013) additionally showed that they possess the same radial concentration of light, as traced by the Sérsic index (Sérsic 1968; see Graham & Driver 2005 for a modern review in English). Moreover, massive bulges today are old. Their mass (not to be confused by their luminosity-weighted age) is dominated by old stars (MacArthur et al. 2009), and therefore such luminous bulges should be visible in images of the early universe. That is, some fraction of the compact massive objects reported at $z \sim 2 \pm 0.6$ are expected to be today’s compact massive bulges. By calculating the number density of compact massive bulges at $z \sim 0$, done for the first time in this work, we are able to address whether this fraction is low or instead if it might equal 1 and thus fully account for the fate of the distant compact massive objects.

Rather than some great mystery of unexplained galaxy growth, we are exploring the relatively mundane alternative idea that Daddi et al. (2005) and Trujillo et al. (2006a, 2006b) simply observed the bulges of today’s bright early-type galaxies at high $z$ but did not know it. To address this, we have performed a preliminary search for nearby ($\lesssim 100$ Mpc), early-type disk galaxies with bulges having $R_e \lesssim 2$ kpc and $M_B \approx 10^{11} M_\odot$. This was done by checking on the galaxies presented in a handful of published papers listed in Table 1. This proved to be sufficient to illustrate that compact, massive spheroids exist in substantial numbers around us today. Section 2 of this paper presents the galaxies found, and the structural properties of their spheroidal component are also provided there. Section 3 provides a general discussion of these findings and the growth of disks in our universe. Section 4 finishes by re-iterating our main conclusions.

It should be noted that studies of the high-$z$ galaxies typically report the smaller, circularized half-light radii rather than the major-axis half-light radii. Our approach is thus conservative.
### Table 1

| Gal. Id. | Type      | Inc. (deg) | z   | Dist (Mpc) | \(M_{\text{bulge}}\) | \(R_{\text{bulge}}\) (kpc) | \(M_{\text{bulge}}\) (mag) | \(M_{\text{corr1}}\) (mag) | \(M_{\text{corr2}}\) (mag) | \(M/L\) | Mass*corr1 (10^11 M\(_{\odot}\)) |
|----------|------------|------------|-----|------------|----------------------|---------------------------|-----------------------------|-----------------------------|-----------------------------|--------|----------------------------------|
| ESO 357-G10 | SA(s)0*   | 37.6       | 0.0193 | 79.0       | 1.7                  | 1.52                     | −24.33                      | −24.37                      | ...             | 0.8   | 0.9                             |
| NGC 484   | SA0*       | 45.1       | 0.0170 | 68.4       | 2.8                  | 1.69                     | −24.63                      | −24.65                      | ...             | 0.8   | 1.2                             |
| NGC 1161  | SA(l)0/5   | 33.6       | 0.0065 | 28.4       | 2.5                  | 1.77                     | −24.20                      | −24.27                      | ...             | 0.8   | 0.8                             |
| NGC 3665  | SA0/5      | 39.1       | 0.0069 | 32.4       | 2.7                  | 1.98                     | −24.36                      | −24.37                      | ...             | 0.8   | 0.9                             |
| NGC 5266  | SA0        | 54.2       | 0.0100 | 40.8       | 2.8                  | 1.84                     | −24.79                      | −24.82                      | ...             | 0.8   | 1.4                             |
| NGC 5419  | SA(al)0*   | 43.9       | 0.0138 | 54.8       | 1.4                  | 1.74                     | −24.60                      | −24.63                      | ...             | 0.8   | 1.2                             |
| NGC 7796  | S0         | 27.9       | 0.0112 | 48.5       | 2.2                  | 1.72                     | −24.47                      | −24.48                      | ...             | 1.0   |                                 |

**Notes.** Column 1: Galaxy identification. Column 2: Morphological Type. Column 3: Disk inclination such that 90° corresponds to an edge-on disk. Column 4: Redshift taken from the NASA/IPAC Extragalactic Database (NED). Column 5: Distance from corresponding paper unless otherwise specified: NED = (Virgo + GA + Shapley) distance from NED using \(H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}\); B09 = Blakeslee et al. (2009); Ton = Tony et al. (2001) and corrected according to Blakeslee et al. (2002). Column 6: Sérsic index. Column 7: major-axis, effective half-light radius of the galaxy’s bulge component. Column 8: Near-infrared magnitude. Column 9: Magnitude corrected for Galactic dust extinction (Schlafly & Finkbeiner 2011), \((1 + z)^2\) cosmological dimming, and K-corrected using \(+1.5\)z (Poggianti 1997). Column 10: Magnitude additionally corrected for internal dust using the correction from Driver et al. (2008). Column 11: Stellar mass-to-light ratio (assumes a 12 Gyr old population of solar metallicity and a Chabrier (2003) initial mass function: Baldry et al. 2008 their Figure A1). Column 12: Stellar mass derived using column 9 for the S0s and column 10 for the spirals, together with column 11.

1. The galaxy rather than bulge parameters are presented.
2. NGC 4649 (M60) is a particularly difficult galaxy to decompose and as such its bulge parameters may not be reliable.
3. 3.6 \(\mu\)m magnitude rather than K- or \(K_s\)-band.
First, we inspected the sample of 175 early-type disk galaxies modeled by Laurikainen et al. (2010), and then the ATLAS3D sample (Cappellari et al. 2011) of 260 nearby ($D < 42$ Mpc), predominantly northern hemisphere, early-type galaxies that have had the stellar bulge-to-total flux ratios derived by Krajnović et al. (2013). The fifth catalog paper that we inspected was the spiral dominated compendium of Graham & Worley (2008), which resulted in the identification of targets in four additional papers (see Table 1). Having checked these papers, our Table 1 includes 20 known bulges along with the known compact massive galaxy NGC 1277 (van den Bosch et al. 2012), plus one additional galaxy, as opposed to a bulge, which also meets the above size and mass criteria. All but three of the 22 systems have $R_e < 2$ kpc. All but four have $M_b \geq 0.9 \times 10^{11} M_\odot$.

The major-axis, half-light radii of the spheroids are presented in Table 1, based on the galaxy distances that are also listed there. The circularized half-light radii would be even smaller, by a factor of $\sqrt[3]{b/a}$, where $b/a$ is the minor-to-major axis ratio of the bulge. This information was not readily available for many of our bulges, and so we have used the more conservative, larger radii. The published Sérsic indices have additionally been collated and given in Table 1 for ease of reference. Our preference has been for near-infrared data sets because the magnitudes are more reliable: they are less affected by dust and possible low-level star formation. The absolute magnitudes were then corrected for redshift dimming (5 log $[1 + z]$), foreground Galactic extinction (Schlafly & Finkbeiner 2011), and $K$-corrected (1.5 $z$; Poggianti 1997), which resulted in insignificant changes of typically 0.01–0.02 mag.

In the case of NGC 5493 (Krajnović et al. 2013), the whole galaxy is rather compact ($R_e = 2.46$ kpc)—although this is the largest system in our sample—and massive ($M_b = 10^{11} M_\odot$).

This galaxy is not unique in the nearby universe. The intermediate-scale disk in NGC 1332, which does not dominate at large radii like large-scale disks do, is such that the size of this galaxy is only slightly larger than 2 kpc (G. A. D. Savorgnan et al. 2015, in preparation). However, here we include the bulge rather than the galaxy parameters for NGC 1332. A third and possible fourth example are NGC 1277 ($M_b = 1.2 \times 10^{11} M_\odot$) and NGC 5845 (excluded here because $M_b = 0.5 \times 10^9 M_\odot$), as already pointed out by van den Bosch et al. (2012) and Jiang et al. (2012), respectively. However, if the disks of these galaxies were to continue to grow, until they resembled the more stereotypical S0 galaxies today, with $B/D$ flux ratios of 1/3 and $R_e/b_{\text{disk}} \approx 0.2 \times 10^3 M_\odot$), then their galaxy sizes would likely exceed 2 kpc while the spheroidal component remained compact.

For reference, it was observed that the bulges with stellar masses $M_b \geq 2 \times 10^{11} M_\odot$ tend to have major-axis, half-light radii $R_e > 2.5$ kpc, and as such were not included here.

We elected not to apply any internal dust correction to the lenticular galaxies, but only to the spiral galaxies. The most massive lenticular galaxies are not representative of the typical dusty disk galaxy from which the dust corrections stem, and they likely contain little widespread dust. The following $K$-band dust correction from Driver et al. (2008) was applied to the bulges of the spiral galaxies:

$$M_{\text{bulge}}^{\text{corr}} = M_{\text{bulge}} - 0.11 - 0.79[1 - \cos(i)]^{-2.77},$$  

where $i$ is the inclination of the disk such that $i = 90^\circ$ corresponds to an edge-on orientation. For the Dullo & Graham (2013) sample of five lenticular galaxies, the stellar masses derived from the $V$-band magnitudes (RC3, de Vaucouleurs et al. 1991) agree with those derived from the $K$-band magnitudes when no dust correction is applied and $M/L_K = 0.8$ and $M/L_V = 2.5$ is used. While the Sombrero lenticular galaxy contains widespread dust in its disk, as do other lenticular galaxies (e.g., Temi et al. 2007), it may be that ion sputtering (e.g., Draine 2003) from a hot X-ray gas halo has destroyed the dust in the massive lenticular galaxies, although we have not checked for such X-ray halos in our sample. However, if we are mistaken and dust is present, it will mean that our estimated stellar masses should be increased. As shown in Driver et al. (2008), the average correction due to dust in the thousands of disk galaxies modeled as a part of the Millennium Galaxy Catalog (Liske et al. 2003; Allen et al. 2006) is <0.14 mag if the inclination is <45°, and 0.18, 0.28, and 0.45 mag if the inclination is 55°, 65°, and 75°, respectively.

Some of the near-infrared magnitudes in Table 1 were derived from Two Micron All-Sky Survey (2MASS) images (Skrutskie et al. 2006). As noted by Schombert & Smith (2012), the 2MASS total magnitudes are known to not capture all of a galaxy’s light; they miss flux at large radii. However, for most S0s this appears to be contained to, on average, 1/10 of a magnitude (Scott et al. 2013, their Figure 2), no doubt due to the rapid decline of the S0 galaxy’s outer exponential light profile. For S0s with intermediate (i.e., not large) scale disks that do not dominate their galaxy’s light at large radii, and if the Sérsic index of the bulge is large, then several tenths of a mag may be missed, as with the elliptical galaxies. The Galactic-extinction-corrected $B - K_s$ colors (via NED but from the RC3, 2MASS, and Schlafly & Finkbeiner 2011) range from about 3.65 to 4.05. Given the expected color range of 3.85–4.03 for a 6–12.5 Gyr old population in model S0 galaxies (Buzzoni 2005), perhaps a couple of tenths of mag are missing from some 2MASS magnitudes. If one was to correct for this, it too would act to make the bulge masses bigger than reported here.

A Hubble constant of $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$ (e.g., WMAP 3-year; Riess et al. 2011) was used. However, if it is smaller, for example, 67.3 km s$^{-1}$ Mpc$^{-1}$ (Planck Collaboration 2014), then the absolute magnitudes will brighten by 0.18 mag and the stellar masses will increase by 18%. Based on Type Ia supernova data, Rigault et al. (2015) have also downwardly revised $H_0$ to 70.6 ± 2.6 km s$^{-1}$ Mpc$^{-1}$. A mass increase of 18% would result in 18 of the 22 systems in Table 1 having stellar masses $\geq 10^{11} M_\odot$.

2.1. Example Profile: NGC 5419

While information about the surface brightness profile decompositions can be found in the papers mentioned in Table 1, we felt that it may be instructive to include an example of how the outer exponential profile can increase the galaxy size over the bulge size. We have somewhat randomly chosen

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3 Krajnović et al. (2013) reported that their bulge/disk decomposition for NGC 5493 differed markedly from Laurikainen et al. (2010). Given this uncertainty, we use the whole galaxy rather than a result from a decomposition.
NGC 5419 from Laurikainen et al. (2010). This was chosen because (a) the Laurikainen et al. paper simply contains the greatest number of compact massive spheroids in our Table 1, and (b) this particular galaxy was modeled by Dullo & Graham (2014) as an elliptical galaxy, while they noted that a disk might be present. Sandage & Tammann (1981) did not support the original elliptical galaxy classification in the Second Reference Catalogue of de Vaucouleurs et al. (1976), but instead considered NGC 5419 to be a lenticular galaxy, as did Laurikainen et al. (2010) based on their near-infrared K-band analysis.

Therefore, we re-investigate this galaxy using a Spitzer Space Telescope 3.6 μm image (see Figure 1), which was reduced following the procedures described in A. D. Savorgnan et al. (2015, in preparation). The light profile was extracted by allowing the ellipticity and position angle to vary about a fixed center using the IRAF task ELLIPSE (Jedrzejewski 1987) and is shown in Figure 2.

Our modeling of the 3.6 μm light profile within 60″ matches the solution to the K-band data in Laurikainen et al. (2010). We also find that a single Sérsic function is inadequate; the curvature of the light profile and the residual light profile reveal the presence of additional components. Figure 2 shows how the addition of an outer exponential and a very faint lens (fit with a Ferrers function) provides a better fit. These were the components employed by Laurikainen et al. (2010). From this, one can see that the half-light radius of the galaxy (R_{e, gal} = 53″6) is much greater than the half light radius of the inner spheroid (R_{e, sph} = 8″4). Laurikainen et al. (2010) reported that their bulge+lens+disk model had a bulge Sérsic index n = 1.4 and half-light radius R_e = 6″5. They reported a disk scale length h = 32″3, while our exponential model has h = 33″1.

One may wonder if there is also a contribution from an extended envelope around this galaxy due to its location at the center of the poor cluster Abell S753. Indeed, Sandage & Bedke (1994) referred to this galaxy as having an extended outer envelope, and Seigar et al. (2007; see also Pierini et al. 2008) established that intracluster light tends to have an exponential profile, i.e., the same radial decline as seen in disks. However, Bettoni et al. (2001) have reported a rotational velocity reaching 90 km s^{-1} by the inner 5″, betraying the presence of at least an inner disk. In an extreme scenario, one may speculate that this galaxy has an intermediate-scale disk (the “lens” component in Figure 2, which shows up in both the ellipticity and position angle profiles) plus intracluster stars that produce the near-exponential light profile at larger radii. More extended kinematics would be helpful in discriminating between these options.

The cluster-centric location of NGC 5419 is interesting, and it further prompted us to pursue the suggestion by L. Cortese (2015, private communication) to check on the environment (e.g., field, group, cluster) of our sample. Table 2 shows this information, along with the R_e/h size and B/T flux ratios obtained by the papers given in Table 1. While a few of the galaxies are the brightest of their small galaxy group, NGC 1316 (the interacting galaxy Fornax A) is the only other member of a substantial-sized group. This rules out the idea that the compact massive spheroids might be encased in an exponential-like 3D envelope of intracluster light rather than a 2D disk.

3. RESULTS

3.1. The Mass–size and Size–concentration Diagrams

In Figure 3(a) we do not compare our data with the size–mass relation for early-type galaxies as given by Shen et al. (2003) because of the biases in their data, which are explained in Graham & Worley (2008). Lange et al. (2015) have, however, fit the double power-law model from Shen et al. (2003) to the galaxy size–mass data from several thousand nearby (0.01 ≤ z ≤ 0.1) early-type (morphologically identified diskless) galaxies taken from the Galaxy And Mass Assembly (GAMA) survey (Driver et al. 2011). The galaxy magnitudes had been converted into stellar masses by Taylor et al. (2011), and the effective half-light galaxy sizes derived by Kelvin et al. (2012) who fit single Sérsic models to images in 10 bands (ugrizYZHK_s). We have taken the K_{s}-band results from Lange et al. (2015) and show their mass–size relation in Figure 3(a).

Given that Figure 6 from Lange et al. (2015) reveals that the double power law cannot fully capture the curvature in the GAMA data at M_{nu} > (1–2) × 10^{11}M_{⊙}—where galaxies have larger radii than the double power-law model—we have therefore additionally included the mass–size relation from Graham et al. (2006); see Equation (2.11) in Graham (2013). While Figure 3(a) reveals that the mass–size relation of local...
early-type galaxies has larger radii at a given mass than the distant spheroids, it also reveals that the masses and sizes of our local bulges overlap with those of the distant spheroids (Damjanov et al. 2011). Our data appear more clustered in Figure 3(a) simply because we have been stricter with the mass and size limit for our local bulge sample.

In Figure 3(b) we show the sizes and Sérsic indices of our local compact massive systems and the overlap with galaxies in the redshift interval $1.4 < z < 2.7$, as given by Damjanov et al. (2011, their Table 2). We have excluded from Damjanov et al. those galaxies with no reported Sérsic index and those fit with an $R_{e}/b$ surface brightness model having a fixed value of $n$, such as 4. As with our bulge data, the high-$z$ galaxy data in Damjanov et al. have also been taken from a compilation of different surveys: 17 in their case. Their galaxy selection criteria are thus varied, and it can be seen in Figure 3 to contain a much larger range of sizes and masses than our data. Comparing the data points, we conclude that not all compact, massive spheroids need to have undergone significant structural and size evolution since $z \lesssim 2.5$.

3.2. The Number Density of Local, Compact Massive Spheroids

Twenty-one of the 22 systems (20 bulges plus 2 galaxies) are within 90 Mpc, with the additional system at 103.6 Mpc. Excluding this furthest bulge gives a number density of $(6.9 \pm 1.5) \times 10^{-6}$ Mpc$^{-3}$ for the sample of 21. All of these systems have stellar masses in the range $0.7 \times 10^{11} < M_\star/M_\odot < 1.4 \times 10^{11}$. Ten of the 13 systems with $M_\star \geq 10^{11} M_\odot$ are within 70 Mpc, giving a similar number density$^4$ of $(7.0 \pm 2.2) \times 10^{-6}$ Mpc$^{-3}$. It needs to be remembered that these densities are a lower limit because we have not conducted a volume-limited, all-sky survey for compact massive spheroids. However, the ATLAS$^{3D}$ survey did sample all of the bright galaxies over half the sky to a depth of 42 Mpc. Given that it contains three compact, massive systems, this corresponds to a number density of $(1.9 \pm 1.1) \times 10^{-5}$ Mpc$^{-3}$. This value is $2.75 \pm (58\%)$ times higher, but there is a larger uncertainty assuming Poissonian errors.

While Taylor et al. (2010) reported a reduction, at fixed size and mass, of at least 5000 in the co-moving number density of compact massive galaxies from $z \sim 2.3$ to $z \sim 0.1$, we find that there is a roughly comparable (within a factor of a few) number density of compact massive systems at $z = 0$ and $z \sim 2.5$. Bezanson et al. (2009) report a number density of $(3 \pm 1) \times 10^{-5}$ Mpc$^{-3}$ at this higher redshift, for systems with stellar mass densities greater than one billion solar masses within their innermost sphere of radius 1 kpc (or $M_\star > 10^{11} M_\odot$, $R_e < 2.88$ kpc). Muzzin et al. (2013, their Figure 5) report a number density of $\sim 5 \times 10^{-3}$ Mpc$^{-3}$ at $2 < z < 3$ for all (compact and extended) quiescent galaxies with $M_\star \sim 10^{11} M_\odot$, in fair agreement with the value of $\sim 4 \times 10^{-5}$ Mpc$^{-3}$ for the quiescent galaxies at $z = 3 \pm 0.5$ with $M_\star > 0.4 \times 10^{11} M_\odot$ reported by Straatman et al. (2014). At these high redshifts, it is speculated here that the bulk of the disk formation (which will remove “galaxies” from satisfying the compactness criteria), may be yet to occur, and thus one may have a cleaner sample of “nakedbulges” with which to make a comparison with the number density of bulges in the local universe. At yet higher redshifts the “nakedbulges” may likely still be developing themselves (e.g., Dekel & Burkert 2014).

Barro et al. (2013) report a similar number density as Bezanson et al. (2009) at $z = 2.5$, even though Barro et al. used a lower stellar mass limit of $0.1 \times 10^{11} M_\odot$ for their sample (cf. $1.0 \times 10^{11} M_\odot$ used by Bezanson et al. 2009). Barro et al. reported that their number density increased as the redshift dropped, peaking at about $2.3 \times 10^{-4}$ Mpc$^{-3}$ by $z = 1.2$, before dropping to lower densities as the redshift decreased further. Taken together, this suggests that the most massive, quiescent spheroids were in place first, with the less massive spheroids appearing later at lower redshifts (possibly connecting with the luminous blue compact galaxies forming at $z < 1.4$; Guzmán et al. 1997). The above peak density at $z = 1.2$ is, at least in part, larger than the value we have found because Barro et al. included galaxies having a much broader range in stellar mass than we did. In a separate study, van der Wel et al. (2014) used a stellar mass limit $> 0.5 \times 10^{11} M_\odot$ and found a peak density at $z \sim 1.2$ of $1 \times 10^{-4}$ Mpc$^{-3}$.

The mass range sampled in our study only spans a factor of two, from 0.7 to $1.4 \times 10^{11} M_\odot$. Our number density per unit dex in mass, as recorded in mass functions, is therefore five times higher, giving $3.5 \times 10^{-5}$ Mpc$^{-3}$ dex$^{-1}$ (or $\approx 10^{-4}$ Mpc$^{-3}$ dex$^{-1}$ if using the volume-limited ATLAS$^{3D}$ results) at $M_\star \approx 10^{11} M_\odot$. These values are roughly 2–6 times lower than that from Barro et al. (2013), whose galaxy mass range exceeded 1 dex, and roughly 1–3 times lower than that from van der Wel et al. (2014), whose mass range was less than 1 dex. A proper comparison is, however, complicated because the local bulge mass function is not quite flat from 0.1 to $1.4 \times 10^{11} M_\odot$, but increases as one moves to the lower-mass end (e.g., Driver et al. 2007). For this reason, our number density for local compact massive bulges, as estimated above, is expected to be less than the actual number density in the decade-wide mass range from, say, 0.14 to $1.4 \times 10^{11} M_\odot$. Using a constant stellar M/L ratio across this mass range, to convert the bulge luminosity function in Driver et al. (2007) into a mass function, the actual number density in this decade range might be ~40% higher, although predicting this properly requires knowledge of the slope of the mass function for local compact bulges. We hope to perform a more complete, volume-limited investigation of compact massive bulges within 100 Mpc in a forthcoming paper, enabling us to construct the mass function of local compact bulges with $M_\star > 10^{10} M_\odot$. This can then be better compared with the mass function at higher redshifts.

The Wide-field Nearby Galaxy-cluster Survey (WINGS) has reported the existence of many compact massive galaxies in nearby $(0.04 < z < 0.07)$ clusters. Including substantially lower mass galaxies than us, Valentinuzzi et al. (2010) reported that 22% of the WINGS galaxies with $0.3 \times 10^{11} < M_\star/M_\odot < 4 \times 10^{11}$ are compact, with a median size of $1.61 \pm 0.29$ kpc (and a median Sérsic index of $3 \pm 0.6$). For their cluster galaxy sample they derived a lower limit (because they excluded field galaxies) for the number density of $(1.31 \pm 0.09) \times 10^{-3}$ Mpc$^{-3}$ within the co-moving volume between $z = 0.04$ and $z = 0.07$. This density drops to $(0.46 \pm 0.05) \times 10^{-3}$ Mpc$^{-3}$ when they increase their lower mass limit from $0.3 \times 10^{11} M_\odot$ to $0.8 \times 10^{11} M_\odot$ (their Table 1).

$^4$ The usual dependence on the Hubble constant — in this case $H_0^2$ — has been omitted given that the spherical volumes used have not been exactly matched to any particular outermost galaxy’s distance.
They observed that the bulk of their compact galaxies are lenticular galaxies, which are known to have ~30% smaller disk sizes in galaxy cluster environments (e.g., Gutiérrez et al. 2004; Head et al. 2014).

Using the Padova Millennium Galaxy and Group Catalogue (PM2GC) spanning 0.03 < z < 0.11, Poggianti et al. (2013a, 2013b) explored outside of clusters—most galaxies reside in the field or group environment—and concluded that 4.4% of local field and group galaxies with stellar masses \(0.3 \times 10^{11} < M_\odot / M_\odot < 4 \times 10^{11}\) are compact, and that this 4.4%—most of which are lenticular galaxies—has a median mass-weighted age of 9.2 Gyr, and corresponds to a number density of \((4.3) \times 10^{-4} \text{ Mpc}^{-3}\), or basically \(3.2 \times 10^{-4} \text{ Mpc}^{-3}\) dex\(^{-1}\) given their mass range sampled.

Although the above two studies treated the lenticular galaxies as single-component systems when measuring both their ages and their circularized half-light radii, we suspect that it is the bulges of these galaxies that are the primary, compact massive spheroidal component. In a sense, we may therefore be dealing with the same type of galaxy as they are. While we do not try to resolve the question as to why their compact, massive galaxies were not found by others who searched in the SDSS database, we do provide a couple of comments. Disk galaxies viewed edge-on will of course have circularized half-light radii that are notably smaller than the values obtained if they are viewed face-on. It may be of interest to see if the Valentiniuzzi et al. (2010) and Poggianti et al. (2013a, 2013b) detections are dominated by massive, edge-on disk galaxies. It may additionally be interesting to see the results (sizes, masses, number densities) after careful bulge/disk decompositions have been performed for these WINGS and PM2GC samples.

To recap our findings, we measure a lower limit of \(3.5 \times 10^{-5} \text{ Mpc}^{-3} \text{ dex}^{-1}\) (or \(\approx 10^{-4} \text{ Mpc}^{-3} \text{ dex}^{-1}\) if using the volume-limited ATLAS3D results) for compact \((R_e \lesssim 2 \text{ kpc})\) bulges with \(M_\odot \approx 10^{11} M_\odot\).

4. DISCUSSION

4.1. The Rise of Disks

As noted in the Introduction, within the literature, minor mergers are the overwhelmingly preferred, albeit still problematic, solution to try to transform the compact, massive spheroids at high redshifts into larger spheroids by today. While our discovery of numerous compact massive spheroids at \(z = 0\) suggests that this evolutionary path did not always transpire, we can still ask about minor mergers. If (wet or dry) minor mergers had built the disks, the observations may then be telling us that most central galaxies have had preferred “Great Planes” on which their minor neighbors were located prior to infall and disk (rather than bulge) building. Some support for this idea can be found in the disks-of-satellites around the Milky Way and Andromeda (Kroupa et al. 2005; Metz et al. 2007; Ibata et al. 2013; Pawlowski et al. 2014). What is of course different in our scenario is that these Great Planes are not just a recent, local phenomenon but

\[\text{Note. Column 1: Galaxy identification.}\]

\[\text{a The galaxy rather than bulge parameters were used.}\]

\[\text{T}^{\text{in}} \text{ Bulge/disk parameters may not be reliable.}\]

\[\text{b NGC 1332 has had its disk fit with a Sérsic model having}\]

\[n = 0.5, \text{ for which the scale length } h = R_{\text{e,disk}} / 0.82 (\text{ rather than } R_{\text{e,disk}} / 1.68 \text{ as is the case when } n = 1)\]

\[\text{Columns 2: Velocity dispersion (km s}^{-1})\text{ from HyperLeda (Makarov et al. 2014), except for NGC 1277 (van den Bosch et al. 2012). Columns 3 and 4: Bulge-to-disk size ratio and bulge-to-total flux ratio, respectively. For the lenticular galaxies (and NGC 6646), values were taken from the respective papers. For the spiral galaxies, the dust-corrected values were derived in Graham & Worley (2008). Column 5: Environment of the galaxy. BCG = Brightest Cluster Galaxy, BGG = Brightest Group Galaxy. }\]

\[\text{NGC 2599}\]

\[\text{NGC 3884}\]

\[\text{NGC 7490}\]

\[\text{UGC 2862}\]

\[\text{NGC 3147}\]

\[\text{NGC 6504}\]

\[\text{NGC 6646}\]

\[\text{NGC 507}\]

\[\text{NGC 1316}\]

\[\text{NGC 5493}\]

\[\text{NGC 4649}\]

\[\text{NGC 3640}\]

\[\text{Table 2}\]

\[\begin{array}{llll}
\text{Gal.Id.} & \text{Galaxy Properties} & \text{Environment} \\
\hline
\text{NGC 2599} & \text{230} & 0.19 & 0.24 \text{ Field?} \\
\text{NGC 3884} & \text{209} & 0.20 & 0.22 \text{ Abell 1367 cluster (N = 90)} \\
\text{NGC 7490} & \text{232} & 0.52 & 0.95 \text{ Group (N = 22)} \\
\text{UGC 2862} & \text{215} & 0.43 & 0.58 \text{ Group (N = 11)} \\
\text{NGC 3147} & \text{204} & 0.20 & 0.24 \text{ BCG, poor cluster Abell S753} \\
\text{NGC 5493} & \text{259} & 0.27 & 0.48 \text{ Field} \\
\end{array}
\]
would need to have always been present over the past 10−13 Gyr (see Goerdt et al. 2013).

Hammer et al. (2005, 2009) have reasoned that many rotating stellar disks could have been built in major gas-rich mergers, with the disk forming due to the net angular momentum of the gas in the merger event (e.g., Barnes 2002; Robertson et al. 2006). Even in gas-poor (dry) mergers, Naab & Burkert (2003) report that disks can form if the net angular momentum is not canceled out (Fall 1979). Given that rotating spiral galaxies at z ≈ 0.65 are half as abundant as they are today (Neichel et al. 2008), disk growth since z = 2 ± 0.6 has obviously occurred, and the outer regions of galaxies with prominent bulges are known to be younger (e.g., Pérez et al. 2013; Li et al. 2015). Arnold et al. (2011) additionally remarked that lenticular galaxies might form through a two-phase inside-out assembly with the inner regions built early via a violent major merger, and wet minor mergers (rather than gas accretion) subsequently contributing to their outer parts.

It is recognized that there have not been enough galaxy merger events to transform the distant compact massive galaxies into today’s ordinary-sized elliptical galaxies (e.g., Man et al. 2015), and therefore the above mechanisms cannot, on their own, be invoked to fully explain the growth of disks around the compact massive galaxies seen at high, z such that they have become today’s lenticular galaxies with typical disk-to-bulge flux ratios of 3 (i.e., bulge/total = 1/4). Observing higher gas fractions of lower metallicity at higher redshifts, Béthermin et al. (2015) favor large gas reservoirs over major mergers as the cause of the intense star formation observed in massive galaxies at high redshifts. Following the idea of cyclical galaxy metamorphosis (White & Rees 1978; Navarro & Benz 1991; White & Frenk 1991; Steinmetz & Navarro 2002; see also Bournaud & Combes 2002), Graham (2013) advocated earlier suggestions that “cold” gas flows may have contributed to the development of these disks, via either spherical accretion of \( \sim 10^{4} - 10^{5} \) K gas (e.g., Birnboim & Dekel 2003; Birnboim et al. 2007) or streams (e.g., Kereš et al. 2005; Dekel et al. 2009; Kereš & Hernquist 2009; Danovich et al. 2014).

This alternative process, which can operate in parallel with mergers (e.g., Welker et al. 2015), involves the accretion of gas from not just the halo (e.g., Kauffmann et al. 1993, their Section 2.7; Kauffmann et al. 1999, their Section 4.5; Genzel et al. 2006) and possible molecular gas reservoirs for some galaxies (e.g., Tacconi et al. 2008; Santini et al. 2014; Chapman et al. 2015) but also cold filamentary flows from the cosmic web (e.g., Ceverino et al. 2010, 2012; Goerdt et al. 2012; Rubin et al. 2012; Stewart et al. 2013). Although such cold gas accretion is yet to be convincingly demonstrated as a common phenomenon, it has the power to subsequently build a disk that transforms into stars. Indeed, it has been noted for well over a decade that the mass of a galaxy could double, due to gas accretion, in just a few Gyr (e.g., Katz et al. 1996; Bournaud & Combes 2002). The discovery of very low metallicity gas (0.02 solar) 37 kpc from a sub-L* galaxy with solar metallicity by Ribaudo et al. (2011) revealed the presence of such gas, and we now know that there is lots of low metallicity gas in the halos of galaxies (e.g., Lehner et al. 2013; Prochaska et al. 2014). Furthermore, Bouché et al. (2013) have revealed the inflow (as opposed to just presence) of this material around a z = 2.3 galaxy that has kinematics, metallicity, and star formation typical of a rotationally supported disk, and it is such that the gas accretion rate is well matched to the star formation rate (see also Conselice et al. 2013). It has also been established that there is a high spatial covering fraction of Lyα gas clouds within 300 kpc of all galaxy types at high z (Wakker & Savage 2009; Prochaska et al. 2011; Thom et al. 2011; Stocke et al. 2013; Tumlinson et al. 2013), and a review of cool gas in high-z galaxies can be found in Carilli & Walter (2013). In particular, even quiescent elliptical galaxies can have a massive cool reservoir around them (Thom et al. 2012; Tumlinson et al. 2013; Zhu et al. 2014; O’Sullivan et al. 2015). Although not surrounding a pre-existing compact, massive bulge, Prescott et al. (2015) report on the rotation of an 80 kpc Lyα nebula at z ~ 1.67 with an implied total mass of \( 3 \times 10^{11} M_\odot \) within a 20 kpc radius. While this is a developing field, extensive evidence for gas accretion at many redshifts is reviewed by Combes (2014, 2015b).

Figure 3. (a) Stellar mass–size diagram, where the sizes of the local bulges are represented here by the major-axis effective half-light radius \( R_e \). The curves show the parameterized fit to local “elliptical” galaxy data from Graham et al. (2006, solid line) and Lange et al. (2015, specifically their Figure A9) and Equation (3), and their final K-band entry in Table 3, dashed line. The z = 0 bulge data are from Table 1, while the 1.4 < z < 2.7 data are from Damjanov et al. (2011). Local bulges with \( M_\star \geq 2 \times 10^{11} M_\odot \) have \( R_e \geq 2.5 \) kpc and were thus not included here because they are not considered to be compact galaxies. (b) Size–concentration diagram, where the concentration is quantified by the Sérsic index n.
It seems likely that the compact massive galaxies would act as natural gravitational seeds around which filaments or streams of cold gas would flow inward and build disks that form stars. The existence of early-type galaxies with dual, large-scale counter-rotating stellar disks (e.g., NGC 4550, Rubin et al. 1992; NGC 3032, Young et al. 2008) supports the idea of disk growth via the accretion of external gas clouds (e.g., Coccato et al. 2015, and references therein), although it may also be due to minor mergers. Presumably feeding is usually from the same direction, given the low frequency of significant (by mass) counter-rotation, and after settling to the mid-plane the rotation is aligned. Small counter-rotating stellar disks and kinematically decoupled cores do, however, reveal that this is not always the case, and gas accretion can form interesting features such as warps, gas-star misalignments, and polar rings (e.g., Briggs 1990; Jog & Combes 2009; Davis et al. 2011; Mapelli et al. 2015). However, rather than only random accretion orientations, Pichon et al. (2011) explain how cold streams can build a disk in a coherent planer manner (see also Danovich et al. 2012, 2014; Prieto et al. 2013; Stewart et al. 2013; Cen 2014; Wang et al. 2014), which is of key importance. A second key aspect is the rapid formation of some of these disks (e.g., Agertz et al. 2009; Brooks et al. 2009), which would naturally explain the older ages of many lenticular galaxy disks today. It also implies significant galaxy growth independent of the merging of distinct entities such as dark matter halos. This process of gas accretion is still observed today in massive early-type galaxies (e.g., Davis et al. 2011).

Disk growth in early-type galaxies is an ongoing phenomenon (e.g., Yi et al. 2005; Kaviraj et al. 2007; Fabricius et al. 2014), albeit at lower levels today as less gas is available (e.g., Combes et al. 2007; Sage et al. 2007; Huang et al. 2012; Catinella et al. 2013). The molecular gas usually resides in kpc-scale, rotating disks (e.g., Inoue et al. 1996; Wiklind et al. 1997; Das et al. 2005; Okuda et al. 2005), as does the H1 gas (e.g., Serra et al. 2012, 2014, and references therein). Young et al. (2008), for example, detail the slow ongoing growth of the disk in NGC 4526, a galaxy whose bulge has a half-light radius equal to 1.43 kpc (Krajnović et al. 2013) and a stellar mass of $0.55 \times 10^{11}$ (which, along with other bulges, was not massive enough to be included in our sample). Perseus A is yet another example that is also still accreting cold gas (Salomé et al. 2006).

As noted in Section 2, NGC 1277, NGC 1332, NGC 5493 and NGC 5845 are examples of local early-type galaxies where the disk does not dominate the light at large radii, as in prototypical lenticular galaxies. These disks are an order of magnitude larger than nuclear disks and referred to as intermediate-sized disks. Given that the amount of gas accretion can vary, it would be natural for such disks to exist. They are not a new phenomenon (e.g., Scorzà & van den Bosch 1998 and references therein), but some readers may not be familiar with their existence. At $z \approx 2$, the lower-mass spheroids, with less gravitational pull, and which likely formed from a smaller overdensity in the early universe, may naturally experience a smaller subsequent supply of gas from cold streams and build their disks more gradually. Free-floating, “compact elliptical” dwarf galaxies (e.g., Huxor et al. 2013; Paudel et al. 2014) might represent spheroids that never acquired a significant disk, while those in the vicinity of much larger neighbors are thought to have been largely stripped of their disks.

The theoretical work of Steinmetz & Navarro (2002, and references therein) suggested that a galaxy’s morphology is a transient phenomenon. Galaxies do not simply progress from the “blue cloud” to the “red sequence” (Faber et al. 2007) but can move in the opposite direction. While the latter pathway may not be traversed in full today, because less gas is available, there are felled examples of galaxies in the “green valley” (e.g., Cortese & Hughes 2009; Marino et al. 2011). Elliptical galaxies may initially be built through major mergers of disk galaxies (and perhaps from a violent disk instability; Ceverino et al. 2015) and then proceed to grow a new stellar disk through gas accretion (White & Frenk 1991), which remains intact until the next significant merger (see Salim et al. 2012 and Conselice et al. 2013 for supporting arguments, and Fang et al. 2012 and Bresolin 2013 for caution in some cases). The number of cycles may, however, be low (i.e., 1 or 2) rather than several (3–5). Evidence for a bulge-then-disk scenario may exist within the Milky Way (e.g., Zoccali et al. 2006). Furthermore, the hierarchical models from Khochfar & Silk (2006), for example, present diskless galaxies at $z = 2$, which evolve into disk galaxies with a bulge-to-total mass ratio equal to 0.2 by $z = 0$ due to gas accretion from the halo, cold streams, and minor mergers.

There have recently been reports of infant, premature disks detected in some of the high-redshift, compact massive galaxies (Chevance et al. 2012 and references therein). In a study of 14 compact massive galaxies at $z = 2.0 \pm 0.5$, van der Wel et al. (2011) reported that 65 ($\pm15$)% are disk dominated, appearing highly flattened on the sky and having disks with a median half-light radius of 2.5 kpc. This corresponds to a median scale length of 1.5 kpc, which is half the size of disks today, e.g., Graham & Worley (2008, their Figure 3). These high-z disks were observed to harbor compact central components, i.e., bulges. Although most early-type galaxies around us today are known to be lenticular disk galaxies—thanks to studies such as ATLAS3D (Emsellem et al. 2011)—there are of course still some massive, slow or non-rotating, elliptical galaxies. Some of these may be the “ordinary-sized” elliptical galaxies, observed at high $z$, while others likely formed from more recent, major merger events. Some of the “ordinary-sized” elliptical galaxies at high $z$ may have also acquired disks, but they would appear as intermediate-sized disks if insufficient gas was accreted to build a larger-scale disk around an already large galaxy.

Following the deep observations by Szomoru et al. (2010) to verify the compactness of a galaxy at $z = 1.91$ found by Daddi et al. (2005), we note that future work should be mindful that shallow surveys at any redshift could miss the outer disks of galaxies to varying degrees and may largely just recover the inner bulge if they are particularly shallow. If that was to occur, one would effectively, although accidentally, manage to identify higher number densities of compact massive systems.

### 4.2. Stellar Ages and Stellar Mass Loss

The above scenario for disk growth around compact “bulges” requires the massive bulges of nearby disk galaxies to be old. Although beyond the scope of the current investigation, it will be of interest to explore the ages of the

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Based on $M_{V} = -20.4$ mag and using $M/L_{V} = 5$ (Krajnović et al. 2013).
bulges and disks in the current sample of galaxies. However, MacArthur et al. (2009) have already shown that bulges in both early- and late-type disk galaxies do indeed have old mass-weighted ages, with less than 25% by mass of the stars being young, second- or third-generation stars built from metal-enriched gas. Based on stellar populations and radial gradients, MacArthur et al. (see also Fisher et al. 1996) concluded that early-formation processes are common to bulges and that secular processes or “rejuvenated” star formation generally contribute minimally to the stellar mass budget of bulges (see also Moorthy & Holtzman 2006; Thomas & Davies 2006; Jablonka et al. 2007), yet it has biased luminosity-weighted age estimates in the past. Such “frostings” of young stars, of up to 25% by mass, can give the impression of positive luminosity-weighted age gradients, i.e., bulges are younger at their centers, and have misled some studies (which assumed a single stellar population) into missing the fact that the bulk of the stellar mass in most bulges is old.8 This follows Kuntschner & Davies (1998), who revealed that the obvious lenticular galaxies in the Fornax cluster have ages that are younger than the more spheroid-dominated galaxies in the cluster.

These works imply that the bulk of the stellar mass in today’s massive bulges already existed at high redshifts, and therefore these stellar systems should be what we are observing in deep images of our young universe. Curiously, Saracco et al. (2009) reported that there are two kinds of early-type galaxy at z ≈ 1.5: an old (∼ 3.5 Gyr) population that needs to experience a factor of 2.5–3 size evolution to have sizes equal to today’s early-type galaxies, and a young (∼ 1 Gyr) population (perhaps those that have recently acquired their disks) that already has sizes consistent with today’s population of early-type galaxies. In this regard, it will be interesting to know if their old population is best described with a single Sérsic model, while their young population is better described by a bulge+disk model rather than a single-component Sérsic model. Furthermore, if a younger disk has formed, or bulges developed at different epochs, they may have different initial stellar mass functions (IMFs), resulting in differing composite IMFs for the early-type galaxies today (e.g., Dutton et al. 2013; McDermid 2015, and references therein).

Gradual stellar mass loss due to stellar winds is a part of the aging process for passively evolving spheroids (e.g., de Jager et al. 1988; Ciotti et al. 1991; Jungwiert et al. 2001), as is the conversion of visible stars into dark remnants such as neutron stars and stellar mass black holes. If a fraction x of the initial mass is lost from a galactic system due to stellar winds, or Type Ia supernovae clearing out gas, then there will be an adiabatic expansion because the galaxy is no longer as tightly bound and it will therefore reach a new equilibrium such that its size has increased by 1/(1 − x) (e.g., Jeans 1961, p. 299; Hills 1980, their Equation (6)). Of course, if any stellar ejecta remains in a galaxy—which seems likely in massive galaxies with strong potential wells—perhaps eventually ending up as hot X-ray gas, then the expansion of the galaxy will be reduced depending on the radial expance of this gas. After the young stars (<1 Gyr) have evolved, stellar winds likely account for just a ∼ 10% reduction to the stellar mass of the passive, compact massive galaxies seen at z ∼ 2 (Damjanov et al. 2009; but see Poggianti et al. 2013b). Fan et al. (2008) had previously suggested that AGN feedback may blow out the gas in distant massive galaxies and cause them to expand by factors of 3 or more. Of course, if this had happened, then we would be left having to explain where all of the compact massive bulges in the universe today came from.

4.3. Stellar Density

Given the smaller half-light radii that early-type galaxies had at higher redshifts, before they acquired their disks, the stellar densities within those half-light radii were 1 to 2 orders of magnitude greater than the stellar densities inside the half-light radii of today’s large early-type galaxies. This led Zirm et al. (2007) to conclude that it is a problem for models of early-type galaxy formation and evolution. Buitrago et al. (2008) claimed that within the inner 1 kpc of the high-z galaxies, they have densities equal to globular clusters. This led them to advocate a scenario in which globular clusters and distant compact massive galaxies may have a similar origin, while at the same time suggesting that the more massive halos (not the globular clusters) started collapsing earlier and dragged along a larger amount of baryonic matter that later formed stars. However, they overestimated the typical globular cluster size by a factor of 10/3 and thus underestimated a typical globular cluster’s density by a factor of 37, undermining their conclusions.

Bezanson et al. (2009) revealed that the inner regions (<1 kpc) of today’s early-type galaxies have stellar densities that are 2–3 times lower than those of the distant compact massive galaxies of the same mass. However, the majority of galaxies in our sample have bulge-to-total ratios of 1/2–1/4 (Table 2), while Laurikainen et al. (2010) found an average ratio of 1/4 for their sample of lenticular galaxies. That is, the local massive bulges are 2–4 times less massive than the galaxy within which they reside. In comparing galaxies of the same mass in Figure 2d from Bezanson et al. (2009), one is effectively comparing the high-redshift galaxies with local bulges that are 2–4 times less massive, possibly accounting for the lower density observed in these lower-mass bulges. If one compares the quiescent, compact massive galaxies at high redshift with today’s bulges of the same mass, one may find that they have the same density within the inner kpc. Hussain et al. (2009) reported that there is no central (<1 kpc) density mismatch (van Dokkum et al. 2014). They suggested that “the entire population of compact, high-redshift red galaxies may be the progenitors of the high-density cores of present-day ellipticals,” by which they mean spheroids. We, however, consider the evolution to have been very different, such that a 2D disk is built within and around the spheroid that undergoes no substantial size evolution, rather than the continual development of a 3D envelope around a spheroid that effectively undergoes significant size growth.

4.4. Velocity Dispersions

If there is indeed no evolution of the distant spheroids, then their velocity dispersion should remain the same. Now, if a stellar disk builds within and around them, then the galaxy mass today will have increased. As a result, if one was to compare the velocity dispersions of the distant compact spheroids with the...
velocity dispersions of \( z = 0 \) disk galaxies having the same total stellar mass, one would actually be sampling local bulges that are less massive than the distant spheroids. The local galaxies of the same mass, containing compact bulges of 2–4× lower mass, are naturally expected to have lower velocity dispersions. Indeed, this general behavior has been observed (e.g., Cenarro & Trujillo 2009; Cappellari et al. 2009; Newman et al. 2010).

If one assumes \( M_b \propto \sigma^4 \), then a 2–4× difference in stellar mass will be associated with a \( \sim 1.2–1.4\times \) difference in velocity dispersion. If one attempts to bypass the photometric stellar mass estimate and use a dynamical/virial mass estimate \((\sigma^2 R_{e,\text{gal}})\) for the lenticular galaxies, the same issue occurs. This is because of the enhanced \( R_{e,\text{gal}} \) due to the presence of the disk component. If a galaxy’s half-light radius is 3–6 times larger than the half-light radius of its central bulge, then the velocity dispersion of the bulge coupled with the galaxy size will produce a galaxy virial mass that is 3–6 times larger than what one would obtain for the bulge. This will act to artificially separate the compact high-\( z \) spheroids from local massive bulges in a diagram of dynamical mass versus velocity dispersion. A note to keep in mind is that disk growth, as with envelope growth, may lead to the compression of the original inner bulge and a slight enhancement in the central velocity dispersion (Andredakis 1998; Debattista et al. 2013).

4.5. Depleted Cores

The presence of partially depleted cores in massive spheroids is thought to be a result of major, dry merger events (e.g., Begelman et al. 1980; Faber et al. 1997; Merritt et al. 2007). The large elliptical galaxies with sizes several times that of the high-\( z \) compact massive spheroids, and with a deficit of stars over their inner tens of parsecs to a few hundred parsecs, likely formed this way. The orbital decay of the binary supermassive black hole, created by the galaxy merger, proceeds by slingshotting the central stars out of the core of the newly formed galaxy. However, as noted by Dullo & Graham (2013), the presence of such partially depleted cores in the bulges of massive disk galaxies (e.g., Dullo & Graham 2013) presents a conundrum because these disk galaxies may be unlikely to have formed from such major merger events.\(^9\) One potential solution is that the bulges may have formed first, and the disks were subsequently accreted and grew (Driver et al. 2013; Graham 2013). It may therefore be interesting to check for partially depleted cores in the current sample of disk galaxies in Table 1. Application of the core-Sérsic model (Graham et al. 2003) to Hubble Space Telescope images—due to their superior spatial resolution over a sufficiently wide field of view—will reveal which bulges have an inner deficit of flux relative to the inward extrapolation of their outer Sérsic light profile. Knowledge of which bulges have partially depleted cores, coupled with information about their stellar age, should shed even further light on the formation history.

4.6. Formation Paths and a Cautionary Remark on the \( n = 2 \) or \( n = 2.5 \) Division of Bulges

Surveying predominantly compact, passive, spheroidal galaxies at 1.4 < \( z < 2.0 \), with \( 10^{10} < M_\odot / M_{\odot} < 10^{11} \), Cimatti et al. (2008, see van Dokkum et al. 2008 for higher redshifts and higher masses) noted that the galaxy sizes are typically such that \( R_e \lesssim 1 \) kpc and are thus much smaller than early-type galaxies of comparable mass in the present-day universe. However, the bulges of most disk galaxies at \( z \approx 0 \) have compact sizes with \( R_e \lesssim 2 \) kpc, and many bulges with \( 10^{10} < M_\odot / M_{\odot} < 10^{11} \) have \( R_e \lesssim 1 \) kpc (e.g., Graham & Worley 2008; Graham 2013). The growth of disks in and around the compact, high-\( z \) spheroids could therefore explain their apparent disappearance by today.

This possible explanation may at first glance appear somewhat at odds with the claim in the interesting paper by van Dokkum et al. (2013) that disk models, in which bulges were fully assembled at high redshift and disks gradually formed around them, can be ruled out. However, the first distinction in these two remarks is of course that disks do not simply form around spheroids but are additionally embedded within them, which is why bulge/disk decompositions continue the disk all the way into the centers of galaxies. It would therefore be of interest to perform a bulge/disk decomposition of the average surface density profiles, at different redshift intervals, that were constructed by Dokkum et al. (2013, their Figure 3). This would allow one to check how well their \( z = 0 \) Milky-Way-like galaxy profile that they built resembles the Milky Way, and thus to know if their stacked profiles are reliable or perhaps effected by dust or some other issue.\(^{10}\) A reliable decomposition of an evolving population (free from “progenitor bias”) would of course enable one to quantify how much the disk and bulge (including pseudobulge) components have changed between the different redshifts. The second point of distinction is that van Dokkum et al. (2013) were referring to the inner 2 kpc radius of Milky-Way-mass spiral galaxies, rather than \( 10^{11} M_\odot \) galaxies. The Milky Way has a bulge mass of \( 0.91 \times 10^{10} M_\odot \) and a bulge-to-total stellar mass ratio of 0.15 (Licquia & Newman 2014); it also has a half-light radius of 0.66 kpc (Graham & Driver 2007). Therefore, within an inner radius of 2 kpc, the bulges of Milky-Way-like galaxies are dominated by the disk rather than the bulge. Due to the greater prominence of bulges in early-type disk galaxies than in late-type disk galaxies (see Figure 21 in Graham 2001), the inner regions of today’s massive galaxies—which host the once distant, compact massive spheroids—are expected to have changed over time, as already observed by van Dokkum et al. (2010, their Figure 6).

Within the bulge-then-disk growth scenario, the existence of the distant massive spheroids having \( n < 2 \) implies that local galaxies with bulges having \( n < 2 \) need not be pseudobulges formed from the secular evolution of a stellar disk. This topic is reviewed in Graham (2013, 2014), where it is noted that bulges with Sérsic \( n < 2 \) need not be pseudobulges even if they are also rotating (e.g., Eliche-Moral et al. 2011; Scannapieco et al. 2011; Keselman & Nusser 2012; Saha et al. 2012; dos Anjos & da Silva 2013; Graham 2014; Querejeta et al. 2015).

In passing, we remark that formation paths in galaxy clusters in which the disks of spiral galaxies fade and lose their pattern, and possibly end up with relatively brighter bulges (e.g., Johnston et al. 2012, and references therein), to become lenticular galaxies can still operate. That is, lenticular galaxies

\(^9\) Major galaxy collisions may be more inclined to result in elliptical galaxies than disk galaxies, although see Naab & Burkert (2003).

\(^{10}\) The lack of any central bulge within the inner kpc of the \( z = 0 \) profile is at odds with Milky-Way-like disk galaxies, and the high average Sérsic index \( (n = 2.6 \pm 0.4) \) also suggests that their average profile is not representative of Milky-Way-like galaxies, but rather an intermediate-luminosity early-type galaxy that has a very different bulge-to-total mass ratio.
likely have more than one evolutionary path, as can their bulges (e.g., Cole et al. 2000; Springel et al. 2005), and the presence of both classical and pseudobulges in the same lenticular galaxy would seem to support this (e.g., Erwin et al. 2003). At the same time, the preservation, i.e., the lack of evolution, of compact massive spheroids from \( z = 2 \pm 0.6 \) until today has implications for studies of the evolution of the black hole–bulge mass scaling relations (reviewed in Graham 2015, and references therein). The \( M_{\text{bh}}/M_{\text{bulge}} \) ratio would not be expected to decrease in these particular systems since \( \approx 1.4 \).

McLure et al. (2013) reported that 44\% \pm 12\% of their \( z = 1.4 \pm 0.1 \) sample of relatively passive galaxies (specific star formation rate, sSFR \( \lesssim 0.1 \text{ Gy}^{-1} \)) with \( M_{\star} \geq 0.6 \times 10^{11} M_{\odot} \) have a disk-like morphology. While at face value this claim may appear to support the notion that flattened 2D disks have developed, their morphological (disk-like) claim was based on a Sérsic index divide at \( n = 2.5 \) such that they labeled galaxies with \( n < 2.5 \) to be late-type galaxies. They adopted this divide because Shen et al. (2003) had used it to separate the bright, local galaxy population. Shen et al. (2003) could do this because their SDSS sample contained relatively few dwarf early-type galaxies that have \( n < 2.5 \). However, bulges can have \( n < 2.5 \). Therefore, some/many (?) of the galaxies in the sample of McLure et al. (2013) with \( n < 2.5 \) may still be rather "naked bulges," rather than disk-dominated galaxies. Indeed, the similar distributions for their passive sample with \( n < 2.5 \) and \( n \geq 2.5 \) in the size–mass diagram (their Figure 8) would suggest this.

The practice of considering all high-\( z \), compact, massive objects to be disk galaxies if their Sérsic index is less than 2–2.5 is unfortunately rather common (e.g., Hathi et al. 2008; Chevance et al. 2012; Fathi et al. 2012; Muzzin et al. 2012) and may have effectively misled many researchers. For this reason we have provided this cautionary text against this practice.

5. CONCLUSIONS

The compact massive galaxies at redshifts \( z \approx 2 \pm 0.6 \) have similar stellar masses and sizes (and thus stellar densities) and radial concentrations of light as bright bulges in local disk galaxies. Moreover, the number density is not different by hundreds or thousands but is within a factor of a few. We have identified 21 compact \( (R_e \lesssim 2 \text{ kpc}) \), massive \((0.7 \times 10^{11} < M_{\star}/M_{\odot} < 1.4 \times 10^{11}) \) spheroids within 90 Mpc, giving a number density of \( 6.9 \times 10^{-6} \text{ Mpc}^{-3} \) (or \( 3.5 \times 10^{-5} \text{ Mpc}^{-3} \) per unit dex\(^{-1} \) in stellar mass). This is, however, a lower limit because we have not performed a volume-limited search. Based on a sub-sample taken from a smaller volume-limited sample, this density may be \( 2.75 \pm 0.58 \% \) times higher at around \( 10^{-4} \text{ Mpc}^{-3} \) dex\(^{-1} \).

This observation eliminates the need to grow all of the high-\( z \) compact massive spheroids by a factor of 3 to 6 by \( z = 0 \), a challenge that had remained unexplained for the past decade. Rather, many of these high-\( z \) spheroids need to remain largely unchanged in order to match the massive bulges in today’s early-type disk galaxies. Therefore, any study that may have claimed to have accounted for the size growth of quiescent galaxies would have inadvertently, and most likely unknowingly, introduced an equally puzzling problem. If all the distant, compact massive spheroids had evolved, we would then be faced with a second unexplained mystery, namely, where did the compact massive bulges in the local universe come from and why are they not observed in deep images of the \( z = 2.0 \pm 0.6 \) universe.

We conclude that stellar disks have since grown around many compact massive spheroids observed at \( z = 2.0 \pm 0.6 \) and in so doing transformed their morphological type from elliptical to early-type disk galaxy (i.e., lenticular galaxies and early-type spiral galaxies). Following Graham (2013), we again speculate that some of the less massive compact spheroids at high redshifts may now reside at the centers of late-type spiral galaxies and/or are today’s compact dwarf elliptical galaxies—which either were largely stripped of their disk or never acquired one.

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