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Duncan Forbes  
*Swinburne University of Technology*

Luciana Sinpetru  
*University of Edinburgh*

Giulia Savorgnan  
*Swinburne University of Technology*

Aaron Romanowsky  
*San Jose State University, aaron.romanowsky@sjsu.edu*

Christopher Usher  
*Liverpool John Moores University*

See next page for additional authors

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The SLUGGS Survey: stellar masses and effective radii of early-type galaxies from Spitzer Space Telescope 3.6 μm imaging

Duncan A. Forbes, 1, * Luciana Sinpetru, 2, Giulia Savorgnan, 1
Aaron J. Romanowsky, 3, 4, Christopher Usher 5 and Jean Brodie 4

1 Centre for Astrophysics and Supercomputing, Swinburne University, Hawthorn VIC 3122, Australia
2 Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
3 Department of Physics and Astronomy, San Jose State University, One Washington Square, San Jose, CA 95192, USA
4 University of California Observatories, 1156 High Street, Santa Cruz, CA 95064, USA
5 Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK

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ABSTRACT
Galaxy starlight at 3.6 μm is an excellent tracer of stellar mass. Here we use the latest 3.6 μm imaging from the Spitzer Space Telescope to measure the total stellar mass and effective radii in a homogeneous way for a sample of galaxies from the SAGES Legacy Unifying Globulars and Galaxies (SLUGGS) survey. These galaxies are representative of nearby early-type galaxies in the stellar mass range of 10 < log M_*/M⊙ < 11.7 and our methodology can be applied to other samples of early-type galaxies. We model each galaxy in 2D and estimate its total asymptotic magnitude from a 1D curve-of-growth. Magnitudes are converted into stellar masses using a 3.6 μm mass-to-light ratio from the latest stellar population models of Röck et al., assuming a Kroupa initial mass function. We apply a ratio based on each galaxy’s mean mass-weighted stellar age within one effective radius (the mass-to-light ratio is insensitive to galaxy metallicity for the generally old stellar ages and high metallicities found in massive early-type galaxies). Our 3.6 μm stellar masses agree well with masses derived from 2.2 μm data. From the 1D surface brightness profile, we fit a single Sérsic law, excluding the very central regions. We measure the effective radius, Sérsic n parameter and effective surface brightness for each galaxy. We find that galaxy sizes derived from shallow optical imaging and the 2MASS survey tend to underestimate the true size of the largest, most massive galaxies in our sample. We adopt the 3.6 μm stellar masses and effective radii for the SLUGGS survey galaxies.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: fundamental parameters – galaxies: individual.

1 INTRODUCTION
The total stellar mass is a fundamental parameter for any galaxy. Not only do many other galaxy properties vary with stellar mass, but an accurate measure of stellar mass is required to probe the dark matter content (i.e. the total mass minus the stellar mass) in a galaxy. However, measuring the total stellar mass is problematic, even once the total luminosity has been accurately measured. For example, a common approach is to measure the total luminosity of a galaxy at near-infrared (IR) wavelengths for which the light mostly comes from old stars that dominate the mass and the effects of dust are much reduced compared to optical wavelengths. A typical approach is to use the full-sky ground-based near-IR imaging of the 2MASS survey (Jarrett et al. 2003). However, it has been reported that the 2MASS reduction pipeline systematically underestimates the total luminosity and size of large, nearby galaxies due to a truncation of their surface brightness profiles (Schombert & Smith 2012; Scott, Graham & Schombert 2013).

An alternative approach is to use the 3.6 μm band of the Spitzer Space Telescope (Werner et al. 2004) or the 3.4 μm band of the WISE Space Telescope (Wright et al. 2010). Such wavelengths are particularly well suited to measure the stellar masses of galaxies. For example, Norris et al. (2014) concluded that photometry from WISE can ‘...provide extremely simple, yet robust stellar mass tracers for dust free older stellar populations...’. This is because the 3.4–3.6 μm light from galaxies is dominated by the light from old stars and it is less affected by variations in the star formation history than shorter wavelengths. Although intermediate-aged stars, hot dust and polycyclic aromatic hydrocarbons may contribute to the emission at 3.6 μm, these sources are negligible for most early-type galaxies which are dominated by old stellar populations (Meidt et al. 2012; Querejeta et al. 2015).

* E-mail: dforbes@swin.edu.au
Here we use 3.6 \( \mu \text{m} \) imaging from the Spitzer Space Telescope. The 3.6 \( \mu \text{m} \) mass-to-light ratio (M/L\(_{3.6}\)) has virtually no dependence on metallicity and only a very small dependence on age for old stellar ages. We use the latest single-burst stellar population models (Röck et al. 2015) which are based on empirical mid-IR stellar spectra (Cushing, Rayner & Vacca 2005; Rayner, Cushing & Vacca 2009). These models cover a range of metallicity, ages and initial mass function (IMF) slopes. They are shown to reproduce well the mid-IR colours of early-type galaxies. For a Kroupa IMF, these models give M/L\(_{3.6}\) \sim 0.8 for a stellar population mean age of 9 Gyr, with a variation between different isochrones, i.e. from BaSTI and Padova, of \sim 0.05. For a metallicity range of [Fe/H] = \sim 0.4 to solar (i.e. typical of the mean values for massive early-type galaxies), the variation is insignificant at \sim 0.02. We note that the Flexible Stellar Population Synthesis (Conroy & Gunn 2010) models with asymptotic giant branch circum-stellar dust included (Villaume, Conroy & Johnson 2015) also give M/L\(_{3.6}\) \sim 0.8 for a 9 Gyr old, moderately metal-rich population. Meidt et al. (2014) adopted a constant value of M/L\(_{3.6}\) = 0.6 for their Muñoz-Mateos et al. (2015), hereafter S4G) sample, although their sample was dominated by late-type galaxies with younger mean ages on average.

Stellar mass-to-light ratios have a strong dependence on the IMF. The M/L\(_{3.6}\) values quoted above refer to a Kroupa IMF. Salpeter and other IMFs tend to have higher M/L\(_{3.6}\) values by a factor of \sim 1.5–3 (Röck et al. 2015), which would lead to larger stellar masses for a given 3.6 \( \mu \text{m} \) luminosity. Recent work indicates that the IMF for early-type galaxies is skewed to low-mass stars (see e.g. Ferré-Mateu, Vazdekis & de la Rosa 2013; Martín-Navarro et al. 2015; McConnell, Lu & Mann 2016). Currently, it is not yet clear what is causing the IMF variations nor whether these variations are confined to galaxy central regions, high-metallicity regions or spheroids. Here we adopt a Kroupa IMF for our global M/L\(_{3.6}\) but caution that the stellar masses for massive elliptical galaxies may need revising upwards.

Since M/L\(_{3.6}\) varies with stellar age, an age-appropriate ratio should be employed. Here we adopt an age dependent mass-to-light ratio from the Röck et al. (2015) models using mean stellar ages from the literature. We assume a Kroupa IMF. The SAGES Legacy Unifying Globulars and Galaxies (SLUGGS) survey targets 25 nearby massive early-type galaxies in different environments and 3 so-called bonus galaxies (Brodie et al. 2014). We study the kinematics and metallicity of both the galaxy itself and its system of globular clusters to large galactocentric radii. The sample galaxies are chosen to cover a range of key parameters including stellar mass and physical size. Until now, the approach in the SLUGGS survey to measure stellar mass has been to obtain the extinction-corrected K-band (2.2 \( \mu \text{m} \)) magnitude from the 2MASS extended galaxy catalogue and apply the correction of Scott et al. (2013) for missing light. We then applied a constant M/L\(_{2.2}\) = 1 irrespective of stellar metallicity or age. A value of unity is simplistic, but a reasonable approximation for a very old stellar population with a Kroupa IMF (Bruzual & Charlot 2003).

The effective radii (\( R_e \)) of the SLUGGS galaxies are listed in Brodie et al. (2014, hereafter B14), which are based on Cappellari et al. (2011). Cappellari et al. used sizes from both optical and near-IR imaging. They noted that the near-IR sizes from the 2MASS survey (Jarrett et al. 2003) for the largest, most massive galaxies appear to be systematically underestimated and they scaled up their near-IR sizes to match the optical sizes on average. A recent study by van den Bosch (2016) also found the 2MASS survey to underestimate the sizes (and total fluxes) of nearby galaxies. Accurate galaxy effective radii are important in order to compare galaxies on a similar relative scale. For example, the SLUGGS survey and other integral field spectroscopy studies derive kinematic profiles as a function of effective radii and measure properties such as specific angular momentum within 1 \( R_e \) (Arnold et al. 2014; Alabi et al. 2015; Foster et al. 2016). Thus, the photometric effective radii need to be accurate in order to correctly compare kinematic properties between different galaxies. Effective radii, combined with accurate stellar masses, are needed to probe the dark matter fraction within a given multiple of \( R_e \). The Spitzer Space Telescope imaging presented here offers an opportunity to revisit the sizes and masses of the SLUGGS early-type galaxies.

In the next sections, we present the 3.6 \( \mu \text{m} \) data from the Spitzer Space Telescope and our methodology for deriving total magnitudes, stellar masses and effective radii for 27 SLUGGS early-type galaxies. These new measurements are compared with literature values. In an appendix, we list the measurements for six additional nearby early-type galaxies, which we include for the interested reader.

## 2 Spitzer DATA

Here we use images from the IRAC instrument of the Spitzer Space Telescope, which has a pixel scale of 1.22 arcsec over a 5.2 × 5.2 arcmin\(^2\) field of view. We have downloaded the latest (2016 July) available 3.6 \( \mu \text{m} \) basic calibrated data frames from the Spitzer Heritage Archive. These Astronomical Observation Requests (AORs) are detailed in Appendix A (for SLUGGS galaxies) and C (for non-SLUGGS galaxies). These data have been corrected for scattered light, dark current, flat-fielded and flux-calibrated. The MOPEX package is used to assemble the long-exposure (>1 s) frames into an image mosaic showing the field of view around each target galaxy. An example of the final mosaic for NGC 1407 is shown in Fig. 1.
3 MEASURING TOTAL MAGNITUDES

To measure the total light from each galaxy, we model the galaxy in 2D using the IRAF task ellipse and obtain the total magnitude of the galaxy model. The galaxy centre was initially allowed to vary, but if it varied by more than 1 pixel, we fixed it to the average central value. For a few galaxies (i.e. NGC 4486, 4594, 5866 and 7457), we could not obtain a good galaxy model with a radially varying position angle (PA) and so in these cases, we fixed the PA to a representative value based on the radial trend. The model extends in galactocentric radius until the integrated magnitude at that radius is less than 0.02 mag different from the previous (penultimate) radius. Thus, we effectively adopt the asymptotic total magnitude of the model galaxy. We estimate our combined photometric and systematic uncertainty to be $\pm 0.05$ mag. We do not correct our $3.6\mu m$ magnitudes for Galactic extinction (which are less than 0.01 mag). The total $3.6\mu m$ magnitudes that we measure in the Vega system and other basic properties of the SLUGGS galaxies are given in Table 1.

Table 1. SLUGGS galaxy sample and properties. 

| Galaxy [NGC] | Type | Core | Dist. (Mpc) | Age (Gyr) | $m_{3.6}$ (mag) | $\log M_*$ ($M_\odot$) | $R_e$ (arcsec) | $\mu_e$ (mag arcsec$^{-2}$) | $n$ |
|--------------|------|------|-------------|-----------|----------------|-----------------------|-------------|--------------------------|-----|
| 720          | E5   | 1    | 26.9        | 7.8       | 6.92           | 11.27                 | 29.1         | 17.54                    | 3.8 |
| 821          | E6   | 3    | 23.4        | 12.9      | 7.57           | 11.00                 | 43.2         | 19.03                    | 6.0 |
| 1023         | S0   | 3    | 11.1        | 13.5      | 6.01           | 10.99                 | 48.0         | 17.61                    | 4.2 |
| 1400         | E1/S0| 1    | 26.8        | 13.8      | 7.44           | 11.08                 | 25.6         | 17.87                    | 5.0 |
| 1407         | E0   | 1    | 26.8        | 12.0      | 6.16           | 11.60                 | 93.4         | 19.19                    | 4.9 |
| 2768         | E6/S0| 2    | 21.8        | 13.3      | 6.68           | 11.21                 | 60.3         | 18.70                    | 3.8 |
| 2974         | E4/S0| 3    | 20.9        | 11.8      | 7.47           | 10.93                 | 30.2         | 17.99                    | 4.3 |
| 3115         | S0   | 3    | 9.4         | 9.0       | 5.58           | 10.93                 | 36.5         | 16.75                    | 4.7 |
| 3377         | E5-6 | 3    | 10.9        | 11.3      | 7.09           | 10.50                 | 45.4         | 18.81                    | 5.9 |
| 3607†        | S0   | 1    | 22.2        | 13.5      | 6.51           | 11.39                 | 48.2         | 18.33                    | 5.3 |
| 3608         | E1-2 | 1    | 22.3        | 13.0      | 7.41           | 11.03                 | 42.9         | 19.00                    | 5.3 |
| 4111         | S0   | –    | 14.6        | 6.0       | 7.24           | 10.52                 | 10.1         | 15.71                    | 3.0 |
| 4278         | E1-2 | 1    | 15.6        | 13.7      | 6.84           | 10.95                 | 28.3         | 17.51                    | 6.2 |
| 4365         | E3   | 1    | 23.1        | 13.4      | 6.31           | 11.51                 | 77.8         | 18.96                    | 4.9 |
| 4374         | E1   | 1    | 18.5        | 13.7      | 5.81           | 11.51                 | 139.0        | 19.71                    | 8.0 |
| 4459         | S0   | 3    | 16.0        | 11.9      | 6.76           | 10.98                 | 48.3         | 18.52                    | 5.4 |
| 4473         | E5   | 1    | 15.2        | 13.0      | 6.74           | 10.96                 | 30.2         | 17.67                    | 5.0 |
| 4474         | S0   | 3    | 15.5        | 11.1      | –              | 10.23                 | 17.0         | –                        | –   |
| 4486         | E0/cD| 1    | 16.7        | 12.7      | 5.30           | 11.62                 | 86.6         | 18.24                    | 5.1 |
| 4494         | E1-2 | 3    | 16.6        | 11.0      | 6.68           | 11.02                 | 52.5         | 18.53                    | 4.5 |
| 4526         | S0   | –    | 16.4        | 13.6      | 6.17           | 11.26                 | 32.4         | 17.05                    | 3.6 |
| 4564         | E6   | 3    | 15.9        | 13.3      | 7.78           | 10.58                 | 14.8         | 16.93                    | 3.2 |
| 4594†        | Sa   | 1    | 9.5         | 12.5      | 4.56           | 11.41                 | 72.0         | 17.06                    | 3.2 |
| 4649         | E2/S0| 1    | 16.5        | 13.2      | 5.33           | 11.60                 | 79.2         | 18.06                    | 4.6 |
| 4967         | E6   | 3    | 12.5        | 13.4      | 5.85           | 11.15                 | 95.8         | 19.08                    | 5.3 |
| 5846         | E0-1/S0| 3  | 24.2        | 12.7      | 6.50           | 11.46                 | 89.8         | 19.38                    | 5.2 |
| 5866†        | S0   | –    | 14.9        | 5.9       | 6.50           | 10.83                 | 23.4         | 16.59                    | 2.8 |
| 7457         | S0   | 3    | 12.9        | 6.1       | 7.94           | 10.13                 | 34.1         | 18.67                    | 2.6 |

Notes. Columns are (1) galaxy name, † = bonus galaxy, (2) Hubble type, (3) 1 = core, 2 = intermediate, 3 = cusp central light profile, (4) distance from B14 (typical uncertainty is $\pm 0.05$ dex), (5) mean stellar age from McDermid et al. (2015), see text for exceptions, (6) 3.6 $\mu m$ apparent magnitude in the Vega system (typical uncertainty is $\pm 0.05$), (7) stellar mass (typical uncertainty is $\pm 0.1$ dex), (8) effective radius (typical uncertainty is $+0.18$ and $-0.13$ dex), (9) $\mu_e$ (typical uncertainty is $+0.52$ and $-1.11$ mag.), (10) S´ersic $n$ (typical uncertainty is $+0.13$ and $-0.11$ dex). Spitzer $3.6\mu m$ imaging is not available for NGC 4474: $M_*$ and $R_e$ are from 2MASS 2.2 $\mu m$ imaging.

We follow a similar reduction procedure to that of Savorgnan & Graham (2016, hereafter SG16). Thus, when multiple pointings are available, an overlap correction is applied to create a uniform background level. Using IRAF, we determine the sky background level and rms at multiple points on the outskirts of each mosaicked image. The sky values are averaged to give a final value for the sky background of each image, which is subtracted from the image. Finally, bright stars and other unwanted objects are masked out of the mosaic. For further details, see SG16.

Unfortunately, the 3.6 $\mu m$ data for the low-mass SLUGGS galaxy NGC 4474 are not useful for measuring the total light (and hence mass) or galaxy size. In this case, the galaxy is only partially visible as it is near the edge of the available Spitzer pointing. We therefore adopt its stellar mass ($\log M_*=10.23$) from its 2MASS K-band magnitude and its effective radius ($R_e=1.5$ kpc) from B14.
lie in between these two studies. We are systematically brighter than S4G by \~0.18 mag, on average. Our measurements agree fairly well with SG16 with the exception of four galaxies that are more than 0.3 mag brighter than us (and have even larger discrepancies with S4G magnitudes when in common). Three of the galaxies, NGC 5846, NGC 4374, and NGC 4486, feature a partially depleted core at their centre (Lauer et al. 2007; Krajnovi´c et al. 2013). The total magnitudes of SG16 do not take this into account, i.e. they masked out the core and fit a S´ersic profile (rather than a core-S´ersic profile) to the galaxy light. This effectively overestimates the total magnitude of each galaxy by the amount of light ‘missing’ due to the depleted core, i.e. \~0.2–0.3 mag. For NGC 4697, we suspect that the best-fitting profiles of SG16 overestimated the spheroid effective radius and consequently its luminosity. Their 1D surface brightness profile for this galaxy is less extended than the best-fitting effective radius itself.

4 CALCULATING TOTAL STELLAR MASSES

To calculate the total 3.6 µm luminosity in solar units in the Vega system for each galaxy, we convert the 3.6 µm apparent magnitude into a total luminosity assuming that the absolute magnitude of the Sun to be $M_{3.6} = 3.24$ (Oh et al. 2008) and taking its distance from Table 1. We note that the distances, usually based on surface brightness fluctuations, contribute an uncertainty of \~0.1 dex to the luminosity.

We multiply the luminosity by the 3.6 µm mass-to-light ratio from the single stellar population models of Röck et al. (2015). In particular, we use M/L$_{3.6}$ appropriate for each galaxy’s mean mass-weighted stellar age within 1 $R_e$ taken from McDermid et al. (2015), supplemented by values from Rembold, Pastoriza & Bruzual (2005) for NGC 720, Norris, Sharles & Kuntschner (2006) for NGC 3115, Spolaor et al. (2008) for NGC 1400 and 1407 and Sanchez-Blazquez et al. (2006) for NGC 4594. These ages are given in Table 1. The 3.6 µm mass-to-light ratio that we apply varies from \~0.60 to 1.0. We use the Padova isochrones for solar metallicity (which is a reasonable value for our early-type galaxies within 1 $R_e$; McDermid et al. 2015). We note that the equivalent BaSTI isochrones differ by only 0.01 for our typical age. We estimate that the uncertainty in M/L$_{3.6}$ due to differences in isochrone tracks (\~0.03), mean age uncertainty (\~0.05) and metallicity variations (\~0.02), combined with our measurement and distance uncertainties, give a final uncertainty of about 0.1 dex in log stellar mass. We also assume a Kroupa IMF. As noted in the Introduction, although there is evidence for an IMF skewed to low-mass stars, the effect seems largely limited to the central regions of the most massive galaxies. Nevertheless, this gives rise to a systematic underestimate of the stellar masses of the most massive galaxies.

Each galaxy in this study has a total stellar mass determined from the total K-band (2.2 µm) magnitude from the 2MASS survey. The 2MASS 2.2 µm magnitude is corrected for missing flux according to Scott et al. (2013) and we take the absolute magnitude of the Sun to be $M_{2.2} = 3.28$ (table 2.1 from Binney & Merrifield 1998). The stellar mass has been calculated in previous SLUGGS papers assuming a fixed M/L$_{2.2} = 1.0$ irrespective of stellar age (e.g. Alabi et al. 2016). A value of unity is reasonably representative of an old, metal-rich stellar population with a Kroupa-like IMF.

In Fig. 3, we show a comparison of our new 3.6 µm-based stellar masses versus the stellar mass obtained from the $K$ band. We find an excellent overall correspondence with the stellar masses derived using the $K$ band. Galaxies with lower 3.6 µm masses relative to the previous 2.2 µm masses (i.e. that lie above the unity line) tend to be those with young (∼6 Gyr) mean stellar ages. The overall excellent agreement indicates that both 3.6 and 2.2 µm total magnitudes give reliable stellar masses (under the same assumption of a Kroupa IMF). Given the small difference in 2.2 versus 3.6 µm stellar masses, we will continue to adopt the $K$-band stellar mass of log $M_*=10.24$ for NGC 4474 for which we are unable to measure a 3.6 µm magnitude.

5 MEASURING GALAXY SIZES

Each galaxy surface brightness profile is fit with a single S´ersic law (Graham & Driver 2005). We exclude the inner 2 pixels (2.44 arcsec), i.e. we only fit radii that are larger than the effective full width at half-maximum (FWHM) resolution of the Spitzer Space Telescope. This also means that the presence of any nuclear star cluster or active galactic nuclei does not affect the fits. Most of our galaxies reveal central surface brightness profiles that can be well described as either a core or a cusp (Lauer et al. 2007; Dullo & Graham 2013; Krajnovi´c et al. 2013), as listed in Table 1. In the case of cusps, they are generally well fit by a single S´ersic profile. On the other hand,
for core profiles, we exclude the so-called depleted core region from the fits. Thus, the fitting range for each galaxy is either >2 pixels for the cusp, intermediate and unknown galaxies and greater than the depleted core region for the core galaxies.

The fits to the 3.6 μm surface brightness profile for each SLUGGS galaxy are shown in Appendix B. The central region excluded from each fit is indicated by open circles and can be most clearly seen in the Sérsic profile minus data residual profiles. The code used for the fitting process is the same as SG16. For most galaxies, SG16 fit multiple components to each galaxy. However, they did fit a single Sérsic profile to three large SLUGGS galaxies. In these cases, our effective radii agree very well with their value, i.e. NGC 4374: 139.0 versus 129.8 arcsec, NGC 4486: 86.6 versus 87.1 arcsec and NGC 5846: 89.8 versus 83.4 arcsec.

We list the (equivalent circular) effective radii from the single Sérsic fits to our 3.6 μm surface brightness profiles in Table 1. A typical uncertainty associated with the effective radius of the SLUGGS galaxies is calculated based on the average of the uncertainties of the 14 early-type galaxies effective radii in the sample of SG16 with single Sérsic fits compared to those from other studies (see SG16 for details). The 1σ uncertainty of +0.18 and −0.13 dex thus takes into account both random and systematic errors. If we only considered random measurement errors, a smaller uncertainty would result. Table 1 also lists the other fitting parameters, i.e. the Sérsic n value and the surface brightness at the effective radius μ₀.

Again, we adopt the typical uncertainties found for the 14 early-type galaxies to model correctly given the bright nearby foreground star (despite our efforts to mask it from the 2D modelling process).

For the massive Virgo galaxies, we have excellent agreement for NGC 4374 (M84) with Kormendy et al. and Chen et al. For NGC 4365, 4486 and 4649 (M60), we have good agreement with Vika et al., but we find systematically smaller sizes than Chen et al. and significantly smaller sizes than Kormendy et al. (and Blom et al. 2012 for NGC 4365). We suspect that this is because these galaxies have elongated isophotes in their outer regions, i.e. light that goes beyond the Spitzer mosaic (whereas NGC 4374 has very circular outer isophotes and is well contained within our mosaic).

For NGC 4486 (M87), Kormendy et al. derive a size that is 6–8× that of other studies (corresponding to ~50 kpc). Their single Sérsic fit includes the extended light of the cD envelope. Our measured 3.6 μm effective radii for NGC 1407 and NGC 5846 are similar to those used by Chen et al. (2010) and Napolitano et al. (2014) but significantly larger than B14.

We compare our 3.6 μm sizes and stellar masses with the Virgo cluster galaxies of Chen et al. (2010) in fig. 5. Chen et al. fit single Sérsic profiles to multifilter SDSS imaging of ~100 Virgo cluster early-type galaxies. We convert their measurements into physical properties assuming a Virgo distance of 16.5 Mpc, and log M/L_g = 0.7 from Bell et al. (2003) for red galaxies. Fig. 5 shows that the distribution of sizes and stellar masses from our 3.6 μm measurements for the SLUGGS galaxies are consistent with that of the Virgo early-type galaxies from Chen et al. (2010). Thus, we expect our new stellar masses and effective radii for the SLUGGS galaxies to be representative of nearby early-type galaxies in general.
It is clear from Table 2 that a wide variety of galaxy effective radii can be found in the literature for massive galaxies (even when restricted to a single Sérsic fit). We recognize that our effective radii derived from Spitzer 3.6 µm imaging may be updated by deeper imaging studies (perhaps leading to even larger $R_e$ values if a single Sérsic continues to be adopted), however, our Spitzer imaging provides a homogenous set of improved effective radii for the SLUGGS survey which we now adopt.

### 6 CONCLUSIONS

Using archival Spitzer Space Telescope imaging of the nearby early-type galaxies from the SLUGGS survey, we have created 3.6 µm mosaic images of each galaxy (excluding NGC 4474 for which Spitzer imaging was not available). After masking out foreground stars and other unwanted features, we modelled each galaxy and derived total asymptotic magnitudes. Our total magnitudes generally lie in between those of 3.6 µm literature studies for the galaxies in common. These total magnitudes are converted into stellar masses using the single stellar population models of Röck et al. (2015). The 3.6 µm flux from early-type galaxies is an ideal tracer of stellar mass as the mass-to-light ratio at this wavelength is very insensitive to metallicity and only mildly sensitive to age for old stellar populations. Here we use M/L$_{3.6}$ from Padova isochrones that is adjusted for each galaxy’s mean stellar age while assuming a Kroupa IMF. We estimate the final uncertainty in log stellar mass to be ±0.1 dex. We find that our 3.6 µm stellar masses have a strong linear correlation with stellar masses derived at 2.2 µm, after correcting the 2MASS K-band fluxes for missing light.

From our 2D galaxy modelling, we fit a single Sérsic law to the 3.6 µm surface brightness profile in 1D. We exclude the central 2 pixels in all galaxies (corresponding to the FWHM of the Spitzer Space Telescope) and, in addition, exclude the central core of the massive galaxies that contain so-called depleted cores. As well as new effective radii ($R_e$), we derive the surface brightness at 1 $R_e$ and the Sérsic $n$ parameter. Our 3.6 µm sizes show good agreement with literature values from optical imaging as used by B14 and show that sizes from the 2MASS (K-band) survey systematically underestimate the true size (as found previously by Cappellari et al. 2011). For the larger, more massive galaxies, we find that the optical sizes used by B14 are also systematically underestimated relative to the sizes from our 3.6 µm imaging and deep optical imaging in the literature. Our new sizes and stellar masses show good agreement with those of Virgo cluster early-type galaxies measured from SDSS imaging. We now adopt the sizes and stellar masses, measured in a homogeneous way from our 3.6 µm imaging, for galaxies in the SLUGGS survey. Our methodology can be adopted by other studies requiring more accurate effective radii and stellar masses for nearby early-type galaxies.

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**Table 2. Massive Galaxy sizes.**

| Galaxy [NGC] | 3.6 µm (arcsec) | B14 (arcsec) | Kor09 (arcsec) | Chen10 (arcsec) | Vika13 (arcsec) | Other |
|--------------|----------------|--------------|---------------|----------------|---------------|-------|
| (1)          | (2)            | (3)          | (4)           | (5)            | (6)           | (7)   |
| 1407         | 93             | 63           | –             | –              | –             | 100 (P15) |
| 4365         | 78             | 53           | ~154          | 97             | 78            | 126 (B12) |
| 4374         | 139            | 53           | ~135          | 131            | 96            | –     |
| 4486         | 87             | 81           | ~630          | 105            | 82            | –     |
| 4649         | 79             | 66           | ~118          | 105            | 68            | –     |
| 5846         | 90             | 59           | –             | –              | –             | 81 (N14) |

Notes. Columns are (1) galaxy name, effective radii in arcseconds from (2) 3.6 µm imaging (this work), (3) Brodie et al. (2014), (4) Kormendy et al. (2009), (5) Chen et al. (2010), (6) Vika et al. (2013), and (7) other published SLUGGS works (i.e. Blom et al. 2012; Napolitano et al. 2014; Pota et al. 2015).
APPENDIX A

Summary of AORs of SLUGGS galaxies downloaded in 2016 July from the Spitzer Heritage Archive (http://sha.ipac.caltech.edu) are given in Table A1.

Table A1. Spitzer Space Telescope Astronomical Observation Requests for SLUGGS Galaxies.

| Galaxy | Astronomical Observation Requests |
|--------|----------------------------------|
| 720    | r49345024, r49345280             |
| 821    | r41569216, r49418752, r49419008  |
| 1023   | r4432640, r50631168, r50631936, r52778496, r52778752, r52779908, r52779264, r52779520, r52779776, r52780032 |
| 1400   | r49436416                        |
| 1407   | r49434096, r49343832             |
| 2768   | r18031872                        |
| 2974   | r18032384, r49613056             |
| 3115   | r4441085                         |
| 3377   | r4444928, r49411328, r50545664, r50545920, r50546176, r52910336, r52910592, r52910848, r52911004, r52911360, r52911616, r52911872 |
| 3607   | r4449536, r49389312, r49614592, r49614848 |
| 3608   | r18033408, r49606736, r49614848  |
| 4111   | r30984192, r31015424, r42249216, r42249472, r50528000, r50528256, r50528512, r52912128, r52912384, r52912640, r52912896, r52913152, r52913408 |
| 4278   | r4461568, r49616128              |
| 4365   | r11115264, r49358386, r49358592, r50576640, r50577152, r50577664, r52976640, r52976896, r52977152, r52977408, r52977664, r52977920 |
| 4374   | r4463872, r50608128, r50608640, r50609152, r52971264, r52971520, r52971776, r52972032, r52972288, r52972544 |
| 4459   | r11378944, r49501696, r49501952 |
| 4473   | r11377920, r49393904, r49340160, r50554368, r50554880, r50555392, r5055556, r5055565, r50555824, r50556080, r53006336, r53006592 |
| 4474   | –                                 |
| 4486   | r12673792, r49337856, r49338112, r50576384, r50576896, r50577408, r52962304, r52962560, r52962816, r52963072, r52963328, r52963584 |
| 4494   | r18035200                        |
| 4526   | r4472064, r49341440, r49341696, r49595904, r50644736, r50644992, r50645248, r52992768, r52993024, r52993280, r52993792, r52994048 |
| 4564   | r14572032, r49510912, r49511168, r50647040, r50647296, r50647552, r52942592, r52942848, r52943104, r52943360, r52943616, r52943872 |
| 4594   | r5171824, r5518080, r5059328, r50595840, r50596846, r52765965, r52765952, r52766208, r52766464, r52766720, r52766976, r52767232 |
| 4649   | r4476672, r49337344, r49337600, r50590208, r50590976, r50591488, r52967680, r52967936, r52968192, r52968448, r52968704, r52968960 |
| 4697   | r10896896, r49359872, r49360128, r50622464, r50622720, r50622976, r52809728, r52809984, r52810240, r52810496, r52810752, r52811008 |
| 5846   | r4491264, r6130272, r49369368, r49364224 |
| 5866   | r5526016, r5526272               |
| 7457   | r18037504, r50547200, r50547456, r50547712, r52946176, r52946432, r52946688, r52946944, r52947200, r52947456 |
APPENDIX B

Sérsic fits to 3.6 \( \mu \)m surface brightness profiles of SLUGGS galaxies are shown in Figs B1 to B9.

Figure B1. Sérsic fit to 3.6 \( \mu \)m surface brightness profile and residuals as a function of circular equivalent radius. The upper panel shows the data points (with excluded data points shown by open circles) and the best-fitting Sérsic profile in red. Parameters for the Sérsic fit are given in the top right. The dashed line shows 3 \( \Delta \) the rms of the sky background level. \( \Delta \) gives the rms of the residuals in mag arcsec\(^{-2}\). The lower panel shows the residuals of the Sérsic model fit minus the surface brightness data.

Figure B2. Sérsic fit to 3.6 \( \mu \)m surface brightness profile and residuals as a function of circular equivalent radius. The upper panel shows the data points (with excluded data points shown by open circles) and the best-fitting Sérsic profile in red. Parameters for the Sérsic fit are given in the top right. The dashed line shows 3 \( \Delta \) the rms of the sky background level. \( \Delta \) gives the rms of the residuals in mag arcsec\(^{-2}\). The lower panel shows the residuals of the Sérsic model fit minus the surface brightness data.
Figure B3. Sérsic fit to 3.6 μm surface brightness profile and residuals as a function of circular equivalent radius. The upper panel shows the data points (with excluded data points shown by open circles) and the best-fitting Sérsic profile in red. Parameters for the Sérsic fit are given in the top right. The dashed line shows 3× the rms of the sky background level. Δ gives the rms of the residuals in mag arcsec $^{-2}$. The lower panel shows the residuals of the Sérsic model fit minus the surface brightness data.

Figure B4. Sérsic fit to 3.6 μm surface brightness profile and residuals as a function of circular equivalent radius. The upper panel shows the data points (with excluded data points shown by open circles) and the best-fitting Sérsic profile in red. Parameters for the Sérsic fit are given in the top right. The dashed line shows 3× the rms of the sky background level. Δ gives the rms of the residuals in mag arcsec $^{-2}$. The lower panel shows the residuals of the Sérsic model fit minus the surface brightness data.
Figure B5. Sérsic fit to 3.6 µm surface brightness profile and residuals as a function of circular equivalent radius. The upper panel shows the data points (with excluded data points shown by open circles) and the best-fitting Sérsic profile in red. Parameters for the Sérsic fit are given in the top right. The dashed line shows $3 \times \text{rms}$ of the sky background level. $\Delta$ gives the rms of the residuals in mag arcsec$^{-2}$. The lower panel shows the residuals of the Sérsic model fit minus the surface brightness data.

Figure B6. Sérsic fit to 3.6 µm surface brightness profile and residuals as a function of circular equivalent radius. The upper panel shows the data points (with excluded data points shown by open circles) and the best-fitting Sérsic profile in red. Parameters for the Sérsic fit are given in the top right. The dashed line shows $3 \times \text{rms}$ of the sky background level. $\Delta$ gives the rms of the residuals in mag arcsec$^{-2}$. The lower panel shows the residuals of the Sérsic model fit minus the surface brightness data.
Figure B7. Sérsic fit to 3.6 µm surface brightness profile and residuals as a function of circular equivalent radius. The upper panel shows the data points (with excluded data points shown by open circles) and the best-fitting Sérsic profile in red. Parameters for the Sérsic fit are given in the top right. The dashed line shows $3\times$ the rms of the sky background level. $\Delta$ gives the rms of the residuals in mag arcsec$^{-2}$. The lower panel shows the residuals of the Sérsic model fit minus the surface brightness data.

Figure B8. Sérsic fit to 3.6 µm surface brightness profile and residuals as a function of circular equivalent radius. The upper panel shows the data points (with excluded data points shown by open circles) and the best-fitting Sérsic profile in red. Parameters for the Sérsic fit are given in the top right. The dashed line shows $3\times$ the rms of the sky background level. $\Delta$ gives the rms of the residuals in mag arcsec$^{-2}$. The lower panel shows the residuals of the Sérsic model fit minus the surface brightness data.
**APPENDIX C**

Six additional (non-SLUGGS) galaxies have been measured in this study using the procedure described above. In Table C1, we list the AORs and in Table C2, the measured 3.6 \( \mu \text{m} \) properties for these additional galaxies. Figs C1 and C2 show Sérsic fits to their 3.6 \( \mu \text{m} \) surface brightness profiles.

![Figure C1](image1.png)  
**Figure C1.** Sérsic fit to 3.6 \( \mu \text{m} \) surface brightness profile and residuals as a function of circular equivalent radius. The upper panel shows the data points (with excluded data points shown by open circles) and the best-fitting Sérsic profile in red. Parameters for the Sérsic fit are given in the top right. The dashed line shows 3 \( \times \) the rms of the sky background level. \( \Delta \) gives the rms of the residuals in mag arcsec\(^{-2} \). The lower panel shows the residuals of the Sérsic model fit minus the surface brightness data.

### Table C1. *Spitzer Space Telescope* Astronomical Observation Requests for non-SLUGGS Galaxies.

| Galaxy [NGC] | Astronomical Observation Requests |
|-------------|----------------------------------|
| 1052        | r11516672, r49600512, r49612288 |
| 2549        | r26602240, r49447424, r4947680, r49619712 |
| 3379        | r44456096, r49411584, r4941840, r50629376, r50629632, r50629888, r52832512, r52832768, r52833024, r52833280, r52833536, r52833792, r52834048 |
| 3665        | r49465344, r49465600 |
| 3998        | r4452608, r42242560, r42242816, r49622784, r50586368, r50586624, r50586880, r52892416, r52892672, r52892928, r52893184, r52893440, r52893696 |
| 4551        | r49510400, r49510636 |

### Table C2. Non-SLUGGS galaxy properties.

| Galaxy [NGC] | Type | Core | Dist. | Age | \( m_{3.6} \) | \( M_\ast \) | \( R_e \) | \( \mu_e \) (mag arcsec\(^{-2} \)) | \( n \) |
|--------------|------|------|-------|-----|------------|-------------|--------|-----------------|------|
| 1052         | E3-4/S0 | 1   | 19.4  | 13.0 | 7.12       | 11.02       | 21.9   | 17.16           | 3.4  |
| 2549         | S0    | 3   | 12.3  | 8.9  | 7.75       | 10.28       | 14.7   | 16.88           | 3.1  |
| 3379         | E0-1  | 1   | 10.3  | 13.7 | 5.92       | 10.96       | 54.9   | 18.02           | 5.7  |
| 3665         | S0    | –   | 33.1  | 13.2 | 7.12       | 11.48       | 50.5   | 18.95           | 5.4  |
| 3998         | S0    | 2   | 13.7  | 13.7 | 7.04       | 10.76       | 19.1   | 16.92           | 4.0  |
| 4551         | E     | 3   | 16.1  | 13.2 | 8.67       | 10.24       | 13.8   | 17.45           | 2.1  |

*Notes. Columns are (1) galaxy name, (2) Hubble type, (3) core, 1 = core, 2 = intermediate, 3 = cusp central light profile, (4) distance, (5) mean stellar age from McDermid et al. (2015), except for NGC 1052 from Milone, Rickes & Pastoriza (2007), (6) 3.6 \( \mu \text{m} \) apparent mag, (7) stellar mass, (8) effective radius, (9) \( \mu_e \), (10) Sérsic \( n \).*
Figure C1. Sérsic fit to 3.6 μm surface brightness profile and residuals as a function of circular equivalent radius for non-SLUGGS galaxies. The upper panel shows the data points (with excluded data points shown by open circles) and the best-fitting Sérsic profile in red. Parameters for the Sérsic fit are given in the top right. The dashed line shows 3 × the rms of the sky background level. Δ gives the rms of the residuals in mag arcsec$^{-2}$. The lower panel shows the residuals of the Sérsic model fit minus the surface brightness data.

Figure C2. Sérsic fit to 3.6 μm surface brightness profile and residuals as a function of circular equivalent radius for non-SLUGGS galaxies. The upper panel shows the data points (with excluded data points shown by open circles) and the best-fitting Sérsic profile in red. Parameters for the Sérsic fit are given in the top right. The dashed line shows 3 × the rms of the sky background level. Δ gives the rms of the residuals in mag arcsec$^{-2}$. The lower panel shows the residuals of the Sérsic model fit minus the surface brightness data.

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