

The Kaleidoscope survey: strong gravitational lensing in galaxy clusters with radial arcs

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ABSTRACT

We measure the dark matter density profiles of six galaxy clusters: A383, MS 2137–23, MACS J0326.8–0043, MACS J1427.6–2521, MACS J0417.5–1154, and MACS J0949.8+1708. Each cluster contains at least one radial arc, a unique physical feature that allows for more precise measurements of the inner mass profile ($R < 50$ kpc) from strong lensing. We present the first strong lensing analysis for MACS J0326 and MACS J1427. We use a combination of *Hubble Space Telescope* imaging and Multi-Unit Spectroscopic Explorer (MUSE) spectroscopy from the ESO Kaleidoscope Clusters Survey, a large ‘filler’ program, to identify and measure redshifts for multiply imaged systems and obtain the 2D stellar velocity dispersion for each centrally located brightest cluster galaxy (BCG). The BCG kinematics are used to subtract the baryonic mass component from the inner mass profile. We find total mass density profiles consistent with previous works using a combination of strong lensing and BCG kinematics. The overall shape of these profiles appears core-like, with an average dark matter slope measurement of $\gamma \sim 0.66$. These results demonstrate the ongoing need for the construction of observational models for galaxy clusters, and show how galaxy-scale kinematics can be used to disentangle baryonic and dark matter concentrations in cluster cores.

Key words: techniques: imaging spectroscopy – galaxies: clusters: general – galaxies: clusters: individual: (Abell 383, MS 2137–23, MS 0326.8–0043, MS 1427.6–2521).

1 INTRODUCTION

Galaxy clusters, which are home to the largest concentrations of mass in our Universe, are the ideal cosmic laboratories for studying the properties of baryonic and dark matter (DM). One way the study of these matter distributions can be accomplished is by utilizing the fact that the high mass density of galaxy clusters distorts and magnifies the light emitted by background sources. This unique process, known as gravitational lensing, occurs when a massive object lying along the line of sight between an observer and a background source bends the path of the light travelling from the background source (for reviews of lensing, see e.g. Massey, Kitching & Richard 2010; Kneib & Natarajan 2011; Hoekstra et al. 2013; Kilbinger 2015; Treu & Ellis 2015; Bartelmann & Maturi 2017). This distortion can result in the appearance of multiple images of a background source around the massive object. Quantifying the amplification and the positions of the lensed images allows the total mass distribution

of the cluster to be mapped with high accuracy (e.g. Jauzac et al. 2014; Johnson et al. 2014; Richard et al. 2014; Coe, Bradley & Zitrin 2015; Caminha et al. 2017; Diego et al. 2018; Mahler et al. 2018; Williams, Sebesta & Liesenborgs 2018; Lagattuta et al. 2019; Sharon et al. 2020), and modelling the effects of lensing allows for a high-resolution measurement of the DM density profile (Kneib et al. 2004; Broadhurst et al. 2005; Smith et al. 2005; Limousin et al. 2008; Newman et al. 2009; Richard et al. 2010; Jauzac et al. 2016; Jauzac, Harvey & Massey 2018). As a result, strong gravitational lensing can be an effective tool for studying the distribution of the DM mass component in galaxy clusters, although the region that is well constrained by strong lensing is demarcated by the spatial location of lensed images in relation to the centre of the cluster ($R \sim 200$ kpc). However, lensing’s ability to probe the mass distribution of this inner region is unparalleled, which is useful because the precise shape of the inner DM mass profile is not yet well understood.

Numerical collisionless cold dark matter (CDM) simulations, which represent our current physical understanding of the Universe, have generally predicted cluster-scale DM distributions that increase toward the centre of the cluster following the shape of the Navarro–

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Frenk–White (NFW) profile (Navarro, Frenk & White 1996), where the DM density, ρ_{DM} , increases as $\sim r^{-\gamma}$, where the inner slope, γ , is equal to 1. Subsequent simulations with higher resolution have suggested that this profile is not necessarily universally applicable, as the inner slope may be slightly shallower (Merritt et al. 2006; Navarro et al. 2010; Gao et al. 2012). Additionally, recent simulations have shown that adding baryons can also move the inner slope away from $\gamma = 1$, as seen in the steeper slopes obtained in studies performed using the cosmological simulation suites BAHAMAS, Hydrangea/Cluster-EAGLE, and TNG (Chan et al. 2015; McCarthy et al. 2017; Bahé et al. 2019). On a smaller scale, Bose et al. (2019) conducted an analysis of the APOSTLE (Fattahi et al. 2016; Sawala et al. 2016) and AURIGA (Grand et al. 2017) simulations of the inner profile of dwarf galaxies and obtained slope measurements between $\gamma \sim 1.3$ and 1.8. These disparate measurements all point to the need for observational data to serve as a point of comparison.

Modelling the DM density profile of galaxy clusters can be accomplished by placing constraints on the baryonic and DM mass components near the centre of the cluster. This is most effectively done by using strong lensing to probe the gravitational potential at the centre of the cluster (Zitrin et al. 2012), and can be further constrained by the inclusion of stellar kinematic measurements of the brightest cluster galaxy (BCG, Kelson et al. 2002), which dominates the baryonic mass budget at the centre of the cluster. This combination of lensing and kinematics is uniquely powerful because it allows the distribution of dark and baryonic matter in the centre of the cluster to be separated, a crucial step for measuring the slope of the inner DM profile. Previous studies using this method have found shallow slope values; each of these papers used long-exposure, long-slit spectroscopy and *Hubble Space Telescope* (HST) imaging for their models, and parametrize the cluster-scale DM halo using the generalized form of the NFW profile. Sand et al. (2004) modelled six clusters and found slope values between 0.52 – 0.57; Sand et al. (2008) remodelled two of these clusters, Abell 383 and MS2137, using updated methods, and found slope values of around 0.45 for both clusters, with some significant statistical uncertainties in the latter model. Newman et al. (2013a, hereafter N13), which also remodelled these two clusters as a part of a broader sample of seven clusters, measured an average slope of 0.50 ± 0.13 . The measurements from N13 were examined in more detail in He et al. (2020), using the Hydrangea/Cluster-EAGLE hydrodynamic simulation suite to investigate the ability of this combination of lensing and kinematics to accurately recapture the inner slope measurement. The results of this paper suggest that there is a strong degeneracy between the asymptotic generalized NFW slope and the scale radius, r_s , which means that incorrectly estimating the scale radius, done using weak lensing in N13, could lead to much shallower measurements of the inner DM profile. However, using the mean inner slope of the DM density profile, rather than the asymptotic generalized NFW slope, was shown to be a better metric of comparison between observational models and simulated clusters. This result indicates that as long as the DM density profile in the centre clusters is well constrained by some combination of observational measurements, then the inner slope can be measured accurately.

However, the values for the inner DM slope still vary widely, though the reason for this discrepancy is not clearly due to methodology, intrinsic cluster mass distributions, or some other factor. Recent papers by Sartoris et al. (2020) and Biviano et al. (2023) have used stellar kinematic measurements of the BCG in combination with cluster member kinematics, obtained from integral-field unit (IFU) spectroscopy, as a method to constrain the overall mass profile of the cluster. Sartoris et al. found an inner slope measurement of

0.99 ± 0.04 for the cluster Abell S1063, and Biviano et al. found an inner slope of $0.7^{+0.2}_{-0.1}$ for the cluster MACS J1206.2–0847. These divergent measurements indicate that the distribution of DM in galaxy clusters may be more diverse than suggested by simulations, which in turn demonstrates the need for more observational models to be made to characterize the potential forms of these distributions.

In this paper, we present the DM inner slope measurements for six different galaxy clusters, using a combination of strong lensing and kinematic measurements of the BCG. We select these clusters from the ESO Kaleidoscope Clusters survey (PID 0104.A-0801; PI: A. Edge), a large ‘filler’ program structured around the identification of bright strong-lensing features in galaxy clusters using new IFU spectroscopy from Multi-Unit Spectroscopic Explorer (MUSE) on the Very Large Telescope (VLT). Each of these clusters has a unique physical feature: a ‘radial arc’, or a lensed galaxy image located within 5 kpc of the BCG. We note that these radial arcs are preferentially produced in clusters with shallow inner slopes. The proximity of this lensed image to the BCG serves as an additional constraint on the inner total density profile in the strong lensing model, which cannot normally measure this region without extrapolating the lens model inward as this region is baryon-dominated. We also choose to use a dual pseudo-isothermal elliptical profile to model the cluster-scale DM haloes (Elíasdóttir et al. 2007), which avoids the degeneracy between the scale radius and the inner slope measurement pointed out in He et al. (2020).

We present new strong lensing and BCG kinematic velocity dispersion measurements for four clusters: Abell 383 (A383 hereafter), MS 2137–23 (MS2137 hereafter), MACS J0326.8–0043 (MACS J0326 hereafter), and MACS J1427.6–2521 (MACS J1427 hereafter). We also include in this paper two more clusters that were observed in the Kaleidoscope survey: MACS J0417.5–1154 (MACS J0417 hereafter), and MACS J0949.8 + 1708 (MACS J0949 hereafter). We utilize previously published strong lensing models for these two clusters since we have no new strong lensing constraints to add to the existing models, and only add the measurement of the stellar velocity dispersion profile of the BCG to obtain the inner DM slope value. We refer the reader to Jauzac et al. (2019) and Allingham et al. (2023) for more details on the lens models of MACS J0417 and MACS J0949, respectively.

The paper is organized as follows. The data, observations, and the creation of the VLT/MUSE catalogues used for each cluster are presented in Section 2. Section 3 discusses the construction of the mass models, and Section 4 details the kinematic modelling for the BCG. In Section 5, we present our results, and in Section 6, we discuss their implications and describe future work on this problem. We then conclude in Section 7.

We assume a standard Lambda-CDM (Λ CDM) cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. All magnitudes are measured in the AB system unless stated otherwise.

2 OBSERVATIONS

2.1 Photometry

2.1.1 Hubble Space Telescope imaging

We utilize imaging from the Advanced Camera for Surveys (ACS) onboard HST obtained from the Cluster Lensing And Supernova survey with Hubble (CLASH) survey (Postman et al. 2012) in the F814W, F6606W, and F435W passbands for A383 and MS2137 in order to identify multiple images (see Table 1 for details). We also use imaging from the Wide Field Camera 3 (WFC3) in the F105W,

Table 1. Summary of *HST* observations.

Name	RA	Dec.	Band	PID	P.I.	Exp. time [s]	Obs. date
A383	42.0141667	−3.5291389	ACS/F435W	12065	Postman	4250	2010-12-28
			ACS/F606W			4210	2011-01-18
			ACS/F814W			8486	2010-12-08
			WFC3/F105W			3620	2011-01-18
			WFC3/F125W			3320	2011-01-05
			WFC3/F140W			2411	2011-01-18
			WFC3/F160W			5935	2010-11-19
MS 2137	325.0632083	−23.6611667	ACS/F435W	12102	Postman	4026	2011-09-29
			ACS/F606W			17 920	2006-05-16
			ACS/F814W			8132	2011-08-21
			WFC3/F105W			2814	2011-09-09
			WFC3/F125W			2514	2011-09-02
			WFC3/F140W			2311	2011-09-09
			WFC3/F160W			5029	2011-08-21
MACS J0326	51.708118	−0.7310381	ACS/F814W	11103	Ebeling	500	2008-11-13
			ACS/F606W			500	2007-11-17
MACS J1427	216.9144704	−25.3506079	ACS/F814W	12884	Ebeling	1440	2014-07-21
MACS J0417	64.3945486	−11.9088174	ACS/F606W	12009	von der Linden	7152	2011-01-20
			ACS/F435W			2000	2017-06-16
MACS J0949	147.4659359	17.1195712	ACS/F606W	14096	Coe	1013	2015-11-20

Notes. The name of the cluster is given in the first column, and the RA and Dec. are given in degrees (J2000) in the second and third columns. The band is listed in the fourth column, the PID for each band is given in the fifth column, and the P.I. for the observation is given in the sixth column. Finally, the exposure time is given in the seventh column, and the observation date for the exposure is given in the eighth column.

F125W, *F140W*, and *F160W* passbands in order to perform source identification. All imaging was obtained from MAST.¹ Basic data reduction procedures were applied to all imaging using HSTCAL and standard calibration files. TWEAKREG was used to register individual frames to a common ACS reference image, after which ASTRODRIZZLE was used to co-add the frames together.

The observations of MACS J0326 and MACS J1427 are shallower and consist of fewer bands. *F606W* and *F814W* images are available for MACS J0326 and are sourced from the *HST* SNAP program 11103 (PI: Ebeling). The single *F814W* image available for MACS J1427 is taken from archival data made available by *HST* SNAP program 12166 (PI: Ebeling).

We additionally use the *F606W* bands from the Reionization Lensing Cluster Survey (RELICS, PID: 14096, PI: Coe) for both MACS J0949 and MACS J0417 to obtain photometric measurements of the BCG. We also include the *F435W* band from the *HST* programme 12009 (PI: von der Linden) for MACS J0417 as an additional check on our *F606W* measurements. These images were not used for any other purpose in the course of constructing the lens models.

A summary of the observations, exposure times, and bands used for each cluster are listed in Table 1. Sources for the first three clusters were identified using SEXTRACTOR (Bertin & Arnouts 1996) in dual mode on the *F814W* and *F606W* passband images. Sources for MACS J1427 were identified using MUSE spectroscopy. Sources for MACS J0949 and MACS J0417 were taken from their existing lens models.

2.1.2 HST catalogues

We create new catalogues of multiple image systems from the *HST* imaging for A383, MS2137, MACS J0326, and MACS J1427. We identify arc systems used for lens modelling within the images based

on geometry, colour, and morphology. The properties of the arcs for these four clusters are listed in Tables 2–5. For A383, MS2137, and MACS J0326, we build a galaxy catalogue for each cluster using SEXTRACTOR in dual mode on the *F814W* and *F606W* passband images, with threshold parameters DETECT_THRESH = 1.5 and DETECT_MINAREA = 20. Detections with error flags or unreliable magnitude measurements (i.e. MAG_AUTO = −99) were dropped, and detections with a stellarity measurement greater than 0.5 were removed as they are more likely to be stars rather than galaxies. Only objects that appeared in both passbands were kept in the final catalogue. Further information on the construction of the galaxy catalogue can be found in Section 3.2. For MACS J1427, we build a galaxy catalogue based on the MUSE detections. For MACS J0417 and MACS J0949, we use the galaxy and arc system catalogues from their existing lens models.

2.2 Spectroscopy

2.2.1 VLT–MUSE observations

The VLT/MUSE observations for each cluster are summarized in Table 6. Each cluster observation consisted of three individual exposures (imaged sequentially) of 970 s each. To minimize the effect of observational systematics, we apply a small dither (0.3 arcsec) between each exposure, and each frame is rotated 90° clockwise relative to the previous frame. The observations were then stacked together to create a single cube with a total exposure of 2910 s. The resulting average seeing and airmass of the stacked cube are reported in Table 6.

Data reduction of the MUSE cubes was performed using the standard procedures of the esorex pipeline (MUSE-KIT-2.4.1; Weilbacher, Streicher & Palsa 2016), along with additional calibration and cleaning steps (as described in e.g. Richard et al. 2021 or Lagattuta et al. 2022). Bias subtraction and flat fielding were performed with basic calibration files using illumination and twilight exposures with dates closest to that of the source exposure. Flux calibration and

¹The data described here can be found on MAST.

Table 2. Properties of the multiple images that were used as constraints in the lens model of A383. RA and Dec. are given in degrees (J2000). The redshifts for each image are either the spectroscopic value, where the redshift has no error bars, or the lensing model output value, in which case error bars are provided. The rms for the best fit is measured in the image plane for each family of multiple images. The apparent magnification μ of each multiple image is also listed.

ID	RA	Dec.	z	rms (arc-sec)	μ
1.1	42.0128100	-3.5257360	4.63	0.87	24.9 ± 5.3
1.2	42.0100370	-3.5306870	4.63	0.30	>50
1.3	42.0094730	-3.5284480	4.63	0.67	12.9 ± 4.7
1.4	42.0201622	-3.5313367	4.63	0.71	4.4 ± 2.2
2.1	42.0100213	-3.5312905	1.01	0.99	>50
2.2	42.0118119	-3.5328386	1.01	0.95	13.8 ± 1.8
2.3	42.0143250	-3.5288310	1.01	1.52	1.8 ± 0.5
3.1	42.0124986	-3.5352872	2.55	0.56	8.1 ± 0.7
3.2	42.0095063	-3.5331842	2.55	0.39	16.6 ± 4.5
3.3	42.0100403	-3.5332656	2.55	0.74	2.6 ± 1.3
3.4	42.0159643	-3.5351566	2.55	0.62	6.2 ± 5.6
4.1	42.0092467	-3.5339770	2.55	0.09	8.2 ± 3.2
4.2	42.0091187	-3.5334797	2.55	0.41	16.9 ± 4.1
4.3	42.0117750	-3.5352866	2.55	0.42	6.7 ± 2.3
5.1	42.0136400	-3.5263550	6.03	0.87	9.5 ± 3.4
5.2	42.0191904	-3.5329396	6.03	0.71	4.8 ± 4.3
6.1	42.0177121	-3.5314173	1.55 ± 0.28	0.56	15.3 ± 8.7
6.2	42.0139503	-3.5332126	1.55 ± 0.28	0.36	15.2 ± 7.8
6.3	42.0088477	-3.5280946	1.55 ± 0.28	0.20	7.7 ± 3.2
6.4	42.0153782	-3.5267347	1.55 ± 0.28	0.40	3.1 ± 1.7
7.1	42.0170194	-3.5239029	4.15 ± 0.79	0.87	18.3 ± 9.6
7.2	42.0148667	-3.5231278	4.15 ± 0.79	0.96	>50
7.3	42.0130417	-3.5229194	4.15 ± 0.79	1.05	11.0 ± 3.6
8.1	42.0153375	-3.5235164	1.75 ± 0.46	0.33	>50
8.2	42.0141083	-3.5232670	1.75 ± 0.46	0.37	>50
9.1	42.0165440	-3.5331830	4.27 ± 1.37	1.12	>50
9.2	42.0171721	-3.5326837	4.27 ± 1.37	0.04	18.5 ± 9.6
9.3	42.0161051	-3.5264773	4.27 ± 1.37	0.72	12.6 ± 4.6
9.4	42.0078024	-3.5279351	4.27 ± 1.37	0.89	5.0 ± 2.2

Table 3. Properties of the multiple images that were used as constraints in the lens model of MS 2137. The format of each column is the same as the format for Table 2.

ID	RA	Dec.	z	rms (arc-sec)	μ
1.1	325.0653010	-23.6627183	3.086	0.24	3.8 ± 1.5
1.2	325.0573784	-23.6552507	3.086	0.97	3.2 ± 1.8
1.3	325.0639173	-23.6617792	3.086	0.76	1.1 ± 0.45
2.1	325.0627881	-23.6595561	1.19	0.27	31.7 ± 8.0
2.2	325.0660593	-23.6669070	1.19	0.16	2.8 ± 1.1
3.1	325.0647182	-23.6572985	1.495	0.08	7.9 ± 2.8
3.2	325.0623619	-23.6570179	1.495	0.77	50.2 ± 7.1
3.3	325.0667908	-23.6653782	1.495	0.68	3.9 ± 1.1
3.4	325.0590207	-23.6614473	1.495	0.26	3.5 ± 1.3
4.1	325.0617177	-23.6570091	1.495	2.07	17.3 ± 2.4
4.2	325.0654996	-23.6574819	1.495	0.43	3.5 ± 1.9
4.3	325.0671724	-23.6648956	1.495	0.13	4.5 ± 1.5
4.4	325.0671724	-23.6648956	1.495	0.41	2.7 ± 1.1
5.1	325.0631385	-23.6593017	1.496	0.40	3.8 ± 0.84
5.2	325.0630167	-23.6601998	1.496	0.73	0.59 ± 1.1
5.3	325.0649681	-23.6677483	1.496	1.43	2.6 ± 1.6

Table 4. Properties of the multiple images that were used as constraints in the lens model of MACS J0326. The format of each column is the same as the format for Table 2.

ID	RA	Dec.	z	rms (arc-sec)	μ
1.1	51.70533	-0.73235	3.755	1.57	9.2 ± 0.1
1.2	51.7140244	-0.7348069	3.755	0.96	3.2 ± 2.2
1.3	51.7072192	-0.7311556	3.755	0.38	6.0 ± 0.16
2.1	51.7055216	-0.7305184	1.248	0.48	22.7 ± 5.3
2.2	51.7057628	-0.7316436	1.248	0.56	11.7 ± 3.4
2.3	51.7082900	-0.7303000	1.248	0.54	4.2 ± 0.6
2.4	51.71047	-0.73444	1.248	0.93	22.6 ± 4.3
3.1	51.7018015	-0.7310976	5.878	0.85	4.1 ± 2.3
3.2	51.7067455	-0.7370053	5.878	0.65	6.7 ± 2.3
3.3	51.7048216	-0.7359669	5.878	0.29	22.0 ± 10.5
3.4	51.7106978	-0.7288662	5.878	0.53	7.9 ± 2.3
3.5	51.7093690	-0.7301727	5.878	0.59	11.3 ± 3.4

Table 5. Properties of the multiple images that were used as constraints in the lens model of MACS J1427. The format of each column is the same as the format for Table 2. ID numbers marked with an asterisk refer to predicted counter-images of each system that were not used in the final model.

ID	RA	Dec.	z	rms (arc-sec)	μ
1.1	216.9148671	216.9148671	0.8836	0.24	1.9 ± 1.4
1.2	216.9148671	216.9148671	0.8836	0.24	11.2 ± 3.3
1.3*	216.9165342	-25.3486428	0.8836	0.24	3.7 ± 1.9
2.1	216.9106579	-25.3536281	1.23655	0.174	7.6 ± 2.8
2.2	216.9199276	-25.3461304	1.23655	0.174	25 ± 5.1
2.3*	216.9131520	-25.3518332	1.23655	0.174	1.2 ± 1.1

telluric correction were performed with the standard star taken closest to the date of the source exposure. After an initial reduction process to align individual exposures, we re-run the final calibration step (the ‘scipost’ phase) to improve flux variation between individual IFU slices. This is achieved using an auto-calibration algorithm included in the MUSE reduction pipeline, but we first apply a mask to eliminate flux from bright cluster members and intracluster light that bias the measurement. Finally, we apply the ZURICH ATMOSPHERIC PURGE (ZAP; Soto et al. 2016) to the fully reduced final data cube in order to eliminate strong skyline residuals after sky subtraction.

2.2.2 VLT–MUSE catalogues

We performed source extraction for four clusters following the procedure detailed in Lagattuta et al. (2022); we briefly describe the procedure here. The clusters we evaluated were A383, MS2137, MACS J0326, and MACS J1427. Spectroscopic redshifts were obtained for objects in the MUSE cubes with a proprietary program called SOURCE INSPECTOR, developed and hosted by CRAL (Centre de Recherche Astrophysique de Lyon). SEXTRACTOR (Bertin & Arnouts 1996) was first run on the MUSE data using the muselet routine from mpdaff (Bacon et al. 2016; Piqueras et al. 2017),² which identifies sources with flux above the local continuum level by subtracting the average flux measured around a narrow wavelength range from the average flux within that wavelength range. This

²<https://mpdaff.readthedocs.io/en/latest/muselet.html>

process creates a pseudo-narrow-band for each wavelength range, or slice. A narrow-band cube was formed by combining all the slices together, and SEXTRACTOR was run on each slice to identify emission peaks. Unique detections in the cube had their spectrum extracted after peaks at different wavelength slices that are spatially ‘close’ to each other (i.e. within the same seeing disc) were combined into multiline objects. Single-line objects, like Ly- α and [O II], were also extracted. The spectra of sources that were identified using bright objects in the existing *HST* imaging were also extracted. A final sky correction was applied by subtracting, from each spectrum, the sum of the 500 nearest blank spaxels (spaxels not associated with any detection in the field) that were located within a 0.4–4.0 arcsec circular annulus centred on the target object.

Each spectrum was then evaluated using SOURCE INSPECTOR, which calculated five possible redshift fits for each spectrum using the tool Marz (Hinton 2016). Redshift fits were visually inspected by three individual users, with each user able to select one of the Marz values or manually enter a different value. Each fit was assigned a confidence ‘rating’ between 0–3, where 3 is a confirmed detection (redshift identified from multiple features or one unambiguous feature, such as a Ly- α or [O II] doublet), 2 is a probable detection (several lines that are noisy, which boosts the redshift error, or a single feature that is probably known but could also be something else (i.e. a blended [O II] line that could also be a wide [O III] line or noisy Ly- α), 1 is a possible detection (a best guess, though this is very uncertain), and 0 is no detection (no features, just noise). The selections of the three users were then evaluated against each other, and a complete catalogue was created for each cluster based on the agreement between these selections. Redshifts with a confidence rating of 3 were strongly agreed upon by all three users; redshifts with a confidence rating of 2 were tentatively agreed upon by all three users; and redshifts with a confidence rating of 1 were included as a ‘best guess’. Confidence 1 redshifts were not included in the final lens models unless they were assigned to lensed galaxies whose positions were supported by the structure of the lens model. A full catalogue for the clusters modelled in this paper (A383, MS2137, MACS J0326, and MACS J1427) can be found in the appendix at the end of this paper in Tables A6, A7, A8, and A9, respectively. Catalogues for MACSJ0949 and MACSJ0417 are not included in this paper as we did not perform source inspections for these clusters; we refer the reader to Jauzac et al. and Allingham et al. for details. Arc systems selected from *HST* photometry were confirmed with these redshift catalogues where possible. A histogram of all newly identified MUSE sources is given in Fig. 1. The redshift desert in MUSE, which spans between $1.5 \lesssim z \lesssim 2.9$, indicates an area where spectroscopic identifications of galaxies are difficult to acquire, since no strong nebular emission lines from galaxies at these redshifts fall into the wavelength range covered by MUSE. Identification thus relies on the presence of weaker lines that are still distinct from continuum emission. The presence of the redshift desert is represented by the lack of identified objects in this region, as seen in the figure.

3 MASS MODELLING

Strong lensing is a powerful tool for modelling the mass distribution of galaxy clusters, but lensing as a technique cannot differentiate between baryonic and DM without ancillary information. This can be partially alleviated by breaking up the overall mass distribution into different ‘clumps’ of matter, such as cluster member galaxies or galaxy-scale perturbers, and modelling them as separate distributions from the main DM halo of the cluster. The BCG is a distinct

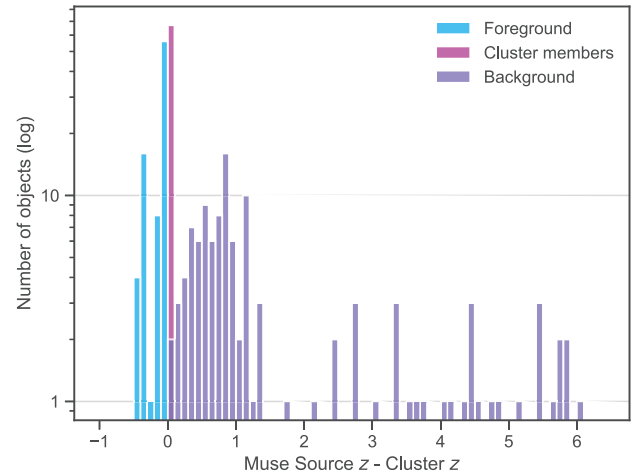


Figure 1. Distribution of MUSE source redshifts for all clusters modelled in this paper: A383, MS2137, MACS J0326, and MACS J1427. Redshifts for MACS J0949 and MACS J0417 are not included as we did not perform source inspection for these clusters. All redshifts are plotted relative to 0, where 0 is equivalent to the cluster redshift and thus denotes all the cluster members identified via MUSE.

component of any cluster mass model, and in the case of radial arcs, it is particularly important to model it separately because it affects the lensing potential of the cluster more strongly (Newman et al. 2011). The parametrization of the BCG can be done in a few different ways, but in this paper, we elect to utilize a combination of kinematic measurements from VLT/MUSE and photometry from *HST* imaging to place physical constraints on the distribution of mass in the BCG. This combination of kinematics and lens modelling is a useful technique utilized in many different papers to perform this type of analysis, from N13 to recent papers like Bergamini et al. (2023). We describe the parametrization of the cluster mass in this section, and in the following section, we detail the kinematic measurements of the BCG.

3.1 LENSTOOL

Strong lens models for each cluster in our sample were constructed using the software LENSTOOL (Jullo et al. 2007), an algorithm that models lensing clusters using a parametric approach. One cluster-scale halo and several smaller substructure haloes are combined to create the model, where each halo is treated as a pseudo-isothermal ellipsoidal mass distribution (dPIE, or PIEMD; Limousin, Kneib & Natarajan 2005). The parameters for each halo are: the x and y positions of the centre, the ellipticity, e , the position angle, θ , the core radius, r_{core} , the effective velocity dispersion, σ , and the truncation radius of the cluster halo, r_{cut} .

Markov Chain Monte Carlo (MCMC) sampling is used to sample the posterior density of the model, which is expressed as a function of the likelihood of the model (as described in Jullo et al. 2007). This function is minimized as

$$\chi_{SL}^2 = \sum_i \chi_i^2$$

where the sum is performed over the different families of multiple images in the model, and χ_i^2 , the chi-square value for each multiply

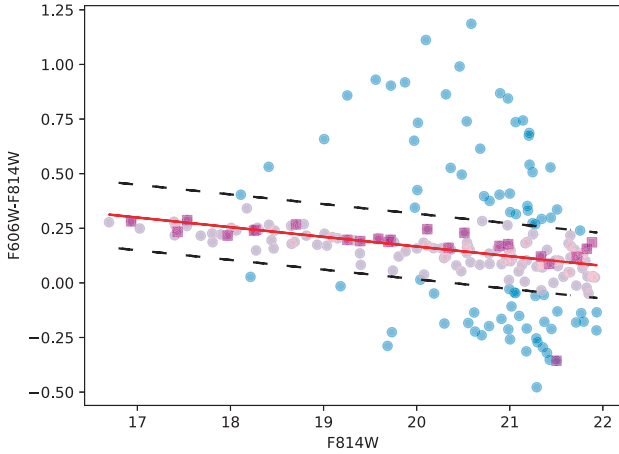


Figure 2. Example colour–magnitude diagram for A383. All sources identified by SEXTRACTOR are plotted as blue circles, and MUSE sources identified around the cluster redshift ($z = 0.187$) are overplotted as purple squares. The solid red line corresponds to the best fit for the red sequence, with a slope of -0.044 ± 0.015 and an intercept of 1.05 ± 0.30 . The boundary ($\sigma = 0.15$) for cluster member selection is marked by the dashed black lines, and the sources identified as cluster members are marked as light purple circles.

imaged source, is given as

$$\chi_i^2 = \sum_{j=1}^{n_i} \frac{(\theta_{\text{obs}}^j - \theta^j(\mathbf{p}))^2}{\sigma_{ij}^2}.$$

θ_{obs}^j is the vector position of the observed multiple image j , θ^j is the predicted vector position of the image j , n_i is the number of images in system i , σ_{ij} is the error of the position of image j , which is fixed to 0.5 arcsec for multiple images, and $\mathbf{p}$ represents each parameter optimized within the model. The model with maximum likelihood thus minimizes the distance between the observed and predicted positions of the multiple images. This distance is referred to as the rms. The optimized model is then used to solve for the best-fitting set of parameters of each halo.

3.2 Cluster member galaxies

Cluster member galaxies for all clusters (except MACS J1427) are selected using the cluster red sequence method (Gladders & Yee 2000), which classifies galaxies as cluster members if they have colors consistent with the red sequence at the cluster redshift. An example red sequence for the cluster A383 is shown in Fig. 2. In the case of MACS J1427, the archival data available at the necessary resolution to perform red sequence fitting consists of only a single *HST* filter. Red sequence fitting, which requires at minimum two different pass bands, can thus not be performed to isolate cluster members. Instead, we utilize spectroscopic redshifts from MUSE to identify a total of 30 sources at or around the cluster redshift ($0.30 < z < 0.33$), which we define as the cluster member galaxies for this cluster, with the caveat that this selection can be improved with additional observations.

For all clusters, we follow the assumption that luminosity traces mass (refer to the discussion in Harvey, Kneib & Jauzac 2016) to model each cluster member with galaxy-scale PIEMD haloes, where the positional parameters for each halo (x , y , e , θ) are fixed to the properties of their light distribution as measured with SEXTRACTOR

(Bertin & Arnouts 1996). The remaining PIEMD parameters (σ , r_{core} , r_{cut}) are then rescaled to match a reference galaxy with luminosity L^* following the Faber & Jackson (1976) relation:

$$\begin{cases} \sigma = \sigma^* \left(\frac{L}{L^*} \right)^{1/4} \\ r_{\text{core}} = r_{\text{core}}^* \left(\frac{L}{L^*} \right)^{1/2} \\ r_{\text{cut}} = r_{\text{cut}}^* \left(\frac{L}{L^*} \right)^{1/2} \end{cases}$$

The mass of each halo is then derived with the following relation:

$$M = \frac{\pi}{G} (\sigma^*)^2 r_{\text{core}}^* \left(\frac{L}{L^*} \right)$$

where σ^* , r_{core}^* , and r_{cut}^* are the reference velocity dispersion, core radius, and truncation radius, respectively. Previous models have demonstrated that r_{core}^* is small in galaxy-scale haloes and has a minimal effect on mass models (e.g. Covone et al. 2006; Elíasdóttir et al. 2007; Limousin et al. 2007b). r_{core}^* is thus fixed to 0.15 kpc for cluster galaxies. The remaining two parameters, velocity dispersion and cut radius, are optimized by the model for a reference galaxy L^* in each cluster. The velocity dispersion is allowed to vary between 27 and 250 km s^{−1}, and the cut radius between 3 and 50 kpc. The cut radius is constrained to an upper limit in order to account for tidal stripping of galactic DM haloes (Limousin et al. 2007a, 2009; Natarajan et al. 2009; Wetzel & White 2010; Niemiec et al. 2019). We differentiate between models using χ^2 and rms statistics, where a low rms generally indicates a better model.

3.3 Multiple images

Each model is constrained using the positions of multiply imaged sources, or arcs. Arcs are identified through a combination of MUSE spectroscopy, visual identification of sources with matching colour and morphology, and, where relevant, referencing previous models constructed for these clusters. The positions for each source with spectroscopy were fixed to the MUSE detections, which was especially relevant for each of the radial arcs, as their exact substructure and shape is obscured by the BCG light and can only be disentangled using MUSE. The properties of the multiple image systems for each cluster modelled in this paper are described in Tables 2–5.

3.4 Lens models

A summary of the MCMC fit values for each cluster can be found in Table A5.

3.4.1 A383

A383 ($z = 0.187$) was first modelled using LENSTOOL in Sand et al. (2004). It was later remodelled in Sand et al. (2008) in response to criticism levelled against the initial modelling method’s assumptions ignoring cluster substructure, and using spherically symmetric mass distributions; the 2008 model used a full 2D strong lensing model to avoid making these assumptions. The cluster was then observed by CLASH (Postman et al. 2012), and the discovery of a multiply imaged system at $z = 6.027$ was reported in Richard et al. (2011), while a mass model was presented in Newman et al. (2011, 2013a). Zitrin et al. (2011) then identified four new multiple image systems and presented an updated model, which was later refined with additional spectroscopy for one system by Zitrin et al. (2015).

A total of nine systems of multiple images are used to constrain the current lens model. The properties of the systems are presented in Table 2. Systems 1, 2, and 9 are all fixed to the spectroscopic redshift measured and optimized from the MUSE cubes. The redshifts of the remaining systems were solved for by the lens model. Systems 2–9 are used in previous lens models of this cluster (Sand et al. 2008; Newman et al. 2011, 2013a; Richard et al. 2011; Zitrin et al. 2011, 2015), while system 1 is a new identification confirmed by MUSE spectroscopy. The spectroscopic redshifts for the multiple images are listed in Table A6.

3.4.2 MS2137–223

MS 2137–23 ($z = 0.313$) was first modelled with LENSTOOL in Sand et al. (2004) and then updated in Sand et al. (2008) using a full 2D strong lensing model. Donnarumma et al. (2009) presented a mass profile for the cluster based on strong gravitational lensing and *Chandra X-ray Observatory* imaging. Newman et al. (2013b) later created a mass model with similar imaging and new Keck spectroscopy for seven multiply imaged sources, and extended stellar velocity dispersions for the BCG. The lack of multiple images in these models caused them to all have slightly different results for the mass profiles. CLASH observations (Postman et al. 2012) were later carried out on the cluster, and a new model with an additional multiply imaged system with a confirmed spectroscopic redshift was published in Zitrin et al. (2015). A spectroscopic study conducted with the K-band Multi-Object Spectrograph (KMOS) has also recently been performed that includes several galaxies in MS 2137 (Tiley et al. 2020).

We use a total of four systems of multiple images to optimize this lens model. The properties of the systems are presented in Table 3. All systems have redshifts from MUSE observations. System 1 was first identified in Zitrin et al. (2015), but only with photometric information. We confirm its redshift here with MUSE spectroscopy. The remaining systems are referenced in previous works (Sand et al. 2008; Donnarumma et al. 2009; Newman et al. 2013a; Zitrin et al. 2015). We note that while system 2 is not a new detection, this is the first time this arc has been included in a parametric lens model. We are able to include it because it has a confirmed redshift measurement from MUSE spectroscopy. Systems 3 and 4 are parts of the same giant radial arc, and are adopted here as separate constraints in order to refine our lens model.

3.4.3 MACSJ 0326.8–0043

MACS J0326 ($z = 0.447$) was first discovered by the MASSive Cluster Survey SNAPshot programs (MACS, PI: Ebeling; Ebeling, Edge & Henry 2001; Mann & Ebeling 2012), which amassed a sample of the most X-ray luminous galaxy clusters based on X-ray sources detected by the Röntgen Satellit (*ROSAT*) All-Sky Survey (Voges et al. 1999). These programs were designed to carry out *HST* observations of very X-ray luminous sources to obtain a statistically robust sample of massive distant clusters of galaxies. This is the first published strong lensing mass model for this cluster.

Three systems are used in this lens model, with all systems having at least one image redshift from MUSE. The properties of the arc systems are presented in Table 4. All three arcs are new identifications as this cluster has not previously been modelled. System 2 is a clear tangential arc located north-east of the BCG, and has been split into a northern and southern part for the purposes of this model. These arcs, 2.1 and 2.2, are MUSE detections, as is 2.3, which is the northern

radial arc shown in Fig. 3. Image 2.4 is predicted by the model and is located on a similarly coloured source. Systems 1 and 3 are Lyman- α emitters. Images 3.1, 3.2, and 3.3 are MUSE identifications, while 3.4 and 3.5 are predicted multiple images from the model. Image 1.2 is a MUSE identification, while images 1.3 and 1.4 are fixed to locations predicted by the model and are confirmed by the presence of similarly coloured sources in the image. Image 1.4 is of particular interest, as it hints at another radial arc next to the BCG. Fig. 3 seems to indicate the presence of another source in this area, but the shallowness of the *HST* image makes it difficult to confirm. Deeper spectroscopic observations would be able to confirm the legitimacy of this arc.

3.4.4 MACSJ 1427.6–22521

MACS J1427 ($z = 0.318$) was first observed in the MACS program (Ebeling et al. 2001). This is the first published strong lensing mass model for this cluster.

Two multiple image systems are used to construct the lens model; the first is the radial arc located near the BCG (1.1), with a spectroscopic redshift of $z = 0.884$, while the second is another source with a spectroscopic redshift of $z = 1.237$ (2.1). The properties of these systems are presented in Table 5. The multiple image systems used to construct the lens model for this cluster are based primarily on the identification of their colour and morphology is not possible within the single available band of *HST* imaging. The lens model predicts additional counter-images for these systems, but there is no significant emission present in the MUSE cube at these locations that would allow for the verification of these counter-images, and inspection of the *HST* imaging also does not confirm or rule out their existence. The predicted positions of the counter-images are listed in Table 5, but should be treated as potential candidates rather than a confirmed identification of a lensed arc.

3.5 Additional clusters with radial arcs

The clusters presented thus far are not the only clusters in the larger Kaleidoscope sample of MUSE cubes that have radial arcs. In the interest of completeness, we introduce the two remaining clusters in the sample with radial arcs. These clusters have both been modelled using LENSTOOL outside this paper following the methods already described in Section 3.1, which allows us to directly incorporate them into our broader analysis of the density profiles of galaxy clusters with radial arcs. These two clusters are MACS J0417 and MACS J0949. Both clusters were first observed by MACS (Ebeling et al. 2001; Mann & Ebeling 2012).

MACS J0417 was modelled in Mahler et al. (2019) as a part of the RELICS (Coe et al. 2019), as well as in Jauzac et al. (2019, J19), which included MUSE spectroscopy. We utilize the fiducial model from J19 in our analysis. The cluster is at a redshift of $z = 0.443$, and is constrained with a total of 17 lensed systems, three of which have spectroscopic redshifts confirmed by MUSE. System 1, a quadruply imaged galaxy, is of particular interest, as it includes a radial arc whose position is identified from emission lines detected in MUSE, as it is otherwise obscured by the BCG in the available *HST* imaging. Unlike the other five clusters in our sample, MACS J0417 has a fairly elongated cluster core, which can be observed both visually by the separation in projection of the second and third brightest cluster galaxies from the BCG, as well as in the X-ray analysis (see J19), which show extended emission along the SE-NW axis. These factors

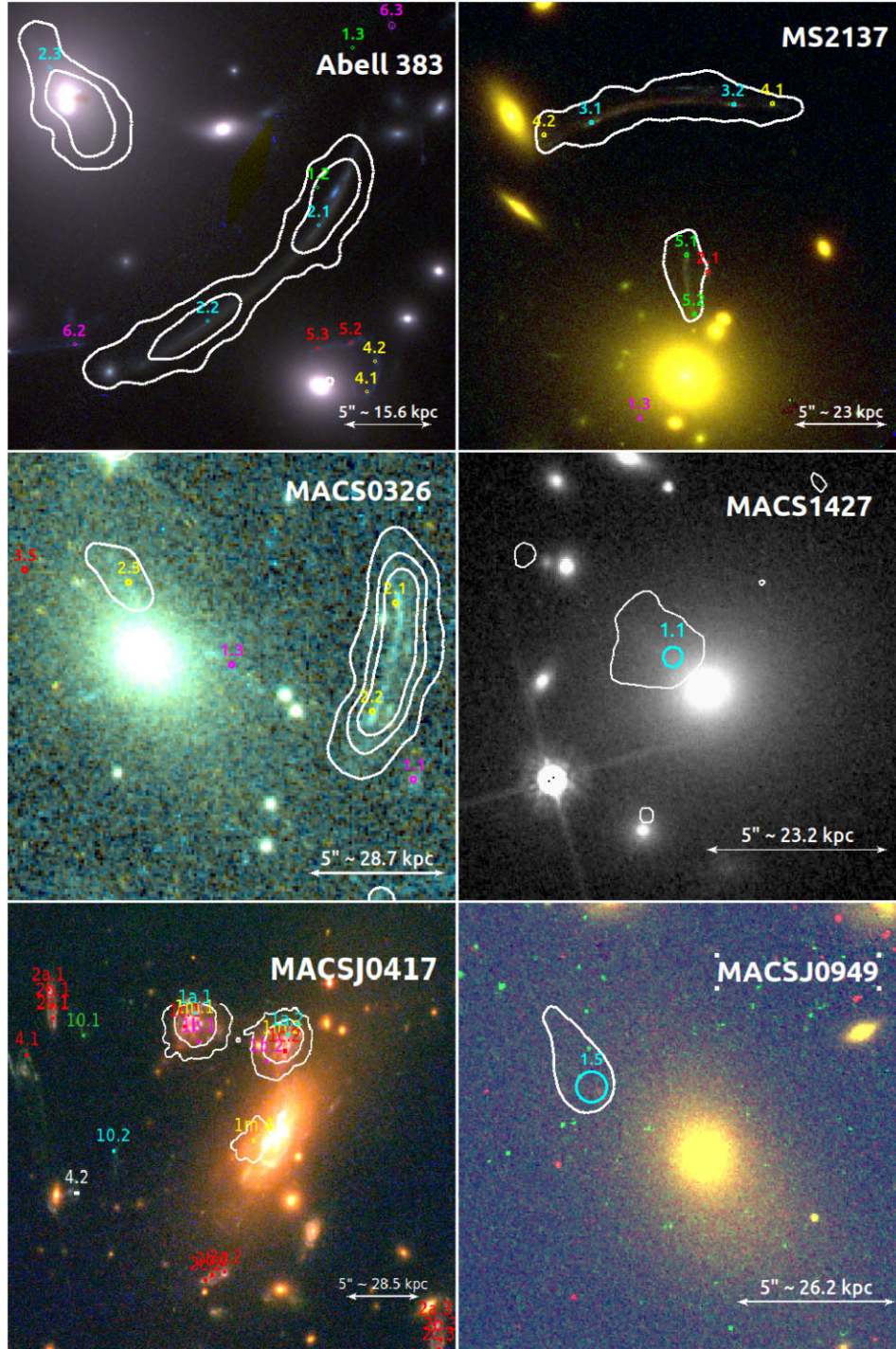


Figure 3. Snapshots of the radial arcs in each cluster. All images are oriented north-up, east-left. Each individual arc in a system is labelled as a pair of numbers, i.e. 1.1. In the case where an arc is labelled, for example, 1a.1, the letter corresponds to a subdivision of the same lensed galaxy 1. Each arc ‘family’ is marked in a different colour for clarity. Top left: A383 image of the BCG with MUSE detection contours for the radial arc and its nearby tangential counterpart at 7495 Å overplotted in white. Multiple image systems in this region are also shown. Top right: MS 2137 image of the BCG with MUSE detection contours of the radial arc and the nearby tangential arc at 9300 Å overplotted in white. Multiple image systems in this region are also shown. Middle left: MACS J0326 image of the BCG with MUSE detection contours of the radial arc at 8376 Å overplotted in white. Multiple image systems in this region are also shown. Middle right: MACS J1427 image of the BCG with MUSE detection contours of the radial arc at 7020 Å overplotted in white. Multiple image systems in this region are also shown. Bottom left: MACSJ0417 image of the BCG with MUSE detection contours of the radial arc and its nearby counterpart images at 6975 Å overplotted in white. Multiple image systems in this region are also shown. Bottom right: MACSJ0949 image of the BCG with MUSE detection contours of the radial arc at 7160 Å overplotted in white. Multiple image systems in this region are also shown.

Table 6. Summary of VLT/MUSE observations used.

Cluster	Seeing (arcsec)	Airmass	P.I.	Exp. time [s]	Obs. date	ESO project code
A383	1.0	1.74	Edge	2910	2019-11-17	0104.A-0801(B)
MS2137	1.0	1.86	Edge	2910	2019-06-28	0103.A-0777(A)
MACS J0326	0.5	1.09–1.11	Edge	2910	2019-09-21	0103.A-0777(A)
MACS J1427	1.0–1.5	1.01–1.06	Edge	2910	2018-03-14	0100.A-0792(A)
MACS J0417	1.6	1.8	Edge	2910	2017-12-12	0100.A-0792(A)
MACS J0949	0.71	1.4	Edge	2910	2020-02-20	0104.A-0801(A)

Notes. The name of the cluster is given in the first column, the seeing for the observation is given in the second column, and the airmass for the observation is given in the third column. The P.I. for the observation is given in the fourth column, the exposure time is given in the fifth column, the observation date is given in the sixth column, and the ESO project code is given in the seventh column.

Table 7. Values for the BCG of each cluster extracted from the photometric fitting process.

Cluster	Filter	b/a	θ	Magnitude	r_{core} [kpc]	r_{cut} [kpc]
A383	ACS/F606W	0.87	81.77	18.82	3.32	23.8 ± 5.6
MS2137	ACS/F625W	0.86	73.56	18.40	0.76	66.2 ± 12.3
MACS J0326	ACS/F606W	0.55	46.66	19.56	1.74	77.9 ± 6.4
MACS J1427	ACS/F814W	0.90	−2.85	17.88	0.23	7.0 ± 0.31
MACS J0949	ACS/F606W	0.52	31.12	19.96	2.81	70.6 ± 4.2
MACS J0417	ACS/F606W	0.33	−34.10	19.58	6.85	101.4 ± 29

Notes. The first column lists the cluster, and the second column lists the filter used for the photometric fit of the BCG. The third column lists the b/a value, the fourth column lists the position angle θ , the fifth column lists the magnitude of the BCG in the listed filter, and the sixth and seventh columns list the r_{core} and r_{cut} fit values. The errors for r_{core} are extremely small and are thus not listed.

indicate that the cluster is likely the result of a recent merger, possibly oriented along the line of sight, which makes it the most dynamically complex cluster of our sample.

Finally, we include MACS J0949 in our sample, using the strong lens model recently published in Allingham et al. (2023). The cluster is at a redshift of $z = 0.383$, and X-ray data suggest that it is a postmerger in the process of relaxing. The strong lens model is constrained with a total of six lensed systems, two of which have spectroscopic redshifts confirmed by MUSE. Similarly to the other clusters in this paper, its radial arc is also detected by MUSE.

4 BCG KINEMATICS

We introduce kinematic constraints into the total density profile of each cluster in order to more closely examine the shape of the mass distribution in the inner 10 kpc of the cluster. Following the methods used in Sand et al. (2004) and Newman et al. (2013b), we include the velocity dispersion of the BCG as an additional constraint for our LENSTOOL model. We incorporate this constraint by measuring observable properties of the BCG through a combination of photometry and spectroscopy. We model the BCG as a separate dPIE mass halo within LENSTOOL, with its parameters fixed to the values obtained from these measurements. The following subsections discuss the measurements of the observable properties of the BCG that we use to fix the parameters of the BCG mass halo, as well as to constrain the lens model using our kinematic measurements. We discuss the combination of kinematics and lensing more thoroughly in Section 5.3.

4.1 BCG photometry

We measure the surface brightness profile of the BCG in each cluster using *HST* imaging, where preference was given to the ACS/F606W filter to more closely align the photometric fit with the wavelengths used in the kinematic fit since these BCGs are largely red and dead.

This band was used for A383, MACS J0326, MACS J0949, and MACS J0417, while the ACS/F814W filter is used for MACS J1427. However, in MS2137, where the BCG is near the chip gap, the F625W filter was used. In MACS J1427, where this band is not available, the F814W filter was used instead. Surrounding objects in the field are masked out using a SExtractor segmentation map, and the point spread function is modelled using a field star and a selection of surrounding sky. We model the BCG light using the 2D dPIE equation, adopting the specific form used in LENSTOOL (Limousin et al. 2005):

$$\Sigma_{\text{dPIE}}(R) = \frac{\sigma_0^2 r_{\text{cut}}}{2G(r_{\text{cut}} - r_{\text{core}})} \left(\frac{1}{\sqrt{r_{\text{core}}^2 + R^2}} - \frac{1}{\sqrt{r_{\text{cut}}^2 + R^2}} \right),$$

where r_{core} is the core radius, r_{cut} is the cut radius, and σ_0 is the central velocity dispersion of the BCG. The half-light radius, r_h , is related to the cut radius as $r_h \approx r_{\text{cut}}$, and in the limit $r_{\text{core}}/r_{\text{cut}} \ll 1$, the projected effective radius is $R_e \approx (3/4)r_{\text{cut}}$.

We fit this equation by using the light profile extracted from isophotal measurements of the BCG. We first fix the geometric parameters of ellipticity, position angle, and centre coordinates of the central isophote to the values we obtain from fitting a de Vaucouleurs $R^{1/4}$ profile to the 2D data using GALFIT (Peng et al. 2002, 2010). We then use the PYTHON Astropy Elliptical Isophote Analysis routine to find the best-fitting model for the 2D data out to about 20 kpc, where the light from other objects in the field begins to dominate the light from the BCG, and run the fit in the bilinear area integration mode. The 1D surface brightness profile is then fit to the dPIE equation, with only σ_0 allowed to vary during the fit.

Finally, since we use the mass of the BCG as a constraint in our modelling, we require a stellar mass-to-light ratio to transform the dPIE fit to the light into the mass of the BCG. We obtain this value by performing a spectral energy distribution (SED) fit of the combined photometric (see Table 1) and spectroscopic (see Table 6) data using

Table 8. Values for the velocity dispersion profile for the BCG of each cluster. The quoted σ values are measured at the mid-point of each bin.

Cluster	Bin [arcsec]	Bin [kpc]	σ [km s ⁻¹]
A383	0.0–0.26	0.0–0.81	285 ± 14
	0.46–0.66	1.44–2.07	329 ± 12
	0.86–1.06	2.69–3.32	263 ± 10
	1.26–1.46	3.94–4.57	272 ± 10
	1.66–1.86	5.19–5.82	295 ± 13
	2.06–2.26	6.45–7.07	318 ± 15
	2.46–2.66	7.70–8.32	296 ± 16
	2.86–3.06	8.95–9.57	322 ± 17
	3.30–3.66	10.33–11.45	316 ± 20
MS2137	4.46–5.06	13.96–15.83	341 ± 24
	5.86–7.26	18.34–22.72	409 ± 28
	0.0–0.50	0.0–2.30	337 ± 13
	0.50–1.0	2.30–4.60	350 ± 9
	1.0–1.5	4.60–6.90	334 ± 8
	1.5–2.0	6.90–9.20	374 ± 10
MACS J0326	2.0–2.5	9.20–11.50	378 ± 13
	3.0–3.5	13.80–16.09	404 ± 19
	0.43–0.73	2.47–4.19	238 ± 15
	0.73–1.08	4.19–6.20	276 ± 15
MACS J1427	1.08–1.66	6.20–9.52	291 ± 17
	0.0–0.38	0.0–1.76	320 ± 9
	0.38–0.75	1.76–3.48	312 ± 9
	0.75–1.12	3.48–5.19	297 ± 10
MACSJ0949	1.12–1.5	5.19–6.95	301 ± 11
	1.5–1.88	6.95–8.71	326 ± 16
	1.88–2.25	8.71–10.43	344 ± 21
	2.25–2.62	10.43–12.14	407 ± 31
MACSJ0417	0.0–0.71	0.0–3.71	300 ± 12
	0.71–1.42	3.71–7.43	292 ± 10
	1.42–2.13	7.43–11.14	282 ± 12
	2.13–3.18	11.14–16.63	323 ± 24
MACSJ0417	0.0–0.85	0.0–4.85	380 ± 13
	0.85–1.7	4.85–9.70	388 ± 13
	1.7–2.55	9.70–14.56	399 ± 15
	2.55–3.4	14.56–19.40	429 ± 22

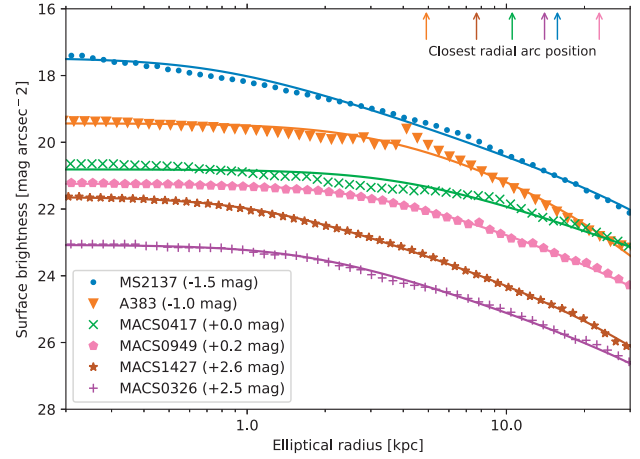
Notes. The first column lists the cluster, the second column lists the total extent of each bin in arcsec, the third column lists the total extent of each bin in kpc, and the fourth column lists the measured velocity dispersion in that bin.

PPXF (Cappellari 2017). We use the FSPS models library (Conroy, Gunn & White 2009, Conroy & Gunn 2010) generated in Cappellari (2023) as the basis for the fit, which was created using a Salpeter initial mass function with a mass range between 0.08 and 100 $M_{\odot}$. These models do not explicitly include the effect of gas or dust. The spectra for these stellar population synthesis (SPS) models were created using the MILES stellar library (Sánchez-Blázquez et al. 2006, Falcón-Barroso et al. 2011). We use the library of these spectra to fit the stellar mass-to-light ratio of the BCGs in each cluster.

The resulting parameters, surface brightness profiles, and dPIE fits are presented in Table 7 and Fig. 4. This fit allows us to easily create a separate mass halo for each BCG whose properties are fixed to these photometric values. We specifically fix the ellipticity, the position angle, and the values of r_{core} and r_{cut} . The only free parameter is then the velocity dispersion, σ_0 , which serves as a constraint on the mass profile in our model.

4.2 Velocity dispersion profile

We utilize BCG kinematics in tandem with lensing to break down the total mass distribution of the cluster into more clearly defined

**Figure 4.** Surface brightness profiles of the BCGs for all six clusters, measured using the filters listed in Table 7. The dPIE fit for each profile is plotted as the solid line of the same colour as each cluster. The magnitudes for each cluster are offset by the listed values to provide visual clarity. Colour-coded arrows are plotted along the top to show the approximate distance from the BCG to the barycentre of the radial arc in each cluster.

baryonic and DM segments. Modelling the BCG mass using stellar dynamics allows us to place limits on the contribution of the BCG to the total cluster density profile in the very inner portion of the cluster (<10 kpc), which in turn allows us to more precisely examine the behavior of DM in this region.

We elect to model the kinematics of the BCG by creating a profile of the velocity dispersion in different bins, stepping out from the centre of the BCG until the S/N ratio dips below a cut-off threshold of 30, which is equivalent to a distance of about ~ 20 kpc for each cluster. We note that this profile increases with radius because the measurement begins to sample the cluster potential at larger radii; thus only the lower values of σ characterize the BCG itself. We utilize the MUSE observations from the Kaleidoscope survey to make these measurements of the velocity dispersion. As these observations are all short exposures, we choose to bin the cubes using concentric circular annuli, which maximizes the S/N ratio in each bin and is applied to the BCGs in each cluster under our guiding assumption that each BCG can be described by a spherical mass distribution (see Section 4.3 for more details). The width of each annulus is determined by the S/N ratio, where we require each bin to be large enough to obtain a total S/N ratio greater than 30. We fit each spectrum over a rest-frame wavelength of 4860–7160 Å, which includes the regions where MUSE sensitivity is strongest and excludes regions where sky line residuals are very large.

Nearby bright stars and galaxies are masked out before the fit is performed for each BCG, and bins where these objects interfere strongly with the BCG light are excluded. We choose to mask out surrounding galaxies despite their potential contribution to the velocity dispersion profile because we do not know where they are located in the 3D space of the cluster. Additionally, failing to mask these objects distorts the velocity dispersion toward non-physical values. This is particularly relevant for MACS J1427, which has a bright foreground star situated within 5 arcsec of the BCG. While masking this star allows for an effective measurement of the velocity dispersion, we are unable to continue fitting past about 10 kpc due to the contamination from the flux of this star and the surrounding cluster galaxies.

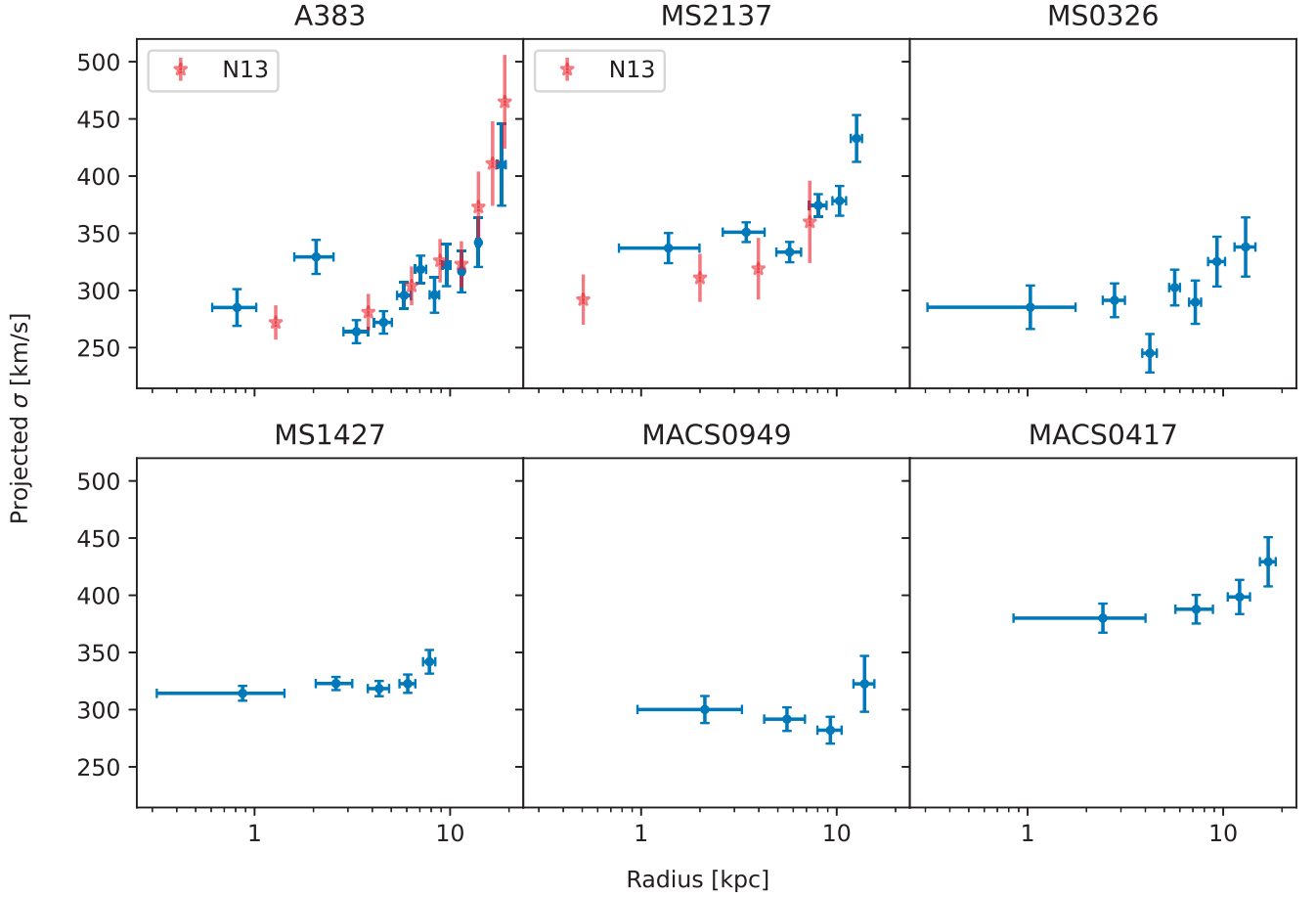


Figure 5. BCG stellar velocity dispersion profiles for all six clusters. The error in the velocity dispersion is denoted by the error bars along the Y-axis, while the error bars on the X-axis signify the width of the bin used to make the measurement. The data points are centred at the middle of each bin, and each point corresponds to the reported σ value in Table 8. For the clusters A383 and MS2137, the values reported in N13 are overplotted as red stars for reference.

The PPXF fit for each cluster relies on the use of additive and multiplicative polynomials in order to match the template spectra to the observed VLT/MUSE spectrum. These polynomials are adjusted until the fit in the highest S/N bin of each cluster no longer improves. One first-order multiplicative polynomial is used for every cluster except MS2137, which uses a third-order polynomial, and a fifth-order additive polynomial is used for every cluster.

We are able to compare our measurements for the velocity dispersion directly to the results found in Newman et al. (2013a). Fig. 5 shows the velocity dispersion profiles for all six clusters analysed in this paper, and additionally shows how our results compare to those derived in N13 for the clusters A383 and MS2137. The N13 results are based on a Keck/LRIS 23.7 ks exposure with 0.8 arcsec seeing for A383, and a Keck/ESI 6.7 ks exposure with 0.7 arcsec seeing for MS2137. Relative to the MUSE data, the archival Keck data have a $10\times$ and $3\times$ longer exposure time for A383 and MS2137. Measured seeing conditions were on average 0.2 arcsec narrower. However, the advantage of MUSE rests in the ability of IFU observations to capture information about the entire structure of the BCG. In other words, area recovers depth. This is well supported by our measured profiles, because while there is some variation in the innermost bins, the shape of the profile for A383 and MS2137 is generally well reproduced by our measurements. This suggests that our characterization of the BCG profile in the MUSE data is consistent with archival measurements, despite the difference in observing conditions.

4.3 Velocity anisotropy

The dynamical analysis performed in this paper is accomplished under one critical assumption: that the BCGs in this work can be modelled with the spherical Jeans equation. This simplification relies on the assumption that each BCG has an isotropic velocity dispersion and can be described by using spherically symmetric geometry. We choose to rely on this assumption in the creation of the combined kinematic-strong lensing model because BCGs generally lack significant anisotropy (see Kronawitter et al. (2000), which studied 21 giant ellipticals and found that the velocity anisotropy was less than $\beta < 0.3$ for the majority of the sample, and Santucci et al. (2023), which measured a similar value for central ellipticals). Choosing to treat the BCGs in this way significantly speeds up the computational time required for the optimization procedure in LENSTOOL (by a factor of at least 10). However, it is worth considering whether this assumption would have an impact on our mass modelling procedure, as MACS J0417 does have a velocity gradient reaching across the major axis of the BCG, which is likely due to the actively evolving dynamical state of the ongoing merger happening within the cluster.

To test the validity of this assumption, we employ two different methods to evaluate what effect anisotropy would have on our lens models. First, we use the form of the anisotropic Jeans equation and fix the anisotropy parameter β to a small, constant value ($\beta = 0.3$) to examine how this affects our results. Second, for MACS J0417,

we employ the more robust external modelling program JAMPY (Cappellari 2020) in conjunction with MgeFit (Cappellari 2002) to examine the specific effect that the presence of velocity anisotropy in the BCG might have on the measurement of the cluster mass profile. Introducing a constant anisotropy value shifts the value of the derived velocity dispersion by roughly $\pm 5 \text{ km s}^{-1}$ in all cases. The more robust examination of anisotropy in MACS J0417 results in around the same changes. This small shift is not significant for the measurements presented in this paper, as the deviation is encapsulated in the error budget intrinsic to the models. In future work, it would be worth re-examining this question in the context of mass models that are created using multiwavelength analysis, such as models that specifically constrain components like the intracluster medium or intracluster light by incorporating X-ray imaging into the model.

5 RESULTS

5.1 Mass models

5.1.1 Abell 383

One cluster-scale DM halo is used to model the cluster, and a total of four galaxy-scale haloes are included to separately model the mass distribution of the BCG, as well as three cluster members located near systems 3 and 4. The best fit parameters for these haloes are given in Table A1. The integrated density profile is presented in Fig. 7. A snapshot of the radial arc in the south-west portion of the cluster is shown in Fig. 3. The cluster, multiple images, and the critical lines for the model at $z = 3.0$ are shown in Fig. 6.

5.1.2 MS 2137–23

One cluster-scale DM halo is used to model the cluster, and two galaxy-scale haloes are used to separately model the mass distribution of the BCG and one cluster member located near systems 3 and 4. The parameters for these haloes are given in Table A2. The integrated density profile is presented in Fig. 7. A snapshot of the radial arc in the north-east portion of the cluster is presented in Fig. 3. The cluster, multiple images, and the critical lines for the model at $z = 3.0$ are shown in Fig. 6.

5.1.3 MACS J0326.8–0043

One cluster-scale DM halo is used to model the cluster, one galaxy-scale halo is used to separately model the mass distribution of the BCG, and one additional halo is included for the bright cluster member located near system 3. The best-fitting parameters for these haloes are given in Table A3. The integrated density profile is presented in Fig. 7. A snapshot of the two radial arcs near the BCG are shown in Fig. 3. The cluster, multiple images, and the critical lines for the model at $z = 3.0$ are shown in Fig. 6.

5.1.4 MACS J1427.6–2521

This cluster has not been mass modelled before. One cluster-scale DM halo is used to model the cluster and one galaxy-scale halo is used to separately model the mass distribution of the BCG. The best-fitting parameters for these haloes are given in Table A4. The integrated density profile is presented in Fig. 7. A snapshot of the radial arc is shown in Fig. 3. The cluster, multiple images, and the critical lines for the model at $z = 3.0$ are shown in Fig. 6.

5.1.5 MACS J0417.5–1154

We refer the reader to Jauzac et al. (2019) and Mahler et al. (2019) for more details regarding this mass model. The only modification we make to the model described in J19 is the introduction of the parameters listed in Table 7 to constrain the mass halo for the BCG. A snapshot of the radial arc is presented in Fig. 3. The integrated density profile is presented in Fig. 7.

5.1.6 MACS J0949.8 + 1708

We refer the reader to Allingham et al. (2023) for more details regarding this mass model. The only modification we make to the model described in this paper is the introduction of the parameters listed in Table 7 to constrain the mass halo for the BCG. A snapshot of the radial arc is presented in Fig. 3. The integrated density profile is presented in Fig. 7.

5.2 Lensing model prior distributions

The above models each contain different parameters that are optimized over a parameter space that differs slightly between clusters. The given parameter space for each parameter takes the form of a uniform distribution, which is the default distribution for priors in LENSTOOL (Jullo et al. 2007). This ensures that the full parameter space for each individual parameter is explored without biasing the search toward any particular value. The specific boundaries for each parameter space are provided in Table 9, and the corner plots for the key parameters in the fitting procedure are displayed in Fig. 8. These parameters are the r_{core} parameter for the DM halo, and the velocity dispersions for both the DM halo and the BCG, which are essentially scaling factors for determining the mass distribution of the primary dPIE cluster-scale DM and BCG stellar mass haloes within the lens models. There is a strong correlation between the velocity dispersion of the DM halo and the measurement for r_{core} . Additionally, the lens model parameters are not very well constrained in MACS J1427, which is due to the lack of constraints within the lens model. The models for MACS J0949 and MACS J0417 are unchanged from their published versions, save for the addition of the explicitly constrained BCG, and are included here for completeness.

5.3 Combining kinematic profile with lensing

Stellar kinematics generally probe the total mass distribution, but in the case of galaxies, where significant amounts of stellar light are concentrated, the mass profile is strongly dominated by baryons. We can thus combine the kinematic measurements of the BCGs of these clusters, which effectively measure the baryonic mass, with strong lensing models, which are sensitive to DM, to disentangle the degeneracy between dark and baryonic matter. We elect to employ kinematic measurements of the BCG in our models to more accurately probe the mass distribution at the centre of these galaxy clusters. We separately parametrize the BCG using a dPIE profile with LENSTOOL, using parameters derived from photometry. We leave the velocity dispersion as the only free parameter for this profile. We can then constrain the BCG velocity dispersion using our real kinematic measurements from MUSE. In this way, we can use physical measurements of the BCG to constrain the lens model.

The velocity dispersion of the BCG is incorporated as a constraint into the model through a-posteriori analysis of the MCMC LENSTOOL model. The original LENSTOOL model is first modified to incorporate

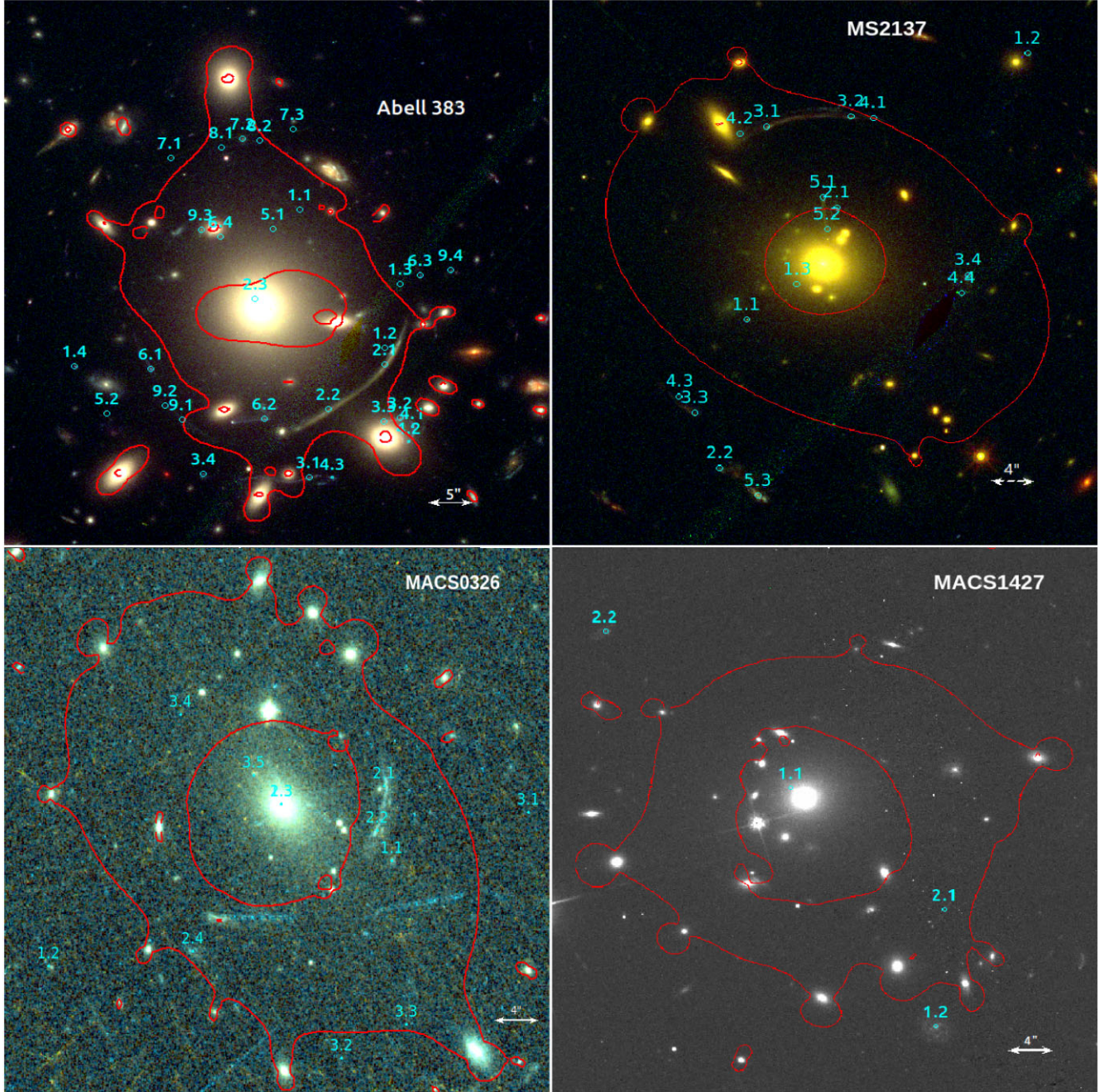


Figure 6. Images of the four clusters newly modelled in this paper. All images are oriented north-up, east-left. Top left: *HST* composite color image of A383 created using a combination of WFC3/IR imaging in the red (*F*160W) and ACS imaging in the green (*F*814W) and blue (*F*606W). Multiply imaged galaxies are labelled in cyan. The red curve marks the location of the critical curve for a source at $z = 3.0$. Top right: false colour image of MS 2137 created using a combination of WFC3/IR imaging in the red (*F*160W) and ACS imaging in the green (*F*814W) and blue (*F*606W). Multiply imaged galaxies are labelled in cyan. The red curve marks the location of the critical curve for a source at $z = 2.5$. Lower left: false colour image of MACS J0326 created using a combination of ACS imaging in the green (*F*814W) and blue (*F*606W). Multiply imaged galaxies are labelled in cyan. The red curve marks the location of the critical curve for a source at $z = 3.0$. Lower right: *F*814W image of MACS J1427. Multiply imaged galaxies are labelled in cyan. The red curve marks the location of the critical curve for a source at $z = 1.2$.

photometric information (discussed in Section 4.1) for the BCG into the model. This is done by creating a separate mass halo to account for the BCG, with the parameters r_{core} and r_{cut} fixed to the values obtained from the surface brightness profile fit. Ellipticity and position angle are also fixed to the values from the GALFIT fitting. The remaining free parameter in the halo, σ_0 , is left free as a proxy for the stellar mass-to-light ratio (Sand et al. 2004, 2008; Bergamini et al. 2019).

This parameter is given a prior that is informed by measurements of the stellar mass-to-light ratio.

Adding this information to the model allows us to directly calculate a model version of the velocity dispersion of the BCG based on Jeans fitting. In this work, we assume that each BCG can be described by a spherical mass distribution, and we do not explicitly incorporate velocity anisotropy into our models, as any effects from including

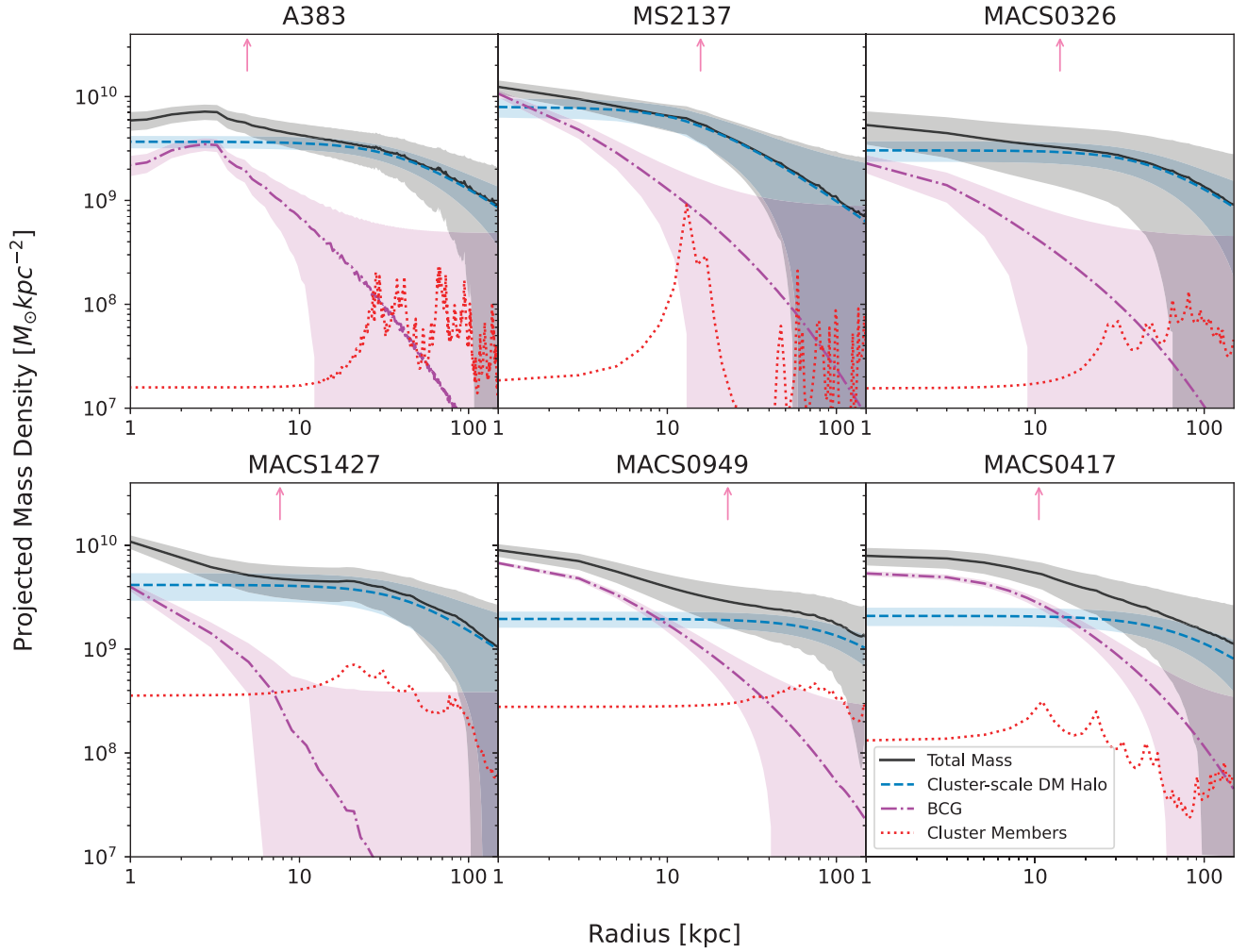


Figure 7. The integrated density profiles for all six clusters studied in this work. The uncertainty in the measurement is plotted as the shaded region around the line, and only incorporates the uncertainty returned by LENSTOOL; systematic errors are not included. Uncertainty measurements are not included for the mass profile of the cluster member galaxies as they are too large to be meaningful. Density is measured in units of $\log (M_{\odot}/\text{kpc}^2)$. The arrows denote the distance between the BCG and the barycentre of the nearest radial arc used as a constraint in the lens model.

this component do not have a large impact on the measured velocity dispersion (see the discussion in Section 4.3). The form of the spherical Jeans equation is thus as follows:

$$\sigma_{\text{los}}^2(R) = \frac{2G}{\sum_*} \int_R^{\infty} \frac{v_*(r)M(r)\sqrt{r^2 - R^2}}{r^2} dr,$$

where v_* describes the 3D profile and $\sum_*$ refers to the 2D profile of the stellar component of the BCG. These profiles are drawn directly from the photometric fits to the BCG described in Section 4.1. $M(r)$ accounts for the total enclosed mass inside a radius, r , and must thus account for both the stellar and DM mass. We draw the value for the enclosed mass directly from the LENSTOOL model at this stage, as the degeneracy between DM and stellar mass makes it difficult to avoid double-counting the mass of the BCG if we add it separately to the LENSTOOL value. We can then calculate a model velocity dispersion for the BCG at any given radius, R .

The optimization of the LENSTOOL model with respect to the stellar kinematics is performed by adding the error from the model to the

error of the stellar kinematics,

$$\chi_{\text{VD}}^2 = \sum_i \frac{(\sigma_i - \sigma_i^{\text{obs}})^2}{\Delta_i^2},$$

where Δ_i is the uncertainty in the observed velocity dispersion measurements, and i represents the radial bins where the velocity dispersion was measured. The optimized best-fitting LENSTOOL model is then the one that minimizes the difference of the model velocity dispersion within each radial bin relative to the measured velocity dispersion within those bins.

The calculation of the velocity dispersion error is performed after the lensing minimization has been completed, separately from LENSTOOL. As a result, the velocity dispersion and lensing likelihoods can be treated as independent from each other, and the total likelihood is then the product of the velocity dispersion and lensing likelihoods, where we assume that both the lensing and dynamical models carry equal weight in the final calculation. The resulting ‘best-fitting’ model is then simply the model that minimizes the total

Table 9. Prior distributions for LENSTOOL parameters optimized in the fitting procedure. The priors for Δx and Δy are given in units of arcseconds relative to the centre of the cluster, which is fixed to the position of the BCG. The values in the prior column indicate the lower and upper bounds of the uniform prior assigned to each parameter.

Parameter	Units	Prior
Cluster-scale DM dPIE halo		
Δx	arcsec	(−5, 5)
Δy	arcsec	(−5, 5)
ϵ	–	(0, 0.8)
θ	deg	(0, 180)
r_{core}	kpc	(1, 100)
σ_0	km s ^{−1}	(500, 1000)
BCG dPIE halo		
A383 σ_0	km s ^{−1}	(220, 420)
MS 2137 σ_0	km s ^{−1}	(120, 500)
MACS J0326 σ_0	km s ^{−1}	(100, 350)
MACS J1427 σ_0	km s ^{−1}	(100, 700)
MACS 0949 σ_0	km s ^{−1}	(250, 450)
MACS 0417 σ_0	km s ^{−1}	(350, 600)
Cluster galaxy scaling		
σ_*	km s ^{−1}	(25, 250)
$r_{\text{cut}*}$	kpc	(3, 50)
dPIE haloes of individually optimized galaxies		
ϵ	–	(0, 0.8)
θ	deg	(0, 180)
r_{core}	kpc	(0, 1)
r_{cut}	kpc	(0, 10)
σ_0	km s ^{−1}	(10, 300)
Unknown redshifts		
z	–	(1, 7)

$\chi^2 = \chi_{\text{SL}}^2 + \chi_{\text{VD}}^2$. This treatment of the likelihoods as independent quantities follows previous work done to combine dynamics and lensing models (e.g. Sand et al. 2004, Newman et al. 2013b).

Maximizing the global likelihood function allows us to separate DM and baryons into distinct profiles, as seen in Fig. 7. In doing so, we can compare the DM and baryon profiles (blue and purple/red lines, respectively) to the total mass distribution (black line) to see the relative contributions of each as a function of radius. Each of these profiles possess a core-like structure within the inner 50 kpc. This is perhaps not unexpected, given that all of these clusters have radial arcs, which are preferentially produced in mass distributions with a shallow inner slope. However, the agreement between the shape of the profile for each of these clusters is fairly significant, as it shows that the DM distribution in the centre of the cluster is centrally concentrated.

5.4 Cluster dark matter density profile

We use a dPIE profile to construct the density profile of the DM halo for these clusters. Since we do not use the usual NFW profile, an examination of the properties of the dPIE profile is worth considering.

The obvious test of this profile is to compare it against a ‘non-core’ model. In Newman et al. (2013a), this comparison between a core and non-core model was performed by using a gNFW profile and a ‘cored’ NFW profile, with the cored model being ultimately favoured. In our case, we choose to use dPIE profiles over NFW because we lack weak lensing information for the clusters MACS J1427 and MACS J0326. As shown in Limousin, Beauchesne & Jullo

(2022), weak lensing is crucial for placing reasonable priors on the scale radius of the NFW profile, and without these priors any attempts to use LENSTOOL to create NFW profiles will result in models that are degenerate with their own parameters. As a result, until we are able to perform weak lensing analyses for these clusters and obtain priors on their parameters, the information we derive from NFW fitting will have a low statistical significance. While we can investigate weak lensing modelling, the *HST* data for these clusters are too shallow to perform a meaningful fit to the data (e.g. the number density of background sources is too low). Additionally, the lack of multiple bands makes weak lensing analysis difficult to incorporate as the contamination from foreground and cluster objects will be almost impossible to remove (Jauzac et al. 2012; Niemiec et al. 2023). Since only two of the clusters covered in this work have published weak lensing models (see Newman et al. 2013b; Jauzac et al. 2019; Allingham et al. 2023), we elect not to repeat this analysis, since the available data are the same, and we are not introducing new weak lensing modelling techniques. Additionally, by not using an NFW profile to model the cluster DM profile, we avoid the degeneracy between the scale radius and the asymptotic gNFW profile slope that was demonstrated in He et al. (2020), and do not bias our results toward low slope values as a result of measurement choices in a weak lensing profile. We leave the potential exploration of NFW profiles to future work.

Instead, we choose to create ‘core’ and ‘non-core’ dPIE models following the approach presented in Limousin et al. (2022). We perform this test by restricting the r_{core} radius to be smaller than 10 kpc to create ‘non-cored’ models, and comparing the resulting models against our ‘cored’ dPIE models, where the core radius was left as a free parameter. The results of this experiment are definitive. In each case, the χ^2 value of the ‘non-cored’ model increased significantly in comparison to the cored model. For instance, the ‘cored’ model for MACS J0326 has a χ^2 of 23.4, with an rms of 0.37 arcsec. In comparison, the ‘non-cored’ model has a χ^2 of 179, with an rms of 3.3 arcsec, which indicates that the model is unable to reproduce the observational constraints. This discrepancy is consistent across all six clusters, indicating that ‘non-cored’ models are not favoured as a solution.

6 DISCUSSION

Strong lensing is a powerful tool for examining the inner slope of the DM density profile, which can then be used to compare with, and improve upon the information used to build CDM simulations. The clusters modelled in this paper all have radial arcs, which are uniquely suited for providing more precise constraints in the inner part of the cluster, i.e. near the BCG.

6.1 How rare are radial arcs?

Radial arcs are still relatively uncommon among lenses, both because the geometric requirements for their appearance are so stringent, and then even when they do appear, they can easily be obscured by the light of surrounding galaxies and the BCG (Bartelmann 2010). Visual examination of Fig. 3, for example, would not immediately make the presence of a radial arc obvious; it is only through spectroscopic confirmation that we can definitively say an arc is present and assign it a redshift, which defines its power as a constraint. As a result, building a large sample of clusters with radial arcs is not trivial. The six clusters selected in this paper are chosen from a data set of around 150 MUSE cubes (PID 0104.A-0801; PI A. Edge) from the Kaleidoscope survey, a large ‘filler’ program, and are selected

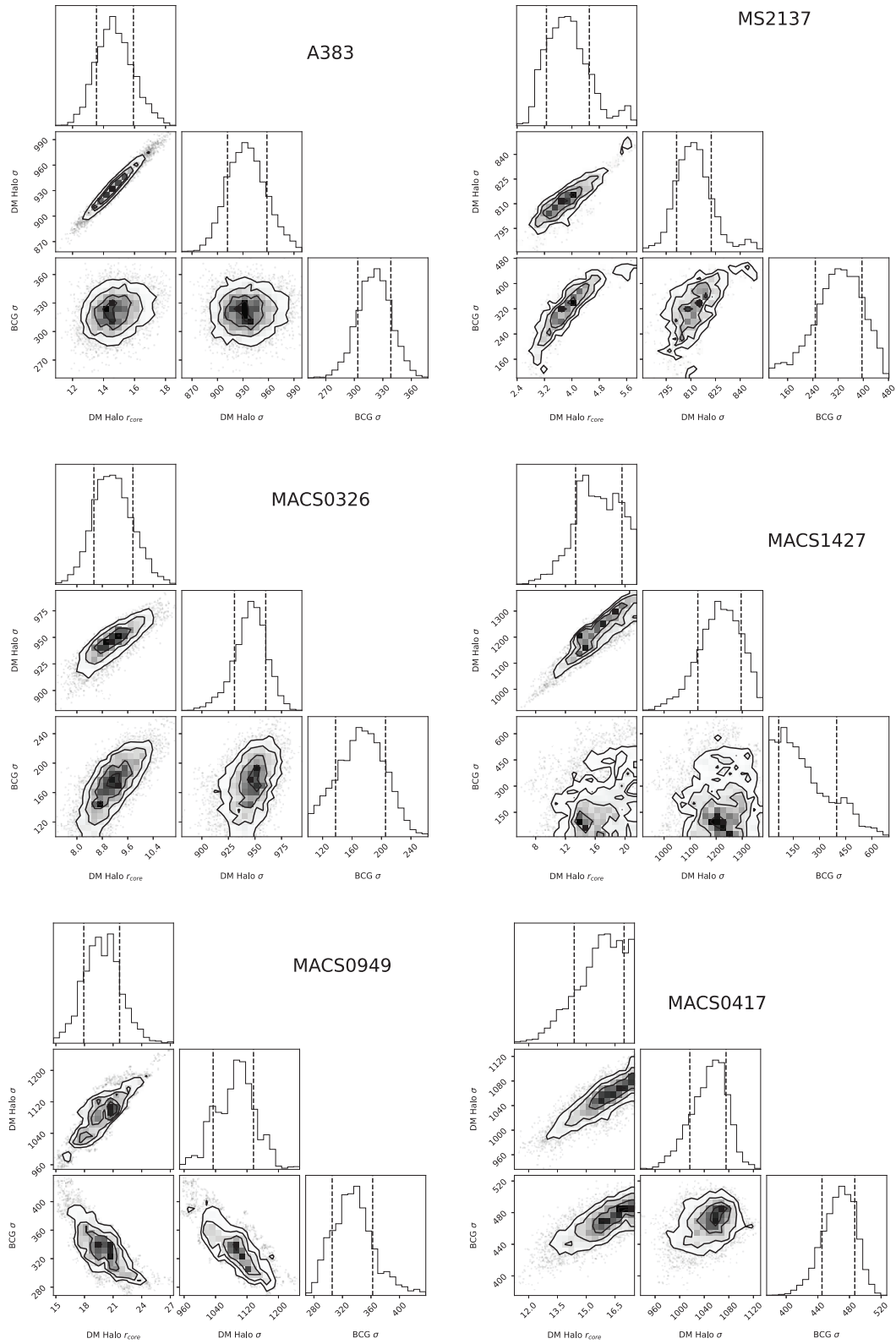


Figure 8. Corner plots of the relevant parameters from the LENSTOOL fitting procedure of the six clusters presented in this chapter. The DM halo of the cluster is denoted as the ‘DM’ halo. The vertical lines mark the 1σ region.

from within that data set specifically for the presence of radial arcs. The ratio of clusters with radial arcs versus clusters without these arcs in the Kaleidoscope sample is around 4 per cent, which easily shows that radial arcs, while a powerful constraint on the inner DM profile, are a very unique physical feature and cannot be relied upon to appear in lensing analyses of cluster mass profiles at scale.

An additional, equally important consideration for the robustness of our measurements is that the model and slope profiles presented in this work exclusively represent clusters that contain radial arcs. This naturally means that all of these clusters are more core-like, as total density distributions steeper than $\rho \propto r^{-2}$ do not produce radial arcs (see Hattori, Kneib & Makino 1999). As a result, we incur another degree of selection bias in our results by excluding systems that might be more cuspy. While we do plan to examine this in the future using other clusters in the Kaleidoscope survey, it is useful to mention what potential impact this bias might have by referring to previous work done by Sand et al. (2004) and Newman et al. (2013a) on A383 and MS2137.

In each of these papers, these two clusters were a part of a larger sample, which included clusters that had tangential arcs but did not have radial arcs. The authors could thus perform a comparison of their results relative to clusters without radial arcs, and the shallowness of the inner DM density profiles for both A383 and MS2137 did not differ significantly from the profiles of clusters with only tangential arcs. These results are encouraging, and we plan to more thoroughly test the robustness of our own sample in future work. In this paper, we present our models as a specific study of density distributions for clusters with radial arcs and shallow IFU spectroscopy, rather than an examination of the general shape of the DM density profile for all clusters. Despite these limitations, however, we are able to obtain measurements for the inner DM slope that are both consistent with previous mass models and are in agreement with other observational measurements from literature, thus demonstrating the strength of using radial arcs as lensing constraints in tandem with MUSE spectroscopy.

6.2 Comparison with previous work

6.2.1 Abell 383

A383 has been modelled numerous times, due to its properties and fortuitous magnification of a background $z \sim 6$ galaxy. The most recent model was created using a combination of strong and weak lensing, and was part of a compilation of models built using the complete sample of CLASH clusters (Zitrin et al. 2015; Z15). The multiple image systems used in Z15 correlate to those used in this paper, with the exception of our system 1, which is a new detection. System 1 in Z15 is associated here with our system 2; and the remaining systems are numbered in accordance to Z15. We note that our system 2 is a combination of Z15 system 1 and system 2, as we treat the tangential arc and the radial arc as the same system based on our MUSE observations.

Systems 1–5 are fixed to spectroscopic redshifts, where systems 1, 2, and 5 are measured from our MUSE spectroscopy, and are identical to the values presented in previous literature, including Z15. Systems 3 and 4 are not detected in our MUSE data. We thus fix these to the redshift $z = 2.55$, a spectroscopic measurement obtained by Newman et al. (2011). The remaining redshifts are derived by our model, and they generally tend to be lower, but within ± 0.5 of the values found by Z15, with one exception. System 8 is a more severe underestimation at a model redshift of $z = 1.746$ compared to a model redshift of $z = 3.1$ from Z15.

Despite the difference in best-fitting redshifts, our mass estimates are generally in agreement. In Z15, the mass enclosed in 100 kpc is $\sim 6 \times 10^{13} M_{\odot}$. In our model, we find that the mass enclosed in the same radius is $\sim 5.5 \pm 0.06 \times 10^{13} M_{\odot}$. The other major model for this cluster that we reference in this paper is from Newman et al. (2013a), which finds an enclosed mass within 100 kpc of $\sim 6 \times 10^{13} M_{\odot}$. Our mass estimate thus matches well with the most recent parametric and light-traces-mass lens models of this cluster.

The error in the mass estimate is larger in the outskirts of the cluster as opposed to the inner regions, consistent with expectations from strong lensing models that are expected to be most accurate in the region enclosed by the critical curve. The total χ^2 error estimate is ~ 54 , as well, which correlates to the mass profile error, and an rms of 0.53 arcsec.

The integrated density profile shown in Fig. 7 is measured by summing the value of all pixels encapsulated within an annulus of width $r(n) - r(n-1)$, where n corresponds to the step number.

6.2.2 MS 2137–23

MS 2137 has similarly been modelled several times since the work by Sand et al. (2008). The most recent model is again from Zitrin et al. (2015). We break system 5, the large tangential arc, into two different pieces in order to improve the resolution of the model. Our systems 3 and 4 correspond to system 1 in Z15. System 2 in Z15 corresponds to our system 5, and system 3 in Z15 corresponds to our system 1. We add one new detection to the model: system 2, which we confirm via MUSE spectroscopy to be at $z = 1.191$. This system corresponds to the second radial arc near the BCG, which had been noted before in photometry but lacked a spectroscopic detection both of itself and of a counter image that would make it viable to include in the lens model.

The most direct comparison we can make between our model and that of Z15 is the mass estimate. Z15 reports a total 2D integrated mass of $M(R < 100 \text{ kpc}) \sim 4 \times 10^{13} M_{\odot}$. A similar estimate of our mass within the same radius yields a value of $3.6 \pm 0.1 \times 10^{13} M_{\odot}$.

The error in the mass profile is relatively small since our model is well constrained by the inclusion of five systems with spectroscopic redshifts, with a total χ^2 error estimate of ~ 40 and an rms of 0.67 arcsec.

6.2.3 MACS J0326.8–0043

This is the first published strong lensing model for MACS J0326, as well as the first mass estimate. Each system used to build the model has a spectroscopic redshift, which contributes to the reduction of overall systematic errors (Johnson et al. 2014). Four multiple images out of the 12 used in the model are predictions made by the model (see Table 3). The redshift used for each system is fixed to the spectroscopic redshift of the arc with the highest S/N ratio, and is constrained to four significant figures. We report a total integrated mass of $M(R < 100 \text{ kpc}) \sim 6 \times 10^{13} M_{\odot}$. The χ^2 value found for the model is 28.44, while the overall rms in the image plane is 0.77 arcsec. The largest contributors to the rms are images 1.1 and 2.4, which are predicted images. Because the model is constructed using only two shallow *HST* bands (each band has a short exposure time of 500 s; see Table 1), it is somewhat difficult to do the usual colour and morphology comparison typically used to identify other strongly lensed galaxies. As a result, the positions of the predicted images are merely predictions, and are subject to change if deeper spectroscopic or photometric observations are acquired for this cluster.

6.2.4 MACS J1427.6–2521

This is the first published strong lensing model for MACS J1427, and is also the first examination of this cluster in the visual band. However, it was discussed in Ebeling et al. (2010) as a part of a survey of X-ray bright clusters from the MACS survey using *Chandra* data. The *HST* data used for the cluster are archival, and was observed as part of a SNAP project (PID 12884; PI: Harald Ebeling). Although only one *HST* band makes it difficult to identify multiple images based on the usual criteria of colour and morphology, using it as a spatial reference alongside the MUSE redshifts makes it possible to create a basic lens model for the cluster. We report a total integrated mass of $M(R < 100 \text{ kpc}) \sim 8 \times 10^{13} M_{\odot}$. We obtain a total χ^2 of ~ 43 with an rms of 0.81 arcsec. Better quality imaging will almost certainly change the details of the model, but the current iteration still provides valuable information about the general shape of the mass in the cluster. Because the goal of this paper is to present lens models constructed mostly based on MUSE data, it is outside the scope of the current work to perform a thorough comparison of the mass profile against the existing *Chandra* data used in Ebeling et al. (2010) for this cluster. However, deeper *HST* imaging and a subsequently improved lens model would make such a comparison more robust, and is thus left for future work.

6.2.5 MACS J0417

The lens model used for this cluster is identical to that presented in J19. There are two BCGs in this cluster, but only the southern one has a radial arc. In J19, both BCGs are separately parametrized with individual dPIE haloes. In this work, we fix the parameters of the southern BCG to the properties we derive from our photometric measurements (see Table 7). The second change we make from the J19 model is to impose an additional selection criterion on the best-fitting model from MCMC chain through our kinematic constraints. The resulting model does not differ strongly from J19 in the overall mass distribution. The reduced χ^2 for the model in this paper is ~ 0.91 , compared to ~ 0.9 from J19, and the rms is 0.41 arcsec, compared to 0.38 arcsec from J19. Furthermore, the enclosed mass within 200 kpc is measured to be $1.8 \pm 0.04 \times 10^{14} M_{\odot}$, which is in agreement with the measurement from J19 from $1.78 \times 10^{14} M_{\odot}$. This also indicates that the model is in agreement with Mahler et al. (2019), which has similar values for the mass, rms, and χ^2 . The main change is in the value of the inner density slope, which we discuss more in Section 6.3. In the lensing only model, this value is $\gamma \sim 0.55$, whereas in the lensing and BCG kinematics model the slope is $\gamma \sim 0.6$. These values still fall within the full width at half-maximum of the probability distribution function (PDF), however.

6.2.6 MACS J0949

The lens model for this cluster is identical to that presented in Allingham et al. (2023). The authors use a separate parametrization of the BCG as well, so the only change we make to the model is to fix these parameters to the properties we derive from our photometric measurements (see Table 7). The enclosed mass within 200 kpc found by Allingham et al. is $2.0 \times 10^{14} M_{\odot}$, while the model in this paper finds a value of $2.1 \pm 0.07 \times 10^{14} M_{\odot}$ in the same radius. Allingham et al. find a χ^2 of 4.71 with an rms of 0.15 arcsec, while the kinematic model we use finds a χ^2 of 8.4 with an rms of 0.3 arcsec. The model could likely be improved with a finer resolution of bins inside the MUSE cube for our measured velocity dispersions.

6.3 Inner dark matter density profile

While strong lensing models measure the total density near the critical curves, lensing alone cannot independently distinguish between the contributions of baryonic and DM. Breaking this degeneracy is crucial to understanding the physics occurring at the centre of these clusters. To that end, we introduce stellar kinematics into the model to constrain the effect of the baryonic mass of the BCG on the overall density distribution. We restrict our analysis to the kinematics of the BCG exclusively, as this is by far the most dominant stellar component in this region. Following the procedure laid out in Newman et al. (2013b), we measure the inner slope $\gamma = -d \log \rho_{\text{DM}} / d \log r$ over the range $r/r_{200} = 0.003 - 0.03$, which roughly corresponds to a range of 5–50 kpc.

We select these boundaries because the profile is strongly dominated by baryonic mass within 5 kpc, so the profile will always increase sharply within this region and is thus not a good indication of the shape of the DM density profile (see Newman et al. 2013b), and outside of 50 kpc, the profile is dominated by DM (e.g. Fig. 7). The intermingling between baryonic and DM is thus best probed in the interior of this region. The resulting measurements of the slope of the lens models within this range are shown in two ways in Fig. 9. The primary results used in this work to estimate the slope measurements are plotted in the top portion of this figure, which shows the inner slope as measured from the total mass density of the lens model with the stellar component of the BCG subtracted. We choose to use this method to measure the inner slope because directly measuring the slope from the parametrized cluster-scale dPIE halo leads to results that may be misleading. The bottom component of Fig. 9 shows the measurement of the inner slope across the same range using the DM halo. The resulting slope values are almost universally cored. This correlates with the results presented in Fig. 7, which show near-universally flat dPIE haloes in all six clusters. However, the shape of the dPIE halo does not begin to match the total mass density profile until after roughly 20–30 kpc, which is the cut-off threshold for the region where the BCG stellar mass should dominate. The measurements of the cluster-scale DM halo within the lens model are thus not necessarily a good reflection of the actual shape of the DM in the centre of the cluster, especially because additional mass components that are not explicitly constrained within the lens model may be affecting the shape of the mass profile, such as intracluster light. As a result, rather than assuming that the cluster-scale DM halo represents the ‘true’ distribution of DM in the cluster, we use the total mass obtained from the strong lensing models, which is a good measurement of the mass of the cluster regardless of the state of the individual components that make up that mass distribution, and subtract the mass of the BCG, which we explicitly parametrize using the photometric and kinematic measurements described in this work, to obtain the inner slope measurements we report for each of these clusters. The overall results suggest that each of these profiles is very cored, with an average slope measurement of $\gamma \sim 0.66$ for all six clusters. Of all six clusters, MACS J1427 is the most poorly constrained, and could benefit the most from additional observations. However, its probability density is still centred firmly below 1.0, which suggests that it is more likely to be a cored cluster than a cuspy cluster.

These results, when taken in aggregate, demonstrate that clusters with radial arcs tend to present core-like density profiles. This is in-line with our current physical understanding of lensing, which requires the geometric shape of the mass distribution needed to produce radial arcs to be more core-like.

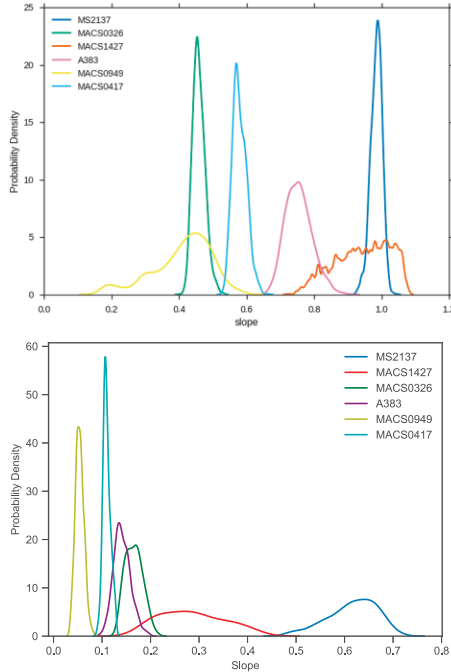


Figure 9. Top: density probability distribution for the slope measurements in all six clusters, as calculated from the slope of the total mass density profile with the slope of the BCG subtracted. The probability density is calculated from the MCMC chain run for each model and is based on the derived parameters for the cluster DM halo. Bottom: density distribution for the slope of the parametrized dPIE cluster-scale DM halo in each cluster.

7 CONCLUSIONS AND SUMMARY

We select four clusters with radial arcs from a total sample of 150 clusters observed with MUSE, and construct strong lensing models for these clusters, using at least two systems with spectroscopic redshifts from MUSE in each model. The radial arcs impose an additional constraint on the mass distribution near the centre of the cluster, enabling a more precise examination of the inner density profiles for these clusters than is typical of strong lensing, as the relative scarcity of radial arcs means that these profiles are usually extrapolated into the inner region of the cluster. We add another two clusters with radial arcs that have already been modelled to our sample, for a total of six clusters with radial arcs. We note that radial arcs are preferentially produced in mass distributions with a shallow inner slope, and each of these clusters has a demonstrably shallow slope measurement regardless of whether photometric and kinematic measurements of the BCG are incorporated into the lensing model; however, including a central kinematic probe reduces systematics of the model.

We additionally utilize stellar kinematics from the BCG to impose further constraints on the inner density profile following the methods used in Newman et al. (2013b). This allows us to constrain the contribution of the baryonic mass to the overall cluster density profile. We obtain a mean DM slope value of $\gamma \sim 0.66$ for all clusters, which is higher but generally consistent with the measurements from N13 ($\gamma \sim 0.5$). Fig. 10 places our results into context with several other observational papers, as well as with the results from the C-EAGLE simulations in He et al. (2020). Of the five additional observational papers presented in the figure, N13 and Sand et al. (2004) follow the methods presented in this paper to obtain their slope measurements. Annunziatella et al. (2017) use a blend of X-ray, strong lensing, and

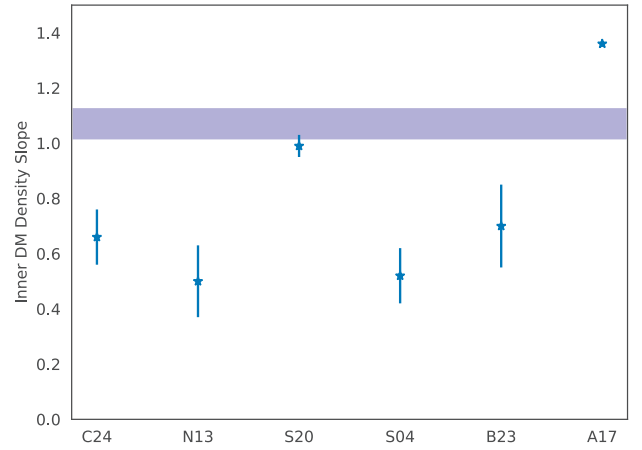


Figure 10. The average inner DM density slope as measured from five different papers, plotted from left to right as: this work (an average of six clusters), N13 (an average of seven clusters), Sartoris et al. (2020) (Abell 1063), Sand et al. (2004) (an average of four clusters), Biviano et al. (2023) (MACS J1206.2 – 0847), and Annunziatella et al. (2017) (MACS J0416 – 2403). The expected slope measurement from the C-EAGLE simulations as reported in He et al. (2020) is plotted as the blue shaded region.

BCG kinematics to obtain their measurement, although they assume a single power-law mass profile, which may overestimate the inner slope if the 3D mass profile steepens with radius. Sartoris et al. (2020) and Biviano et al. (2023) exclusively use cluster member kinematics to obtain their slope measurements. These disparate values and techniques clearly show the observational tension currently facing this measurement.

These results were typically obtained with shallow exposure times and in below-average observational conditions, which demonstrates that these techniques can be used to gain a general understanding of the shape of cluster density profiles without the need for deeper, more observationally constrained *HST* or spectroscopic data. However, we emphasize that our models and results can only improve with the addition of these types of data, and while the overall shape of our profiles should not change drastically, the overall measurements we obtain may shift. This can be seen in the difference of the work performed in Sand et al. and N13. In Sand et al., the authors derive a mean slope value of 0.5 for A383 and MS2137 using archival *HST* imaging and spectroscopy from Keck, whereas in N13, which used deeper *HST* images at a better wavelength for kinematic analysis, and deeper spectroscopy from Keck, the mean slope value for these two clusters is closer to 0.85. This shift is an example of the sort of change that we may expect to see if our models are ever redone in the future with, in particular, deeper observational data, which will allow for more reliable identification of multiply imaged systems.

Future work on this subject will make use of the techniques employed in this paper, applied on other galaxy clusters from the Kaleidoscope survey. Further analysis will include clusters without radial arcs and will exploit the Kaleidoscope sample to fully benefit from the uniform depth and selection of clusters that characterizes the survey.

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DATA AVAILABILITY

All *HST* data used for this work are available on the MAST archive. All VLT/MUSE data used for this work are available on the ESO Science Archive. The lensing mass models and other data products will be shared by the authors upon request.

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APPENDIX: LENS MODEL PROPERTIES AND MUSE CATALOGUE

Table A1. Parameters for the best-fitting lens model of A383. Error bars correspond to 1σ confidence level as inferred from the MCMC optimization. The parameters are provided for the cluster dark matter halo (dPIE DMH), the BCG halo (dPIE BCG), and each of the galaxy-scale perturbers included in the model (perturbers 1–3). ΔRA and $\Delta\text{Dec.}$ are defined in relation to the BCG, located at $\text{RA} = 2:48:03.37$ and $\text{Dec.} = -3:31:45.29$. Position angles are measured north of west, and the ellipticity ϵ is defined as $(a^2 - b^2)/(a^2 + b^2)$. r_{cut} is fixed to 1000 kpc for the cluster DM halo.

Object	ΔRA (arcsec)	$\Delta\text{Dec.}$ (arcsec)	ϵ	θ ($^\circ$)	r_{core} (arcsec)	r_{cut} (arcsec)	σ (km s $^{-1}$)
dPIE DMH	0.43	2.26	0.17	106.66	50.80	1000.	878.22
dPIE BCG	0	0	–	–	–	–	325.59
Perturber 1	14.69	–16.10	0.79	96.31	0.31	5.89	189.58
Perturber 2	–0.17	–23.49	0.37	139.62	0.89	5.00	139.13
Perturber 3	3.27	–20.82	0.77	92.84	0.81	2.00	290.66

Table A2. Parameters for the best-fitting lens model of MS 2137. Error bars correspond to 1σ confidence level as inferred from the MCMC optimization. The parameters are provided for the cluster dark matter halo (dPIE DMH) and the BCG halo (dPIE BCG). ΔRA and $\Delta\text{Dec.}$ are defined in relation to the centre of the BCG, located at $\text{RA}=21:40:15.16$ and $\text{Dec.} = -23:39:40.09$. Position angles are measured north of west, and the ellipticity ϵ is defined as $(a^2 - b^2)/(a^2 + b^2)$. r_{cut} is fixed to 1000 kpc for the cluster DM halo.

Object	ΔRA (arcsec)	$\Delta\text{Dec.}$ (arcsec)	ϵ	θ ($^\circ$)	r_{core} (arcsec)	r_{cut} (arcsec)	σ (km s $^{-1}$)
dPIE DMH	0.24	0.012	0.35	148.77	13.51	1000.	784.81
dPIE BCG	–9.53	14.13	–	–	–	–	250.3

Table A3. Parameters for the best-fitting lens model of MACS J0326. Error bars correspond to 1σ confidence level as inferred from the MCMC optimization. The parameters are provided for the cluster dark matter halo (dPIE DMH) and the BCG halo (dPIE BCG). ΔRA and $\Delta\text{Dec.}$ are defined in relation to the centre of the BCG, located at $\text{RA}=3:26:49.96$ and $\text{Dec.} = -0:43:51.47$. Position angles are measured north of west, and the ellipticity ϵ is defined as $(a^2 - b^2)/(a^2 + b^2)$. r_{cut} is fixed to 1000 kpc for the cluster DM halo.

Object	ΔRA (arcsec)	$\Delta\text{Dec.}$ (arcsec)	ϵ	θ ($^\circ$)	r_{core} (arcsec)	r_{cut} (arcsec)	σ (km s $^{-1}$)
dPIE DMH	–0.92	–0.75	0.23	134.57	42.17	1000.	924.55
dPIE BCG	17.56	–20.75	–	–	–	–	189.44

Table A4. Parameters for the best-fitting lens model of MACS J1427. Error bars correspond to 1σ confidence level as inferred from the MCMC optimization. The parameters are provided for the cluster dark matter halo (dPIE DMH) and the BCG halo (dPIE BCG). ΔRA and $\Delta\text{Dec.}$ are defined in relation to the centre of the BCG, located at $\text{RA} = 21:40:15.16$ and $\text{Dec.} = -23:39:40.09$. Position angles are measured north of west, and the ellipticity ϵ is defined as $(a^2 - b^2)/(a^2 + b^2)$. r_{cut} is fixed to 1000 kpc for Halo 1.

Object	ΔRA (arcsec)	$\Delta\text{Dec.}$ (arcsec)	ϵ	θ ($^\circ$)	r_{core} (arcsec)	r_{cut} (arcsec)	σ (km s $^{-1}$)
dPIE DMH	0.24	0.012	0.35	148.77	13.51	1000.	784.81
dPIE BCG	0	-0.018	-	-	-	-	277.92

Table A5. Statistical values derived from the MCMC fitting for the models of each cluster presented in Section 3. The columns show the likelihood, $\log L$; the rms deviation from the predicted positions of the multiple images from their observed positions in the image plane, rms, and the reduced χ^2 .

Cluster	$\log L$	rms	χ^2
A383	18.73	0.61	35.76
MS2137	16.01	0.70	14.22
MACS J0326	11.05	0.85	23.08
MACS J1427	7.41	0.61	0.83
MACSJ0417	47.66	0.49	44.29
MACSJ0949	80.17	0.41	17.58

Table A6. Measured redshifts in A383.

ID	RA	Dec.	z	QF
1	42.01870947	-3.53513970	0.196	3
3	42.01413524	-3.53591378	0.195	3
4	42.00714291	-3.53595815	0.412	3
7	42.00745227	-3.53755278	0.960	3
11	42.01410348	-3.52926656	0.188	3
18	42.15254730	-3.53287324	1.010	3
50	42.02032160	-3.53682543	1.011	3
57	42.01432510	-3.52883110	1.011	3
61	42.00947290	-3.52844810	4.633	3
70	42.01179557	-3.53284732	1.009	3
79	42.01001298	-3.53386725	1.505	3
80	42.01003680	-3.53068700	4.634	3
83	42.01280980	-3.52573640	4.636	3
180	42.00583728	-3.53475354	0.928	3
208	42.01527605	-3.53287594	0.190	3
242	42.00980114	-3.53086269	1.010	3
313	42.02047584	-3.53382125	1.092	3
394	42.01915633	-3.53195987	0.373	3
410	42.01286378	-3.53353040	1.010	3
451	42.00810054	-3.53202013	0.186	3
493	42.01919295	-3.53294806	6.031	3
501	42.01157428	-3.52974105	0.186	3
737	42.00958438	-3.53049744	1.010	3
786	42.01923866	-3.52626206	0.194	3
1007	42.01156363	-3.52457326	0.656	3
1014	42.01560756	-3.52639592	0.190	3
1103	42.01513734	-3.52105068	0.195	3
1150	42.02093902	-3.52339690	0.890	3
1183	42.01893922	-3.52259989	0.094	3
1353	42.01953604	-3.52455550	0.937	3
1482	42.01180784	-3.52436324	0.656	3
1578	42.01363994	-3.52635524	6.032	3
:	:	:	:	:
:	:	:	:	:
:	:	:	:	:
:	:	:	:	:
1601	42.02098120	-3.52583488	0.824	3
1741	42.01678438	-3.52648827	0.373	3
17	42.01396670	-3.53270560	0.279	2
135	42.02019771	-3.53514563	0.137	2
154	42.01317449	-3.53516389	0.191	2
329	42.00860414	-3.53278628	0.188	2
570	42.00709600	-3.53079003	0.764	2
584	42.02237334	-3.53141806	0.182	2
1141	42.00768973	-3.52797491	1.276	2
1223	42.02037639	-3.52286060	0.186	2

Table A6 – continued

ID	RA	Dec.	z	QF
1377	42.01522849	−3.52388490	0.000	2
1407	42.00603086	−3.52378361	4.943	2
1531	42.01179860	−3.52578326	0.188	2
1582	42.01767138	−3.52618242	0.191	2
1953	42.01700107	−3.52165509	0.593	2
5	42.01549764	−3.53712308	0.189	1
77	42.01967533	−3.53680155	0.187	1
82	42.01976480	−3.52540490	6.259	1
110	42.01184380	−3.53511810	2.681	1
112	42.02161230	−3.52512230	5.033	1
262	42.01449268	−3.53497007	0.000	1
270	42.01340539	−3.53364156	0.159	1
316	42.00696144	−3.53265637	0.185	1
457	42.02281348	−3.53305797	0.000	1
746	42.00876902	−3.52981517	0.195	1
793	42.00807525	−3.52938858	0.183	1
859	42.01083523	−3.52946545	0.187	1
914	42.00876656	−3.52927118	1.559	1
988	42.01139524	−3.52879504	0.187	1
996	42.01737083	−3.52816428	1.580	1
1526	42.01010281	−3.52584537	0.192	1
1923	42.01348284	−3.52118876	0.184	1

Notes. Column 1 is the ID of the source. Columns 2 and 3 are the RA and Dec. in degrees (J2000). Column 4 is the redshift of the source. Column 5 is the quality flag (QF) assigned to the redshift. The QF scales in quality from largest to smallest; a flag value of 3 indicates that we have high confidence in the value for the redshift, whereas a flag value of 1 indicates that we have low confidence in the value for the redshift.

Table A7. Measured redshifts in MS 2137.

ID	RA	Dec.	z	QF
2	325.0612502	−23.66751981	0.163	3
8	325.0629407	−23.65686360	1.495	3
51	325.0591929	−23.66169910	1.494	3
90	325.0650339	−23.66763583	1.496	3
93	325.0587208	−23.66655827	−4.0E-5	3
143	325.0631642	−23.66114100	0.314	3
265	325.0658341	−23.66693218	1.191	3
305	325.0600151	−23.66525997	0.317	3
432	325.0624174	−23.65700482	1.495	3
554	325.0717926	−23.66225558	0.539	3
557	325.0554316	−23.65875178	0.974	3
564	325.0658002	−23.66232491	0.123	3
575	325.0652998	−23.66272321	3.086	3
579	325.0659165	−23.65859792	0.313	3
594	325.0660545	−23.65719416	0.323	3
717	325.0626655	−23.66044969	0.313	3
796	325.0625407	−23.66026792	0.313	3
804	325.0608755	−23.65919716	0.314	3
899	325.0603961	−23.65473848	1.265	3
978	325.0641418	−23.65707151	1.495	3
982	325.0655182	−23.65546970	0.311	3
984	325.0577362	−23.65544930	0.313	3
1022	325.0573735	−23.65524711	3.086	3
1047	325.0631649	−23.65676262	1.495	3
1085	325.0646960	−23.65727918	1.495	3
1098	325.0681213	−23.65712822	0.317	3
1213	325.0627779	−23.65956801	1.191	3
1437	325.0607713	−23.65322025	0.317	3
1467	325.0555769	−23.65364726	0.281	3
1477	325.0710864	−23.65315590	0.315	3
⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮
263	325.0614965	−23.66630868	0.000	2
290	325.0612886	−23.66452073	0.316	2
307	325.0596807	−23.66552547	0.314	2
616	325.0577885	−23.66006395	0.315	2
689	325.0631461	−23.65977012	1.496	2
1129	325.0649292	−23.65706087	1.492	2
1	325.0557350	−23.66728671	0.999	1
4	325.0613087	−23.66945031	0.310	1
63	325.0581008	−23.65941150	5.509	1
69	325.0639614	−23.66911864	0.000	1
166	325.0574263	−23.66726300	0.281	1
221	325.0605980	−23.66653599	0.328	1
224	325.0592894	−23.66707065	1.543	1
242	325.0622637	−23.66447865	0.323	1
269	325.0616751	−23.66637744	2.459	1
299	325.0544046	−23.66521798	0.222	1
318	325.0596921	−23.66584184	0.000	1
431	325.0621176	−23.66431571	0.639	1
503	325.0536364	−23.66107318	0.316	1
580	325.0633467	−23.66185286	0.316	1
644	325.0648793	−23.66182589	0.937	1
654	325.0642144	−23.66216598	0.000	1
657	325.0602975	−23.66170037	0.000	1

Table A7 – *continued*

ID	RA	Dec.	z	QF
805	325.0543628	−23.66046275	0.311	1
814	325.0653077	−23.66082818	2.744	1
868	325.0544333	−23.66021964	0.000	1
869	325.0580939	−23.66019602	0.318	1
1128	325.0631522	−23.65935947	1.496	1
1261	325.0699090	−23.65869802	0.000	1
1389	325.0630390	−23.66044158	0.000	1

Notes. Column 1 is the ID of the source. Columns 2 and 3 are the RA and Dec. in degrees (J2000). Column 4 is the redshift of the source. Column 5 is the quality flag (QF) assigned to the redshift. The QF scales in quality from largest to smallest; a flag value of 3 indicates that we have high confidence in the value for the redshift, whereas a flag value of 1 indicates that we have low confidence in the value for the redshift.

Table A8. Measured redshifts in MACS J0326.

ID	RA	Dec.	z	QF
1	51.70806634	−0.73727226	0.440	3
13	51.70810324	−0.73102918	0.448	3
15	51.71595908	−0.72429963	0.058	3
16	51.71636815	−0.73054060	1.431	3
18	51.70415754	−0.72469514	0.000	3
20	51.71355394	−0.72488020	1.247	3
21	51.71485312	−0.72508425	0.449	3
26	51.70869202	−0.72576593	0.447	3
29	51.70178080	−0.73721435	1.179	3
32	51.70734694	−0.72652196	0.443	3
37	51.70639179	−0.72749385	0.453	3
42	51.71263975	−0.72735037	0.452	3
46	51.70401058	−0.72803930	0.438	3
50	51.71014411	−0.72838957	0.449	3
52	51.70845413	−0.72881622	0.000	3
54	51.70380841	−0.72941315	1.248	3
55	51.70662959	−0.72941321	0.232	3
57	51.71376910	−0.72767990	0.776	3
61	51.70590437	−0.73047397	0.446	3
62	51.70549223	−0.73047924	1.248	3
68	51.71396070	−0.73078547	0.458	3
69	51.71124680	−0.73372370	0.494	3
74	51.70481740	−0.73595180	5.880	3
76	51.71123314	−0.73155115	0.455	3
78 _M	51.70655724	−0.73162210	0.000	3
78 _P	51.70691830	−0.72437400	4.980	3
81	51.71233054	−0.73199644	1.098	3
84	51.70674370	−0.73699870	5.879	3
86	51.70180090	−0.73108310	5.878	3
88	51.71547523	−0.73306727	0.356	3
103	51.71046650	−0.73443810	1.248	3
108	51.70190169	−0.73491512	0.448	3
⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮
113	51.71150751	−0.73442642	0.446	3

Table A8 – *continued*

ID	RA	Dec.	z	QF
116	51.71221832	−0.73567774	0.804	3
121	51.7005703	−0.73653835	0.444	3
122	51.70323641	−0.73677771	0.325	3
138	51.70211192	−0.73705436	1.272	3
139	51.71652064	−0.73709426	0.804	3
152	51.70378826	−0.73798640	1.181	3
160	51.71135863	−0.72256970	0.453	3
161	51.71602364	−0.72303510	0.441	3
5	51.71293750	−0.72474400	1.145	2
23	51.70883990	−0.73340260	0.248	2
34	51.70202020	−0.72244300	4.788	2
39	51.70925786	−0.72748144	0.455	2
41	51.71549023	−0.72772794	0.458	2
44	51.71477132	−0.72779148	3.235	2
60	51.70565583	−0.73065953	0.453	2
85	51.70532607	−0.73234988	3.755	2
94	51.70138800	−0.73333498	0.414	2
155	51.70649017	−0.73827485	0.450	2
17	51.70943969	−0.72450109	0.447	1
35	51.71171314	−0.72674022	1.248	1
47	51.70971234	−0.72803052	0.452	1
53	51.70219623	−0.72919887	0.440	1
62	51.70046960	−0.72423605	4.012	1
68	51.70504950	−0.72801140	3.755	1
77	51.70667121	−0.73145698	0.000	1
86	51.70681907	−0.73258985	0.443	1
87	51.71079159	−0.73274959	0.434	1
90	51.70686528	−0.73301888	0.446	1
105	51.70739184	−0.73472983	0.448	1
118	51.70982389	−0.73588872	0.436	1
145	51.70424116	−0.73770541	0.441	1

Notes. Column 1 is the ID of the source. Columns 2 and 3 are the RA and Dec. in degrees (J2000). Column 4 is the redshift of the source. Column 5 is the quality flag (QF) assigned to the redshift. The QF scales in quality from largest to smallest; a flag value of 3 indicates that we have high confidence in the value for the redshift, whereas a flag value of 1 indicates that we have low confidence in the value for the redshift.

Table A9. Measured redshifts in MACS J1427.

ID	RA	Dec.	z	QF
25	216.91619884	−25.35766428	0.317	3
26	216.92217694	−25.35378681	0.000	3
31	216.90642465	−25.35723329	1.236	3
32	216.91803386	−25.35737324	0.000	3
36	216.92494939	−25.35576190	0.232	3
40	216.91399381	−25.35600037	0.325	3
41	216.91008760	−25.35561308	0.313	3
42	216.91088341	−25.35678064	0.883	3
50	216.91485845	−25.35028410	0.884	3
54	216.91193940	−25.35514541	0.319	3
64	216.91063525	−25.35363405	1.236	3
75	216.91544327	−25.34620637	0.662	3
84	216.91035987	−25.34988187	0.309	3
88	216.91447505	−25.35061860	0.318	3
93	216.91584053	−25.35056782	0.312	3
94	216.91691114	−25.35060176	0.319	3
99	216.91571850	−25.35135379	0.000	3
101	216.92028056	−25.35105752	0.320	3
108	216.91500246	−25.35168478	0.313	3
114	216.91434723	−25.35196763	0.207	3
117	216.91959666	−25.35234976	0.321	3
118	216.91229301	−25.35263420	0.325	3
122	216.91602417	−25.35293113	0.322	3
131	216.91432235	−25.35339907	0.313	3
132	216.91465475	−25.35352760	0.001	3
133	216.91264386	−25.35362011	0.883	3
148	216.91775549	−25.35420614	0.312	3
156	216.90745832	−25.35435398	4.323	3
162	216.90934813	−25.35488005	0.324	3
167	216.90690018	−25.35510802	0.313	3
180	216.90829896	−25.35540450	0.914	3
191	216.91571984	−25.34906701	0.317	3
193	216.90811293	−25.34955274	0.328	3
195	216.91512646	−25.34888806	0.316	3
196	216.91563524	−25.34970724	0.316	3
207	216.91835520	−25.34833384	0.325	3
217	216.92013294	−25.34813976	0.320	3
219	216.90701865	−25.34757320	0.695	3
225	216.90930004	−25.34377121	0.322	3
226	216.91207270	−25.34651632	0.663	3
234	216.90966217	−25.34486568	0.856	3
⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮
241	216.92268855	−25.34577380	0.322	3
251	216.91990633	−25.34613558	1.239	3
1	216.91549900	−25.35909370	0.232	2

Table A9 – *continued*

ID	RA	Dec.	z	QF
56	216.91033590	−25.35151940	0.813	2
68	216.91654650	−25.35620440	6.043	2
72	216.91702200	−25.35768770	3.961	2
73	216.91282910	−25.34527350	6.042	2
81	216.92296584	−25.34974507	0.000	2
96	216.91911505	−25.35069157	0.780	2
102	216.92348540	−25.35112651	0.437	2
103	216.90951026	−25.35120070	0.315	2
138	216.92258186	−25.34430751	1.119	2
199	216.91479272	−25.34911416	0.000	2
218	216.90615033	−25.34387282	0.915	2
220	216.91306431	−25.34663774	0.315	2
2	216.90763630	−25.35900540	0.326	1
22	216.91948152	−25.35840617	0.346	1
34	216.91844686	−25.35742171	2.055	1
35	216.91288324	−25.35744786	0.321	1
53	216.92419220	−25.35758180	3.711	1
57	216.91773293	−25.35578650	0.347	1
58	216.91795080	−25.34248430	5.987	1
74	216.92431599	−25.35543093	0.231	1
77	216.91119860	−25.34467890	4.474	1
121	216.91576496	−25.35285091	1.381	1
140	216.90804218	−25.35371079	0.907	1
141	216.91940086	−25.35381755	0.309	1
144	216.91105772	−25.35395397	0.398	1
164	216.92323652	−25.35479505	0.317	1
169	216.92067451	−25.35487997	0.575	1
170	216.91419559	−25.34846838	4.019	1
172	216.90966979	−25.35508015	0.318	1
173	216.92047912	−25.35515232	0.575	1
176	216.90934137	−25.35527508	0.328	1
185	216.90949896	−25.34656741	1.208	1
201	216.91901817	−25.34852172	1.040	1
208	216.91808783	−25.34834611	3.349	1
213	216.90558929	−25.34828333	0.913	1
232	216.90673382	−25.34649694	0.783	1
248	216.91130553	−25.34609367	0.327	1
254	216.91156687	−25.34619676	0.319	1

Notes. Column 1 is the ID of the source. Columns 2 and 3 are the RA and Dec. in degrees (J2000). Column 4 is the redshift of the source. Column 5 is the quality flag (QF) assigned to the redshift. The QF scales in quality from largest to smallest; a flag value of 3 indicates that we have high confidence in the value for the redshift, whereas a flag value of 1 indicates that we have low confidence in the value for the redshift.

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