

The KALEIDOSCOPE survey: a new strong and weak gravitational lensing view of the massive galaxy cluster MACS J1423.8+2404

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Accepted 2024 September 2. Received 2024 August 14; in original form 2024 May 3

ABSTRACT

We present a combined strong and weak gravitational-lensing analysis of the massive galaxy cluster MACS J1423.8+2404 ($z = 0.545$, MACSJ1423 hereafter), one of the most dynamically relaxed and massive cool-core clusters discovered in the Massive Cluster Survey at $z > 0.5$. We combine high-resolution imaging from the *Hubble Space Telescope* (*HST*) in the *F606W*, *F814W*, and *F160W* pass-bands with spectroscopic observations taken as part of the KALEIDOSCOPE survey with the Multi-Unit Spectroscopic Explorer mounted on the Very Large Telescope. Our strong lensing analysis of the mass distribution in the cluster core is constrained by four multiple-image systems (17 individual images) within redshift range $1.779 < z < 2.840$. Our weak lensing analysis of the cluster outskirts, confined to the *HST* field of view, is based on a background galaxy catalogue with a density of $57 \text{ gal arcmin}^{-2}$. We measure a projected mass of $M(R < 200 \text{ kpc}) = (1.6 \pm 0.05) \times 10^{14} M_{\odot}$ from our strong lensing model, and a projected mass of $M(R < 640 \text{ kpc}) = (6.6 \pm 0.6) \times 10^{14} M_{\odot}$ when combining with our the weak lensing constraints. Our analysis of the cluster mass distribution yields no evidence of substructures, confirming the dynamically relaxed state of MACSJ1423. Our work sets the stage for future analysis of MACSJ1423 in the upcoming Canadian Near-Infrared Imager and Stiltless Spectrograph Unbiased Cluster Survey for the *JWST*.

Key words: gravitational lensing: strong – gravitational lensing: weak – galaxy: clusters – dark matter.

1 INTRODUCTION

In the Λ cold dark matter (Λ CDM) cosmological concordance model, where the mass of the Universe is dominated by dark matter, structures form hierarchically. As predicted by the standard model of cosmology (Klypin & Shandarin 1983), the anisotropic collapse of matter on large scales gives rise to large-scale web-like structures known as the cosmic web (Bond, Kofman & Pogosyan 1996; Parkinson et al. 2012; Kilbinger et al. 2013). Overall, the cosmic web is a complex distribution consisting of walls, filaments, nodes, and voids. The web itself contains nearly all matter in the Universe, with the majority (both baryonic and dark) residing along the filaments and these nodes.

Galaxy clusters are the most massive observable objects in our Universe. They form through the accretion of matter from their

surroundings and mergers with smaller galaxy groups and clusters. They reside at the intersection of filaments that funnel matter on to them, and are thus called nodes of the cosmic web (Springel, Frenk & White 2006). Characterized by extreme masses and dynamical environments, galaxy clusters represent one of the best laboratories to study dark matter and constrain cosmology (Kratochvil, Haiman & May 2010; Applegate et al. 2014; Kelly et al. 2014; von der Linden et al. 2014; Mantz et al. 2015, 2016c; Jauzac et al. 2016, 2018; Hofmann et al. 2017; Schwinn et al. 2017, 2018; Grandis et al. 2019; Robertson et al. 2019; Shirasaki, Lau & Nagai 2020; Chiu et al. 2023; Lyskova et al. 2023).

So far, dark matter has eluded direct detection, and identifying its nature and key properties remains one of the biggest challenges of modern astrophysics and cosmology. While direct detection is an ongoing objective for particle physicists, astronomers have managed to indirectly observe it through gravitational lensing, i.e. the distortion of the light emitted from a background object by an

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intervening mass concentration acting as the lens, such as a galaxy cluster. Due to their large masses (the majority of which is dark matter), galaxy clusters strongly deform space–time around them, resulting in deflections of light from distant background sources that manifest by dramatic magnification and distortion of the lensed sources.

Gravitational lensing in galaxy clusters can be mainly observed under two regimes. The strong lensing regime is observed in high-density regions of the cluster. In this case, distortions are large, and background galaxies can be observed under the form of gravitational arcs and multiple images. Oppositely, the weak lensing regime is observed in less dense regions and distortions remain very small, necessitating a statistical analysis to extract this lensing signal. Weak lensing generally provides an overall mass estimate of the cluster, and helps trace the distribution of low-mass substructures present in the outskirts of clusters, direct tracers of the past, and/or ongoing dynamical events (Kneib & Natarajan 2011; Jauzac et al. 2016, 2018). Using galaxy clusters as gravitational lenses is common practice to study the dynamics and evolution and thus trace their dark matter distribution. This is the main scope of the analysis presented in this paper.

Galaxy clusters can be observed at almost all evolution times. The observer can thus witness different dynamical processes and evolutionary states. In this analysis, we concentrate on dynamically relaxed cluster, i.e. galaxy cluster which tend to show a relatively cool-core, with uniform properties such as temperature and density profiles (Vikhlinin et al. 2006; Mantz, Allen & Morris 2016b). This cluster population provides insights into the physics of the intracluster medium (ICM) and its interactions with cluster galaxies (Mantz et al. 2016a). The restriction to clusters with the highest possible degree of dynamical relaxation (for which the assumption of hydrostatic equilibrium should be most valid) allows for the most precise test of the CDM model predictions (Schmidt & Allen 2007). Studying massive relaxed clusters at high-redshift ($z > 0.5$) are key to understand structure formation and evolution over cosmological time-scales as they trace back to around redshift $z = 0.5$, i.e. 7 billion years after the big bang. One way to do so is to use all-sky surveys to detect all clusters, providing us with the capacity to lead statistical analyses. While the upcoming years are expected to be extremely bright with the successful launch of the *JWST* on 2021 December 25 and the *Euclid Space Telescope* (Racca et al. 2016; Euclid Collaboration 2022; Troja et al. 2023) on 2023 July 1, the upcoming first light of the Vera Rubin Observatory, and the future launch of the *Nancy Grace Roman Space Telescope*, we here concentrate on observations taken with the largest X-ray survey dedicated to galaxy clusters, the MAssive Cluster Survey (MACS hereafter; Ebeling, Edge & Henry 2001).

MACS is an X-ray cluster survey which provides a complete sample of massive and X-ray luminous galaxy clusters at redshifts $z > 0.3$. Cluster candidates were selected from the ROSAT (Röntgensatellit) Bright Source Catalogue (Voges et al. 1999), based on their X-ray flux and X-ray hardness ratio cuts. The sample included 124 spectroscopically confirmed clusters at $0.3 < z < 0.7$ thanks to observations taken with the University of Hawaii’s 2.2 m and the Keck 10 m telescopes.

In this paper, we concentrate on one of the MACS clusters, MACSJ1423.8+2404 (MACSJ1423 hereafter). MACSJ1423 is a massive cluster with a virial mass of $M_{\text{vir}} = 4.52^{+0.79}_{-0.64} \times 10^{14} M_{\odot}$ (Schmidt & Allen 2007) at redshift, $z = 0.545$, with an X-ray luminosity $L_{\text{X,bol}} = 3.7 \times 10^{45} \text{ erg s}^{-1}$ (Ebeling et al. 2007). MACSJ1423 is part of the ‘high-redshift’ MACS subsample com-

posed of 12 galaxy clusters at $z > 0.5$, and has been the subject of several analyses since its discovery.

LaRoque et al. (2003) examined its system’s Sunyaev–Zel’dovich (SZ) morphology and galaxy distribution which revealed a cool-core, relaxed cluster. The first gravitational-lensing analysis of MACSJ1423 was published in Limousin et al. (2010), followed up by Zitrin et al. (2011, 2015), and Merten et al. (2015). All of which confirmed the conclusion of the SZ analysis, MACSJ1423 is a dynamically relaxed cluster. As noted by Limousin et al. (2010, hereafter L10), MACSJ1423 is a nearly virialized cluster with very little substructure. The system is a part of the sample targeted by the Cluster Lensing And Supernova survey with *Hubble* (CLASH, Prog.ID: 12790, PI: M. Postman; Postman et al. 2012) and has been used in several statistical studies, where its relaxed dynamical state has been particularly important for cosmological work using the baryon fraction (LaRoque et al. 2003; Allen et al. 2004; Schmidt & Allen 2007). MACSJ1423 has also been used to study the triaxiality of galaxy clusters (Limousin et al. 2013) and was included in several statistical cluster-lensing analyses (Zitrin et al. 2011, 2015; Limousin et al. 2013; Applegate et al. 2014; Merten et al. 2015).

MACSJ1423 was also observed as part of the KALEIDOSCOPE survey (Prog.ID: 0102.A-0718(A), P.I: A. Edge), the largest snapshot survey of massive clusters, with more than 200 cluster cores observed so far, taken with the Multi-Unit Spectroscopic Explorer (MUSE) spectrograph mounted on the Very Large Telescope (VLT). The target list is comprised of X-ray selected clusters at $z > 0.15$ from the ROSAT All Sky Survey (RASS), with the primary sample being the MACS sample. Clusters are selected on the basis of their X-ray luminosities, $L_{\text{X}} > 3 \times 10^{44} \text{ erg s}^{-1}$ (0.1–2.4 keV). The field of view of MUSE (1 arcmin $\times$ 1 arcmin) covers the strong lensing region, i.e. inner core, of most galaxy clusters (typically 15–10 arcsec), and thus provides spectroscopic observations for most galaxies (foreground, cluster or background objects) in the field. KALEIDOSCOPE observations have already proved extremely successful, they have been used for detailed cluster analyses (e.g. Jauzac et al. 2019; Mahler et al. 2019; Lagattuta et al. 2023), including SMACS J0723.3–7327, the first released cluster observed by the *JWST* (Caminha et al. 2022; Pascale et al. 2022; Diego et al. 2023; Mahler et al. 2023).

We here present a strong and weak lensing analysis of MACSJ1423 built on the legacy observations of this cluster from space and the ground and the use of new mass modelling methods. The paper is organized as follows: Section 2 summarizes the data used in this work. The strong and weak lensing analyses are described in Sections 3 and 4, respectively. Section 5 presents the combined strong and weak lensing analysis, along with the resulting mass distribution of the cluster. Finally, we discuss our results and put them in perspective of previous works on MACSJ1423 in Section 6. Throughout this paper, we assume a flat cosmological model with $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, and a Hubble constant $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. In this cosmology, 1 arcsec = 6.38 kpc at the redshift of the cluster, $z = 0.545$. All magnitudes are given in the AB system (Oke 1974).

2 OBSERVATIONS

2.1 Hubble Space Telescope

MACSJ1423 was first observed on 2004 June 16 with the *Advanced Camera for Surveys* (ACS) onboard the *Hubble Space Telescope* (*HST*) for 4.5 and 4.6 ks with the *F555W* and *F814W* pass-bands, respectively (GO: 9722, PI: Ebeling). In 2006, MACSJ1423 was then imaged again with ACS in the *F814W* pass-band (Prog.ID:

Table 1. List of *HST* observations of MACSJ1423 available. In this work, we use the CLASH observations in the *F606W*, *F814W*, and *F160W* pass-bands. Columns 1 and 2 give the right ascension and declination of the observed field in degrees. Column 3 lists the instruments and filters. Columns 4 and 5 give the exposure time in seconds and the observation date, respectively. Finally, columns 6 and 7 provide the programme ID and the PI respectively.

RA (J2000)	Dec. (J2000)	Instrument/Filter	Exp. Time (s)	Obs. Date	Prog. ID	PI
215.9524858	24.0803087	ACS/ <i>F555W</i>	4500.000	2004-06-16	9722	Ebeling
215.9524858	24.0803087	ACS/ <i>F814W</i>	4590.000	2004-06-16	9722	Ebeling
215.9525000	24.0803056	ACS/ <i>F814W</i>	2184.000	2006-03-24	10493	Gal-Yam
215.9495000	24.0784722	WFC3/ <i>F225W</i>	3592.000	2013-02-22	12790	Postman
215.9494593	24.0784797	WFC3/ <i>F275W</i>	3680.000	2013-01-13	12790	Postman
215.9495000	24.0784722	WFC3/ <i>F390W</i>	1152.000	2013-01-13	12790	Postman
215.9494604	24.0784607		1237.000	2013-02-22	12790	Postman
215.9495000	24.0784722	ACS/ <i>F435W</i>	1032.000	2012-12-31	12790	Postman
215.9496433	24.0787853		1066.000	2013-03-05	12790	Postman
215.9497915	24.0786826	ACS/ <i>F475W</i>	1092.000	2013-02-03	12790	Postman
215.9496433	24.0787853		1092.000	2013-03-12	12790	Postman
215.9497915	24.0786826	ACS/ <i>F606W</i>	1088.000	2013-01-13	12790	Postman
215.9495000	24.0784722		1032.000	2013-02-05	12790	Postman
215.9495000	24.0784722	ACS/ <i>F775W</i>	1032.000	2013-01-13	12790	Postman
215.9495000	24.0784722		1032.000	2013-01-19	12790	Postman
215.9494984	24.0785257	ACS/ <i>F850LP</i>	1065.000	2012-12-31	12790	Postman
215.9494702	24.0785183		1103.000	2013-01-19	12790	Postman
215.9495000	24.0784722		1032.000	2013-02-03	12790	Postman
215.9495000	24.0784722		1032.000	2013-03-12	12790	Postman
215.9497638	24.0784634	WFC3/ <i>F105W</i>	1305.869	2013-01-22	12790	Postman
215.9495000	24.0784722		1508.802	2013-02-05	12790	Postman
215.9495000	24.0784722	WFC3/ <i>F110W</i>	1005.802	2013-01-19	12790	Postman
215.9494572	24.0783802		1005.868	2013-03-12	12790	Postman
215.9494138	24.0784107	WFC3/ <i>F125W</i>	1005.868	2012-12-31	12790	Postman
215.9495000	24.0784722		1508.802	2013-01-01	12790	Postman
215.9495000	24.0784722	WFC3/ <i>F140W</i>	1305.869	2013-01-22	12790	Postman
215.9494572	24.0783802		1005.868	2013-02-05	12790	Postman
215.9495377	24.0786077	WFC3/ <i>F160W</i>	1005.868	2012-12-31	12790	Postman
215.9497638	24.0784634		1005.868	2013-01-19	12790	Postman
215.9495000	24.0784722		1508.802	2013-02-03	12790	Postman
215.9495000	24.0784722		1508.802	2013-03-12	12790	Postman

10493, PI: Gal-Yam). Finally, MACSJ1423 is part of CLASH survey (Postman et al. 2012) and was thus observed again with *ACS* and the *Wide Field camera 3/IR (WFC3)* in the *F225W*, *F275W*, *F390W*, *F435W*, *F475W*, *F606W*, *F775W*, *F850LP*, *F105W*, *F110W*, *F125W*, *F140W*, and *F160W* pass-bands. A list of all available observations of MACSJ1423 with *HST* is given in Table 1.

For the analysis presented in this paper, we use the CLASH data products in the *F606W*, *F814W*, and *F160W* pass-bands.¹ For a galaxy cluster at redshift $z = 0.545$, it is important to use filters that capture the rest-frame optical light, particularly the 4000 Å break to identify the old and red galaxies in the cluster. Given the cluster redshift, the combination of *F606W* and *F814W* is best for getting this old population (see Section 3.2). Additionally, *F160W*, in combination with *F606W* and *F814W*, is well-suited for identifying background galaxies in the cluster (see Section 4.1.3). The mosaics were produced using the MOSAICDRIZZLE pipeline (Koekemoer et al. 2002; Koekemoer et al. 2011). These consist of drizzled science images in counts/s, along with associated inverse variance weight images, which are scaled so that they can be used to create the root mean square (rms) mosaics that are in the same units as the drizzled science image mosaics.

2.2 Chandra X-ray Observatory

MACSJ1423 was first observed in the X-rays on 2001 June 1 with the *Advanced CCD Imaging Spectrometer (ACIS)* onboard the *Chandra X-ray Observatory* for 18.53 ks (Obs.ID: 1657, P.I: Vanspey-broeck). The cluster was observed again on 2003 August 18 for 115.57 ks (Obs.ID: 4195, P.I: Allen). We reduce the data as in Beauchesne et al. (2024) with the *Chandra* pipeline CIAO² 4.15 (Fruscione et al. 2006) and CALDB 4.10.7 and produce a counts map in the broad energy band (i.e. [0.5, 7] keV). These X-ray observations are used for comparison with our lensing analysis.

2.3 Ground-based spectroscopy and photometry

2.3.1 Subaru and Canada France Hawaii Telescope (CFHT)

MACSJ1423 was observed in the B, V, R_c , I_c , and z' bands with the SuprimeCam wide-field imager on the Subaru telescope (Miyazaki et al. 2002), and in the u^* and K bands with MegaCam and Wide-field Infrared Camera (WIRCam) on the Canada France Hawaii Telescope (CFHT). The data reduction techniques were adapted to deal with the special characteristics of the Suprime-Cam and MegaCam; details are given by Donovan (2007). The resulting imaging data are used

¹https://archive.stsci.edu/missions/hst/clash/macs1423/data/hst/scale_30mas/

²<https://cxc.cfa.harvard.edu/ciao/>

Table 2. Summary of the VLT/MUSE observations of MACSJ1423 taken as part of the KALEIDOSCOPE Survey. Columns 1 and 2 give the right ascension and declination of the observed field in degrees (J2000). Column 3 gives the redshift of the cluster. Column 4 lists the ESO Programme ID. Columns 5 and 6 list the exposure time in seconds and observing date, respectively. Column 6 gives the average seeing at the time of observation. The programme ID and PI name are given in columns 7 and 8, respectively.

RA (J2000)	Dec. (J2000)	z	Exp. Time (s)	Obs. Date	Seeing (arcsec)	ESO Programme	PI
215.949458	24.078472	0.5432	2910	2019-03-18	0.57	0102.A-0718(A)	Edge

to compute photometric redshifts for all galaxies in a $0.5 \times 0.5 \text{ deg}^2$ field following the methodology described in Ma et al. (2008). To estimate the spectral energy distribution (SED) for all objects within the field of view and to ensure that the images for all bands have the same effective spatial resolution of 1 arcsec, the imaging data in various pass-bands are seeing-matched using the technique described in Kartaltepe et al. (2008). SOURCE-EXTRACTOR (Bertin & Arnouts 1996, or SExtractor) was used in dual image mode to create the object catalogue with *R*-band image as the reference detection image. An adaptive SED fitting code LE PHARE (Arnouts et al. 1999; Ilbert et al. 2006, 2009) was used to determine the photometric redshifts for galaxies with $m_{R_c} < 24.0$. To reduce the fraction of catastrophic errors and to mitigate the systematic trends in the difference between spectroscopic and photometric redshifts, LE PHARE adjusts the photometric zero points by using galaxies with spectroscopic redshifts as training points. More details are given in Ma et al. (2008).

2.3.2 W.M. Keck Observatory

L10 observations were taken with the Low Resolution Imager and Spectrograph (LRIS; Oke et al. 1995, Prog.ID: H26aL, PI:Henry) and the Deep Imaging Multi-Object Spectrograph (DEIMOS; Cowley et al. 1997) on the 10 m Keck Telescope on Mauna Kea.

LRIS observations provided spectroscopic redshifts for three multiple image systems in the cluster. The reduction of these data is described in detail in Kelson et al. (2002). Redshifts of the galaxies in the cluster field were obtained from LRIS and DEIMOS and published by L10. Cluster members were defined as galaxies with redshifts within ± 0.05 of the cluster redshift $z_{\text{cluster}} = 0.545$.

2.3.3 The Very Large Telescope

Panoramic, integral-field spectroscopic coverage of MACSJ1423 was obtained with MUSE (Bacon et al. 2010) at the VLT, as part of the KALEIDOSCOPE cluster survey (P.ID: 0102.A-0718(A), PI: A. Edge). Observations were taken on 2019 March 17 during grey time, under clear sky conditions, with an average seeing of 0.57 arcsec and three 970 s exposures, spanning the wavelength range 4800–9300 Å. To reduce systematic effects of bad pixels and variable detector sensitivity, a small (0.5 arcsec) dither was applied between exposure. Each exposure was also rotated by 90° from the previous one. However, to maximize integrated depth, the centres of each exposure were coincident – save for the small dither offset. Thus, the total exposure time over most of the field of view ($1 \times 1 \text{ arcsec}^2$) is 2910 s. Specific details of these observations are given in Table 2.

The data reduction and spectroscopic extraction were performed by our team following the method presented in Lagattuta et al. (2022), which we briefly summarize here. The reduction occurs in two part. First, we follow the procedure described in the public MUSE

Data Reduction Pipeline User Manual.³ Namely, we apply bias and flat-field correction, wavelength calibration, line-spread function (LSF) modelling, and sky-subtraction to two-dimensional ‘pixel table’ configurations of each exposure, using nightly calibration files that accompany the raw science frames. During this step, we also calibrate the flux levels of the data and correct for telluric absorption using a standard star observed immediately after the science frames. Following these corrections, we interpolate the pixels of each exposure on to a regular grid, combine all exposures together, and restructure the data into a cube. After the initial reduction phase, we apply two additional reduction calibrations to the combined cube directly. We model and correct low-level flat-field residuals caused by intracluster light (known as ‘autocalibration’, see e.g. section 2.5 in Richard et al. 2021). Additionally, we apply the Zurich Atmospheric Purge algorithm (ZAP; Soto et al. 2016) to remove any significant sky-line residuals that remain following sky subtraction.

After reducing the cube, we select targets for spectroscopic extraction using two distinct but complementary techniques. In the first method, we identify objects in the *HST* images that fall in the MUSE Field of View (FoV). We measure the position and shape of these objects using SExtractor, then convolve the shapes with the MUSE point spread function (PSF) to better match their size in the data cube. The second method also relies on SExtractor, but this time it is run on the cube directly, to identify prominent emission-line objects that may not have significant stellar continuum. We cross-match the two samples to remove any duplicate detections and extract a spectrum for all remaining targets using the optimally weighted Horne (1986) procedure. Following extraction we run each spectrum through the redshift-fitting software MARZ (Hinton et al. 2016), which provides an initial redshift guess for each object. We then visually inspect the results, accepting or modifying the best-fit MARZ redshift as needed.

The final redshift catalogue for MACSJ1423 contains 66 entries, consisting of two stars, three foreground galaxies ($z < z_{\text{cluster}}$), 39 cluster members, and 16 background galaxies ($z > z_{\text{cluster}}$). A list of cluster member galaxies is given in Table 3, while multiple-image systems are summarized in Table 4. We note that these results highlight MUSE’s remarkable efficiency as a spectroscopic detector in crowded (i.e. cluster-core) fields, allowing us to cleanly measure the redshifts of not only multiply imaged galaxies, but also intervening objects along the line of sight.

3 STRONG GRAVITATIONAL LENSING ANALYSIS

3.1 Multiple image systems

The position, shape, and geometry of multiple images of background galaxies will depend on the mass distribution in the galaxy cluster lens, the distance of the source galaxies, together with the alignment

³<https://www.eso.org/sci/software/pipelines/muse/>

Table 3. Cluster members spectroscopically confirmed by VLT/MUSE observations in MACSJ1423. Columns 1 and 2 give the right ascension and declination in degrees (J2000). Column 3 gives their respective measured spectroscopic redshift with VLT/MUSE.

RA (J2000)	Dec. (J2000)	z
215.9494838	24.0784459	0.545 (BCG)
215.9523294	24.0707291	0.539
215.9427198	24.0727851	0.537
215.9539395	24.0714300	0.539
215.9586154	24.0710327	0.533
215.9477283	24.0727531	0.546
215.9525992	24.0742691	0.541
215.9517541	24.0741379	0.554
215.9489410	24.0763359	0.537
215.9462858	24.0754164	0.562
215.9474872	24.0761680	0.547
215.9493174	24.0769683	0.555
215.9493511	24.0767400	0.560
215.9448420	24.0770788	0.545
215.9497831	24.0779724	0.523
215.9496876	24.0773563	0.548
215.9484518	24.0770044	0.517
215.9453596	24.0784154	0.546
215.9565067	24.0779951	0.530
215.9516898	24.0782917	0.537
215.9581679	24.0787077	0.552
215.9584832	24.0793582	0.535
215.9448590	24.0785557	0.533
215.9462005	24.0795718	0.531
215.9433649	24.0802384	0.543
215.9510899	24.0808902	0.532
215.9582277	24.0812035	0.552
215.9507082	24.0813282	0.551
215.9403157	24.0823716	0.560
215.9502609	24.0842187	0.550
215.9462506	24.0848389	0.546
215.9472276	24.0841258	0.549
215.9537427	24.0845512	0.554
215.9494303	24.0852384	0.552
215.9451689	24.0847458	0.545
215.9474839	24.0856535	0.546
215.9499363	24.0865008	0.542
215.9488118	24.0860833	0.563
215.9532771	24.0868116	0.540

between the observer, the cluster, and the lensed sources. As a result, in order to constrain the mass distribution of MACSJ1423, we use the positions of the identified multiple image systems as constraints for our strong lensing mass model, i.e. in the core of the cluster.

3.1.1 Previous work

Prior to this analysis, three multiple image systems were reported in L10, and another one in Zitrin et al. (2015, hereafter Z15). These systems are listed in Table 4 as systems 1–4. For L10, systems 1 and 2 belong to a single background galaxy, resolved in two components with multiple images organized in an Einstein-cross configuration. A central fifth image is also predicted at the position of the brightest cluster galaxy (BCG) located at the very centre of MACSJ1423. Due to its large halo of stars, and the fact that central images are usually demagnified, multiple images located in this region are generally

Table 4. Multiple image systems used as constraints in our strong lensing analysis of MACSJ1423. Column 1 lists the ID of the multiple images. Columns 2 and 3 give the right ascension and declination in degrees (J2000). Column 4 gives the redshift of each system. Redshifts without error bars correspond to spectroscopic measurements while the presence of error bars highlight the redshifts optimized by our mass model. While spectroscopic redshifts were already measured with LRIS and DEIMOS by L10, we highlight with an * the systems for which we confirm spectroscopic redshifts with MUSE observations. Column 5 gives the magnification estimated from our strong lensing mass model for each multiple images.

ID	RA (deg)	Dec. (deg)	z	μ
1.1	215.9577155	24.0746537	2.84	3.49 ± 0.52
1.2	215.9494609	24.0818270	2.84	7.08 ± 1.45
1.3	215.9444674	24.0806542	2.84	9.25 ± 2.04
1.4	215.9459355	24.0763898	2.84	10.89 ± 1.79
1.5	215.9497029	24.0791219	2.84	0.99 ± 0.36
2.1	215.9576456	24.0745519	2.84	3.50 ± 0.52
2.2	215.9495433	24.0817288	2.84	7.15 ± 1.49
2.3	215.9443426	24.0803974	2.84	10.97 ± 2.39
2.4	215.9458112	24.0763495	2.84	11.87 ± 1.96
3.1*	215.9465404	24.0836281	1.779	8.82 ± 1.53
3.2*	215.9523020	24.0831945	1.779	16.74 ± 3.82
3.3*	215.9551508	24.0811756	1.779	13.71 ± 2.45
4.1	215.9481287	24.0771353	1.797 ± 0.062	5.07 ± 1.09
4.2	215.9558429	24.0771761	1.797 ± 0.062	4.15 ± 0.52
4.3	215.9502463	24.0821356	1.797 ± 0.062	11.79 ± 3.18
4.4	215.9459358	24.0817256	1.797 ± 0.062	5.57 ± 0.73
4.5	215.9490200	24.0780830	1.797 ± 0.062	1.48 ± 0.38

very difficult, if not impossible, to detect. On the other hand, system 3 is seen in a naked-cusp configuration, with three images on the same side of the cluster. Another multiple image system is found by Z15, composed of five images, and which includes a radial arc. Systems 1 and 2 in L10 are taken as a single system in Z15 without the central radial arc (image 1.5 in L10). All systems can be seen in Fig. 1.

3.1.2 This work

The four systems discussed in the previous section are used. We combine the identifications from the two analyses of L10 and Z15 (see Table 4 and Fig. 1), and thus use the 4 systems discussed in Section 3.1.1.

In contrast to L10, we add the fourth system of Z15, system 4 in Table 4, while systems 1, 2, and 3 are considered in the same manner in L10. Adding to that, systems 1 and 2 correspond to the same multiply imaged galaxy, but for which L10 identified two components, thus we split it in two sets of constraints. We then use the central radial arc of system 1 as done by L10.

To summarize, we use four multiple image systems: system 1 with five multiple images, including the central radial arc (image 1.5), system 2 with four multiple images, system 3 with three multiple images, and system 4 with five multiple images, including another central radial arc. Systems 1, 2, and 3 are all spectroscopically confirmed. However, the MUSE observations are not of enough quality for us to measure a spectroscopic redshift with high confidence for system 4. We obtained a low confidence measurement of $z = 1.878$ which is discussed in more detail in Section 3.3, however we let the redshift of this system free to vary in our mass model.

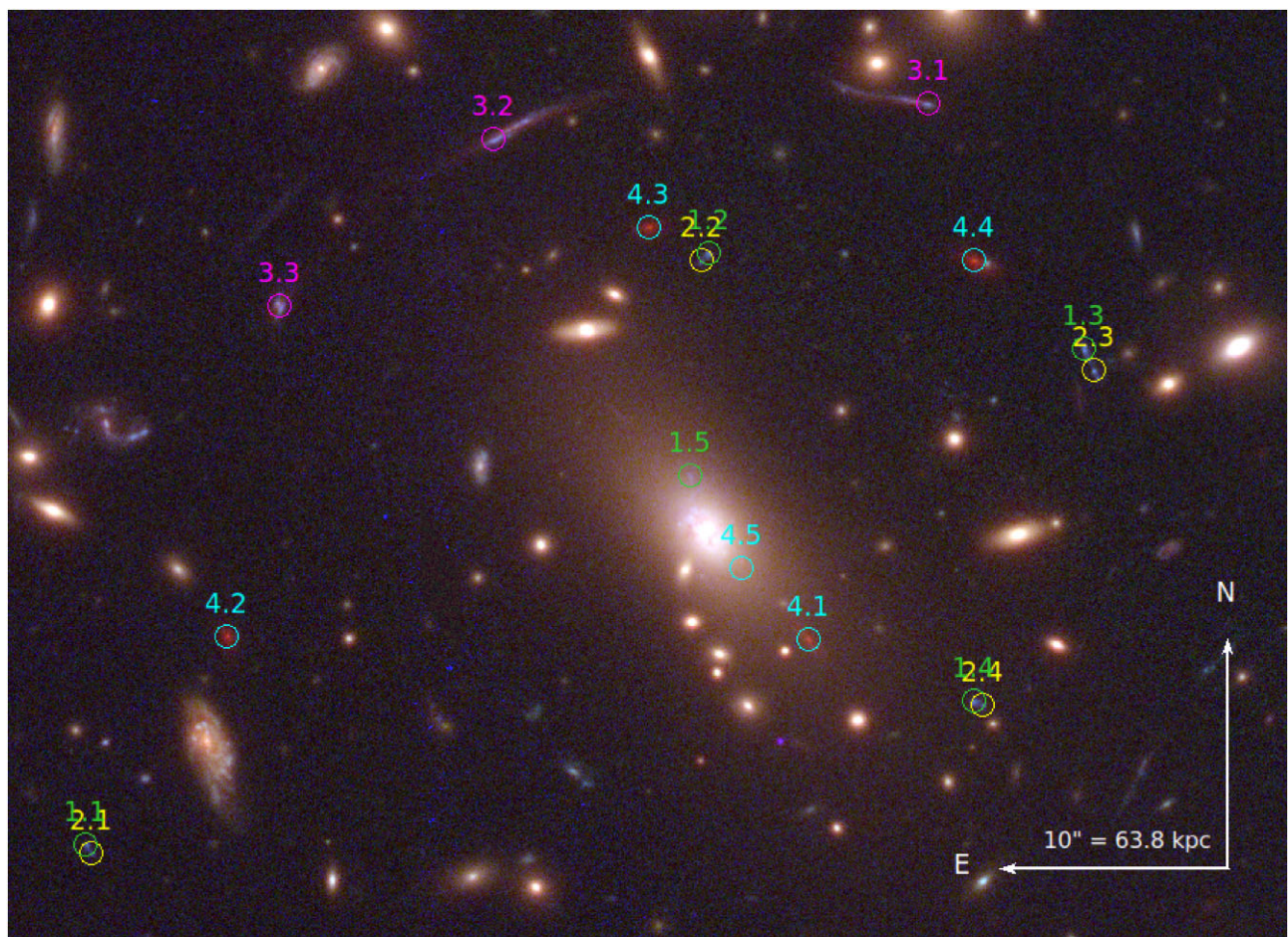


Figure 1. *HST* colour composite image of the central region of MACS J1423 created using the *F606W* for blue, *F814W* for green, and *F160W* for red colours. Multiple image systems are highlighted with coloured circles and ID following the list given in Table 4. The five multiple images of system 1 are shown in green, the four multiple images of system 2 in yellow, the three multiple images of system 3 in magenta, and the five multiple images of system 4 in cyan.

3.2 Cluster members

The mass modelling technique used in this paper account for the matter contribution from cluster members. Consequently, a well-defined catalogue of cluster members is needed. We here present the process of getting such a catalogue.

3.2.1 Previous work

L10 obtained spectroscopic redshift measurements with LRIS and DEIMOS as described in Section 2. These observations provided spectroscopic confirmation of multiple image systems, together with spectroscopy of cluster galaxies within the field of MACS J1423, and allowed them to build a cluster member catalogue. Galaxies with redshifts within ± 0.05 of the cluster redshift, $z_{\text{cluster}} = 0.545$, were considered cluster members. The final cluster member catalogue was composed of 30 galaxies, including the brightest cluster galaxy (BCG).

3.2.2 This work

Galaxy clusters are known to have a well-defined and very regular population of early-type elliptical and lenticular galaxies, called the red sequence (Gladders & Yee 2000). These red sequence galaxies show a tight relation between their colour and magnitude

(Baum 1959; Visvanathan & Sandage 1977). SExtractor (Bertin & Arnouts 1996) is used in dual mode to extract the *F606W* and *F814W* photometry for cluster galaxies. The sequence of stars is identified using the surface brightness and magnitude of the detected sources (the MAG_AUTO versus MU_MAX diagram) as shown in Fig. 2, and then removed from the catalogue. A colour–magnitude diagram is then created to identify the red sequence itself as shown in Fig. 3. Sources considered as bad detections (with a quoted magnitude of 99 from SExtractor) are removed along with sources at the edges of the *HST*/ACS field of view. A 2σ clipping fit is used to fit the red sequence, and a visual inspection is performed to remove any remaining contamination such as merging non-cluster galaxies in the sample. Any remaining artefacts such as star spikes and edge effects are discarded from our catalogue. Cluster members in the inner region of the cluster ($R < 260$ kpc) are confirmed using spectroscopic redshifts measured with our VLT/MUSE observations (see Section 2.3.3). Our final cluster member catalogue contains 66 galaxies, out of which 39 are spectroscopically confirmed, including the BCG.

3.3 Parametric mass modelling

In the cluster core, where we assume light traces, i.e. that dark matter haloes (at both cluster and galaxy-scales) follow the light distribution,

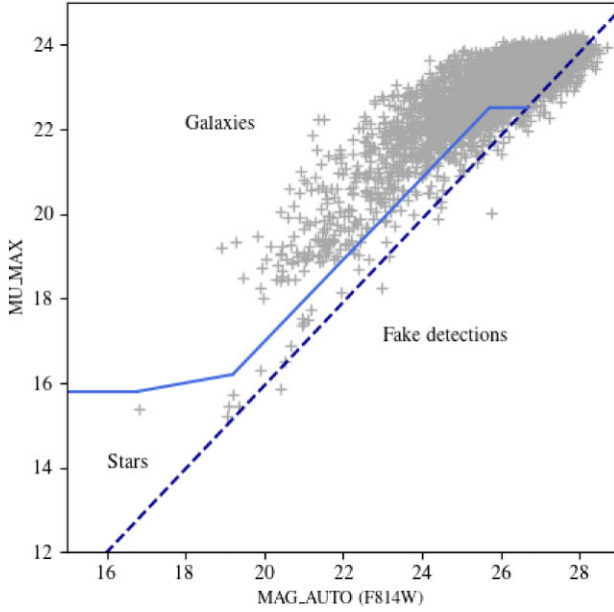


Figure 2. Magnitude (MAG_AUTO) versus surface brightness (MU_MAX) diagram for MACSJ1423 in the F814W pass-band. Such a diagram allows us to disentangle stars and fake detections from galaxies. The blue polygon highlights the sequence of stars and the limit for fake detections. The grey markers within the polygon are the star sequence and the ones outside are objects identified as galaxies in the cluster.

we use a parametric mass model. The total mass distribution in this region is decomposed into large- and small-scale components to model cluster and galaxy-scale matter distributions, respectively. Each component is modelled assuming a dual pseudo-isothermal elliptical density profile (dPIE; Elíasdóttir et al. 2007) characterized by seven parameters: position (α , δ), position angle (θ), ellipticity (e), velocity dispersion (σ), and two scale radii, the core and the cut radii (r_{core} and r_{cut}). The three-dimensional density distribution of the dPIE is written as

$$\rho(r) = \frac{\rho_0}{(1 + r^2/r_{\text{core}}^2)(1 + r^2/r_{\text{cut}}^2)}, \quad \text{with } r_{\text{cut}} > r_{\text{core}}, \quad (1)$$

where ρ_0 is the central density of the core. To reduce the number of free parameters in the lens model, position, ellipticity, and angle position of galaxy-scale components are fixed to follow their light distribution. In addition, Faber–Jackson empirical scaling relations (Faber & Jackson 1976) are used for the remaining parameters. In this case, we consider that for each cluster galaxy, the core radius, r_{core} , the cut radius, r_{cut} , and the velocity dispersion, σ_0 , scale with the galaxy luminosity, L , as follows:

$$\begin{aligned} \sigma_0 &= \sigma_0^* \left(\frac{L}{L^*} \right)^{1/4}, \\ r_{\text{core}} &= r_{\text{core}}^* \left(\frac{L}{L^*} \right)^{1/2}, \\ r_{\text{cut}} &= r_{\text{cut}}^* \left(\frac{L}{L^*} \right)^{\alpha} \end{aligned} \quad (2)$$

where L^* is the typical luminosity of an elliptical galaxy at the cluster redshift, and r_{core}^* , r_{cut}^* , σ_0^* are the dPIE parameters. α is the slope which is fixed to 1/2, following the work by Jullo & Kneib (2009) and Niemiec et al. (2020).

The publicly available lens modelling software LENSTOOL is used for the mass reconstruction. There is one cluster scale halo in our

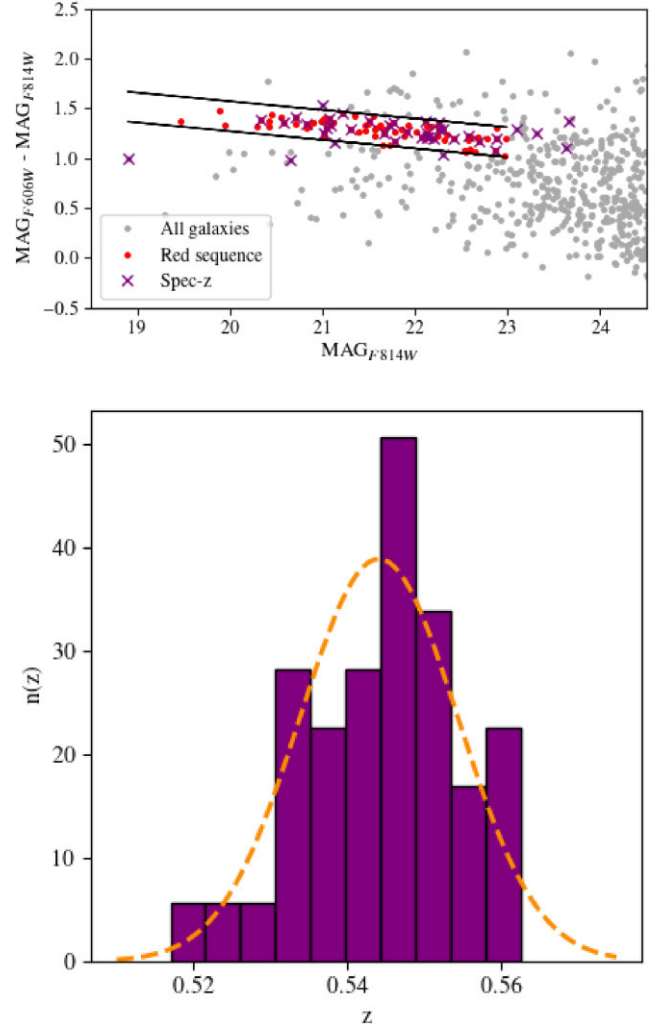


Figure 3. *Top:* Colour ($\text{mag}_{F606W} - \text{mag}_{F814W}$) versus magnitude (m_{F814W}) diagram for MACSJ1423. All sources from the source extraction done in this work are shown in grey, and the red sequence galaxies are highlighted in red marked within the black lines. The cluster members with spectroscopic redshifts are marked by purple cross. We consider all galaxies within the 2σ of the linear fit as cluster members. *Bottom:* Histogram of the redshift of spectroscopically confirmed cluster members within MUSE data. The best Gaussian fit is overlaid in orange dashed line.

model, for which all the parameters are let free to vary except for the cut radius, which generally lies outside the strong lensing region making it difficult to be constrained by our model and is thus fixed to $r_{\text{cut}} = 1000$ kpc. For the small-scale haloes, we have 65 cluster members, modelled using scaling relations with $\text{mag}_0 = 20.05$ at the MACS 1423 cluster redshift in the ACS/F814W pass-band. Their positions are fixed to that of cluster galaxies, along with their position angle and ellipticity. However, core radii are fixed to a very small value of $r_{\text{core}}^* = 0.15$ kpc, while cut radii and velocity dispersions are let free to vary with $5 < r_{\text{cut}}^* < 50$ kpc and $100 < \sigma_0^* < 250$ km s $^{-1}$, respectively. The BCG in the cluster is modelled separately from the rest of cluster members, since extremely luminous central cluster galaxies often not follow the scaling relations given in equation (2) (Newman et al. 2013a, c).

The free parameters of the different potentials are optimized, using the positions of strongly lensed multiple images as constraints. The goodness of our model to meet the observational constraints is mea-

Table 5. Best-fitting parameters for our strong lensing mass model of the core of MACS J1423. Values given in brackets are fixed in our model, while the ones quoted with error bars are being optimized. The coordinates of the cluster and BCG haloes are given in arcsec relative to the cluster centre (RA, Dec.)=(215.94944 24.078499). The log-likelihood ($\ln(\mathcal{L})$), χ^2 , χ^2_{ν} , and rms are given in the bottom of the table.

Components	ΔRA (arcsec)	$\Delta\text{Dec.}$ (arcsec)	e	θ (deg)	r_{core} (kpc)	r_{cut} (kpc)	σ_0 (km s $^{-1}$)
Cluster halo	-1.2 ± 0.6	-0.5 ± 1.1	0.4 ± 0.04	117 ± 1	137 ± 23	[1000]	1186 ± 57
BCG	$[-0.07]$	$[-0.22]$	[0.62]	[310]	[0.15]	49 ± 40	442 ± 30
L* Galaxy	–	–	–	–	[0.15]	22 ± 11	211 ± 30
$\ln(\mathcal{L}) = -36.17$	$\chi^2 = 17.03$	$\chi^2_{\nu} = 1.13$	rms = 0.90 arcsec				

sured with rms and χ^2 . The rms is the difference between observed multiple image positions and predicted position from the model. For the model described, consisting of one large scale halo and 66 small-scale haloes, constrained by the 17 multiple images discussed in Section 3.1, we obtain an rms for our best-fit mass model of 0.90 arcsec, and a reduced χ^2_{ν} of 1.13. The model predicts a redshift of $z = (1.79 \pm 0.06)$ for system 4, which agrees well with the tentative spectroscopic redshift derived from the VLT/MUSE observations ($z = 1.878$, see Section 2.3.3). The best-fitting parameters of our strong lensing mass model are listed in Table 5. The mass contours for this strong lensing only model is shown in yellow colour in Fig. 4. The corresponding surface mass density of MACS J1423 as a function of distance from the cluster centre is shown in Fig. 7 in magenta colour. We measure a projected mass enclosed in the strong lensing region of $M(R < 200 \text{ kpc}) = (1.83 \pm 0.04) \times 10^{14} M_{\odot}$.

4 WEAK GRAVITATIONAL LENSING ANALYSIS

4.1 Weak lensing catalogue

In the weak lensing regime, the shapes of lensed background sources carry the lensing signal and as a result are used to constrain the mass distribution. Such signal is weak and thus difficult to measure for a single background source. Therefore, a statistical analysis is necessary to extract this faint signal. We here present the construction of the weak lensing background galaxy catalogue for MACS J1423. The source detection, photometry, and shape measurements are performed with the stacked images in the *F606W*, *F814W*, and *F160W* pass-bands. We refer the reader to (Jauzac et al. 2012, 2015b, J12, and J15, respectively hereafter) for more details on the method used to generate the weak lensing catalogue, and only give here a summary of the different steps.

4.1.1 The ACS source catalogue

To detect sources and measure their shapes, we use the *HST*/ACS *F814W* filter. The publicly available weak lensing shape measurement algorithm, PYRRG,⁴ based on Rhodes, Refregier & Groth (2000) and presented in Harvey et al. (2019), is used for the construction of the catalogue, including the measurements of shapes. The first step consists in using the ‘hot–cold’ method in Leauthaud et al. (2007) to optimally extract sources from the image using SEXTRACTOR (Bertin & Arnouts 1996). In this method, two SEXTRACTOR scans of the image are performed: the hot scan to find the smaller and fainter sources, and the cold scan to find the larger and brighter sources using different minimum. The two catalogues are then

combined. Following the detection of ‘hot–cold’ sources, the sample is cleaned by removing duplicate detections and any sources close to stars or saturated pixels. The ‘hot–cold’ method ensures we keep the larger objects. Based on the distribution of sources in the magnitude (MAG_AUTO) versus peak surface brightness (MU_MAX) plane, sources are classified as stars, galaxies, and fake detections (see Leauthaud et al. 2007; R14; J15 for more details). Fake detections are then removed from our catalogue, and the sequence of stars is kept for the modelling of the PSF, mandatory step in the measurement of shapes.

4.1.2 Shape measurements

The next step consists on measuring shapes of background objects. This necessitates accounting for instrumental effects, and the position of the telescope, which will impact the true shape of galaxies. PYRRG was constructed accordingly, and is thus correcting for such effects. It models the PSF of individual exposures for all the images considered, and corrects all galaxy shapes for it. It measures the PSF from the stars in each individual exposures, comparing the second and fourth-order moments to various TINY TIM models of the PSF (Krist, Hook & Stoeckl 2011). TINY TIM is an easy-to-use standard *HST* modelling software which, thanks to detailed information on the telescope and instruments, models the PSF of the different instruments. It provides access to PSF models that properly matches the conditions of *HST* observations under different conditions. PYRRG combines the best-fit PSF over all the individual exposures to get a final PSF model that matches the observations at hands. Having the modelled PSF, the next step is to then correct galaxy moments from it, and measure the shape of these galaxies.

In PYRRG, the ellipticity, $e = (e_1, e_2)$, with e_1 and e_2 the two components of ellipticity, and the size parameter, d , are defined as

$$e_1 = \frac{I_{xx} - I_{yy}}{I_{xx} + I_{yy}},$$

$$e_2 = \frac{I_{xy}}{I_{xx} + I_{yy}},$$

$$d = \sqrt{\frac{I_{xx} + I_{yy}}{2}}, \quad (3)$$

where I_{ij} are the second-order weighted Gaussian moments. The shear estimator, $\tilde{\gamma}$, is measured using the ellipticity together with the polarizability, G ,

$$\tilde{\gamma} = C \frac{e}{G} \quad (4)$$

where C is the calibration constant. The polarizability, G , is calculated using equation (28) in Rhodes et al. (2000), and the calibration constant, C , is fixed to 0.86, as given in Leauthaud et al. (2007).

⁴<https://pypi.org/project/pyRRG/>

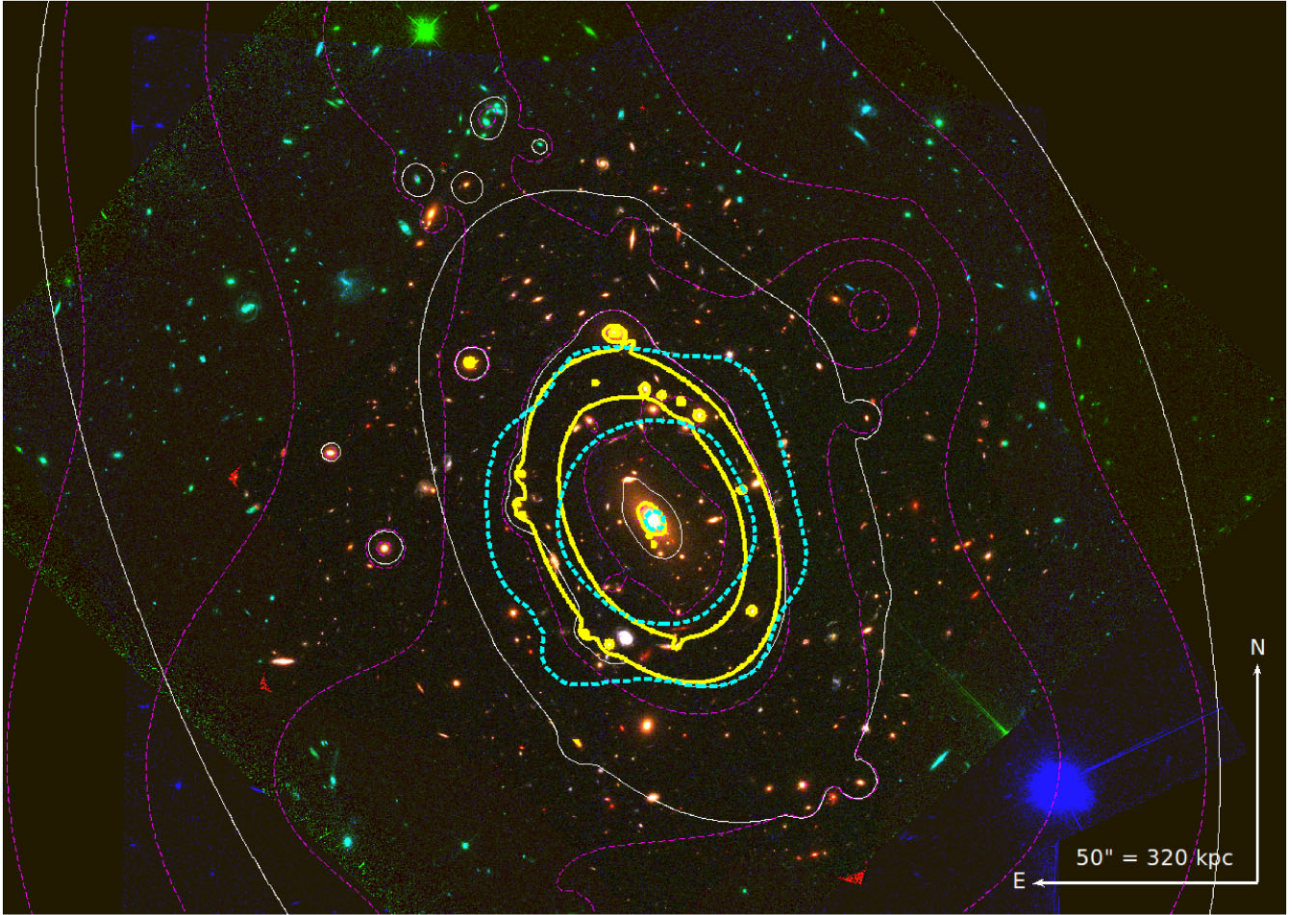


Figure 4. *HST* colour composite image of the central region of MACS J1423 created using the *F606W* for blue, *F814W* for green, and *F160W* for red colours. The thick solid yellow and thin dashed magenta contours show the mass distribution obtained with our strong lensing and weak lensing mass reconstruction as described in Sections 3.3 and 4.2, respectively. The mass contours obtained with our combined mass model, as presented in Section 5, are shown with thin solid white contours. The thick dashed cyan contours represent the X-ray surface brightness from the *Chandra* observations.

4.1.3 Background galaxy selection

We now have a weak lensing catalogue with all shapes of galaxies measured with PYRRG. However, this catalogue is still contaminated by foreground and faint cluster galaxies. The weak lensing signal is carried by background galaxies, but can be diluted by the presence of cluster members and/or foreground sources. Despite removing cluster member galaxies from the catalogue, the catalogue remains contaminated by faint, small, and bluer cluster galaxies (mimicking the colour of background objects), and foreground objects for which redshifts measurements are not available. We thus use a colour–colour selection for galaxies without photometric and/or spectroscopic information as done by J15. In the case of MACS J1423, we place our selection in the $(\text{mag}_{F435W} - \text{mag}_{F814W})$ versus $(\text{mag}_{F435W} - \text{mag}_{F606W})$ colour–colour parameter space. In the colour–colour diagram, regions dominated by the unlensed population (cluster and foreground galaxies) are identified using the available spectroscopic and/or photometric redshifts. The weakly lensed galaxies are then separated from the unlensed population by a defined polynomial region using this calibrated selection (see J15 for more details). As a final step, to remove galaxies with ill-determined shape parameters. The final weak lensing catalogue contains 723 background galaxies, corresponding to a density of ~ 57 galaxies arcmin^{-2} , compared to other massive clusters such

as $\sim 100 \text{ arcmin}^{-2}$ from J15, $\sim 42 \text{ arcmin}^{-2}$ from N23 in the deep *Hubble Frontier Fields*, and $\sim 13 \text{ arcmin}^{-2}$ from Umetsu et al. (2012) in the Subaru sample.

4.2 Grid mass modelling

In contrast to the parametric strong lensing analysis in the core of the cluster, in the outskirts, we use a non-parametric mass modelling technique to map the mass distribution (Jauzac et al. 2012, 2015a, 2016; Gonzalez et al. 2020; Niemiec et al. 2020, 2023).

In MACS J1423, we here use a multiscale grid of potentials to decompose the matter distribution. The multiscale grid method (Jullo & Kneib 2009; Jauzac et al. 2012) uses an irregular grid composed of radial basis functions (RBFs) to add flexibility to the lensing mass reconstruction. RBFs are real value functions with radial symmetry fixed at all the nodes of the grid. The multiscale grid is created from a smoothed lightmap of the cluster, and is recursively refined in the densest regions. The distribution of the cluster members is used to create a lightmap. We use SExtractor segmentation map to extract the light corresponding to these galaxies from the *HST F814W* image and smooth it with a Gaussian kernel to get a smoothed lightmap. On this smoothed lightmap, an hexagonal geometry of grid centred on the cluster core is adopted which recursively split into

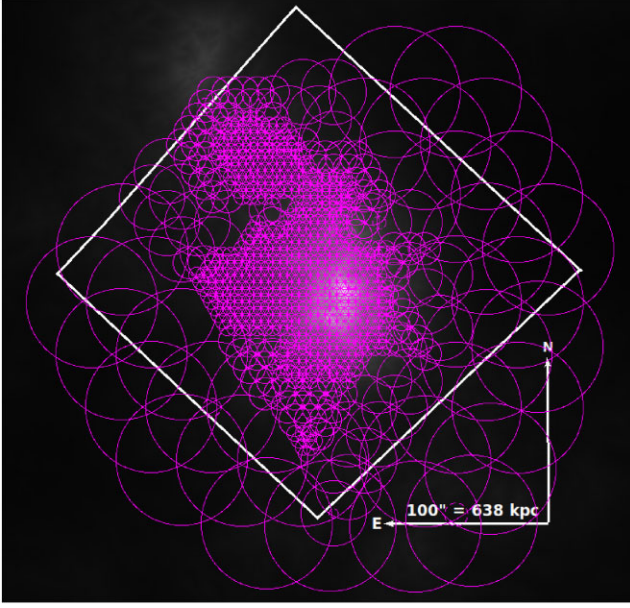


Figure 5. Smooth light map of MACS J1423. The non-parametric grid of potentials used for our weak lensing analysis is highlighted with magenta circles. The grid is multiscale, i.e. with a finer resolution in the densest regions of the cluster. The grid is composed of 162 RBFs, the densest regions modelled by RBFs with a core radius of 10.6 arcsec. The ACS field of view is shown by the white box.

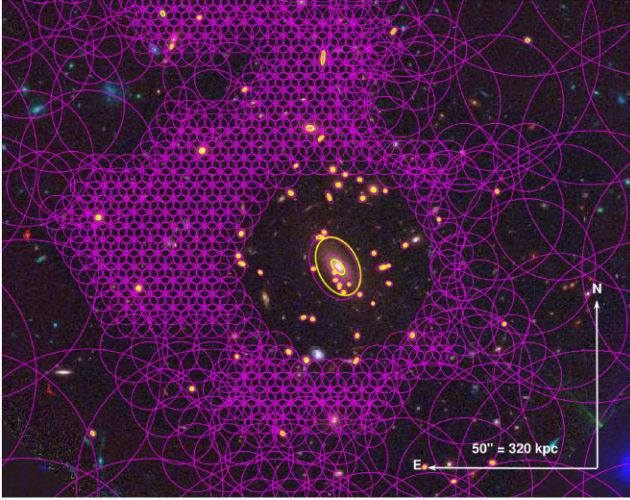


Figure 6. A zoom-in colour composite image on the core of MACS J1423 to highlight the combined strong and weak lensing analysis pursued in this work. The strong lensing mass components, fixed to the best-fitting parametric mass model, are shown in yellow, and the non-parametric grid potentials are shown in magenta.

six equilateral triangles (see Jullo & Kneib 2009, for more detail). Each RBF is modelled with a truncated isothermal mass distribution (TIMD; i.e. a circular version of dPIE used for our parametric mass modelling in Section 3.3). This profile consists of a two component pseudo-isothermal mass distribution with a core radius, s , defined as the distance between an RBF and its closest neighbour, and a cut radius, t (Jullo & Kneib 2009). The true convergence field, $\kappa(\theta)$, is

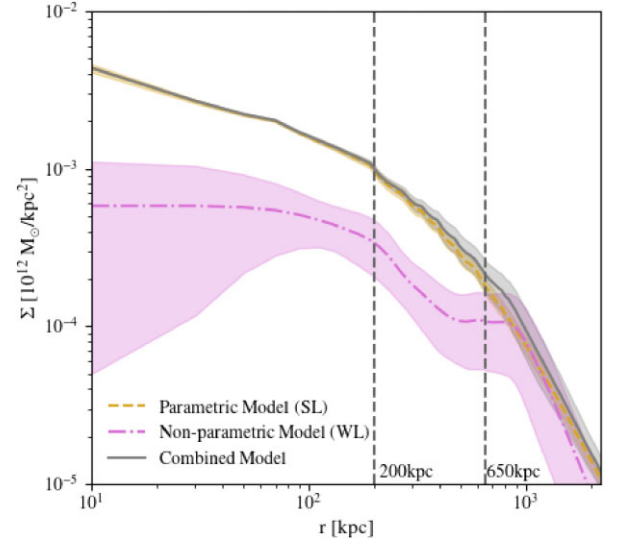


Figure 7. The surface mass density profiles of MACS J1423. The only strong lensing (Section 3) and weak lensing (Section 4) analysis are represented in yellow and magenta colour, respectively. The profile in grey colour shows the combined model. The two vertical dark grey dashed lines represents the end of strong lensing and weak lensing regions, respectively from left to right.

given by:

$$\kappa(\theta) = \frac{1}{\Sigma_{\text{crit}}} \sum_i v_i^2 f(|\theta_i - \theta|, s_i, t_i), \quad (5)$$

where the RBF at the grid node, θ_i , is defined as:

$$f(R, s, t) = \frac{1}{2G} \frac{t}{t-s} \left(\frac{1}{\sqrt{s^2 + R^2}} - \frac{1}{\sqrt{t^2 + R^2}} \right). \quad (6)$$

In a TIMD profile, the scaling factor, v_i^2 , is the velocity dispersion at the centre of the gravitational potential, i . The cut radii of all grid potentials are fixed to $s = 3t$ (Jullo & Kneib 2009).

Following this, the shear field is written as

$$\gamma_1(\theta) = \sum_i v_i^2 \Gamma_1^i(|\theta_i - \theta|, s_i, t_i), \quad (7)$$

$$\gamma_2(\theta) = \sum_i v_i^2 \Gamma_2^i(|\theta_i - \theta|, s_i, t_i), \quad (8)$$

where Γ_1 and Γ_2 are given in equation (A8) in Elíasdóttir et al. (2007).

The ellipticity measurements in the weak lensing regime can be approximately given as a liner relation,

$$\mathbf{e} = \mathbf{M}_{\gamma} \mathbf{v} + \mathbf{n}, \quad (9)$$

where $\mathbf{v}$ contains the amplitude of the RBFs and $\mathbf{n}$ gives the intrinsic ellipticity and the noise in the shape measurements. The shear components of the matrix $\mathbf{M}_{\gamma}$ containing the cross-contribution of each individual RBF to each individual weak lensing source are scaled by a ratio of angular diameter distances. The elements of this matrix for the two shear components are given by:

$$\Delta_1^{(j,i)} = \frac{D_{LS,i}}{D_{OS,i}} \Gamma_1^i(|\theta_i - \theta_j|, s_i, t_i), \quad (10)$$

$$\Delta_2^{(j,i)} = \frac{D_{LS,i}}{D_{OS,i}} \Gamma_2^i(|\theta_i - \theta_j|, s_i, t_i), \quad (11)$$

where the elements corresponds to the contribution from each unweighted RBFs j to the shear of image i , and Γ_1 and Γ_2 are given in equation (A8) in Elíasdóttir et al. (2007).

After testing different grid resolutions, we converge on an optimal grid composed of 628 RBFs. Core radii, s , are ranging from 5 and 40 arcsec. The grid is constructed using the smoothed lightmap of the cluster which is made using publicly available scripts.⁵ The resulting grid is shown in Fig. 5 on the smoothed cluster lightmap. Each circle on the lightmap represents one RBF potential, and the densest region corresponds to $s = 5$ arcsec. Our grid only model, covering the full ACS field (100 arcsec or 640 kpc), uses only background galaxies as constraints. The surface mass density for the corresponding model is shown in Fig. 7. The projected surface mass within the full ACS field is $M(R < 640 \text{ kpc}) = (2.1 \pm 0.8) \times 10^{14} M_{\odot}$.

5 COMBINING STRONG AND WEAK LENSING

In order to obtain a full mass reconstruction of MACSJ1423, we need to combine our parametric strong lensing mass model with the non-parametric weak lensing one. For that, we follow the sequential method described initially in J15 and then developed further in Niemiec et al. (2020, 2023). First, the core is modelled using the strong lensing constraints as described in Section 3. To the best-fit parametric model of the core, the multiscale grid of potentials described in Section 4.2 is added in the outskirts of the cluster. The observed ellipticity from the sum of the two components of our model can be written as

$$\mathbf{e}_m = M_{\gamma v} \mathbf{v} + \mathbf{e}_{\text{param}} + \mathbf{n}, \quad (12)$$

where $\mathbf{v}$ contains the amplitude of the RBFs of the multi-scale grid, $\mathbf{e}_m = (\mathbf{e}_1, \mathbf{e}_2)$ corresponds to the individual shape measurements of the weak lensing sources, and $\mathbf{e}_{\text{param}}$ is the fixed ellipticity from the best fit strong lensing model. $\mathbf{n}$ represents the galaxy shape noise component, and $M_{\gamma v}$ is the matrix which contains the contribution of individual RBFs. This matrix is presented in Section 4.2.

As said before, we proceed to a sequential fit. The parametric model presented in Section 3.3 is fixed at its best-fitting values. As shown in Fig. 7, the error on the parametric model in the cluster core is much smaller than the error on the grid model. Consequently, fixing this component to the best-fitting should not have a significant impact on the overall error propagation and model-fitting process. The RBF amplitudes are then estimated from the weak lensing constraints. This also ensures that strong lensing constraints are not taken into account twice. Already optimized cluster scale dark matter halo and cluster member galaxies are combined with the RBF grid potentials. As explained in Section 4.2, grid potentials are removed from the cluster core due to the absence of weak lensing constraints in this region. A zoom-in combined parametric and non-parametric potentials is shown in Fig. 6. The projected surface mass density resulting from our combined strong and weak lensing mass model of MACSJ1423 is shown in Fig. 7. We also decompose the contribution of the strong and weak lensing optimization in Fig. 8. We measure a (combined strong and weak lensing) projected mass over the full *HST*/ACS field of view ($R < 100$ arcsec) of $M(R < 640 \text{ kpc}) = (6.6 \pm 0.6) \times 10^{14} M_{\odot}$.

6 DISCUSSION AND CONCLUSION

6.1 Comparison between different models

There are three main models presented in this paper: the parametric model for the cluster inner core, the non-parametric grid model the outskirts, and the combined model accommodating both strong and

weak lensing regions. Mass contours corresponding to all these three models are shown in Fig. 4. In addition to these contours, we also show the smoothed X-ray surface brightness contours. A general trend in the elongation of the system is seen for all models even if some deviations can be seen in mass contours from the grid only model as compared to the parametric and combined models. Fig. 7 shows the two-dimensional surface density profile for our three models. As seen in Fig. 7, the amplitude of the grid only model is low compared to the parametric and combined model throughout the cluster region. In the core of the cluster, this is assignable to the absence of strong lensing constraints and the contribution from any cluster scale halo. However for the outer regions, either the grid only model is underestimating the mass or there is an overestimation from the parametric model. A plausible explanation to the later can be that outer regions of the cluster are affected by the elongation of the cluster scale halo (with $r_{\text{cut}} = 1000$ kpc). To inspect this, we ran a parametric model including weak lensing constraints in the outskirts along with strong lensing constraints in the core. The presence of constraints (weak lensing) in the outer regions of the cluster can be used to constrain r_{cut} of the cluster scale halo. The difference in the surface density was not resolved even after constraining the cluster scale r_{cut} . Similar problems are also seen in Niemiec et al. (2023) with a much more complicated cluster using same techniques as described in this paper. The reason for this difference in the amplitude between the grid only and combined model in the outskirts needs to be investigated.

6.2 Comparison with previous works

In L10, mass modelling is slightly different than in this work, even if both analyses uses LENSTOOL. While we optimize the BCG independently from the other cluster galaxies (which are assumed to follow a scaling relation), L10 assumed the BCG follows the scaling relation presented in equation (2). They measure a projected mass within 65 arcsec (~ 415 kpc) of $M_{\text{L10}}(R < 415 \text{ kpc}) = (4.3 \pm 0.6) \times 10^{14} M_{\odot}$ which is within the errorbars of our strong + weak lensing analysis, $M(R < 415 \text{ kpc}) = (4.4 \pm 0.3) \times 10^{14} M_{\odot}$.

Z15 uses a different algorithm than in this work, LTM (light-traces-mass), and its dPIE+NFW (Navarro–Frenk–White; Navarro, Frenk & White 1996b) version of it. Z15 quotes an rms of 1.21 arcsec, and 1.47 arcsec for LTM and dPIE+NFW, respectively, slightly higher than the rms of 0.9 arcsec obtained with our strong lensing analysis. Zitrin et al. (2011) measure a projected strong lensing mass enclosed within an effective Einstein radius of 20 arcsec (~ 130 kpc) of $M_{\text{Z11}}(R < 130 \text{ kpc}) = (1.30 \pm 0.40) \times 10^{14} M_{\odot}$. This is in good agreement with what we obtain $M(R < 130 \text{ kpc}) = (0.96 \pm 0.01) \times 10^{14} M_{\odot}$ for our strong lensing model.

The Sunyaev–Zel’dovich (SZ) effect analysis presented in LaRoque et al. (2003) quotes a mass of $M_{\text{LR03}}(R < 415 \text{ kpc}) = 5.0^{+3.1}_{-0.9} \times 10^{14} M_{\odot}$. The *Chandra* X-ray analysis from Schmidt & Allen (2007) quotes a mass of $M_{\text{SA07}}(R < 415 \text{ kpc}) = 3.1^{+0.9}_{-0.7} \times 10^{14} M_{\odot}$. The SZ measurement fall within the error bars of mass estimates we obtain with this work. However, the mass estimate obtained from the X-ray analysis is lower than what we measure. L10 discuss this discrepancy and provide a possible explanation to the line-of-sight elongation of MACSJ1423. A summary of all masses compared to in this work is given in Table 6 and Fig. 9.

Recently, Mowla et al. (2024) discovered a $z = 8$ galaxy, calling it the Firefly Sparkle arc in MACSJ1423 using *JWST* data. They measure magnification between 16 and 26, with the centre of the arc being magnified by a factor of 24 using a strong lensing model. When compared to work presented in this paper, we measure

⁵https://github.com/AnnaNiemiec/grid_lenstool

Table 6. A summary table to compare the mass of MACS J1423 with previous works. The masses measured within 130, 200, 415, and 640 kpc using different methods are quoted in units of $10^{14} M_{\odot}$. The other works in the table corresponds to: LaRoque et al. (2003, hereafter LR03) and Schmidt & Allen (2007, SA07), Zitrin et al. (2011, hereafter Z11), Limousin et al. (2010, hereafter L10). We do not include our WL only model in the inner regions of the cluster i.e. for $R < 130$ and $R < 200$ kpc due to lack of WL constraints in these regions. Similarly, we do not include our SL only model in outer regions of the cluster i.e. for $R < 415$ and $R < 640$ kpc due to lack of SL constraints in these regions.

	Method	LR03	SA07	L10	Z11	This work
$R < 130$ kpc	SL only	–	–	–	1.3 ± 0.4	0.96 ± 0.01
	SL + WL	–	–	...	–	0.97 ± 0.02
$R < 200$ kpc	SL only	–	–	...	–	1.82 ± 0.05
	SL + WL	–	–	...	–	1.85 ± 0.05
$R < 415$ kpc	SZ	$5.0^{+3.1}_{-0.9}$	–	–	–	–
	X-rays	–	$3.1^{+0.9}_{-0.7}$	–	–	–
	WL only	–	–	–	–	1.3 ± 0.4
	SL + WL only	–	–	4.3 ± 0.6	–	4.4 ± 0.3
$R < 640$ kpc	WL only	–	–	–	–	2.1 ± 0.8
	SL + WL only	–	–	...	–	6.6 ± 0.6

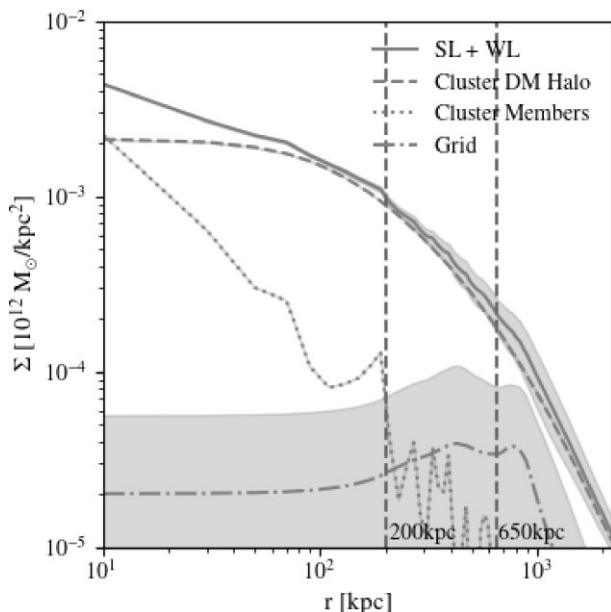


Figure 8. The surface mass density profiles of MACSJ1423. The full combined strong and weak lensing model is represented by the solid line. The different components of this model i.e. cluster scale halo, cluster members, and the grid potentials are shown in dashed, dotted, and dashed–dotted lines, respectively. The two vertical dark grey dashed lines represents the end of the strong and weak lensing regions respectively from left to right.

a magnification of 6 with our strong lensing only model and a magnification of 17 with our strong + weak lensing model. The reason for this difference may be the fact that our models do not include a faint galaxy located near this lensed arc, which may be giving a boost in the magnification locally. Fig. 10 shows the firefly galaxy in white and this local galaxy in red.

6.3 The baryonic mass distribution

6.3.1 Gas and stellar mass distribution

We follow the procedure presented in Beauchesne et al. (2024) to estimate the X-ray gas-density and gas-mass profiles for MACS 1423

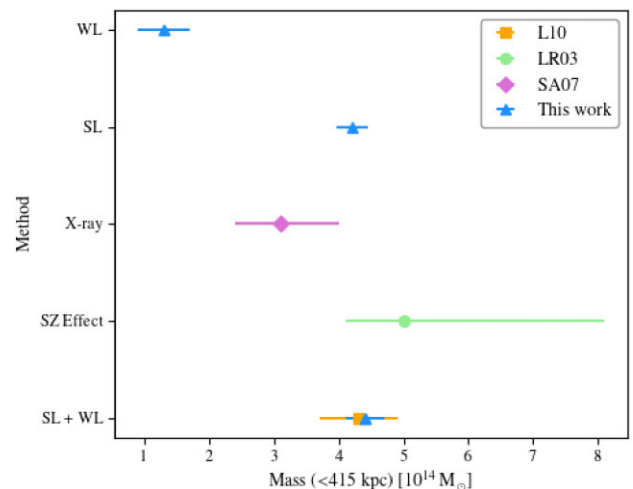


Figure 9. A visual representation of the different masses given in Table 6. The methods used to estimate the enclosed mass within 415 kpc is shown from previous studies: Limousin et al. (2010, hereafter L10), LaRoque et al. (2003, hereafter LR03), and Schmidt & Allen (2007, hereafter SA07).

using *Chandra* data (see Section 2.2). The X-ray peak emission in the cluster is also measured using the publicly available code PYPROFFIT (Eckert et al. 2020). We find that the X-rays and lensing distributions are aligned, i.e. the X-rays peak at the centre of the cluster location of BCG. We measure a gas mass of $M_{\text{gas}}(R < 200 \text{ kpc}) = (0.16 \pm 0.0002) \times 10^{14} M_{\odot}$. The gas mass is converted into gas fraction by taking the ratio between the gas mass and the mass of the cluster with 200 kpc. We estimate a gas fraction of $f_{\text{gas}}(R < 200 \text{ kpc}) = 0.08 \pm 0.01$.

To measure the stellar mass distribution, we follow the procedure described in Jauzac et al. (2015a). We estimate the stellar masses of cluster galaxies using the relation $\log(M_*/L_K) = az + b$, where z is the redshift of the cluster, here $z = 0.545$. The relation established by Arnouts et al. (2007) for quiescent (red) galaxies in the VVDS survey (Le Fèvre et al. 2005), adopting a Salpeter initial mass function (IMF), and L_K is the luminosity in K band. The parameters a and b

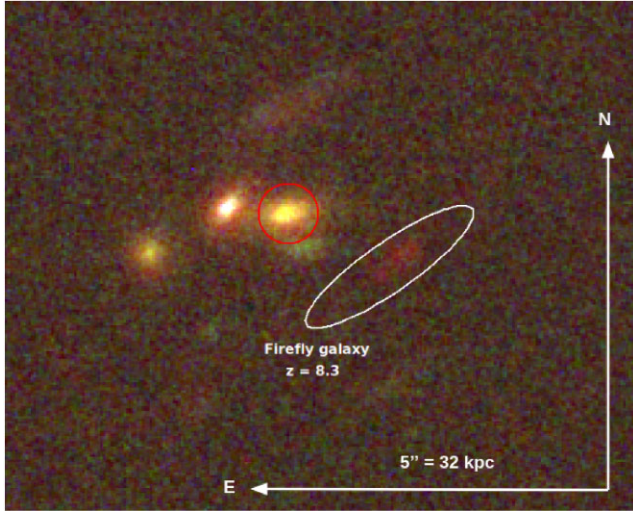


Figure 10. The firefly galaxy at $z = 8.3$ found by Mowla et al. (2024) is shown by the white ellipse. The galaxy highlighted in red may be giving a boost in the magnification locally. This *HST* image is created using the F606W for blue, F814W for green, and F160W for red colours.

are given by:

$$a = -0.18 \pm 0.03,$$

$$b = -0.05 \pm 0.03.$$

We apply this relation to our 66 cluster member galaxies. First, we estimate the K -band luminosity of our galaxies observed in F814W band using the theoretical models from Bruzual & Charlot (2003). Assuming a range of exponentially decaying star histories within the range $\tau = 0.1$ – 2 Gyr, we estimate a typical colour ($m_{F814W} - m_K$) = 1.5199 (AB system). We measure a total stellar mass within the full ACS field of view, $M_*(R < 640 \text{ kpc}) = (5.7 \pm 0.5) \times 10^{12} M_\odot$ and mass-to-light ratio of $M_*/L_K = 0.7 \pm 0.1 M_\odot/L_\odot$. The fraction of total mass in stars, f_* , is estimated by taking the ratio between the total stellar mass and the total mass of the cluster derived from our combined strong and weak lensing analysis. We find a stellar fraction of $f_* = 0.006 \pm 0.001$ across the ACS field of view.

6.3.2 Baryon fraction

We use the derived gas and stellar masses to estimate the baryon fraction within the cluster. Fig. 11 shows the mass contribution from the gas and stars in the cluster as well as the baryon fraction. We see that the gas fraction increases as a function radius while the stellar fraction drops as we move away from the centre. Within the ACS field of view, 640 kpc from the centre core, we measure a gas fraction of 0.09 ± 0.01 and a stellar fraction of 0.006 ± 0.001 . The total baryon fraction within this radius is thus $f_b = 0.095 \pm 0.012$. The cosmic baryon fraction measured by Planck Collaboration VI (2020) is 0.154 and the baryon fraction in cluster is 0.153 (Krolewski & Percival 2024). The discrepancy might be due to several factors. Since the selection of cluster members mostly considered red galaxies and the ones spectroscopically confirmed are confined to the MUSE field (only $1 \text{ arcmin} \times 1 \text{ arcmin}$), the contribution from less massive star-forming galaxies is not accounted for. Moreover, we are not including the stellar mass from the ICL which can account for 10–40 per cent of the total stellar mass in the cluster (Gonzalez, Zaritsky & Zabludoff 2007; Giodini et al. 2009; Laganá et al. 2013).

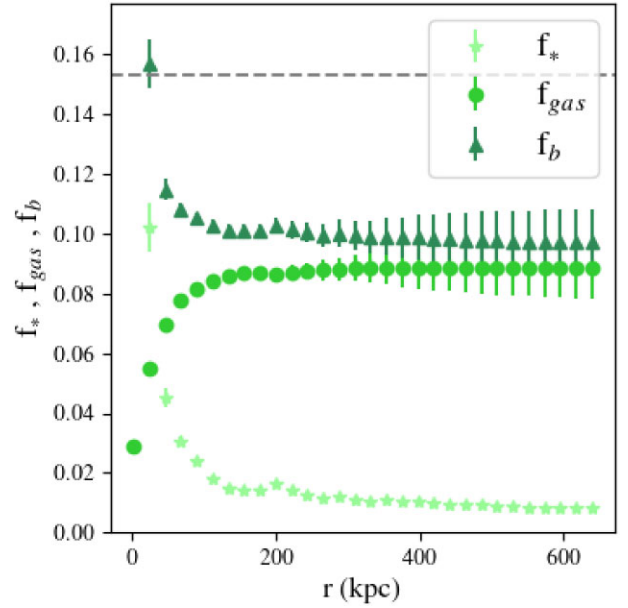


Figure 11. Fractions of stars, gas, and baryons within the ACS field of view, 640 kpc from the centre core. The grey dashed line represents the baryon fraction in cluster (Krolewski & Percival 2024).

6.4 A possible test bench for dark matter

Estimating the three-dimensional matter distribution in galaxy clusters plays an important role in testing the Λ CDM. Owing to the fact that lensing is sensitive to the integrated mass along the line of sight, the mass of a cluster is often overestimated due to the presence of mass concentrations not physically related to the cluster or to divergences from the spherical symmetry (Gavazzi 2005). It was common practice to study dark matter distribution in clusters using X-rays and the assumption of spherical symmetry until departures from isothermality and spherical symmetry was found in *XMM-Newton* and *Chandra* observations in the core of several clusters. Moreover, the CDM paradigm predicts highly elongated axis ratios for dark matter haloes in clusters (Wang & White 2009), contradicting the assumption of spherical shape. In a study by Gavazzi (2005), it was found that the discrepancy between the X-ray and gravitational lensing measurements can be explained by a non-spherical shape of clusters. Evidently, several studies suggest that prominent strong lensing observations are often accompanied by preferential elongations along the lines of sight or major axes preferentially oriented towards the lines of sight (Corless, King & Clowe 2009; Peng et al. 2009).

The three-dimensional shape of the MACSJ1423 has been investigated in the past by Morandi & Limousin (2012) and Limousin et al. (2013), concluding that the cluster is rather triaxial in shape and elongated along the line of sight. Morandi & Limousin (2012) find that the cluster is triaxial, with a dark matter halo axis ratio of 1.53 ± 0.15 and 1.44 ± 0.07 , on the plane of sky and along the line of sight, respectively. Their study suggested that the mass discrepancy between X-rays and lensing can be solved with such a geometry. As mentioned earlier, the mass estimate from our strong + weak lensing analysis is larger than the X-rays, which might be due presence of structure along the line of sight as noted by Limousin et al. (2010), (2013) and Morandi & Limousin (2012).

The Λ CDM model predicts a cuspy central density profile for dark matter haloes (Navarro, Eke & Frenk 1996a; Gao et al. 2012), while

observations indicate a flattened core (Sand et al. 2008; Navarro et al. 2010). Understanding dark matter distribution is crucial for studying the formation of galaxies and clusters, and understanding the properties of dark matter. Precise mass measurements using gravitational lensing and ground-based spectra can help constrain central density profiles (Newman et al. 2011, 2013b, c). In particular, the presence of radial arcs in the core of clusters are a now well recognized and powerful tool to constrain the very central ($R < 20$ kpc) mass distribution in galaxy clusters (Hattori, Kneib & Makino 1999). As discussed in Section 3.1, MACSJ1423 has two radial arcs (images 1.5 and 4.5), making this cluster an excellent candidate to be used as a dark matter test bench following similar methods as the ones presented in Wyithe, Turner & Spergel (2001) and Newman et al. (2013a). The recent analysis by Cerny et al. 2024 (submitted to MNRAS) presents a new way to use radial arcs as dark matter probes, following the work from Newman et al. (2013a). Cerny et al. 2024 (submitted to MNRAS) utilize lower-quality *HST* and VLT/MUSE KALEIDOSCOPE data, enabling systematic analysis without extensive high-resolution spectroscopy. Such analysis considering MACSJ1423 as part of a cluster sample is being pursued by our team.

6.5 Summary and conclusion

We present a combined strong and weak lensing mass model of the massive galaxy cluster MACSJ1423 at $z = 0.545$, one of 12 high-redshift MACS clusters (Ebeling et al. 2001). We model the cluster using a sequential fit which is composed of two different steps: (i) the modelling of the strong lensing region using a parametric mass model for which we assume that light traces mass, and (ii) the modelling of the weak lensing region using a multiscale grid of potentials in order to include more flexibility in the modelling of this region where the lensing signal is much more diffuse than in the core.

Our strong lensing model is optimized using four multiple image systems, of which system 3 is spectroscopically confirmed with MUSE. We take advantage of VLT/MUSE observations of the core of MACSJ1423, taken as part of the KALEIDOSCOPE survey which allowed us to confirm existing spectroscopic measurements of multiple image systems together with obtaining new spectroscopic measurements for 39 cluster galaxies. We compile a cluster galaxy catalogue composed of 66 galaxies using the red sequence technique and calibrated with our VLT/MUSE spectroscopic redshift measurements. Our best-fit mass model recovers the multiple image positions with an rms of 0.90 arcsec, and yields a projected enclosed mass of $M(R < 200 \text{ kpc}) = (1.82 \pm 0.05) \times 10^{14} M_{\odot}$.

In contrast to the parametric model in the core, since the positions of mass clumps are not known in the outskirts, a more flexible, non-parametric grid of mass potentials is used. The weakly lensed background galaxies, carrying the weak lensing signal, are used as constraints in the outskirts. We use 723 background galaxies selected within the *HST*/ACS field of view, i.e. a density of 57 gal arcmin $^{-2}$. The weak lensing only model yields a projected enclosed mass of $M(R < 640 \text{ kpc}) = (3.8 \pm 0.8) \times 10^{14} M_{\odot}$.

To combine strong and weak lensing analyses, we use the sequential fit method as described in Jauzac et al. (2015b) and Niemiec et al. (2020, 2023). To the parametric best-fit model of the cluster core, a non-parametric grid is added to model outskirts of clusters. The combined strong and weak lensing analysis of MACSJ1423 yields a mass of $M(R < 200 \text{ kpc}) = (1.85 \pm 0.05) \times 10^{14} M_{\odot}$ in the core, and an enclosed mass of $M(R < 640 \text{ kpc}) = (6.6 \pm 0.6) \times 10^{14} M_{\odot}$ within the full *HST*/ACS field of view ($R < 100$ arcsec).

The high mass, strong lensing power and relaxed dynamical state of MACSJ1423 are powerful criteria to use as a possible dark matter test bench. The mass discrepancy between our lensing analysis and X-rays suggests elongation along the line of sight, indicating triaxial geometry of the cluster. This can be used to further investigate and test the Λ CDM paradigm of the Universe. Furthermore, the high redshift of the cluster, helps in understanding of the formation and evolution of structure in the early Universe.

ACKNOWLEDGEMENTS

NP was supported by the Science and Technology Facilities Council (STFC, grant numbers ST/S05365/1, ST/V506643/1, and ST/W507428/1). MJ was supported by the United Kingdom Research and Innovation (UKRI) Future Leaders Fellowship ‘Using Cosmic Beasts to uncover the Nature of Dark Matter’ (grant numbers MR/S017216/1 and MR/X006069/1). NP, AN, DL, and GM acknowledge support from the UKRI FLF grant numbers MR/S017216/1 and MR/X006069/1 as well. ML acknowledges the Centre National de la Recherche Scientifique (CNRS) and the Centre National des Etudes Spatiales (CNES) for support. This research was supported by the International Space Science Institute (ISSI) in Bern, through the ISSI International Team project #476 (‘Cluster Physics From Space To Reveal Dark Matter’).

DATA AVAILABILITY

The CLASH *HST* data used for this work are available on the MAST archive in the CLASH repository for MACSJ1423.⁶ The lensing mass models and other data products will be shared by authors on request.

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