

**Precision modeling of Webb’s first cluster lens SMACSJ 0723.3–7327**

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**ABSTRACT**

Exploiting the fundamentally achromatic nature of gravitational lensing, we present a lens model for the massive galaxy cluster SMACS J0723.3–7323 (SMACS J0723, z = 0.388) that significantly improve upon earlier work. Building on strong-lensing constraints identified in prior Hubble Space Telescope (HST) observations, the mass model utilizes 21 multiple-image systems, 16 of which were newly discovered in Early Release Observational (ERO) data from the James Webb Space Telescope (JWST). The resulting lens model maps the cluster mass distribution to an RMS spatial precision of 1′′.08 and is publicly available\(^a\). Consistent with previous analysis, our study shows SMACS J0723.3–7323 to be well described by a single cluster-scale component centered on the location of the brightest cluster galaxy, but deviates by adding two more diffuse components West of the cluster. A comparison of the galaxy distribution, the mass distribution, and gas distribution in the core of SMACS J0723 based on HST/JWST, and Chandra data finds a fairly concentrated regular elliptical profile but also signs of recent merger activity, possibly close to our line of sight. The exquisite sensitivity of NIRCAM/JWST reveals in spectacular fashion both the extended intra-cluster-light distribution and numerous star-forming clumps in magnified background galaxies. The high-precision lens model derived here for SMACS 0723 demonstrated impressively the power of combining HST and JWST data for studies of structure formation and evolution in the distant Universe.

1. **INTRODUCTION**

Clusters of galaxies grow and evolve through large-scale merging processes and offer many valuable observables for astrophysical and cosmological studies of our Universe. In statistically representative samples, they uniquely constrain key parameters of complex physical processes, such as struc-

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\( ^a \) [https://www.dropbox.com/sh/3iatmz5k4hafzqf/AAAh0lVgLgpBVoL6q4vYZkFGa/?dl=0]
ture formation, but also the cosmological parameters characterizing the underlying world model (Jullo et al. 2007; Schwinn et al. 2016). By measuring the mass distribution within clusters, we also gain insight into cluster-specific properties, such as their dark-matter content, the spatial distribution and clustering of dark matter, and the cluster’s merger history (Bradač et al. 2008; Umetzu et al. 2009). Furthermore, offsets between the location of baryonic and dark-matter profiles have been used to probe the nature of dark matter (e.g., its self-interaction cross-section, Markevitch et al. 2004; Harvey et al. 2019).

Strong gravitational lensing provides an observational measure of the enclosed total mass of a cluster at a given radius and thus represents a powerful tool for studying both dark and luminous matter. Lensing occurs when the presence of mass generates a large enough curvature in space–time near the cluster centre to make different light paths from the same distant source converge within the field of view of the observer. Since the first spectroscopic confirmation of a giant gravitational arc in Abell 370 (Soucail et al. 1987), strong gravitational lensing has evolved into a valuable technique for measuring the total mass of clusters over a wide range of evolutionary states and redshifts (e.g., Limousin et al. 2007; Richard et al. 2011).

By refining the mass model of the lensing cluster through the identification of strong-lensing features, it is possible to quantify the magnifying power of the cluster for background sources at a given redshift, thereby calibrating galaxy clusters as cosmic telescopes for studies of the high-redshift Universe (e.g., Mahler et al. 2019; Fox et al. 2022). The correct identification of multiply imaged background sources is crucial in this context, because these are the features that most precisely probe the mass distribution in the cluster core. The high angular resolution of the Hubble Space Telescope (HST) (and now JWST) has proven crucial for such work to determine the source morphology and properly match lensed images as originating from the same source.

The most ambitious example of this quest to date was the Hubble Frontiers Field initiative (HFF, Lotz et al. 2016) which comprised very deep HST observations (~180 orbits per target) in seven optical and near-infrared passbands. The HFF observed six massive clusters ($M \approx 10^{15} M_\odot$) at $z = 0.3–0.6$, selected for their lensing power and, specifically, their capability to strongly magnify very distant ($z > 6$) galaxies. The resulting deep images revealed a remarkable collection of hundreds of multiple images and were showcased in numerous publications (e.g., Jauzac et al. 2014, 2016; Mahler et al. 2018).

Providing an order-of-magnitude improvement in sensitivity, the James Webb Space Telescope (JWST) represents another dramatic step forward in our efforts to probe the distant Universe to ever larger depth with gravitational lensing. The enormous promise of JWST is exemplified in the release of JWST’s first deep cluster observation, results from which are discussed and assessed in this paper.

Our paper is structured as follows. After a brief introduction of the target and the history of its discovery (Section 2), we summarize the most relevant ground- and space-based observations of SMACS 0723 in Section 3. Section 4 provides an overview of the analysis and modeling techniques used, and Section 5 describes the results obtained. We present a summary and conclusions in Section 6.

2. SMACSJ0723

SMACS J0723 was discovered in the course of the southern extension of the Massive Cluster Survey (MACS; Ebeling et al. 2001) and is included in the partial release of the MACS sample by Repp & Ebeling (2018).

The system’s initial identification as a putative distant cluster was based on the presence of an unidentified X-ray source, 1RXSJ072319.7–732735, comprising 64 photons detected in a 531 s exposure accumulated during the ROSAT All-Sky Survey (RASS; Voges et al. 1999). The source’s high X-ray hardness ratio of 0.95 (HR1 in RASS parlance), very high even at the relatively high neutral-hydrogen density of more than $10^{21}$ cm$^{-2}$ at the source’s low Galactic latitude ($b = -23$ deg), its high likelihood of being extended, as well as the absence of alternative plausible optical counterparts in shallow, archival Digital Sky Survey images, rendered 1RXSJ072319.7–732735 a prime candidate for follow-up observations. Consequently, SMACS J0723 was targeted in imaging and low-resolution spectroscopy observations with the 3.5m New Technology Telescope at the European Southern Observatory (ESO) in 2002 and 2003, respectively, which unambiguously confirmed the system as a massive cluster and established its tentative redshift as $z = 0.404$.

3. OBSERVATIONS AND DATA REDUCTION

3.1. Optical and NIR imaging

3.1.1. James Webb Space Telescope

SMACS J0723 was observed in early June 2022 with several instruments aboard JWST as part of the observatory’s Early Release Observations. Specifically, deep imaging was performed in the NIRCAM filters F090W, F150W, F200W, F277W, F356W, and F444W (Fig. 1). The central field was also imaged with MIRI and NIRISS.

Our analysis combines pre-JWST observations (described below) with NIRCAM data and NIRSpec spectroscopy.

3.1.2. Hubble Space Telescope

SMACS J0723 was observed several times with multiple instruments aboard the Hubble Space Telescope (HST): first in the optical regime with the Wide Field and Planetary Camera 2 (WFPC2; in F606W and F814W filters) in 2008 (GO-11103,
Figure 1. JWST/ NIRCam image of a $2 \times 2$ arcmin$^2$ area centred on the brightest cluster galaxy (BCG) of SMACS J0723. The overlaid white contours show the X-ray surface brightness (adaptively smoothed to 3$\sigma$ significance using the algorithm of Ebeling et al. 2006) as observed with Chandra. Contours are spaced logarithmically by factors of 1.5, starting at three times the background level. The astrometric alignment of the two underlying images is accurate to about 1$''$. The overlaid magenta contours show the mass density distribution of the derive lensing mass profile and show remarkable agreement with the X-ray. In addition, the excess of mass on the right part of the cluster can also be hinted from the smooth low surface brightness ICL.

3.2. Spectroscopy

3.2.1. ESO

Shallow (3\times970 s) observations of the cluster were undertaken in March 2019 moderate seeing conditions (0.72$''$) for Programme 0102.A-0718(A) (PI Edge) with the MUSE integral field spectrograph on the ESO Very Large Telescope. The observation covered a 1$\times$1 arcmin$^2$ region centered on the BCG of SMACS J0723 and yielded spectra in the range from 475 to 930 nm for both lensing features and foreground/cluster galaxies.

The reduction of the MUSE data cube was performed using the official ESO pipeline (Weilbacher et al. 2020), with a number of specific improvements regarding self-calibration and sky subtraction specific to the crowded fields of lensing clusters. These are extensively discussed in Lagattuta et al. (2022) and Richard et al. (2021).

3.2.2. JWST
As part of the JWST’s Early Release Observations of SMACS J0723, the observatory also acquired spectroscopic data with the Micro-Shutter-Array (MSA) NIRSpec of 58 individual galaxies, as well as spectra of all objects in the entire field with NIRISS in Wide-Field Slitless mode. The total on-source exposure time ranged from 1.5 to 5 hrs. Our first analysis presented here uses primarily NIRSpec MSA data of various multiple images in the form of reduced 2D spectra and 1D extracted spectra directly available in the data release.

3.3. X-ray imaging spectroscopy

SMACS J0723 was observed with the Advanced CCD Imaging Spectrometer (ACIS-I) aboard the Chandra X-ray Observatory on April 14, 2014. The observations (Sequence Number 801329; ObsID 15296; PI Murray) were performed in VFAINT mode for a total duration of 19.8 ks. We performed a standard reduction of the data using CIAO\textsuperscript{4} and CALDB\textsuperscript{9}. We removed point sources automatically detected by the WAVEDETECT routine or by visual inspection. Background flares were corrected by running the DEFLARE tool in the 9.5–12 keV band and for the whole energy range. We used the blank-sky background data associated with the observation as provided by the standard pipeline.

4. METHODS

4.1. Strong-lensing mass modelling

We compute a mass model of SMACS J0723 based on strong-lensing constraints identified in the cluster core, using the publicly accessible strong-mass modeling algorithm Lenstool (Jullo et al. 2007). We provide a short summary of our approach here and refer the reader to Kneib et al. (1996), Smith et al. (2005), Verdugo et al. (2011) and Richard et al. (2011) for more details. The cluster mass distribution is modeled as a series of dual pseudo-isothermal ellipsoid (dPIE, Elíasdóttir et al. 2007) parametric mass halos with seven free parameters: the position Δ\(\alpha\), Δ\(δ\) relative to a reference location; ellipticity \(\epsilon\); position angle \(\theta\); normalization \(\sigma_0\); truncation radius \(r_{\text{cut}}\); and core radius \(r_{\text{core}}\). We use as constraints the positions of prominent light peaks in each lensed image, as well as their spectroscopic redshifts where available (see Section 5.2). The Lenstool algorithm uses a Monte Carlo Markov Chain (MCMC) formalism to explore the parameter space and identifies the best fit as the set of parameters that minimizes the scatter between the observed and predicted image-plane positions of the lensed features.

The lens plane is modeled as a combination of cluster-scale and galaxy-scale dPIE halos. For the cluster-scale DM halos, we fix the truncation radius \((r_{\text{cut}})\) at 1500 kpc since it is too far beyond the strong-lensing region to be constrained by multiple images. All other parameters are optimized unless otherwise indicated.

Galaxy-scale halos represent the contribution to the lensing potential from cluster member galaxies (e.g., Jauzac et al. 2019; Sharon et al. 2020). Their positional parameters (Δ\(\alpha\), Δ\(δ\); \(\epsilon\); \(\theta\)) are fixed to their observed values as measured with Source Extractor (Bertin & Arnouts 1996). The cluster-member catalog relies on HST photometry, as the two filters F606W and F814W (which straddle the Balmer break at the cluster redshift) provide a color gradient that allow us to isolate cluster member galaxies in the so-called red sequence (Gladders & Yee 2000). To keep the number of model parameters manageable in terms of computing time, the slope parameters of the galaxy-scale potentials are scaled to their observed \(i\)-band luminosity with respect to \(L^\ast\), using a parametrised mass-luminosity scaling relation (see Limousin et al. 2007 and discussion therein about the validity of such parametrisation), leaving only the cut radius, \(r_{\text{cut}}\), and the central velocity dispersion, \(\sigma_0\), free to vary. The BCG is modeled separately, since extremely luminous central cluster galaxies often do no follow the general scaling relation (Newman et al. 2013b,a). The models derived here are publicly available\textsuperscript{2}; a constantly updated website will refer to other repositories\textsuperscript{3}.

4.2. X-ray analysis

To recover the properties of the gaseous intracluster medium (ICM) from the existing short Chandra X-ray observation of SMACS J0723, we model the spectrum of the emission with the Astrophysical Plasma Emission Code (APEC)\textsuperscript{4}, adopting abundance ratios as provided by Asplund et al. (2009). To account for foreground absorption, we complement this main spectral component with a photoelectric-absorption model\textsuperscript{5}. The contribution from background emission is incorporated by creating an empirical model of the blank-sky background with B-spline functions whose coefficients were obtained through a fit of the blank-sky spectrum for the ACIS-I CCD on which the cluster is observed. We then keep the shape of the background spectrum constant in the fitting procedure and allow only its normalization to vary.

We perform all modeling within the \textsc{Sherpa} fitting environment (Freeman et al. 2001) combined with the \textsc{Python} wrapper of the \textsc{MultiNest} nested sampling package (Buchner et al. 2014; Feroz et al. 2019) to explore the parameter

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\textsuperscript{4} https://cxc.cfa.harvard.edu/ciao/

\textsuperscript{5} http://atomdb.org/

\textsuperscript{2} https://sites.google.com/view/guillaume-mahler-astronomer/smacs0723-precise-lens-modelling

\textsuperscript{3} https://www.dropbox.com/sh/3iatmz5k4hafzqf/AAAh0vLggBVoLP6qxsYZkFGa?dl=0

\textsuperscript{4} https://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/manual/XSmodelPhabs.html
Figure 2. Color image of SMACS J0723 with multiple images used in our models highlighted in green. Red and cyan curves are the critical curves at redshift $z=8.0$ for the two models, cyan is the model without additional clump and in red our main model from which we performed our analysis. The white square encloses the 'Beret' galaxy, a highly stretched spiral at $z = 1.16$ only partially multiply imaged (Sect. 5.2).

spaces of our model in the 0.5-8.0 keV energy band. As appropriate for the mostly low photon statistics per bin, we use a Poisson likelihood similar to $c\text{stat}^6$. Depending on the fit, not all emission model parameters are left free to vary. We consider the background normalization a nuisance parameter and marginalize over it in our best-fit estimates of all physical model parameters.

5. RESULTS

5.1. Cluster galaxies

In order to obtain an independent assessment of the dynamical state of SMACS J0723 as probed by the spatial and velocity distribution of the system’s member galaxies, we examine the MUSE data cube and extract a catalogue of 26 spectroscopically confirmed cluster members (Table 1).

Using the ROSTAT package of Beers et al. (1990) we derive an improved cluster redshift of $z = 0.3877$ for SMACS J0723 and determine the cluster velocity dispersion as $\sigma = 1180^{+180}_{-180}$ km s$^{-1}$. We show the corresponding redshift histogram in Fig. 3. Within the statistical uncertainties set by the small sample size, the radial-velocity distribution exhibits no significant substructure indicative of an active merger along an axis that lies close to our line of sight. We note, however, that the radial velocity of the BCG is clearly offset from the centroid of the distribution; this implied peculiar velocity might reflect incomplete relaxation after a recent line-of-sight merger.

5.2. Strong-lensing constraints

The strong-lensing features that constrain our lens model are given by the image-plane locations of multiple images of

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6 https://heasarc.gsfc.nasa.gov/xanadu/sspec/manual/XSappendixStatistics.html
lensed sources, identified either in previous \textit{HST} images or in the new \textit{JWST} observations.

Golubchik et al. (2022) identify five arc candidates in the field of SMACS J0723 and report three multiple-image systems that have spectroscopic redshifts. We confirm all of these in our examination of all available data and identify 16 additional multiple-image systems. Through careful inspection of the MUSE datacube (Section 3.2), we also secure an additional spectroscopic redshift for one of the systems photometrically identified by Golubchik et al. (2022); System 3 ($z = 1.9914$).

Initial inspection of the NIRSpec MSA spectroscopic data yields an additional spectroscopic redshift for system 3.2 ($z = 7.4518119$), confirming a star-forming region in image 7.2 to be at $z = 5.1727$, the highest spectroscopically confirmed image behind this cluster (Figure 4). We also confirm the redshift for the 'Beret' galaxy (Fig. 2), a highly stretched spiral galaxy only partially multiply imaged, at $z = 1.16$, which we do not include as a constraint.

All individual images are marked in Figure 2, and Table 2 summarizes the positions and spectroscopic redshifts (where available). Although all systems without spectroscopic confirmation should in principle be considered tentative identifications, we propose to adopt Systems 1, 2, and 3 as secure, in view of their unique morphology, identical for all of their multiple images.

\begin{table}[h]
\centering
\begin{tabular}{cccc}
\hline
R.A. & Dec & $z$ \\
\hline
110.80001 & -73.45269 & 0.3791 \\
110.80062 & -73.44852 & 0.3936 \\
110.80247 & -73.45867 & 0.3904 \\
110.80451 & -73.45615 & 0.3862 \\
110.81613 & -73.45119 & 0.3841 \\
110.81726 & -73.44940 & 0.3930 \\
110.81824 & -73.45462 & 0.3908 \\
110.81841 & -73.44827 & 0.3936 \\
110.81852 & -73.45524 & 0.3848 \\
110.82437 & -73.45991 & 0.3809 \\
110.82514 & -73.45454 & 0.3767 \\
110.82571 & -73.45869 & 0.3885 \\
110.82639 & -73.45999 & 0.3909 \\
110.82688 & -73.45463 & 0.3912 (BCG) \\
110.83269 & -73.45691 & 0.3867 \\
110.83683 & -73.45652 & 0.3981 \\
110.83763 & -73.45617 & 0.3895 \\
110.83780 & -73.45360 & 0.3864 \\
110.84009 & -73.45587 & 0.3908 \\
110.84564 & -73.45134 & 0.3845 \\
110.84875 & -73.46031 & 0.3970 \\
110.85310 & -73.45666 & 0.3838 \\
110.85378 & -73.45006 & 0.3844 \\
110.85506 & -73.45020 & 0.3864 \\
110.85574 & -73.45574 & 0.3815 \\
110.85626 & -73.45070 & 0.3872 \\
\hline
\end{tabular}
\caption{Right ascension and declination (J2000) as well as redshifts of the 26 cluster members identified in the MUSE observation of the core of SMACS J0723. The BCG is marked.}
\end{table}

\begin{table}[h]
\centering
\begin{tabular}{cccccc}
\hline
System ID & R.A. [deg] & Decl. [deg] & $z_{\text{spec}}$ & $\mu$ \\
\hline
1.1 & 110.8404700 & -73.4509750 & 1.449 & 3.793 \\
1.2 & 110.8427000 & -73.4547469 & 1.449 & 7.980 \\
1.3 & 110.8387600 & -73.4586919 & 1.449 & 3.080 \\
2.1 & 110.8384158 & -73.4510136 & 1.3779 & 3.415 \\
2.2 & 110.8405796 & -73.451389 & 1.3779 & 15.357 \\
2.3 & 110.8361008 & -73.4587836 & 1.3779 & 2.837 \\
3.1 & 110.8252662 & -73.4596951 & 1.9914 & 7.474 \\
3.2 & 110.8318272 & -73.4551207 & 1.9914 & 1.200 \\
3.3 & 110.8302941 & -73.4485580 & 1.9914 & 2.166 \\
3.4 & 110.8232158 & -73.4547636 & 1.9914 & 0.627 \\
4.1 & 110.8050400 & -73.4545361 & – & 10.028 \\
4.2 & 110.8068100 & -73.4583581 & – & 5.067 \\
4.3 & 110.8130600 & -73.4486939 & – & 3.283 \\
5.1 & 110.8237229 & -73.4518119 & 1.425 & 7.214 \\
5.2 & 110.8221554 & -73.4527017 & 1.425 & 24.826 \\
5.3 & 110.8207298 & -73.4601281 & 1.425 & 2.237 \\
6.1 & 110.8321200 & -73.4543750 & – & 1.039 \\
6.2 & 110.8217000 & -73.4541080 & – & 1.164 \\
6.3 & 110.8294800 & -73.4489140 & – & 2.706 \\
6.4 & 110.8228900 & -73.4616310 & – & 2.200 \\
7.1 & 110.8356027 & -73.4517354 & – & 6.897 \\
7.2 & 110.8365200 & -73.4530053 & – & 9.385 \\
7.3 & 110.8302054 & -73.4607783 & – & 2.326 \\
8.1 & 110.8292595 & -73.4557225 & – & 0.118 \\
8.2 & 110.8237650 & -73.4574778 & – & – \\
8.3 & 110.8296182 & -73.4473761 & – & – \\
\hline
\end{tabular}
\caption{Securely identified multiple-image systems, denoted by a "System.ID" nomenclature. "System" specifies the group of images originating from the same source galaxy, whereas "ID" refers to the name of the individual image. R.A. and Decl. are the right ascension and declination (J2000) of the image. $z$ is the measured spectroscopic redshift. Where errors are listed, the cited values are the mean redshift and the $1\sigma$ uncertainty from the lens-model optimisation.}
\end{table}
**Figure 4.** Identified emission lines of image 17.2, as revealed in NIRSpec/G395m observations. The combination of strong [OIII]5007 and Hα, associated with weaker [OIII]4959 and [NII], makes this redshift very robust.

| System ID | R.A. [deg] | Decl. [deg] | $z_{spec}$ | $\mu$ |
|-----------|------------|-------------|------------|-------|
| 9.1       | 110.8213633| -73.4505622| –          | 3.570 |
| 9.2       | 110.8166542| -73.4536869| –          | 3.789 |
| 9.3       | 110.8177396| -73.4589208| –          | 2.613 |
| 10.1      | 110.8206913| -73.4506744| –          | 3.712 |
| 10.2      | 110.8162196| -73.4534906| –          | 4.459 |
| 10.3      | 110.8171638| -73.4589111| –          | 2.541 |
| 11.1      | 110.8205446| -73.4525444| –          | 2.268 |
| 11.2      | 110.8203379| -73.4527633| –          | 29.317|
| 11.3      | 110.8204463| -73.4596864| –          | 2.247 |
| 12.1      | 110.7954292| -73.4485406| –          | 2.984 |
| 12.2      | 110.7945008| -73.4490581| –          | 10.357|
| 13.1      | 110.8125550| -73.4480347| –          | 3.006 |

| System ID | R.A. [deg] | Decl. [deg] | $z_{spec}$ | $\mu$ |
|-----------|------------|-------------|------------|-------|
| 13.2      | 110.8027083| -73.4548592| –          | 13.741|
| 13.3      | 110.8048946| -73.4588756| –          | 15.500|
| 14.1      | 110.8219646| -73.4490944| –          | 2.741 |
| 14.2      | 110.8112242| -73.4545281| –          | 2.961 |
| 14.3      | 110.8137933| -73.4589608| –          | 2.982 |
| 15.1      | 110.8257175| -73.4501981| –          | 3.158 |
| 15.2      | 110.8200154| -73.4538917| –          | 3.676 |
| 15.3      | 110.8212175| -73.4601403| –          | 2.487 |
| 16.1      | 110.8083567| -73.4493158| –          | –     |
| 16.2      | 110.8017854| -73.4525411| –          | –     |
| 16.3      | 110.8057167| -73.4590708| –          | –     |
| 17.1      | 110.7954292| -73.4485406| 5.1727     | 5.345 |
5.3. Mass distribution

5.3.1. Excess mass

The presence of two bright galaxies north-west of the BCG motivate the inclusion of an additional large-scale halo in our model to better accommodate two nearby multiply imaged galaxies (Systems 17 and 18, see 5.2). Moreover, the presence of another excess of diffuse light west of the BCG leads us to add a second large-scale component to account for the additional multiple image System 20.

To assess the importance of these additions, we run two models: one with only a cluster-scale halo around the BCG (Comparison Model in Table 5), and another one including the two additional large-scale halos described above near the two observed peaks of intra-cluster light (Fiducial model in Table 5). Figure 2 is showing the location of those clumps and Table 5 reference the specific parameters we obtained. Going further in the analysis, we only used the most complex models as it is the only one that can recover the geometry of System 20.

5.3.2. Comparison with previous works

We compare the results of our improved strong-lensing analysis with previous findings for SMACS J0723. Two of these existing models are part of the public release of RELICS cluster models, derived with Lenstool and GLAFIC. In addition, we compare our result to the recently published model of Golubchik et al. (2022), obtained using the LTM software.

Table 3 lists and compares the masses from all existing lens models for SMACS J0723 at three different radii: 128 kpc, 200 kpc, and 400 kpc. Here, 128 kpc corresponds to the largest cluster-centric distance of the strong-lensing constraints common to all models (this multiple-image system is labeled System 4 in our analysis). The masses within 200 kpc can be compared to the larger study by Fox et al. (2022) on 74 different clusters, whereas the radius of 400 kpc is the largest radius shared by all mass maps.

The full profile shown in Fig 5 highlights the differences between the various mass profiles. The LTM mass density falls significantly below other measurements at about 300 kpc. Additionally, Golubchik et al. (2022) reports a high RMS uncertainty of 2°/3. The RELICS models’ RMS (obtained through private communication) of 0°.5 is typical for similar cluster lens models based on a fairly limited number of multiple-image-systems. By contrast, our new models (which employ many more strong-lensing constraints) show an RMS of 1°/8, a value that falls near the high end of cluster mass models of similar complexity. While we quote masses at different radii for the different existing strong-lensing models in Table 3, Golubchik et al. (2022) give masses at two different radii, corresponding to Einstein radii derived with their model for source redshifts of z = 1.45 and z = 2: $M_{\text{Golubchik+22}, 78 \text{kpc}} = (3.42 \pm 0.47) \times 10^{13} \, M_\odot$, and $M_{\text{Golubchik+22}, 90 \text{kpc}} = (4.15 \pm 0.58) \times 10^{13} \, M_\odot$ respectively. Our model gives masses of $M_{\text{this work}, 78 \text{kpc}} = (3.79 \pm 0.01) \times 10^{13} \, M_\odot$, and $M_{\text{this work}, 90 \text{kpc}} = (4.69 \pm 0.01) \times 10^{13} \, M_\odot$and show a higher mass value. This disagreement beyond statistical uncertainties can be due to the assumption in the modelling and the addition of spectroscopic redshifts.

5.3.3. Dynamical state of SMACS J0723

The distribution of cluster members in SMACS J0723 suggests a single cluster-scale component. However, in order to recover the geometry of the newly discovered multiple images thanks to the JWST observations properly, i.e. minimize the RMS of our model, the overall mass distribution appears more complicated. Indeed, JWST observations allow us to see the ICL distribution in SMACS J0723, and while there are no evident substructure in the cluster member galaxy distribution West and South-West of the BCG, the distribution of the ICL shows extended features in these directions. These could be interpreted as remnant/tracers of a past dynamical activity in the cluster, and thus motivated the inclusion of 2 more large-scale halos in our mass model, named ICL1 and
ICL2 in Table 5. This final mass model has an RMS of 1\'0.08, compared to 1\'26 with a model which only includes a single cluster-scale halo around the BCG.

As discussed in Sect. 5.1, the radial velocity distribution of the cluster members obtained thanks to the MUSE data does not show any indication of the presence of substructures. However, the offset between the radial velocity of the BCG and the centroid of the distribution is an indication of an incomplete relaxation state of SMACSJ0723. The relatively complex mass distribution we obtain with our strong-lensing analysis is supporting this statement. The ICL is an extremely important component of the cluster mass distribution, a unique tracer of its dynamical history and its underlying dark matter distribution as demonstrated in recent works (e.g., Montes & Trujillo 2014; Montes 2019, 2022; Gonzalez et al. 2021; Deason et al. 2021). While it has remained extremely difficult to study with ground- and space-based telescopes so far, JWST is opening a new era. Without these observations, our mass model in the West and South-West regions would have been constructed based on a purely statistical motivation, i.e., reduce the RMS, and not supported by physical evidences of the presence of mass in the West and South-West regions of SMACSJ0723.

5.4. Magnification measurements

Thanks to the increased number of multiply imaged systems, as well as the availability of partial spectroscopic coverage to anchor the mass and shape of the cluster lens, we are able to derive magnification maps for SMACSJ0723 across the footprint of all JWST instruments. Figure 5.4 shows the magnification map obtained for sources at redshift \( z = 9 \).

### Table 4. Surface area in the source plane, \( \sigma_\mu \), above a given magnification factor, \( \mu \) for this work and previous models. We quote \( \sigma_\mu (> \mu) \) for \( \mu > 3, 5, \) and 10 for all models, and for a source at redshift \( z = 9 \).

| Model                  | \( \sigma_\mu(\mu > 3) \) | \( \sigma_\mu(\mu > 5) \) | \( \sigma_\mu(\mu > 10) \) |
|------------------------|---------------------------|---------------------------|----------------------------|
| this work              | 1.52                      | 1.0                       | 0.7                        |
| RELICS-Lenstool        | 1.5                       | 0.95                      | 0.5                        |

Following the method presented by Wong et al. (2012) and then applied to HFF analyses (e.g., Jauzac et al. 2014, 2015; Lam et al. 2014; Wang et al. 2015; Hoag et al. 2016), we use the surface area in the source plane, \( \sigma_\mu \), above a given magnification factor, \( \mu \), as a metric to quantify the efficiency of the lensing configuration to magnify high-redshift galaxies. \( \sigma_\mu \) is directly proportional to the unlensed comoving volume covered at high redshift at a given magnification \( \mu \). Figure 6 shows the evolution of \( \sigma_\mu (> \mu) \) as a function of the magnification obtained from our final mass model of SMACSJ0723 for a source at a redshift \( z = 9 \). Our model yields \( \sigma_\mu(\mu > 3) = 1.52 \, \text{arcmin}^2 \), \( \sigma_\mu(\mu > 5) = 1.0 \, \text{arcmin}^2 \), and \( \sigma_\mu(\mu > 10) = 0.7 \, \text{arcmin}^2 \). We compare these values with measurements obtained with the RELICS model which uses LENSTOOL, i.e., the same mass modeling algorithm as in this work. The values are listed in Table 4. The pre-JWST model gives smaller areas than what is obtained with the model presented in this paper, highlighting the fact that SMACSJ0723 lensing power is stronger than initially thought.
equivalent hydrogen column density of \( n_H = 1.94^{+0.03}_{-0.03} \times 10^{21} \) cm\(^{-2}\). Fig. 9 (left) shows the global spectrum as well as the best-fit spectral model with 68 per cent uncertainties (as represented by the associated subset of the sampled parameter distributions). Our best-fit value for \( n_H \) is consistent at less than 1σ with the total hydrogen (i.e., HI and HII) column density of \( 2.21 \times 10^{21} \) cm\(^{-2}\) measured by Willingale et al. (2013).

We attempt to constrain spatial variations in the ICM temperature by fitting separate spectral models to the data in the regions marked in Fig. 8. Acknowledging the reduced signal in these smaller regions, we adopt the Galactic total \( n_H \) value; we also freeze the metallicity at \( Z = 0.3 \) for these fits, in agreement with typical metal-abundance values observed for non-relaxed clusters at similar redshift (Ettori et al. 2015). The results, shown in Fig. 9 (right), are consistent with a constant ICM temperature but suggest (at less than 2σ significance) a slight drop in \( kT \) in the very core of SMACS J0723.

5.5.3. Gas mass

We perform a multiscale deprojection of the gas density and gas mass using the \texttt{pyPROFit} python package developed by Eckert et al. (2020). The analysis uses counts and background maps in the 0.5-2.0 keV energy band; an associated monochromatic exposure map for an energy of 1.2 keV, as well as the values from our best-fit spectral model. The resulting profiles of the ICM density and the cumulative gas mass are shown in Fig. 10.

5.5.4. Global properties

For reference, we summarize all global cluster properties derived for SMACS J0723 from the only existing, dedicated X-ray observation in Table 6.

6. DISCUSSION AND CONCLUSION

We create a strong-lensing mass model of the galaxy cluster SMACS J0723 at \( z = 0.39 \), the first strong-lensing cluster observed with \textit{JWST}. Our model uses \textit{JWST} ERO data, as well as archival, multi-wavelength data of the cluster from optical to X-ray wavelengths and combining both imaging and spectroscopy. We identify 16 new multiple-image systems, increasing the total number of known strongly lensed galaxies in this field to 21.

The mass model reveals only one cluster-scale halo, plus two large-scale halos that account for mass traced by the cluster ICL; it is able to reproduce the positions of strong lensing features of the cluster to within an RMS of 1″.08.

In comparison, the X-ray and the low surface brightness features – which appear clearly at the large scales, and are revealed in the imaging using a median filtering – reveal the potential remnant of stars from previous merger events.

In this regard, \textit{JWST} reveals evidence of a more complex activity than previously thought. Indeed \textit{JWST} reveals the...
Figure 7. Magnification map obtained from our mass model for a source at redshift $z = 9$. Overlaid are the different footprints of the JWST instruments.

ICL distribution, which traces past dynamical events, in this case a merger closely aligned with the line of sight ETC.

The clear power of JWST improves the identification of multiple images, with exquisite details, were it now seems easily possible to identify galaxies at redshift greater than 5. In addition, the NIRCAM sensitivity to the infrared reveals a vast number of cluster member stellar clumps, and we were able to identify the low surface brightness ICL, giving unmatched distribution of the stellar content and hint of the past dynamical history of the cluster. The discovery power from JWST offering a window to the infrared universe, is not yet fully grasped and many surprises lie ahead of us.

The combined evidences from our analysis of the mass distribution, radial velocities of cluster galaxies, and ICM properties suggest that SMACS J0723 recently underwent a major merger along an axis close to our line of sight but is well on its way toward relaxation, as reflected in the almost perfect alignment of the X-ray peak with the BCG and the overall mass distribution, and the increase of ICM cooling in an emerging compact gaseous cluster core.

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Figure 8. Regions of interest for our measurements of the ICM temperature overlaid on the Chandra ACSI-I image of SMACS J0723 (left; 2″ pixels, 0.5–7 keV, logarithmic intensity scaling) and on the JWST image of the system (right). The dashed circles have radii of 100, 200, 400, and 1000 kpc, respectively, at the cluster redshift. The cyan square marks the region shown in Fig. 1.

Figure 9. Left: Global spectrum of the observed ICM emission within 1 Mpc of the X-ray peak. Overlaid in red is the best-fit APEC model and the associated 68 per cent confidence range. Right: ICM temperature measurements within the regions shown in Fig. 8; vertical bars represent 1σ uncertainties, horizontal bars represent the width of the respective annulus. The ambient ICM temperature in the combined regions beyond $r = 100$ kpc (i.e., within the annulus from 200 to 1000 kpc) with its 1σ error is shown as an orange rectangle.
Table 5. Candidate Lens Models and Best-Fit Parameters

| Model name  | Component | $\Delta \alpha$ | $\Delta \delta$ | $\varepsilon$ | $\theta$ | $\sigma_0$ | $r_{cut}$ | $r_{core}$ |
|------------|-----------|-----------------|---------------|--------------|----------|-----------|--------|----------|
| Fiducial model | DM | -1.4$^{+0.1}_{-0.2}$ | 1.4$^{+0.0}_{-0.0}$ | 0.8$^{+0.0}_{-0.0}$ | 5.1$^{+0.1}_{-0.2}$ | 930.4$^{+9.9}_{-2.5}$ | [1500.0] | 17.2$^{+0.5}_{-0.1}$ |
| | BCG | [-0.0] | [0.0] | [0.16] | [29.2] | 420.7$^{+3.3}_{-4.6}$ | 5.3$^{+0.5}_{-0.2}$ | 0.3$^{+0.0}_{-0.0}$ |
| | ICL 1 | 40.2$^{+0.1}_{-0.0}$ | 11.3$^{+0.4}_{-0.2}$ | 0.01$^{+0.0}_{-0.0}$ | 21.5$^{+1.3}_{-0.8}$ | 457.5$^{+3.4}_{-18.7}$ | 78.8$^{+0.4}_{-0.6}$ | 12.2$^{+0.2}_{-1.3}$ |
| | ICL 2 | 42.2$^{+0.2}_{-0.5}$ | -7.7$^{+0.0}_{-0.1}$ | 0.7$^{+0.06}_{-0.08}$ | 27.8$^{+0.3}_{-1.5}$ | 265.5$^{+9.9}_{-2.7}$ | 29.7$^{+0.8}_{-1.0}$ | 7.1$^{+0.5}_{-0.4}$ |
| | L$^*$ Galaxy | – | – | – | – | 198.8$^{+0.1}_{-0.0}$ | 61.0$^{+0.8}_{-2.5}$ | [0.15] |
| | BIC = 1356 AICc = 1277 | – | – | – | – | – | – | – |
| Comparison model | DM | -0.1$^{+0.0}_{-0.0}$ | 0.5$^{+0.0}_{-0.0}$ | 0.85$^{+0.0}_{-0.0}$ | 6.1$^{+0.1}_{-0.1}$ | 1008.2$^{+2.4}_{-3.5}$ | [1500.0] | 13.2$^{+0.2}_{-0.2}$ |
| | BCG | [-0.0] | [0.0] | [0.16] | [29.2] | 341.0$^{+3.3}_{-2.4}$ | 5.3$^{+0.1}_{-0.3}$ | 0.1$^{+0.0}_{-0.0}$ |
| | NorthWest Gal | 30.0$^{+0.1}_{-0.1}$ | 21.1$^{+0.2}_{-0.1}$ | 0.0$^{+0.05}_{-0.06}$ | 1.9$^{+0.1}_{-0.2}$ | 263.5$^{+3.8}_{-2.6}$ | 9.2$^{+0.8}_{-1.3}$ | 1.4$^{+0.1}_{-0.2}$ |
| | L$^*$ Galaxy | – | – | – | – | 195.3$^{+0.8}_{-0.9}$ | 15.0$^{+0.9}_{-1.2}$ | [0.15] |
| | BIC = 1210 AICc = 1140 | – | – | – | – | – | – | – |

$^a$ $\Delta \alpha$ and $\Delta \delta$ are measured relative to the reference coordinate point: $(\alpha = 110.82675, \delta = -73.454628)$

$^b$ Ellipticity ($\varepsilon$) is defined to be $(a^2 - b^2)/(a^2 + b^2)$, where $a$ and $b$ are the semi-major and semi-minor axes of the ellipse

$^c$ Quantities in brackets are fixed parameters

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Figure 10. Profiles of the ICM density (left) and the cumulative gas mass (right) as determined from a spherical deprojection analysis.

| R.A. Dec (J2000) | $kT$ | $f_{(0.1-2.4)}$ keV | $f_{(0.5-2.0)}$ keV | $f_{(0.5-7)}$ keV | $f_{(2-10)}$ keV | $f_{\text{bolometric}}$ |
|-----------------|------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 7 : 23 : 18.04 | 18.00$^{+1.54}_{-1.37}$ | 32.13$^{+12.24}_{-1.10}$ | 23.19$^{+0.91}_{-0.81}$ | 58.19$^{+1.30}_{-1.33}$ | 43.62$^{+2.46}_{-2.35}$ | 73.32$^{+2.33}_{-2.30}$ |
| 7 : 23 : 18.04 | 18.57$^{+0.64}_{-0.64}$ | 13.40$^{+0.52}_{-0.47}$ | 33.63$^{+0.75}_{-0.77}$ | 25.21$^{+1.42}_{-1.47}$ | 42.37$^{+1.35}_{-1.33}$ | 73.32$^{+2.33}_{-2.30}$ |

Table 6. Global X-ray properties of SMACS J0723. Unabsorbed fluxes and total luminosities (both point-source corrected) are listed in units of $10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and $10^{44}$ erg s$^{-1}$, respectively.
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