



Dark matter dynamics in Abell 3827: new data consistent with standard cold dark matter

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Accepted 2018 March 4. Received 2018 February 24; in original form 2017 August 14

ABSTRACT

We present integral field spectroscopy of galaxy cluster Abell 3827, using Atacama Large Millimetre Array (ALMA) and Very Large Telescope/Multi-Unit Spectroscopic Explorer. It reveals an unusual configuration of strong gravitational lensing in the cluster core, with at least seven lensed images of a single background spiral galaxy. Lens modelling based on *Hubble Space Telescope* imaging had suggested that the dark matter associated with one of the cluster's central galaxies may be offset. The new spectroscopic data enable better subtraction of foreground light, and better identification of multiple background images. The inferred distribution of dark matter is consistent with being centred on the galaxies, as expected by Λ cold dark matter. Each galaxy's dark matter also appears to be symmetric. Whilst, we do not find an offset between mass and light (suggestive of self-interacting dark matter) as previously reported, the numerical simulations that have been performed to calibrate Abell 3827 indicate that offsets and asymmetry are still worth looking for in collisions with particular geometries. Meanwhile, ALMA proves exceptionally useful for strong lens image identifications.

Key words: astroparticle physics – gravitational lensing: strong – galaxies: clusters: individual: Abell 3827 – dark matter.

1 INTRODUCTION

Determining the properties of dark matter has become a priority of astrophysics and particle physics. In the standard Λ cold dark matter (Λ CDM) cosmological model, dark matter has significant interactions with standard model particles through only the gravitational force (e.g. Massey, Kitching & Richard 2010; Kneib & Nataraajan 2011). It therefore neither emits nor absorbs light, and appears invisible. Nonetheless, over the course of cosmic history, dark matter's gravitational attraction assembled the Universe's large-scale structure, and governed the evolution of galaxies. Dark matter has pulled together both ordinary and dark material into a series of collisions – then eventual mergers – between ever-larger structures (Vogelsberger et al. 2014; Schaye et al. 2015).

Several particle physics theories of dark matter predict additional forces *between* dark matter particles, hidden entirely within the dark sector (Cyr-Racine & Sigurdson 2013; Peter et al. 2013). The most direct way to measure these hypothesized forces is to observe the trajectory of dark matter during collisions with other dark matter. In effect, astrophysical mergers can be treated as enormous particle colliders (Clowe et al. 2004, 2006; Bradač et al. 2008; Merten et al. 2011; Clowe et al. 2012; Dawson et al. 2012; Gastaldello et al. 2014; Chon & Böhringer 2015; Harvey et al. 2015; Molnar & Broadhurst 2015, 2017; Ng et al. 2015; Golovich et al. 2016, 2017; Jee et al. 2016; Kim, Peter & Wittman 2017; Monteiro-Oliveira et al. 2017). In simulated mergers assuming Λ CDM, the (non-interacting) dark matter remains tightly bound near stars (Schaller et al. 2015). If dark-sector forces exist, simulations of mergers predict dark matter to temporarily lag behind stars, which serve as collisionless test particles (Randall et al. 2008; Massey, Kitching & Nagai 2011; Dawson et al. 2013; Kahlhoefer et al. 2014; Harvey et al. 2014; Robertson et al. 2017a,b). In some simulations, the distribution of

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dark matter is also stretched into asymmetric tails (Kahlhoefer et al. 2014).

Two properties of galaxy cluster Abell 3827 (RA = 22 h 01' 49".1, Dec. = $-59^{\circ} 57' 15''$, $z = 0.099$; De Plaa et al. 2007) make it uniquely interesting for studies of dark matter dynamics. Firstly, the cluster core contains four similarly bright galaxies, all spectroscopically confirmed as members by Carrasco et al. (2010). These four galaxies must be undergoing a simultaneous, high speed merger, because this amount of substructure is unique: most clusters have reached a steady state with only a single brightest central galaxy. Secondly, directly behind the cluster core lies a spiral galaxy ($z = 1.24145 \pm 0.00002$; Massey et al. 2015) that is rich in morphological structure. The background spiral has been gravitationally lensed by the cluster, and multiple images of it wrap around all four of the central galaxies. These images can be used to infer the spatial distribution of (dark plus stellar) mass in the cluster and its galaxies.

One of Abell 3827's central galaxies lies very close to a set of gravitationally lensed images, so the distribution of its mass is particularly well constrained. Analysis of the gravitational lensing in optical imaging suggested that this galaxy's dark matter is offset by $1.62^{+0.47}_{-0.49}$ kpc from its stars (Massey et al. 2015), and possibly asymmetric (Taylor et al. 2017). This could have been caused by a dark sector force with interaction cross-section $\sigma/m \gtrsim 1 \text{ cm}^2 \text{ g}^{-1}$, where m is the (unknown) mass of the dark matter particle (Kahlhoefer et al. 2015). The most difficult part of this analysis was the identification of features in the faint, background spiral galaxy, which lie superimposed on a very bright foreground galaxy (see appendix B in Massey et al. 2015).

In this paper, we present new integral field unit (IFU, i.e. 2D) spectroscopy of Abell 3827 at near-IR and millimetre wavelengths: where the foreground galaxies are faint, but the background spiral galaxy remains bright. We describe the new data in Section 2. We describe our analysis techniques in Section 3, and reconstruct the spatial distribution of dark matter in Section 4. We discuss the consequences of our results in Section 5. Throughout this paper, we adopt a cosmological model with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, in which 1 arcsec corresponds to 1.828 kpc at the redshift of the cluster. Adjusting this cosmological model perturbs the inferred physical distances, and the absolute normalization of inferred masses.

2 DATA

2.1 Pre-existing imaging

Broad-band imaging of Abell 3827 has been obtained by the Gemini telescope at optical wavelengths (Carrasco et al. 2010) and by the *Hubble Space Telescope* (*HST*; programme GO-12817) in the F336W (UV), F606W, and F814W (optical) and F160W (IR) bands (Massey et al. 2015).

This revealed four similarly bright elliptical galaxies (N1–N4) within 10 kpc radius, and a background lensed spiral galaxy (with a red bulge and blue spiral arms), whose multiple images are threaded throughout the cluster core. In this paper, we exclusively use the *HST* imaging. As described in Taylor et al. (2017), we reveal the background lensed galaxy by fitting and subtracting foreground emission from the five brightest cluster galaxies and two Milky Way stars using the MUSCADET method (Joseph, Courbin & Starck 2016) (Fig. 1).

2.2 ALMA integral field spectroscopy

In 2016 October, we obtained a 5.2 h observation of Abell 3827 with the Atacama Large Millimetre Array (ALMA; programme 2016.1.01201.S). The band 3 data sample frequencies 89.9–93.8 GHz and 101.8–105.6 GHz with spectral resolution 15.6 MHz (47.8 km s^{-1}). Observations were conducted with 44 12 m antennas in the C40-6 configuration. Flux and bandpass calibration were obtained from J2056–4714, and the phase calibrator was J2208–6325.

Data were reduced using CASA software v4.7.2 (McMullin et al. 2007). Spectral data cubes were created using the CLEAN algorithm, with channel averaging and natural weighting to maximize sensitivity. This yielded a synthesized beam of $\sim 0.48 \text{ arcsec} \times 0.39 \text{ arcsec}$, and a 1σ noise level of $0.08 \text{ mJy beam}^{-1}$ for each 31.3 MHz channel. In addition, to minimize potential extended flux being resolved out, we created a second spectral cube with a (u, v) taper applied that yielded a synthesized beam of $\sim 0.87 \text{ arcsec} \times 0.82 \text{ arcsec}$ and 1σ noise level of $0.15 \text{ mJy beam}^{-1}$.

The background $z = 1.24$ galaxy is visible in emission from the 230.5 GHz CO(2–1) transition, redshifted to 102.8 GHz (Fig. 2). However, the emission is fainter than expected from an extrapolation of near-IR emission (a somewhat indirect chain using [O II] emission to estimate star formation rate and hence far-infrared luminosity, then using the Solomon & Vanden Bout 2005 relation to predict CO luminosity). Our exposure time was therefore only just sufficient to detect spatial structure in the line emission; no continuum emission is detected beneath the foregrounds.

2.3 VLT/MUSE integral field spectroscopy

In 2016 June, we obtained a 4 h integration of Abell 3827 using the Multi-Unit Spectroscopic Explorer (MUSE) IFU spectrograph (Bacon et al. 2010) on the European Southern Observatory (ESO) Very Large Telescope (VLT). We combined these data (programme 295.A-5018) with a pre-existing 1 h exposure from programme 294.A-5014. All the observations were obtained in dark time, with V band seeing better than 0.7 arcsec and good atmospheric transparency. The data sample wavelengths 475.0–935.1 nm with 0.125 nm binning and spectral resolution $R = 4000$ at the red end.

Data were reduced using v1.0 of the ESOREX pipeline, which extracts the spectra, applies wavelength and flat-field calibration, then forms the data cube. Each hour on sky included 3×20 min exposures, dithered by ~ 10 arcsec. We aligned the individual exposures by registering the images of stars, then removed cosmic rays and pixel defects, and stacked the exposures using the EXP_COMBINE routine. Flux calibration was achieved using ESO standard stars that were reduced in an identical manner.

The background galaxy is visible in emission from the [O II] $\lambda\lambda 3726.8, 3729.2$ line doublet, redshifted to 835.5 nm. In each spatial pixel, we model the spectrum of foreground continuum emission as a low-order polynomial either side of 835.5 nm. We subtract this foreground emission, then integrate the remaining line flux as an [O II] narrow-band image (Fig. 3). We also use a two-Gaussian model to fit the [O II] doublet line ratio (3728.9/3726.2), line-of-sight velocity, and line width. Both components of the line are assumed to have the same width, and the measurement of spectral line width is corrected for instrumental broadening.

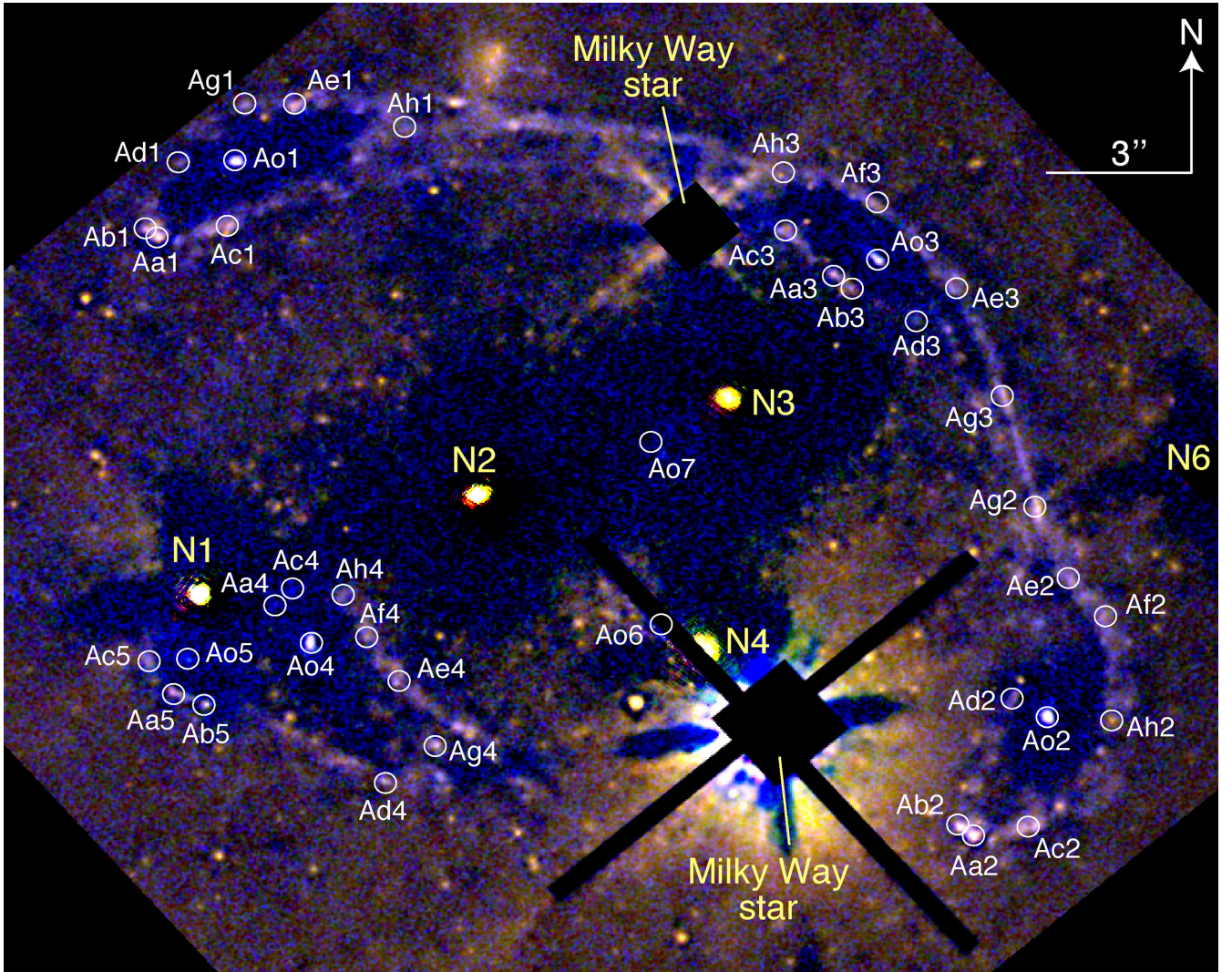


Figure 1. HST image of the core of Abell 3827 in $F814W$ (red), $F606W$ (green), and $F336W$ (blue) bands. Light from two foreground stars and five foreground galaxies (labelled in yellow) has been subtracted to reveal the background lens system. The colour scale is linear. Multiply imaged components of the background spiral galaxy, identified either in this image or in ALMA/MUSE data are labelled in white. In our cosmological model, 3 arcsec = 5.5 kpc at the redshift of the cluster.

3 ANALYSIS

3.1 Strong lens image identifications

The multiply imaged background source is a spiral galaxy consisting of a red bulge ‘Ao’ inside a blue ring of star formation knots ‘Aa’–‘Ah’. Its rotational support is apparent from the $\sim 200 \text{ km s}^{-1}$ velocity gradient apparent across the galaxy in the MUSE data (and present at low S/N in ALMA data, but not shown in Fig. 2).

Features in the observed image have been variously identified as multiple versions of the background galaxy’s bulge or star-forming regions (Williams & Saha 2011; Massey et al. 2015; Taylor et al. 2017). Many of these features are deeply embedded within the light from foreground galaxies. After foreground subtraction using GALFIT (Peng et al. 2010), and based on its apparent colour and morphology, Massey et al. (2015) identified a point-like source immediately south of galaxy N1 as the fifth (sorted by arrival time in the best-fitting mass model) multiple image of knot Aa.

Our new data indicate that this identification was incorrect. Our ALMA data show that the feature south of N1 is at the same systemic

velocity and similar CO(2–1) flux as the source’s central bulge. The feature’s line-of-sight velocity is also inconsistent with that of star formation knot Aa. Our MUSE data also support a new interpretation that the feature is an additional image of the bulge, which we now call Ao5. This identification of the source’s central bulge implies that images of knots Aa and Ac must be further south-east. The ALMA data is too low S/N to detect them, and the MUSE data have only barely sufficient angular resolution, but candidate features can be seen in *HST* imaging after our improved foreground subtraction using MUSCADET (Joseph, Courbin & Starck 2016). These features were hidden behind the foreground emission from N1, and are fainter than the foreground cluster’s many globular clusters. Indeed, the chain of three or four sources between Ao4 and Ao5 appears to be an unfortunate alignment of foreground globular clusters, confusingly unrelated to the background source.

Building upon this new hypothesis, and incorporating additional features resolved by ALMA and ordered by MUSE, a new set of multiple-image identifications Ao and Aa–h become clear (Table 1). This configuration of multiple-image identifications was not amongst those considered in appendix B of Massey et al. (2015).

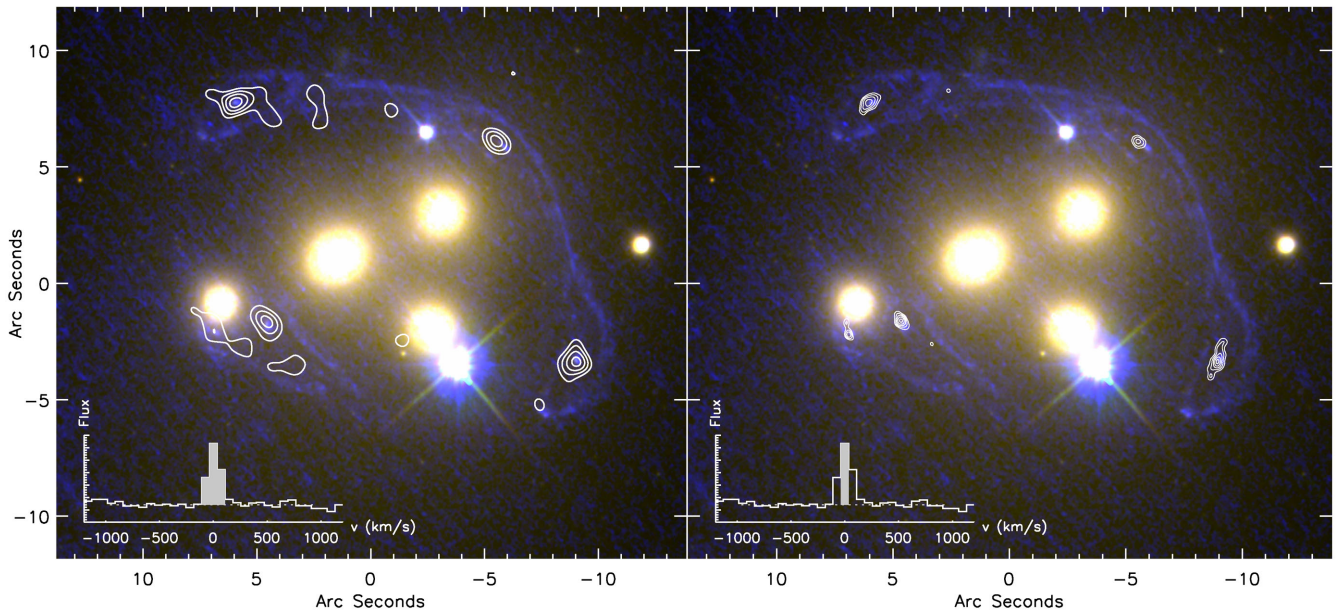


Figure 2. ALMA detection of CO(2–1) emission in the lensed spiral, as contours overlaid on the *HST* image from Fig. 1, before foreground subtraction. Left: CO(2–1) emission collapsed over $\pm 100 \text{ km s}^{-1}$ from the systemic redshift and (u, v) tapered to a 0.8 arcsec beam, to show the full emission. The 1σ noise level is $0.15 \text{ mJy beam}^{-1}$, and contours show $3\sigma, 4\sigma, 5\sigma, 6\sigma$. Right: CO(2–1) emission from a single, central ALMA channel, at natural 0.47 arcsec resolution, to identify multiple images of the source’s bulge. The 1σ noise level is $0.08 \text{ mJy beam}^{-1}$, and contours show $4\sigma, 5\sigma, 6\sigma, 7\sigma$. The inset spectra have a linear scale and include a dotted line at zero flux.

We shall now demonstrate that this new configuration yields a model of the lens’s mass distribution with higher Bayesian evidence and better consistency with observed lensed image positions.

3.2 Mass model

To ensure that we can draw robust conclusions, we use two independent algorithms to infer the mass distribution in the lens. Both have been tested in a blind analysis of strong lensing data for which the true mass distribution is known (Meneghetti et al. 2017). Firstly, we use *LENSTOOL* v6.8.1 (Jullo et al. 2007). Its parametric mass models may not capture all the complexity of a real mass distribution, but it allows quantities of scientific interest (such as the position of dark matter) to be parametrized explicitly and to be fitted directly from data. Secondly, we use *GRALE* (Liesenborgs, De Rijcke & Dejonghe 2006). This ‘freeform’ method possesses more flexibility to represent a real mass distribution and, by inferring unphysical distributions, to highlight errors in e.g. source image identification. However, interpretation is later required to extract quantities of scientific interest.

3.2.1 *LENSTOOL*

Our *LENSTOOL* mass model consists of dark matter in one cluster-scale Pseudo-Isothermal Elliptical Mass Distribution (PIEMD; Limousin et al. 2005; Elíasdóttir et al. 2007), plus the four bright galaxies’ stellar and dark matter with, respectively, Hernquist and Pseudo-Isothermal Skewed Potential (PISP; Taylor et al. 2017) distributions. A PISP distribution reduces to a PIEMD if its skewness $s = 0$. We also fit a PISP component to the dark matter associated with faint member galaxy N6, but assume it has negligible stellar mass and skewness to reduce parameter space. Including mass associated with galaxies farther from the cluster core yields indistinguishable results but slows the analysis dramati-

cally, so we omit them. Finally, we allow an external shear (e.g. Hogg & Blandford 1994). This had not been included by Massey et al. (2015).

Parameters of the dark matter components are adjusted to reduce the rms of distances between the source galaxy’s predicted and observed positions in the image plane, $\langle \text{rms} \rangle_i$. The parameters’ posterior probability distribution function (PDF) is explored by a Markov Chain Monte Carlo (MCMC) iteration, with a constant proposal distribution after a burn-in phase (*LENSTOOL*’s `RUNMODE = 3`) and priors identical to those in Taylor et al. (2017). For example, the location and amount of each galaxy’s dark matter is given a flat prior 2 arcsec either side of its stars. Taylor et al. (2017) reported failed convergence of skewness parameters; this has been solved by a much longer Markov Chain that samples the PDF 100 000 times, and by ensuring that the skewness angle ϕ_s wraps far from any peak in the PDF. We assume statistical uncertainty of 0.5 arcsec on the location of Ao6 and Ao7, which are detected only in ground-based data, and 0.15 arcsec on the location of every other image.

Parameters of the stellar mass components are derived from *GALFIT* fits to flux in the *F606W* band, with the flux converted into mass via Bruzual & Charlot (2003) models, assuming a Chabrier (2003) initial mass function, solar metallicity, and a single burst of star formation at redshift $z_f = 3$. These parameters are fixed during the optimization.

3.2.2 *GRALE*

Our *GRALE* mass model incorporates a grid of approximately 1300 Plummer spheres (Plummer 1911) in a $50 \text{ arcsec} \times 50 \text{ arcsec}$ region centred on (RA: 330.47043, Dec.: -59.945804). An iterative procedure adaptively refines the grid in dense regions, and uses a genetic algorithm to adjust the mass in each Plummer sphere. The genetic algorithm optimizes the product of (a) the fractional degree of overlap between multiple images of the same source in the

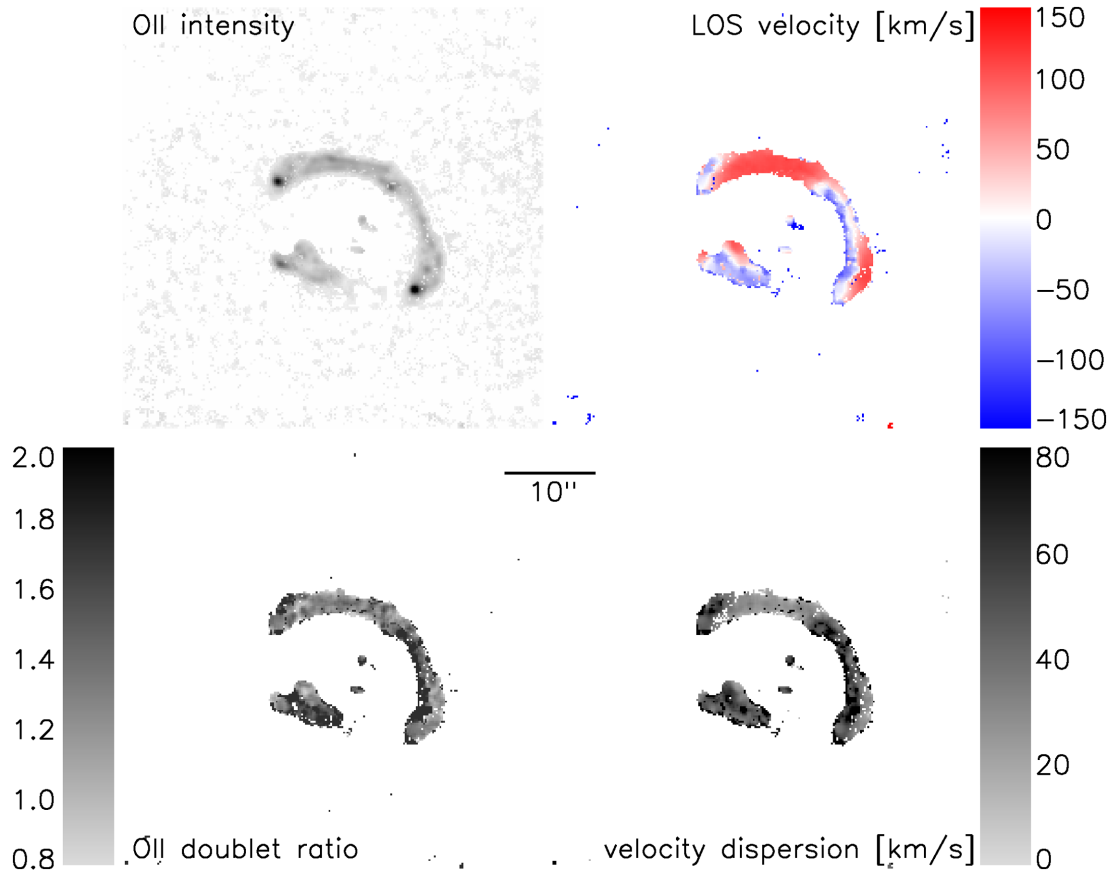


Figure 3. MUSE data compressed into a 2D narrow-band image of [O II] doublet line emission from the lensed spiral galaxy, after subtraction of the foreground continuum emission (top left). To cross-identify regions of the galaxy in a way that is independent of the spatially varying lensing flux magnification, the other panels show parameters of a model fitted to the line doublet’s spectral energy distribution in each spatial pixel where line emission is detected with $S/N > 3$. The parameters are the line’s local line-of-sight velocity (top right), the flux ratio between the doublet’s two components (bottom left) and the spectral line width (bottom right).

source plane and (b) a fitness measure penalizing the presence of false counter-images in regions where they are not observed.

GRALE represents an external shear by adding mass to the unconstrained area outside the multiple-image region. The mass typically ends up at the boundary of the reconstruction; it indicates a mass in that direction, but not necessarily at that exact location. Indeed, Liesenborgs et al. (2008) show that the external mass can be re-distributed over a large region, so that it becomes imperceptible, without degrading the fit.

We run 20 mass reconstructions with different random seeds. In total, this produces 26 786 optimized Plummer spheres. We average the inferred mass distributions; their rms provides an estimate of statistical error.

4 RESULTS

Inferred mass maps are presented in Fig. 4. Results from LENSTOOL and GRALE are now more consistent with each other. They also provide a better fit to the data than they were when assuming the source identifications of (Massey et al. 2015). The new parameters of LENSTOOL’s best-fitting model are presented in Table 2. This model achieves $\langle \text{rms} \rangle_i = 0.13$ arcsec, or $\chi^2 = 31.7$ with 29 degrees of freedom, likelihood $\log(\mathcal{L}) = 59.9$, and Bayesian evidence $\log(\mathcal{B}) = -11.5$. The mass peak reconstructed by GRALE outside the multiple-

image region imposes an external shear near N1 consistent with that fitted by LENSTOOL.

Central images Ao6 and Ao7 have split GRALE’s previous reconstruction of a bimodal cluster (consisting of N1 plus everything else) into four distinct mass concentrations, one around each galaxy. There is no reason for the genetic algorithm to prefer either, yet the new model is more physical. Adding the central images also creates a prediction (from both LENSTOOL and GRALE) for a diffuse trail of source emission south-west of Ag4, including counter-images of Ab, Ad, and Ag. These are possibly demagnified and observed, but the whole area is unclear in *HST* imaging because of the bright foreground star and confusion with globular clusters. Both models predict demagnified images of the star formation knots tightly packed around Ao6, and loosely packed around Ao7, as are visible in MUSE data but with insufficient confidence to be used as input constraints.

Our LENSTOOL analysis suggests a $\sim 2\sigma$ statistical significance for the offset of N1. However, the absolute value of the offset is far smaller than in Massey et al. (2015), and its significance disappears entirely when combining with our GRALE analysis and allowing for systematic, model-induced biases of up to ~ 0.21 arcsec for this configuration of lenses (Massey et al. 2015).

Statistical errors on the position of dark matter associated with N2, N3, and N4 are tightened by our new detection of central images Ao6 and Ao7. They would be dramatically improved if more

Table 1. Locations of multiply imaged components of the background spiral galaxy. Images *Aon* are the bulge, and images *A[a–h]n* are knots of star formation in the spiral arms.

Name	RA	Dec.
Ao1	330.474 79	−59.943 58
Ao2	330.466 49	−59.946 65
Ao3	330.468 28	−59.944 11
Ao4	330.474 07	−59.946 23
Ao5	330.475 29	−59.946 34
Ao6	330.470 44	−59.946 14
Ao7	330.470 54	−59.945 14
Aa1	330.475 59	−59.944 00
Aa2	330.467 25	−59.947 32
Aa3	330.468 71	−59.944 21
Aa4	330.474 43	−59.946 05
Aa5	330.475 46	−59.946 52
Ab1	330.475 71	−59.943 95
Ab2	330.467 41	−59.947 26
Ab3	330.468 52	−59.944 28
Ab5	330.475 15	−59.946 58
Ac1	330.474 87	−59.943 94
Ac2	330.466 69	−59.947 26
Ac3	330.469 20	−59.943 96
Ac4	330.474 24	−59.945 96
Ac5	330.475 71	−59.946 34
Ad1	330.475 37	−59.943 59
Ad2	330.466 85	−59.946 56
Ad3	330.467 84	−59.944 46
Ad4	330.473 27	−59.947 01
Ae1	330.474 20	−59.943 27
Ae2	330.466 27	−59.945 89
Ae3	330.467 45	−59.944 28
Ae4	330.473 15	−59.946 44
Af2	330.465 89	−59.946 10
Af3	330.468 26	−59.943 81
Af4	330.473 48	−59.946 20
Ag1	330.474 71	−59.943 27
Ag2	330.466 61	−59.945 50
Ag3	330.466 94	−59.944 88
Ag4	330.472 76	−59.946 81
Ah1	330.473 05	−59.943 40
Ah2	330.465 83	−59.946 67
Ah3	330.469 22	−59.943 64
Ah4	330.473 72	−59.945 99

of the source galaxy’s structure could be seen in the central images (e.g. with deeper ALMA data). However, the position of N2’s dark matter shows a large scatter in our current *GRALE* analysis, and can change in a *LENSTOOL* analysis if the prior is adjusted on the position of the cluster-scale halo. In the MCMC chain of our *LENSTOOL* analysis, the positions of N3 and N4 are degenerate with each other. Furthermore, we have an a priori expectation that only N1 is sufficiently close to space-resolution lensed images to be constrained with kiloparsec accuracy (even when the lens identifications are unambiguous Harvey, Kneib & Jauzac 2016, and they may still not all be correct here).

The inferred location of the dark matter associated with each galaxy N1–N4 appears consistent with the location of its stars. Deeper ALMA or *HST* observations would clarify the status of N2, N3, and N4. However, given various parameter degeneracies in our current analysis, and the potential for systematic errors at a level comparable to their offsets, we cannot here conclude that any offset is physically significant.

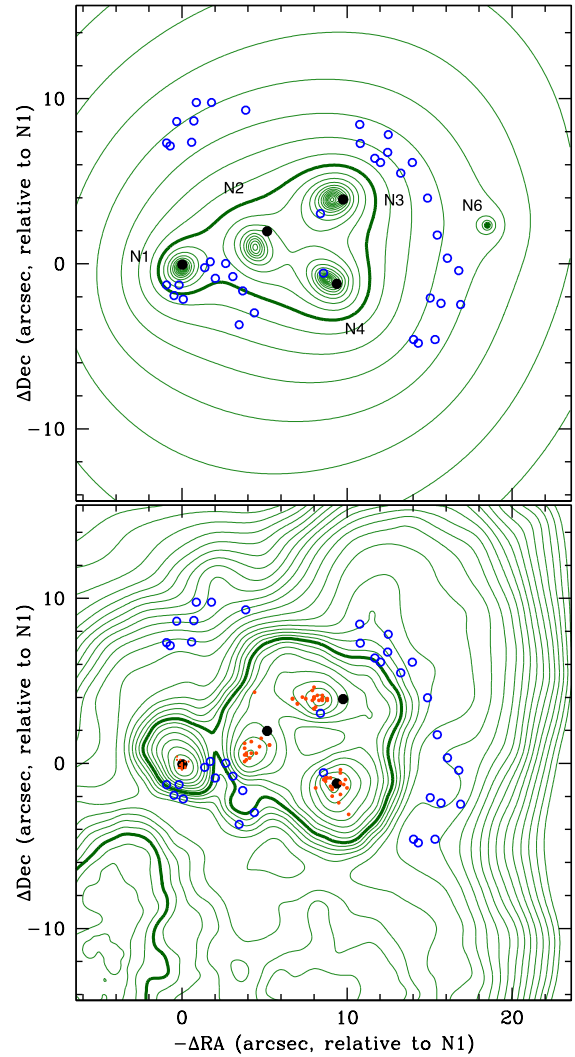


Figure 4. Top: map of total mass in the cluster core, reconstructed using *LENSTOOL*, and averaging over the posterior PDF. Green contours show the projected mass density, spaced logarithmically by a factor 1.15; the thick contour shows convergence $\kappa = 1$ for $z_{\text{ell}} = 0.099$ and $z_{\Lambda} = 1.24$ ($\Sigma_{\text{crit}} = 1.03 \text{ g cm}^{-2}$). Blue circles show the lensed images. Black dots show cluster ellipticals N1–N4. Bottom: total mass, as in the top panel but reconstructed via *GRALE*. Red dots show local maxima in individual realizations of the mass map.

The total mass of the dark matter components of galaxies N1–N4 is formally $1.47^{+0.16}_{-0.19}$, $1.54^{+0.24}_{-0.31}$, $2.44^{+0.14}_{-0.31}$, and $2.26^{+0.16}_{-0.32} \times 10^{12} M_{\odot}$, and that of the cluster-scale halo is $2.79^{+0.53}_{-0.56} \times 10^{14} M_{\odot}$ (see equation 10 of Limousin et al. 2005). However, these calculations depend approximately linearly on our unconstrained choice of r_{cut} .

De-lensed images of the background galaxy, assuming the best-fitting *LENSTOOL* model, are presented in Fig. 5; results from *GRALE* are similar. It is a ring galaxy reminiscent of the $z = 1.67$ lensed source in Zwicky cluster Cl0024+1654 (Colley, Tyson & Turner 1996; Jones et al. 2010). Its central component is by far the brightest in CO(2–1) emission. A large reservoir of dusty, molecular gas in a galaxy’s bulge would be unusual at $z = 0$, but not at $z = 1.24$, when bulges are still forming stars. Assuming *LENSTOOL*’s best-fitting mass model, the luminosity-weighted amplification of its [O II] emission is $\mu = 144$, summing over all the images. Taking into account this amplification, its apparent [O II] luminosity implies a total star

Table 2. Parameters of LENSTOOL’s best-fitting mass model. Quantities in square brackets were fixed during optimization. Errors on other quantities show 68 per cent statistical confidence limits, marginalizing over uncertainty in all other parameters. Stellar mass components are modelled as Hernquist profiles, with their mass, scale radius, and ellipticity calculated from *F606W* broad-band emission. Dark matter components are modelled as PIEMDs with a 1D velocity dispersion, core and cut radii, and ellipticity; or PISPs with an additional skewness. Positions are given in arcseconds relative to (RA: 330.475 18, Dec.: $-59.945\,985$), except galaxies’ dark matter components, which are relative to the position of their stars. Angles are anticlockwise from west. The external shear is $(1.47^{+0.97}_{-0.01})$ per cent, at angle $(92^{+24}_{-94})^\circ$.

		x (arcsec) Δx (arcsec)	y (arcsec) Δy (arcsec)	Mass (M_\odot) σ_v (km s^{-1})	r_{sc} (arcsec) r_{core} (arcsec)	r_{cut} (arcsec)	ϵ	ϕ_ϵ ($^\circ$)	s	ϕ_s ($^\circ$)
N1	stars	[0.00]	[0.00]	$[1.00 \times 10^{11}]$	[0.53]		[0.12]	[61]		
	dark matter	$0.09^{+0.10}_{-0.09}$	$-0.28^{+0.13}_{-0.12}$	166^{+9}_{-11}	[0.10]	[40]	$0.12^{+0.25}_{-0.00}$	56^{+52}_{-18}	$0.14^{+0.08}_{-0.28}$	102^{+12}_{-106}
N2	stars	[5.13]	[2.00]	$[2.47 \times 10^{11}]$	[0.79]		[0.17]	[39]		
	dark matter	$-0.81^{+0.19}_{-0.20}$	$-0.59^{+0.33}_{-0.29}$	170^{+13}_{-18}	[0.10]	[40]	$0.38^{+0.01}_{-0.25}$	129^{+16}_{-22}	$0.10^{+0.09}_{-0.15}$	41^{+94}_{-23}
N3	stars	[9.75]	[3.93]	$[2.76 \times 10^{11}]$	[0.33]		[0.05]	[31]		
	dark matter	$-0.57^{+0.14}_{-0.14}$	$0.08^{+0.24}_{-0.16}$	214^{+6}_{-14}	[0.10]	[40]	$0.14^{+0.07}_{-0.08}$	14^{+18}_{-8}	$-0.09^{+0.09}_{-0.07}$	41^{+67}_{-27}
N4	stars	[9.32]	[-1.12]	$[2.06 \times 10^{11}]$	[1.37]		[0.39]	[127]		
	dark matter	$-0.54^{+0.34}_{-0.11}$	$0.40^{+0.09}_{-0.20}$	206^{+7}_{-15}	[0.10]	[40]	$0.32^{+0.33}_{-0.00}$	144^{+12}_{-65}	$0.12^{+0.11}_{-0.12}$	104^{+53}_{-58}
N6	stars	[18.60]	[2.43]	[0]						
	dark matter	[0.00]	[0.00]	61^{+13}_{-27}	[0.10]	[40]	[0.00]	[0]	[0]	[0]
Cluster	dm	$8.61^{+0.89}_{-0.90}$	$-0.28^{+1.04}_{-0.79}$	842^{+77}_{-89}	30^{+5}_{-7}	[1000]	$0.50^{+0.07}_{-0.15}$	62^{+2}_{-2}	[0]	[0]

formation rate of $\sim 1 M_\odot \text{yr}^{-1}$, using the Kennicutt (1998) calibration and a Chabrier (2003) initial mass function. Canonical dust extinction of about $A_V \sim 1$ mag could raise this by a factor 2–3. Other than its role in gravitational lensing due to its location behind a cluster, it is not an intrinsically unusual galaxy.

5 CONCLUSIONS

Previous studies of galaxy cluster Abell 3827 (Williams & Saha 2011; Massey et al. 2015) imaging suggested that the dark matter associated with at least one of its galaxies is offset from its stars. This is predicted by simulations of self-interacting dark matter in which the exchange particle is light (Harvey et al. 2014; Kahlhoefer et al. 2014; Robertson et al. 2017b). Prompted by this potentially exciting result, further simulations (Kahlhoefer et al. 2015) suggested that the offset could be observable in (rare) systems where a massive galaxy intersects a cluster’s *Einstein* radius, and its 3D motion happens to be near the plane of the sky. A strongly lensing merger between two field galaxies has shown a similar offset (Shu et al. 2016).

In this paper, ALMA has proved an exceptional tool to identify background lensed images, with high spatial resolution at wavelengths where foreground galaxy clusters are virtually transparent. Whilst there is no guarantee that we have perfected the source identifications in Abell 3827, it is now possible to construct lens models with residuals that are consistent with noise, and robust between very different modelling approaches. The consistency between parametric and non-parametric lens models lends confidence to the conclusions. Indeed, both ALMA data and deviations from physically expected mass distributions in a free-form mass reconstruction could be a powerful discriminator between future source identifications.

Our new analysis shows that there is no statistically significant offset between galaxies and their dark matter in Abell 3827, projected on to the plane of the sky. Galaxy N1 is best constrained. Assuming statistical errors only, its offset in our LENSTOOL model is $0.29^{+0.12}_{-0.13}$ arcseconds or $0.54^{+0.22}_{-0.23}$ kpc. Following Kahlhoefer et al. (2015)’s reasoning that any offset requires dark matter self-interactions to balance a gravitational restoring force that can be calculated, this measurement implies an interaction cross-section $(\sigma/m) \cos(i) = 0.68^{+0.28}_{-0.28} \text{cm}^2 \text{g}^{-1}$, where i is the inclination of the galaxy’s 3D motion with respect to the plane of the sky. That

this angle is unknown makes it difficult to infer an upper limit on σ/m from this system without further information.

Nonetheless, the unusual configuration of Abell 3827, with four bright central galaxies and a background spiral galaxy with complex morphology is multiply imaged between them, makes it still interesting for studies of dark matter dynamics. Regardless of possible particle interactions, as a galaxy enters a cluster, its dark matter halo is gradually stripped via tidal gravitational forces. Simulations disagree about the time-scale and the orbits on which dark matter stripping occurs in the inner tens of kiloparsecs (Diemand, Kuhlen & Madau 2007; Peñarrubia, McConnachie & Navarro 2008; Wetzel, Cohn & White 2009; Bahé et al. 2012), but this dissipation is a key ingredient in semi-analytic models of galaxy formation (e.g. Dariush et al. 2010). Observations of dark matter mass-loss in galaxies entering a galaxy cluster from the field (Mandelbaum et al. 2006; Limousin et al. 2007, 2012; Parker et al. 2007; Natarajan et al. 2009; Gillis et al. 2013; Niemiec et al. 2017) have never been followed inside ~ 1 Mpc, and measurements of strong lensing clusters with multiple central galaxies, like those in Table 2, could constrain this for the first time.

ACKNOWLEDGEMENTS

The authors are grateful for helpful conversations with Jean-Paul Kneib, Subir Sarkar, and Felix Kahlhoefer. RM and TDK are supported by Royal Society University Research Fellowships. Durham authors were also supported by the UK Science and Technology Facilities Council (grant numbers ST/P000541/1, ST/H005234/1, ST/I001573/1, and ST/N001494/1). JL acknowledges the computational resources and services provided by the VSC (Flemish Supercomputer Center), funded by the Research Foundation Flanders (FWO) and the Flemish Government, department EWI. LLRW would like to acknowledge the computational resources of the Minnesota Supercomputing Institute. JM has received funding from the European Union’s FP7 and Horizon 2020 research and innovation programmes under Marie Skłodowska-Curie grant agreement numbers 627288 and 664931.

Facilities. This paper uses ALMA observations ADS/JAO.ALMA#2016.1.01201.S. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI

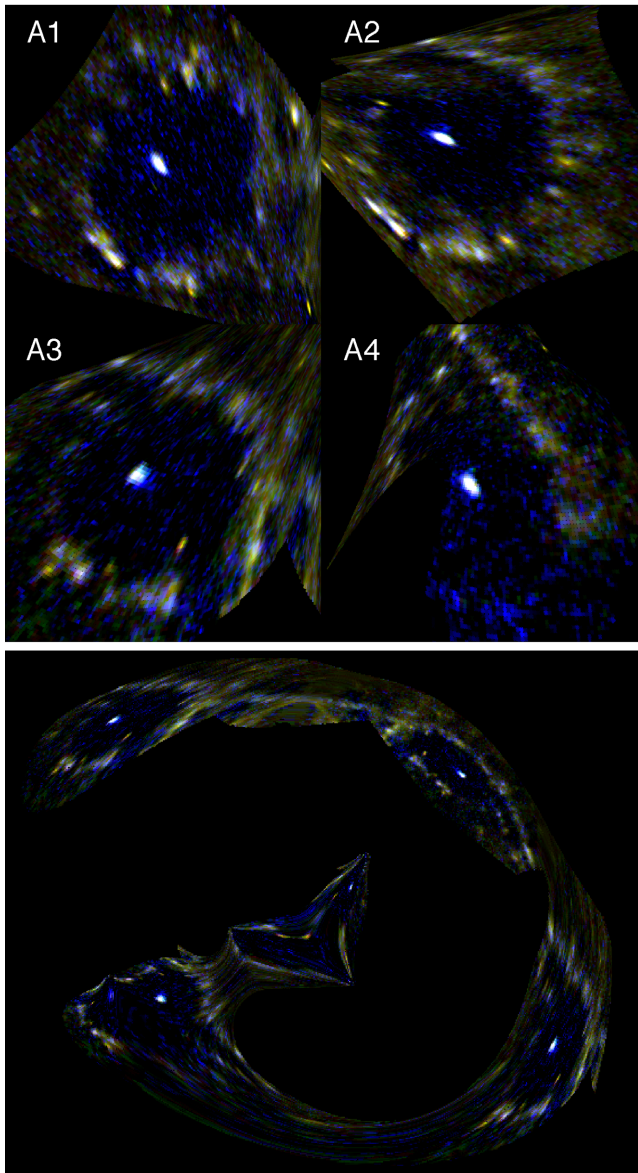


Figure 5. Top: De-lensed images of the $z = 1.24$ source galaxy, after foreground subtraction as in Fig. 1 and assuming the best-fitting lens model produced by LENSTOOL in Table 2. Each panel is $1.5 \text{ arcsec} \times 1.5 \text{ arcsec}$, and centred on (RA = 22 h 01' 53".0, Dec. = $-59^\circ 56' 44''$). Results from GRALE are similar. Bottom: re-lensed version of the above realization of source A3, the centre of the triple. The predicted brightness of the central images A6 and A7 changes slightly if other versions of the source are re-lensed.

(Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ. This paper uses data from observations made with ESO Telescopes at the La Silla Paranal Observatory under programmes 093.A-0237 and 294.A-5014. We thank the Director General for granting discretionary time, and Paranal Science Operations for running the observations. This paper uses data from observations GO-12817 with the NASA/ESA *HST*, obtained at the Space Telescope Science Institute, which is operated by AURA Inc, under NASA contract NAS 5-26555. All data are available from the telescopes' archives. This paper used the DiRAC Data Centric system at Durham University, operated by the Institute for Compu-

tational Cosmology on behalf of the STFC DiRAC HPC Facility (www.dirac.ac.uk). This equipment was funded by BIS National E-infrastructure capital grant ST/K00042X/1, STFC capital grant ST/H008519/1, and STFC DiRAC Operations grant ST/K003267/1 and Durham University. DiRAC is part of the UK National e-Infrastructure.

REFERENCES

- Bacon R. et al., 2010, in McLean I. S., Ramsay S. K., Takami H., eds, Proc. SPIE Conf. Ser. Vol. 7735, Ground-based and Airborne Instrumentation for Astronomy III. SPIE, Bellingham, p. 773508
- Bahé Y., McCarthy I., Crain R., Theuns T., 2012, *MNRAS*, 424, 1179
- Bradač M., Allen S. W., Treu T., Ebeling H., Massey R., Morris R. G., von der Linden A., Applegate D. A., 2008, *ApJ*, 687, 959
- Bruzual G., Charlot S., 2003, *MNRAS*, 344, 1000
- Carrasco E. et al., 2010, *ApJ*, 715, 160
- Chabrier G., 2003, *PASP*, 115, 763
- Chon G., Böhringer H., 2015, *A&A*, 574, 132
- Clowe D., Gonzalez A., Markevitch M., 2004, *ApJ*, 604, 596
- Clowe D., Bradač M., Gonzalez A., Markevitch M., Randall S., Jones C., Zaritsky D., 2006, *ApJ*, 648, L109
- Clowe D., Markevitch M., Bradač M., Gonzalez A., Massey R., Zaritsky D., 2012, *ApJ*, 758, 128
- Colley W., Tyson J., Turner E., 1996, *ApJ*, 461, L83
- Cyr-Racine F.-Y., Sigurdson K., 2013, *Phys. Rev. D*, 87, 3515
- Dariush A., Raychaudhury S., Ponman T., Khosroshahi H., Benson A., Bower R., Pearce F., 2010, *MNRAS*, 405, 1873
- Dawson W., 2013, *ApJ*, 772, 131
- Dawson W. et al., 2012, *ApJ*, 747, L42
- De Plaa J., Werner N., Bleeker J., Vink J., Kaastra J., Méndez M., 2007, *A&A*, 465, 345
- Diemand J., Kuhlen M., Madau P., 2007, *ApJ*, 667, 859
- Elíasdóttir Á. et al., 2007, preprint ([arXiv:0710.5636](https://arxiv.org/abs/0710.5636))
- Gastaldello F. et al., 2014, *MNRAS*, 442, L76
- Gillis B. et al., 2013, *MNRAS*, 431, 1439
- Golovich N., Dawson W., Wittman D., Ogreaan G., van Weeren R., Bonafede A., 2016, *ApJ*, 831, 110
- Golovich N., van Weeren R., Dawson W., Jee W., Wittman D., 2017, *ApJ*, 838, 110
- Harvey D. et al., 2014, *MNRAS*, 441, 404
- Harvey D., Massey R., Kitching T., Taylor A., Tittley E., 2015, *Science*, 347, 1462
- Harvey D., Kneib J.-P., Jauzac M., 2016, *MNRAS*, 458, 660
- Hogg D., Blandford R., 1994, *MNRAS*, 268, 889
- Jee M., Dawson W., Stroe A., Wittman D., van Weeren R., Brüggén M., Bradač M., Röttgering H., 2016, *ApJ*, 817, 179
- Jones T., Swinbank A., Ellis R., Richard J., Stark D., 2010, *MNRAS*, 404, 1247
- Joseph R., Courbin F., Starck J.-L., 2016, *A&A*, 589, 2
- Jullo E., Kneib J.-P., Limousin M., Elíasdóttir Á., Marshall P., Verdugo T., 2007, *New J. Phys.*, 9, 447
- Kahlhoefer F., Schmidt-Hoberg K., Frandsen M., Sarkar S., 2014, *MNRAS*, 437, 2865
- Kahlhoefer F., Schmidt-Hoberg K., Kummer J., Sarkar S., 2015, *MNRAS*, 452, L54
- Kennicutt R. C., 1998, *ARA&A*, 36, 189
- Kim S., Peter A., Wittman D., 2017, *MNRAS*, 469, 1414
- Kneib J.-P., Natarajan P., 2011, *A&AR*, 19, 47
- Liesenborgs J., De Rijcke S., Dejonghe H., 2006, *MNRAS*, 367, 1209
- Liesenborgs J., De Rijcke S., Dejonghe H., Bekaert P., 2008, *MNRAS*, 389, 415
- Limousin M., Kneib J.-P., Natarajan P., 2005, *MNRAS*, 356, 309
- Limousin M., Kneib J.-P., Bardeau S., Natarajan P., Czoske O., Smail I., Ebeling H., Smith G., 2007, *A&A*, 461, 881
- Limousin M. et al., 2012, *A&A*, 544, 71

- McMullin J. P., Waters B., Schiebel D., Young W., Golap K., 2007, in Shaw R. A., Hill F., Bell D. J., eds, *ASP Conf. Ser. Vol. 376, Astronomical Data Analysis Software and Systems XVI*. Astron. Soc. Pac., San Francisco, p. 127
- Mandelbaum R., Seljak U., Kauffmann G., Hirata C., Brinkmann J., 2006, *MNRAS*, 368, 715
- Massey R., Kitching T., Richard J., 2010, *Rep. Prog. Phys.*, 73, 086901
- Massey R., Kitching T., Nagai D., 2011, *MNRAS*, 413, 1709
- Massey R. et al., 2015, *MNRAS*, 449, 3393
- Meneghetti M. et al., 2017, *MNRAS*, 472, 3177
- Merten J. et al., 2011, *MNRAS*, 417, 333
- Molnar S., Broadhurst T., 2015, *ApJ*, 800, 37
- Molnar S., Broadhurst T., 2017, *ApJ*, 841, 46
- Monteiro-Oliveira R., Cypriano E., Machado R., Lima Neto G., Ribeiro A., Sodré L., Dupke R., 2017, *MNRAS*, 466, 2614
- Natarajan P., Kneib J.-P., Smail I., Treu T., Ellis R., Moran S., Limousin M., Czoske O., 2009, *ApJ*, 693, 970
- Ng K., Dawson W. A., Wittman D., Jee M. J., Hughes J. P., Menanteau F., Sifón C., 2015, *MNRAS*, 453, 1531
- Niemiec A. et al., 2017, *MNRAS*, 471, 1153
- Parker L., Hoekstra H., Hudson M., van Waerbeke L., Mellier Y., 2007, *ApJ*, 669, 21
- Peñarrubia J., McConnachie A., Navarro J., 2008, *ApJ*, 672, 904
- Peng C., Ho L., Impey C., Rix H.-W., 2010, *AJ*, 139, 2097
- Peter A., Rocha M., Bullock J. S., Kaplinghat M., 2013, *MNRAS*, 430, 105
- Plummer H., 1911, *MNRAS*, 71, 460
- Randall S., Markevitch M., Clowe D., Gonzalez A., Bradač M., 2008, *ApJ*, 679, 1173
- Robertson A., Massey R., Eke V., 2017a, *MNRAS*, 465, 569
- Robertson A., Massey R., Eke V., 2017b, *MNRAS*, 467, 4719
- Schaller M., Robertson A., Massey R., Bower R., Eke V., 2015, *MNRAS*, 453, L58
- Schaye J. et al., 2015, *MNRAS*, 446, 521
- Shu Y., Bolton A., Moustakas L., Stern D., Dey A., Brownstein J., Burles S., Spinrad H., 2016, *ApJ*, 820, 43
- Solomon P., Vanden Bout P., 2005, *ARA&A*, 43, 677
- Taylor P., Massey R., Jauzac M., Courbin F., Harvey D., Joseph R., Robertson A., 2017, *MNRAS*, 468, 5004
- Vogelsberger M. et al., 2014, *Nature*, 509, 177
- Wetzel A., Cohn J., White M., 2009, *MNRAS*, 395, 1376
- Williams L., Saha P., 2011, *MNRAS*, 415, 448
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This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.