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# Dark matter dynamics in Abell 3827: new data consistent with standard Cold Dark Matter

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## ABSTRACT

We present integral field spectroscopy of galaxy cluster Abell 3827, using ALMA and VLT/MUSE. 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 HST 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 centered on the galaxies, as expected by  $\Lambda$ CDM. 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:** dark matter — astroparticle physics — galaxies: clusters: individual: Abell 3827 — gravitational lensing: strong

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## 1 INTRODUCTION

Determining the properties of dark matter has become a priority of astrophysics and particle physics. In the standard  $\Lambda$ CDM cosmological model, dark matter has significant interactions with standard model particles through only the gravitational force (e.g. Massey, Kitching & Richard 2010; Kneib & Natarajan 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 (Peter et al. 2012; Cyr-Racine & Sigurdson 2013). The most direct way to measure these hypothesised 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; Ng et al. 2015; Harvey et al. 2015; Jee et al. 2016; Golovich et al. 2016, 2017; Kim, Peter & Wittman 2017; Monteiro-Oliveira et al. 2017). In simulated mergers assuming  $\Lambda$ 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; Harvey et al. 2014; Kahlhoefer et al. 2014; Robertson et al. 2017a,b). In some simulations, the distribution of dark matter is also stretched into asymmetric tails (Kahlhoefer et al. 2014).

Two properties of galaxy cluster Abell 3827 (RA=22h 01' 49".1, Dec=−59° 57' 15",  $z=0.099$ , De Plaa et al. 2007; Carrasco et al. 2010; Williams & Saha 2011), make it uniquely interesting for studies of dark matter dynamics. First, the cluster core contains four similarly-bright galaxies. They 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. Second, 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 galaxy has been gravitationally lensed by the cluster, and its multiple images 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  $\sigma/m \gtrsim 1\text{cm}^2/\text{g}$ , where  $m$  is the (unknown) mass of the dark matter particle (Kahlhoefer et al. 2015). The most difficult part of this analysis was the iden-

tification of features in the faint, background spiral, right next to a very bright foreground galaxy (see Appendix B in Massey et al. 2015).

In this paper, we present new Integral Field Unit (*i.e.* 2D) spectroscopy of Abell 3827 at near-IR and millimetre wavelengths: where the foreground cluster is 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  $H_0 = 70\text{ km/s/Mpc}$ , in which  $1''$  corresponds to 1.828 kpc at the redshift of the cluster. Adjusting this cosmological model perturbs the inferred physical distances, and the absolute normalisation 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) (figure 1).

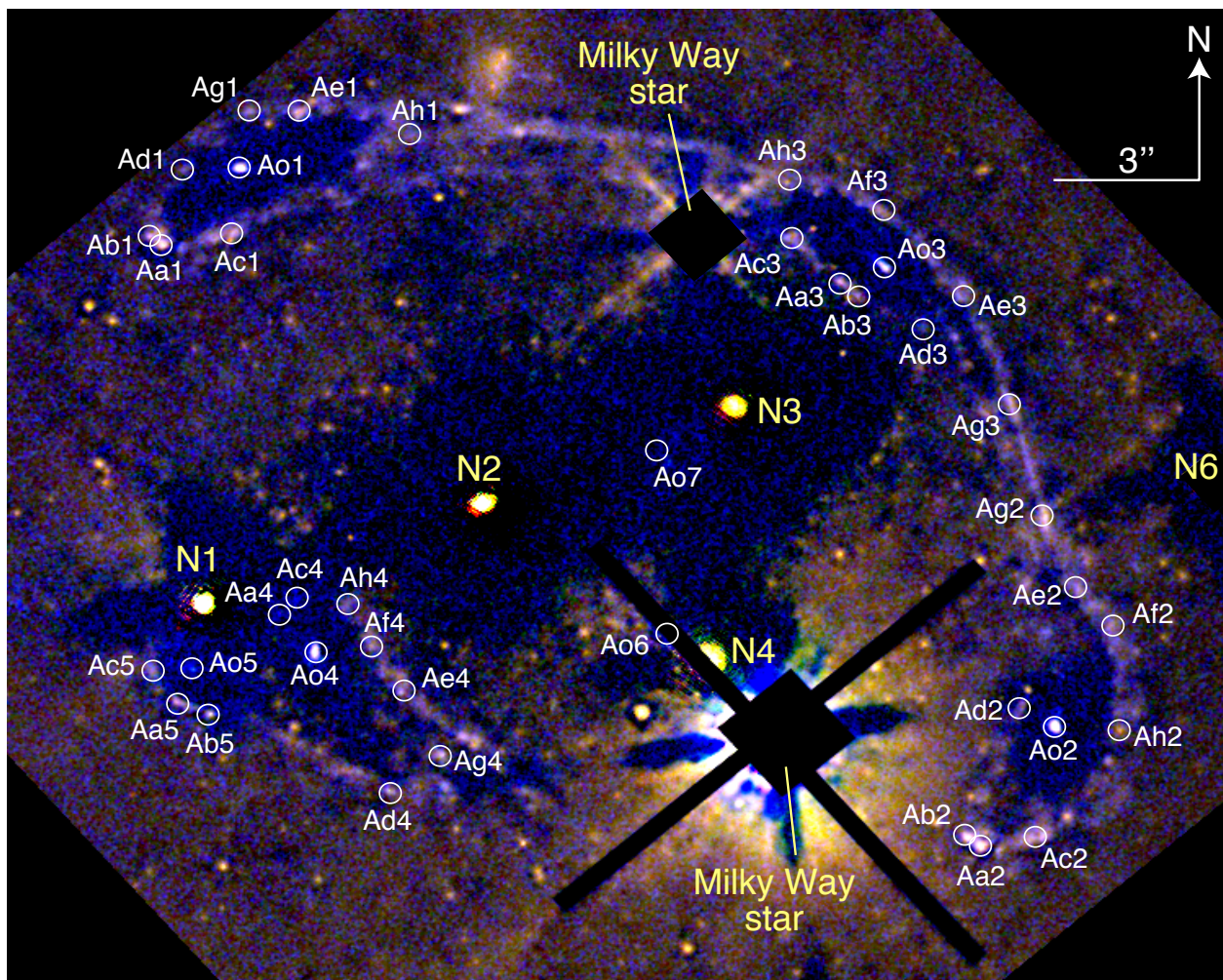
### 2.2 ALMA integral field spectroscopy

In October 2016, we obtained a 5.2 hour 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). Observations were conducted with 44 12 m antennae 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 maximise sensitivity. This yielded a synthesised beam of  $\sim 0.48'' \times 0.39''$ , and a  $1\sigma$  noise level of 0.08 mJy/beam for each 31.3 MHz channel. In addition, to minimise potential extended flux being resolved out, we created a second spectral cube with a  $(u, v)$  taper applied that yielded a synthesised beam of  $\sim 0.87'' \times 0.82''$  and  $1\sigma$  noise level of 0.15 mJy/beam.

The background  $z = 1.24$  galaxy is visible in emission from the 230.5 GHz CO(2-1) transition, redshifted to 102.8 GHz (figure 2). However, the emission is fainter than





**Figure 1.** *Hubble Space Telescope* 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,  $3'' = 5.5$  kpc at the redshift of the cluster.

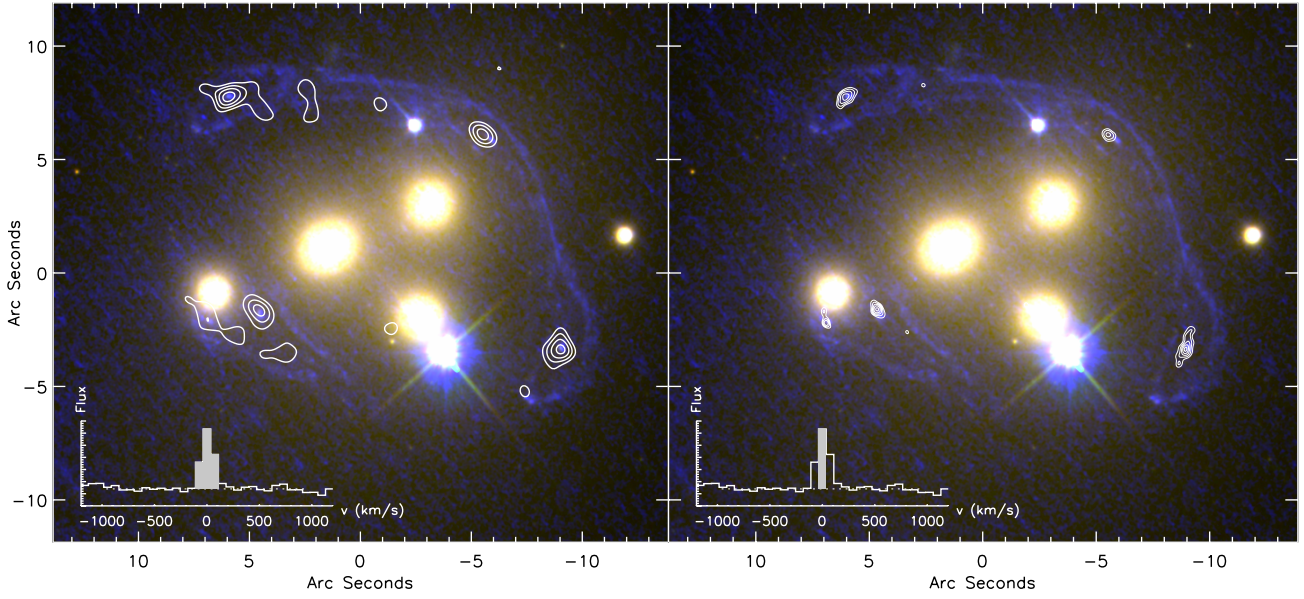
expected from an extrapolation of near-IR emission (a somewhat indirect chain using  $[\text{OII}]$  emission to estimate star formation rate and hence far-infrared luminosity, then using the Solomon & Vanden Bout 2005 relation to predict CO luminosity). Our exposure time was therefore only just sufficient to detect spatial structure in the line emission; no continuum emission is detected beneath the foregrounds.

### 2.3 VLT/MUSE integral field spectroscopy

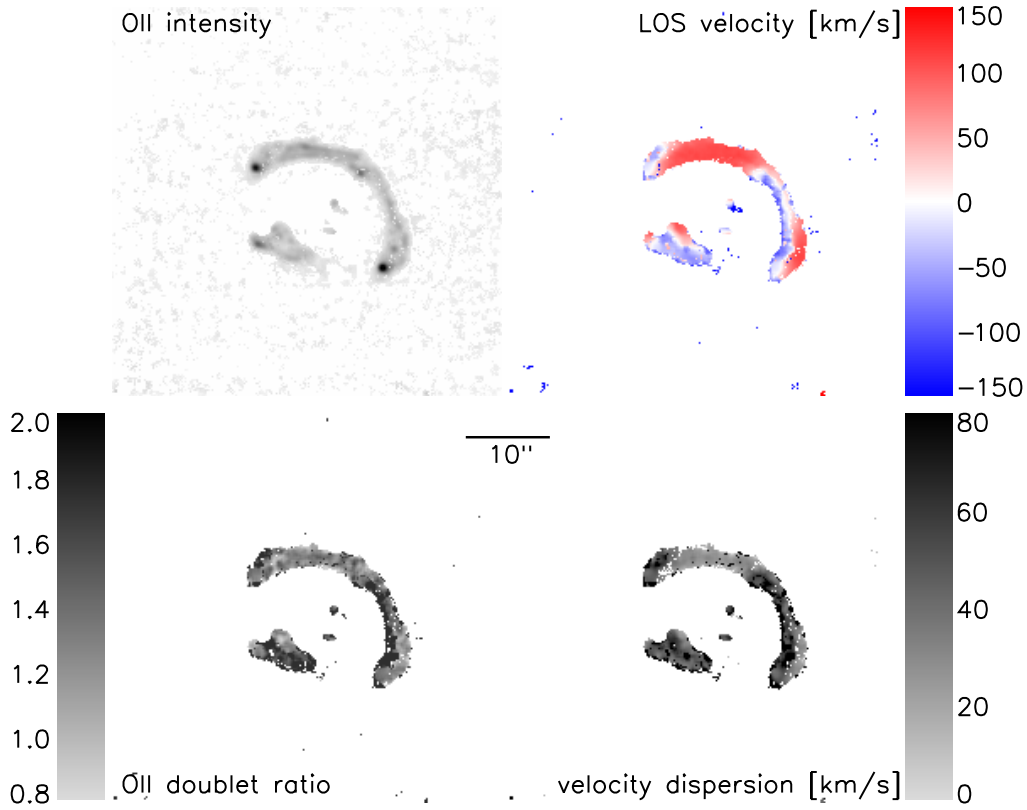
In June 2016, we obtained a 4 hour integration of Abell 3827 using the Multi-Unit Spectroscopic Explorer (MUSE) Integral Field Unit (IFU) spectrograph (Bacon et al. 2010) on the European Southern Observatory (ESO) Very Large Telescope (VLT). We combined these data (programme 295.A-5018) with a pre-existing 1 hour exposure from programme 294.A-5014. All the observations were obtained in dark time, with  $V$ -band seeing better than  $0.7''$  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  $3 \times 20$  minute exposures, dithered by  $\sim 10''$ . 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 which were reduced in an identical manner.

The background galaxy is visible in emission from the  $[\text{OII}] \lambda 3726.8, 3729.2$  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  $[\text{OII}]$  narrow-band image (figure 3). We also use a two-Gaussian model to fit the  $[\text{OII}]$  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 2.** ALMA detection of CO(2-1) emission in the lensed spiral, as contours overlaid on the HST image from figure 1, before foreground subtraction. *Left:* CO(2-1) emission collapsed over  $\pm 100$  km/s from the systemic redshift and  $(u, v)$  tapered to a  $0.8''$  beam, to show the full emission. The  $1\sigma$  noise level is 0.15 mJy/beam, and contours show 3, 4, 5, 6 $\sigma$ . *Right:* CO(2-1) emission from a single, central ALMA channel, at natural  $0.47''$  resolution, to identify multiple images of the source's bulge. The  $1\sigma$  noise level is 0.08 mJy/beam, and contours show 4, 5, 6, 7 $\sigma$ . The inset spectra have a linear scale and include a dotted line at zero flux.



**Figure 3.** MUSE data compressed into a 2D narrow-band image of [OII] 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*).



### 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  $\sim 200$  km/s velocity gradient apparent across the galaxy in the MUSE data (and present at low S/N in ALMA data, but not shown in figure 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-fit 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). 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). First, 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 parameterised explicitly and to be fitted directly from data. Second, we use GRALE (Liesenborgs, De Rijcke & Dejonghe 2006). This ‘freeform’ method possesses

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

Name	RA	Dec
Ao1	330.47479	−59.94358
Ao2	330.46649	−59.94665
Ao3	330.46828	−59.94411
Ao4	330.47407	−59.94623
Ao5	330.47529	−59.94634
Ao6	330.47044	−59.94614
Ao7	330.47054	−59.94514
Aa1	330.47559	−59.94400
Aa2	330.46725	−59.94732
Aa3	330.46871	−59.94421
Aa4	330.47443	−59.94605
Aa5	330.47546	−59.94652
Ab1	330.47571	−59.94395
Ab2	330.46741	−59.94726
Ab3	330.46852	−59.94428
Ab5	330.47515	−59.94658
Ac1	330.47487	−59.94394
Ac2	330.46669	−59.94726
Ac3	330.46920	−59.94396
Ac4	330.47424	−59.94596
Ac5	330.47571	−59.94634
Ad1	330.47537	−59.94359
Ad2	330.46685	−59.94656
Ad3	330.46784	−59.94446
Ad4	330.47327	−59.94701
Ae1	330.47420	−59.94327
Ae2	330.46627	−59.94589
Ae3	330.46745	−59.94428
Ae4	330.47315	−59.94644
Af2	330.46589	−59.94610
Af3	330.46826	−59.94381
Af4	330.47348	−59.94620
Ag1	330.47471	−59.94327
Ag2	330.46661	−59.94550
Ag3	330.46694	−59.94488
Ag4	330.47276	−59.94681
Ah1	330.47305	−59.94340
Ah2	330.46583	−59.94667
Ah3	330.46922	−59.94364
Ah4	330.47372	−59.94599

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 dramatically, so we omit them. Finally, we allow an external shear (e.g. Hogg & Blandford 1994).

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  $2''$  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  $\phi_s$  wraps far from any peak in the PDF. We assume statistical uncertainty of  $0.5''$  on the location of Ao6 and Ao7, which are detected only in ground-based data, and  $0.15''$  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 optimisation.

### 3.2.2 GRALE

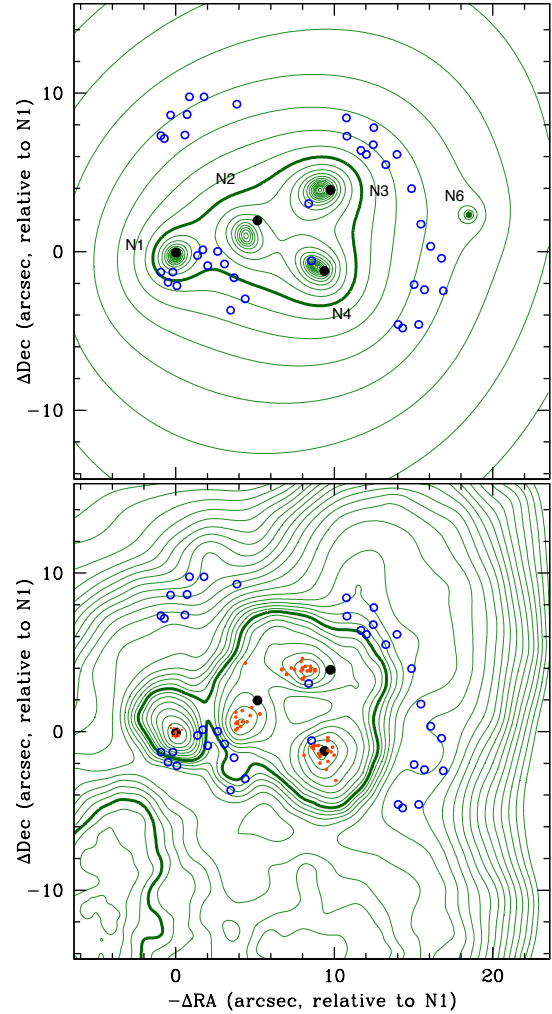
Our GRALE mass model incorporates a grid of approximately 1300 Plummer spheres (Plummer 1911) in a  $50'' \times 50''$  region centered on (RA: 330.47043, Dec:  $-59.945804$ ). An iterative procedure adaptively refines the grid in dense regions, and uses a genetic algorithm to adjust the mass in each Plummer sphere. The genetic algorithm optimises the product of (a) the fractional degree of overlap between multiple images of the same source in the source plane and (b) a fitness measure penalising the presence of false counter-images in regions where they are not observed.

We run twenty mass reconstructions with different random seeds. In total, this produces 26786 optimised Plummer spheres. We average the inferred mass distributions; their rms provides an estimate of statistical error.

## 4 RESULTS

Inferred mass maps are presented in figure 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) (whose LENSTOOL model had  $\langle \text{rms} \rangle_i = 0.26''$ ). The new parameters of LENSTOOL's best-fit model are presented in Table 2. This model achieves  $\langle \text{rms} \rangle_i = 0.13''$ , or  $\chi^2 = 31.7$  with 29 degrees of freedom, likelihood  $\log(\mathcal{L}) = 59.9$ , and Bayesian evidence  $\log(\mathcal{B}) = -11.5$ .

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 around each galaxy. There is no reason for the genetic algorithm to prefer either, yet the new model is more physical.



**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  $z_{cl} = 0.099$  and  $z_A = 1.24$  ( $\Sigma_{crit} = 1.03 \text{ g/cm}^2$ ). 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 realisations of the mass map.

Adding the central images also creates a prediction (from both LENSTOOL and GRALE) for a diffuse trail of source emission southwest 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  $\sim 0.21''$  for this configuration of lenses

**Table 2.** Parameters of LENSTOOL’s best-fit mass model. Quantities in square brackets were fixed during optimisation. Errors on other quantities show 68% statistical confidence limits, marginalising 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 (R.A.: 330.47518, Dec.:  $-59.945985$ ), except galaxies’ dark matter components, which are relative to the position of their stars. Angles are anticlockwise from West. The external shear is  $(1.47^{+0.97}_{-0.01})\%$ , at angle  $(92^{+24}_{-94})^\circ$ .

		$x ['']$ $\Delta x ['']$	$y ['']$ $\Delta y ['']$	Mass [ $M_\odot$ ] $\sigma_v$ [km/s]	$r_{sc} [']$ $r_{core} [']$	$r_{cut} [']$	$\epsilon$	$\phi_\epsilon [^\circ]$	$s$	$\phi_s [^\circ]$
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]

(Massey et al. 2015). The mass peak reconstructed by GRALE outside the cluster core imposes an external shear near N1 consistent with that fitted by LENSTOOL.

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 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.

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-fit LENSTOOL model, are presented in figure 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-fit mass model, the luminosity-weighted amplification of its [OII] emission is  $\mu = 144$ , summing over all the images. Taking into account this amplification, its apparent [OII] luminosity implies an total star-formation rate of  $\sim 1 M_\odot/\text{yr}$ , using the Kennicutt (1998) calibration and a Chabrier (2003) initial mass function. Canonical dust extinction of about  $A_V \sim 1$  magnitude 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

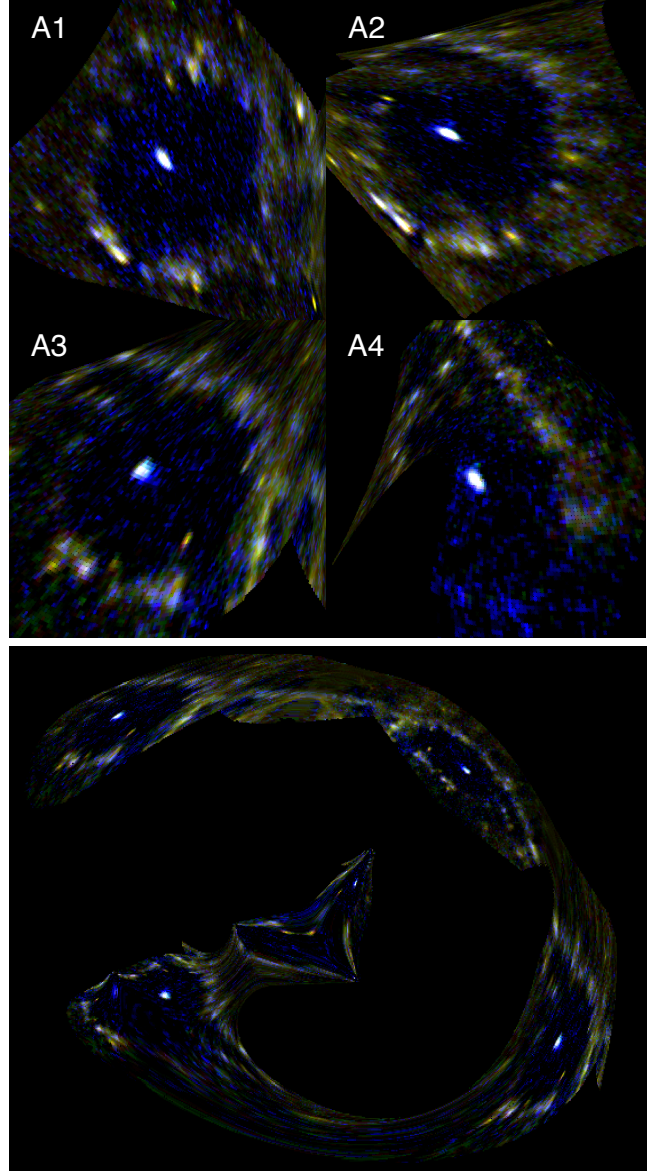
now possible to construct lens models with residuals that are consistent with noise, and robust between very different modelling approaches. The consistency between parametric and non-parametric lens models lends confidence to the conclusions. Indeed, both ALMA data and deviations from physically expected 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 onto 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  $(\sigma/m) \cos(i) = 0.68^{+0.28}_{-0.29} \text{ cm}^2/\text{g}$ , 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  $\sigma/m$  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 timescale and the orbits on which dark matter stripping occurs in the inner tens of kiloparsecs (Diemann, 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  $\sim 1$  Mpc, and measurements of strong lensing clusters with multiple central galaxies, like those in table 2, could constrain this for the first time.

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**Figure 5.** *Top:* De-lensed images of the  $z = 1.24$  source galaxy, after foreground subtraction as in figure 1 and assuming the best-fit lens model produced by LENSTOOL in table 2. Each panel is  $1.5'' \times 1.5''$ , and centered on (RA=22h 01' 53''.0, Dec=-59° 56' 44''). Results from GRALE are similar. *Bottom:* Re-lensed version of the above realisation of source A3, the centre of the triple. The predicted brightness of the central images Ao6 and Ao7 changes slightly if other versions of the source are re-lensed.

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## REFERENCES

- Bacon R. et al. 2010, SPIE 7735, 773508  
 Bruzual G. & Charlot S., 2003, MNRAS 344, 1000  
 Bahé Y., McCarthy I., Crain R. & Theuns T. 2012 MNRAS 424, 1179  
 Bradač M. et al. 2008 ApJ 687, 959  
 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 ApJL 648, 109  
 Clowe D., Markevitch M., Bradač M., Gonzalez A., Massey R. & Zaritsky D. 2012 ApJ 758, 128  
 Colley W., Tyson J. & Turner E. 1996 ApJL 461, 83  
 Cyr-Racine F.-Y. & Sigurdson K. 2013 PhRvD 87, 3515  
 Dariush A., Raychaudhury S., Ponman T., Khosroshahi H., Benson A., Bower R. & Pearce F. 2010 MNRAS 405, 1873  
 Dawson W. et al. 2012 ApJL 747, 42  
 Dawson W. 2013, ApJ, 772, 131  
 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, arXiv:0710.5636  
 Gastaldello F. et al. 2014 MNRAS Lett. 442, 76  
 Gao L., De Lucia G., White S. & Jenkins A. 2004 MNRAS 352, L1  
 Gillis B. et al. 2013 MNRAS 431, 1439  
 Golovich N., Dawson W., Wittman D., Ogle G., van Weeren R. & Bonafede A. 2016 ApJ 831, 110  
 Golovich N., van Weeren R., Dawson W., Jee W. & Wittman D. 2017, ApJ in press (arXiv:1703.04803)  
 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 456  
 Hogg D. & Blandford R. 1994 MNRAS 268, 889  
 Jauzac M. et al. 2014 MNRAS 443, 1549  
 Joseph R., Courbin F. & Starck J.-L. 2016 A&A 589, 2  
 Jee M., Dawson W., Stroe A., Wittman D., van Weeren R., Brüggén M., Bradac M. & Röttgering H. 2016 ApJ 817, 179  
 Jones T., Swinbank A., Ellis R., Richard J. & Stark D. 2010 MNRAS 404, 1247  
 Jullo E., Kneib J.-P., Limousin M., Elíasdóttir Á., Marshall P. & Verdugo T. 2007 NJPh 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 Lett. 452, 54  
 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&A Rev. 19, 47  
 Liesenborgs J., De Rijcke S. & Dejonghe H. 2006 MNRAS 367, 1209  
 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  
 Mahdavi A., Hoekstra H., Babul A., Balam D. & Capak P. 2007 ApJ 668, 806  
 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  
 McMullin J. P., Waters B., Schiebel D., Young W. & Golap K. 2007 Astronomical data analysis software and systems XVI 376, 127  
 Meneghetti M. et al. 2017 MNRAS submitted, arXiv:1606.04548  
 Merten J. et al. 2011 MNRAS 417, 333  
 Monteiro-Oliveira R., Cypriano E., Machado R., Lima Neto G., Ribeiro A., Sodré L. & Dupke R. 2017 MNRAS 466, 2614  
 Nagai D. & Kravtsov A. 2005 ApJ 618, 557  
 Natarajan P., Kneib J.-P., Smail I., Treu T., Ellis R., Moran S., Limousin M. & Czoske O. 2009 ApJ 693, 970  
 Ng K. et al. 2015 MNRAS 453, 1531  
 Niemiec A. et al. 2017 arXiv:1703.03348  
 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. et al. 2012 arXiv:1208.3026  
 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 Lett. 453, 58  
 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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