STRONG LENGING ANALYSIS OF THE GALAXY CLUSTER MACS J1319.9+7003 AND THE DISCOVERY OF A SHELL GALAXY

Adi Zitrin\textsuperscript{1,2}

Submitted to the Astrophysical Journal

ABSTRACT

We present a strong-lensing (SL) analysis of the galaxy cluster MACS J1319.9+7003 (z = 0.33, also known as Abell 1722), as part of our ongoing effort to analyze massive clusters with archival HST imaging. We spectroscopically measured with Keck/MOSFIRE two galaxies multiply-imaged by the cluster. Our analysis reveals a modest lens, with an effective Einstein radius of $\theta_e(z = 2) = 12 \pm 1''$, enclosing $2.1 \pm 0.3 \times 10^{13} M_\odot$. We briefly discuss the SL properties of the cluster, using two different modeling techniques, and make the mass models publicly-available\textsuperscript{a}. Independently, we identified a noteworthy, young Shell Galaxy (SG) system forming around two likely interacting cluster members, 20'' north of the BCG. SGs are rare in galaxy clusters, and indeed, a simple estimate yields that they are only expected in roughly one in several dozen, to several hundred, massive galaxy clusters (the estimate can easily change by an order-of-magnitude within a reasonable range of characteristic values relevant for the calculation). Taking advantage of our lens model best-fit, mass-to-light scaling relation for cluster members, we infer that the total mass of the SG system is $\sim 1.3 \times 10^{11} M_\odot$, with a host-to-companion mass ratio of about 10:1. Despite being rare in high density environments, the SG constitutes an example to how stars of cluster galaxies are being efficiently redistributed to the Intra Cluster Medium. Dedicated numerical simulations for the observed shell configuration, perhaps aided by the mass model, might cast interesting insight on the interaction history and properties of the two galaxies. An archival HST search in galaxy cluster images can reveal more such systems.

Subject headings: galaxies: clusters: general — galaxies: clusters: individual (MACS J1319.9+7003; Abell 1722) — galaxies: evolution — galaxies: formation

1. INTRODUCTION

Shell Galaxies (SGs) are, typically, elliptical galaxies, surrounded by low surface brightness shells, or at times, cones, seen as concentric arcs around the SG center. The first SGs were noted some 50-60 years ago (Arp 1966, see also Zwicky 1956), and then in earnest around the early 1980's (Malin & Carter 1983), and have been then studied observationally, analytically, and by numerical simulations (e.g. Malin & Carter 1983; Quinn 1984; Schweizer & Ford 1985; Athanassoula & Bosma 1985; Dupraz & Combes 1986; Hernquist & Quinn 1988, and references therein). Significantly improved computer power in recent years has become particularly useful for simulating such galaxies with greater detail (e.g. Cooper et al. 2011; Ebrová et al. 2012; Ebrova 2013), generating renewed interest in these systems (see also Canalizo et al. 2007; Sikkema et al. 2007; Bennert et al. 2008; Foster et al. 2014).

The shells are a particular tidal feature that forms as a result of an interaction between two galaxies (see for a recent review of shell galaxies Ebrova 2013, and references therein), in particular a highly-radial, minor merger (Quinn 1984, but see also Hernquist & Spergel 1992). The shells consist of stars stripped by the interaction, oscillating in the system’s potential well and forming faint envelopes near the turnaround radii (e.g. Dupraz & Combes 1986; Hernquist & Quinn 1988). Shells are relatively common around elliptical galaxies (at least 10\% show shells, e.g. Malin & Carter 1983; Athanassoula & Bosma 1985; Ebrova 2013), but are quite rare around spiral or disk galaxies (cf. Schweizer & Seitzer 1988; Foster et al. 2014; Fardal et al. 2007). Despite being seen mostly around elliptical galaxies, most shells have been observed in the field rather than in clusters of galaxies (e.g. Malin & Carter 1983; Athanassoula & Bosma 1985). This is likely a result of various factors, primarily the low cross-section for small impact parameter galaxy encounters within the cluster ($\pi r_{\text{core}}^2$, where $r_{\text{core}}$ is the typical galaxy’s core size), the collisionlessness of dark matter and stars, combined with high encounter velocities which lower the chances for merger within the cluster. In addition, it is conceivable the Intra Cluster Light may also play a role in smoothing the shell structure in clusters so it becomes harder to observe due to lack of contrast.

The number of shells, and distance between them can shed light on the interaction or merger history of the two galaxies as in each passage of the smaller galaxy at the host’s center (Gu et al. 2013), more material is stripped to form an expanding front (e.g. Quinn 1984; Ebrova 2013). The shape of the shell, especially in the case of narrow cones, adds useful information that can be then used to tighten the constraints on the initial configuration, relative masses, and velocities (Hernquist & Quinn 1988; Ebrova et al. 2012), although significant degeneracies exist. Also, color information and gradients, if seen, might add information relevant for a population synthesis of the shell stars and the system’s history (e.g. Bílek et al. 2016; Sikkema et al. 2007).

\textsuperscript{1} Cahill Center for Astronomy and Astrophysics, California Institute of Technology, MC 240-17, Pasadena, CA 91125, USA; adizitrin@gmail.com
\textsuperscript{2} Hubble Fellow
\textsuperscript{a} ftp://wise-ftp.tau.ac.il/pub/adiz/MACS1319/
Here, we present a SG system caught relatively-early on, so that only one highly symmetric shell is seen on each side of the system where the distance of the shell on one side is half the distance on the other side, and the two interacting galaxies are both still observed (Bílek et al. 2016). The SG is formed in a massive galaxy cluster, MACS J1319.9+7003 (hereafter M1319, \(z = 0.33\); Mauz et al. 2010; Ebeling et al. 2010; also known as Abell 1722 Abell et al. 1989), where, as mentioned, SGs are generally considered less common.

The system was identified in the framework of our ongoing effort (e.g. Zitrin & Broadhurst 2016) to lens-model massive clusters with available Hubble imaging, towards the launch on the James Webb Space Telescope (JWST). Since one of the main goals of JWST is to target galaxies in the era of reionization, strong lensing (SL) by galaxy clusters will continue being of increasing importance for detecting the faintest, highest-redshift galaxies. In addition, M1319 has another interesting aspect due to its high mass, towards the launch on the James Webb Space Telescope (JWST). Since one of the main goals of JWST is to target galaxies in the era of reionization, strong lensing (SL) by galaxy clusters will continue being of increasing importance for detecting the faintest, highest-redshift galaxies. In addition, M1319 has another interesting aspect due to its high mass.

We primarily use archival Hubble Space Telescope (HST) observations of the galaxy cluster M1319, in which we identified the lensed features and noted the SG. These data include imaging in four bands from HST programs 10266 and 10491 (PI: Ebeling) available through the Hubble Legacy Archive: a F606W image (total exposure time 1200s), taken on 2005-11-04, and a F814W image (total exposure time 1440s), taken on 2011-01-22, with the ACS/WFC; and F110W and F140W, 705.88s each, taken on 2011-07-17 with the WFC3/IR.

We ran SExtractor (Bertin & Arnouts 1996) in dual-mode to obtain the photometry of objects in the cluster field, useful for identifying multiply-imaged galaxies as well as the red-sequence cluster members (§3). We then use the resulting catalogs as input and run the Bayesian Photometric Redshift program (BPZ; Benitez 2000; Coe et al. 2006), to derive photometric redshifts, especially examining multiple-image candidates.

We observed the cluster field with the Multi-Object Spectrometer For Infra-Red Exploration (MOSFIRE; McLean et al. 2012) on the Keck 1 telescope, for approximately half an hour, consisting of sets of 120s exposures, on 2015 June 10, placing a slit along the SG system, and on multiple-images 1.1 and 2.2 seen in Figure 1. Observations were carried out in the H-band, primarily to examine if a prominent Paschen-beta (Paβ) line was present in the SG and to capture redshifted optical or long-UV spectral lines from the multiply-imaged systems. We adopted a dither pattern of ±2′′ along the slit.

Data reduction was performed using the official MOSFIRE pipeline3. For each flat-fielded slit we extracted the 1D spectrum using a 11 pixel boxcar (≈ 1′′) centered on the target, and a similar procedure was adopted in quadrature to derive the 1σ error distribution. We use two stars with known magnitudes, on which slits were placed in order to track possible drifts, for estimating the absolute depth of our observations. We reach a 3σ flux density limit of \(2.1 \times 10^{-18} \text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}\) between the spectral lines, for a marginally-resolved line FWHM=5Å line translates into a 3σ line flux limit of \(1.8 \times 10^{-18} \text{erg cm}^{-2} \text{s}^{-1}\), in good agreement with the MOSFIRE exposure time calculator (yielding 3σ \(2 \times 10^{-18} \text{erg cm}^{-2} \text{s}^{-1}\) and with our expectations based on previous observations and taking into account the different exposure times (e.g. Zitrin et al. 2015a).

The absolute calibration also agrees to within 10% typically, with the nominal MOSFIRE absolute calibration files (C. Steidel, private communication). No prominent lines were detected in the SG slit, disfavoring exotic, AGN-related mechanisms for the observed lines, such as ionization cones or jet-related features (a typical FWHM of \(3000 \text{km/s}\)). This spectrum is thus not shown. The reduced 2D and 1D spectra of multiple images 1.1 and 2.2 are shown in Fig. 2, corresponding to \(z_s = 1.55\) for system 1, and \(z_s = 3.52\) for system 2, although the latter is less certain, as we show and discuss in Fig. 2.

3 http://www2.keck.hawaii.edu/inst/mosfire/drp.html
Fig. 1.— Central field of the galaxy cluster M1319. The SG is marked with a dashed rectangle whose length is ≃ 20′′ (1′′ is 4.75 kpc at the cluster’s redshift), and is inset for show also as a stamp in the upper-right corner, with higher contrast. The image also shows two sets of multiply-imaged galaxies we identified and measured spectroscopically with Keck/MOSFIRE. We constructed two complementary SL models (see text for details) for the cluster using those two system, excluding image 2.3 (rendered a candidate, less secure identification marked with “c” above). The critical curves from the models are marked in white and green, for a source at redshift $z = 1.55$ (system $1$), enclosing an area with an effective Einstein radius of $\theta_e(z = 1.55) = 11 \pm 1′′$. The image is constructed from F110W and F140W HST/WFC3 imaging (see §2).
Fig. 2.— Spectra of multiple images 1.1 (upper subfigure) and 2.2 (bottom subfigure). Each subfigure shows both the 2D (upper inset) and 1D spectra (bottom inset; black curve), including a slightly smoothed version of the 1D spectra for illustrative purposes (blue curve). The $1\sigma$ error is also shown as a pink shaded region. In image 1.1 we identify the two [N II] doublet lines ($\lambda\lambda 6549,6583$ Å) bracketing the prominent H$\alpha$ line ($\lambda 6563$ Å), and additionally, the [S II] ($\lambda 6717$ Å) doublet-line seems to be present as well (the expected position of the other doublet line, [S II] ($\lambda 6731$ Å), falls on a skyline). These correspond to a redshift of $z = 1.55$ in excellent agreement with the photometric redshift (and 95% C.L.) of 1.44 [1.20-1.68]. Image 2.2 is fainter and line identification is less secure. We utilize the redshift prediction from our lens model, $z \sim 3.4 - 3.6$, to best-fit a redshift of 3.52 following the likely – but tentative – identification of the [O II] doublet ($\lambda\lambda 3726,3729$ Å), the He I ($\lambda 3889$ Å), and [Ne III] ($\lambda 3868$ Å) lines ([Ne IV] and [Ne V] are also covered in the slit but are not identified). We add purple markers to note the position of these faint lines.
total galaxy component of the model. The power-law exponent is the same for all galaxies and is a free parameter of the model. This mass density map is then smoothed with a 2D Gaussian, whose width is also a free parameter of the model, to obtain the smooth dark matter component (this is why this method is referred to as LTM - both the galaxy and dark matter component follow the light). The two components are then combined with a relative weight – the third free parameter of the method, which along with the overall normalization, brings the number of free parameters to four. A two component external shear is usually also added to allow for further flexibility, and to improve the fit we sometimes allow single bright galaxies to be freely weighted in the minimization and deviate from the nominal mass-to-light ratio adopted (in our case, only the BCG is left to be freely weighted). We also leave the ellipticity of the BCG a free parameter.

We first ran a model fixing the redshift of system 1 to $z = 1.55$ as indicated by our MOSFIRE data (Fig. 2), but allowing the redshift of system 2 to vary given the line identification in this system was ambiguous. We ran various models with different priors and found that they place system 2 at $z \sim 3.5$, a noticeably higher redshift than initially implied by its $z \sim 1.6$ [1.2–1.9] photometric redshift. Following the model’s preference we searched more carefully for spectroscopic solutions around $z \sim 3.5$ for system 2, and managed to identify the [O II] doublet for system 2, and managed to identify the [O II] doublet and thus infer – even if somewhat more tentatively – a redshift of $z = 3.52$ for system 2. We fixed its redshift to this value and reran the model whose resulting critical curves are seen in Figure 1. The minimization of the model included about a thousand Monte Carlo Markov Chain (MCMC) steps, and the final LTM model has an image reproduction rms of 0.6″.

We also construct a complementary, fully-parametric model using our so-called PIEMDeNFW pipeline (see Zitrin et al. 2015b): Pseudo Isothermal Elliptical Mass Distributions are used to model the cluster galaxies, scaled by their light (following the prescription of Jullo et al. 2007), and the DM component is an analytic elliptical NFW (Navarro et al. 1996) form. This method is particularly relevant for our case since it adopts well-tested scaling relations (see also Monna et al. 2016) for the cluster galaxies and thus gives an empirical separation between the galaxies, and cluster-scale dark components, so that we can estimate directly what is the mass of the SG. The final rms for this model is $\sim 1''$, slightly higher than that of the LTM model.

The two mass distributions and profiles (Fig. 3) are in rough agreement – with some differences expected given their different parametrizations and the small number of constraints available. In that sense they can be referred to as preliminary models. Both models however agree well – to within 5% – regarding the size of the lens (see Fig. 1): we measure an effective Einstein radius of $\theta_E(z = 1.55) \approx 11''$ for the redshift of system 1, and $\theta_E(z = 3.52) \approx 14''$ for that of system 2. The critical curves for these redshifts enclose $\sim 1.8 \times 10^{13}$ and $\sim 2.6 \times 10^{13}$ $M_\odot$, respectively, and the two models agree within 10% on these mass measurements. For $z = 2$, a value often used for comparison, we find $\theta_E(z = 2) \approx 12''$ enclosing $\sim 2.1 \times 10^{13}$ $M_\odot$. Note the nominal uncertainties we typically adopt for these quantities are 10% on the Einstein radii and 15% on the enclosed mass. These nominal uncertainties are only slightly higher than the typical statistical uncertainties but encompass better the underlying systematics (Zitrin et al. 2015b).

Note that the final rms of our pipeline is often somewhat higher than in other schemes: the LTM model, and for self-consistency purposes also the fully-parametric PIEMDeNFW model, are in practice constructed on a grid, whose resolution is, for speed-up purposes, comparable to or somewhat lower than that of HST. In significant magnification regions the round-up of the average source position to the grid’s lower resolution pixel scale, introduces a finite, non-negligible rms error of order 0.1″ per system, contributing quite significantly to the global, quoted imprecision of the model (but, importantly, without harming its reliability nor prediction power). These points have been recently emphasized in more length in a community effort to compare lens modeling techniques to simulated clusters (Meneghetti et al. 2016), and we refer the interested reader to that work for more discussion on this end⁴.

4. DISCUSSION AND SUMMARY

M1319 is a massive galaxy cluster, with an X-ray inferred mass of $M_{500} = 4.8 \pm 0.9 \times 10^{14} M_\odot$ (Mantz et al. 2010), and a measured velocity dispersion of $\sim 1000$ km/s, in good agreement with its weak-lensing (WL) measurement suggesting $\sigma_{WL} = 1160 \pm 140$ km/s (Jerges et al. 2002). Naturally, not all massive clusters have SL regions in proportion to their overall mass. For maximizing the SL properties there is great importance to how the matter is distributed within the cluster, for example, its concentration (Broadhurst et al. 2008) and elongation along the line of sight (e.g. Hennawi et al. 2007; Sereno et al. 2010; Merten et al. 2015), or alternatively, if there are substantial mass clumps and/or effective ellipticity boosting the critical area and lensing cross section (e.g. Redlich et al. 2012; Zitrin et al. 2013).

Part of the motivation for our work here is to systematically map cluster lenses with archival HST imaging, so that the best cosmic telescopes could be designated before the launch of JWST. M1319 lies at high ecliptic latitude where the zodiacal IR background is low, which might be beneficial for JWST studies of high-redshift galaxies. For $z_s = 15$, for example, we find an effective Einstein radius of $\theta_E(z = 15) \approx 16''$, enclosing $3.1 \times 10^{13} M_\odot$. This is a relatively small lens size compared to other massive clusters (MACS clusters in particular, e.g. Zitrin & Broadhurst 2016, or those selected for the Hubble Frontier Fields program, see Lotz et al. 2016), so that our analysis revealed M1319 is perhaps not in the top class of lensing clusters. Nonetheless, while larger lenses may be more efficient, also somewhat smaller lensing clusters such as M1319 are worth observing, and can usefully magnify faint background sources with – in this case – the advantage that most moderately-magnified region lies well within HST’s (and JWST’s) near-infrared CCDs.

Another main motivation to studying this massive cluster followed the detection of the SG. We now estimate

⁴ Also note we aim to improve this numerically in the near future.
approximately the chances of seeing such a system forming in a galaxy cluster. To form such a symmetric well-aligned SG, the encounter should occur with an impact parameter of the scale of the host’s core. This renders the cross section ($\sigma_{SG} = \pi r_{core}^2$) for such a configuration of order kpc$^2$ (adopting a galaxy core radius of $\sim 0.5 - 1$ kpc). The resulting mean free path before such an event, $l = 1/(n\sigma_{SG})$, where $n$ is the number density of galaxies which we take as $\sim 1000$ Mpc$^{-3}$, a typical thumb number for massive clusters, comes out to be of order $l \sim 1/(10^{-2}) \sim 1000$ Mpc. In contrast, the radius of massive clusters is of order $\sim 1$ Mpc, including that of M1319 (Mantz et al. 2010), which means each galaxy has order tenth of a percent to become a SG, in each crossing of the cluster (in general the crossing time is of order Gyr so that only few crossings per galaxy are expected). To obtain the chances a cluster would produce a SG we need to multiply by the number of galaxies in the cluster for which we take a nominal 1000 galaxies per cluster. However, we only need to account for the fraction of galaxy pairs with low enough relative velocities. We assume a (radial) velocity dispersion of 1000 km/s and account only for velocities – with respect to the mean velocity – lower than the escape velocity from the SG host which we take as 200 km/s. This yields to first order approximation $(200/1000)^2 \sim 1\%$ of the galaxies (or an order of magnitude less, if actually counting only the possible pairs rather then approximating as above). Assuming the dissipation time scale of the shells, i.e. the timeframe in which the shells can be observed after having formed, is of order Gyr, in total we get that the chances to see a shell galaxy is of order one in a few dozen to one in a few hundred massive clusters. Note that we neglected the mass distribution of cluster galaxies and did not demand certain mass ratios. Note also that the estimate is susceptible to the different assumptions, especially the galaxy core radius (affecting the cross section per galaxy) or escape velocity, that within a reasonable value range can easily change the estimate by an order-of-magnitude. Overall, this calculation shows why SGs are rare in clusters (note however that we do not refer to the BCG in our estimate here, for which other assumptions may apply). A search for SGs in archival HST imaging of other massive clusters would be interesting, to confront and reassess this estimate.

We can exploit our mass model’s best-fit M/L scaling relation for cluster galaxies to estimate the masses of the SG. Our mass model suggests a total mass of $\sim 1.3 \times 10^{11} M_\odot$ for the SG system, yielding a mass-to-light ratio of $M/L_B \sim 15$; a typical value for cluster galaxies. The luminosities, or magnitudes, of the SG host (F814W=20.61 AB) and companion (F814W=22.50 AB) suggest a minor merger of mass ratio of roughly 10:1. Clearly, this is an upper limit as some stars of the companion are already distributed to the shells, so it has been somewhat more massive to begin with, than its current luminosity suggests. While we leave detailed modeling of this system to future work, from the mere fact that both the host and progenitor are still observed, and that only two shells are seen, one of them half the distance of the other from the center, it is immediately implied that this a relatively young system compared to the expected merger timescale for this mass ratio (typically of order several Gyr, see for

---

**Fig. 3.** — Resulting mass models. Upper panel shows the mass-density kappa map for a source at $z_s = 1.55$, the redshift of system 1, for the LTM model; the Middle Panel for the PIEMDeNFW model; and the Bottom Panel shows the resulting kappa profile from the two models. Some notable differences are seen, which are, however, not surprising given the low number of constraints and different parametrizations. For further discussion on differences between the methods see Zitrin et al. (2015b); Meneghetti et al. (2016).
Fig. 4.— The Shell Galaxy in Color-Magnitude space. Figure shows four different color-magnitude diagrams from photometric catalogs generated for the central field of M1319. We plot all objects (blue open circles) cross-matched between the different bands in the central 1.5′ × 1.5′ field. The SG, marked with filled red, lies exactly on the top of easily-identifiable cluster-member red sequence, leaving little doubt it is indeed a cluster member. Future spectroscopic redshifts will help to confirm his assumption.

example Ebrova 2013; Lotz et al. 2008; Boylan-Kolchin et al. 2008; Jiang et al. 2008). Indeed, new generations of numerical simulations are now capable of simulating complex SG systems with high resolution (Cooper et al. 2011; Ebrová et al. 2012). Given the rarity of SGs in massive clusters, and perhaps accompanied by our public mass model, it might be interesting to dedicatedly simulate this system in future work.

ACKNOWLEDGMENTS

AZ thanks the reviewer of this work for useful comments. AZ thanks Sirio Belli for his contribution to the Keck/MOSFIRE observations and analysis. AZ is very grateful for a proof read of this manuscript and insightful comments by Ivana Ebrova. While we defer numerically simulating the SG in detail to future work, AZ is indebted to Chris Hayward for help in simulations setup, and acknowledges useful discussions with Margaret Geller, Richard Ellis, Sterl Phinney, Andrew Wetzel, Cameron Hummels, Phil Hopkins, Benny Trakhtenbrot, Dan Stern, Tom Broadhurst, Holland Ford, Re’em Sari and Harald Ebeling. Comments received from Michal Bilek are appreciated. Principal support for this work was provided by NASA through Hubble Fellowship grant #HST-HF2-51334.001-A awarded by STScI, which
is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract NAS 5-26555. This work is in part based on previous observations made with the NASA/ESA Hubble Space Telescope. Data presented herein were obtained at the W.M. Keck Observatory. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

REFERENCES
Abell, G. O., Corwin, Jr., H. G., & Olowin, R. P. 1989, ApJS, 70, 1
Arp, H. 1966, ApJS, 14, 1
Athanassoula, E., & Bosma, A. 1985, ARA&A, 23, 147
Benitez, N. 2000, ApJ, 536, 571
Bennert, N., Canalizo, G., Jungwiert, B., et al. 2008, ApJ, 677, 846
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Bílek, M., Cuillandre, J.-C., Gwyn, S., et al. 2016, A&A, 588, A77
Boylan-Kolchin, M., Ma, C.-P., & Quataert, E. 2008, MNRAS, 383, 93
Broadhurst, T., Umetsu, K., Medezinski, E., Oguri, M., & Rephaeli, Y. 2008, ApJ, 685, L9
Broadhurst, T., Benitez, N., Coe, D., et al. 2005, ApJ, 621, 53
Canalizo, G., Bennert, N., Jungwiert, B., et al. 2007, ApJ, 669, 801
Coe, D., Benitez, N., Sánchez, S. F., et al. 2006, AJ, 132, 926
Coe, D., Bradley, L., & Zitrin, A. 2015, ApJ, 800, 84
Cooper, A. P., Martínez-Delgado, D., Helly, J., et al. 2011, ApJ, 743, L21
Donahue, M., Ettori, S., Rasia, E., et al. 2016, ApJ, 819, 36
Dupraz, C., & Combes, F. 1986, A&A, 166, 53
Ebeling, H., Edge, A. C., Mantz, A., et al. 2010, MNRAS, 407, 83
Ebrova, I. 2013, ArXiv e-prints
Ebrová, I., Jílková, L., Jungwiert, B., et al. 2012, A&A, 545, A33
Edwards, L. O. V., Alpert, H. S., Trierweiler, I. L., Abraham, T., & Beizer, V. G. 2016, MNRAS, 461, 230
Fardal, M. A., Guhathakurta, P., Babul, A., & McConnachie, A. W. 2007, MNRAS, 380, 15
Foster, C., Lux, H., Romanowsky, A. J., et al. 2014, MNRAS, 442, 3544
Gu, M., Ho, L. C., Peng, C. Y., & Huang, S. 2013, ApJ, 773, 34
Hennawi, J. F., Dalal, N., Bode, P., & Ostriker, J. P. 2007, ApJ, 654, 714
Herquist, L., & Quinn, P. J. 1988, ApJ, 331, 682
Herquist, L., & Spergel, D. N. 1992, ApJ, 399, L117
Irgens, R. J., Lilje, P. B., Dahle, H., & Maddox, S. J. 2002, ApJ, 579, 227
Jiang, C. Y., Jing, Y. P., Faltenbacher, A., Lin, W. P., & Li, C. 2008, ApJ, 675, 1095
Jullo, E., Kneib, J.-P., Limousin, M., et al. 2007, New Journal of Physics, 9, 447
Lotz, J. M., Jonsson, P., Cox, T. J., & Primack, J. R. 2008, MNRAS, 391, 1137
Lotz, J. M., Koekemoer, A., Coe, D., et al. 2016, arXiv, 1605.06567
Malin, D. F., & Carter, D. 1980, Nature, 285, 643
—. 1983, ApJ, 274, 534
Mantz, A., Allen, S. W., Ebeling, H., Rapetti, D., & Drlica-Wagner, A. 2010, MNRAS, 406, 1773
McLean, I. S., Steidel, C. C., Epps, H. W., et al. 2012, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 8446, Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 0
Meneghetti, M., Rasia, E., Vega, J., et al. 2014, ApJ, 797, 34
Meneghetti, M., Natarajan, P., Coe, D., et al. 2016, arXiv, 1606.04548
Merten, J., Meneghetti, M., Postman, M., et al. 2015, ApJ, 806, 4
Monna, A., Seitz, S., Geller, M. J., et al. 2016, ArXiv e-prints
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Quinn, P. J. 1984, ApJ, 279, 596
Redlich, M., Bartelmann, M., Waizmann, J.-C., & Fedeli, C. 2012, arXiv, 1205.0966
Schweizer, F., & Ford, Jr., W. K. 1985, in Lecture Notes in Physics, Berlin Springer Verlag, Vol. 232, New Aspects of Galaxy Photometry, ed. J.-L. Nieto, 145
Schweizer, F., & Seitzer, P. 1988, ApJ, 328, 88
Sereni, M., Jetzer, P., & Lubini, M. 2010, MNRAS, 403, 2077
Sikkena, G., Carter, D., Peletier, R. F., et al. 2007, A&A, 467, 1011
Umetsu, K., Zitrin, A., Gruen, D., et al. 2016, ApJ, 821, 116
Windhorst, R. A., Cohen, S. H., Hathi, N. P., et al. 2011, ApJS, 193, 27
Zitrin, A., & Broadhurst, T. 2016, arXiv, 1607.02119
Zitrin, A., Ellis, R. S., Belli, S., & Stark, D. P. 2015a, ApJ, 805, L7
Zitrin, A., Broadhurst, T., Umetsu, K., et al. 2009, MNRAS, 396, 1985
Zitrin, A., Meneghetti, M., Umetsu, K., et al. 2013, ApJ, 762, L30
Zitrin, A., Fabris, A., Merten, J., et al. 2015b, ApJ, 801, 44
Zwicky, F. 1956, Ergebnisse der exakten Naturwissenschaften, 29, 344