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COSMOLOGY

An excess of small-scale gravitational lenses observed in galaxy clusters

Massimo Meneghetti^{1,2,3*}, Guido Davoli^{1,4}, Pietro Bergamini¹, Piero Rosati^{5,1}, Priyamvada Natarajan⁶, Carlo Giocoli^{1,5,7}, Gabriel B. Caminha⁸, R. Benton Metcalf⁷, Elena Rasia^{9,10}, Stefano Borgani^{9,10,11,12}, Francesco Calura¹, Claudio Grillo^{13,14}, Amata Mercurio¹⁵, Eros Vanzella¹

Cold dark matter (CDM) constitutes most of the matter in the Universe. The interplay between dark and luminous matter in dense cosmic environments, such as galaxy clusters, is studied theoretically using cosmological simulations. Observations of gravitational lensing are used to characterize the properties of substructures—the small-scale distribution of dark matter—in clusters. We derive a metric, the probability of strong lensing events produced by dark-matter substructure, and compute it for 11 galaxy clusters. The observed cluster substructures are more efficient lenses than predicted by CDM simulations, by more than an order of magnitude. We suggest that systematic issues with simulations or incorrect assumptions about the properties of dark matter could explain our results.

In the standard cosmological model, the matter content of the Universe is dominated by cold dark matter (CDM), collisionless particles that interact with ordinary matter (baryons) only through gravity. Gravitationally bound dark-matter halos form hierarchically, with the most massive systems forming through mergers of smaller ones. As structure assembles in this fashion, large dark-matter halos contain smaller-scale substructure in the form of embedded subhalos.

The most massive dark-matter halos at the present time are galaxy clusters, with masses of $\sim 10^{14}$ to $\sim 10^{15}$ solar masses ($M_{\odot}$, one solar mass is 2×10^{30} kg). Galaxy clusters contain about a thousand member galaxies that are hosted in subhalos. The detailed spatial distribution of dark matter in galaxy clusters can be mapped by observing gravitational lensing of distant background galaxies. When distant background galaxies are in near perfect alignment with the massive foreground cluster, strong gravitational

lensing occurs. Strong lensing—nonlinear effects produced by the deflection of light—results in multiple distorted images of individual background galaxies that can be detected in Hubble Space Telescope (HST) imaging.

The probability and strength of these nonlinear strong lensing effects can be predicted theoretically from simulations of structure formation (1). We test these predictions using observations of galaxy clusters, combining lensing data from the HST with spectroscopic data from the Very Large Telescope (VLT). Our observed sample of lensing clusters is split into three sets for this analysis: (i) a reference sample comprising three clusters with well-constrained mass distributions (mass models): MACS J1206.2-0847 (MACSJ1206) at redshift $z = 0.439$, MACS J0416.1-2403 (MACSJ0416) at $z = 0.397$, and Abell S1063 (AS1063) at $z = 0.348$ (2–6); (ii) a sample that includes the publicly available mass models for four Hubble Frontier Fields clusters [HFF, (7)], namely Abell 2744 at $z = 0.308$, Abell 370 at $z = 0.375$, MACS J1149.5+2223 (MACSJ1149) at $z = 0.542$, and MACS J0717.5+3745 (MACSJ0717) at $z = 0.545$; and (iii) four clusters from the Cluster Lensing and Supernova Survey with Hubble [CLASH, (8)] project, with recent mass reconstructions [(9), their “Gold” sample]: RX J2129.7+0005 (RXJ2129) at $z = 0.234$, MACS J1931.8-2635 (MACSJ1931) at $z = 0.352$, MACS J0329.7-0211 (MACSJ0329) at $z = 0.450$, and MACS J2129.4-0741 (MACSJ2129) at $z = 0.587$. A color-composite image of MACSJ1206, one of the clusters in our reference sample (i), is shown in Fig. 1. Images of the other clusters are shown in figs. S1 to S3.

Owing to their large masses, all these galaxy clusters act as strong lenses, producing multiple images of numerous background galaxies. To reconstruct their mass distributions, we combine the images with available spectroscopic data (3, 10). For each cluster, the mem-

bership of hundreds of galaxies is confirmed spectroscopically, and their redshifts have been measured. The spectroscopy has also allowed identification of tens of multiply imaged background sources per cluster.

Mass models for the reference cluster sample were constructed by using the publicly available parametric lens inversion code LENSTOOL (11) and published previously (6). Clusters were modeled as a superposition of large-scale components to account for the large-scale cluster dark-matter halos, and small-scale components that describe the substructure. We associate the spatial positions of cluster member galaxies with the locations of dark-matter substructure. The detailed mass distribution in these cluster galaxies is constrained using stellar kinematics measurements of cluster member galaxies from the VLT spectroscopy.

The mass models for the clusters in the other two samples are built similarly (12); however, unlike the reference sample, the mass distribution in the cluster member galaxies is not constrained using data from stellar kinematics. For the HFF sample, a suite of lensing mass models constructed independently by several groups are publicly available from the Mikulski Archive for Space Telescopes (MAST); we used only those built using LENSTOOL for consistency [e.g., (13, 14)]. For the “Gold” sample, we use published models (9) that were also built with LENSTOOL.

The multiple images of distant sources lensed by foreground galaxy clusters have angular separations of several tens of arcseconds. The most distorted gravitational arcs occur near lines that enclose the inner regions of the cluster, referred to as critical lines, which delineate the region where strong lensing occurs. The size of the critical lines depends on the redshifts of the background sources. Substructures within each cluster act as smaller-scale gravitational lenses embedded within the larger lens. If these substructures are massive enough and compact enough, they can also produce additional local strong lensing events on much smaller scales with separations of less than a few arcseconds. These small-scale features are expected to appear around the critical lines produced by individual cluster galaxies. We refer to these localized features as Galaxy-Galaxy Strong Lensing (GGSL) events. Sufficiently high-resolution mass reconstructions are necessary to recover these smaller-scale critical lines. For example, Fig. 1 shows the network of critical lines in MACSJ1206 for two possible source redshifts, $z = 1$ and $z = 7$. The cluster produces a large-scale critical line extending to 15 to 30 arc sec and many smaller-scale critical lines around individual substructures, as shown in the insets. The presence of secondary critical lines indicates that the substructures are centrally concentrated and massive enough to act as individual strong lenses.

¹Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Istituto Nazionale di Astrofisica Via Gobetti 93/3, I-40129, Bologna, Italy. ²National Institute for Nuclear Physics, viale Berti Pichat 6/2, I-40127 Bologna, Italy. ³Division of Physics, Mathematics, and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA. ⁴Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), viale Berti Pichat 6/2, I-40127 Bologna, Italy. ⁵Dipartimento di Fisica e Scienza della Terra, Università di Ferrara, via Saragat 1, I-44122 Ferrara, Italy. ⁶Department of Astronomy, 52 Hillhouse Avenue, Steinbach Hall, Yale University, New Haven, CT 06511, USA. ⁷Dipartimento di Fisica e Astronomia, Università di Bologna, via Gobetti 93/2, 40129 Bologna, Italy. ⁸Kapteyn Astronomical Institute, University of Groningen, Postbus 800, 9700 AV Groningen, Netherlands. ⁹Osservatorio Astronomico di Trieste, Istituto Nazionale di Astrofisica, Via Tiepolo, 11, I-34131 Trieste, Italy. ¹⁰Institute for Fundamental Physics of the Universe, Via Beirut 2, 34014 Trieste, Italy. ¹¹Department of Physics, University of Trieste, via Tiepolo 11, I-34131 Trieste, Italy. ¹²National Institute for Nuclear Physics, Via Valerio 2, I-34127 Trieste, Italy. ¹³Dipartimento di Fisica, Università degli Studi di Milano, via Celoria 16, I-20133 Milano, Italy. ¹⁴Niels Bohr Institute, University of Copenhagen, Lyngbyvej 2, 4. sal 2100 Copenhagen, Denmark. ¹⁵Corresponding author. Email: massimo.meneghetti@inaf.it

Fig. 1. Color-composite image of the central region of the galaxy cluster MACSJ1206. (A to D) The image combines HST observations in the filters F105W, F110W, F125W, F140W, F160W (red channel), F606W, F625W, F775W, F814W, F850LP (green channel), and F435W and F475W (blue channel). The dashed and solid lines in (A) show the critical lines of the cluster for source redshifts of 1 and 7, respectively. Panels (B), (C), and (D) zoom into three GGSLE events enclosing sources at redshifts 1.425, 4.996, and 3.753, respectively. The white lines in those panels show the critical lines of the lenses for the corresponding source redshifts. In (B) and (D), the background lensed sources are bluer than the foreground lensing galaxies. In (C), the lensed source is not visible in the HST image but is detected in an observation with the Multi-Unit Spectroscopic Explorer (MUSE) spectrograph on the VLT (12). The source is detected at a wavelength of $\sim 7289 \text{ \AA}$, corresponding to the redshifted Lyman- α spectral line of hydrogen, at locations indicated by the cyan contours. The white crosses indicate the positions of four multiple images of the source. Equivalent images for all the other clusters are shown in figs. S1 to S3.

We identify three GGSLE events in the core of the cluster MACSJ1206, shown in Fig. 1, B to D: a ring-shape image (an Einstein ring) originating from a source at $z = 1.42$; a triply imaged galaxy at $z = 3.75$ (15); and an Einstein cross with four distinct images of a source at $z = 4.99$. The consistency between the shapes of the GGSLE events and the predicted critical lines from the lens modeling, also shown in Fig. 1, B to D, validates our multiscale mass model.

Just as the observed gravitational arcs are lensed images of distant galaxies, the critical lines are the lensed counterparts of the caustic lines (1), shown in Fig. 2, B and D. The caustics enclose the regions in which sources have to be located to be strongly lensed by substructures. We quantify the probability of observing GGSLE events using the fraction of

the area of the sky inside the caustics produced by substructures. Figure 3 shows how the GGSLE probability varies as a function of the source redshift for all clusters in our three samples. For MACSJ1206 (upper limit of the reference sample), it is $\sim 10^{-3}$ at $z > 2$. This probability can in turn be converted into an expected number of GGSLE events by assuming the properties of the background source population of galaxies that can be lensed. Using galaxies seen in the Hubble Ultra-Deep Field (HUDF) (16) as a representative template for the properties of the background lensed sources, we calculate that $\lesssim 3$ GGSLE events should occur in MACSJ1206, in agreement with the observations. Equivalent estimates for MACSJ0416 and AS1063 predict ~ 1 and ~ 0.9 events, respectively. In these two cases, our calculations

underpredict the number of observed GGSLE events, as three candidate events have been reported in each of the two clusters (17, 18). This underestimate is likely because the HUDF may not be an appropriate template for background sources in these two clusters (12). Nevertheless, we find that GGSLE events are detected in multiple clusters. Twenty-four GGSLE candidate events have been found in other CLASH clusters, including four events in MACSJ1149 and one event in each of the clusters MACSJ0717, RXJ2129, and MACSJ0329 (18).

We next consider whether the observed number of GGSLE events are consistent with theoretical predictions within the standard cosmological model. We performed the same analysis and computed the GGSLE probability for 25 simulated galaxy clusters, which have masses, redshifts, morphologies, and mass concentrations similar to those in our three observed samples (12). The cosmological hydrodynamical simulations from which these simulated clusters are drawn (19) incorporate gas cooling, star formation, and energy feedback from supernovae and accreting supermassive black holes (SMBHs).

Figure 2 shows a comparison between the critical lines and the caustics of MACSJ1206 (panels A and B) and those of a simulated cluster of similar mass and concentration (panels C and D). MACSJ1206 has many more secondary critical lines within the observed area. The fractional area of the source plane that is enclosed by substructure caustics is larger in observed clusters than predicted by the simulated sample, as is the probability of GGSLE events. Figure 3 shows that the GGSLE probability differs by more than an order of magnitude between the observations and simulations.

We performed several tests to investigate potential sources of this discrepancy (12). The results remain unchanged even when energy feedback from active galactic nuclei powered by SMBH accretion—which alters the internal structure of halos—is disabled in the simulations. This feedback suppresses star formation in substructures, altering the slope of their inner density profiles, making them less centrally concentrated and, hence, weaker gravitational lenses. Even without feedback, we are unable to completely bridge the gap between simulations and observations. Simulations without feedback are also grossly discrepant from observations for other well-measured quantities, such as the total fraction of baryons in clusters converted into stars. The mass and spatial resolutions of our simulations are sufficiently high to resolve the typical substructures included in the lensing mass models (12). We also exclude the possibility that the computed GGSLE probability could be enhanced by unassociated halos along the line-of-sight (LOS) to these clusters. Including multiple lens planes in the models generated using cosmological simulations, we find that the substructure

Fig. 2. Comparison between an observed and a simulated gravitational lens.

(A) The projected mass map (called convergence) of MACSJ1206 (color bar), overlaid with the critical lines for sources at redshift $z = 7$ (solid white lines). The dashed polygon delimits the region of the HST image within which cluster galaxies were selected and included in the lens model. (B) The caustics corresponding to the principal (in gray) and to the secondary critical lines (in red) of MACSJ1206 (12). The dashed gray line shows the limits of the field of view in (A) mapped into the

source plane (12). The GGSL probability is calculated by dividing the area of the secondary caustics by that enclosed by the dashed gray line. (C) The projected mass map and the critical lines for sources at redshift $z = 7$ of a simulated cluster with a mass similar to that of MACSJ1206 (12). The dashed polygon is the same as in (A). (D) Caustics of the simulated cluster shown in (C). Although the main critical lines and caustics have similar extents, the secondary critical lines and caustics are larger and more numerous in the lens model of MACSJ1206 than in the simulation.

critical lines and caustics are negligibly affected by halos along the LOS (12). The observationally constrained lens models reproduce the shapes and sizes of the observed GGSL events, e.g., the model-predicted image positions match the observations within ~ 0.5 arc sec.

The discrepancy between observations and simulations may be due to issues with either the CDM paradigm or simulation methods. Gravitational lensing has previously been used to probe detailed properties of dark-matter halos associated with individual cluster galaxies [e.g., (20, 21)]. Simulations show that the mass and radial distributions of subhalos are nearly universal (22). Varying results have been reported for the level of agreement between lens model predictions and simulations for other derived quantities; e.g., the mass distribu-

tion functions of substructure derived from lensing data agree with simulations, but their radial distributions are more centrally concentrated in observations than in simulations (5, 14, 15). Strong lensing clusters also contain more high-circular velocity subhalos (i.e., subhalos with maximum circular velocities $V_{\text{circ}} > 100 \text{ km s}^{-1}$) compared with simulations (5, 15, 23). The maximum circular velocity is given by

$$V_{\text{circ}} = \max \sqrt{\frac{GM(r)}{r}} \quad (1)$$

where G is the gravitational constant, $M(r)$ is the galaxy mass profile, and r is the distance from the galaxy center. Figure 4 shows that, in our lens models, observed galaxies have larger circular velocities than their simulated analogs at a fixed mass. This implies that dark-

matter subhalos associated with observed galaxies are more compact than theoretically expected. Observed substructures also appear to be in closer proximity to the larger-scale cluster critical lines. Explaining this difference requires the existence of a larger number of compact substructures in the inner regions of simulated clusters. Baryons and dark matter are expected to couple in the dense inner regions of subhalos, leading to alterations in the small-scale density profile of dark matter, so it could be that current understanding of this interplay is incorrect. Alternatively, the difference could arise from incorrect assumptions about the nature of dark matter.

Previous discrepancies between the predictions of the standard cosmological model and data on small scales have arisen from

observations of dwarf galaxies and of satellites of the Milky Way, known as the “missing satellite” (24, 25), “cusp-core” (26), and “too-big-to-fail” problems (27, 28), discrepancies with planes of satellite galaxies (29). The discrepancy that we report is unrelated to those issues. Previous studies revealed that observed small satellite galaxies were fewer in number and were less compact than ex-

pected from simulations; here, we find the opposite results for cluster substructures. The GGSL events that we observe show that subhalos are more centrally concentrated than predicted by simulations; i.e., there is an excess not a deficit. Hypotheses advocated to solve previous controversies on dwarf galaxy scales would only exacerbate the discrepancy in GGSL event numbers that we report.

Our results therefore require alternative explanations. One possibility is numerical effects arising from the resolution limits of simulations (30). However, known numerical artefacts are not effective enough at disrupting satellites. We investigated this issue (12) and found that it can change the predicted GGSL event rate by at most a factor of 2, which is insufficient to explain the nearly order-of-magnitude discrepancy that we find. Any numerical artefacts would also appear on galactic scales, where they would worsen the missing satellite problem.

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Fig. 3. The GGSL probability as a function of source redshift. The mean GGSL probability for our reference sample is shown with a solid dark blue line. The light blue dot-dashed and violet dotted lines plot the computed GGSL probability for the HFF and CLASH Gold samples. The median GGSL probability measured from simulations is given by the orange dashed line (12). The colored bands show the 99.9% confidence intervals for each dataset. The discrepancy between observations and simulations is about an order of magnitude.

Fig. 4. Circular velocities and positions of substructures in simulated and observed galaxy clusters. (A) Substructure circular velocity as a function of substructure mass M_{sub} . The circular velocity is a proxy for the concentration of the substructure mass. The solid black line shows the average relation for the reference sample (6). The colored circles show the simulations, color-coded by the substructure distance from the cluster center R in units of the cluster virial radius R_{vir} . The orange dashed curve shows the best-fitting model relation for simulated substructures whose distance is less than 15% of the virial radius. This is roughly the region around the cluster center probed by strong lensing. The observed relation is always above that derived from the simulations, indicating that observed substructures are more compact than the simulated ones. (B) Mean cumulative distribution of the substructure distances from the

cluster center, $N(>x)$. The distances are scaled by the virial radius of the host cluster, $x = R/R_{\text{vir}}$. The blue and orange lines show the distributions for the observed reference sample and the simulations, respectively. The vertical dashed line shows the mean size of the main critical lines of MACSJ1206, MACSJ0416, and AS1063, θ_E .

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the results. E.R. and S.B. produced the numerical simulations and the subhalo catalogs. R.B.M. produced the multilens plane simulations used to test effects of matter along the line of sight. M.M., P.N., and F.C. wrote the manuscript, including contributions from all the other authors. **Competing interests:** The authors declare no competing interests. **Data and materials availability:** Our simulation snapshots and simulated subhalo catalogs (both in GADGET file format), along with lens models for the clusters in the reference and CLASH Gold samples (as LENSTOOL parameter files), are available at https://dx.doi.org/10.20371/INAF/DS/2020_00001. The lens models of the clusters in the HFF sample were taken from <https://archive.stsci.edu/prepds/frontier/lensmodels/>; we used version v4 of the CATS and Sharon maps. The GLAMER software for ray-tracing and the code used to measure the GGS� cross sections are available at Zenodo (31, 32).

SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/369/6509/1347/suppl/DC1
Materials and Methods
Table S1
Figs. S1 to S12
References (33–110)
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An excess of small-scale gravitational lenses observed in galaxy clusters

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Gravitational lenses in galaxy clusters

The large mass of a galaxy cluster deflects light from background objects, a phenomenon known as gravitational lensing. The large-scale gravitational lens caused by the whole cluster can be modified by smaller-scale mass concentrations within the cluster, such as individual galaxies. Meneghetti *et al.* examined these small-scale gravitational lenses in observations of 11 galaxy clusters. They found an order of magnitude more small-scale lenses than would be expected from cosmological simulations. The authors conclude that there is an unidentified problem with either prevailing simulation methods or standard cosmology.

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