A massive, dead disk galaxy in the early Universe

Sune Toft1, Johannes Zabl1,2, Johan Richard3, Anna Gallazzi3, Stefano Zibetti4, Moire Prescott5, Claudio Grillo6, Allison W. S. Man7, Nicholas Y. Lee1, Carlos Gómez-Guijarro1, Mikkel Stockmann1, Georgios Magdis4,5 & Charles L. Steinhardt1

At redshift \( z = 2 \), when the Universe was just three billion years old, half of the most massive galaxies were extremely compact and had already exhausted their fuel for star formation1–4. It is believed that they were formed in intense nuclear starbursts and that they ultimately grew into the most massive local elliptical galaxies seen today, through mergers with minor companions5,6, but validating this picture requires higher-resolution observations of their centres than is currently possible. Magnification from gravitational lensing offers an opportunity to resolve the inner regions of galaxies7. Here we report an analysis of the stellar populations and kinematics of a lensed galaxy at \( z = 2.1478 \) compact galaxy, which—surprisingly—turns out to be a fast-spinning, rotationally supported disk galaxy. Its stars must have formed in a disk, rather than in a merger-driven nuclear starburst8. The galaxy was probably fed by streams of cold gas, which were able to penetrate the hot halo gas until they were cut off by shock heating from the dark matter halo9. This result confirms previous indirect indications10–13 that the first galaxies to cease star formation must have gone through major changes not just in their structure, but also in their kinematics, to evolve into present-day elliptical galaxies.

We obtained deep spectroscopy using the XSHOOTER instrument on the Very Large Telescope (VLT) of a compact quiescent galaxy that is gravitationally lensed by the \( z = 0.588 \) cluster of galaxies MACS J2129.4−0741 (hereafter MACS2129−1; ref. 14; (Extended Data Fig. 1), and as a consequence appears 4.6 ± 0.2 times brighter and extends over 3″ on the sky.

In Fig. 1, we show the position of the XSHOOTER slit on a Hubble Space Telescope (HST) colour-composite image and on the reconstructed source plane. The galaxy is stretched along its major axis and we derive a spatially resolved spectrum typical of quiescent \( z \approx 2 \) galaxies.

---

Figure 1 | Spectrum of MACS2129−1. Rest-frame ultraviolet–optical two-dimensional and one-dimensional XSHOOTER spectra, adaptively rebinned to a constant \( S/N \) per bin. The flux density (\( f_\lambda \)) is plotted as a function of the observed wavelength (\( \lambda_{\text{obs}} \)) and the rest-frame wavelength (\( \lambda_{\text{rest}} = \lambda_{\text{obs}}/(1 + z) \), where \( z \) is the redshift). The bottom panel shows a close up of the most important absorption features, binned to a resolution of 9.6 Å (observed). The dashed red line shows the best-fitting stellar population model. Grey regions indicate windows of high telluric absorption; orange regions indicate important emission lines. The insets show colour-composite HST images of the galaxy on the image plane and on the reconstructed source plane, with the position of the slit overlaid.

---

1Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 32, København Ø, 2100, Denmark. 2Institut de Recherche en Astrophysique et Planétologie (IRAP), Université de Toulouse, CNRS, UPS, F-31400 Toulouse, France. 3Université Lyon, Université Lyon 1, ENS de Lyon, CNRS, Centre de Recherche Astrophysique de Lyon UMR5574, F-69220 Saint-Genis-Laval, France. 4Istituto Nazionale di Astrofisica–Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, 50125 Firenze, Italy. 5Department of Astronomy, New Mexico State University, 1320 Frerger Mall, Las Cruces, New Mexico 88003-8001, USA. 6Dipartimento di Fisica, Università degli Studi di Milano, via Celoria 16, I-20133 Milano, Italy. 7European Southern Observatory, Karl-Schwarzschild-Straße 2, 85748 Garching bei München, Germany. 8Institute for Astronomy, Astrophysics, Space Applications and Remote Sensing, National Observatory of Athens, GR-15236 Athens, Greece.

© 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.
post-starburst galaxies, with a strong Balmer break and a number of strong absorption features. We fit a spectroscopic redshift of $z = 2.1478 \pm 0.0006$ and constrain the stellar populations through modelling of the rest-frame ultraviolet-to-optical spectrum, the absorption line indices, and the spatially integrated rest-frame ultraviolet-to-near-infrared (NIR) colours derived from 16-band HST/Infrared Array Camera (IRAC) photometry. The best-fitting spectrum reveals a massive, old, post-starburst galaxy consistent with negligible ongoing star formation, and at most solar metallicity (that is, $\log(M/M_\odot) = 11.15 \pm 0.23$, $\log[\text{Age (yr)}] = 8.97 \pm 0.26$, $A_V = 0.6 \pm 0.6$ mag, $\log(Z/Z_\odot) = 0.56 \pm 0.55$) (Extended Data Table 1). We derive a velocity dispersion of $\sigma = 329 \pm 73$ km s$^{-1}$ from absorption lines in the spatially integrated spectrum (Fig. 1) using a penalized pixel-fitting method ($p$PXF)\(^\text{15}\) with the best-fitting spectral energy distribution model as a template.

Interestingly, the absorption lines are tilted in the two-dimensional spectrum. We extract individual rows that represent approximately $\Delta r$ km s$^{-1}$ (grey shading). PSF (FWHM) indicates the full-width at half-maximum of the PSF.

\[ V_{\text{max,obs}}(r) = \sigma_{\text{obs}} + \sigma_{\text{sm}}(r). \]

This is particularly relevant in the central regions where the steep gradient of rotational velocity translates into artificially high apparent velocity dispersions. We find that $\sigma_{\text{obs}}(r)$ is well represented by velocity smearing ($\sigma_{\text{sm}}$) alone, but can also accommodate a small intrinsic constant dispersion ($\sigma_{\text{int}} = 59 \pm 7$ km s$^{-1}$). In the central bin, $\sigma_{\text{obs}}$ is about 0.5 standard deviation above the modelling predictions, leaving room for enhanced central dispersion; however, as there is no indication of a bulge in the stellar mass map (Fig. 3), any bulge is unlikely to be very prominent. From the dynamical modelling we conclude that the galaxy is a rotation-dominated disk with $V_{\text{max}}/\sigma_{\text{int}} > 3.3$ (97.5\% confidence).

We detect weak, centrally concentrated nebular emission lines [O\textsc{iii}] at wavelength $\lambda = 5,007$ Å, [H\textsc{ii}] (5,411 Å), H\alpha (6,563 Å), and [N\textsc{ii}] (6,583 Å). The (extinction-corrected) H\alpha flux corresponds to a star-formation rate of SFR $< 1.1 M_\odot$ yr$^{-1}$, an upper bound since the line ratios indicate an active galactic nucleus (AGN) or a low-ionization nuclear emission-line region (LINER) as the dominant ionizing source\(^\text{17}\), consistent with what is found in local post-starburst galaxies\(^\text{18}\). The emission lines are redshifted by a systematic velocity shift of $V_A = 236$ km s$^{-1}$ with respect to the absorption lines, possibly owing to AGN outflows (see Extended Data Fig. 2 and Extended Data Table 1).

Using our well-constrained lens model and multi-band HST imaging, we reconstruct the galaxy on the source plane and derive spatially resolved maps of median-likelihood estimates of stellar population parameters (Fig. 3). The projected mass distribution is smooth, ruling out the possibility of a close major merger causing the velocity gradient.

---

**Figure 2** | Rotation and dispersion curve for MACS2129$-$. Velocity offsets $\Delta V$ and dispersions $\sigma$ as a function of distance from the centre of the galaxy $\Delta r$, derived from $p$PXF fits to the individual spatial lines in the full spectrum. Error bars represent statistical uncertainties associated with the fitting and systematic uncertainties added in quadrature. The grey shading shows the 68% confidence interval for the thin disk model fits to the black squares. The observed dispersion is high in the centre and drops off symmetrically with distance, consistent with the effect of point spread function (PSF) smearing of the velocity gradient, and a constant dispersion of up to about 100 km s$^{-1}$ (grey shading). PSF (FWHM) indicates the full-width at half-maximum of the PSF.

**Figure 3** | Stellar population maps on the reconstructed source plane. Shown are two-dimensional maps of the stellar mass surface density $M_\star$, the specific SFR, the stellar age and the dust extinction in the rest-frame i-band, $A_i$. These are created from fits to the HST imaging, using the same stellar population library as used to fit the full spectrum. The insets at bottom right show 68% confidence intervals for the derived parameters. The PSF is shown in Fig. 4. The younger knot in the top right corner, which may be an ongoing minor merger, does not give rise to the extra light seen in Fig. 4, or influence the conclusions based on azimuthally averaged profiles (see Methods).

than observed previously in any galaxy that has ceased star formation (quenched). This is a conservative lower bound, as corrections for the effects of inclination, alignment of the slit, and unresolved resolution will all drive the ratio up.

We take these into account, as well as the effect of gravitational lensing, by performing a full Markov chain Monte Carlo dynamical modelling analysis. We find the velocity shifts to be well represented by the rotation curve of a thin, circular, rotating disk with a maximum rotational velocity of $V_{\text{max}} = 532^{+67}_{-49}$ km s$^{-1}$ at $R_{\text{max}} = 0.5 \pm 0.3$ kpc. This implies a dynamical mass within $r_e$ of $\log(M_{\text{dyn}}/M_\odot) = 11.0^{+0.1}_{-0.2}$ (and a total dynamical mass of $11.3^{+0.2}_{-0.1}$).

We model the observed dispersions by taking into account the effect of point spread function (PSF) smearing $\sigma_{\text{obs}}(r) = \sigma_{\text{sm}} + \sigma_{\text{int}}(r)$. This is particularly relevant in the central regions where the steep gradient of rotational velocity translates into artificially high apparent velocity dispersions. We find that $\sigma_{\text{obs}}(r)$ is well represented by velocity smearing ($\sigma_{\text{sm}}$) alone, but can also accommodate a small intrinsic constant dispersion ($\sigma_{\text{int}} = 59^{+7}_{-6}$ km s$^{-1}$). In the central bin, $\sigma_{\text{obs}}$ is about 0.5 standard deviation above the modelling predictions, leaving room for enhanced central dispersion; however, as there is no indication of a bulge in the stellar mass map (Fig. 3), any bulge is unlikely to be very prominent. From the dynamical modelling we conclude that the galaxy is a rotation-dominated disk with $V_{\text{max}}/\sigma_{\text{int}} > 3.3$ (97.5% confidence).

---

© 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.
The three other maps show indications of radial gradients, with the galaxy centre having a specific SFR about 2 dex lower, stellar populations about 0.2 dex older, and extinction about 0.6 mag higher than the outer regions (see Extended Data Fig. 3). Note, however, that the specific SFR is consistent with zero everywhere (see error map). The quiescent nature of MACS2129−1 is further supported from its non-detection in deep Spitzer/Multiband Imaging Photometer for Spitzer (MIPS) 24−μm observations, corresponding to a lensing-corrected 3σ upper limit of SFR < 5M⊙ yr⁻¹.

We fit the two-dimensional surface brightness distribution of the galaxy on the source plane. Figure 4 shows the reconstructed F160W image, the best-fitting Sersic model (centralized effective radius r_e = 1.73 ± 0.34 kpc, Sersic index n = 1.01 ± 0.06, axis ratio a/b = 0.59 ± 0.09), and the residual (image minus model), which shows visual hints of spiral arm structure. Also shown are one-dimensional profiles of the best-fitting model (black curve), the F160W light distribution (red curve) and the projected stellar mass distribution (grey area) estimated from the spatially resolved spectral energy distribution fits. The galaxy is resolved on scales of about 250 pc, allowing accurate constraints on its inner profile to around r_e/5. The light and mass profiles are well represented by an exponential disk law (n = 1) out to 5 kpc (approximately 3r_e), as expected if the galaxy is a rotation-dominated disk. The outer regions (r > 3r_e) have excess low surface brightness light compared to the model, which is not associated with notable excess stellar mass.

MACS2129−1 presents a range of features typical of z > 2 compact quiescent galaxies: it falls on the stellar mass−size relation for quiescent galaxies, it has a post-starburst spectrum with evolved stellar populations, a SFR more than 100 times below the z = 2 SFR−M∗, relation, and M_g/M∗ = 1.55 ± 0.40 (within r_e), similar to what is found in other z > 2 quiescent galaxies. However, the increased sensitivity and resolution provided by gravitational lensing reveal underlying detailed kinematic properties and structure that are typical of late-type galaxies.
METHODS

Selection of MACS2129—1. MACS J2129.4−0741 at $z = 0.588$ was first listed in the Massive Cluster Survey (MACS) catalogue14. It was observed as part of the CLASH survey58 with the HST/ACS and WFC3 in 16 broadband filters, from the near-ultraviolet to the near-infrared, and with Spitzer/IRAC in the 3.6-μm and 4.5-μm channels. Lensing models for the cluster have been developed and presented15–16. In Extended Data Fig. 1 we show a composite–colour image constructed from the CLASH data, with the position of the XSHOOTER slit overlaid on MACS J2129−1 with a position angle of $\sim 10^{\circ}$, as shown in Fig. 1. Photometric standard star observations of LTJ7987, LTJ2128, Feige110 and LTJ7987 were taken during the same nights as the science observations. For each of the observing blocks, at least one telluric star was observed at similar air mass and with the same instrumental setup as the science frames. The average seeing was about 0.5″ in the J-band, estimated based on header information provided by the observatory which we calibrated based on point sources (telluric stars) to direct FWHM measurements. This seeing estimate is somewhat uncertain and we estimate an uncertainty of about 0.1″.

An analysis of this dataset has previously been published18. Here we take advantage of notable advances in data reduction and analysis techniques to revisit the observations. The ESO XSHOOTER pipeline (v. 2.6.0) with small modifications18, was used in the reduction. In the near-infrared we achieved the best reduction with a nodding reduction, which we, for consistency, used also for the UVB and VIS data.

The offsets between the individual exposures were not ideally chosen for a nodding reduction of an object as extended as MACS2129−1. Whereas for half of the observing blocks a nod throw of 3″ was used, which is not ideal but acceptable, for two of the four observing blocks consecutive frames had very similar position differences, rendering these pairs useless for a standard nodding reduction. As a solution, we combined frames in these observing blocks in a not strictly temporal order, and rejected two frames in each. In this way we obtained for each of these two observing blocks one pair with a 3″ nod and one with a 2″ nod throw. Excluding the rejected frames we had a total on-source time of 2.67 h.

We reduced the data in pairs of two frames and corrected each of the reduced nodding pairs for the telluric transmittance16. We then corrected from air to vacuum wavelength scale and converted to the heliocentric wavelength using the heliocentric velocity standard. The rejected frames we had a total on-source time of 2.67 h. For the two observing blocks one pair with a 3″ nod throw. Excluding

does not change by more than 5%.

The reason that the model magnification is so stable for MACS2129−1 is its position 1 arcmin west of the core, outside the strong lensing region where the magnification is high and sensitive to mass substructures associated with the high density of cluster galaxies. Outside the core, the lensing magnification is dominated by the diffuse dark-matter distribution of the cluster, which is well constrained by the multiply imaged galaxies. A good level of precision and accuracy in the reconstruction of images far from the critical curves is a general result, which has been established within the HST Frontier Fields initiative, through detailed comparison of blind predictions of several modellers on simulated galaxy clusters39.

Spectral stellar population characterization. We constrained the global stellar mass, age, metallicity and extinction of MACS2129−1 by fitting the spatially integrated ultraviolet–NIR XSHOOTER spectrum with stellar population synthesis models, following the procedure described in ref. 4 but adopting a different model library that better reproduces the current star-formation activity.

In brief, we use a library of 500,000 model spectra based on BC03 stellar population models convolved with random star-formation histories. We assume a Chabrier initial mass function60. The star-formation histories are modelled with a delayed exponential41, on top of which random bursts of star formation can occur (library A). We also consider a star formation history library with no additional bursts (library B). The metallicity of the models varies along with the star-formation history and dust is implemented as in ref. 42. We adopt a Bayesian approach in which all models in the library are compared to the observed spectrum. Details of the adopted star-formation history, metallicity and dust library as well as the method used have previously been published41.

As a benchmark we fit the UVB–VIS–NIR spectrum pixel by pixel (fit 1), but as a test of the robustness of the fit we also perform a fit to observed spectral indices: D4000n, Hβ, [Mg2Fe], [MgFe], combined with optical–NIR (CLASH) and mid-infrared (MIR) (IRAC) broadband data (fit 2). The marginalized median-likelihood parameters are listed in Extended Data Table 1. Reassuringly, these all agree to within estimated uncertainties. The galaxy is massive, old, and within uncertainties consistent with being void of dust and star formation. The metallicity is quite uncertain, but has an upper confidence limit of approximately solar in all fits. The large uncertainties on the metallicity are reflected in the uncertainties of the other parameters compared to fits assuming a fixed metallicity3, but we choose to keep it a free parameter in the fit, because we do not have much empirical evidence for a fixed value. In fitting the global properties in the spatially integrated spectrum, we also consider a fit to a `central' [$r < 0.5''$], and an `outer' (0.5″ $< r < 1.4''$) extraction to look for spatial variations.

Derivation of rotation curve. We used pPXF (v. 6.0) to determine the velocity centroid (redshift) and dispersion both for the integrated spectrum and individual spatial rows of the rectified two-dimensional spectrum. The individual rows correspond to a spatial extent of 0.21′′ each. Because the individual rows have low $S/N$ for kinematic fitting (central row $S/N = 3 \, \AA^{-1}$ at 1.05″ $S/N = 1 \, \AA^{-1}$), it is crucial to minimize the degrees of freedom and maximize the amount of information. In this sense, we derive our fiducial results based on the best-fitting stellar population fits and used only low-order correction polynomials (second-order additive and multiplicative over the full rest-frame range from 3,750 Å to 5,650 Å, excluding only a window from 4,200 Å to 4,750 Å (the gap between the J and H bands) and the $[O\,iii]$ ($\lambda = 4,959 \, Å$ and 5,007 Å) lines. Certainly, the inclusion of the 4,000 Å break combined with low-order correction polynomials is a potential concern
for template mismatch. We quantified potential template mismatch as in other studies, through a range of tests including different correction polynomials, different templates, and different wavelength ranges. The full error budget includes both statistical and systematic uncertainties.

We determined the statistical uncertainties by running pPXF on 1,000 realizations of the data. These realizations were created by randomly perturbing the best-fitting model obtained by pPXF using the estimated uncertainties from the pipeline’s error spectrum. This method correctly accounts for the increased noise in the emission and absorption lines, if the correction error spectrum is correct. In this sense, correlated noise is a potential problem, as it is not accounted for by the pipeline. However, the correlation is mostly removed in the re-binned spectrum used for our analysis. Moreover, statistical uncertainties are on the same order as the statistical uncertainty, which is 58 km s⁻¹.

To test for template mismatch, we performed several tests on the integrated spectrum. For instance, we simulated the appearance of straight lines on the detector. For a straight line, the intensity along the line is given by the equation:

\[ I(x) = I_0 \cos(2\pi x / \lambda) \]

where \( I_0 \) is the intensity at the center of the line and \( \lambda \) is the wavelength. If the absorption lines appear tilted, we could simulate the appearance of straight lines on the detector. We found that afterria the tilting, the line appears straight.

The single observed slit position angle limits our ability to break degeneracies between 0 and 1. All parameters were varied simultaneously during the fitting of the model. The single observed slit position angle limits our ability to break degeneracies. However, our Galactic modelling provides firm constraints on the position and orientation of the galaxy with respect to the slit on the source plane. We used the Galactic modelling to determine the position of the centre of the slit relative to the disk centre (Xc, Yc), where a positive offset in both parameters indicates a slippage. From this, we conclude that we can safely use the rotation curve out to about 1.4 kpc.

We used the systematic uncertainties derived for the integrated spectrum also for the individual spatial extractions, because we expect the template mismatch uncertainties to be of similar extent. In addition, to make sure that the result does not depend on a single line (for example, owing to residuals), we repeated the test including and excluding wavelengths 1,600 km s⁻¹ wide in the fit of the individual spatial extractions. The uncertainties from this test were added in quadrature.

The tilted absorption lines are not artefacts of the reduction. Owing to the relatively small nod throw, the object itself can potentially contaminate the region used for background subtraction, especially in the outer parts of the galaxy. Therefore, we simulated the effect of the nodding strategy on the spatial profile and on the rotation curve. From this we conclude that we can safely use the rotation curve out to about 1.4 kpc.

As XSHOOTER is an echelle spectrograph, the geometrical mapping between the non-rectified and the rectified frame could potentially cause systematic effects, but we do not find any evidence of this. The residuals between predicted and actual positions of calibration lamp images do not deviate by more than one pixel and skylines are straight in the rectified output frames.

Dynamical modelling. We model the rotation curve using a thin disk model with seven parameters: the offset angle between the slit and the major axis of the disk (θ), the maximum velocity of the disk (Vmax), the radius at which the disk reaches Vmax (Rmax), the position of the centre of the slit relative to the disk centre (Xc, Yc), where a positive offset in both parameters indicates a slippage. From this, we conclude that we can safely use the rotation curve out to about 1.4 kpc.

The single observed slit position angle limits our ability to break degeneracies. However, our Galactic modelling provides firm constraints on the position and orientation of the galaxy with respect to the slit on the source plane. We used the Galactic modelling to determine the position of the centre of the slit relative to the disk centre (Xc, Yc), where a positive offset in both parameters indicates a slippage. From this, we conclude that we can safely use the rotation curve out to about 1.4 kpc.

Dynamical modelling. We model the rotation curve using a thin disk model with seven parameters: the offset angle between the slit and the major axis of the disk (θ), the maximum velocity of the disk (Vmax), the radius at which the disk reaches Vmax (Rmax), the position of the centre of the slit relative to the disk centre (Xc, Yc), where a positive offset in both parameters indicates a slippage. From this, we conclude that we can safely use the rotation curve out to about 1.4 kpc.

The single observed slit position angle limits our ability to break degeneracies. However, our Galactic modelling provides firm constraints on the position and orientation of the galaxy with respect to the slit on the source plane. We used the Galactic modelling to determine the position of the centre of the slit relative to the disk centre (Xc, Yc), where a positive offset in both parameters indicates a slippage. From this, we conclude that we can safely use the rotation curve out to about 1.4 kpc.
of the magnification found among the 1,979 realizations, and two represent the best and worst seeing plausible for our data. The results, summarized in Extended Data Table 2, are consistent with our benchmark model and show that lens model and seeing uncertainties are sub-dominant for our analysis when compared with observational uncertainties.

**Spatially resolved stellar population characterization.** The exquisite multi-band HST coverage, combined with the increased depth and resolution provided by the lensing, offers an opportunity to study trends in the spatially resolved stellar population characterization. In the present N/S for robust stellar population characterization, we include only the F850LP, F105W, F110W, F125W, F140W and F160W band images in the fits. The bluer bands are too shallow and noisy over most of the galaxy's extent to provide useful information. Next, we PSF-match the images, and adaptively smoothed them, using ADAPTSMOOTH47,48. Smoothing masks were constructed for the reddest images (F125W, F140W and F160W), by requiring a minimum S/N = 10 and a maximum smoothing radius of 3 pixels. These three masks were then combined and used to smooth all six images in the same way.

We then performed stellar population characterization for each pixel in the matched, smoothed images, and constructed two-dimensional maps of stellar mass, age, extinction (A) and specific SFR based on the median of their likelihood distributions (using the same technique as used in the benchmark fit of the spectrum). These maps were then transformed to the source plane using our well constrained best-fitting lensing model (Fig. 3). Error maps were constructed from the 68% confidence intervals of the fits to the individual pixels. In an absolute sense these parameters are subject to rather large uncertainties (see insets in Fig. 3) owing to age/dust/metallicity model degeneracies; however, because individual spatial bins are independent (on scales larger than 3 pixels), the relative spatial structure is much more robust, and the integrated properties are consistent with those derived from the full spectral fit.

In Extended Data Fig. 3 we show radial profiles of the azimuthally averaged stellar population parameters (solid line). These show evidence for radial gradients with older stellar populations, higher extinction and lower specific SFR in the centre than in the outer parts. The shaded areas represent the pixel-to-pixel scatter in the median values in the elliptical apertures, not taking into account the uncertainties on the individual estimates. The amplitudes of these regions provide a rough representation of the random errors on the parameters, that is, owing to measurement errors alone. (We note that this scatter slightly underestimates the real random error due to pixel-to-pixel correlation, for example, because of the smoothing.) Also shown are the median-likelihood parameter values for the two spectral extractions, which are consistent with the photometric fits.

Despite the large systematic uncertainties, trends in physical parameters are evident and should be considered robust under the hypothesis that there is no radial trend in the possible systematic bias affecting our estimates. Given the homogeneity of the observables throughout the radial extent of the galaxy and also the relatively small range in physical parameters, we have no reason to expect any radially varying systematic bias.

The gradients are not driven by the age/dust degeneracy because that would result in opposite slopes for age and dust profiles. Also shown is the average specific SFR gradient derived from adaptive optics observations of similar-mass z ∼ 2 star-forming galaxies52, which has been interpreted as evidence of inside-out morphological quenching. The specific SFR gradient in MACS2129−1 has a similar shape, but is depressed by a factor of >100. The observed age gradient suggests that quenching in MACS2129−1 proceeded from the inside out, over a timescale of about 300 million years.

Inspection of the maps shows an off-centre clump, with a younger stellar population and less extinction than the rest of the galaxy. This may indicate an ongoing minor merger, but we cannot confirm this because it is not detected in the spectrum. Masking out the clump does not change the derived radial stellar population gradients much.

**Surface brightness fits.** We used Galfit49 to fit the source plane F160W (rest-frame optical) two-dimensional surface brightness profile with a Sersic model. As a PSF model we used a point source, reconstructed on the source plane in the same way as MACS2129−1 (see inset in Fig. 2). In addition to the formal fitting errors, uncertainties in the lensing model used for source plane reconstruction must be taken into account. We do this by re-running Galfit on 98 different reconstructed images and matching PSFs, selected to sample the full range of lensing model realizations. The derived parameters are very stable (see Extended Data Fig. 6), with mean and standard deviations of r_e = 20.9 ± 0.6 pixels, a/b = 0.59 ± 0.01, r_e,ex = 1.73 ± 0.05 kpc, n = 1.01 ± 0.01, position angle PA = −45.17 ± 0.96°, demonstrating that lensing model uncertainties do not much affect the shape and size of the galaxy on the source plane. The main potential systematic uncertainty on our lens modeling is associated with the implementation of substructure. As a conservative upper limit on this uncertainty, we repeated the Galfit analysis on two extreme sets of model realization: one where the nearby cluster galaxy has zero mass and one where it has twice the mass. In the first case we obtain r_e = 24.9 ± 0.6 pixels, a/b = 0.49 ± 0.01, r_e,ex = 1.89 ± 0.03 kpc, n = 0.89 ± 0.01, PA = −35.49 ± 0.38°, and in the second r_e = 18.2 ± 0.5 pixels, a/b = 0.62 ± 0.01, r_e,ex = 1.55 ± 0.04 kpc, n = 1.07 ± 0.01, PA = −58.0° ± 1.8°.

From these results we derive conservative estimates of the total errors (statistical and maximum systematic added in quadrature) for the Galfit parameters: r_e = 20.9 ± 1.8 pixels, a/b = 0.59 ± 0.09, r_e,ex = 1.73 ± 0.27 kpc, n = 1.01 ± 0.06, PA = −45.0 ± 12.8°.

We also repeated the dynamical modelling with these models, but found no notable changes in the results. This analysis is sensitive only to the brightest, central part of the galaxy which is not strongly affected by the substructure, and its error budget is dominated by the limited S/N of the spectrum, and PSF smearing. Finally, we note that masking out the north-east clump does not noticeably change the two-dimensional fit or the one-dimensional profile. It is thus not the main source of the ‘excess light’ seen at large radii.

To test what structural parameters we would have derived for MACS2129−1 in the absence of lensing we repeated our Galfit analysis on a ‘de-lensed’ version of the source-plane F160W image. This image was created by re-binning the F160W source plane image to the pixel scale of WFC3, convolving it with the WFC3 PSF, scaling its brightness by the inverse of the magnification factor and inserting it into an empty region of the original F160W image. The best-fitting parameters r_e,ex = 1.92 ± 0.02 kpc and n = 1.02 ± 0.03 are similar, demonstrating that MACS2129−1 would have been identified as a compact exponential disk, even in the absence of lensing.

**Emission lines may imply AGN outflow.** We decompose the stellar continuum and nebular emission lines in the visible—NIR spectrum using pPXF + Gandalf50.

Detected lines in the central and outer extractions are listed in Extended Data Table 1. The emission lines are centrally concentrated. To estimate the height of the ionizing field, we calculate the line ratios log(N[1]n/Hα) = −0.06 ± 0.10 and log(O[11]/Hβ) > 0.45 ± 0.08. The latter is a lower bound, since Hβ is undetected, and estimated assuming case B recombination (Hβ/Eβ = 2.9) and no extinction.

These ratios are inconsistent with O and B stars being the main ionizing source, but consistent with the expectations from AGN or a LINER51.

The emission lines have dispersions similar to those measured from the absorption lines (σ_e = 382 km s⁻¹), but are redshifted by 238 km s⁻¹. Velocity offsets of this order are expected from bipolar AGN outflows. Usually these are blueshifted, but in some local Seyfert galaxies redshifted lines are observed, when the angle of the bicone outflow is small with respect to the main plane of the host galaxy51. Alternatively, the redshift could be caused by spatially unresolved patchy star formation or dust in the inner part of the disk, but since the emission is centrally concentrated and the line ratios suggest AGN origin, this is a less likely scenario.

An exotic interpretation of the weak redshifted emission lines is that MACS2129−1 is a high-redshift analogue of the so-called ‘offset AGN’, observed in a large fraction of local early-type or post-merger galaxies in over-dense environments52.

The offsets in these are interpreted as being caused by dual black holes only one of which is accreting; this is a sign of a major merger in the recent past53. Simulations show that if the merger were gas-rich (gas fraction >0.5) it would have commenced 1–2 billion years earlier53, and that the gas in the remnant under such conditions can quickly rearrange itself in a rapidly spinning central disc54. This is a plausible alternative formation scenario for the massive stellar disk observed in MACS2129−1, consistent with its mean stellar age (around 750 million years).

**Rotation may be common in high-redshift quiescent galaxies.** The exponential profile and late type kinematics of MACS2129−1 appear in tension with the commonly accepted picture derived from lower-resolution data, that high-redshift quiescent galaxies are predominantly dispersion-dominated6 protobulges with de-Vaucouleurs-like profiles55,56, a picture that provides a straightforward link to their low-redshift descendants57. However, there is a growing body of indirect evidence that quiescent galaxies may grow more disk-like and rotation-dominated with redshift. A number of studies have found a fraction of quiescent galaxies to have exponential disk-like surface brightness profiles, both at high11,13,36,57 and intermediate redshifts58. Indeed, the best candidate low-redshift direct descendant of a z = 2 compact quiescent galaxy was found to be a rapidly rotating exponential disk59. Also, it has been argued that the average observed axis ratios of z ∼ 2 compact quiescent galaxies are consistent with the majority of them being disks60.

Recently it was argued that dynamical mass of z = 2 quiescent galaxies with exponential disk-like profiles, calculated from unresolved spectroscopy was higher than expected from their stellar mass, which was interpreted as evidence for unresolved rotation61. The resolved kinematics for MACS2129−1 allows us to test this interpretation. If we calculate the dynamical mass in the same way as this study log(M_dyn/σ_e,maj) = (R[n]σ_e,maj/G, where [R[n]] = 8.87 ± 0.83 ± 0.024 m, is the Sersic index, σ_e is the spatially integrated velocity dispersion, and r_e,maj is the major axis effective radius, we find log(M_dyn/σ_e,M) = 11.65 ± 0.14, a factor of 2 higher than the total dynamical mass derived from resolved kinematics.
log([M_{\text{dyn}, \text{ref}}(V_{\text{max}})/M_\odot]) = 1.30 \pm 0.14 \text{ (assuming that } \log([M_{\text{dyn}, \text{ref}}(V_{\text{max}})]) = 2 \log \[M_{\text{dyn}, \text{ref}}(V_{\text{max}})] \text{). In the framework of the abovementioned study, the implied log([M_{\text{dyn}}]/M_\odot) = -0.39 \pm 0.37 \text{ suggests a contribution from unresolved rotation of up to } V\sigma = 3 \text{; however, given the error bars, the result is not statistically significant. We note that assuming } \beta = 5 \text{ and } r_\epsilon \text{, instead of } r_{\text{model}} \text{ (as often done in the literature), brings the unresolved } \log([M_{\text{dyn}}(V_{\text{max}})]) = 5.7 \sigma r_{\epsilon} G/11.33 \pm 0.09 \text{ into perfect agreement with the value derived from the resolved kinematics.}

Gravitational lensing currently offers the best way to quantitatively directly the ubiquity of rotation in high-redshift quenched galaxies until we have the Extremely Large Telescopes. Ground-based adaptive optics observations with 8–10 m telescopes can in principle resolve un-lensed examples, but will struggle with sensitivity when the signal is spread out. The James Webb Space Telescope will have the sensitivity required, but not quite the desired spatial resolution.

So far, three gravitationally lensed quiescent galaxies have been studied spectroscopically, MACS2129−1 (z = 2.1), RG1M0150 (z = 2.6) and COSMOS 0505+4901 (z = 2.8). The first two show clear evidence of rotation, the third did not have sufficient S/N for us to be able to tell. Gravitational lensing of quiescent galaxies is a rare phenomenon, but with systematic investigation of the large number of massive clusters available from existing and future surveys, it will be possible to build statistical samples of quiescent galaxies with resolved spectroscopy, one galaxy at a time.

**SFR limit from Spitzer/MIPS.** We derive an upper limit on the SFR in MACS2129−1 from its non-detection by Spitzer/MIPS at 24μm (Principal Investigator M. Yun). From the root mean square of the 24-μm map we derive a 3σ upper limit of F_{24μm} = 45 μJy. We then correct for an upper limit on the total infrared luminosity of (2.3 ± 0.0) × 10^{11}L_\odot, where L_\odot is the solar luminosity, by assuming various local (M82, Arp220) and high-redshift main-sequence and starburst templates from ref. 62. We then correct for magnification and derive an upper limit for the SFR of <5M_\odot yr^{-1}, using the Kennicutt relation (modified to a Chabrier IMF).

**Code availability.** The code used to perform the stellar population characterization from the XSHOOTER spectrum and the multi-band photometry is not publicly available, since full user documentation and interface are not yet developed. The base simple stellar population models adopted are publicly available at http://www.bruzual.org/bc03/. The adopted star-formation history library and the Bayesian base simple stellar population models adopted are publicly available at http://www.stsci.edu/hst/. The analysis also uses HST data from the CLASH programme ID 12460, which is publicly available at http://archive.stsci.edu/. The reduced XSHOOTER two-dimensional spectrum used for the kinematic analysis and the binned one-dimensional spectrum used for the stellar population synthesis analysis is available at https://sid.esra.dk/sharelink/g9S5Mq2zJ7. The best-fitting stellar population model to the full XSHOOTER spectrum is available on request.

30. Postman, M. et al. The cluster lensing and supernova survey with Hubble: an overview. Astrophys. J. Suppl. Ser. 553, 668 (2012).
31. Zitrin, A. et al. The cluster lensing and supernova survey with Hubble (CLASH): strong-lensing analysis of A383 from 16-band HST/WFC3/ACIS imaging. Astrophys. J. 742, 117 (2011).
32. Zitrin, A. et al. Hubble Space Telescope combined strong and weak lensing analysis of the CLASH sample: mass and magnification models and systematic uncertainties. Astrophys. J. 801, 44 (2015).
33. Mennara, A. et al. Precise strong lensing mass profile of the CLASH cluster MACS 2129. Mon. Not. R. Astron. Soc. 466, 4094–4106 (2017).
34. Geier, S. et al. VLT/X-Shooter near-infrared spectroscopy and HST imaging of gravitationally lensed z~2 compact quiescent galaxies. Astrophys. J. 777, 83 (2013).
35. Zabl, J. et al. Deep rest-frame far-UV spectroscopy of the giant Lyman emitter ‘Himiko’. Mon. Not. R. Astron. Soc. 451, 2050 (2015).
36. Selsing, J. et al. An X-Shooter composite of bright 1 < z < 2 quasars from UV to infrared. Astron. Astrophys. 585, A87 (2016).
37. Christensen, L. et al. The low-mass end of the fundamental relation for gravitationally lensed star-forming galaxies at 1 < z < 6. Mon. Not. R. Astron. Soc. 427, 1953–1972 (2012).
38. Julio, E. et al. A Bayesian approach to strong lensing modelling of galaxy clusters. New J. Phys. 9, 447–478 (2007).
39. Meneghetti, M. et al. The Frontier Field Lens Modeling Comparison Project. Preprint at https://arxiv.org/abs/1606.04548 (2016).
40. Shabir, G. Galactic stellar and substellar initial mass function. Publ. Astron. Soc. Pacif. 115, 763–795 (2003).
41. Sandage, A. Star formation rates, galaxy morphology, and the Hubble sequence. Astron. Astrophys. 161, 89–101 (1986).
42. Charlot, S. & Fall, M. A simple model for the absorption of starlight by dust in galaxies. Astrophys. J. 539, 718–731 (2000).
43. Zibetti, S. et al. Resolving the age bimodality of galaxy stellar populations on kpc scales. Mon. Not. R. Astron. Soc. 468, 1902–1916 (2017).
44. Valdes, F. et al. The Indo-US Library of Coudé Feed Stellar Spectra. Astrophys. J. Suppl. Ser. 152, 251–259 (2004).
45. Wu, Y. et al. Coudé-feed stellar spectral library—Atmospheric parameters. Astrophys. J. 525, A71 (2001).
46. Prescott, M., Martin, C. L. & Dey, A. Spatially resolved gas kinematics within a Lyman-alpha nebula: evidence for large-scale rotation. Astrophys. J. 799, 62 (2015).
47. Zibetti, S. Introducing ADAPTSMOOTH, a new code for the adaptive smoothing of astronomical images. Preprint at https://arxiv.org/abs/0911.4956 (2009).
48. Zibetti, S. et al. Resolved stellar mass maps of galaxies—all method and implication for global mass estimates. Mon. Not. R. Astron. Soc. 400, 1181–1198 (2009).
49. Peng, C. Y. et al. Detailed structural decomposition of galaxy images. Astron. J. 124, 266–293 (2002).
50. Sarzi, M. et al. The SAURON project—V. Integral-field emission-line kinematics of 48 elliptical and lenticular galaxies. Mon. Not. R. Astron. Soc. 366, 1151–1200 (2006).
51. Müller-Sánchez, F. et al. Outflows from active galactic nuclei: kinematics of the narrow-line and coronal-line regions in Seyfert galaxies. Astrophys. J. 739, 69 (2011).
52. Comerford, J. M. & Green, J. E. Offset active galactic nuclei as tracers of galaxy mergers and supermassive black hole growth. Astrophys. J. 789, 112 (2014).
53. Lutz, J. et al. The effect of mass ratio on the morphology and time-scales of disc galaxy mergers. Mon. Not. R. Astron. Soc. 404, 575–589 (2010).
54. Hopkins, P. et al. How do disks survive mergers? Astrophys. J. 691, 1168–1201 (2009).
55. Szomoru, D., Franx, M. & van Dokkum, P. Sizes and surface brightness profiles of quiescent galaxies at z ~ 2. Astrophys. J. 748, 121 (2012).
56. McGrath, E. et al. Morphologies and color gradients of luminous evolved galaxies at z~1.5. Astrophys. J. 682, 303–318 (2008).
57. Stockton, A., Canalizo, G. & Mathai, A. A disk galaxy of old stars at z~2.5. Astrophys. J. 605, 37–44 (2004).
58. Hsu, L.-Y., Stockton, A. & Shin, H.-Y. Compact quiescent galaxies at intermediate redshifts. Astrophys. J. 796, 92 (2014).
59. Trujillo, I. et al. NGC 1277: a massive compact relic galaxy in the nearby Universe. Astrophys. J. 780, 120 (2014).
60. Hill, A. et al. A stellar velocity dispersion for a strongly-lensed, intermediate-mass quiescent galaxy at z~2.8. Astrophys. J. 819, 74 (2016).
61. Puech, M. et al. IMAGES III. The evolution of the near-infrared Tully-Fisher relation over the last 6 Gyr. Astron. Astrophys. 489, 173–187 (2008).
62. Magdis, G. et al. The evolving interstellar medium of star-forming galaxies at z~2 as probed by their infrared spectral energy distribution. Astrophys. J. 760, 6 (2012).
63. Coe, D. et al. CLASH: precise new constraints on the mass profile of the galaxy cluster A2261. Astrophys. J. 757, 22 (2012).
64. Puech, M. et al. 3D spectroscopy with VLT/GIRAFFE. IV. Angular momentum and dynamic support of intermediate redshift galaxies. Astron. Astrophys. 466, 83–92 (2012).
Extended Data Figure 1 | HST colour-composite image of the lensing cluster MACS2129—1. Indicated is the position of the XSHOOTER slit on the target, which has been magnified and stretched by an average factor of about 4.6 by the foreground cluster. The image is a colour composite (B = F435W + F475W; G = F555W + F606W + F775W + F814W + F850LP; R = F105W + F110W + F125W + F140W + F160W) constructed from CLASH data\textsuperscript{63}. 

© 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.
Extended Data Figure 2 | Emission line characterization in three spatial extractions of the X-SHOOTER spectrum. The top, middle and bottom panels show the full (|r| < 1.36″), central (|r| < 0.5″) and outer (0.5″ < |r| < 1.36″) extractions, respectively, where |r| is the absolute spatial distance to the center of the galaxy. Plotted is the flux-density (fλ) versus the observed wavelength (λobs) and the rest-frame wavelength (λrest). As described in the legend, the coloured lines represent spectral decomposition into nebular emission lines and stellar continuum, obtained with pPXF/GANDALF. The pink line displays the best-fitting composite model; the green line is the best-fitting stellar continuum; the blue and dark red lines represent the best-fitting emission lines with and without a statistically significant detection, respectively. Shaded regions indicate spectral regions of low atmospheric transmission or high background that have been excluded from the fit. On each panel the best-fitting (B.F.) systematic velocity shift Vel and dispersion σel of the detected emission (em) lines are indicated.
Extended Data Figure 3 | Radial stellar population gradients. The full lines show azimuthally averaged radial profiles of median-likelihood stellar population synthesis parameters, derived from the maps in Fig. 3 in elliptical apertures following the best-fitting two-dimensional surface brightness fit. The shaded areas represent the pixel-to-pixel scatter in the median values in the elliptical apertures, not the uncertainties on the individual estimates (see main text). The filled circles with error bars show the median-likelihood parameters and their 68% confidence range from the spectral fits to the central and outer extractions. The dotted line shows the average specific SFR ($sSFR$) profile from a sample of star-forming (SF) galaxies$^{22}$ of mass and redshift similar to that of MACS2129$-1$. 

© 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.
Extended Data Figure 4 | Properties of MACS2129−1 compared to different galaxy populations. 

a, Stellar masses and sizes (major-axis effective radii, $r_{e,\text{maj}}$) of $2 < z < 2.5$ galaxies in the CANDELS survey\(^2\). MACS2129−1 falls on the relation for quiescent galaxies. The error bars include both statistical and systematic errors associated with the fitting added in quadrature. 

b, $V_{\text{max}}/\sigma_{\text{int}}$ versus ellipticity for the two lensed $z > 2$ compact quiescent galaxies MACS2129−1 and RG1M0150 (ref. 7) compared to similar-mass local galaxies. The grey histogram shows the $V/\sigma$ posterior distribution from our modelling. MACS2129−1 is thus similar to local late types\(^6\),\(^6\) (blue), while RG1M0150 is similar to local early types (red). 

c, The dynamical to stellar mass ratio (within $r_e$) of MACS2129−1 is similar to previously observed $z > 2$ compact quiescent galaxies, including the strongly lensed RG1M0150, and to $z \approx 2$ star-forming galaxies of similar age\(^8\). 

\(^1\) van der Wel, A. \textit{et al.} (2014) 
\(^2\) Newman, J. \textit{et al.} (2015) 
\(^3\) Emsellem, E., Puech, M., \textit{et al.} (2007, 2008) 
\(^4\) Erb, D. \textit{et al.} (2006) 
\(^5\) van de Sande, K. \textit{et al.} (2013)
Extended Data Figure 5 | Correlations between lensing model parameters and derived structural parameters for MACS2129−1. Shown are the average light-weighted (‘l.w.’) magnification, the orientation of maximum magnification at the position of MACS2129−1 (‘magni. orient.’), the magnification along this axis (‘major magni.’) and perpendicular to it (‘minor magni.’). These were obtained from 1,979 lensing model realizations (black) sampling the full probability distribution. Also shown are correlations with the galaxy (‘gal’) axis ratios ($a/b$) and position angles (PA) of MACS2129−1 derived from Galfit analysis of reconstructed source-plane images for a subsample of 98 representative realizations (red).
Extended Data Figure 6 | Structural parameters. Distributions of the Sersic model parameter $n$, the effective radius $r_e$, the axis ratio $a/b$ and the position angle PA, derived from two-dimensional surface brightness fits with Galfit, of the source-plane images generated from 98 representative realizations of the lensing model. We adopt the median values of these distributions and their standard deviations as our best-fitting parameters.
Extended Data Figure 7 | Variations of the magnification over MACS2129–1. Results are shown for a typical realization (middle row), and for the realizations with the maximum (top row) and minimum (bottom row) magnifications for different positions (pos.) within the galaxy. The columns (from left to right) show the observed F160W image, the magnification map, the seeing convolved (FWHM = 0.5″) F160W image, the seeing convolved light (F160W)-weighted magnification map, the source-plane image (crosses at same position) and the average light-weighted magnification contributing to each spatial bin in the XSHOOTER slit (shown in the bottom row). The minor variations are caused by the galaxy 3.5″ west of MACS2129–1 (see middle row).
Extended Data Figure 8 | Posterior distributions for the parameters in our dynamical modelling of the rotation and dispersion curves. Distributions are shown for the seven free parameters of the model: the offset angle between the slit and the major axis of the disk $\Theta_{\text{off}}$, the disk inclination $i$, the maximum velocity of the disk $V_{\text{max}}$, the radius at which the disk reaches $V_{\text{max}}$ ($R_{\text{max}}$), the position of the centre of the slit relative to the disk centre ($X_c$, $Y_c$), and the intrinsic velocity dispersion $\sigma_{\text{int}}$, which is assumed to be constant across the disk. Also shown are inferred distributions for $V_{\text{max}}/\sigma_{\text{int}}$ and the dynamical mass $M_{\text{dyn}}$. The open histograms show the distributions with priors $\Theta_{\text{off}} = 22^\circ \pm 10^\circ$ and $|X_c| < 0.4$ kpc. Filled histograms with the additional prior inclination $i = 53.8^\circ \pm 2.13^\circ$, all derived from Galfit modelling.
Extended Data Table 1 | Stellar population parameters and emission line fluxes

a

| Parameter          | Library A, Fit 1       | Library B, Fit 1       | Library A, Fit 2       | Library B, Fit 2       |
|--------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Log(Age/yr)        | 8.97±0.26             | 9.02±0.25             | 8.87±0.25             | 8.86±0.23             |
| Log(Z/Z⊙)          | −0.56±0.55            | −0.58±0.54            | −0.53±0.53            | −0.51±0.51            |
| A_i [mag]          | 0.60±0.90             | 0.33±0.88             | 0.73±0.73             | 0.70±0.50             |
| Log(M_*/M⊙)        | 11.15±0.23            | 11.10±0.26            | 11.05±0.19            | 11.03±0.19            |
| SFR [M⊙/yr]        | 0.0±13.6              | 0.0±2.0               | 0.9±86.1              | 0.5±14.1              |

b

| Parameter          | Center (|r|<0.5″) | Outer (0.5″ < |r| < 1.4″) |
|--------------------|-------------|-------------|
| Log(Age/yr)        | 9.03±0.24   | 8.96±0.27   |
| Log(Z/Z⊙)          | −0.49±0.56  | −0.56±0.57  |
| A_i [mag]          | 0.77±0.94   | 0.60±0.98   |
| sSFR [yr⁻¹]        | 0.0±4.6±10  | 0.0±6.2±10  |

| Emission Line       | [OIII]5007 [erg/s/cm²] x10⁻¹⁸ | Hα6563 [erg/s/cm²] x10⁻¹⁸ | [NII]6583 [erg/s/cm²] x10⁻¹⁸ | [NII]6583 [erg/s/cm²] x10⁻¹⁸ | σ_{el} [km/s] | V_{el} [km/s] |
|---------------------|-------------------------------|-----------------------------|-------------------------------|-------------------------------|---------------|--------------|
| Total               | 2.8±0.2                      | 1.4±0.3                     | 3.3±0.8                      | 1.0±0.3                      | 5.3±0.7       | 382          | 236          |
| Central             | 2.1±0.2                      | 1.1±0.2                     | 2.9±0.5                      | -                            | 2.5±0.5       | 463          | 258          |
| Outer               | -                             | -                           | -                             | -                            | 0.5±0.2       | 265          | 320          |

a. Median likelihood and 16%-84% confidence intervals for the parameters of our stellar population characterization of MACS2129–1. The age and metallicity (Z) are light-weighted. The SFR is the mean over the last 10⁷ years. The SFR and stellar mass (M_*) are corrected for magnification. A_i is the extinction in the rest-frame i-band. sSFR = SFR/M_*, is the specific star formation rate. Library A is our default library, while Library B includes only models without additional random bursts of star formation. Fit 1 is performed on the whole XSHOOTER spectrum pixel by pixel, while Fit 2 is performed on absorption-line indices and optical–NIR–MIR photometry. b. Median likelihood and 16%-84% confidence intervals for the parameters of our stellar population characterization of MACS2129–1 using Library A/Fit 1, for a central (|r|<0.5″) and an outer (0.5″ < |r| < 1.4″) extraction, where |r| is the absolute spatial distance to the center of the galaxy. c. Detected emission-line fluxes, widths (σ_{el}) and systematic velocity offsets V_{el} (relative to the absorption lines), in three spatial extractions of the XSHOOTER spectrum (see Extended Data Fig. 2). The total is extracted at |r|<1.4″.
Extended Data Table 2  |  Dynamical modelling results

**a**

| Parameter             | Median | 67% Confidence |
|-----------------------|--------|-----------------|
| $\Theta_{\text{off}}$ [deg] | 26.4   | [16.6, 29.4]    |
| Inclination [deg]     | 53.8   | [51.9, 54.7]    |
| $R_{\text{max}}$ [kpc] | 0.5    | [0.2, 1.3]      |
| $V_{\text{max}}$ [km/s] | 532    | [483, 599]      |
| $X_c$ [kpc]           | 0.0    | [-0.3, 0.2]     |
| $Y_c$ [kpc]           | 0.0    | [-0.2, 0.0]     |
| $\sigma_{\text{intr}}$ [km/s] | 59     | [16, 116]       |
| $V_{\text{max}} / \sigma_{\text{intr}}$ | 22     | [4.27]          |
| $\log(M_{\text{dyn}}/M_\odot)$ | 11.0   | [10.9, 11.1]    |

**b**

| Model realizations     | $V_{\text{max}}$ [km/s] | $R_{\text{max}}$ [kpc] | $\sigma_{\text{intr}}$ [km/s] |
|------------------------|--------------------------|-------------------------|-------------------------------|
| Benchmark              | 532$^{+67}_{-49}$        | 0.5$^{+0.8}_{-0.3}$     | 59$^{+57}_{-44}$              |
| Max magnification      | 524$^{+52}_{-54}$        | 0.4$^{+0.7}_{-0.3}$     | 62$^{+57}_{-44}$              |
| Min magnification      | 539$^{+67}_{-55}$        | 0.5$^{+0.8}_{-0.3}$     | 55$^{+59}_{-39}$              |
| Max seeing             | 543$^{+80}_{-50}$        | 0.6$^{+0.9}_{-0.4}$     | 49$^{+55}_{-36}$              |
| Min seeing             | 517$^{+51}_{-51}$        | 0.4$^{+0.6}_{-0.3}$     | 77$^{+51}_{-38}$              |

*a* Dynamical modelling results from our benchmark model. 
*b* Dynamical modelling results, using four different realizations of the seeing and lensing kernels spanning the extreme highest and lowest magnifications found in our 1,979 realizations, and the worst and best seeing allowed by our data. Results are listed for the parameters of the model given above. In all cases the results are derived with the following priors: the offset angle between the slit and the major axis of the disk $\Theta_{\text{off}} = 22^\circ \pm 10^\circ$, the $X$ position of the centre of the slit relative to the disk centre $|X_c| < 0.4$ kpc and disk inclination $i = 53.8^\circ \pm 2.13^\circ$. 

© 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.