

A giant galaxy in the young Universe with a massive ring

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In the local ($z \approx 0$) Universe, collisional ring galaxies make up only $\sim 0.01\%$ of galaxies¹ and are formed by head-on galactic collisions that trigger radially propagating density waves^{2–4}. These striking systems provide key snapshots for dissecting galactic disks and are studied extensively in the local Universe^{5–9}. However, not much is known about distant ($z > 0.1$) collisional rings^{10–14}. Here we present a detailed study of a ring galaxy at a look-back time of 10.8 Gyr ($z = 2.19$). Compared with our Milky Way, this galaxy has a similar stellar mass, but has a stellar half-light radius that is 1.5–2.2 times larger and is forming stars 50 times faster. The extended, diffuse stellar light outside of the star-forming ring, combined with a radial velocity on the ring and an intruder galaxy nearby, provides evidence for this galaxy hosting a collisional ring. If the ring is secularly evolved^{15,16}, the implied large bar in a giant disk would be inconsistent with the current understanding of the earliest formation of barred spirals^{17–21}. Contrary to previous predictions^{10–12}, this work suggests that massive collisional rings were as rare 11 Gyr ago as they are today. Our discovery offers a unique pathway for studying density waves in young galaxies, as well as constraining the cosmic evolution of spiral disks and galaxy groups.

The ring galaxy (ID 5519, hereafter R5519) was discovered in our systematic search for $z \gtrsim 2$ spiral galaxies in the Cosmic Evolution Survey (COSMOS) field of the FourStar Galaxy Evolution survey (ZFOURGE²²). We used ZFOURGE catalogue images to identify spiral structures in galaxies within the photometric redshift range of $1.8 \lesssim z_p \lesssim 2.5$. Owing to the surface brightness dimming and smaller sizes of galaxies at $z > 1$, our visual identification of spiral features was restricted to galaxies with illuminated pixels larger than a radius of $0''.5$ (>4 kpc at $z \approx 2$) in the Hubble Space Telescope (HST) images. Our

visual inspection simultaneously identified ring galaxies and other morphologically distinct objects such as mergers and gravitationally lensed galaxies. R5519 was flagged as one of the largest galaxies among the ~ 4000 galaxies inspected, with a clear ring structure as well as a large diffuse disk (Fig.1 and Supplementary Figs.1–2).

We confirm the spectroscopic redshift of R5519 to be $z_s = 2.192 \pm 0.001$ based on our Keck/MOSFIRE near-infrared (NIR) spectroscopy and Keck/OSIRIS adaptive-optics aided NIR integral field spectroscopy (Supplementary Figs.3–4). A joint analysis of the MOSFIRE and OSIRIS spectroscopic data, in combination with the ground-based H α narrow-band image from the ZFOURGE catalogue, shows that the H α kinematics are consistent with a tilted rotating and expanding/contracting circular ring model (Fig.2, Methods). Taking the inclination angle ($i = 29^\circ \pm 5^\circ$) and the position angle ($PA = 28^\circ \pm 10^\circ$) from an ellipse fit to the ring morphology (Supplementary Table 1, Supplementary Fig.1) as inputs to the kinematic model, the inferred rotational velocity at the fixed ring radius ($R_{\text{ring}} = 5.1 \pm 0.4$ kpc) is $V_{\text{rot}} = 90 \pm 75$ km/s and the radial expansion/contraction velocity is $V_{\text{rad}} = 226 \pm 90$ km/s. The velocity error bars represent uncertainties from observational measurements. The systematic errors caused by uncertain ranges of PA and i are of the same order of magnitude (Supplementary Figs.5–9).

We verify that R5519 resides in a small galaxy group environment, reminiscent of the loose groups in which local collisional ring galaxies (CRGs) such as the Cartwheel galaxy are found^{1,4,5}. A companion galaxy (ID 5593, hereafter G5593) is confirmed at a projected distance of ~ 30 kpc from R5519 with a 3D-HST survey²³ grism redshift of $z_{\text{grism}} = 2.184^{+0.005}_{-0.006}$ (Fig.1). An additional group candidate (ID 5475, hereafter G5475) is found at a projected distance of ~ 40 kpc away (Fig.1), with a photometric redshift²² of $z_p = 2.1 \pm 0.1$. If G5593 is the intruder of R5519, then the inferred timescale after collision is $\tau_c > 39^{+65}_{-15}$ Myr; this is a lower limit due to unknown projection effects.

R5519 has a total UV+IR star formation rate (SFR) of 80.0 ± 0.2 $M_\odot \text{ yr}^{-1}$ and a stellar mass of $\log(M_*/M_\odot) = 10.78 \pm 0.03$. In comparison, G5593 has a total SFR of 123 ± 2 $M_\odot \text{ yr}^{-1}$ and $\log(M_*/M_\odot) = 10.40 \pm 0.04$ (Table 1, Methods). The furthest group candidate (G5475) within a 50 kpc projected distance from the ring is a compact quiescent galaxy. The morphology of G5593 shows double nuclei and a tidal tail (Fig.1), suggestive of an ongoing merger of its own. We find no active galactic nucleus (AGN) signatures in R5519 nor in its companions based on the ZFOURGE AGN catalogue²⁴ and our MOSFIRE spectrum. The derived interstellar medium (ISM) properties indicate that R5519 is metal-rich ($12 + \log(\text{O}/\text{H}) = 8.6\text{--}8.8$) (Supplementary Information, Supplementary Fig.3).

R5519's ring has the highest contrast in HST F125W and F160W images (Fig.1). At $z_s = 2.19$, F125W and F160W filters include contributions from strong emission lines such as [OII] $\lambda 3727$ and [OIII] $\lambda 5007$, respectively. The prominent ring structure in these bands

is consistent with the ring being dominated by emission from luminous star-formation regions. The ground-based $H\alpha$ narrow-band image suggests that the bulk ($\sim 45\text{--}70\%$) of recent star formation occurs on the ring (Methods). We find tentative evidence for the existence of an off-centre “nucleus” based on the redder colour of one spatially resolved region in the deep $K_{s\text{tot}}$ and HST near-infrared images (Methods, Supplementary Fig.2, Supplementary Table 2). For a range of extreme star-formation histories (10 Myr burst and constant SFR), we derive for R5519 a total stellar mass between $10^{10.5} - 10^{10.8} M_{\odot}$, and stellar ages between 0.05–2 Gyr (Methods, Supplementary Fig.10).

The ring of R5519 is small compared with local CRGs. For example, 90% of rings in the local CRG sample¹ have ring radius $\gtrsim 5$ kpc. R5519’s SFR is at least $4\times$ larger than local CRGs²⁵ of similar stellar masses (Table 1, Supplementary Fig.11). The enhanced SFR of R5519 compared with local CRGs is understandable in the context that high- z star-forming galaxies have a larger molecular gas fraction²⁶. The average star formation rate surface density (Σ_{SFR}) of R5519 is $\sim 0.3 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-1}$, typical of a star-forming galaxy at $z \approx 2$, and $\sim 4\text{--}8$ times larger than local CRGs such as Arp 147 and the Cartwheel^{9,27}. Interestingly, nearby CRGs show moderately elevated SFR relative to $z \sim 0$ isolated disks²⁵, whereas R5519 does not have a substantially higher SFR in relation to its $z \approx 2$ peers (Supplementary Fig.11). Both R5519 and its companion G5593 lie within the 0.3 dex scatter of the $M_{*}\text{--SFR}$ “main-sequence”²⁸ relation of star-forming galaxies at $z \approx 2$. CRGs are rare laboratories to study star formation in interacting galaxies^{4,9}. Future observations on the molecular gas would be important in revealing the details of the star formation processes in R5519.

One of the most striking features of R5519 is the extended stellar light outside of the ring in multiple wavelengths (Fig.1, Supplementary Fig.2). We have ruled out R5519 as a regular merger or a gravitationally lensed system (see Supplementary Information). We quantify the size of the diffuse light by measuring R_{80} , the radius within which 80% of the total luminosity is included (Methods, Table 1, Supplementary Figs.12–13). Comparing with other $z \approx 2$ galaxies in the 3D-HST catalogue²⁹, R5519’s R_{80} is 2.4σ larger than the mean size (5.4 kpc) of all late-type galaxies ($\log(M_{*}/M_{\odot}) > 9.5$) and 1.5σ larger than the mean value (7.1 kpc) of the most massive ($\log(M_{*}/M_{\odot}) \geq 10.6$) late-type galaxies at $z \approx 2$ (Fig.3). A morphological inspection on the other unusually large (1σ above the mean) and massive late-type galaxies in the COSMOS field reveals that most (4/7) of them are probably mergers (Fig.3). Excluding the 4 mergers, the mean value of the most massive galaxies at $z \approx 2$ is 6.4 kpc and is 2.6σ lower than R5519. Compared with our Milky Way’s stellar disk, the half-light radius of R5519 is 1.5–2.2 times larger and its R_{80} is 1.2–1.8 times larger (Methods).

If R5519 is a secularly evolved resonant ring¹⁵ (see Supplementary Information), then the giant disk and the implied large bar (half length ~ 5 kpc, similar to the Milky Way’s bar) is challenging to understand at this redshift. Diffuse stellar disks and/or bars as large as those of R5519 have not been conclusively reported in observations or simulations at $z > 2$ [ref.^{14,17,18,20}]. For the rare, smaller (< 1 kpc in radius) barred spiral galaxies formed in simulations at $z > 2$ [ref.^{17,19,21}], they are relatively isolated and do not reside in an active environment like R5519. Our interpretation of a collisional ring instead of a secularly evolved ring can be verified by high spatial resolution imaging with the *James Webb Space Telescope* (JWST) in the mid-IR wavelength.

If R5519 is exhibiting a first ring after collision in the classic model of an expanding wave^{4,6,8}, the large R_{disk} and small R_{ring} imply different collisional timescales ($\tau_c \geq 80$ Myr and $\tau_c \leq 50$ Myr, see Supplementary Information). The inconsistency in τ_c can be reconciled if the current ring in R5519 is a second ring after the collision. A local analogy would be the Cartwheel galaxy^{5,9}, when Cartwheel’s outer ring fades and the inner second ring dominates. A second ring would

explain the small ratio of R_{ring} and R_{disk} . The large diffuse emission can be accounted for as the first expanding ring sweeps up the pre-collisional disk. The thickness (3.7 ± 0.3 kpc; Methods) of the ring, the size ratio of the first to the second ring (~ 2.2 , taking R_{80} in the rest-frame optical as the radius of the first ring), SFR, age, and metallicity are broadly consistent with the analytical model predictions of successive rings⁷.

The diffuse light induced by the expanding ring is difficult to observe in local CRGs because of the low surface density of the redistributed stars²⁵. R5519’s extended disk has a rest-frame B-band (HST F160W) surface brightness of ~ 20 AB mag arcsec^{−2}. Such a bright outer disk has yet to be seen in local CRGs (Supplementary Fig.14). The diffuse emission outside of R5519’s ring ($\gtrsim 6.5$ kpc) contains $\gtrsim 50\%$ of the total light in the rest-frame B band, whereas for local CRGs, most of the B-band luminosity is on and within the ring (Supplementary Fig.14). Without an intrinsic luminosity evolution with redshift, local CRGs’ rings and extended disks would be undetectable at $z \approx 2$ with current observations (see Supplementary Information). However, if high-redshift CRGs follow the “main-sequence” relation at $z \approx 2$ as R5519 does, then they would be bright enough to be detected in the 3D-HST WFC3 images (Supplementary Fig.14).

An alternative scenario to explain the large diffuse light outside of the ring is through satellite perturbations. Recent CRGs in the Evolution and Assembly of GaLaxies and their Environments (EAGLE) simulations¹³ show that interaction with multiple satellites at $z > 2$ can cause $> 50\%$ of the stellar particles of the CRG host to be tidally perturbed outside of the ring ~ 120 Myr after the collision (Supplementary Figs.15–16). Similar to the EAGLE ring, the diffuse stellar light of R5519 could be tidally induced by small satellites or represents an ongoing accretion of small satellites. In this scenario, the ring can be either the first or a successive ring.

Both our observation, and the EAGLE simulations, imply that the volume number density of massive ($\log(M_{*}/M_{\odot}) \gtrsim 10.0$) CRGs at $z \approx 2$ is as small as $z \sim 0$ (Supplementary Information). This seems contrary to previous predictions that CRGs are more common at high redshift^{10–12}. Using a scaling relation of $(1+z)^{4.5}$ from a previous study¹⁰, CRGs are expected to be ~ 140 times more common at $z \approx 2$. Considering only the massive CRG hosts, the expected number density at $z \approx 2$ is still $\gtrsim 10\times$ larger than at $z \sim 0$ (Methods). We speculate that a combined effect of a rising merger rate, a decreased fraction of large spiral disks, and the lack of local-like galaxy groups at high redshift could cause the slow CRG number density change¹³ in the past 11 Gyr (Supplementary Information). If R5519 is a density wave ring similar to local CRGs, it is an unequivocal sign of the existence of a thin disk in the young universe, critical for understanding the onset of spiral galaxies^{20,21,30}.

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Author Contributions T.Y. wrote the manuscript and had the overall lead of the project. A.E. carried out the EAGLE simulation analysis and contributed to the writing of the simulation results. I.L., G.K. and C.L. contributed significantly to the overall science interpretation, data analysis and making of the figures. L.A., J.C., K.-V.T., K.G. contributed significantly to the photometric and kinematic data analysis. All other coauthors contributed by their varied contributions to the science interpretation, data analysis and assistance with Keck observations. All co-authors contribute to the commenting on this manuscript as part of an internal review process.

Competing interests statement The authors declare no competing interests.

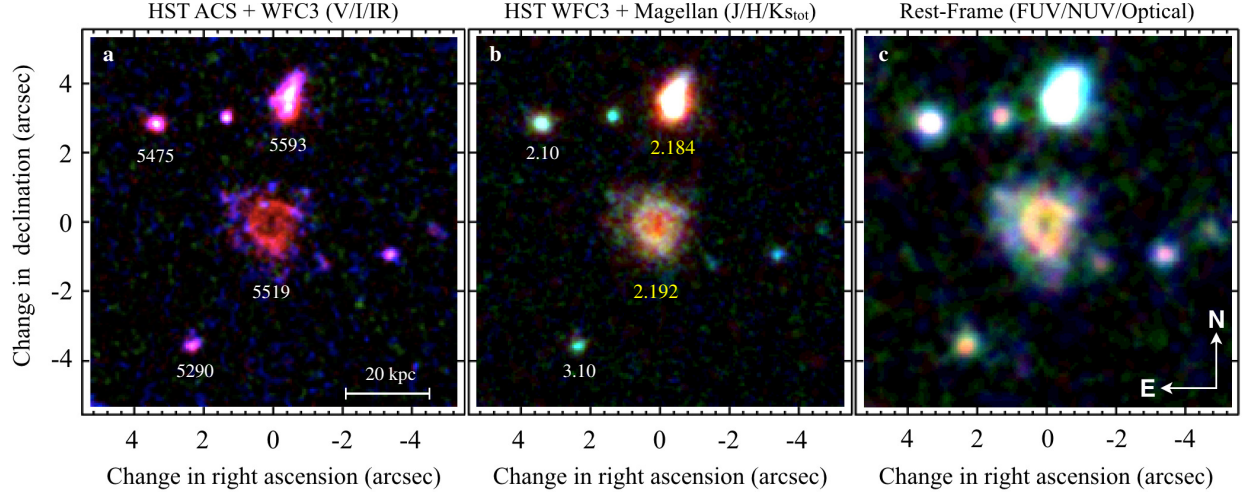


Figure 1 – Multi-wavelength views of R5519 and its neighbouring environment. **a**, a three-colour image combining HST V-band/ACS F606W (blue), I-band/ACS F814W (green), and IR-band/WFC3 F125W+F140W+F160W (red) images. Panel **a** shows the highest spatial resolution (full width at half maximum ~ 1.7 - 2.2 kpc) view of R5519. The numbers under each object denote the ZFOURGE catalogue ID. The contrast of the image is tuned to highlight the double nuclei and tail-like structure of the companion galaxy G5593. **b**, Blue/Green/Red (HST F125W/F160W/Magellan $K_{s\text{tot}}$) colour image. The $K_{s\text{tot}}$ image is a super deep K-band detection image in ZFOURGE (Methods). This image highlights the resolved ring structure on top of the longest-wavelength image from the ground-based ZFOURGE $K_{s\text{tot}}$ band (rest-frame R). The ZFOURGE photometric redshifts are labelled in white, with confirmed spectroscopic redshifts in yellow. **c**, Blue/Green/Red (combined rest-frame FUV/NUV/optical) colour image. The images are generated by stacking HST and ZFOURGE catalogue images that correspond to rest-frame FUV, NUV, and optical wavelengths (see Supplementary Information). The pixel scale for image **a** is $0''.06$ as sourced from the 3D-HST survey. For **b-c**, a pixel scale of $0''.15$ is used to match the ground-based images²². A logarithmic stretch is used for all images in this work.

Objects	R5519	G5593	G5475
Right ascension (J2000)	$10^h00^m14.3847^s$	$10^h00^m14.3815^s$	$10^h00^m14.081^s$
Declination (J2000)	$+2^\circ 14' 05.476''$	$+2^\circ 14' 09.167''$	$+2^\circ 14' 08.469''$
Redshift z	$2.192^{+0.0001}_{-0.0001}$	$2.184^{+0.005}_{-0.006}$	$2.10^{+0.07}_{-0.07}$
Stellar mass ($\log_{10}(M_*/M_\odot)$)	$10.78^{+0.03}_{-0.03}$	$10.40^{+0.04}_{-0.04}$	$9.55^{+0.03}_{-0.04}$
$\text{SFR}_{\text{IR+UV}} (M_\odot \text{ yr}^{-1})$	$80^{+0.2}_{-0.2}$	123^{+2}_{-2}	0
$\text{SFR}_{\text{H}\alpha} (M_\odot \text{ yr}^{-1})$	38-48	-	-
	0.2-0.4	~ 0.54	-
$\Sigma_{\text{SFR}} (M_\odot \text{ yr}^{-1} \text{ kpc}^{-2})$			
$i (^\circ)$	29^{+5}_{-5}	-	-
$PA (^\circ)$	28^{+10}_{-10}	-	-
Ring average radius (kpc)	$5.1^{+0.4}_{-0.4}$	-	-
inner radius (kpc)	$2.7^{+0.2}_{-0.2}$	-	-
outer radius (kpc)	$6.5^{+0.2}_{-0.2}$	-	-
ring thickness (kpc)	$3.7^{+0.3}_{-0.3}$	-	-
R_{50} (kpc)	$7.6^{+0.2}_{-0.2}$	$3.3^{+0.1}_{-0.1}$	$1.5^{+0.2}_{-0.2}$
R_{80} (kpc)	$11.8^{+0.3}_{-0.3}$	$4.9^{+0.2}_{-0.2}$	$2.5^{+0.2}_{-0.2}$
Rotational velocity $V_{\text{rot}} (km \text{ s}^{-1})$	90^{+75}_{-75}	-	-
Radial (expansion) velocity $V_{\text{rad}} (km \text{ s}^{-1})$	226^{+90}_{-90}	-	-

Table 1 – Physical properties of R5519 and its neighbours. The z values for R5519, G5593, and G5475 are MOSFIRE z_s , HST z_{grism} , and ZFOURGE z_p , respectively. For all sources, the stellar masses are calculated based on the spectral energy distribution from the ZFOURGE photometry and the $\text{SFR}_{\text{IR+UV}}$ are derived on the basis of the combined rest-frame IR and UV luminosities. The range of $\text{SFR}_{\text{H}\alpha}$ values reflects different assumptions about attenuation laws. Σ_{SFR} is estimated by dividing the total SFR by an assumed total SFR area, with the range of values reflecting different assumptions (Methods). PA and i are measured on the basis of the ellipse fit to the combined HST F125W+F140W+F160W image. The inner and outer radii and thickness of the ring are derived from a double ellipse fit, whereas the average radius is based on a single ellipse fit (Methods, Supplementary Fig.1). R_{50} and R_{80} are the radii where 50% and 80% of the total luminosity are enclosed in the combined HST F125+F140W+F160W band, respectively. The rotational and radial velocities are derived at the 5 kpc ring radius using a tilted rotating and expanding circular ring model (Methods).

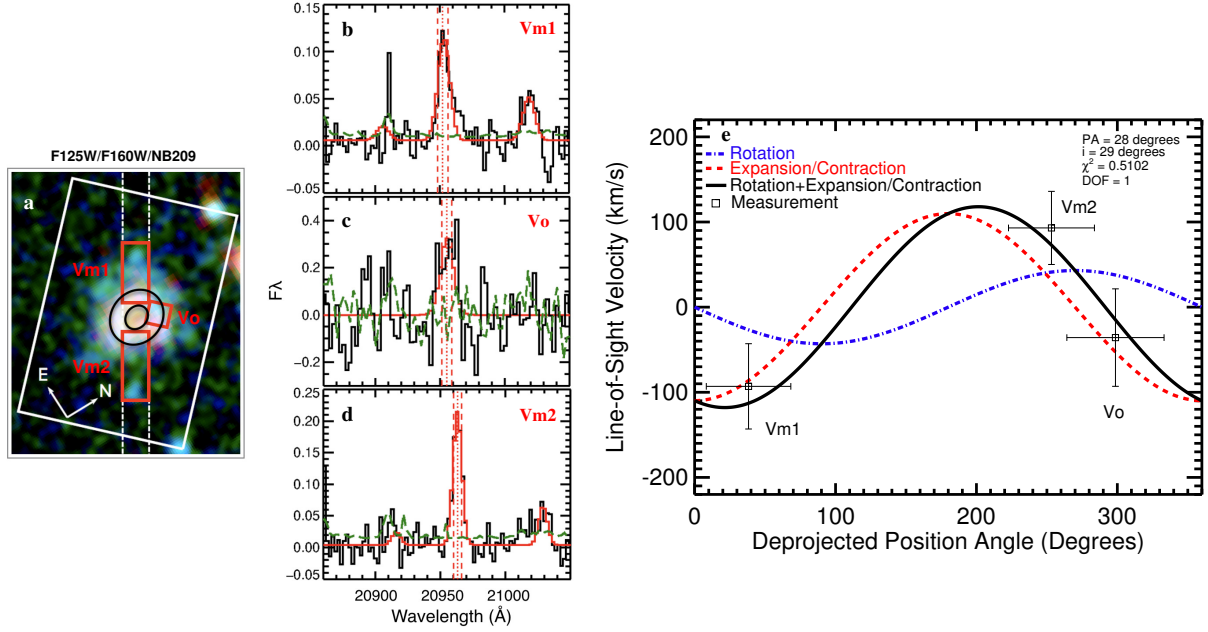


Figure 2 – A joint analysis of the MOSFIRE and OSIRIS ring kinematics. **a**, Spatial alignment of the OSIRIS (white box; field-of-view $4''.5 \times 6''.4$) and MOSFIRE (white dashed box; slit width $0''.8$) observations on the Blue/Green/Red three-colour image (HST F125W/F160W/ZFOURGE NB209 H α narrow band). The black circles show the best-fit double ellipse to the ring structure. The red boxes mark the three position angles where the line-of-sight velocities (MOSFIRE: Vm1, Vm2; OSIRIS: Vo) are measured (see also Supplementary Figs.5-6). **b-d**, The observed H α spectra (black), best-fit (red) and 1 σ noise (green) for Vm1, Vm2 and Vo. F λ is the observed flux of the spectra. The red vertical dotted and dashed lines show the determined velocity centre and its uncertainty range, respectively. The uncertainty range is a conservative measure using the 1 σ width of a Gaussian line profile (Methods). The flux unit for **b, d** is $10^{-17} \text{ ergs/s/cm}^2/\text{\AA}$, and for **c**, the flux unit is $10^{-20} \text{ ergs/s/cm}^2/\text{\AA}$. **e**, Fitting an expanding/contracting tilted circular ring model to the line-of-sight velocity versus deprojected position angle diagram. The vertical errors of Vm1, Vm2, and Vo are defined by the uncertainty range of the line centre in **b-d**; the horizontal error is defined by the alignment uncertainty in **a**. The model uses a fixed inclination $i = 29^\circ$ and a kinematic major axis of PA = 28 $^\circ$. The black curve is the best-fit model with contributions from both rotation (blue) and expansion/contraction (red). The expansion/contraction component is detected for a varied range of PA = 0 – 45 $^\circ$ and $i = 20 - 45^\circ$ (Methods, Supplementary Figs.7-9).

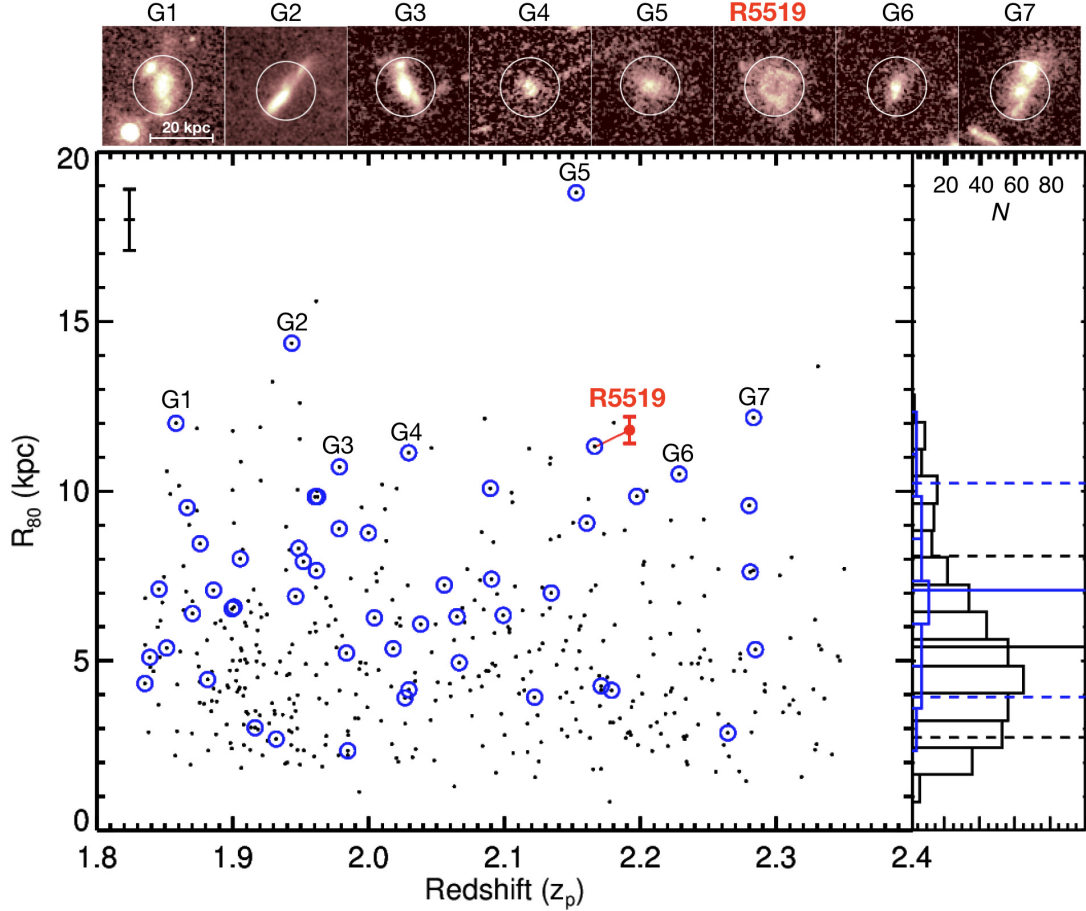


Figure 3 – Comparing the size of R5519 with the size distribution of late-type galaxies at $z \approx 2$. The z_p and R_{80} values are from the 3D-HST survey and its mass-size catalogue in the COSMOS field (Methods). The typical error bar for R_{80} , defined as an average error propagated through the 1σ model error of the effective radius in 3D-HST, is shown in the top left corner. The black dots show all galaxies with $\log(M_*/M_\odot) \geq 9.5$. The blue circles highlight the most massive objects, defined as $\log(M_*/M_\odot) \geq 10.6$. The histograms (right) show the size distribution for all (black) and the most massive (blue) galaxies. The horizontal solid and dashed lines mark the mean and the 1σ scatter of the size distributions. Including R5519, there are eight objects (labelled G1-G8) that have unusually large sizes (defined as 1σ above the mean size of the most massive galaxies). The F160W band morphologies for these eight objects are shown as postage-stamp images at the top. The red filled circle shows z_s and our non-parametric measurement of R_{80} for R5519. We note that the inferred R_{80} for the 3D-HST sample is based on an empirical relation for a large sample of galaxies; individual galaxies may deviate from this relation due to scatter (Methods).

METHODS

Throughout we adopt a Λ cold dark matter cosmology, where Λ is the cosmological constant, with $\Omega_M=0.307$, $\Omega_\Lambda=0.693$, and $H_0=67.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$, consistent with the Planck measurements³¹ and the cosmological parameters used in EAGLE simulations¹³. At the redshift of $z=2.19$, the look-back time is 10.8 Gyr and one arcsecond corresponds to a physical scale of 8.49 kpc. All magnitudes are in AB units³², unless otherwise specified.

1 Size of the Ring and the Extended Diffuse Emission

1.1 Size of the ring We use the original 3D-HST CANDELS version of the F125W, F140W and F160W images^{33,34} to quantify the size of the ring structure. We fit both a single ellipse and a double ellipse of a constant width to the imaging data using a χ^2 minimisation procedure. In both approaches, we divide the ring azimuthally into $N=180$ intervals and use the average full width at half maximum (FWHM) of the surface brightness (SB) along each azimuthal angle interval to determine the inner and outer edges of the ring. The baseline of the FWHM is chosen as the average SB in the central pixels of the ring (red cross in Supplementary Fig.1). We smooth the images by 3 pixels ($0''.18$) to enhance the signal-to-noise ratio (SNR).

In the single-ellipse approach, we use data points on the outer edge of the ring as the input and weight each azimuthal angle with the median SB within each azimuthal interval. The free parameters of a single ellipse model are: the centre (x_c, y_c), major axis radius (a), axis ratio (b/a or inclination angle i) and position angle (PA). In the double ellipse approach, we use the inner and outer edges of the ring as double constraints and weigh each azimuthal angle with the median SB within each azimuthal interval. The additional free parameter in the double ellipse model is the width (ΔR) of the ring. We find that both approaches provide reasonably good fits to the data (Supplementary Table 1). We carry out the fit on both the single bands (F125W, F160W) and the combined band (F125W+F140W+F160W). The results are consistent within 1σ of the statistical errors. The best-fit ellipses and parameters are shown in Supplementary Fig.1 and Supplementary Table 1.

1.2 Size of the diffuse stellar light We quantify the size of the diffuse stellar light in a model-independent way by measuring the accumulated luminosity within a circular aperture of an increasing radius (Supplementary Fig.12). We calculate R_{50} , R_{80} , and R_{95} where 50%, 80% and 95% of the total luminosity is enclosed. The choice of the three radii is to facilitate comparison with other samples of galaxies: R_{50} is comparable to the effective radius R_e of a Sersic profile; R_{80} is a recently popularised parameter to study the size evolution of galaxies with redshifts³⁵; R_{95} describes the outer edge of the galaxy. For a Sersic profile of $n=0.5$ and $n=1.0$, R_{95} corresponds to a radius of $\sim 2.1R_e$ and $\sim 2.9R_e$, respectively³⁶.

The diffuse stellar light of R5519 is present in multiple wavebands (Supplementary Fig.2). To test the dependence of the measured size on wavelength, image depth, and the point spread function (PSF), we carry out the measurement on the deep ZFOURGE K_{s10t} image and the high-spatial resolution HST F125+F140W+F160W image; we then repeat the measurements on the PSF matched ZFOURGE image, including a stacked rest-frame FUV image. The PSF is best characterised by a Moffat profile of two parameters: FWHM and β , where β describes the overall shape of the PSF. The PSF matched images are carefully generated by the ZFOURGE team using a Moffat profile with FWHM of $0''.9$ and $\beta=0.9$ [ref.²²]. Our stacked rest-frame FUV image is produced from the PSF-matched ground-based UBV images (see Supplementary Information).

We summarise the derived R_{50} , R_{80} , and R_{95} in Supplementary Table 4. The error bars are derived by perturbing the measurements within 1σ of the sky background. The PSF-matched images yield on average a larger size of 1.4 ± 0.6 kpc at all wavelengths. For images of similar depth and PSF, the bluest wavelength yields the largest size, e.g., the rest-frame FUV size is ~ 1 kpc larger than the rest-frame B band. Note that the diffuse stellar light distribution of R5519 is not circularly symmetric, our R_{50} , R_{80} , and R_{95} can be considered as circularly averaged values. These circularly averaged values are consistent with the size measurement from the surface brightness distribution along the major axis of the ring ellipse below.

1.3 Surface brightness profile in 1D along the major axis We measure the 1D surface brightness distribution SB(R) by averaging three slices along the major axis of the ring ellipse in the deep HST F160W image (Supplementary Fig.13). The three slices are chosen as the best-fit major axis and its 1σ upper and lower limits (red solid and dashed lines in Supplementary Fig.13). Each datapoint along the slice is an average of 4 pixels ($0''.24$) in width, i.e., about one image resolution element ($0''.26$). We stop the measurements when the data are indistinguishable from the 1σ fluctuation of the background noise. A total size of the galaxy is defined by the boundary where the 1D SB drops to the 1σ background noise level. We estimate R5519's total size to be $R_{tot} = 15 \pm 1$ kpc in radius, with the error bar indicating the uncertainty in identifying the boundary that is consistent with the noise. The R_{tot} agrees with our measured $R_{95} = 15.6 \pm 0.6$ kpc using the circular aperture on the combined F125W+F140W+F160W image (Supplementary Table 4). We measure the ring's inner and outer radius (R_{in} and R_{out}) based on the FWHM of the ring feature. We use the SB in the centre of the ring as the baseline of the FWHM. We find $R_{in}=2.1$ kpc and $R_{out}=6.7$ kpc, broadly consistent with the 2D double ellipse fit (Supplementary Table 1).

The method we use to derive R_{tot} and R_{95} may not be practical for local CRGs such as the Cartwheel galaxy, where the ring dominates the luminosity in the outer disk (e.g., Supplementary Fig.14). The method we use for R_{tot} is very similar to the commonly used R_{B25} for local CRGs²⁵. R_{B25} refers to the radius where the SB drops to a standard level of surface brightness of $25.00 \text{ mag arcsec}^{-2}$ in the B band for angular dimensions³⁷. Instead of using a fixed SB, we use the 1σ sky background that is more suitable for high-redshift observations.

The average SB of the diffuse disk estimated from the average light between R_{out} and R_{95} is $0.42 \mu\text{Jy arcsec}^{-2}$ in F160W. Assuming a cosmological SB dimming form of $(1+z)^{-4}$, the average SB of R5519's diffuse disk observed at $z \sim 0$ would be $19.8 \text{ mag arcsec}^{-2}$ in the B band. This is almost four magnitudes brighter than the SB of the brightest outer disk of nearby CRGs²⁵. Using the average SB of the diffuse disk as the baseline of the FWHM yields a ~ 0.5 kpc increase/decrease in the size of the inner/outer radius. The average SB of the ring as calculated between R_{in} and R_{out} is $1.04 \mu\text{Jy arcsec}^{-2}$. The peak SB inside the ring is $1.15 \mu\text{Jy arcsec}^{-2}$. Therefore the relative SB between the ring and the outer disk is $0.6\text{--}0.7 \mu\text{Jy arcsec}^{-2}$.

1.4 Comparing with 3D-HST $z \approx 2$ late-type galaxies To put the size of R5519 in context with other $z \approx 2$ galaxies, we compare its R_{80} with 3D-HST galaxies measured on the same F160W images²⁹ in Fig.3. The sizes of 3D-HST galaxies have been modelled by Sersic profiles through several well-established studies^{29,35,38}. We use the mass-size catalogue data from the 3D-HST survey²⁹ and apply the same conversion between Sersic index n , effective radius R_e and R_{80} as previous studies^{29,35,38}. In order to minimise systematic errors of R_{80} , we only include galaxies with flux $\text{SNR} > 20$ on the F160W image and have good Sersic model fits ($\text{SNR} > 5$ for both R_e and n). We select data with 3D-HST photometric redshifts (zp) of $1.8 < z < 2.4$ and $\log(M_*/M_\odot) > 9.5$, to match our ZFOURGE target selection criteria. Only late-type ($n < 2.5$) galaxies are used. We then cross-correlate the 3D-HST zp with the high-precision ($\sim 2\%$) ZFOURGE photometric redshifts²² and exclude targets with $zp < 1.5$ or $zp > 2.5$. We also exclude targets that have inconsistent stellar masses ($\Delta \log(M_*/M_\odot) > 0.5$) from these two catalogues. Targets without ZFOURGE zp or M_* remain in the sample. A total of $N=440$ objects satisfy these selection criteria.

The empirical conversion between R_{80} , R_e , and n is based on large samples. The conversion is not guaranteed for individual galaxies. For example, the R_{80} for G4 and G5 in Fig.3 is probably inaccurate and reflects the scatter in the empirical conversion. R5519 was included in the Sersic profile modelling of previous 3D-HST studies²⁹. The inferred R_{80} of R5519 from the 3D-HST catalogue²⁹ Sersic R_e (7.6 kpc) and n (0.42) is 11.2 kpc, in broad agreement with our non-parametric measurement (11.8 ± 0.3 kpc). Our model-independent R_{50} for R5519 is also consistent with the Sersic model-based R_e from the 3D-HST catalogue²⁹ within the measurement errors. Both the R_{80} and R_{50} of R5519 are 1.5σ above the scatter of the late-type galaxies at $z \approx 2$ of similar or higher stellar masses ($\log(M_*/M_\odot) \geq 10.6$). We conclude that R5519 is an unusually large galaxy at $z \approx 2$ regardless of the methods we use to quantify its total size.

The large size of R5519 can be further appreciated when compared with

the Milky Way. The scale length (R_s) of the Milky Way's stellar disk is in the range of 2-3 kpc based on a large body of literature³⁹⁻⁴¹. Using $R_{50}=1.68 R_s$ ^{36,42} and $R_{80} \sim 3.2 R_s$ ⁴³, our Milky Way has $R_{50}=3.4-5.0$ kpc and $R_{80}=6.4-9.6$ kpc in its stellar light. According to our best size estimation from HST WFC3 images (Table 1), the R_{50} of R5519 is 1.5-2.2 times larger and R_{80} is 1.2-1.8 times larger than the Milky Way.

2 A Joint Analysis of MOSFIRE and OSIRIS H α Kinematics

The line-of-sight velocity (V_{LOS}) as a function of de-projected position angle (ψ) at a fixed radius on the ring is one of the commonly used methods to derive the expansion/contraction and rotational velocities of CRGs. Following similar analysis of local CRGs^{27,44-46}, we use equations below to describe the relation between V_{LOS} and ψ in a tilted rotating and expanding/contracting circular ring model. An illustration of the geometry and definition of parameters is presented in Supplementary Fig.5:

$$V_{LOS,\psi} = (V_{sys} + (V_{rad} \cos(\psi) - V_{rot} \sin(\psi))) \sin(i), \quad (1)$$

$$\tan(\psi) = \tan(\psi_o) \cos(i); i \neq 90^\circ. \quad (2)$$

$V_{LOS,\psi}$ is the line-of-sight velocity measured at ψ on the ring and V_{sys} is the systematic velocity. V_{LOS} is calculated with respect to the kinematic centre of the galaxy. We take the cosmological expansion out by using the systematic redshift measured on the H α centroid of the total aperture MOSFIRE spectrum ($z_{s,total}$), hence we have $V_{sys} \approx 0$ if $z_{s,total}$ is close to the systematic redshift at the kinematic centre. A positive sign of V_{LOS} means redshift whereas a negative sign means blueshift. V_{rad} is the expansion/contraction velocity at the fixed radius of the ring. V_{rot} is the rotation velocity. The angle ψ is measured counterclockwise from the kinematic major axis. The relation between the observed position angle (ψ_o) and the deprojected ψ is a simple function of the inclination angle i , where $i = 0$ means viewing the disk of the ring face-on and $i = 90$ means edge-on. The corrections between ψ_o and ψ are small for face-on disks, whereas the equations are invalid for edge-on disks (e.g., Supplementary Fig.5).

Note that in Eq. 1, the signs of V_{rad} and V_{rot} can be either positive or negative. In a fiducial case in Supplementary Fig.5, we define an east and a west side similar to the compass on a 2D image. In this case, the east side (with respect to the kinematic major axis) is the far side of the disk relative to the observer, a positive/negative sign of V_{rad} means expanding/contracting radially, and a positive/negative sign of V_{rot} means rotating counterclockwise/clockwise from the kinematic major axis. The signs of V_{rad} and V_{rot} are flipped if the east side is the near side of the ring. Without knowledge of the near and far side of the ring, the equations above provide only a magnitude of the radial velocity (V_{rad}) and rotational velocity (V_{rot}). In the nearby universe, the near and far side of the ring can be determined from an extinction-reddening asymmetry across the minor axis in a tilted galactic disk. This asymmetry is most evident when a galaxy has a prominent bulge: the bulge is viewed through the dust layer on the near side, while the dust is viewed through the bulge on the far side. However, this method is difficult to apply to high-redshift galaxies whose bulge and disk are in the early stages of formation.

The relation between V_{LOS} and ψ at a fixed radius (R) is therefore a function of four parameters: the systematic velocity (V_{sys}), the circular rotational velocity (V_{rot}), the expansion/contraction velocity (V_{rad}) and the inclination angle i (Supplementary Fig.5). One additional hidden parameter is the position angle (PA_0) of the kinematic major axis because ψ is measured with respect to PA_0 . We do not have direct measurement of PA_0 and make the assumption that PA_0 is the position angle of the geometric major axis. We discuss the consequence of this assumption in the SI.

We can obtain three measurements on the V_{LOS} versus ψ diagram by combining our MOSFIRE and OSIRIS H α kinematics. The first two measurements are derived from the MOSFIRE slit spectrum and the third measurement comes from the OSIRIS observation. Our MOSFIRE H α velocity is spatially resolved and a clear relative wavelength separation is seen in the +y and -y spatial direction of the spectrum (Supplementary Fig.6). We align the MOSFIRE H α 2D spectra in its spatial y direction with the NB209 H α narrow-band image. We do this by cross-correlating the spatial H α line

profiles of the MOSFIRE observation with a mock H α spatial line profile derived from the H α narrow-band image. In Supplementary Fig.6, we show the MOSFIRE spectrum aligned spatially with the NB209 image after correcting for the central offset; the error bar ($\sim 0''.2$) of the alignment is estimated by the 1σ scatter of 100 times refit to the convoluted NB209 image using a full range of seeing ($0''.6-0''.9$) sizes experienced in our MOSFIRE observations. We then align the OSIRIS datacube with the NB209 H α narrow band image using the corrected astrometry (see Supplementary Information). The maximum error of the OSIRIS to NB209 alignment is the spatial resolution of our adaptive optics (AO) observations ($0''.3$).

Our measurement is then carried out at the ring radius ($R=5$ kpc) for 3 positions on the ring. We assume that the best-fit ellipse PA is the kinematic position angle PA_0 and fix the inclination angle at the best value of 29° as derived from the ellipse fitting. The uncertainties in ψ are taken as the edge of the MOSFIRE slit and the edge of the OSIRIS H α detection box (Supplementary Fig.6). The line-of-sight velocities from the MOSFIRE spectra are based on the H α emission line centroid of the 1D spectra extracted at the 5 kpc location (Fig.3). Due to the seeing-limited nature of the MOSFIRE observation, the 1D spectra extracted at the 5 kpc position (± 1 pixel) on MOSFIRE is prone to the uncertainty of the PSF characterisation. We test the uncertainties of V_{m1} and V_{m2} by shifting the extracting centre of the 1D spectra within the range of the spatial alignment error ($\sim 0''.2$). Because of the strong correlation of the spatial position and the split of the blue- and redshift of the 2D spectrum, we find that the Gaussian width of the line profiles provides a conservative estimate of the measurement uncertainty in V_{m1} and V_{m2} . As long as the kinematic field is relatively face-on ($< 45^\circ$), the effect of beam-smearing in deriving the H α line centroid is budgeted into the uncertainty from the line width. The low SNR of our OSIRIS spectrum prompts us to use the line width as an upper limit for the uncertainty in determining the line centroid. The uncertainties of the line-of-sight velocities along the MOSFIRE PA (V_{m1} , V_{m2}) and OSIRIS H α (V_o) are therefore taken as the Gaussian width of the line profiles. We also note that whether the measurement is done on a 5 kpc radius circle or the best-fit ellipse does not change the result.

We fitted our three data points with Eq. 1-2 using a χ^2 minimisation procedure, weighted by the inverse square of the total error $\sigma_{x,y} = \sqrt{\sigma^2(V_{LOS,\psi}) + \sigma^2(\psi)}$. We keep V_{sys} at 0, though allowing it as a free parameter to account for any offsets between $z_{s,total}$ and the redshift from the actual kinematic centre of the disk does not change our main conclusion. For our fixed $PA_0 = 28^\circ$ and $i = 29^\circ$, the best-fit expansion/contraction velocity is $V_{rad} = 226 \pm 90$ km/s and $V_{rot} = 90 \pm 75$ km/s (Fig.3). The systematic errors of our kinematic measurement are discussed in the Supplementary Information. Nearby CRGs show a range of V_{rad} (50-220 km/s) and V_{rot} (50-350 km/s). For most nearby CRGs, V_{rot} is larger than V_{rad} ^{9,44}, though in some cases (e.g., Arp 147), V_{rot} can be a few times smaller than V_{rad} ²⁷.

3 Colour, Stellar Mass and Age

3.1 Global We estimate the total stellar mass and average age of the stellar population via spectral energy distribution (SED) fitting to ZFOURGE multi-band photometry. The total photometry is measured on PSF matched ZFOURGE images.

The publicly available catalogue of ZFOURGE provides stellar masses based on the SED-fitting code FAST⁴⁷ in combination with the photometric redshift from EAZY⁴⁸. FAST determines the best-fit parameters of SED models through a χ^2 minimisation procedure⁴⁹. We use 36 passbands of ZFOURGE's total photometry based on the stellar population synthesis (SPS) model grids⁵⁰, a Chabrier IMF⁵¹, a fixed solar metallicity ($1.0 Z_\odot$), an exponentially declining star formation history (SFH), and a Calzetti⁵² extinction law. The ZFOURGE FAST output catalogue⁴⁹ records a total stellar mass of $\log(M_*/M_\odot) = 10.78 \pm 0.03$ for R5519, 10.40 ± 0.04 for G5593, and 9.89 ± 0.09 for G5475. We test the systematic uncertainties of M_* against different SED fitting packages and find a systematic error of ~ 0.2 dex (see in Supplementary Information).

To obtain a lower and upper limit for the stellar mass of R5519 we run FAST assuming two extreme SFH: a constant star-formation model (CSF) with emission lines and a 10 Myr truncated burst with no star formation afterwards (Supplementary Fig.10). The CSF provides an upper limit to

the stellar mass and age of R5519: $\log(M_*/M_\odot) < 10.8$ and $t_{\text{age}} < 2$ Gyr. The truncated star formation model provides a lower limit of $\log(M_*/M_\odot) > 10.5$ and $t_{\text{age}} > 50$ Myr. These are the best constraints we can provide for R5519 from current SED analysis.

3.2 Spatially resolved photometry In ZFOURGE, a super deep K-band detection image (K_{Stot}) was created by combining FourStar/Ks-band observations with pre-existing K-band images²². The K_{Stot} image reveals an off-centre region that we speculate could be the “nucleus” of the pre-collisional galaxy (Supplementary Fig.2). We measure the aperture photometry of this postulated “nucleus” region and compare it with regions on the ring. We use an aperture of a diameter $0''.47$, corresponding to the PSF size of the K_{Stot} image. We then derive the colour differences of the nucleus and the ring based on the PSF matched K_{Stot} and HST F125W, F160W images.

We find that the nucleus is 0.29 mag redder (3.6σ significance) than the average colour of the ring in F160W- K_{Stot} , and 0.42 mag redder (3.9σ significance) in F125W-F160W. The intrinsic colour difference might be larger without the beam-smearing of the PSF. For example, using the HST original images (i.e., without convolving with the PSF of the K_{Stot} band), the nucleus is 0.54 mag redder (5.0σ significance) than the ring in F125W-F160W. The redder colour of the “nucleus” region is consistent with the existence of an off-centre nucleus commonly seen in CRGs⁴. Well-known examples of CRGs with an off-centre nucleus are Arp 147 and NGC 985. Future high-resolution images in the optical and near-infrared bands are required to further confirm the location of this nucleus.

4 Star Formation Rate

4.1 Total star formation rate The SFRs for ZFOURGE sources⁴⁹ are based on the combined rest-frame infrared luminosity ($L_{\text{IR}, 8-1000\mu\text{m}}$) and rest-frame UV luminosity ($L_{\text{UV}, 1216-3000\text{\AA}}$). The UV+IR approach assumes that the IR emission of galaxies comes from dust heated by the UV light of massive stars⁴⁹. L_{IR} is measured on an IR spectral template fitted to the 24, 100 and 160 μm far-IR photometry. The far-IR photometry is measured using apertures of $3''$ - $6''$ from the MIPS/PACS imaging with the de-blending technique⁵³. L_{UV} is measured on the EAZY photometric models⁴⁹. The $\text{SFR}_{\text{UV+IR}}$ for R5519 is calculated to be $80 \pm 0.2 M_\odot \text{ yr}^{-1}$. Note that because of the proximity of the neighbouring galaxy G5593 and the large PSF ($\text{FWHM} > 4''$) of the MIPS and PACS images, the main uncertainties in the $\text{SFR}_{\text{UV+IR}}$ of R5519 and G5593 come from the systematics of de-blending the two sources. G5593 is at a similar redshift as R5519 and is a bright non-AGN source detected in the 24 μm with $\text{SFR}_{\text{UV+IR}} = 123 \pm 2 M_\odot \text{ yr}^{-1}$. G5475 is a quiescent galaxy, consistent with its early-type morphology.

For comparison, we determine the dust-uncorrected SFR from the total $H\alpha$ flux of the MOSFIRE slit spectrum and have $\text{SFR}_{H\alpha(\text{slit}; \text{with dust})} = 3.7 \pm 0.1 M_\odot \text{ yr}^{-1}$. For dust attenuation correction on $H\alpha$ ($A(H\alpha)$), we infer from the stellar dust attenuation obtained via SED fitting ($A_{\text{v}, \text{star}} \approx 1.1$). We test two methods on dust correction. We first use the empirical relation of $A(H\alpha)$ and $A_{\text{v}, \text{star}}$ for $z \approx 2$ star-forming galaxies as a function of $\text{SFR}(\text{SED})$ and M_* (SED)⁵⁴; we have $A(H\alpha) = 0.21 + A_{\text{v}, \text{star}}$. The dust corrected $\text{SFR}_{H\alpha(\text{slit})}$ is therefore $12.4 \pm 0.3 M_\odot \text{ yr}^{-1}$ for the first method. For the second method, we use the classic nebular attenuation curve⁵⁵ with $R_v = 3.1$ and have $A(H\alpha) = 2.53 \times E(B-V)_{\text{HII}}$; Assuming $E(B-V)_{\text{star}} = 0.44 \times E(B-V)_{\text{HII}}$ ⁵², we have $A(H\alpha) = 1.42 \times A_{\text{v}, \text{star}}$ or $A(H\alpha) = 1.42 \times A_{\text{v}, \text{star}}$ ^{56, 57}. The dust corrected $\text{SFR}_{H\alpha(\text{slit})}$ is therefore $15.6 \pm 0.4 M_\odot \text{ yr}^{-1}$ for the second method. Finally, we estimate the slit loss factor by aligning the MOSFIRE slit on the PSF matched $H\alpha$ narrow-band image and calculating the fraction of flux that is outside of the slit on the $H\alpha$ narrow-band image. We derive a slit-loss factor of 3.1 ± 1.1 . The final slit-loss and dust attenuation corrected $\text{SFR}_{H\alpha}$ is $38.4 \pm 13.6 M_\odot \text{ yr}^{-1}$ for the first method and $48.4 \pm 17.2 M_\odot \text{ yr}^{-1}$ for the second method, with errors representing statistical errors contributed mainly by the slit-loss correction uncertainty. Though the $H\alpha$ SFR is $\sim 2\times$ smaller than the $\text{SFR}_{\text{UV+IR}}$, the discrepancy is not surprising given the large uncertainty in dust attenuation and slit loss.

4.2 Spatial distribution and Σ_{SFR} Using the location of the best fit double ellipse and the $H\alpha$ narrow band image, we estimate that ~ 45 - 70% of the star formation occurs on the ring. The upper limit is calculated by assuming that the $H\alpha$ narrow band image traces all recent star formation activity. The lower limit is estimated by including only $H\alpha$ pixels within the ring that are

more than 5σ brighter than the average $H\alpha$ surface brightness. We caution that this estimation does not include uncertainties from the beam-smearing of the $H\alpha$ narrow band image, spatial variation of the dust attenuation, and the contribution of faint SF regions.

Our current data do not have the spatial resolution and SNR to calculate the spatially resolved Σ_{SFR} . We provide two simple estimates for an average Σ_{SFR} . We first use $\text{SFR}_{\text{UV+IR}}$ divided by the circular area within R_{80} and have $\Sigma_{\text{SFR}} \sim 0.2 M_\odot \text{ yr}^{-1} \text{ kpc}^{-1}$. We then use $\text{SFR}_{H\alpha} = 38 M_\odot \text{ yr}^{-1}$ divided by the area of the ring defined by the best-fit ellipse and have $\Sigma_{\text{SFR}} \sim 0.4 M_\odot \text{ yr}^{-1} \text{ kpc}^{-1}$.

4.3 Comparing with local CRGs on the M_* -SFR relation The well-established correlation between SFR and stellar mass M_* is the so-called “main-sequence” for star-forming galaxies. The slope and scatter of the M_* -SFR relation does not evolve significantly from $z \sim 0$ to $z \approx 2$ [ref.²⁸]. At a fixed stellar mass, star-forming galaxies at $z \sim 2$ have ~ 20 times higher SFR compared with $z \sim 0$ star-forming galaxies. Based on $\text{SFR}_{\text{UV+IR}}$, R5519 is a star-forming galaxy that lies within the 1σ scatter (~ 0.3 dex) of the M_* -SFR relation at $z \approx 2$ [ref.⁴⁹].

Local CRGs have moderately higher SFR than other local spirals. To compare R5519 with local CRGs on the M_* -SFR relation, we use a sample of local CRGs²⁵ that have both the SFR and stellar mass measured in a self-consistent way. We exclude two CRGs that have contaminations in their SFR from either a neighbouring galaxy or an AGN. We also include literature data for Arp 147 [ref.²⁷] and the Cartwheel galaxy⁵⁸, as well as our Milky Way⁵⁹. As there is no reported stellar mass for the Cartwheel galaxy, we scale its dynamical mass to a stellar mass using the scaling relation of local galaxies⁶⁰ (Supplementary Fig.11).

Data Availability The imaging data presented here are publicly available from the ZFOURGE survey website (<http://zfourge.tamu.edu/>) and from the 3D-HST archive (<https://archive.stsci.edu/prepds/3d-hst/>). The spectroscopic data of this work was based on observations made with the Keck telescope from the W. M. Keck Observatory. The raw spectroscopic data can be accessed through the publicly available Keck Observatory Archive (<https://www2.keck.hawaii.edu/koa/public/koa.php>). The reduced data and other data that support the plots within this paper and other findings of this study are available from the corresponding author on reasonable request.

Code availability The customised MOSFIRE spectroscopic fitting code used in this work can be found here (<http://astronomy.swin.edu.au/~tyuan/mosfit/>). Scripts related to EAGLE simulations analysis in this paper are available from the second author (A.E., email: ahmedagali70@gmail.com) on reasonable request. Other scripts related to the analysis in this paper are available from the corresponding author (T.Y.) on reasonable request.

Supplementary information accompanies this paper. The author's link to the Supplementary Information (SI) can be found here <http://astronomy.swin.edu.au/~tyuan/paper/>. The SI includes 10 sections, 16 figures and 4 tables.

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A giant galaxy in the young Universe with a massive ring

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SUPPLEMENTARY NOTES

To support our analysis and conclusions in the Letter and the Methods, this supplementary information includes 10 sections with 16 Supplementary Figures and 4 Tables.

We present more details about our observations and data reduction in Section 1 and analysis of multi-wavelength imaging data in Section 2. The ISM properties are derived in Section 3. Discussions on systematic uncertainties associated with our stellar mass and kinematic modelling are presented in Section 4 and 5, respectively. The collisional ring time scale is estimated in Section 6. Our analysis on a $z \sim 2$ ring galaxy in EAGLE simulations is presented in Section 7. We discuss alternative origins of R5519 in Section 8. The implied number density of CRGs at $z \sim 2$ is discussed in Section 9 and we provide possible explanations for the number density evolution of CRGs with redshift in Section 10.

1 Observations and Data Reduction

1.1 Keck/MOSFIRE Slit Spectroscopy Spectroscopic data from the MOSFIRE instrument¹ were obtained on the Keck 1 telescope on Mauna Kea on the 13th of February 2017 (Project Code: Z245). We observed in the K-band with a spectral resolution of $R = 3610$ (i.e., velocity resolution of $\sigma_v = 35$ km/s). An AB dithering pattern with 1.5 arcsecond length was used. The PA of the slits is 58° . The total exposure on the mask was 96 minutes. The average seeing was $0''.8$ during the integration of this particular mask, equivalent to the slit width.

We reduce the data using a similar procedure as our ZFIRE survey². In summary, we use the MOSFIRE data reduction pipeline (DRP) for initial 2D data processing including flat-fielding, spatial rectification, sky subtraction, and wavelength calibration. The wavelength calibration is carried out in vacuum using arc and sky lines, with a typical

residual of $\lesssim 0.1\text{\AA}$. The DRP also generates the associated 2D 1σ spectra that we use for error analysis. An A0V type star is used for telluric and initial flux calibration. We use our customised code to implement telluric correction, flux calibration, 1D spectra extraction, and emission line profile fitting. Because R5519 is an abnormally extended object that does not follow the overall size distribution of $z \sim 2$ ZFOURGE galaxies³, we derive the slit-loss and flux calibration correction factor independently in Methods.

The total observed 1D spectrum for R5519 is presented in Supplementary Fig.3. The emission line fitting procedure involves fitting Gaussian profiles simultaneously to three emission lines: [N II] $\lambda 6548$, 6583 and H α (Supplementary Fig.3). The [S II] doublet lines are fitted as double Gaussians separately. The line profile fitting is conducted using a χ^2 minimisation procedure weighted by the inverse of the variance spectrum. We derive a Balmer absorption correction on the H α emission line based on the weak stellar continuum and find it to be less than $\sim 1\%$ of the observed flux. We therefore do not correct for the small Balmer absorption because the uncertainties in aperture and dust corrections are more than one order of magnitude larger. The redshift calculated from the H α line centroid of the total 1D spectrum is $z = 2.19$ (Supplementary Table 3). We achieve a signal-to-noise ratio (SNR) of 57 on the total flux of the H α emission line and 15 for the [N II] line.

1.2 Keck/OSIRIS Integral Field Spectroscopy In order to obtain spatially resolved H α kinematics, we observed R5519 with the integral-field instrument OSIRIS⁴ in laser guide star (LGS) adaptive optics (AO) mode⁵ on the Keck I telescope on the 8th of December 2017 (Project Code: W276). A total of 2hrs were available for R5519 including standard stars and overheads.

AO with R5519 was quite challenging because the tip-tilt (TT) star had an observed magnitude of $R_{\text{vega}} \sim 19$ and was $51''.1$ away from the target, approaching the Keck LGS AO system limit (e.g., the faintest TT star recorded³ for Keck LGS AO is $R_{\text{vega}} \sim 19.2^1$). We first acquired the TT star and centred it on the OSIRIS 100mas plate in the narrow band filter Kn2 (spectral coverage: $2.036 - 2.141\mu\text{m}$, spectral resolution: ~ 3000 or velocity resolution of $\sigma_v = 42$ km/s, FOV $4.5 \times 6.4''$). We then pointed to the centre of R5519 by applying the coordinate offset from the TT star to the centre of R5519. The offset from the TT star to the IFS centre was measured using well-calibrated HST F125W, F140W, and F160W images from the CANDELS survey⁶⁻⁸ and was accurate to $0''.06$. The final pointing of the OSIRIS field-of-view (FOV) with respect to the ZFOURGE near-IR images is shown in Fig.2. The PA of the OSIRIS is 225° . The weather during the observation was good, with a natural K-band seeing of $\sim 0''.7$ and an attenuation of $\lesssim 0.2$ mag. We were able to close the AO loop for $5 \times 900\text{s}$ exposures on R5519 including one 900s exposure on a blank sky nearby. The net exposure on R5519 is therefore 60mins. A Gaussian fitting to

¹<https://www2.keck.hawaii.edu/optics/lgsao/performance.html>

the point spread function of the TT star yields an average FWHM of $0''.35$, therefore the angular resolution of our AO observation is quoted as $0''.35$ (3.5 spaxels on the 100mas scale).

Individual exposures are first reduced using the OSIRIS DRP (version 4.1.0)⁴. We use the sky subtraction code⁹ to scale the one 900s sky exposure for each of the four exposures. The DRP reassembles the raw data into a vacuum wavelength-calibrated, sky subtracted 3D datacube. We verify the OSIRIS wavelength calibration by comparing the wavelength solution of the DRP with the vacuum wavelength of sky lines¹⁰. We find that DRPv4.1.0 provides a good wavelength solution with an average residual of $\lesssim 0.6\text{\AA}$ in the Kn2 band.

Since we are mainly concerned about kinematics of $H\alpha$ emission lines from the OSIRIS datacube, a first order polynomial function is fit to the continuum for each spaxel and then subtracted out from each spaxel. The subtraction of the continuum improves the removal of lenslet to lenslet variations. To align and coadd the 4 datacubes, we first manually inspect each datacube for $H\alpha$ detections. We find a $\sim 4\sigma$ detection of $H\alpha$ lines averaged on a particular spatial region of 3 by 3 spaxels in the first exposure. We then look for $H\alpha$ detections in the same spatial regions and find a slightly lower SNR of ~ 4 , 3, and 1 in the other 3 datacubes. We shift the centre of the 3×3 spaxel box by 1-5 spaxels to inspect possible spatial offsets. The SNR of the $H\alpha$ line in the box is maximised when the offset of the centre is 0-1 spaxel. We therefore conclude that the four datacube are spatially aligned within the error of 3 spaxels, i.e., about the size of the point-spread-function (PSF) of our AO observations. The final datacube is constructed by coadding the four datacubes, weighted by the SNR of the $H\alpha$ line detected in the brightest region. Telluric correction and initial flux calibration are performed on the final datacube by using one A0V standard star (HIP 26934) observed immediately before the science exposure.

The astrometry of the datacube is determined using the offset position from the TT star to the centre of the IFS with the observed position angle. We then verify the astrometry by comparing the $H\alpha$ 2D map with the narrow-band $H\alpha$ NB209 image.

We manually inspect all spaxels on the final OSIRIS datacube. The datacube is noise-dominated and most spaxels show no $H\alpha$ line detection ($< 2\sigma$) (Supplementary Fig.4). The only region that shows a bona fide (4.4σ) $H\alpha$ detection remains the one box region that we use for aligning the individual exposure. This region spatially matches the brightest location in the NB209 $H\alpha$ narrow-band image within $0''.3$. We also experiment with smoothing and adaptive coadding techniques on the datacube but with no significant improvement in detecting $H\alpha$ lines in any other spatial regions. However, the $H\alpha$ velocity from the single OSIRIS region provides a key constraint on the kinematic modelling of R5519. To further check the robustness of the 4.4σ detection, we use the best-fit velocity field and the NB209 $H\alpha$ image to simulate the OSIRIS observations; we are able to reproduce this detection (Supplementary Fig.4).

2 Multi-wavelength Imaging Data

2.1 ZFOURGE CATALOGUE IMAGES ZFOURGE targets 3 legacy fields including an area of $11'\times 11'$ in the COSMOS field¹¹. The survey provides deep near-IR imaging on the FourStar instrument¹² using five medium-band filters (J1, J2, J3, Hs, Hl) and one broad-band filter (Ks)¹³. Ancillary photometric data providing additional 30 passbands from $0.38\mu\text{m}$ to $8\mu\text{m}$ are included in the survey catalogue. Comprehensive descriptions on the ZFOURGE data products can be found in the ZFOURGE survey paper¹⁴ and in related publications^{15–17}.

The ZFOURGE 2017 data release provides 32 of the 36 passbands images from the U band to the Ks band. Some of these passbands overlap. ZFOURGE catalogue images are fully reduced, calibrated and interpolated on a pixel grid of $0''.15$. ZFOURGE also provides a super deep K-band detection image ($K_{s\text{tot}}$) by combining FourStar/Ks-band

observations with pre-existing K-band images from other catalogues. The average PSF of the $K_{s\text{tot}}$ image is $\text{FWHM} \sim 0''.47$. Note that the far-IR Spitzer/MIPS and Herschel/PACS images exist for R5519 but are not included in the current ZFOURGE data release. Because of the large PSF of the far-IR images, the images of R5519 and its neighbouring galaxy G5593 are blended. We do not include the far-IR images in our current analysis.

The ring structure has the highest contrast in the HST F125W and F160W IR broad bands. At the spectroscopic redshift of R5519, the F125W band covers the strong emission line $[\text{O II}]\lambda 3727$, and the F160W band contains $[\text{O III}]\lambda 5007$ and $\text{H}\beta$ emission lines. Note that because the $H\alpha$ emission line falls in the middle of the NB209 narrow-band filter, the NB209 image is effectively a narrow-band image for the $H\alpha$ and $[\text{N II}]\lambda 6583$ lines (Supplementary Fig.3). We refer to the NB209 filter image as the $H\alpha$ narrow band image. We divide the 32 ZFOURGE passband images into three wavelength bins that correspond to the rest-frame FUV, NUV, and optical bands of R5519. We then stack images in these 3 bins after normalising the counts of the images to 1 and weighting the images by the inverse of the variance. The stacked images are shown on panel-c of Fig.1.

2.2 PHOTOMETRY ZFOURGE provides the aperture ($1''.2$ diameter) and total photometry from 36 passbands, using PSF matched images^{14,18}. The PSF matched images are generated by the ZFOURGE team using a Moffat profile with FWHM of $0''.9$ and $\beta = 0.9$ [*ref.*¹⁴]. A FWHM of $0''.9$ matches the poorest image resolution of ground-based images (e.g., U and G band). The total photometry in the ZFOURGE catalogue is derived by applying an aperture correction factor (4.02 for R5519) based on the deep Ks band image profile. The total flux is the aperture flux multiplied by the correction factor. The same correction factor is applied to all passbands. This method is robust for most $z \sim 2$ galaxies. However, R5519 is more extended and asymmetric (Supplementary Fig.2) than a general $z \sim 2$ galaxy. To be cautious, we remeasure the photometry of R5519 based on a $2''.1$ diameter aperture on 32 PSF matched multi-band images. We do not include the 4 MIPS and PACS images because of their large PSFs may cause contaminations from G5593. We find that our $2''.1$ diameter aperture photometry and the ZFOURGE total photometry yield similar constraints on the SED fitting parameters as described in Section 4 below.

3 ISM properties

3.1 Metallicity: Global Average The global 1D MOSFIRE spectrum is extracted using an aperture of diameter $D = 2''.8$ (see the total spectrum in Supplementary Fig.3). The line fluxes for $[\text{N II}]\lambda 6584$, $H\alpha\lambda 6563$, $[\text{S II}]\lambda 6717, 6731$ are measured on the global 1D spectrum and presented in Supplementary Table 3.

We applied two empirical metallicity calibrations to derive the globally averaged gas-phase oxygen abundance ($12 + \log(\text{O}/\text{H})$). We first use the $\text{N2} = \log([\text{N II}]\lambda 6583/H\alpha)$ index calibrated by the PP04N2 method¹⁹. The PP04N2 yields $12 + \log(\text{O}/\text{H}) = 8.62 \pm 0.02$. The N2 index is the most commonly used diagnostic at high redshift because the adjacency of the $[\text{N II}]$ and $H\alpha$ lines makes the measurement efficient and unaffected by reddening. The PP04N2 method is calibrated based on local H II regions and does not consider that high-redshift galaxies may have different ionisation parameter, ISM pressure and prevalence of shocks to the low-redshift H II regions^{20,21}. A recent diagnostic utilising the ratios of $[\text{N II}]/[\text{S II}]$ and $[\text{N II}]/H\alpha$ has been proposed (the D16N2S2 method²²). The D16N2S2 method has a similar efficiency as the PP04N2 method, but is independent of varying ionisation parameters and the ISM pressure, so is ideal for determining metallicity in high-redshift galaxies. The metallicity for R5519 is calculated to be $12 + \log(\text{O}/\text{H}) = 8.92 \pm 0.06$ based on the D16N2S2 method. The errors are calculated by propagating the statistical uncertainties of the flux measurements.

The metallicity calibration of the PP04N2 method has a 1σ dispersion of 0.18 dex^{19,23}; we therefore do not discuss any systematic/statistical discrepancies below this metallicity calibration uncertainty. Note that the D16N2S2 method uses a solar metallicity of 8.77 and the PP04N2 uses a solar metallicity of 8.69, causing a systematic difference of 0.08 between the two methods. However, the D16N2S2 method yields a metallicity that is 0.3 dex higher, significantly more than the scatter and the solar metallicity offset of the PP04N2 method.

Based on the PP04N2 method, R5519 has similar metallicity (within the ~ 0.18 dex calibration uncertainty) compared with other samples of $z \sim 2$ star-forming galaxies of similar masses^{24,25}. However, based on the D16N2S2 method, R5519 is as metal-enriched as a $z \sim 0$ galaxy of the same mass²⁶. The different conclusions from these two methods highlight the disadvantage of the PP04N2 method to account for different ISM conditions. We adopt the metallicity from the D16N2S2 method because it is more robust against varying ionisation parameter and the ISM pressure²⁷. However, the accuracy of the D16N2S2 method might be limited by the SNR of the [SII] lines.

3.2 Metallicity: Spatial Variation The high SNR and good seeing FWHM of the MOSFIRE spectrum allows us to divide the spectrum into two independent spatial bins. The spatial apertures, labelled A1 and A2 respectively, are chosen to represent the blue-shifted and red-shifted velocity components of the H α emission line (Supplementary Fig.3). Each aperture has a diameter of $D = 1''.4$. The two apertures are spatially resolved, in that their centres are separated by more than the average seeing FWHM ($\sim 0''.8$) of the observation

The [N II] $\lambda 6583/\text{H}\alpha$ ratios for apertures A1 and A2 are identical to the global values within statistical errors (Supplementary Table 3). Using the PP04N2 method, we have $12 + \log(\text{O}/\text{H}) = 8.61 \pm 0.02$ for A1 and $12 + \log(\text{O}/\text{H}) = 8.58 \pm 0.02$ for A2, showing no significant difference. If we use the D16N2S2 calibration, we have $12 + \log(\text{O}/\text{H}) = 8.61 \pm 0.06$ for A1 and $12 + \log(\text{O}/\text{H}) = 8.83 \pm 0.06$ for A2. The component within A1 is 0.2 dex more metal-enriched than the blue component based on the D16N2S2 method, suggesting possible spatial variations in metallicity.

3.3 Electron Density The ratio of the [S II] $\lambda 6717$ and [S II] $\lambda 6731$ lines is a function of the electron density; the ratio decreases as the electron density increases. For example, in the very low density ($n_e < 100 \text{ cm}^{-3}$) environments as found in most local H II regions, the ratio of [S II] $\lambda 6717/[\text{S II}] \lambda 6731$ is ~ 1.4 ; in extremely high density environments ($n_e > 10000 \text{ cm}^{-3}$) the ratio of [S II] $\lambda 6717/[\text{S II}] \lambda 6731$ is ~ 0.44 [ref.²⁸].

In the total aperture spectrum, both the [S II] $\lambda 6717, 6731$ lines are detected at a SNR of 4.6 and 4.7, respectively (Supplementary Table 3). The global electron density is therefore $n_e = 675^{+455}_{-255} \text{ cm}^{-3}$ based on the relation of n_e versus [S II] $\lambda 6717/[\text{S II}] \lambda 6731$ [ref.²⁹].

In aperture A1, the [S II] $\lambda 6731$ line is well detected at a SNR of 12, with the [S II] $\lambda 6717$ line being weaker and at a SNR ~ 2 . In aperture A2, the [S II] $\lambda 6731$ line is not detected (SNR < 1), whereas the [S II] $\lambda 6717$ line is detected at a SNR ~ 9 . Based on the 3σ flux limit of the [S II] $\lambda 6717$ line in A1 and the [S II] $\lambda 6731$ line in A2, the electron density of A1 is estimated to be $n_e \gtrsim 5.7 \times 10^3 \text{ cm}^{-3}$ and $n_e \lesssim 210 \text{ cm}^{-3}$ for A2. However, we caution that the flux limit for the [S II] $\lambda 6731$ line in A2 could be contaminated by a sky line. Given the low SNR of the [S II] lines, we refrain from drawing conclusions about spatial variations in electron density. Deeper observations on [S II] lines are required to improve the accuracy of the electron density measurement and investigate the spatial distributions of n_e .

4 Systematic Uncertainties of the Total Stellar Mass

The ZFOURGE catalogue stellar mass is based on the SED fitting through the FAST fitting code (Methods). We rerun FAST using our updated aperture photometry and the spectroscopic redshift while keep-

ing other inputs the same as the ZFOURGE catalogue; the updated stellar mass agrees with the catalogue value within 0.1 dex. Lowering the metallicity (e.g., 0.2-0.5 $Z_\odot$) does not change the stellar mass significantly (within 0.1 dex) but increases the age by a factor of ~ 2 -3.

To evaluate the robustness of M_* against different SED fitting packages, we run alternative SED-fitting codes such as *Prospector*³⁰ and *LE PHARE*³¹. *LE PHARE* uses a χ^2 minimisation algorithm similar to FAST, whereas *Prospector* is a new SPS modelling framework designed to account for a large number of degenerate parameters that can affect the galaxy SED³⁰. *Prospector* explores the parameter space with a Bayesian MCMC approach and includes Flexible Stellar Population Synthesis models³², variable dust attenuation, re-radiation, a nonparametric SFH and self-consistent nebular emissions³³. With a Chabrier³⁴ IMF, *LE PHARE* returns a stellar mass of $\log(M_*/M_\odot) = 10.65^{+0.08}_{-0.04}$, whereas *Prospector* returns a stellar mass of $\log(M_*/M_\odot) = 10.84^{+0.07}_{-0.06}$ (allowing SFH to vary). We therefore conclude that the total stellar mass estimation of R5519 is $\log(M_*/M_\odot) \approx 10.8$ and robust within the systematic error of 0.2 dex caused by different SED fitting methods. Applying a most extreme star formation history (10 Myr burst) will further reduce the lower limit of the stellar mass by 0.3 dex.

5 Systematic Uncertainties of Kinematic Model Fitting

We test fitting the kinematic data with only a rotation or an expansion/contraction component. We first keep V_{sys} at 0 and then test varying V_{sys} as a free parameter. For a $V_{\text{sys}} = 0$ and $\text{DOF} = 2$, we find that the probability of a rotation-only and expansion/contraction-only model being consistent with our data is $p = 0.07$ and $p = 0.37$, respectively (Supplementary Fig.7). For a varying V_{sys} and $\text{DOF} = 1$, the probability of a rotation-only and expansion/contraction-only model being consistent with our data is $p = 0.05$ and $p = 0.27$, respectively (Supplementary Fig.7). In comparison, the probability of a model with rotation and expansion/contraction ($\text{DOF} = 1$) is $p = 0.475$ (Supplementary Fig.7). We therefore conclude that a rotation and expansion/contraction model provides the best-fit to our data; a rotation-only model is the least consistent with our data, though the expansion/contraction-only model might still be viable.

We then test the assumption of our PA_0 and i by running the model fits for a range of i and PA_0 (Supplementary Fig.8). For a fixed PA_0 , the magnitude of both V_{rad} and V_{rot} decreases with increasing i . For a fixed i , the magnitude of V_{rot} decreases with increasing PA_0 whereas the V_{rad} increases mildly with increasing PA_0 . We have the best-fit $\text{PA}_0 = 28 \pm 10^\circ$ from the ellipse fit. For the purpose of testing the systematic uncertainty, we use $i = 29 \pm 9^\circ$ and $\text{PA}_0 = 28 \pm 10^\circ$. We randomly choose i and PA_0 from the uncertainty range above and rerun the tilted rotation+expansion/contraction ring model 500 times. The resulting 1σ scatter caused by the uncertain range of PA_0 and i for V_{rad} and V_{rot} is 71 km/s and 70 km/s. This is similar to the order of uncertainty caused by the measurement error. We note that an expansion/contraction component of our model is significant as long as the kinematic major axis is not 90° off from the photometric major axis. Deeper, high-spatial resolution IFS observations are required to reduce the systematic and measurement errors.

For the purpose of demonstrating the limitations of applying existing high- z kinematic approaches on complicated systems like R5519, we fit a simple rotating disk model to the MOSFIRE 2D H α spectrum using the Heidelberg Emission Line Algorithm (HELA)^{35,36}. Previous studies have successfully applied HELA in MOSFIRE 2D spectra to derive H α rotation velocities^{35,36}. Briefly, HELA simulates a 3D datacube of H α lines, collapses the datacube into a MOSFIRE slit, and runs an MCMC simulation to determine the best-fit model to the observed H α 2D spectrum. HELA assumes an arctangent rotation curve³⁷

and a constant velocity dispersion, as well as an exponential profile for the radial distribution of H α . We follow the same procedure as described extensively in a previous work³⁶. We limit the inclination angle to the range of 0 – 35°. Supplementary Fig.9 shows the best-fit model from HELA. The residuals on the H α image are significantly larger than other rotating disks at $z \sim 2$ [ref.³⁶]. However, because a smooth exponential 2D profile for the radial distribution of H α is assumed in HELA, it is inconclusive if the residual comes from the deviation from a smooth H α profile in R5519 or from an expansion component in the rotational field³⁸.

To test the self-consistency of our 4.4 σ H α OSIRIS detection, we use the best-fit kinematics at 5 kpc (fixing PA₀ and PA₀ = 28° and $i = 29^\circ$) and the NB209 H α narrow-band image to simulate our OSIRIS observation (Supplementary Fig.4). The simulation uses the NB209 narrow-band H α image after subtracting a small contribution from the continuum estimated from the NB119 narrow-band image. We convert the continuum subtracted NB209 flux into the H α flux using the zero-points provided by ZFOURGE. The H α line centroid is determined using the velocity field from the best-fit tilted rotating and expanding/contracting circular ring model; the width of the H α line is simulated using a convolution of the instrumental width and beam-smearred with the AO-corrected spatial resolution of FWHM = 0''/35. We randomly generate noises using sky spaxels from the observed datacube and run the simulated OSIRIS datacube ~ 500 times. We are able to recover our OSIRIS H α detection within errors (Supplementary Fig.4).

6 Collisional Time Scale

In the classic expanding wave scenario of a first ring after the collision^{39–41}, R_{ring} , R_{disk} (outer-edge of the disk), and n carry important information about the mass ratio ($\mu = M_{*}^{intruder}/M_{*}^{host}$) and the time elapsed (τ_c) after the collision. R_{ring} increases linearly with τ_c and grows faster for a larger μ . If the collision is recent ($\tau_c \lesssim 80$ Myr) or if the intruder galaxy is a dwarf (e.g., $\mu \lesssim 0.1$), R_{disk} and n remain relatively intact compared with the pre-collisional disk of the CRG host⁴². For a larger τ_c , the expanding wave redistributes the disk star and gas to larger radii, producing a larger R_{disk} and smaller n compared with the pre-collisional disk⁴⁰. If the R_{80} we measure is the lower limit for R_{disk} of the pre-collisional disk after the collision, then the R_{80} and n of R5519 argue for a not so recent collision and a massive intruder ($\tau_c > 80$ Myr and $\mu > 0.1$).

The ratio of R_{ring} and R_{disk} provides another constraint on τ_c and μ in the context of a first expanding ring. The small ratio ($R_{ring}/R_{80} \leq 0.48$) suggests a very recent ($\tau_c < 50$ Myr for $\mu \sim 0.1$ and $\tau_c < 20$ Myr for $\mu \sim 1$) collision^{40,42}. Note that $\mu \simeq 0.4$ if G5593 is the intruder. Indeed, the radial and rotational velocities (V_{rad} , V_{rot}) and R_{ring} of R5519 are analogous to the local CRG Arp 147 [ref.⁴³] (Supplementary Fig.14), implying a similar collisional timescale² of ~ 40 Myr. Here we assume a uniform expansion velocity; the derived timescale is uncertain by a factor of ~ 2 due to the systematic and observational uncertainties of V_{rad} . This small τ_c is inconsistent with the large τ_c prompted by R_{disk} and n , and the lower limit (> 50 Myr) of the stellar age on the ring.

7 The EAGLE $z \sim 2$ Ring Galaxy

7.1 Identifying and Analysing the Highest-Redshift Ring Galaxy in EAGLE Simulations EAGLE is a suite of hydrodynamical simulations that follow the formation and evolution of galaxies and the growth of black holes in a cosmologically representative large box^{44,45}. We exploit these simulations to study the formation and evolution of CRGs and their properties in a recent work⁴⁷.

In brief, to identify ring galaxies in EAGLE, we first classify all

the galaxies in the simulations to early-types, late-types and morphologically disturbed (interacting) galaxies based on their flux radial distributions using their face-on mock *ugriz* images. In the second step, we visually inspect the morphologically disturbed galaxies and classify those that have a ring morphology. The last step is to follow the evolution history of each CRG candidate over time and see if there is any satellite(s) that collided with the ring host. Galaxies that have a ring morphology and have collided in their past with neighbouring galaxy(ies) are deemed CRGs; those that have not interacted with other satellites are found to host strong bars and are similar to pseudo-rings at redshift $z = 0$.

Past observational and theoretical work suggests that in addition to the rotational velocity of the gas in these systems, CRGs have non-negligible radial velocities due to the impulse (momentum) caused by the drop-through interaction of the intruder with the disk of the ring host. As an additional check to the collisional origin of our sample, we also study the overall kinematics of the selected CRGs and find those in agreement with the analytic caustic theory^{39,40,50} in which rings form from density waves. Because our previous work focuses on the entire sample of EAGLE CRGs, we do not trace the time evolution of individual CRGs at high- z .

The highest-redshift CRG identified in our simulation work⁴⁷ is at a redshift of $z = 2.23$ and is presented in Supplementary Figs.15-16. Here we analyse the kinematics of this EAGLE CRG in detail. The gravitational softening length for our simulations is 0.7 kpc at $z \sim 2$, i.e., insufficient to resolve any thin/thick disk components. We use four “snapshots”⁴⁶ that have a time resolution of 60 Myr. Snapshots are snapshots stored at finer time steps. Because of the common storage limitations in supercomputers, only a small subset of the particle properties are stored in “snapshots”. In EAGLE, snapshots at $z > 2$ have the fine-time resolution of $\lesssim 100$ Myr, whereas snapshots have time resolution of few hundred Myr⁴⁶. We define time $t=0$ Myr as the time when the ring feature was identified in the snapshot at $z = 2.23$, this is an arbitrarily defined time and is not representative of the exact time when the collision occurred.

In Supplementary Fig.15, we show the radius of the ring as 1D surface density peak of the star particles. We observe that the radius of the ring expands from 5, 6.5 to 15 kpc from $t = 0, 60$ Myr to 120 Myr. We tag the gas and star particles that are identified on the ring formed at $t = 0$ Myr and follow their positions in subsequent times of $t = 60, 120, 180$ Myr. The particles that make up each ring at these three timeframes are mostly composed of new particles that do not come from the ring formed at $t = 0$ Myr; this is consistent with the ring being a wave pattern.

In Supplementary Fig.16, we show the circular rotation and radial velocity of the gas particles at different radii in the $z = 2.23$ CRG for the four time sequences used in Supplementary Fig.15. We only consider the particles that lie within a radius of $r = 30$ kpc from the centre of the galaxy and assume a scale height of $h = 5$ kpc for the disk. In this case, the radial velocity is calculated for gas particles in the plane of the disk, where the plane is determined as that perpendicular to the total stellar spin vector of the galaxy. The radial velocity therefore describes the instantaneous radially outwards (positive) or inwards (negative) motion of the gas particles. Note that the instantaneous radial velocity does not reflect the motion of the density wave.

The large variations in radial velocities at all radii from $t = 0$ Myr to $t = 120$ Myr is likely triggered by the interactions with satellite galaxies as shown in Supplementary Fig.15. The ring feature is disrupted at a later snapshot ($t = 180$ Myr) due to a second passage of a satellite galaxy (Supplementary Fig.15). Hence, this ring feature has a lifespan of less than 180 Myr. This is relatively lower than the lifespan of local CRGs where the ring can expand for > 500 Myr to its maximum radius and to very low surface brightness⁴⁸. For this EA-

GLE CRG host, there are three smaller interacting satellites with stellar masses $M_* \gtrsim 10^9 M_\odot$. The stellar mass ratio between the intruder satellite galaxy and the ring host is ~ 0.38 . The simulated CRG has a stellar mass of $M_* = 1.4 \times 10^{10} M_\odot$ and is the central galaxy within the parent halo. The total mass of the halo hosting these galaxies is $M_{200} = 1.2 \times 10^{12} M_\odot$.

7.2 Comparing the EAGLE CRG with Observations We note that this EAGLE CRG is not meant to be used as a direct comparison with R5519. Indeed, this EAGLE CRG has different physical properties from R5519. For example, in addition to being ~ 0.23 times less massive than R5519, the SFR of the CRG is $3.8 M_\odot \text{ yr}^{-1}$, i.e., ~ 10 times lower than R5519. The factor of ten difference in SFR is an upper limit considering systematic effects when comparing the UV+IR SFR in observations with the EAGLE simulations⁴⁹. The EAGLE CRG has a significant central bulge that is also absent in R5519.

Despite the differences, R5519 is found from a representative volume in the early universe that the EAGLE simulations are designed to match. It is insightful to learn from the simulated galaxy what type of environment that a $z \sim 2$ CRG lives in. We see that the dynamically active environment at $z \sim 2$ causes stellar and gas particles to be tugged to larger radii, resulting in a somewhat large stellar disk that is not usually seen in nearby CRGs. The simulated CRG at $t = 120$ Myr looks morphologically similar to our observed R5519, both show asymmetric clumpy features on and outside of the ring (Supplementary Fig.2 and Fig.15). Our EAGLE simulations lend an alternative explanation for the morphology of R5519: it is possible that frequent satellite interactions at high redshift have triggered a short-lived collisional ring with the outer disk representing either scattered stars from the host and satellites and/or an on-going accretion from small satellites. Finer-time resolution snapshots are required in order to make mock observations for a more quantitative comparison with observations.

Note that in the case of multiple satellite interactions before and after the formation of the first ring, the analytic estimation for τ_c from the classic expanding wave scenario^{39–42} might not be directly applicable to R5519 without refinement. Therefore, the aforementioned inconsistency in τ_c is more a reflection of the inadequacy of the model used to derive it than a true inconsistency.

The snapshot at $t = 180$ Myr (Supplementary Fig.15) may look like it is beginning to form a second ring as predicted by the analytic CRG theory^{50,51}. However, a later snapshot at $t = 240$ Myr (not shown in Supplementary Fig.15) reveals that the CRG is completely destroyed (including its nucleus) by the major merger at $t = 180$ Myr before a second ring can be definitively identified. This highlights the “hostile” environment typical at high redshift that can lead to the demise or short lifetime of CRGs.

8 Discussions on Alternative Origins of R5519

8.1 A gravitationally lensed arc For a scenario that R5519 is a strong gravitational lensing system, we take the radius of the ring ($0''.6$) as an assumed Einstein radius. We find the total mass enclosed would be $M_{\text{Ein}} = 0.85 - 3.9 \times 10^{11} M_\odot$ for a foreground lens redshift range of $z_{\text{lens}} = 0.5 - 1.5$ within the $3.6 - 5$ kpc projected radius of the lens. Note that M_{Ein} increases with z_{lens} . For reference, the current highest redshift galaxy-scale lens is at $z = 1.5$ with the source at $z = 3.417$ [ref.⁵²]. We do not see signatures of this enclosed mass expressed in stellar light (Supplementary Fig.2), unless the foreground lens is a dwarf galaxy below the detection limit¹⁵ ($M_* < 10^9 M_\odot$) of ZFOURGE and with an abnormally large mass-to-light ratio. Furthermore, the persistently diffuse emission outside of the ring in multi-wavelength images is inconsistent with the morphological configuration of a gravitationally lensed arc.

8.2 A regular merger Within the caveats of our kinematic analysis, our data is consistent with a tilted rotating and expanding/contracting

circular ring model. In the classical models of CRG, the ring is a radially expanding density wave. However, kinematic confirmation of the density wave is observationally challenging even for nearby galaxies. The current kinematic data alone is insufficient to rule out a regular merger.

A CRG is a special type of a major merger with a drop-through collision. Only a few percent ($\sim 2\%$) of interacting galaxies are found to be CRGs⁵³. The observational difference between CRGs and other common (regular) mergers is that CRGs are geometrically simpler, characterised by a symmetric ring and a relatively well-preserved disk, whereas regular mergers are morphologically messier and retain less information about the pre-disrupted disk³⁹. The prominent ring and the profile of the stellar light of R5519 is consistent with the definition of a CRG. Note that the chance of finding regular mergers projected as a symmetric ring is lower than finding a CRG⁴². Moreover, in a regular merger or tidal interaction scenario, the star formation in the central regions of galaxies contributes significantly to the total SFR whereas the star formation of a CRG usually occurs on the ring⁵⁴. We do not detect any significant star formation activities in the central regions of the ring in R5519. We therefore think that a CRG origin is a more reasonable explanation for R5519 than a regular merger.

8.3 A secularly evolved ring By secular rings, we mean features recognised in the classifications of normal galaxies, including nuclear, inner, and outer rings⁵⁵. In numerical simulations, such rings tend to be the product of a slow evolution of the spiral pattern due mainly to the influence of gravity torques connected to a bar or a massive oval⁵⁶. The formation of secular rings is related to internal processes such as Lindblad resonances^{55,58}. Secular rings are generally non-circular in intrinsic shape and are commonly found in barred spiral galaxies^{57,58}, i.e., (R)SAB in the revised Hubble classification scheme⁶⁰. Even though in the local universe secular rings are more abundant than CRGs^{55,59}, the Hubble spiral sequence is not yet fully established at $z > 2$ [ref.⁶¹]. Most galaxies at $z > 2$ are clumpy, irregular and have small or no bulge component⁶².

If R5519 is a secularly evolved ring at $z = 2.19$, we find two aspects that are challenging to explain in our current framework of disk galaxy formation and the origin of the Hubble sequence.

(1) The large disk of diffuse light outside of the ring. Although the size of the star-forming ring of R5519 is within the range of other $z \sim 2$ H α rings of secular origin⁶³, the extra diffuse light at large radii of R5519 is not seen in those $z \sim 2$ H α ring galaxies. From the high-resolution HST image, the diffuse disk has a rest-frame B band size of $R_{80} = 11.8$ kpc (Table 1 and Supplementary Table 4). The average outer disk size of the most massive isolated disk galaxy at $z \sim 2$ is $R_{80} = 6.4$ kpc (e.g., Fig.3), a factor of 2 smaller than R5519. R5519’s extended stellar disk is 1.5–2.2 times larger than the Milky Way’s stellar disk⁶⁴ (Methods). Such a large extended disk of a secular origin has not been conclusively reported in observations or simulations at $z > 2$. The reason for the lack of Milky Way like large stellar disks at $z > 2$ is that it takes time to build up angular momentum to sustain such a large disk. For example, the angular momentum of the accreted gas onto halos is proportional to the cosmic time^{65,66}. Recent cosmological hydrodynamical simulations show that large disks do not show up until $z \lesssim 1$ [ref.⁶⁷].

(2) The implied large (~ 5 kpc) bar within R5519. As secularly evolved rings are commonly found in barred spiral galaxies, the 5 kpc radius of the ring in R5519 implies a large bar of up to 5 kpc in semi-major axis. Such a large galactic bar at $z > 2$ has not been reported in simulations or observations. Barred galaxies are in general rare at $z > 2$. The fraction of spiral and barred galaxies decreases with redshift and becomes extremely difficult to find at $z > 2$ [ref.^{61,68–72}]. It is true that the lack of $z > 2$ bars in observations could be caused by the limited spatial resolution and the depth of high-redshift galaxy surveys.

Bars are associated with spiral disks of the Hubble sequence and spirals are easier to observe than bars. Many high-redshift observations have pointed out that spiral galaxies themselves do not fully emerge until $z < 2$ [ref.^{61,71}]. For example, there are less than three galaxies that are observationally confirmed to be spiral galaxies at $z > 2$ ^{70,72} and no conclusive barred spirals have been observationally confirmed at $z > 2$ [ref.^{69,73}].

Cosmological hydrodynamical simulations show that the dynamically active environment at $z > 1$ is hostile to bar formation^{68,69}. In one of our recent work⁷³, we investigate the formation of a barred spiral at $z \sim 2$ in zoom-in cosmological hydrodynamical simulations. We find that such a rare barred spiral galaxy ($R_{80} \sim 2.5$ times smaller and bar size ~ 7 times smaller than R5519) is found in a relatively isolated environment without companions. Our finding is consistent with previous studies that bar formation at high redshift is difficult because any merger or violent gas accretion event would have destroyed the bar^{68,69}. This picture is also consistent with the overall evolution of the Hubble sequence with respect to the evolution of the environment^{74,75}. If we interpret R5519 as one of the outliers that formed a bar in the early universe, then the active group environment it resides in is counterintuitive to findings in simulations. A collisional ring origin, on the other hand, can naturally account for the large diffuse disk and does not require the existence of a large bar in R5519.

Note that non-circular orbits and projection effects can mimic the impression of an expanding/contracting component in the velocity field. Modelling of non-circular orbits requires a deeper and more spatially resolved 2D kinematic map than our current data. However, the projected velocity⁷⁶ of non-circular velocity is usually much lower than the expansion/contracting velocity of CRGs. Most nearby CRGs have large (~ 50 - 200 km/s) expansion velocities^{43,77,78}. The large $V_{\text{rad},5\text{kpc}} = 226 \pm 90$ km/s we derive for R5519 is inconsistent with a secular ring and more consistent with a collisional ring (e.g., $V_{\text{rad},5.8\text{kpc}} = 225 \pm 8$ km/s for Arp 147 [ref.⁴³]).

Finally, a remark on using kinematics to distinguish a CRG from a regular merger and an isolated disk. In the post-collisional disk of a CRG, the departure of the 2D kinematic field from an isolated pure rotational disk is a function of the time elapsed from the collision⁵⁴. We caution that very deep IFS observations and careful modelling are required to distinguish the 2D kinematic field from a post-collisional CRG disk, an isolated rotation-only disk, and a rotation-only disk that is being tidally perturbed. Our preferred interpretation of R5519 being a CRG is based on a combined evidence of kinematical, environmental, and photometric analysis. We urge follow-up observations to further verify/falsify our interpretations.

9 The Implied Number Density of CRG at $z \sim 2$

The co-moving volume of our observation is 1.1×10^6 cMpc³ based on the survey area of the ZFOURGE COSMOS field (11×11 arcmin²) and the redshift range ($z_p = 1.8 - 2.5$). The EAGLE simulations⁴⁷ cover a similar co-moving volume of $(100)^3$ cMpc³. Both our observation and the EAGLE simulations find only one collisional ring galaxy candidate at $z > 1.8$, implying a co-moving volume density (n_c) of $\sim 9 \times 10^{-7}$ cMpc⁻³ or a volume number density rate of $\sim 2 \times 10^{-6}$ cMpc⁻³ Gyr⁻¹ at $z \sim 2$.

We consider the following selection effects that can affect the observed volume number density n_c estimated above.

(1) The ZFOURGE survey is complete¹⁴ to stellar mass $M_* > 10^{9.5} M_\odot$ at $z \sim 2$ and our morphological identification is robust to galaxies that have $R_{80} \gtrsim 4$ kpc. Our estimation of n_c will miss CRGs of small ring sizes or low-mass hosts. However, assuming that the ring size distribution of CRGs does not evolve with redshift, the missing fraction of small rings are $\sim 10\%$. For example, the median ring radius of local CRGs is 15-20 kpc and less than $\sim 12\%$ of local CRGs have

ring radius less than 4 kpc⁵³.

(2) We use the 3D-HST F160W band image for morphological identifications. The 5σ limiting magnitude¹⁴ of the F160W image is 26.4 mag. Rings with surface brightness lower than this detection limit will be missed in our search.

To demonstrate this effect, we simulate what Arp 147 and the Cartwheel galaxy would look like at $z = 2.19$ in the HST F160W band for our current observational depth. Our simulation follows the standard red-shifting methodology⁷⁹ that considers the cosmological angular size evolution, surface brightness dimming and K-correction. We do not apply any intrinsic evolution in galaxy sizes. We then resample and convolve the redshifted images to match the HST F160W pixel size and PSF. We use B band images at $z \sim 0$ for the simulation to minimise the K-correction (HST F160W corresponds to rest-frame B/V band at $z \approx 2$). The B-band images are taken from the local CRG sample⁴² for Arp 147 and the HST archive for the Cartwheel.

The simulated images of Arp 147 and the Cartwheel are shown in Supplementary Fig.14. For comparison, the observed image of R5519 in the same F160W band are zoomed-in to match the same field of view as the simulated images. By simply placing Arp 147 and the Cartwheel at $z = 2.19$, neither of them would be detected in our observations. However, if we manually increase the intrinsic rest-frame B-band luminosity (L_B) by a similar factor (~ 4 - 8) as the increased SFR of R5519 at $z \sim 2$, the average surface brightness of both systems will be above a 5σ detection limit.

Note that the Σ_{SFR} of R5519 is ~ 4 times higher than Arp 147, ~ 8 times higher than the first ring of the Cartwheel and ~ 50 times brighter than the secondary ring of Cartwheel. Our assumed intrinsic luminosity evolution of CRGs in the simulations is consistent with $z \sim 2$ SF galaxies having a higher SFR (and thus being brighter in the rest-frame B band) than local galaxies. For example, based on the empirical relation between SFR and L_B ^{80,81}, a 4–8 times rise in SFR corresponds to an increase of ~ 3 - 5 in L_B .

Combining the constraints of (1) and (2), and based on the mass-size relation at $z \sim 2$ [ref.⁸²], we find that a total F160W magnitude of brighter than 23.9 will allow galaxies to have sufficient number of bright pixels (equivalent to an area of $R_{80} \gtrsim 4$ kpc) to be detected above the 5σ limiting magnitude. Assuming that CRG hosts at $z \sim 2$ are within the 2σ scatter of the SFR- M_* “main-sequence” relation, and based on the empirical relation between the B-band luminosity and SFR^{80,81}, we estimate that our observation is complete for $z \sim 2$ SF galaxies of stellar masses $\gtrsim 10^{10} M_\odot$. Note that the EAGLE ring simulations⁴⁷ also select galaxies of $M_* \gtrsim 10^{10} M_\odot$ at $z \sim 2$.

Both our observation and the EAGLE simulations yield a similar co-moving volume density of $n_c \sim 9 \times 10^{-7}$ cMpc⁻³ for CRGs that are massive ($M_* \gtrsim 10^{10} M_\odot$) and reside within the 2σ scatter of the SFR- M_* relation at $z \sim 2$. Our estimated n_c does not account for galaxies that are 2σ below the “main-sequence” relation at $z \sim 2$. However, those low SFR galaxies are $\gtrsim 100$ rarer than “main-sequence” SF galaxies at $z \sim 2$ [ref.⁸³] and are unlikely to contribute significantly to our estimated n_c .

We do note that our observations will miss low-mass ($M_* \lesssim 10^{10} M_\odot$) galaxies at $z \sim 2$. Our observed number density of massive CRGs at $z \sim 2$ is a factor of ~ 140 less than what is expected from the previous $(1+z)^{4.5}$ scaling relation with the cosmic merger rate⁸⁵. Using a more recent cosmic merger rate scaling relation $(1+z)^{2.2-2.5}$ for high-mass ($M_* \geq 10^{10} M_\odot$) only galaxies⁸⁴, the expectation for massive CRG number density is still a factor of 11-15 larger at $z \sim 2$ than at $z \sim 0$.

Finally, we estimate that the cosmic variance could contribute to an additional 10-20% uncertainty in our observed number density^{86,87}.

10 Possible Explanation for the Number Density Evolution of CRGs with Redshift

We emphasise that our conclusion on the small number density of CRGs at $z \sim 2$ is confined to relatively massive ($M_* \geq 10^{10} M_\odot$) galaxy hosts (Method, Section 8). It is possible that there are more CRGs at high redshift that are below current observational limits. Large expansion velocities will cause collisional rings to be short-lived and therefore difficult to observe. However, it is unknown if our measured expansion velocity of R5519 is typical of other CRGs at high redshift. We speculate two other factors that could lead to the rarity of large collisional rings at high redshift ($z \gtrsim 2$).

Local CRGs are often found in loose groups instead of compact groups or galaxy clusters⁵³. Even though interaction rates are higher in dense environments (e.g., clusters), the high velocity dispersions between cluster members and fly-by interactions can easily destroy the ring features. The galaxy environment at high redshift is similarly very active because of the frequent interactions with satellites and high gas accretion rates^{74,84}. Our $z = 2.23$ EAGLE simulated ring is short-lived (~ 200 Myr before it is completely destroyed by another merger) in this dynamically chaotic high-redshift environment (Supplementary Fig.15). The short lifetime of the ring could make CRGs appear rare in observations even though the required collisions happen frequently. Recent cosmological simulations imply that local-like galaxy groups do not fully emerge until $z \lesssim 2$ [ref.⁸⁸]. Observing the number density of CRGs across cosmic time could therefore provide an alternative constraint on the assembly and evolution of local-like galaxy groups.

Another factor that could make large CRGs hard to find at high redshift is related to the properties of the pre-collisional disk. Most models of nearby collisional ring galaxies assume that the target galaxy has a large thin stellar disk, i.e., the vertical disk scale length is about 1/10 of the radial scale length^{40,41,89,90}. This assumption is valid for most spiral galaxies in the local universe. However, the vertical disk length of $z \sim 2$ galaxies can be a factor of ~ 8 larger⁹¹, as reflected by their high velocity dispersions^{63,92}.

Collisional rings and spiral arms share a close connection in the origin of their structures. Both are considered as a part of the stellar dynamical orbit crowding process in response to a perturbation gravity force^{39,93,94}. The epicyclic oscillations of perturbed stellar orbits drive propagating density waves that are sustainable in large thin disks. However, a heated vertical disk can cause spiral and ring waves to rapidly die out^{95,96}. We speculate that the lack of large spiral galaxies and collisional rings might both be related to the late formation time of thin disks. A large thin disk needs high angular momentum to be stable⁶⁷. Cosmological simulations show that massive ($M_* \geq 10^{10} M_\odot$) galaxies commence the development of their disks between $1 < z < 2$ and large, stable disks are established at only at $z \lesssim 1$ [ref.^{67,97}]. Galactic Archeology also shows that the thin disk of our Milky Way did not form until $z \sim 1$ [ref.⁹⁸].

Finding the onset of large spiral galaxies remains a major problem in galaxy formation⁶¹ and is one of the keys to unlock the origin of the Hubble sequence⁷⁴. Given the different structure of high-redshift disk galaxies (smaller sizes, more turbulent ISM, more chaotic morphology and larger disk height), it becomes challenging to visually separate spiral arms from clumpy, irregular disks at high redshift. For this reason, the earliest formation epoch of spiral galaxies is poorly constrained in theories and observations^{70,72,74,99}. Large ring galaxies, while rare, are relatively easy to identify and follow up in detail, thus providing a unique diagnostic to constrain the onset of thin disks and spiral galaxies.

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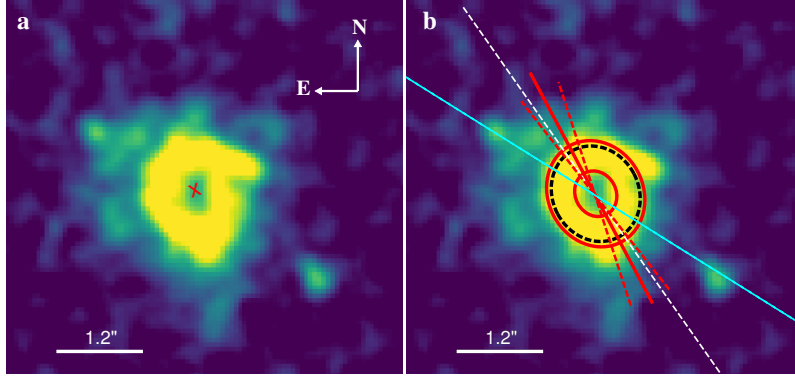
Part of the data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. The authors wish to recognise 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.

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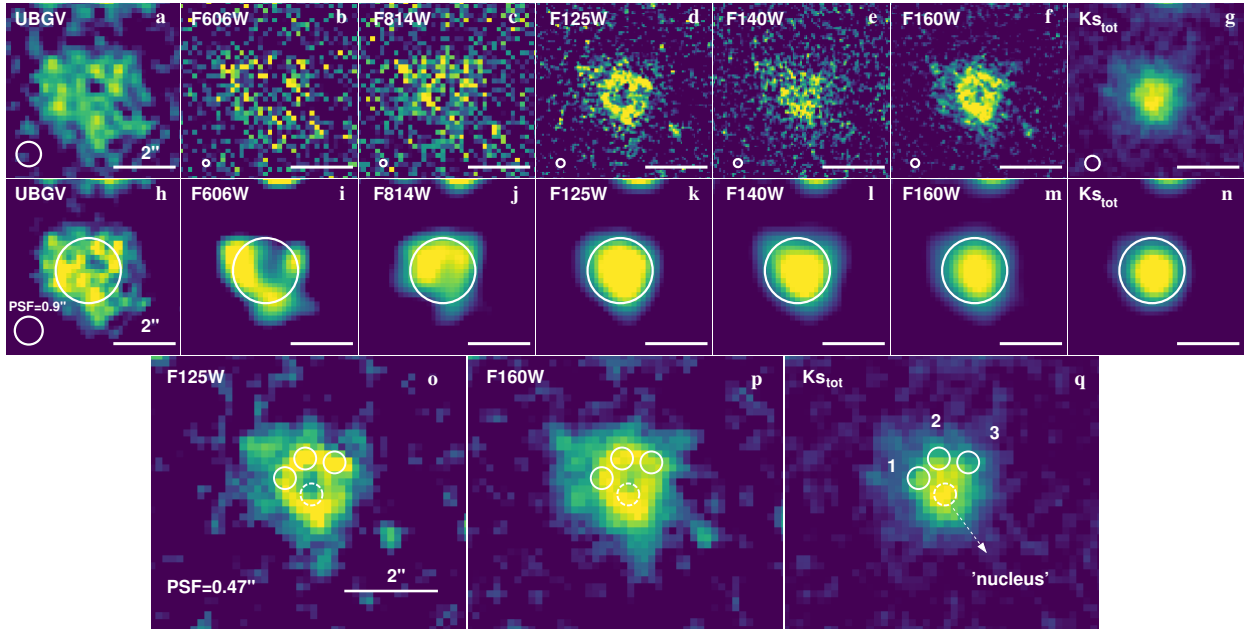
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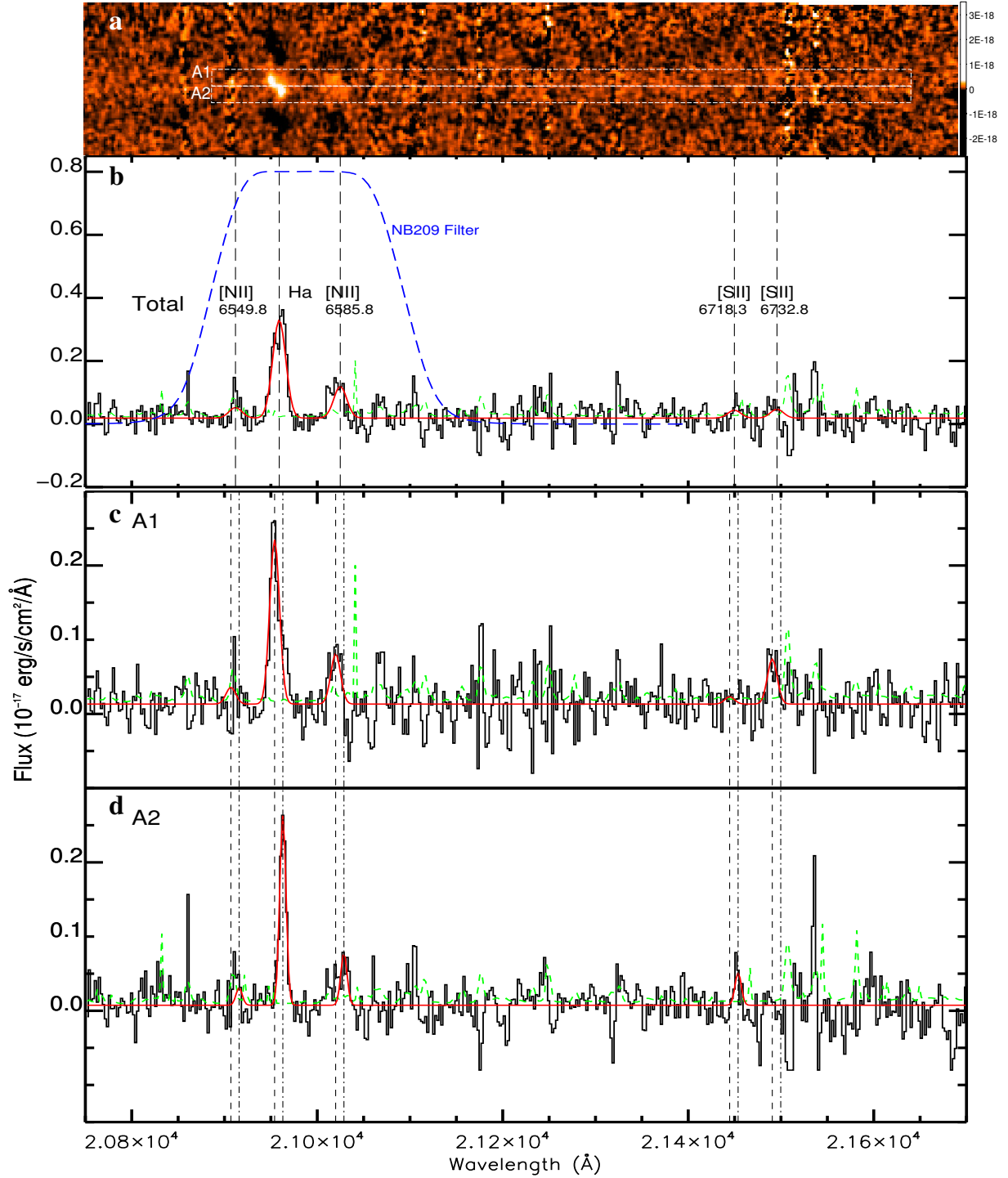
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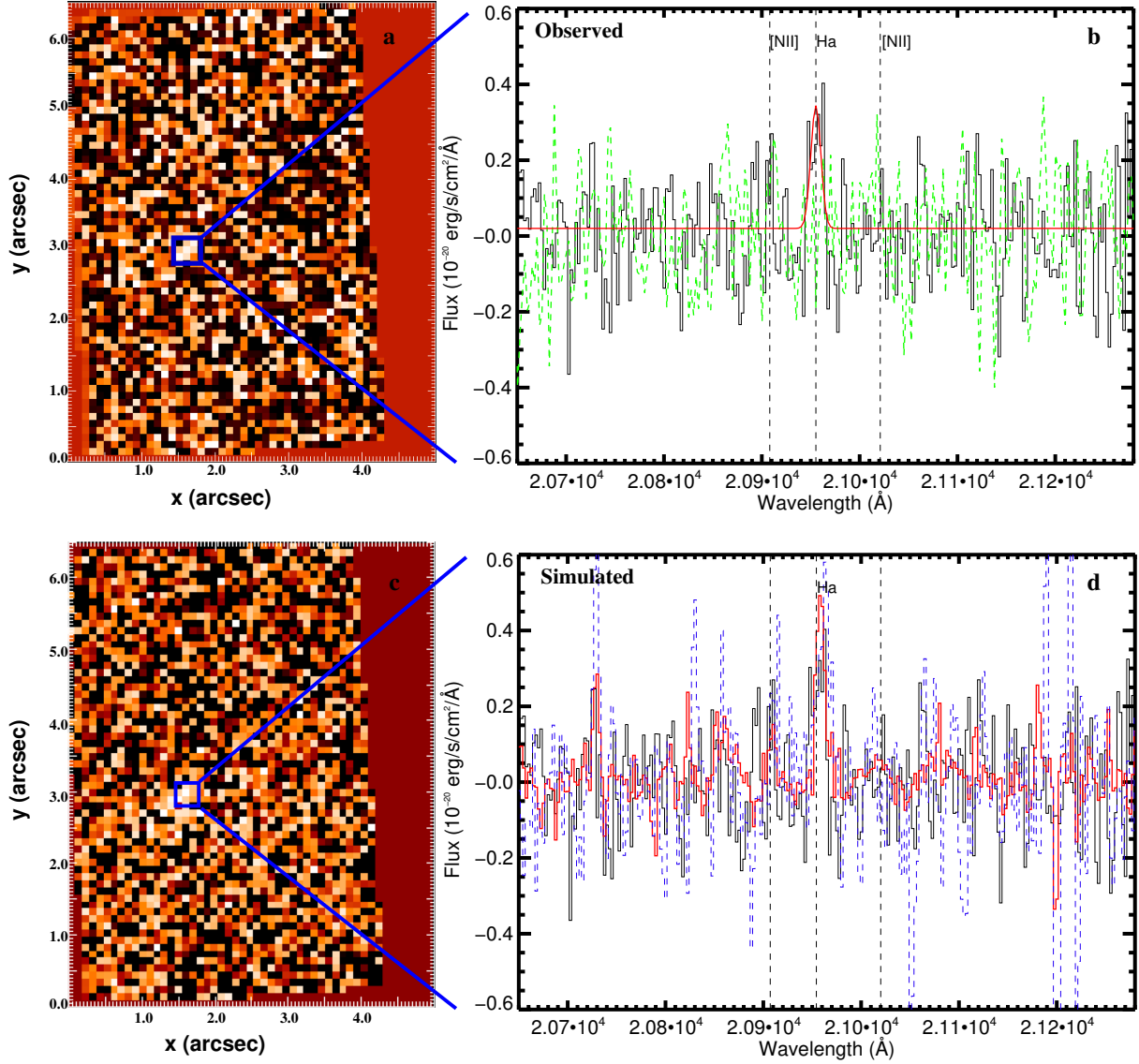
Supplementary Figure 1 – Fitting ellipses to the ring structure in high-resolution HST images. **a**, we use the combined F125W+F140W+F160W HST images from CANDELS^{6,7} to quantify the size of the ring. The red cross shows the initial centre of the ring before the fitting. The image is smoothed by three pixels to increase the signal-to-noise ratio. **b**, the red ellipses show the best-fit double ellipse model, with the red solid and red dashed lines denoting the best-fit position angle (PA) and 1σ errors of the model. The black ellipse shows the best-fit single ellipse model. The cyan dashed line shows the PA of the MOSFIRE slit. For reference, the white dashed line shows the literature PA from the 3D-HST catalogue based on the Sersic profile model fit to the image¹⁰⁰. A scale of $1''.2$ (~ 10 kpc) is shown. The details of the ellipse fit procedure are described in Methods.



Supplementary Figure 2 – Multi-wavelength morphology of R5519. The images are selected from the ZFOURGE catalogue. North is up and East is to the left. A scale of $2''.0$ (~ 17 kpc) is shown as a horizontal bar on each image. All images have a pixel scale of $0''.15$, except for the HST F125W, F140W, and F160W images in the first row, where we show the original 3D-HST CANDELS^{6,7} images with a pixel scale of $0''.06$. **a-g**, the original images selected from the ZFOURGE catalogue. The UBGV stacked image represents the ground-based image in the shortest wavelength. The HST images (F606W, F814W, F125W, F140W, and F160W) cover both the optical and the near-IR wavelengths. The Ks_{tot} band image represents the ground-based image in the longest wavelength. The PSF of each image is marked as an empty white circle at the bottom left. **h-n**, same as the top row, but showing the ZFOURGE PSF convolved images; the images are convolved with a Moffat profile to match the largest PSF (FWHM $\sim 0''.9$) of the ground-based images. The solid white circles indicate a diameter of $2''.1$ used for the global aperture photometry. **o-q**, PSF matched HST F125W, F160W, and ZFOURGE Ks_{tot} band images. The white circles show the apertures used to compare the colours of the postulated “nucleus” (dashed circle) with three regions on the ring (solid circles) (Method). The aperture has a diameter of $0''.47$, equivalent to the PSF of the convolved images.



Supplementary Figure 3 – Keck/MOSFIRE spectra of R5519. zoomed in on the wavelength vicinity of $H\alpha$, $[N II]$, and $[S II]$ lines. **a**, The 2D spectrum. Long white boxes indicate the two spatial apertures (A1, A2) used to extract two spatially resolved 1D spectra. The spatial length of the box is 8 pixels, corresponding to $\sim 1''.4$, about twice the seeing of the observations (thus spatially independent). The flux unit of the colour bar is $\text{ergs/s/cm}^2/\text{\AA}$. **b**, The total 1D spectrum extracted from the combined aperture of A1 and A2. The blue curve is the filter profile for the FourStar narrow band NB209. **c**, The 1D spectrum extracted from aperture A1. **d**, the 1D spectrum extracted from aperture A2. In all 1D spectra panels, the data, 1- σ , and best-fit Gaussian profiles are shown in black, green, and red, respectively. Vertical long-dashed/short-dashed/dash-dotted lines mark the centroids of the best-fit emission lines from the total/A1/A2 aperture.



Supplementary Figure 4 – The observed OSIRIS H α 2D image and simulated H α detection using the best-fit kinematics and the NB209 narrow-band image of R5519. The flux is calculated for per spaxel, i.e., per 0.01 arcsec². **a**, OSIRIS H α 2D map generated by collapsing the datacube along the wavelength vicinity (20930–21000 Å) of H α . Most spaxels have no H α detection (SNR < 1) because of the shallow exposure time. One spatial region shows a robust H α detection (blue box, 3 by 3 spaxels; 1 spaxel = 0.''1). The spatial resolution of our AO observation is $\sim 0.''35$. **b**, The OSIRIS 1D spectrum averaged over the spatial region (blue box on the left) that shows a H α detection (SNR = 4.4). The data, sky residual and best-fit Gaussian line profile are shown in black, green and red, respectively. Vertical dashed lines indicate the best-fit H α wavelength centroid and expected [N II] line centroids. The spatial region of the H α detected provides a key constraint to the kinematic modelling of R5519. **c**, The 2D H α image from the simulated OSIRIS datacube using the best-fit kinematics and H α narrow band image. **d**, Simulated OSIRIS 1D spectrum averaged over the same spatial region as the observations. The red line on **d** is an averaged simulated spectrum from 500 iterations. The blue line shows one random iteration from the simulations. The simulation recovers our H α detection within errors.

Supplementary Table 1 – Ellipse Fit to the Ring Structure

Model (image)	R_{in} kpc (1)	R_{out} kpc (2)	ΔR kpc (3)	R_{ring} kpc (4)	PA ° (5)	i ° (6)	χ^2/DOF (7)
R5519							
Double Ellipse (F125W+F140W+F160W)	2.7±0.2	6.5±0.2	3.7±0.3	-	28±10	29±5	0.97
Single Ellipse (F125W+F140W+F160W)	-	-	-	5.1±0.4	26±12	29±12	0.54

(1) Best-fit inner semi-major axis for the double ellipse model; (2) Best-fit outer semi-major axis for the double ellipse model; (3) Best-fit width of the ring from the double ellipse model; (4) Average semi-major axis from a single ellipse fit. (5) Best-fit position angle; (6) Best-fit inclination angle; (7) reduced χ^2 .

Supplementary Table 2 – Spatially Resolved Aperture Photometry

Photometric Bands	“Nucleus”	Ring region 1	Ring region 2	Ring region 3	Ring average
F125W original (FWHM≈ 0″.26)	26.60±0.07	26.31±0.06	26.08±0.06	26.09±0.06	26.16±0.03
F125W PSF convolved (FWHM≈ 0″.47)	26.53±0.08	26.30±0.05	26.15±0.05	26.26±0.06	26.23±0.03
F160W original (FWHM≈ 0″.26)	25.69±0.06	25.73±0.05	25.70±0.05	25.94±0.05	25.79±0.03
F160W PSF convolved (FWHM≈ 0″.47)	25.72±0.05	25.82±0.05	25.73±0.05	25.96±0.05	25.84±0.03
K_{Stot} (FWHM≈ 0″.47)	24.86±0.05	25.10±0.05	25.21±0.05	25.58±0.06	25.27±0.03
Colour	“Nucleus”	Ring average			
F125W - F160W (original)	0.91±0.09	0.37±0.04			
F125W - F160W (PSF convolved)	0.82±0.10	0.40±0.04			
F160W - K_{Stot} (PSF convolved)	0.85±0.07	0.56±0.04			

Magnitudes are in AB units. An aperture with a diameter of 0″.47 is used to measure photometry.

Supplementary Table 3 – MOSFIRE and OSIRIS Emission Line Measurements of R5519

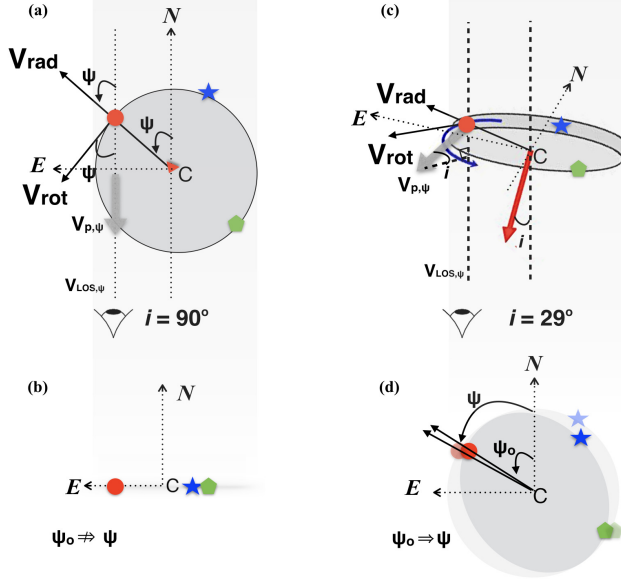
Component	z_s	Line Width km/s	fH α 10^{-17} ergs/s/cm ²	f[N II]	f[S II] λ 6717	f[S II] λ 6731	12+log(O/H) (PP04N2)	12+log(O/H) (D16S2N2)	n_e cm ⁻³
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
MOSFIRE Total	2.19273±0.00002	92±1	5.483±0.106	1.770±0.118	0.441±0.096	0.495±0.105	8.62±0.02	8.92±0.06	675 ⁺⁴⁵⁵ ₋₂₅₅
MOSFIRE A1	2.19197±0.00002	64±1	2.917±0.064	0.894±0.078	<0.301	0.800±0.062	8.61±0.02	8.62±0.07	>5700 (3 σ limit)
MOSFIRE A2	2.19332±0.00001	29±2	2.177±0.042	0.596±0.053	0.375±0.041	<0.32 ¹	8.57±0.02	8.82±0.07	<210 (3 σ limit)
OSIRIS	2.1921±0.0003	64±8	0.42±0.12 ²						

(1) Spatial components as shown in Supplementary Fig.3; (2) Spectroscopic redshifts calculated from the emission line centroid; (3) Emission line Gaussian line width converted to units of velocity dispersion in the rest-frame of the galaxy; (4)-(7) Measured emission line fluxes without aperture or dust correction; (8) Metallicity calculated using the PP04N2 method¹⁹; (9) Metallicity calculated using the D16S2N2 method²²; (10) Electron density calculated based on the line ratio of [S II] λ 6717 and [S II] λ 6731 [ref.²⁹]. ¹ Uncertain due to the contamination from an OH sky line. ² Surface brightness in units of 10^{-17} ergs/s/cm²/r².

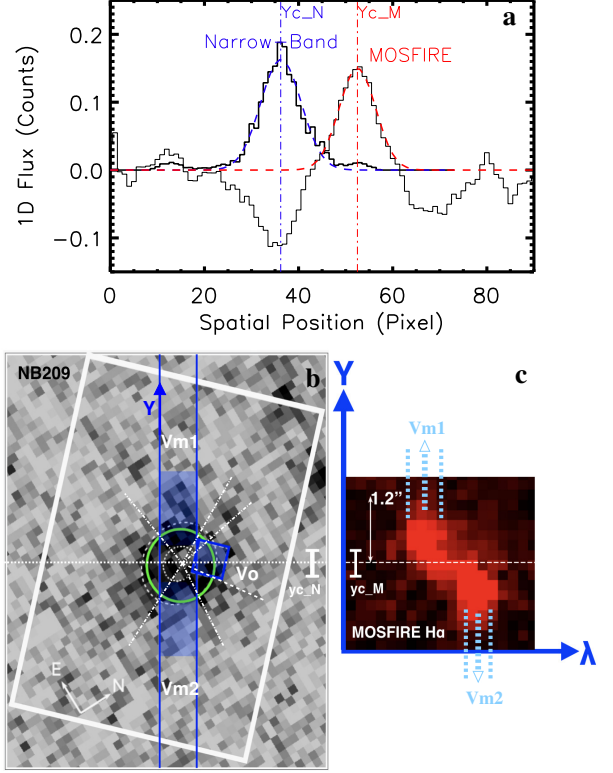
Supplementary Table 4 – Wavelength and PSF dependence of the measured size of the diffuse light

Observed band (approximate rest-frame band)	R_{50} kpc	R_{80} kpc	R_{95} kpc
K_{Stot} (R), FWHM≈ 0″.47	6.4±0.3	9.9±0.4	13.5±0.6
F125W+F140W+F160W (B), FWHM≈ 0″.26	7.6±0.3	11.8±0.3	15.6±0.6
K_{Stot} (R) PSF matched, FWHM≈ 0″.9	7.7±0.2	11.8±0.2	16.0±0.6
F125W+F140W+F160W (B) PSF matched, FWHM≈ 0″.9	8.7±0.2	12.8±0.3	16.5±0.6
UBGV stacked (FUV) PSF matched, FWHM≈ 0″.9	9.7±0.2	13.5±0.1	16.0±0.5

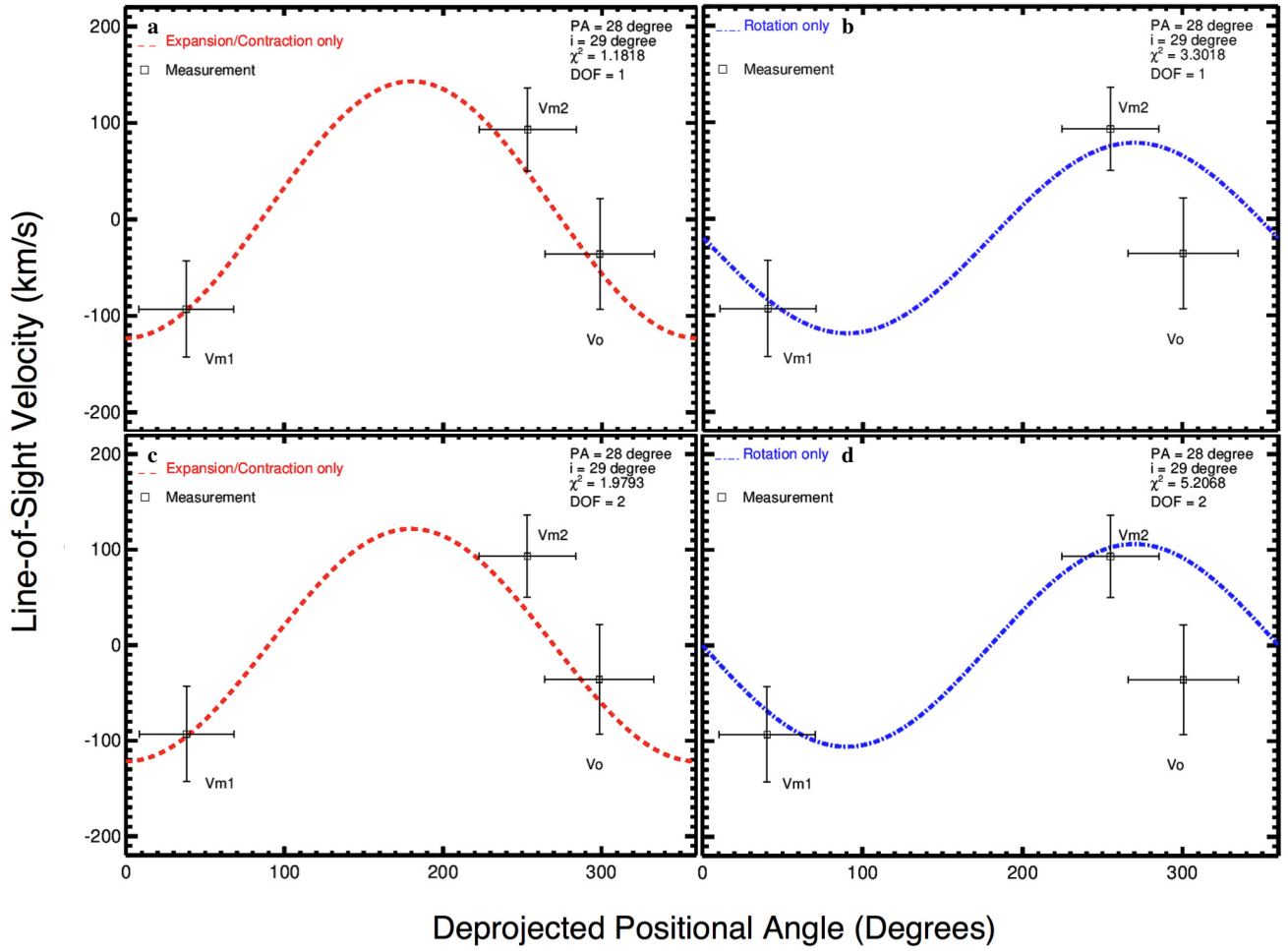
The PSF matched images¹⁴ are generated by ZFOURGE using a Moffat profile with FWHM of 0″.9 and $\beta = 0.9$. The rest-frame FUV image is generated by stacking the PSF matched ZFOURGE ground-based optical (UBGV) images.



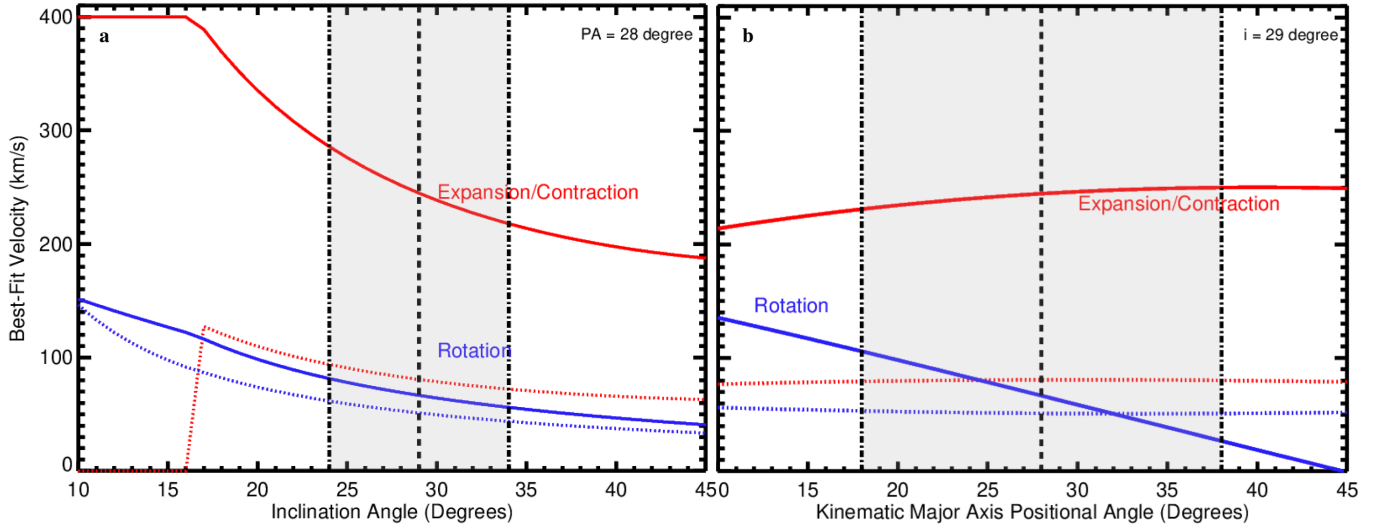
Supplementary Figure 5 – A diagram to illustrate the definitions of variables in Supplementary Information Equations 1-2. Two perpendicular velocity vectors (V_{rad} , V_{rot}) on the ring can be converted to the observed line-of-sight velocity ($V_{\text{LOS},\psi}$) as a function of the observed position angle ψ_o , for inclination angles $i \neq 90^\circ$. ψ_o is defined on the observed 2D image, counterclockwise from the North. (a), observing the disk of the ring edge-on ($i = 90^\circ$); the face-on view of the disk is drawn to show the geometry of the expansion velocity (V_{rad} , positive if pointing away from the disk centre C), rotation velocity (V_{rot} , positive if counter-clockwise from the observed North); $V_{p,\psi}$ is the net de-projected 1D velocity on the plane of the disk. $V_{p,\psi} = V_{\text{LOS},\psi}$ for an edge-on observation; ψ is the position angle ψ de-projected onto the plane of the ring; the red circle, blue star, and green diamond represent 3 data points on the ring. (b), The observed 2D image of (a). The ψ for the 3 data points can not be recovered from ψ_o in this case. (c), Similar to Panel (a) but with an inclination angle of e.g., $i = 29^\circ$. (d), The observed 2D image of Panel (c); the de-projected ψ can be calculated from the measured ψ_o . The correction from ψ_o to ψ is small for a relatively small i .



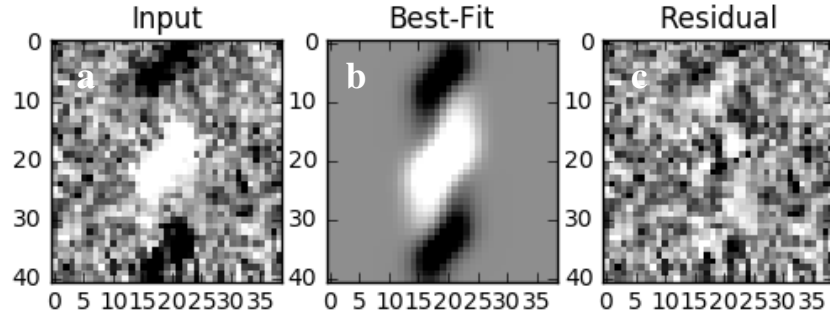
Supplementary Figure 6 – Aligning MOSFIRE and OSIRIS observations on top of the NB209 H α narrow band image. a, Collapsing the NB209 H α narrow band flux (black curve) in the direction of the MOSFIRE slit and cross-correlating with the MOSFIRE H α spatial flux distribution (light black curve). The best-fit Gaussian profiles for the NB209 and the MOSFIRE flux distributions are overlaid in blue dashed and red dashed lines, respectively. The vertical blue and red dot-dashed lines indicate the centroids (Y_{c_N} and Y_{c_M}) of the Gaussian profiles for NB209 and MOSFIRE, respectively. The offset of Y_{c_N} and Y_{c_M} determines the spatial centre of the MOSFIRE 2D spectrum. b, The MOSFIRE slit (vertical blue lines), OSIRIS FOV (white box) on top of the NB209 H α image after alignment. We measure the line-of-sight velocity (V_{m1} , V_{m2} , and V_o) for three PAs on the 5 kpc ring (green circle). The white dash-dotted lines on the NB209 image show the large error range we consider for our PA measurements. The blue shaded areas show spatial areas where V_{m1} , V_{m2} , and V_o are measured from. c, The MOSFIRE 2D H α image aligned to b. The light blue dashed lines on the MOSFIRE H α image show the error range of V_{m1} and V_{m2} . Given the large errors of the PAs, whether we use the best-fit ellipse (white ellipses) or a circular ring (green circle) do not change the measured velocities noticeably.



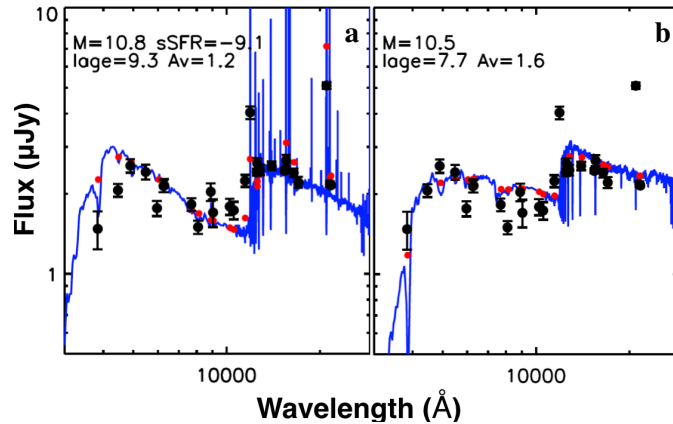
Supplementary Figure 7 – Fitting a rotation only or expansion/contraction only model to the data. The three data points and their uncertainties are the same as Fig.2 in the main text. **a**, Fixing V_{rot} at 0 and fitting the expansion/contraction parameters in Supplementary Eq. 1-2. The red short dashed line shows the best-fit expansion/contraction only model. **b**, Fixing V_{rad} at 0 and fitting the rotational parameters in Supplementary Eq. 1-2. The blue dot-dashed line shows the best-fit rotation only model. For **a** and **b**, we allow the systematic redshift to vary to keep DOF = 1. **c-d**, Similar to **a-b**, but here we fix the systematic redshift at zero.



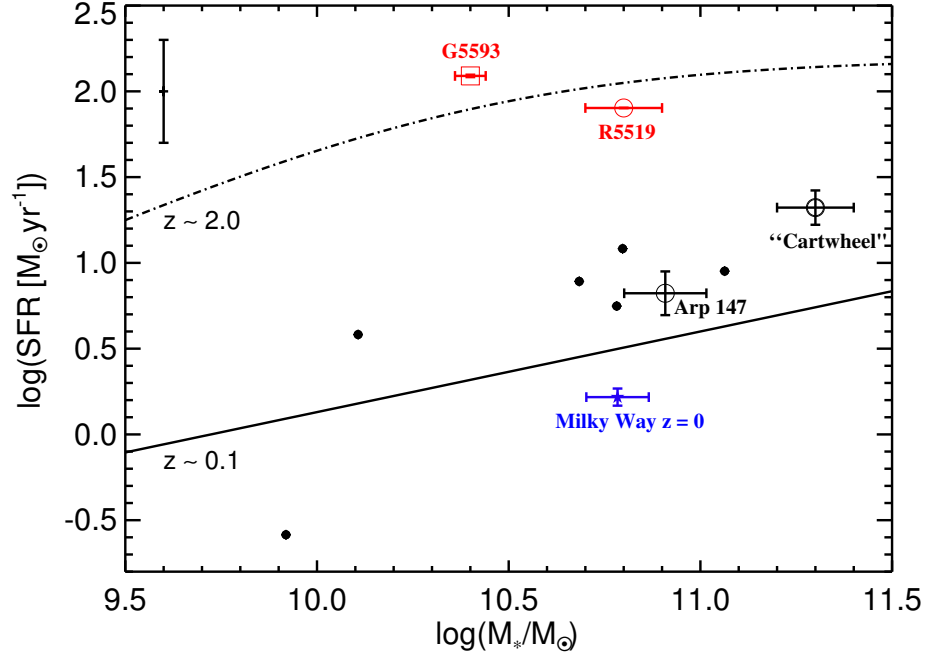
Supplementary Figure 8 – Dependence of the best-fit V_{rot} and V_{rad} on the position angle of the kinematic major axis PA_0 and inclination angle i . **a**, V_{rot} (blue) and V_{rad} (red) as a function of i for a fixed $PA_0=29^\circ$. **b**, V_{rot} (blue) and V_{rad} (red) as a function of PA_0 for a fixed $i = 29^\circ$. The dotted red/blue curves on both panels indicate the 1σ statistical errors of the fitting. The shaded region highlights the uncertainty range of i and PA_0 from the ellipse fit to images of R5519, with the vertical dashed lines mark the best-fit values and the vertical dot-dashed lines mark the 1σ statistical errors of the best-fit values.



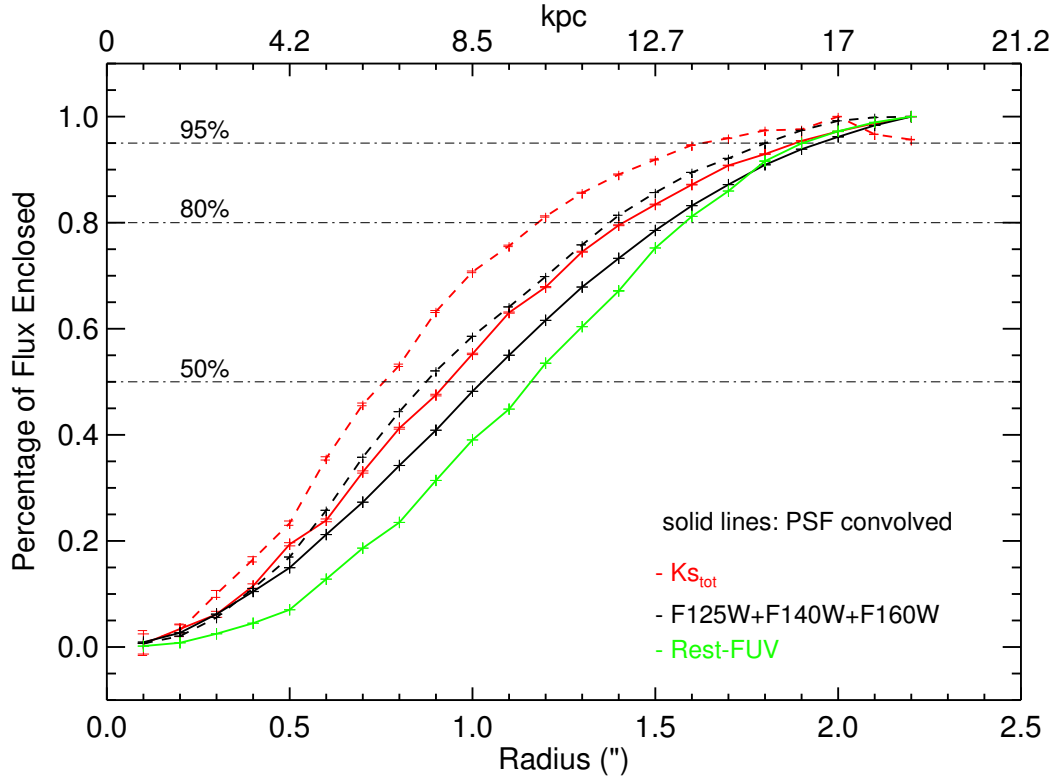
Supplementary Figure 9 – Fitting a simple rotating disk to the MOSFIRE H α 2D spectrum using HELA^{35,36}. In all panels, the y-coordinates are in pixel scales in the spatial direction of the MOSFIRE spectrum and the x-coordinates are in wavelength channels of the spectrum. **a**, Input H α 2D spectrum. **b**, Best-fit rotating disk model from HELA. **c**, Residual (input data minus the best-fit model).



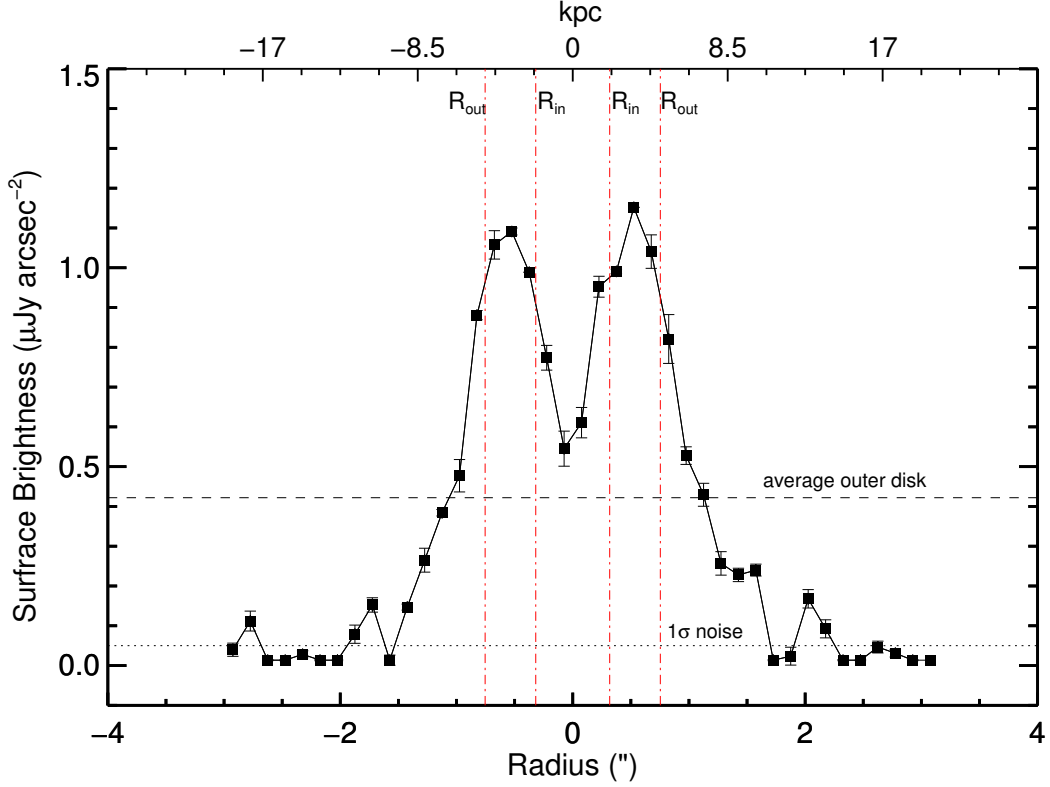
Supplementary Figure 10 – Spectral energy distribution (SED) fitting to the total photometry using two extreme star formation histories (SFHs). **a**, Assuming a constant SFH with emission lines. **b**, Assuming a 10 Myr truncated starburst with no SF afterwards. Black filled circles: observational measurements and associated 1σ statistical errors; red filled circles: modelled flux from the best-fit SED template. Blue curves: best-fit SED models. These two models provide a robust upper and lower limit on the stellar mass and age of R5519.



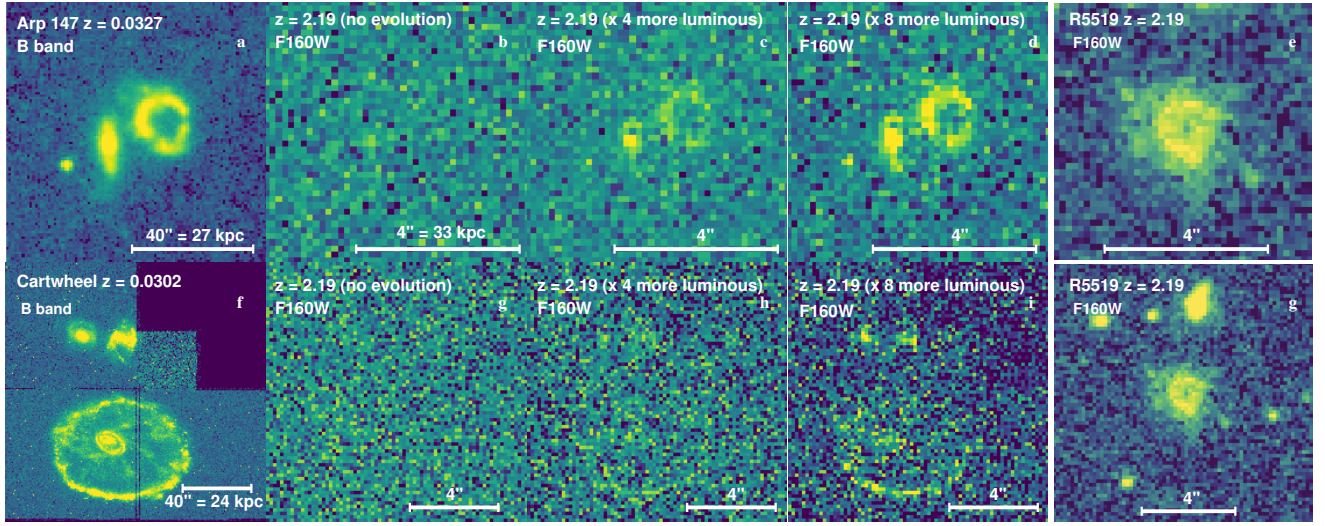
Supplementary Figure 11 – The location of R5519 on the M_* -SFR “main-sequence” relation. The best estimates of M_* and SFR of R5519 (red circle) and its neighbouring galaxy G5593 (red box) are taken from the SED fitting in Table 1. The x-axis errors of R5519 and G5593 are statistical errors presented in Table 1. The y-axis errors of R5519 and G5593 are not shown but are discussed in detail in Methods. The mean M_* -SFR relation^{101, 102} for $z \sim 2$ and $z \sim 0.1$ galaxies is shown as the dash-dotted and solid line, respectively. The vertical error bar on the top left corner shows the constant ~ 0.3 dex scatter of the M_* -SFR relation independent of redshifts¹⁰². We show the positions of the Milky Way, the nearby CRG Arp 147, and the Cartwheel galaxy for comparison. The data and their associated measurement errors of nearby galaxies and the Milky Way are literature values^{43, 103–105}.



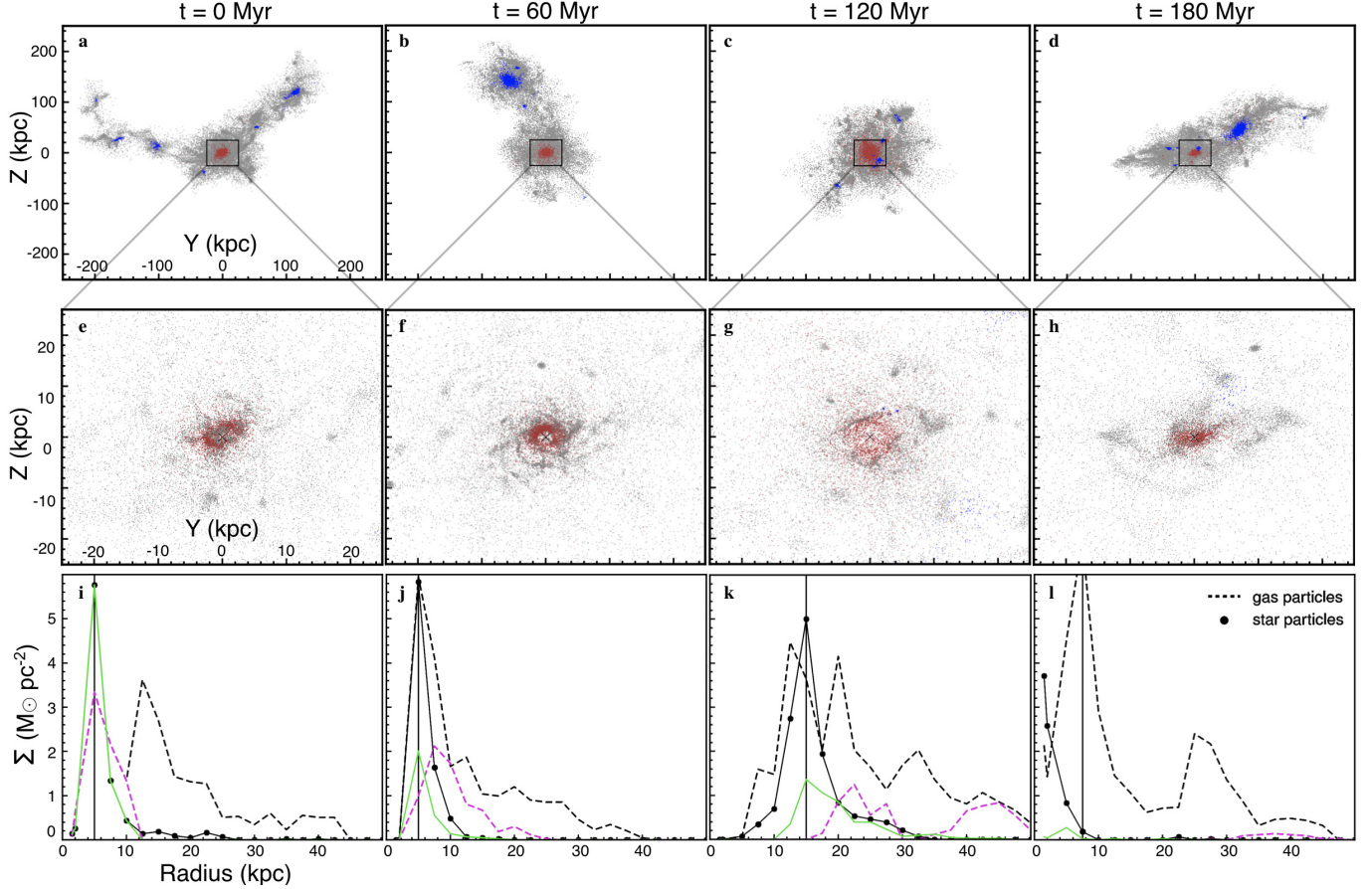
Supplementary Figure 12 – Enclosed total luminosity as a function of radius. The y-axis is the normalised total luminosity within a circular aperture and the x-axis is the projected radius of the aperture. The red, black, and green colours show the measurements on ZFOURGE Ks_{tot} , HST F125W+F140W+F160W, and ZFOURGE stacked rest-frame FUV images, respectively. The solid curves are data measured on the PSF-matched images (FWHM $\sim 0''.9$), whereas the dashed lines are data measured on the original images (see also Supplementary Table 4). Horizontal dot-dashed lines indicate the locations where R_{50} , R_{80} and R_{95} are calculated. This figure demonstrates the dependence of our measured R_{50} , R_{80} , and R_{95} on the image resolution and wavelength.



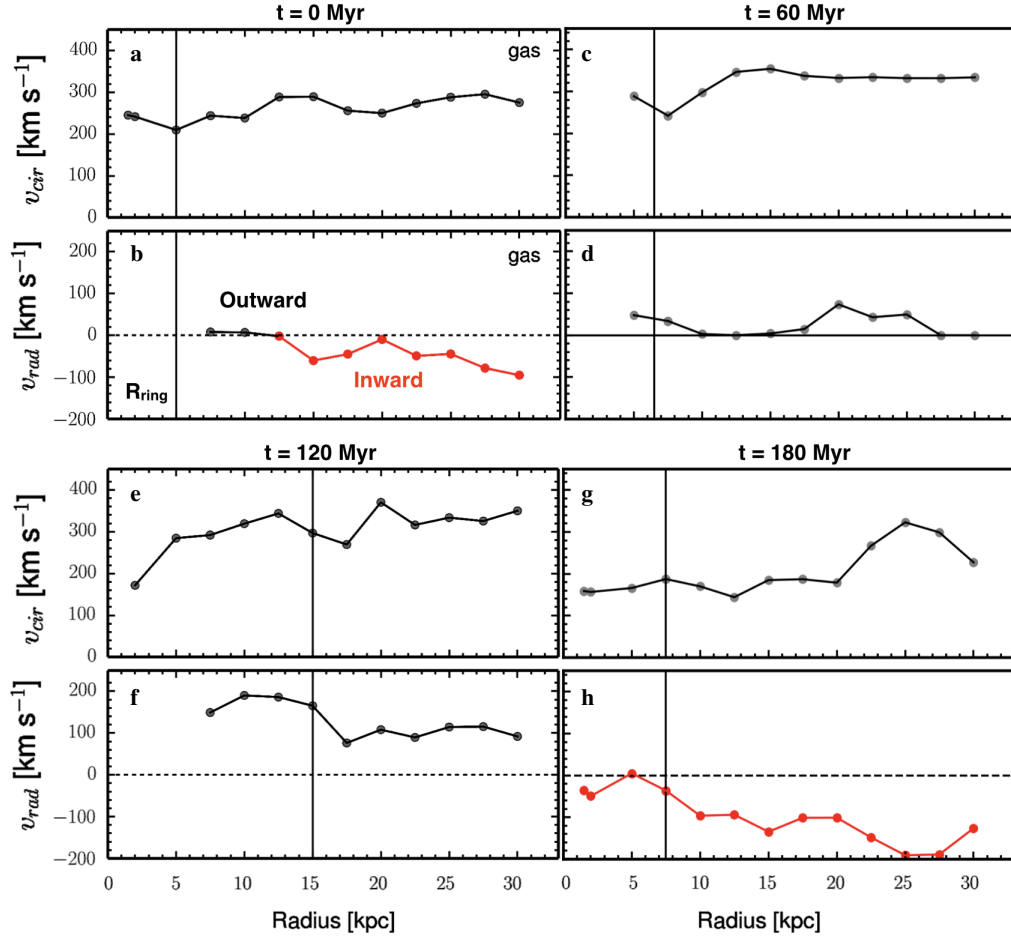
Supplementary Figure 13 – Surface brightness along the major axis of the ring. The 1D surface brightness (SB) is measured on the F160W image along the major axis of the ring ellipse (Supplementary Fig.1). The left-hand side ($R < 0$) corresponds to the North-East side of the slice in Supplementary Fig.1. Three slices (solid and dashed red lines in Supplementary Fig.1) across the ellipse and along the major axis are averaged with each datapoint represents one resolution element ($\sim 0''.26$) of the image. The error of each datapoint represents the 1σ standard deviation of the mean. The 1σ image background noise is shown as the horizontal dotted line. The total size of R5519 as measured where the SB drops to the 1σ noise level is 14–16 kpc, which is consistent with our measured R_{95} using the circular aperture on the combined F125W+F140W+F160W HST image (Supplementary Table 4). Vertical red dash-dotted lines show the best-fit inner and outer ring radius (R_{in} , R_{out}) from the the double ellipse fit in Supplementary Fig.1. Alternatively, R_{in} and R_{out} can be measured based on the 1D SB profile (Method). We find $R_{in}=2.1$ kpc and $R_{out}=2.1$ kpc, broadly consistent with the 2D double ellipse fit (Supplementary Table 1). The average SB of the outer diffuse disk ($R_{out}=6.7$ kpc $< R < R_{95}=16$ kpc) is $\sim 0.42 \mu\text{Jy arcsec}^{-2}$. Changing the baseline of the FWHM to the average SB of the diffuse disk yields a ~ 0.5 kpc increase/decrease in R_{in}/R_{out} .



Supplementary Figure 14 – Simulating the F160W morphology of Arp 147 and Cartwheel at $z = 2.19$. **a**, The ground-based B-band image of a local CRG - Arp 147. **b-d**, Simulated image of Arp 147 in the HST F160W band for the limiting magnitude of our current observations. **b** assumes there is no evolution in the intrinsic properties of Arp 147. **c** and **d** assume that the intrinsic rest-frame B-band luminosity is increased by a factor of 4 and 8, respectively. **e**, Observed HST F160W image of R5519, zoomed to show the same field of view as Arp 147. **f**, The HST B-band image of a local CRG - the Cartwheel galaxy. **g-i**, Simulated image of Cartwheel in the HST F160W band for the limiting magnitude of our current observations. **g** assumes there is no evolution in the intrinsic properties of Cartwheel. **h** and **i** assume that the intrinsic rest-frame B-band luminosity is increased by a factor of 4 and 8, respectively. **g**, Observed HST F160W image of R5519, zoomed to show the same field of view as the Cartwheel galaxy.



Supplementary Figure 15 – The time evolution of a CRG at $z = 2.23$ from the EAGLE cosmological hydrodynamical simulations⁴⁷. The four columns from left to right denote four time “snapshots”⁴⁶ with respect to an arbitrarily defined ring formation time ($t = 0$ Myr). “Snapshots” are defined in the EAGLE simulations as having finer time resolution than snapshots. **a-d**, A 500×500 kpc view, through the simulation Z – Y axes, of the large scale environment in 2D centred on the ring host; red-brown = host galaxy stars, blue = satellite halo stars, and grey=gas particles. **e-h**, A 50×50 kpc zoom-in view of the ring host in 2D, red-brown = young stars with ages < 100 Myr, and grey=gas. **i-l**, The surface mass density for star and gas particles (excluding those from the nucleus) at each radius. The location of the ring feature is defined as the peak of the star particle surface mass density. The green and purple lines show the location of the ring’s star and gas particles identified at $t = 0$ Myr, respectively, and the positions of these particles with radius in the subsequent “snapshots”. In a later time “snapshot” at $t = 240$ Myr (not shown here), the nucleus of the CRG is found to be broken into two parts after the major merger at $t = 180$ Myr .



Supplementary Figure 16 – The circular and radial velocity of the gas particles in the $z = 2.23$ EAGLE CRG. a-h, We show four time “snapshots” with respect to an arbitrarily defined ring formation time ($t = 0$ Myr). For each time “snapshot”, the circular and radial velocity are shown in the upper and lower panels, respectively. This CRG is expanding from $t = 0$ Myr to 120 Myr, but the ring feature is disrupted due to a second passage of a satellite galaxy at time 180 Myr. During these four time snapshots the radius of this CRG ring (defined as the peak of the 1D surface mass density of the stars; see Supplementary Fig. 14) also changes from 5, 6.5, 15, to 7.5 kpc, respectively. The red colour highlights the particle radial velocity that is moving towards the centre of the CRG host.