A giant galaxy in the young Universe with a massive ring

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In the local (z ≈ 0) Universe, collisional ring galaxies make up only ~0.01% of galaxies and are formed by head-on galactic collisions that trigger rapidly propagating density waves. These striking systems provide key snapshots for dissecting galactic disks and are studied extensively in the local Universe. However, not much is known about distant (z > 0.1) collisional rings. 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 unstable, the implied large bar in a giant disk would be inconsistent with the current understanding of the earliest formation of barred spirals. Contrary to previous predictions, 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 ≥ 2 spiral galaxies in the Cosmic Evolution Survey (COSMOS) field of the FourStar Galaxy Evolution survey (ZFOURGE). We used ZFOURGE catalogue images to identify spiral structures in galaxies within the photometric redshift range of 1.8 ≤ z_p ≤ 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 ≈ 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 ± 0.001 based on our Keck/MOSFIRE near-infrared (NIR) spectroscopy and Keck/ZFOURGE adaptive-optics aided NIR integral field spectroscopy (Supplementary Figs. 3–4). A joint analysis of the MOSFIRE and ZFOURGE spectroscopic data, in combination with the ground-based Hα narrow-band image from the ZFOURGE catalogue, shows that the Hα kinematics are consistent with a tilted rotating and expanding/contracting circular ring model (Fig. 2, Methods). Taking the inclination angle (i = 29° ± 5) and the position angle (PA = 28° ± 10) 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 (V_{ring} = 5.1 ± 0.4 kpc) is V_{rot} = 90 ± 75 km/s and the radial expansion/contraction velocity is V_{rad} = 226 ± 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. A companion galaxy (ID 5593, hereafter G5593) is confirmed at a projected distance of ~30 kpc from R5519 with a 3D-HST survey grism redshift of z_{grim} = 2.184 ± 0.005 (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 redshift of z_p = 2.1 ± 0.1. If G5593 is the intruder of R5519, then the inferred timescale after collision is τ_c > 39 ± 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_☉ yr^{-1} and a stellar mass of log(M_*/M_☉) = 10.78 ± 0.03. In comparison, G5593 has a total SFR of 123 ± 2 M_☉ yr^{-1} and log(M_*/M_☉) = 10.40 ± 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 catalogue and our MOSFIRE spectrum. The derived interstellar medium (ISM) properties indicate that R5519 is metal-rich (12 + log(O/H) = 8.6–8.8) (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]λ3727 and [OI]λλ6300, 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 Hz narrow-band image suggests that the bulk (~45-70%) 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 Ks$_{\text{tot}}$ 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 $10^{10.3}$ - $10^{10.8}$ 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 sample have ring radius $\gtrsim$ 5 kpc. R5519’s SFR is at least 4× larger than local CRGs$^{23}$ 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 fraction$^{23}$. The average star formation rate surface density ($\Sigma_{\text{SFR}}$) of R5519 is $\sim$ 0.3 M$_\odot$ yr$^{-1}$ kpc$^{-2}$, typical of a star-forming galaxy at $z \approx$ 2, and $\sim$ 4-8 times larger than local CRGs such as Arp 147 and the Cartwheel$^{24}$. Interestingly, nearby CRGs show moderately elevated SFR relative to $z \sim$ 0 isolated disk$^{23}$, 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$_{\star}$-SFR “main-sequence” relation of star-forming galaxies at $z \approx$ 2. CRGs are rare laboratories to study star formation in interacting galaxies$^{23}$. 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$_{60}$, the radius within which 80% of the total luminosity is included (Methods, Table 1, Supplementary Figs.12-13). Comparing with other $z \sim$ 2 galaxies in the 3D-HST catalogue$^{23}$, R5519’s R$_{60}$ is 2.4$\sigma$ larger than the mean size (5.4 kpc) of all late-type galaxies (log(M$_{\star}$/M$_\odot$) > 9.5) and 1.5$\sigma$ larger than the mean value (7.1 kpc) of the most massive (log(M$_{\star}$/M$_\odot$) $\geq$ 10.6) late-type galaxies at $z \approx$ 2 (Fig.3). A morphological inspection on the other unusually large ($1\sigma$ 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 of the most massive galaxies at $z \approx$ 2 is 6.4 kpc and is 2.6$\sigma$ larger than R$_{5519}$. Compared with our Milky Way’s stellar disk, the half-light radius of R5519 is 1.5-2.2 times larger and its R$_{60}$ is 1.2-1.8 times larger (Methods).

If R5519 is a secularly evolved resonant ring$^{13}$ (see Supplementary Information), then the giant disk and the implied large bar (half length $\sim$ 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 $z \geq$ 2 [ref.[14,15,16,17,18,19]. For the rare, smaller ($< 1$ kpc in radius) barred spiral galaxies formed in simulations at $z > 2$ [ref.[17,18,19]], 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$^{20}$, the large R$_{\text{disk}}$ and small R$_{\text{ring}}$ imply different collisional timescales ($\xi_c$ $\approx$ 80 Myr and $\xi_c$ $\lesssim$ 50 Myr, see Supplementary Information). The inconsistency in $\xi_c$ can be reconciled if the current ring in R5519 is a second ring after the collision. A local analogy would be the Cartwheel galaxy$^{24}$, when Cartwheel’s outer ring fades and the inner second ring dominates. A second ring would explain the small ratio of R$_{\text{ring}}$ and R$_{\text{disk}}$. The large diffuse emission can be accounted for as the first expanding ring sweeps up the pre-collisional disk. The thickness (3.7$\pm$0.3 kpc; Methods) of the ring, the size ratio of the first to the second ring ($\sim$2.2, taking R$_{60}$ 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 rings$^{24}$.

The diffuse light induced by the expanding ring is difficult to observe in local CRGs because of the low surface density of the redistributed star$^{23}$. R5519’s extended disk has a rest-frame B-band (HST F160W) surface brightness of $\sim$20 AB mag arcsec$^{-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) simulation$^{22}$ show that interaction with multiple satellites at $z \geq 2$ can cause $>$50% of the stellar particles of the CRG host to be tidally perturbed outside of the ring $\sim$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$_{\star}$/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$^{20,22}$. Using a scaling relation of (1 + $z$)$^{4.5}$ from a previous study$^{20}$, CRGs are expected to be $\sim$140 times more common at $z \approx$ 2. Considering only the massive CRG hosts, the expected number density at $z \approx$ 2 is still $\approx 10^4 \times$ 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 change$^{23}$ 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$^{21,22}$.

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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 Ks) colour image. The Ks 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 Ks 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 images. A logarithmic stretch is used for all images in this work.

Table 1 – Physical properties of R5519 and its neighbours. The z values for R5519, G5593, and G5475 are MOSFIRE z, HST zphot, and ZFOURGE z, respectively. For all sources, the stellar masses are calculated based on the spectral energy distribution from the ZFOURGE photometry and the SFR(MUV) are derived on the basis of the combined rest-frame IR and UV luminosities. The range of SFR(MUV) values reflects different assumptions about attenuation laws. ΣSFR is estimated by dividing the total SFR by the 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). R50 and R80 are the radii where 50% and 80% of the total luminosity are enclosed in the combined HST F125W+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$\alpha$ 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$\alpha$ spectra (black), best-fit (red) and 1$\sigma$ noise (green) for Vm1, Vm2 and Vo. $F\lambda$ is the observed flux of the spectra. The red vertical dotted and dashed lines show the the determined velocity centre and its uncertainty range, respectively. The uncertainty range is a conservative measure using the 1$\sigma$ width of a Gaussian line profile (Methods). The flux unit for b, d is $10^{-17}$ergs/s/cm$^2$/Å, and for c, the flux unit is $10^{-20}$ ergs/s/cm$^2$/Å. 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 $1\sigma$ 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 $1\sigma$ scatter of the size distributions. Including R5519, there are eight objects (labelled G1-G8) that have unusually large sizes (defined as $1\sigma$ 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 ΩΛ=0.307, ΩM=0.693, and H0=67.7 km s⁻¹ Mpc⁻¹, consistent with the Planck measurement and the cosmological parameters used in EAGLE simulations. 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 units 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 CANDLES version of the F125W, F140W and F160W images 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 χ² minimisation procedure. In both approaches, we divide the ring azimuthally into N=80 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 (xC, yC), 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 weight 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 R20, R80, and R95 where 50%, 80% and 95% of the total luminosity is enclosed. The choice of the three radii is to facilitate comparison with other studies of galaxies: R20 is comparable to the effective radius R e of a Sersic profile; R80 is a recently popularised parameter to study the size evolution of galaxies with redshift; R95 describes the outer edge of the galaxy. For a Sersic profile of n = 0.5 and n = 1.0, R95 corresponds to a radius of ~2.1R e and ~2.9R e, respectively [25–26].

The diffuse stellar light of R5519 is present in multiple wavebands (Supplementary Fig.2). To test the dependence of the measured size on waveband, image depth, and the point spread function (PSF), we carry out the measurement on the deep ZFOURGE Ks07 image and the high-spatial-resolution HST F125W+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 β = 0.9 [27]. Our stacked rest-frame FUV image is produced from the PSF-matched ground-based UBVG images (see Supplementary Information).

We summarise the derived R20, R80, and R95 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 R20, R80, and R95 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 (0.02′) in width, i.e., about one image resolution element (0.026). 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 Rtot = 15 ± 1 kpc in radius, with the error bar indicating the uncertainty in identifying the boundary that is consistent with the noise. The R95 agrees with our measured R95 = 15.6±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 (Ri and Rtot) 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 Ri=2.1 kpc and Rtot=6.7 kpc, broadly consistent with the 2D double ellipse fit (Supplementary Table 1).

The method we use to derive Rtot and R95 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 Rtot is very similar to the commonly used R25 for local CRGs [28]. R25 refers to the radius where the SB drops to a standard level of surface brightness of 25.00 mag arcsec⁻² in the B band for angular dimension 25′. 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 R20 and R95 is 0.42 μJy arcsec⁻² in F160W. Assuming a cosmological SB dimming form of (1+z)⁻2, the average SB of R5519’s diffuse disk observed at z = 2 would be 19.8 μJy arcsec⁻² in the B band. This is almost four magnitudes brighter than the SB of the brightest outer disk of nearby CRG [29]. 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 R20 and R95 is 1.04 μJy arcsec⁻². The peak SB inside the ring is 1.15 μJy arcsec⁻². Therefore the relative SB between the ring and the outer disk is 0.6-0.7 μJy arcsec⁻².

1.4 Comparing with 3D-HST: z ≈ 2 late-type galaxies

To put the size of R5519 in context with other z ≈ 2 galaxies, we compare its R20 with 3D-HST galaxies measured on the same F160W image in Fig.3. The sizes of 3D-HST galaxies have been modelled by Sersic profiles through several well-established studies [30–32]. We use the mass-size catalogue data from the 3D-HST survey and apply the same conversion between Sersic index n, effective radius R e and R50 as previous studies [30,32,35]. In order to minimise systematic errors of Rs0, we only include galaxies with flux SNR > 20 on the F160W image and have good Sersic model fits (SNR > 5 for both Rs0 and n). We select data with 3D-HST photometric redshifts (zp) of 1.8 < z < 2.4 and (log(M/M☉)) > 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 (~2%) ZFOURGE photometric redshifts and exclude targets with zp < 1.5 or zp > 2.5. We also exclude targets that have inconsistent stellar masses (Δlog(M/M☉) ≥ 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 R20, R95, and n is based on large samples. The conversion is not guaranteed for individual galaxies. For example, the R20 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 studies [33]. The inferred Rs0 of R5519 from the 3D-HST catalogue is 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 R50 for R5519 is also consistent with the Sersic model-based Rs0 from the 3D-HST catalogue in the measurement errors. Both the R20 and Rs0 of R5519 are 1.5σ above the scatter of the late-type galaxies. The empirical conversion of R20 indicates that R5519 is an unusually large galaxy at z ≈ 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 ($R_0$) of the Milky Way’s stellar disk is in the range of 2.3 Kpc based on a large body of literature. Using $R_0=6.8$ Kpc and $R_0=3.2$ Kpc for our Milky Way has $R_0=3.4-5.0$ Kpc and $R_0=6.4-9.6$ Kpc in its stellar light. According to our best size estimation from HST WFC3 images (Table 1), the $R_0$ of R5519 is 1.5-2.2 times larger and $R_0=1.2-1.8$ times larger than the Milky Way.

2 A Joint Analysis of MOSFIRE and OSIRIS Hα Kinematics

The line-of-sight velocity ($V_{\text{LOS}}$) as a function of de-projected position angle ($\psi$) 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, we use equations below to describe the relation between $V_{\text{LOS}}$ and $\psi$ 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:

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

$$\tan(\psi) = \tan(\psi_0) \cos(i); \ i \neq 90^\circ$$

$V_{\text{LOS}}$ is the line-of-sight velocity measured at $\psi$ on the ring and $V_{\text{sys}}$ is the systematic velocity. $V_{\text{LOS}}$ 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 Hα centroid of the total aperture MOSFIRE spectrum ($z_{\text{total}}$). Hence we have $V_{\text{LOS}} \approx 0$ if $z_{\text{total}}$ is close to the systematic redshift at the kinematic centre. A positive sign of $V_{\text{LOS}}$ means redshift whereas a negative sign means blueshift. $V_{\text{rad}}$ is the expansion/contraction velocity at the fixed radius of the ring. $V_{\text{rot}}$ is the rotation velocity. The angle $\psi$ is measured counterclockwise from the kinematic major axis. The relation between the observed position angle ($\psi_0$) and the deprojected $\psi$ 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 $\psi_0$ and $\psi$ 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 $V_{\text{rad}}$ and $V_{\text{rot}}$ 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 $V_{\text{rad}}$ means expanding/contracting radially, and a positive/negative sign of $V_{\text{rot}}$ means rotating counterclockwise/clockwise from the kinematic major axis. The signs of $V_{\text{rad}}$ and $V_{\text{rot}}$ 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 ($V_{\text{rad}}$) and rotational velocity ($V_{\text{rot}}$). 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 $V_{\text{LOS}}$ and $\psi$ at a fixed radius (R) is therefore a function of four parameters: the systematic velocity ($V_{\text{sys}}$), the circular rotational velocity ($V_{\text{rot}}$), the expansion/contraction velocity ($V_{\text{rad}}$) and the inclination angle $i$ (Supplementary Fig.5). One additional hidden parameter is the position angle ($PA_0$) of the kinematic major axis because $\psi$ 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 $V_{\text{LOS}}$ versus $\psi$ diagram by combining our MOSFIRE and OSIRIS Hα kinematics. The first two measurements are derived from the MOSFIRE slit spectrum and the third measurement comes from the OSIRIS observation. Our MOSFIRE Hα 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 Hα 2D spectra in its spatial y direction with the NB209 Hα narrow-band image. We do this by cross-correlating the spatial Hα line profiles of the MOSFIRE observation with a mock Hα spatial line profile derived from the Hα 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 (∼0.2) of the alignment is estimated by the 1σ scatter of 100 times fit 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 Hα 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 $\psi$ are taken as the edge of the MOSFIRE slit and the edge of the OSIRIS Hα detection box (Supplementary Fig.6). The line-of-sight velocities from the MOSFIRE spectra are based on the Hα 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 5 kpc position (∼1 pixel) on MOSFIRE is prone to the uncertainty of the PSF characterisation. We test the uncertainties of Vm1 and Vm2 by shifting the extracting centre of the 1D spectra within the range of the spatial alignment error (∼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 Vm1 and Vm2. As long as the kinematic field is relatively face-on (<45°), the effect of beam-smearing in deriving the Hα 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 (Vm1, Vm2) and OSIRIS Hα (Vo) 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 using a χ² minimisation procedure, weighted by the inverse square of the total error $\sigma_\psi = \sqrt{(\sigma^2_{V_{\text{LOS}}} + \sigma^2_{\psi})}$. We keep $V_{\text{sys}}$ at 0, though allowing it as a free parameter to account for any offsets between $z_{\text{total}}$ and the redshift from the actual kinematic centre of the disk does not change our main conclusion. For our fixed $PA_0 = 28°$ and $i = 29°$, the best-fit expansion/contraction velocity is $V_{\text{rad}} = 226 ± 90$ km/s and $V_{\text{rot}} = 90 ± 75$ km/s (Fig.3). The systematic errors of our kinematic measurement are discussed in the Supplementary Information. Nearby CRGs show a range of $V_{\text{rad}}$ (50-220 km/s) and $V_{\text{rot}}$ (50-350 km/s). For most nearby CRGs, $V_{\text{rad}}$ is larger than $V_{\text{rot}}$ (though in some cases (e.g., Arp 147), $V_{\text{rot}}$ can be a few times smaller than $V_{\text{rad}}$)

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 FAST in combination with the photometric redshift from EAZY. FAST determines the best-fit parameters of SED models through a χ² minimisation procedure. We use 36 passbands of ZFOURGE’s total photometry based on the stellar population synthesis (SPS) model grid, a Chabrier IMF, a fixed solar metallicity (1.0 $Z_{\odot}$), an exponentially declining star formation history (SFH), and a Calzetti extinction law. The ZFOURGE FAST output catalogue records a total stellar mass of log($M_*/M_{\odot}$) = 10.78 ± 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 SFHs: 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⊙) < 10.8 and t_age < 2 Gyr. The truncated star formation model provides a lower limit of log(M*/M⊙) > 10.5 and t_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_{phot}) was created by combining FourStar/Ks-band observations with pre-existing K-band images. The K_{phot} 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_{phot} image. We then derive the colour differences of the nucleus and the ring based on the PSF matched K_{phot} 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_{phot}, 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_{phot} 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 CRG8. 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 sources are based on the combined rest-frame infrared luminosity (I_{IR} (8-1000 μm)) and rest-frame UV luminosity (I_{UV} (1216-3000 Å)). The UV+IR approach assumes that the IR emission of galaxies comes from dust heated by the UV light of massive stars. I_{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 technique. I_{UV} is measured on the EAZY photometric models. The SFR_{UV+IR} for R5519 is calculated to be 80±0.2 M⊙ yr^{-1}. Note that because of the proximity of the neighbouring galaxy G5593 and the large PSF (FWHM=4′) of the MIPS and PACS images, the main uncertainties in the SFR_{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. With 24 μm SFR_{UV+IR} = 123 ± 2 M⊙ yr^{-1}, G5475 is a quiescent galaxy, consistent with its early-type morphology.

For comparison, we determine the dust-uncorrected SFR from the total Hα flux of the MOSFIRE slit spectrum and have SFR_{Hα (slit with dust)} = 3.7 ± 0.1 M⊙ yr^{-1}. For dust attenuation correction on Hα (A(Hα)), we infer from the stellar dust attenuation obtained via SED fitting (A_V, star ≈ 1.1). We test two methods on dust correction. We first use the empirical relation of A(Hα) and A_V, star for z ≈ 2 star-forming galaxies as a function of SFR(SED) and M_*, (SED), we have A(Hα) = 0.21 × A_V, star. The dust corrected SFR_{Hα (dust)} is therefore 12.4 ± 0.3 M⊙ yr^{-1} for the first method. For the second method, we use the classic nebular attenuation curve with R_V = 3.1 and have A(Hα) = 2.53 × E(B-V)_{Hα}; Assuming E(B-V)_{Hα} = 0.44 × E(B-V)_{Hα}, we have A(Hα) = 1.42 × A_V, star or A(Hα) = 1.42 × A_V, star. The dust corrected SFR_{Hα (dust)} is therefore 15.6 ± 0.4 M⊙ yr^{-1} for the second method. Finally, we estimate the slit loss factor by aligning the MOSFIRE slit on the PSF matched Hα narrow-band image and calculating the fraction of flux that is outside of the slit on the Hα narrow-band image. We derive a slit-loss factor of 3.1±1.1. The final slit-loss and dust attenuation corrected SFR_{Hα} is 38.4 ± 13.6 M⊙ yr^{-1} for the first method and 48.4 ± 17.2 M⊙ yr^{-1} for the second method, with errors representing statistical errors contributed mainly by the slit-loss correction uncertainty. Though the Hα SFR is ∼25 smaller than the SFR_{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 Hα 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 Hα narrow band image traces all recent star formation activity. The lower limit is estimated by including only Hα pixels within the ring that are more than 5σ brighter than the average Hα surface brightness. We caution that this estimation does not include uncertainties from the beam-smearing of the Hα 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 SFR_{UV+IR} divided by the circular area within R_{50} and have σ_{SFR} ∼ 0.2 M⊙ yr^{-1} kpc^{-1}. We then use SFR_{Hα} = 38 M⊙ yr^{-1} divided by the area of the ring defined by the best-fit ellipse and have σ_{SFR} ∼ 0.4 M⊙ yr^{-1} 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 ∼ 0 to z ∼ 2 [ref.3]. At a fixed stellar mass, star-forming galaxies at z ∼ 2 have ∼20 times higher SFR compared with z ∼ 0 star-forming galaxies. Based on SFR_{UV+IR}, R5519 is a star-forming galaxy that lies within the 1σ scatter (∼0.3 dex) of the M_*-SFR relation at z ∼ 2 [ref.2].

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 CRG [15] 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.19] and the Cartwheel galaxy [16] as well as our Milky Way [13]. 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 galaxies [19] (Supplementary Fig.11).

Data Availability The imaging data presented here are publicly available from the ZFOURGE survey website (https://zfourge.tamu.edu/). 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 ZFOURGE code accompanies this paper. The author’s link to the code is available from the second author (A.E., email: ahmedagali70@gmail.com) on reasonable request.

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

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