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Spiral morphology in an intensely star-forming disk galaxy more than 12 billion years ago

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Spiral galaxies have distinct internal structures including a stellar bulge, disk and spiral arms. It is unknown when in cosmic history these structures formed. We analyze observations of BRI 1335–0417, an intensely star-forming galaxy in the distant Universe, at redshift 4.41. The [C II] gas kinematics show a steep velocity rise near the galaxy center and have a two-armed spiral morphology, which extends from about 2 to 5 kiloparsecs in radius. We interpret these features as due to a central compact structure, such as a bulge; a rotating gas disk; and either spiral arms or tidal tails. These features had formed within 1.4 billion years after the Big Bang, long before the peak of cosmic star formation.

Spiral galaxies contain distinct internal structures: a stellar bulge; a flat, extended rotating disk; and spiral arms that extend through the disk. Observations have established that the total star formation rate in the Universe rose steeply after the Big Bang, reached a peak at redshift z between 1.5 and 3, and declined steadily since then (1). Optical observations provide evidence that stellar bulges have already formed in some massive galaxies by $z \sim 0.5$ to 2.5 (2). Spiral structure has been reported in galaxies at redshifts of $z = 2.18$ (3), $z = 2.01$ (4) and $z = 2.54$ (5). Observations with the Atacama Large Millimeter/submillimeter Array (ALMA) have shown spiral structure in two galaxies at $z = 2.32$ and $z = 2.67$ (6), dynamically cold disks in galaxies at redshift $z \sim 4$ (7–10) and compact central structures, like a bulge, at $z \sim 4$ to 5 (7, 10). It is currently unclear whether the later appearance of spiral structure is due to different formation times or observational limitations.

BRI 1335–0417 (QSO J1338–0432) is a galaxy at redshift $z = 4.4074 \pm 0.0015$ (11), corresponding to 1.4 Gyr after the Big Bang. It is classified as a Hyper Luminous InfraRed Galaxy (HyLIRG) with a luminosity of $3.1 \times 10^{13} L_{\odot}$ (where $L_{\odot}$ is the luminosity of the Sun) at far-infrared wavelengths (12) and a high star formation rate of $5 \pm 1 \times 10^3 M_{\odot} \text{ yr}^{-1}$ (where $M_{\odot}$ is the mass of the Sun), estimated from modeling the spectral energy distribution (13).

We analyzed archival ALMA observations of BRI 1335–0417 in the gas emission line [C II] (rest frame frequency of 1900.5369 GHz, redshifted to around 351 GHz in the observed frame). The data were reduced using standard procedures (14). [C II] line emission from this galaxy was detected in previous observations at lower spatial resolution, which was insufficient to determine the gas distribution and

kinematics (15). Figure 1, A and B, shows the ALMA [C II] intensity and velocity images, with a spatial resolution of $0.20'' \times 0.16''$ full width half maximum (FWHM), which is equivalent to $\sim 1.33 \times 1.11$ kiloparsecs (kpc) at this redshift. Figure 1C shows the dust continuum image at a central frequency of 1863 GHz (rest frame) with spatial resolution of $0.17'' \times 0.14''$ ($\sim 1.16 \times 0.95$ kpc). The root mean square noise in each velocity channel (width of 20 km s^{-1}) is about 0.35 millijansky per beam (mJy beam^{−1}), while that of the dust continuum map is about 0.036 mJy beam^{−1}. Figure 1D shows a composite image of the gas velocities, produced from [C II] velocity channel maps (Fig. 2) that show the [C II] line intensity images at each velocity. In each figure, right ascension (RA) and declination (Dec) offsets are given relative to the position RA = $13^{\text{h}}38^{\text{m}}03^{\text{s}}.416$, Dec = $-04^{\circ}32'35''.02$ (J2000 equinox).

The [C II] line and dust continuum images show a central compact structure surrounded by more extended emission, which could indicate a disk. A spiral morphology is apparent in Fig. 1D, with northern and southern arms extending from 2 to 5 kpc in radius. This spiral morphology is more apparent in the [C II] velocity channel maps (Fig. 2). We compare these maps to previously published CO images (in the $J = 2 \rightarrow 1$ line, where J is the rotational quantum number) which showed different spatial distribution depending on the antenna configuration used for the observations. One CO image showed a structure with a bright central component and a weaker northern component (16), while another showed a complex structure with multiple components (17). Those multiple CO components correspond (in position and velocity) to the northern spiral feature, southern spiral feature and the central disk visible in our [C II] images. [C II] line emission arises from multiple phases of the interstellar medium, including

ionized gas, atomic gas and molecular gas, while CO ($J = 2 \rightarrow 1$) line emission traces only dense molecular gas (18). The difference between [C II] and CO distributions also results from the differences in sensitivity and spatial frequency coverage between the observations. We found no evidence in the [C II] line emission of a bipolar outflow that has been reported based on CO ($J = 7 \rightarrow 6$) observations (14).

The [C II] line velocity rises steeply in the center of the galaxy, reaching about 240-260 km s⁻¹, indicating the presence of a centrally concentrated mass distribution. The velocity is approximately constant at 70-110 km s⁻¹ in the outer parts of the galaxy, along the kinematic major axis, which we show in a position-velocity diagram (PVD; Fig. 1E). A steeply rising and/or constant velocity curve has been measured in other high redshift galaxies (7, 8, 10). Such a velocity curve has been widely observed in nearby spiral galaxies, where it is produced by the gravitational potential of the internal structures (19). The [C II] PVD of BRI 1335-0417 indicates the presence of a central compact structure, such as a stellar bulge, and an extended disk. The rise in velocity appears to be steeper on the northern side than the southern side. A decrease in velocity occurs within a radius of 0.3'' on the southern side, while a slight increase with radius is seen in the northern side. These features could be due to streaming motions along spiral arms, warping of the disk, recent gas accretion (10) and/or a lopsided central gas distribution. These disturbed features are common in nearby galaxies, and have also been found in high-redshift galaxies at $z \sim 4$ (8, 10). Figure 1F shows the velocity dispersions extracted at each position along the kinematic major axis. The velocity dispersions in the outer parts are consistent with a constant ~ 70 km s⁻¹, but increase up to ~ 140 km s⁻¹ in the center. Such central increases are known to be affected by the beam smearing effect (20) – because the spatial resolution is not sufficient to resolve the intrinsic velocity gradient, it is averaged over the beam width, so the observed velocity dispersion increases. We estimate an intrinsic velocity dispersion σ of 71^{+14}_{-11} km s⁻¹ (Fig. 1F) using a method (21) that extracts the velocity dispersions at the outer region of the disk, where the beam smearing is less severe.

We used Fourier analysis (3) to decompose the [C II] intensity image (Fig. 1A) into logarithmic spirals with m arms (Fig. 3A) (14). The best-fitting model is a two-armed spiral morphology with a pitch angle of $26.7^{+4.1}_{-1.6}^\circ$ (95% confidence level). Figure 3B shows this model overlain on the [C II] line intensity image after correction for the inclination angle of 37.8° (i.e., de-projected to be viewed as face-on). The disk inclination was estimated from the axis ratio of the dust continuum image (table S1) (14). The amplitude of the $m = 2$ signal is 6.0 times the noise, while the other modes $m = 1, 3, 4$ have signal-to-noise ratios of 4.0, 2.5 and 2.4 respectively (Fig. 3A).

The $m = 1$ mode corresponds to a one-arm spiral or lopsided morphology. The broad signal in $m = 1$ mode (Fig. 3A) is due to the difference in length of two arms (Fig. 3B). The $m = 3$ and 4 modes correspond to a triangular and boxy shape respectively, which could be produced by a stellar bar structure.

We estimate the inclination-corrected rotational velocity v_{rot} is 179^{+25}_{-18} km s⁻¹ at radius of 0.3'', calculated using the flat part of the PVD (Fig. 1E). The ratio of v_{rot} to the intrinsic velocity dispersion σ quantifies the rotational support of the disk (20). Our estimated ratio $v_{\text{rot}}/\sigma = 2.5^{+0.6}_{-0.4}$, indicating that the [C II] gas disk of this galaxy is rotation-dominated. Similar values have been found for other galaxies observed at $z \sim 4$ (8, 9). Higher ratios have also been reported at redshift of 4 to 5 (7, 10). Additional evidence of a rotating disk is a velocity field that is symmetric across the kinematic minor axis, as we observe in this object (Fig. 1B). Ordered rotation has been found in kinematic data of several galaxies at redshift ~ 4 (22), with such symmetric velocity fields.

We estimate the mass distribution by modeling gas motions under a gravitational potential, composed of a central compact structure and an extended rotating disk (14). The best-fitting effective radius of the compact structure R_e is less than 1.3 kpc (at 95% confidence interval); its mass is 5.2×10^9 to $3.0 \times 10^{10} M_\odot$ depending on the value of R_e . These results are compatible with the typical effective radius and mass of stellar bulges in nearby galaxies (23). The modeled mass of the disk $4.9^{+1.7}_{-2.5} \times 10^{10} M_\odot$ is consistent with the molecular gas mass of $5.1 \times 10^{10} M_\odot$ (16) estimated from the CO ($J = 2 \rightarrow 1$) luminosity (assuming BRI 1335-0417 has element abundances equal to the Sun). We computed the gas disk Toomre parameter Q , which quantifies the gravitational stability of the disk against perturbations (14). We find Q is less than 1 throughout the outer part of the disk (fig. S6), indicating the gas disk is susceptible to gravitational collapse, star formation (7-9) and spontaneous formation of spiral structure (3, 24).

Studies of nearby galaxies have shown that bulges and supermassive black holes coexist in massive galaxies, and that there is a strong correlation between their properties (25). The mass of the central black hole in BRI 1335-0417 has previously been estimated as $M_{\text{BH}} \sim 6 \times 10^9 M_\odot$ (26), although there are systematic effects that could bias this value (27). Our modeled compact structure mass 5.2×10^9 - $3.0 \times 10^{10} M_\odot$ is consistent with the estimated M_{BH} . The ratio of the black hole mass to the compact structure mass is 1 to 0.2, which is higher than the black hole to bulge mass ratio of 0.001 to 0.002 observed in nearby galaxies (25) and includes the possibility of a supermassive black hole without a surrounding

bulge. There is tentative evidence that the black hole-bulge mass ratio in high redshift galaxies could be higher than at low redshift, but the data are inconclusive (28).

Dusty starburst galaxies like BRI 1335–0417 are the progenitors of present-day massive elliptical galaxies, which are dominated by old stellar populations (7). This transformation requires contraction of the disk by angular momentum transport, through gravitational torques driven by non-axisymmetric structures (29). The spiral morphology in BRI 1335–0417 is present at $z = 4.41$, long before the peak of cosmic star formation. Spiral structure could influence the evolution of this galaxy: the angular momentum could be redistributed, triggering gas inflow into the center of the galaxy and driving intense star formation there (29). Such gas inflow cannot be directly detected in our data due to the limited signal to noise ratio.

The two-armed spiral morphology observed in BRI 1335–0417 could have been induced in the disk through tidal interactions (3, 24). Because this galaxy has a rotating disk and a compact structure at its center, sufficient time for their formation is likely to have passed after any major merger event. Cosmological simulations at redshift of 6 (30) show that spiral structure in a rotating disk can appear when the disk is relaxed after a merger event. The two-armed spiral morphology in BRI 1335–0417 extends out to 5 kpc (Fig. 1A), is connected to the galaxy center (Fig. 1D) and is associated with the rotating disk spatially and in velocity (Fig. 2 and Fig. 1E). Tidal-tail features in a galaxy merger are expected occur on larger scales (>10 kpc) (6, 31). We therefore disfavor, but cannot completely rule out, a tidal-tail origin for the observed spiral morphology. Alternatively, a stellar bar structure could play a role in forming the two-armed spiral structure (24, 32). Figure 1, A and C, shows non-axisymmetric structures, which could be due to a stellar bar, and the spiral arms appear to begin from the edge of this bar structure, as seen in nearby disk galaxies and numerical simulation (32).

The high star formation rates of $z > 4$ galaxies like BRI 1335–0417 are commonly explained as the result of major mergers, which could produce distorted galactic kinematics. We find that BRI 1335–0417 has only slightly disturbed, rotation dominated kinematics, which can be well described by a rotating disk model (14). This suggests that the high star formation rate must have been maintained long enough for the disk to form after any major merger event. The Q parameter shows the outer disk of BRI 1335–0417 is unstable, which could be caused by gas accretion along large-scale filaments of the cosmic web (29, 33), and/or minor mergers with accreting satellites (30).

REFERENCES AND NOTES

1. P. Madau, M. Dickinson, Cosmic Star-Formation History. *Annu. Rev. Astron. Astrophys.* **52**, 415–486 (2014). [doi:10.1146/annurev-astro-081811-125615](https://doi.org/10.1146/annurev-astro-081811-125615)
2. S. Tacchella, C. M. Carollo, A. Renzini, N. M. Förster Schreiber, P. Lang, S. Wuyts, G. Cresci, A. Dekel, R. Genzel, S. J. Lilly, C. Mancini, S. Newman, M. Onodera, A.

- Shapley, L. Tacconi, J. Woo, G. Zamorani, Evidence for mature bulges and an inside-out quenching phase 3 billion years after the Big Bang. *Science* **348**, 314–317 (2015). [doi:10.1126/science.1261094](https://doi.org/10.1126/science.1261094) [Medline](#)
3. D. R. Law, A. E. Shapley, C. C. Steidel, N. A. Reddy, C. R. Christensen, D. K. Erb, High velocity dispersion in a rare grand-design spiral galaxy at redshift $z = 2.18$. *Nature* **487**, 338–340 (2012). [doi:10.1038/nature11256](https://doi.org/10.1038/nature11256) [Medline](#)
4. S. Dawson, N. McCrady, D. Stern, M. E. Eckart, H. Spinrad, M. C. Liu, J. R. Graham, Optical and Near-Infrared Spectroscopy of a High-Redshift Hard X-Ray-emitting Spiral Galaxy. *Astron. J.* **125**, 1236–1246 (2003). [doi:10.1086/367792](https://doi.org/10.1086/367792)
5. T. Yuan, J. Richard, A. Gupta, C. Federrath, S. Sharma, B. A. Groves, L. J. Kewley, R. Cen, Y. Birnboim, D. B. Fisher, The Most Ancient Spiral Galaxy: A 2.6-Gyr-old Disk with a Tranquil Velocity Field. *Astrophys. J.* **850**, 61 (2017). [doi:10.3847/1538-4357/aa951d](https://doi.org/10.3847/1538-4357/aa951d)
6. J. A. Hodge, I. Smail, F. Walter, E. Cunha, A. M. Swinbank, M. Rybak, B. Venemans, W. N. Brandt, G. C. Rivera, S. C. Chapman, C.-C. Chen, P. Cox, H. Dannerbauer, R. Decarli, T. R. Greve, K. K. Knudsen, K. M. Menten, E. Schinnerer, J. M. Simpson, P. Werf, J. L. Wardlow, A. Weiss, ALMA Reveals Potential Evidence for Spiral Arms, Bars, and Rings in High-redshift Submillimeter Galaxies. *Astrophys. J.* **876**, 130 (2019). [doi:10.3847/1538-4357/ab1846](https://doi.org/10.3847/1538-4357/ab1846)
7. F. Rizzo, S. Vegetti, D. Powell, F. Fraternali, J. P. McKean, H. R. Stacey, S. D. M. White, A dynamically cold disk galaxy in the early Universe. *Nature* **584**, 201–204 (2020). [doi:10.1038/s41586-020-2572-6](https://doi.org/10.1038/s41586-020-2572-6) [Medline](#)
8. M. Neeleman, J. X. Prochaska, N. Kanekar, M. Rafelski, A cold, massive, rotating disk galaxy 1.5 billion years after the Big Bang. *Nature* **581**, 269–272 (2020). [doi:10.1038/s41586-020-2276-y](https://doi.org/10.1038/s41586-020-2276-y) [Medline](#)
9. K. Tadaki, D. Iono, M. S. Yun, I. Aretxaga, B. Hatsukade, D. H. Hughes, S. Ikarashi, T. Izumi, R. Kawabe, K. Kohno, M. Lee, Y. Matsuda, K. Nakanishi, T. Saito, Y. Tamura, J. Ueda, H. Umehata, G. W. Wilson, T. Michiyama, M. Ando, P. Kamienieski, The gravitationally unstable gas disk of a starburst galaxy 12 billion years ago. *Nature* **560**, 613–616 (2018). [doi:10.1038/s41586-018-0443-1](https://doi.org/10.1038/s41586-018-0443-1) [Medline](#)
10. F. Lelli, E. M. Di Teodoro, F. Fraternali, A. W. S. Man, Z.-Y. Zhang, C. De Breuck, T. A. Davis, R. Maiolino, A massive stellar bulge in a regularly rotating galaxy 1.2 billion years after the Big Bang. *Science* **371**, 713–716 (2021). [doi:10.1126/science.abc1893](https://doi.org/10.1126/science.abc1893) [Medline](#)
11. S. Guilleloteau, A. Omont, R. G. McMahon, P. Cox, P. Petitjean, The second detection of CO at redshift larger than 4. *Astron. Astrophys.* **328**, L1 (1997).
12. C. L. Carilli, K. Kohno, R. Kawabe, K. Ohta, C. Henkel, K. M. Menten, M. S. Yun, A. Petric, Y. Tutui, High-Resolution Imaging of Molecular Line Emission from High-Redshift QSOs. *Astron. J.* **123**, 1838–1846 (2002). [doi:10.1086/339306](https://doi.org/10.1086/339306)
13. J. Wagg, C. L. Carilli, M. Aravena, P. Cox, L. Lentati, R. Maiolino, R. G. McMahon, D. Riechers, F. Walter, P. Andreani, R. Hills, A. Wolfe, Karl G. Jansky Very Large Array Observations of Cold Dust and Molecular Gas in Starbursting Quasar Host Galaxies at $z \sim 4.5$. *Astrophys. J.* **783**, 71 (2014). [doi:10.1088/0004-637X/783/2/71](https://doi.org/10.1088/0004-637X/783/2/71)
14. Materials and methods are available as supplementary materials.
15. J. Wagg, C. L. Carilli, D. J. Wilner, P. Cox, C. De Breuck, K. Menten, D. A. Riechers, F. Walter, [CII] line emission in BRI 1335–0417 at $z = 4.4$. *Astron. Astrophys.* **519**, L1 (2010). [doi:10.1051/0004-6361/201015424](https://doi.org/10.1051/0004-6361/201015424)
16. G. C. Jones, C. L. Carilli, E. Momjian, J. Wagg, D. A. Riechers, F. Walter, R. Decarli, K. Ota, R. McMahon, New constraints on the molecular gas in the prototypical HyLIRGs BRI 1202–0725 and BRI 1335–0417. *Astrophys. J.* **830**, 63 (2016). [doi:10.3847/0004-637x/830/2/63](https://doi.org/10.3847/0004-637x/830/2/63)
17. D. A. Riechers, F. Walter, C. L. Carilli, F. Bertoldi, E. Momjian, Formation of a Quasar Host Galaxy through a Wet Merger 1.4 Billion Years after the Big Bang. *Astrophys. J.* **686**, L9–L12 (2008). [doi:10.1086/592834](https://doi.org/10.1086/592834)
18. J. L. Pineda, W. D. Langer, T. Velusamy, P. F. Goldsmith, A Herschel [C II] Galactic plane survey. I. The global distribution of ISM gas components. *Astron. Astrophys.* **554**, A103 (2013). [doi:10.1051/0004-6361/201321188](https://doi.org/10.1051/0004-6361/201321188)
19. Y. Sofue, J. Koda, H. Nakanishi, S. Onodera, The Virgo High-Resolution CO Survey: II. Rotation Curves and Dynamical Mass Distributions. *Publ. Astron. Soc. Jpn.* **55**, 59–74 (2003). [doi:10.1093/pasj/55.1.59](https://doi.org/10.1093/pasj/55.1.59)
20. A. Burkert, N. M. F. Schreiber, R. Genzel, P. Lang, L. J. Tacconi, E. Wisnioski, S. Wuyts, K. Bandara, A. Beifiori, R. Bender, G. Brammer, J. Chan, R. Davies, A. Dekel, M. Fabricius, M. Fossati, S. Kulkarni, D. Lutz, J. T. Mendel, I. Momcheva, E. J. Nelson, T. Naab, A. Renzini, R. Saglia, R. M. Sharples, A. Sternberg, D. Wilman, E.

- Wuyts, The Angular Momentum Distribution and Baryon Content of Star-forming Galaxies at $z \sim 1-3$. *Astrophys. J.* **826**, 214 (2016). [doi:10.3847/0004-637X/826/2/214](https://doi.org/10.3847/0004-637X/826/2/214)
21. A. W. Green, K. Glazebrook, P. J. McGregor, R. G. Abraham, G. B. Poole, I. Damjanov, P. J. McCarthy, M. Colless, R. G. Sharp, High star formation rates as the origin of turbulence in early and modern disk galaxies. *Nature* **467**, 684–686 (2010). [doi:10.1038/nature09452](https://doi.org/10.1038/nature09452) [Medline](#)
 22. G. C. Jones, C. L. Carilli, Y. Shao, R. Wang, P. L. Capak, R. Pavesi, D. A. Riechers, A. Karim, M. Neeleman, F. Walter, Dynamical Characterization of Galaxies at $z \sim 4-6$ via Tilted Ring Fitting to ALMA [C II] Observations. *Astrophys. J.* **850**, 180 (2017). [doi:10.3847/1538-4357/aa8df2](https://doi.org/10.3847/1538-4357/aa8df2)
 23. D. A. Gadotti, Structural properties of pseudo-bulges, classical bulges and elliptical galaxies: A Sloan Digital Sky Survey perspective. *Mon. Not. R. Astron. Soc.* **393**, 1531–1552 (2009). [doi:10.1111/j.1365-2966.2008.14257.x](https://doi.org/10.1111/j.1365-2966.2008.14257.x)
 24. C. Dobbs, J. Baba, Dawes Review 4: Spiral Structures in Disc Galaxies. *Publ. Astron. Soc. Aust.* **31**, e035 (2014). [doi:10.1017/pasa.2014.31](https://doi.org/10.1017/pasa.2014.31)
 25. J. Kormendy, L. C. Ho, Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies. *Annu. Rev. Astron. Astrophys.* **51**, 511–653 (2013). [doi:10.1146/annurev-astro-082708-101811](https://doi.org/10.1146/annurev-astro-082708-101811)
 26. G. A. Shields, K. L. Menezes, C. A. Massart, P. Vanden Bout, The Black Hole-Bulge Relationship for QSOs at High Redshift. *Astrophys. J.* **641**, 683–688 (2006). [doi:10.1086/500542](https://doi.org/10.1086/500542)
 27. J. E. Mejía-Restrepo, P. Lira, H. Netzer, B. Trakhtenbrot, D. M. Capellupo, The effect of nuclear gas distribution on the mass determination of supermassive black holes. *Nat. Astron.* **2**, 63–68 (2018). [doi:10.1038/s41550-017-0305-z](https://doi.org/10.1038/s41550-017-0305-z)
 28. A. Schulze, L. Wisotzki, Accounting for selection effects in the BH-bulge relations: No evidence for cosmological evolution. *Mon. Not. R. Astron. Soc.* **438**, 3422–3433 (2014). [doi:10.1093/mnras/stt2457](https://doi.org/10.1093/mnras/stt2457)
 29. A. Dekel, A. Burkert, Wet disc contraction to galactic blue nuggets and quenching to red nuggets. *Mon. Not. R. Astron. Soc.* **438**, 1870–1879 (2014). [doi:10.1093/mnras/stt2331](https://doi.org/10.1093/mnras/stt2331)
 30. M. Kohandel, A. Pallottini, A. Ferrara, A. Zanella, C. Behrens, S. Carniani, S. Gallerani, L. Vallini, Kinematics of $z \geq 6$ galaxies from [C II] line emission. *Mon. Not. R. Astron. Soc.* **487**, 3007–3020 (2019). [doi:10.1093/mnras/stz1486](https://doi.org/10.1093/mnras/stz1486)
 31. J. Ren, X. Z. Zheng, D. Valls-Gabaud, P.-A. Duc, E. F. Bell, Z. Pan, J. Qin, D. D. Shi, M. Qiao, Y. He, R. Wen, Long Tidal Tails in Merging Galaxies and Their Implications. *Mon. Not. R. Astron. Soc.* **499**, 3399–3409 (2020). [doi:10.1093/mnras/staa2985](https://doi.org/10.1093/mnras/staa2985)
 32. J. Baba, Short-term dynamical evolution of grand-design spirals in barred galaxies. *Mon. Not. R. Astron. Soc.* **454**, 2954–2964 (2015). [doi:10.1093/mnras/stv2220](https://doi.org/10.1093/mnras/stv2220)
 33. A. Dekel, Y. Birnboim, G. Engel, J. Freundlich, T. Goerdt, M. Mumcuoglu, E. Neistein, C. Pichon, R. Teyssier, E. Zinger, Cold streams in early massive hot halos as the main mode of galaxy formation. *Nature* **457**, 451–454 (2009). [doi:10.1038/nature07648](https://doi.org/10.1038/nature07648) [Medline](#)
 34. C. L. Bennett, D. Larson, J. L. Weiland, G. Hinshaw, The 1% Concordance Hubble Constant. *Astrophys. J.* **794**, 135 (2014). [doi:10.1088/0004-637X/794/2/135](https://doi.org/10.1088/0004-637X/794/2/135)
 35. S. Iguchi, Radio Interferometer Sensitivities for Three Types of Receiving Systems: DSB, SSB, and 2SB Systems. *Publ. Astron. Soc. Jpn.* **57**, 643–677 (2005). [doi:10.1093/pasj/57.4.643](https://doi.org/10.1093/pasj/57.4.643)
 36. A. Remijan, A. Biggs, P. Cortes, B. Dent, J. Di Francesco, E. Fomalont, A. Hales, S. Kamenov, B. Mason, N. Phillips, K. Saini, F. Stoehr, B. Vila Vilaro, E. Villard, ALMA Cycle 7 Technical Handbook (2019). [doi:10.5281/zenodo.4511522](https://doi.org/10.5281/zenodo.4511522)
 37. J. P. McMullin, B. Waters, D. Schiebel, W. Young, K. Golap, in *Astronomical Data Analysis Software and Systems XVI*, R. A. Shaw, F. Hill, D. J. Bell, Eds., vol. 376 of *Astronomical Society of the Pacific Conference Series* (Astronomical Society of the Pacific, 2007), p. 127.
 38. D. S. Briggs, High Fidelity Interferometric Imaging: Robust Weighting and NNLS Deconvolution. *Bull. Am. Astron. Soc.* **27**, 1444 (1995).
 39. T. M. Dame, Optimization of Moment Masking for CO Spectral Line Surveys. arXiv preprint (2011): <https://arxiv.org/abs/1101.1499>
 40. T. A. Davis, M. Bureau, M. Cappellari, M. Sarzi, L. Blitz, A black-hole mass measurement from molecular gas kinematics in NGC4526. *Nature* **494**, 328–330 (2013). [doi:10.1038/nature11819](https://doi.org/10.1038/nature11819) [Medline](#)
 41. D. Krajnović, M. Cappellari, P. T. De Zeeuw, Y. Copin, Kinemetry: A generalization of photometry to the higher moments of the line-of-sight velocity distribution. *Mon. Not. R. Astron. Soc.* **366**, 787–802 (2006). [doi:10.1111/j.1365-2966.2005.09902.x](https://doi.org/10.1111/j.1365-2966.2005.09902.x)
 42. C. Y. Peng, L. C. Ho, C. D. Impey, H.-W. Rix, Detailed Decomposition of Galaxy Images. II. Beyond Axisymmetric Models. *Astron. J.* **139**, 2097–2129 (2010). [doi:10.1088/0004-6256/139/6/2097](https://doi.org/10.1088/0004-6256/139/6/2097)
 43. R. Lange, A. J. Moffett, S. P. Driver, A. S. G. Robotham, C. P. Lagos, L. S. Kelvin, C. Conselice, B. Margalef-Bentabol, M. Alpaslan, I. Baldry, J. Bland-Hawthorn, M. Bremer, S. Brough, M. Cluver, M. Colless, L. J. M. Davies, B. Häußler, B. W. Holwerda, A. M. Hopkins, P. R. Kafle, R. Kennedy, J. Liske, S. Philipps, C. C. Popescu, E. N. Taylor, R. Tuffs, E. van Kampen, A. H. Wright, Galaxy And Mass Assembly (GAMA): $M_{\star} - R_e$ relations of $z = 0$ bulges, discs and spheroids. *Mon. Not. R. Astron. Soc.* **462**, 1470–1500 (2016). [doi:10.1093/mnras/stw1495](https://doi.org/10.1093/mnras/stw1495)
 44. S. P. Driver, P. D. Allen, A. W. Graham, E. Cameron, J. Liske, S. C. Ellis, N. J. G. Cross, R. De Propris, S. Philipps, W. J. Couch, The Millennium Galaxy Catalogue: Morphological classification and bimodality in the colour-concentration plane. *Mon. Not. R. Astron. Soc.* **368**, 414–434 (2006). [doi:10.1111/j.1365-2966.2006.10126.x](https://doi.org/10.1111/j.1365-2966.2006.10126.x)
 45. S. van der Walt, J. L. Schönberger, J. Nunez-Iglesias, F. Boulogne, J. D. Warner, N. Yager, E. Gouillart, T. Yu; scikit-image contributors, scikit-image: Image processing in Python. *PeerJ* **2**, e453 (2014). [doi:10.7717/peerj.453](https://doi.org/10.7717/peerj.453) [Medline](#)
 46. I. Puerari, H. A. Dottori, Fourier analysis of structure in spiral galaxies. *Astron. Astrophys. Suppl. Ser.* **93**, 469 (1992).
 47. M. D. Smith, M. Bureau, T. A. Davis, M. Cappellari, L. Liu, E. V. North, K. Onishi, S. Iguchi, M. Sarzi, WISDOM project - IV. A molecular gas dynamical measurement of the supermassive black hole mass in NGC 524. *Mon. Not. R. Astron. Soc.* **485**, 4359–4374 (2019). [doi:10.1093/mnras/stz625](https://doi.org/10.1093/mnras/stz625)
 48. S. M. Kent, Dark matter in spiral galaxies. I. Galaxies with optical rotation curves. *Astron. J.* **91**, 1301 (1986). [doi:10.1086/114106](https://doi.org/10.1086/114106)
 49. Y. Sofue, M. Honma, T. Omodaka, Unified Rotation Curve of the Galaxy–Decomposition into de Vaucouleurs Bulge, Disk, Dark Halo, and the 9-kpc Rotation Dip–. *Publ. Astron. Soc. Jpn.* **61**, 227–236 (2009). [doi:10.1093/pasj/61.2.227](https://doi.org/10.1093/pasj/61.2.227)
 50. R. Genzel, N. M. F. Schreiber, H. Übler, P. Lang, T. Naab, R. Bender, L. J. Tacconi, E. Wisnioski, S. Wuyts, T. Alexander, A. Beifiori, S. Belli, G. Brammer, A. Burkert, C. M. Carollo, J. Chan, R. Davies, M. Fossati, A. Galametz, S. Genel, O. Gerhard, D. Lutz, J. T. Mendel, I. Momcheva, E. J. Nelson, A. Renzini, R. Saglia, A. Sternberg, S. Tacchella, K. Tadaki, D. Wilman, Strongly baryon-dominated disk galaxies at the peak of galaxy formation ten billion years ago. *Nature* **543**, 397–401 (2017). [doi:10.1038/nature21685](https://doi.org/10.1038/nature21685) [Medline](#)
 51. N. M. Förster Schreiber, R. Genzel, N. Bouché, G. Cresci, R. Davies, P. Buschkamp, K. Shapiro, L. J. Tacconi, E. K. S. Hicks, S. Genel, A. E. Shapley, D. K. Erb, C. C. Steidel, D. Lutz, F. Eisenhauer, S. Gillessen, A. Sternberg, A. Renzini, A. Cimatti, E. Daddi, J. Kurk, S. Lilly, X. Kong, M. D. Lehnert, N. Nesvadba, A. Verma, H. McCracken, N. Arimoto, M. Mignoli, M. Onodera, The SINS Survey: SINFONI Integral Field Spectroscopy of $z \sim 2$ Star-forming Galaxies. *Astrophys. J.* **706**, 1364–1428 (2009). [doi:10.1088/0004-637X/706/2/1364](https://doi.org/10.1088/0004-637X/706/2/1364)
 52. S. Wuyts, N. M. F. Schreiber, E. Wisnioski, R. Genzel, A. Burkert, K. Bandara, A. Beifiori, S. Belli, R. Bender, G. B. Brammer, J. Chan, R. Davies, M. Fossati, A. Galametz, S. K. Kulkarni, P. Lang, D. Lutz, J. T. Mendel, I. G. Momcheva, T. Naab, E. J. Nelson, R. P. Saglia, S. Seitz, L. J. Tacconi, K. Tadaki, H. Übler, P. G. Dokkum, D. J. Wilman, E. Wuyts, KMOS3D: Dynamical Constraints on the Mass Budget in Early Star-forming Disks. *Astrophys. J.* **831**, 149 (2016). [doi:10.3847/0004-637X/831/2/149](https://doi.org/10.3847/0004-637X/831/2/149)
 53. P. Lang, S. Wuyts, R. S. Somerville, N. M. F. Schreiber, R. Genzel, E. F. Bell, G. Brammer, A. Dekel, S. M. Faber, H. C. Ferguson, N. A. Grogin, D. D. Kocevski, A. M. Koekemoer, D. Lutz, E. J. McGrath, I. Momcheva, E. J. Nelson, J. R. Primack, D. J. Rosario, R. E. Skelton, L. J. Tacconi, P. G. van Dokkum, K. E. Whitaker, Bulge Growth and Quenching since $z = 2.5$ in CANDELS/3D-HST. *Astrophys. J.* **788**, 11 (2014). [doi:10.1088/0004-637X/788/1/11](https://doi.org/10.1088/0004-637X/788/1/11)
 54. V. A. Bruce, J. S. Dunlop, R. J. McLure, M. Cirasuolo, F. Buitrago, R. A. A. Bowler, T. A. Targett, E. F. Bell, D. H. McIntosh, A. Dekel, S. M. Faber, H. C. Ferguson, N. A. Grogin, W. Hartley, D. D. Kocevski, A. M. Koekemoer, D. C. Koo, E. J. McGrath, The bulge-disc decomposed evolution of massive galaxies at $1 < z < 3$ in CANDELS. *Mon. Not. R. Astron. Soc.* **444**, 1001–1033 (2014). [doi:10.1093/mnras/stu1478](https://doi.org/10.1093/mnras/stu1478)
 55. G. de Vaucouleurs, Recherches sur les Nebuleuses Extragalactiques. *Ann. Astrophys.* **11**, 247 (1948).
 56. A. W. Graham, S. P. Driver, A Concise Reference to (Projected) Sérsic $R^{1/n}$ Quantities, Including Concentration, Profile Slopes, Petrosian Indices, and Kron

- Magnitudes. *Publ. Astron. Soc. Aust.* **22**, 118–127 (2005). [doi:10.1071/AS05001](https://doi.org/10.1071/AS05001)
57. J. Binney, S. Tremaine, *Galactic Dynamics*: Second Edition (Princeton. Univ. Press, Princeton, NJ, 2008).
 58. E. Noordermeer, The rotation curves of flattened Sérsic bulges. *Mon. Not. R. Astron. Soc.* **385**, 1359–1364 (2008). [doi:10.1111/j.1365-2966.2008.12837.x](https://doi.org/10.1111/j.1365-2966.2008.12837.x)
 59. N. Katz, J. E. Gunn, Dissipational Galaxy Formation. I. Effects of Gasdynamics. *Astrophys. J.* **377**, 365 (1991). [doi:10.1086/170367](https://doi.org/10.1086/170367)
 60. R. Genzel, N. M. Förster Schreiber, P. Lang, S. Tacchella, L. J. Tacconi, S. Wuyts, K. Bandara, A. Burkert, P. Buschkamp, C. M. Carollo, G. Cresci, R. Davies, F. Eisenhauer, E. K. S. Hicks, J. Kurk, S. J. Lilly, D. Lutz, C. Mancini, T. Naab, S. Newman, Y. Peng, A. Renzini, K. Shapiro Griffin, A. Sternberg, D. Vergani, E. Wisnioski, E. Wuyts, G. Zamorani, The SINS/zC-SINF Survey of $z \sim 2$ Galaxy Kinematics: Evidence for Gravitational Quenching. *Astrophys. J.* **785**, 75 (2014). [doi:10.1088/0004-637X/785/1/75](https://doi.org/10.1088/0004-637X/785/1/75)
 61. A. Burkert, R. Genzel, N. Bouché, G. Cresci, S. Khochfar, J. Sommer-Larsen, A. Sternberg, T. Naab, N. F. Schreiber, L. Tacconi, K. Shapiro, E. Hicks, D. Lutz, R. Davies, P. Buschkamp, S. Genel, High-redshift Star-forming Galaxies: Angular Momentum and Baryon Fraction, Turbulent Pressure Effects, and the Origin of Turbulence. *Astrophys. J.* **725**, 2324–2332 (2010). [doi:10.1088/0004-637X/725/2/2324](https://doi.org/10.1088/0004-637X/725/2/2324)
 62. K. C. Freeman, On the Disks of Spiral and S0 Galaxies. *Astrophys. J.* **160**, 811 (1970). [doi:10.1086/150474](https://doi.org/10.1086/150474)
 63. A. Zanella, E. Daddi, G. Magdis, T. Diaz Santos, D. Cormier, D. Liu, A. Cibinel, R. Gobat, M. Dickinson, M. Sargent, G. Popping, S. C. Madden, M. Bethermin, T. M. Hughes, F. Valentino, W. Rujopakarn, M. Pannella, F. Bournaud, F. Walter, T. Wang, D. Elbaz, R. T. Coogan, The [C II] emission as a molecular gas mass tracer in galaxies at low and high redshifts. *Mon. Not. R. Astron. Soc.* **481**, 1976–1999 (2018). [doi:10.1093/mnras/sty2394](https://doi.org/10.1093/mnras/sty2394)
 64. B. Gullberg, A. M. Swinbank, I. Smail, A. D. Biggs, F. Bertoldi, C. D. Breuck, S. C. Chapman, C.-C. Chen, E. A. Cooke, K. E. K. Coppin, P. Cox, H. Dannerbauer, J. S. Dunlop, A. C. Edge, D. Farrah, J. E. Geach, T. R. Greve, J. Hodge, E. Ibar, R. J. Ivison, A. Karim, E. Schinnerer, D. Scott, J. M. Simpson, S. M. Stach, A. P. Thomson, P. van der Werf, F. Walter, J. L. Wardlow, A. Weiss, The Dust and [C II] Morphologies of Redshift ~ 4.5 Sub-millimeter Galaxies at ~ 200 pc Resolution: The Absence of Large Clumps in the Interstellar Medium at High-redshift. *Astrophys. J.* **859**, 12 (2018). [doi:10.3847/1538-4357/aabe8c](https://doi.org/10.3847/1538-4357/aabe8c)
 65. E. Wisnioski, N. M. Förster Schreiber, S. Wuyts, E. Wuyts, K. Bandara, D. Wilman, R. Genzel, R. Bender, R. Davies, M. Fossati, P. Lang, J. T. Mendel, A. Beifiori, G. Brammer, J. Chan, M. Fabricius, Y. Fudamoto, S. Kulkarni, J. Kurk, D. Lutz, E. J. Nelson, I. Momcheva, D. Rosario, R. Saglia, S. Seitz, L. J. Tacconi, P. G. van Dokkum, The KMOS^{3D} Survey: Design, First Results, and the Evolution of Galaxy Kinematics from $0.7 \leq z \leq 2.7$. *Astrophys. J.* **799**, 209 (2015). [doi:10.1088/0004-637X/799/2/209](https://doi.org/10.1088/0004-637X/799/2/209)
 66. P. Lang, N. M. Förster Schreiber, R. Genzel, S. Wuyts, E. Wisnioski, A. Beifiori, S. Belli, R. Bender, G. Brammer, A. Burkert, J. Chan, R. Davies, M. Fossati, A. Galametz, S. K. Kulkarni, D. Lutz, J. T. Mendel, I. G. Momcheva, T. Naab, E. J. Nelson, R. P. Saglia, S. Seitz, S. Tacchella, L. J. Tacconi, K. Tadaki, H. Übler, P. G. van Dokkum, D. J. Wilman, Falling Outer Rotation Curves of Star-forming Galaxies at $0.6 \lesssim z \lesssim 2.6$ Probed with KMOS3D and SINS/zC-SINF. *Astrophys. J.* **840**, 92 (2017). [doi:10.3847/1538-4357/aa6d82](https://doi.org/10.3847/1538-4357/aa6d82)
 67. D. Foreman-Mackey, D. W. Hogg, D. Lang, J. Goodman, emcee: The MCMC Hammer. *Publ. Astron. Soc. Pac.* **125**, 306–312 (2013). [doi:10.1086/670067](https://doi.org/10.1086/670067)
 68. R. C. E. Van Den Bosch, G. Van De Ven, Recovering the intrinsic shape of early-type galaxies. *Mon. Not. R. Astron. Soc.* **398**, 1117–1128 (2009). [doi:10.1111/j.1365-2966.2009.15177.x](https://doi.org/10.1111/j.1365-2966.2009.15177.x)
 69. E. V. North, T. A. Davis, M. Bureau, M. Cappellari, S. Iguchi, L. Liu, K. Onishi, M. Sarzi, M. D. Smith, T. G. Williams, WISDOM project - V. Resolving molecular gas in Keplerian rotation around the supermassive black hole in NGC 0383. *Mon. Not. R. Astron. Soc.* **490**, 319–330 (2019). [doi:10.1093/mnras/stz2598](https://doi.org/10.1093/mnras/stz2598)
 70. M. Mitzkus, M. Cappellari, C. J. Walcher, Dominant dark matter and a counter-rotating disc: MUSE view of the low-luminosity S0 galaxy NGC 5102. *Mon. Not. R. Astron. Soc.* **464**, 4789–4806 (2017). [doi:10.1093/mnras/stw2677](https://doi.org/10.1093/mnras/stw2677)
 71. T. A. Davis, M. Bureau, K. Onishi, M. Cappellari, S. Iguchi, M. Sarzi, WISDOM Project - II. Molecular gas measurement of the supermassive black hole mass in NGC 4697. *Mon. Not. R. Astron. Soc.* **468**, 4675–4690 (2017). [doi:10.1093/mnras/stw3217](https://doi.org/10.1093/mnras/stw3217)
 72. N. Lu, T. Cao, T. Díaz-Santos, Y. Zhao, G. C. Privon, C. Cheng, Y. Gao, C. K. Xu, V. Charmandaris, D. Rigopoulou, P. P. Werf, J. Huang, Z. Wang, A. S. Evans, D. B. Sanders, CO (7-6), [C II] 370 μ m, and [N II] 205 μ m Line Emission of the QSO BRI 1335-0417 at Redshift 4.407. *Astrophys. J.* **864**, 38 (2018). [doi:10.3847/1538-4357/aad3c9](https://doi.org/10.3847/1538-4357/aad3c9)
 73. J. S. Spilker, K. A. Phadke, M. Aravena, M. Béthermin, S. C. Chapman, C. Dong, A. H. Gonzalez, C. C. Hayward, Y. D. Hezaveh, S. Jarugula, K. C. Litke, M. A. Malkan, D. P. Marrone, D. Narayanan, C. Reuter, J. D. Vieira, A. Weiss, Ubiquitous Molecular Outflows in $z > 4$ Massive, Dusty Galaxies. I. Sample Overview and Clumpy Structure in Molecular Outflows on 500 pc Scales. *Astrophys. J.* **905**, 85 (2020). [doi:10.3847/1538-4357/abc47f](https://doi.org/10.3847/1538-4357/abc47f)
 74. A. Toomre, On the gravitational stability of a disk of stars. *Astrophys. J.* **139**, 1217–1238 (1964). [doi:10.1086/147861](https://doi.org/10.1086/147861)
 75. P. Goldreich, D. Lynden-Bell, I. Gravitational stability of uniformly rotating disks. *Mon. Not. R. Astron. Soc.* **130**, 97–124 (1965). [doi:10.1093/mnras/130.2.97](https://doi.org/10.1093/mnras/130.2.97)
 76. M. Cappellari, Improving the full spectrum fitting method: Accurate convolution with Gauss–Hermite functions. *Mon. Not. R. Astron. Soc.* **466**, 798–811 (2017). [doi:10.1093/mnras/stw3020](https://doi.org/10.1093/mnras/stw3020)

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SUPPLEMENTARY MATERIALS

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Materials and Methods

Figs. S1 to S6

Tables S1 and S2

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Data S1 to S4

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Fig. 1. Morphology and kinematics of [C II] line and dust continuum emission in BRI 1335–0417. (A) and (B) the ALMA [C II] line maps of intensity (moment 0) and intensity-weighted velocity (moment 1). The kinematic major and minor axes are shown in panel B with black solid and dotted lines, respectively. (C) the ALMA dust continuum map at a rest-frame frequency of 1863 GHz. (D) a composite color image showing in red the redshifted gas emission with velocity of 30 to 150 km s^{-1} , in yellow gas at the systemic velocity of -30 to 30 km s^{-1} , and in blue the blueshifted gas with velocity of -150 to -30 km s^{-1} . The FWHM of the synthesized beam is $0.20'' \times 0.16''$ in (A), (B) and (D), and $0.17'' \times 0.14''$ in (C), which are shown with ellipses in the bottom left corners. (E) PVD of the observed [C II] line emission, extracted along the kinematic major axis shown in panel B, which has a position angle of 4.5° (table S1). Data were averaging over one beam width (three pixels). (F) the velocity dispersion measured from the line profile at each position of the PVD. The error bars correspond to the sum in quadrature of the profile fitting uncertainty (95% confidence level) and the velocity channel width. The red dashed line shows the estimated intrinsic velocity dispersion of $71^{+14}_{-11} \text{ km s}^{-1}$. Positive position in panels (E) and (F) is the direction toward the north along the kinematic major axis in (B).

Fig. 2 (previous page). Velocity channel maps of the [C II] line emission, showing the spiral structure. Each panel shows an image at a specific velocity of [C II] line emission, labeled in the top left. Overlain with white lines is the best-fitting two-armed logarithmic spiral model, which has a pitch angle $\alpha = 26.7^\circ$ (14). The images have been de-projected to be viewed face-on, using a position angle of 4.5° and inclination of 37.8° (table S1) (14). The FWHM of the synthesized beam is shown with the white ellipse in the left bottom of each panel.

Fig. 3. Fourier analysis of the [C II] line emission. (A) Fourier spectra (14) of logarithmic spiral models with m arms and pitch angles α . The black solid lines show the normalized amplitude as a function of the dimensionless parameter $p = -m/\tan(\alpha)$. The blue shaded region indicates the estimated noise level (14). The $m = 2$ mode has the strongest peak at a pitch angle of $26.7^{+4.1}_{-1.6}^\circ$ (dashed vertical line). (B) the [C II] line intensity image (de-projected version of Fig. 1A) overlaid with the best-fitting two-armed logarithmic spiral (white line, same as in Fig. 2). The FWHM of the synthesized beam is shown by an ellipse in the left bottom corner. The inner and outer dotted lines indicate the boundaries of the region used in the Fourier analysis (14).