A dusty compact object bridging galaxies and quasars at cosmic dawn

Understanding how super-massive black holes form and grow in the early Universe has become a major challenge since it was discovered that luminous quasars existed only 700 million years after the Big Bang. Simulations indicate an evolutionary sequence of dust-reddened quasars emerging from heavily dust-obscured starbursts that then transition to unobscured luminous quasars by expelling gas and dust.

Although the last phase has been identified out to a redshift of 7.6 (ref. 4), a transitioning quasar has not been found at similar redshifts owing to their faintness at optical and near-infrared wavelengths. Here we report observations of an ultraviolet compact object, GNz7q, associated with a dust-enshrouded starburst at a redshift of 7.1899 ± 0.0005. The host galaxy is more luminous in dust emission than any other known object at this epoch, forming 1,600 solar masses of stars per year within a central radius of 480 parsec. A red point source in the far-ultraviolet is identified in deep, high-resolution imaging and slitless spectroscopy. GNz7q is extremely faint in X-rays, which indicates the emergence of a uniquely ultraviolet compact star-forming region or a Compton-thick super-Eddington black-hole accretion disk at the dusty starburst core. In the latter case, the observed properties are consistent with predictions from cosmological simulations and suggest that GNz7q is an antecedent to unobscured luminous quasars at later epochs.

In recent uniform reprocessing of all archival Hubble Space Telescope (HST) imaging and slitless spectroscopy (Methods), GNz7q was identified in the Great Observatories Origins Deep Survey (GOODS) North extragalactic field as a luminous galaxy candidate at a redshift z ≳ 6.5 with a F160W band AB magnitude of 23.09 ± 0.05. Although the source has been detected and highlighted as a potential high-redshift galaxy by previous researchers, it has not been spectroscopically confirmed.

However, the full suite of HST data reveals an unambiguous continuum break at approximately 1.0 μm, which is best explained by a Lyman-α break at z ≳ 7.23 ± 0.05 (Fig. 1).

GNz7q is distinct in the rest-frame ultraviolet (UV) when compared with any other object currently known at similar redshifts (z ≳ 6). Its luminosity falls between that of typical quasars and galaxies and it is quite red in colour (Extended Data Fig. 1), with a rest-frame 1,450-Å luminosity, M_{1,450}, of ∼23.2 mag and a continuum slope, F_{\lambda} ∝ \lambda^{\alpha}, of α = 0.1 ± 0.3 (Methods). This is the reddest continuum slope found among objects at similar redshifts, (α ≲ −1.5 (refs. 9,10)), but is comparable to lower-redshift red quasars identified in the Sloan Digital Sky Survey (SDSS) (Fig. 1). GNz7q is also spatially unresolved in all HST bands (Extended Data Fig. 2) and is bright at rest-frame 3 μm, detected with the Multiband Imaging Photometer for Spitzer (MIPS). These characteristics suggest that GNz7q is a distant, red quasar.

However, GNz7q is not detected in the extremely deep 2-Ms X-ray map of the Chandra Deep Field North. Even accounting for obscuration, we obtain an upper limit (99% confidence level) on the X-ray luminosity of L_X < 3.9 × 10^{42} erg s^{-1} (Methods). This is several orders of magnitude lower than what would be predicted by assuming the correlation between L_X and optical luminosity observed for other quasars (Extended Data Fig. 3). GNz7q is therefore strikingly faint in 2–10-keV X-rays, apparently in tension with its being a quasar. The absence of strong, broad UV emission lines (Fig. 1) in addition to this unique X-ray faintness raises the possibility that GNz7q could instead be an extreme UV compact star-forming object.

One- and three-millimetre observations were carried out with the Northern Extended Millimeter Array (NOEMA) between June 2020 and February 2021 (Methods). The [C ii] 158-μm line was robustly detected at 170 peak intensity at a redshift of z = 7.1899 ± 0.0005, consistent with the Lyman-break redshift. The underlying 1-mm and 3-mm continua are also detected at 160 and 3.96 GHz, respectively. The sky positions of the 1-mm and 3-mm continua and emission line are consistent with the HST source. The [C ii] line is spatially resolved with 3.6-Arcsec beamwidth at a redshift of z = 7.23 ± 0.05 (Methods). This is the reddest continuum slope found among objects at similar redshifts, (α ≲ −1.5 (refs. 9,10)), but is comparable to lower-redshift red quasars identified in the Sloan Digital Sky Survey (SDSS) (Fig. 1). GNz7q is also spatially unresolved in all HST bands (Extended Data Fig. 2) and is bright at rest-frame 3 μm, detected with the Multiband Imaging Photometer for Spitzer (MIPS). These characteristics suggest that GNz7q is a distant, red quasar.

However, GNz7q is not detected in the extremely deep 2-Ms X-ray map of the Chandra Deep Field North. Even accounting for obscuration, we obtain an upper limit (99% confidence level) on the X-ray luminosity of L_X < 3.9 × 10^{42} erg s^{-1} (Methods). This is several orders of magnitude lower than what would be predicted by assuming the correlation between L_X and optical luminosity observed for other quasars (Extended Data Fig. 3). GNz7q is therefore strikingly faint in 2–10-keV X-rays, apparently in tension with its being a quasar. The absence of strong, broad UV emission lines (Fig. 1) in addition to this unique X-ray faintness raises the possibility that GNz7q could instead be an extreme UV compact star-forming object.

One- and three-millimetre observations were carried out with the Northern Extended Millimeter Array (NOEMA) between June 2020 and February 2021 (Methods). The [C ii] 158-μm line was robustly detected at 170 peak intensity at a redshift of z = 7.1899 ± 0.0005, consistent with the Lyman-break redshift. The underlying 1-mm and 3-mm continua are also detected at 160 and 3.96 GHz, respectively. The sky positions of the 1-mm and 3-mm continua and emission line are consistent with the HST source. The [C ii] line is spatially resolved with 3.6-Arcsec beamwidth at a redshift of z = 7.23 ± 0.05 (Methods). This is the reddest continuum slope found among objects at similar redshifts, (α ≲ −1.5 (refs. 9,10)), but is comparable to lower-redshift red quasars identified in the Sloan Digital Sky Survey (SDSS) (Fig. 1). GNz7q is also spatially unresolved in all HST bands (Extended Data Fig. 2) and is bright at rest-frame 3 μm, detected with the Multiband Imaging Photometer for Spitzer (MIPS). These characteristics suggest that GNz7q is a distant, red quasar.

However, GNz7q is not detected in the extremely deep 2-Ms X-ray map of the Chandra Deep Field North. Even accounting for obscuration, we obtain an upper limit (99% confidence level) on the X-ray luminosity of L_X < 3.9 × 10^{42} erg s^{-1} (Methods). This is several orders of magnitude lower than what would be predicted by assuming the correlation between L_X and optical luminosity observed for other quasars (Extended Data Fig. 3). GNz7q is therefore strikingly faint in 2–10-keV X-rays, apparently in tension with its being a quasar. The absence of strong, broad UV emission lines (Fig. 1) in addition to this unique X-ray faintness raises the possibility that GNz7q could instead be an extreme UV compact star-forming object.

One- and three-millimetre observations were carried out with the Northern Extended Millimeter Array (NOEMA) between June 2020 and February 2021 (Methods). The [C ii] 158-μm line was robustly detected at 170 peak intensity at a redshift of z = 7.1899 ± 0.0005, consistent with the Lyman-break redshift. The underlying 1-mm and 3-mm continua are also detected at 160 and 3.96 GHz, respectively. The sky positions of the 1-mm and 3-mm continua and emission line are consistent with the HST source. The [C ii] line is spatially resolved with 3.6-Arcsec beamwidth at a redshift of z = 7.23 ± 0.05 (Methods). This is the reddest continuum slope found among objects at similar redshifts, (α ≲ −1.5 (refs. 9,10)), but is comparable to lower-redshift red quasars identified in the Sloan Digital Sky Survey (SDSS) (Fig. 1). GNz7q is also spatially unresolved in all HST bands (Extended Data Fig. 2) and is bright at rest-frame 3 μm, detected with the Multiband Imaging Photometer for Spitzer (MIPS). These characteristics suggest that GNz7q is a distant, red quasar.
the [C ii] 158-μm line redshift of GNz7q at z = 7.1899, normalized at 1.2 μm, and binned to the same spectral resolution as the GNz7q spectrum. The large open circles show the quasar templates integrated through the HST filter pass bands. The band passes of the ACS/F850LP and WFC3/F105W filters shown at the bottom straddle the spectral break, explaining the faint detection in the former and the suppressed flux density relative to the continuum in the latter.

Fig. 1 | HST near-infrared images and spectrum of GNz7q. The spectrum and photometry show a strong Lyman break at λ$_{\text{Ly}}$ = 1.0 μm. Top: the HST image cutouts (5′ × 5′). The source is unresolved in all deep HST images up to the reddest filter available at 1.6 μm (WFC3/IR F160W). Bottom: the black squares and grey dots and shaded regions respectively show the broadband reddest filter available at 1.6 μm (WFC3/IR F160W). The source is unresolved in all deep HST images up to the effective radius for star-forming galaxies.

The shape of the NIR–mid-infrared (MIR) SED of GNz7q—especially the excess emission at rest-frame 3 μm—cannot easily be explained by emission from stars and ionized gas associated with star-formation activity alone (Fig. 2, Extended Data Fig. 8). Moreover, fitting a profile to the HST images provides a stringent upper limit for the effective radius of only 60 pc for the UV emission (Methods). If this compact emission were attributed to star formation, the SFR surface density from the UV alone would reach ≥5,000 $M_\odot$ yr$^{-1}$ kpc$^{-2}$, two orders of magnitude higher than the UV luminous compact galaxies reported at z > 6 (Methods). The presence of the proximate ND1 galaxy is consistent with the high abundance of companion galaxies reported around luminous quasars at z > 6 (ref. 15).

The precise redshift determination and the rich multiwavelength datasets in the GOODS North field provide a unique opportunity to constrain the host galaxy properties separate from the UV luminous core. Fits to the optical-to-millimetre spectral energy distribution (SED) yield an IR luminosity (rest-frame 8–1,000 μm) of $L_{\text{IR}} = (1.2 ± 0.6) \times 10^{11} L_\odot$ (where $L_\odot$ is the luminosity of the Sun) (Fig. 2). This corresponds to a star-formation rate (SFR) of $1,600 ± 700 M_\odot$ yr$^{-1}$ after removing the potential contribution of the emission associated with the active galactic nucleus (AGN). Regardless of the interpretation, the host of GNz7q is the most vigorously star-forming galaxy at z > 7 found so far. It has an SFR surface density of $≥1,100 M_\odot$ yr$^{-1}$ kpc$^{-2}$, which is at the Eddington limit for star-forming galaxies. Treating GNz7q as a UV compact star-forming object instead of an AGN would increase the SFR estimate. The dust in the host has an effective radius of $r_e = 1.4$ kpc. An upper limit of $r_e ≤ 0.5$ kpc, suggesting that the majority of the far-infrared (NIR) emission is arising from a compact region of ≤0.7 kpc$^2$. No close neighbours are detected in the millimetre line or continuum maps. However, a second source (‘ND1’) is seen in the 1-mm continuum map that is undetected in the deep HST images and can be best explained as a dusty companion about 16 kpc from GNz7q (Methods).

The high dust temperature and relatively faint [C ii] emission may be due to the maximum SFR surface density, as the strong radiation field produced by the intense starburst increases $T_d$ and decreases the abundance of singly ionized carbon. Dust and gas masses are estimated at $M_{\text{dust}} = 1.6 \times 10^9 M_\odot$ and $M_{\text{gas}} = 2.0 \times 10^{10} M_\odot$, making GNz7q one of the most dust- and gas-rich systems known at z > 6 (Methods). The presence of the proximate ND1 galaxy is consistent with the high abundance of companion galaxies reported around luminous quasars at z > 6 (ref. 15).

The dust- and gas-rich nature of the proximate ND1 galaxy is consistent with the high abundance of companion galaxies reported around luminous quasars at z > 6 (ref. 15). The AGN in GNz7q is two orders...
of magnitude fainter than its lower-

z analogue at $z = 4.6$, but with a host SFR about three times higher, suggesting that GNz7q is experiencing an early stage of its transition phase.

The extreme X-ray faintness of GNz7q is a strong indicator of the young age of the quasar. Extrapolating the anticorrelation between the X-ray luminosity and the AGN Eddington ratio ($\lambda_{\text{Edd}}$) to the X-ray component of the host galaxy ($\lambda_{\text{host}}$), we find that GNz7q is consistent with a very high accretion rate ($\lambda_{\text{Edd}} \gtrsim 1$) onto a less massive black hole ($M_{\text{BH}} \sim 10^8 M_\odot$). The dust-corrected optical luminosity $L'_{2,500\text{Å}}$ is used in the upper limit estimate of $\alpha_{\text{ox}}$ for GNz7q. SDSS quasar measurements (black squares) and the best-fit relation (black line) with its 1σ confidence level (grey shaded region) are taken from the literature (Methods). Grey circles are plotted for simulated galaxies (Methods) with AGN bolometric luminosity of $L_{\text{bol}} > 10^{42}$ erg s$^{-1}$. The colour scale and the horizontal range of each red shaded region of $M_{\text{BH}}$ corresponds to those of $a$.

$\alpha_{\text{ox}}$ is defined as $\alpha_{\text{ox}} = \log(L_{2\text{keV}}/L_{2,500\text{Å}})$, where $L_{2\text{keV}}$ is the X-ray luminosity normalized by the quasar bolometric luminosity $L_{\text{bol}}$. We show other populations for comparison: blue quasars at $z = 6$ (blue squares), red quasars at $z = 2$ and dusty starbursts at $z = 0$ (orange squares) taken from the literature (Methods). Grey circles are plotted for simulated galaxies (Methods) with AGN bolometric luminosity of $L_{\text{bol}} > 10^{42}$ erg s$^{-1}$. The colour scale and the horizontal range of each red shaded region of $M_{\text{BH}}$ corresponds to those of $a$. 

Fig. 2 | The spectral energy distribution of GNz7q from optical to radio wavelengths. Photometry is shown for data from HST (0.8–1.6 μm), Spitzer (3.6–24 μm), Herschel (80–500 μm), James Clerk Maxwell Telescope (JCMT) (450 μm and 850 μm), NOEMA (1 mm and 3 mm) and the Karl G. Jansky Very Large Array (JVLA) (3 cm and 20 cm) in the GOODS North field (Extended Data Table 1). Triangles indicate 3σ upper limits. The sum of the best-fit quasar/AGN (black solid) and galaxy (black dashed) templates is shown as a red curve. The radio detection at 20 cm is consistent with the enormous implied SFR of the host galaxy (Methods). For comparison, we also show the SEDs of other source populations at similar redshifts: optically luminous blue quasars at $z = 7.54$ (J1342+0928 (ref. 4); blue squares) and $z = 7.08$ (J1120+0641 (ref. 3); blue stars) and a dusty starburst at $z = 6.90$ (SPT0311-58W (ref. 136); orange circles). The blue curve is drawn with the quasar/AGN template normalized to J1120+6410’s rest-frame UV emission. The orange curve is the best-fit SED for SPT0311-58W, taken from the literature (Methods). The SED of GNz7q falls between these two categories of the dusty starburst and the blue quasar, representing a transient phase between them.

Fig. 3 | The unique X-ray faintness of GNz7q. The 2-Ms deep Chandra data$^12$ provide a stringent upper limit (red dashed line) for the X-ray luminosity, suggestive of a very high accretion rate ($\lambda_{\text{Edd}} \gtrsim 1$) onto a less massive black hole ($M_{\text{BH}} \leq 10^8 M_\odot$). a. Optical to X-ray spectral index $\alpha_{\text{ox}}$ as a function of Eddington ratio ($\lambda_{\text{Edd}}$). The dust-corrected optical luminosity $L'_{2,500\text{Å}}$ is used in the upper limit estimate of $\alpha_{\text{ox}}$ for GNz7q. SDSS quasar measurements (black squares) and the best-fit relation (black line) with its 1σ confidence level (grey shaded region) are taken from the literature (Methods). The upper horizontal axis shows the equivalent black hole mass for GNz7q as a function of $\lambda_{\text{Edd}}$ on the basis of its AGN bolometric luminosity from the UV to millimetre SED fitting (Methods). The red shaded region shows the $\lambda_{\text{Edd}}$ regime of GNz7q extrapolated from the best-fit relation, where the shading becomes darker with increasing $\lambda_{\text{Edd}}$. b. X-ray luminosity ($L_x$) normalized by $L_{\text{bol}}$. We show other populations for comparison: blue quasars at $z = 6$ (blue squares), red quasars at $z = 2$ and dusty starbursts at $z = 0$ (orange squares) taken from the literature (Methods). Grey circles are plotted for simulated galaxies (Methods) with AGN bolometric luminosity of $L_{\text{bol}} > 10^{42}$ erg s$^{-1}$. The colour scale and the horizontal range of each red shaded region of $M_{\text{BH}}$ corresponds to those of $a$. 

Nature | Vol 604 | 14 April 2022 | 263
upper limit of GNz7q, we obtain an Eddington ratio significantly (5.5σ) greater than unity and a black-hole mass of only $M_{\text{BH}} = 10^7 M_\odot$ (Fig. 3a; see also Methods). X-ray-weak quasars are found to be abundant among weak-emission-line quasars (rest-frame equivalent width of C iv EW(C iv) < 10 Å) with more powerful nuclear winds. These trends can be explained by a scenario where the inner region of the accretion disk is strongly inclined to a substantial height owing to the unusually high accretion, which blocks the nuclear ionizing continuum and the X-rays from reaching the broad-line region and external observers. GNz7q is indeed lacking the C iv line in our spectroscopy (EW(C iv) < 10 Å), consistent with this scenario.

These observational results can be compared with cosmological semi-analytic models for progenitors of high-z quasars. Among simulated merger histories, several progenitors with multiwavelength properties similar to GNz7q indeed have relatively low-mass SMBHs ($M_{\text{BH}} = 10^{6.5-7.5} M_\odot$), but still reside in the most massive halos of approximately $10^{11.5-12.5} h^{-1} M_\odot$ at $z = 7.2$ (Fig. 4). These simulations show that all of these progenitors will evolve into optically luminous blue quasars harbouring an SMBH with $M_{\text{BH}} > 10^8 M_\odot$ at $z = 6.4$. This indicates that GNz7q could be the direct progenitor of an optically luminous quasar, although models do not rule out the possibility that GNz7q will fail to finalize its transition at later epochs because of possible mergers with other halos hosting more massive BHs. The simulations and recent observations also predict a tight correlation between $M_{\text{BH}}$ and the X-ray luminosity normalized by infrared luminosity, $L_{\text{X}}/L_{\text{IR,60}}$, confirming that the unique X-ray faintness of GNz7q corresponds to the regime of $M_{\text{BH}} > 10^8 M_\odot$ (Fig. 3b).

Given the short-lived nature of a transitioning red quasar and the intrinsically low sky density of the quasar population, it is remarkable to find GNz7q within the 170 arcmin$^2$ GOODS North field. Assuming instead a total survey area of the entire HST archive of nearly 3 deg$^2$, the identification of GNz7q suggests a sky density of $0.33 \pm 0.22$ deg$^{-2}$ and a lower limit of $3.3 \times 10^{-3}$ deg$^{-2}$ on the basis of the Poisson uncertainty at the 99% single-sided confidence level. However, the quasar luminosity function and the red quasar fraction at $z = 6$ suggest a much lower predicted sky density of $6.8 \pm 1.3$ deg$^{-2}$, even for less luminous red quasars similar to GNz7q. A recent HST study also reports a potentially higher density of less luminous quasars at $z = 8$ than the quasar luminosity function at $z = 5$ (ref. 25). Together, these results may imply that the red and/or less luminous quasar population is more common at $z > 7$ than our understanding to date up to $z = 6$ (ref. 26).

We note in passing that classical colour selections for high-z quasars in ground-based surveys would recover the identification of GNz7q (Methods). This implies that these quasar populations could have been missed in previous surveys owing to their faint nature in the MIR and X-rays and in their rest-frame UV lines, which are here overcome by the uniquely deep and rich multiwavelength datasets of the GOODS North field. A systematic high-resolution, deep imaging survey in the optical–MIR bands may discover additional objects similar to GNz7q. Furthermore, follow-up spectroscopy of broad Balmer lines for $z > 7$ objects will become possible with the launch of the James Webb Space Telescope. This will have the power to decisively determine whether the quasar classification is correct and to determine how common such quasars truly are. Even a non-detection of broad lines would imply intriguing conclusions, that is, the existence of extraordinarily luminous and compact star-forming regions or stark differences between the first quasars and their descendants.

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-022-04454-1.

1. Volonteri, M. The formation and evolution of massive black holes. Science **337**, 544–547 (2012).
2. Inayoshi, K. et al. The assembly of the first massive black holes. Annu. Rev. Astron. Astrophys. **58**, 27–97 (2020).
3. Mortlock, D. et al. A luminous quasar at a redshift of $z = 7.085$. Nature **474**, 616–619 (2011).
4. Bahadou, E. et al. An 800-million-solar-mass black hole in a significantly neutral Universe at a redshift of 7.5. Nature **553**, 473–476 (2018).
5. Hopkins, P. et al. A cosmological framework for the co-evolution of quasars, supermassive black holes, and elliptical galaxies. II. Formation of red ellipticals. Astrophys. J. Suppl. Ser. **175**, 390–422 (2008).
6. Wang, F. et al. A luminous quasar at redshift 7.642. Astrophys. J. Lett. **907**, L1 (2021).
7. Girod, M. et al. The infrared-luminous progenitors of high-z quasars. Mon. Not. R. Astron. Soc. **483**, 1256–1264 (2018).
8. Hathi, N. et al. Near-infrared survey of the GOODS-North field: search for luminous galaxy candidates at $z > 6.5$. Astrophys. J. **757**, 1 (2012).
9. Bouwens, R. et al. UV-continuum slopes of $z \gtrsim 4,000$ galaxies from the HUDF/XDF, HUDFO9, ERS, CANDELS-South, and CANDELS-North fields. Astrophys. J. 793, 115 (2014).
10. Selsing, J. et al. An X-Shooter composite of bright 1<z<2 quasars from UV to infrared. Astron. Astrophys. 585, A167 (2016).
11. Alam, S. et al. The eleventh and twelfth data releases of the Sloan Digital Sky Survey: final data from SDSS-III. Astrophys. J. Suppl. Ser. 219, 2 (2015).
12. Xue, Y. et al. The 2 Ms Chandra Deep Field-North Survey and the 250 ks Extended Chandra Deep Field-South Survey: improved point-source catalogs. Astrophys. J. Suppl. Ser. 224, 16 (2016).
13. Andrews, B. et al. Assessing radiation pressure as a feedback mechanism in star-forming galaxies. Astrophys. J. 727, 97 (2011).
14. Beelen, A. et al. 350 μm dust emission from high-redshift quasars. Astrophys. J. 642, 2 (2006).
15. Decarli, R. et al. Rapidly star-forming galaxies adjacent to quasars at redshifts exceeding 6. Nature 545, 457–461 (2017).
16. Barro, G. et al. CANDELS+3D-HST: compact SFGs at z ≈ 2–3, the progenitors of the first quiescent galaxies. Astrophys. J. 791, 1 (2014).
17. Tsai, C. et al. Super-Eddington accretion in the WISE-selected extremely luminous infrared galaxy W2246-0526. Astrophys. J. 819, 2 (2018).
18. Luo, B. et al. X-ray insights into the nature of PHL 1811 analogs and weak emission-line quasars: unification with a geometrically thick accretion disk? Astrophys. J. 805, 2 (2015).
19. Pu, X. et al. On the fraction of X-ray-weak quasars from the Sloan Digital Sky Survey. Astrophys. J. 900, 2 (2020).
20. Wu, J. et al. A population of X-ray weak quasars. PHL 1811 analogs at high redshift. Astrophys. J. 736, 1 (2011).
21. Valiante, R. et al. From the first stars to the first black holes. Mon. Not. R. Astron. Soc. 457, 3356–3371 (2016).
22. Glikman, E. et al. FIRST-2MASS red quasars: transitional objects emerging from the dust. Astrophys. J. 757, 1 (2012).
23. Gehrels, N. Confidence limits for small numbers of events in astrophysical data. Astrophys. J. 303, 336–346 (1986).
24. Kato, N. et al. Subaru High-z Exploration of Low-Luminosity Quasars (SHELLQs). IX. Identification of two red quasars at z>5.6. Publ. Astron. Soc. Jpn 528, 35 (2020).
25. Matsuda, Y. et al. Subaru High-z Exploration of Low-Luminosity Quasars (SHELLQs). IV. Discovery of 41 quasars and luminous galaxies at 5.7<z<6.9. Astrophys. J. Suppl. Ser. 237, 5 (2018).
26. Morishita, T. et al. SuperBoRG: exploration of point sources at z~8 in HST parallel fields. Astrophys. J. 904, 1 (2020).
27. Ni, Y. et al. QSO obscuration at high redshift (z>7): predictions from the BLUETIDES simulation. Mon. Not. R. Astron. Soc. 495, 2135–2151 (2020).

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s), under exclusive licence to Springer Nature Limited 2022
In this paper, error values represent the 1σ uncertainty, where σ denotes the root mean square or standard deviation; upper limits are indicated at the 3σ level; red symbols in the figures denote GNz7q, unless otherwise specified.

Cosmology
We adopt cosmological parameters measured by the Planck mission, that is, a cold dark matter ($\Lambda$CDM) model, where $\Lambda$ is the cosmological constant, with total matter, vacuum and baryonic densities in units of the critical density, $\Omega_m = 0.76$, $\Omega_b = 0.24$ and $\Omega_{\Lambda} = 0.04$, respectively, and Hubble constant, $H_0 = 100h$ km s$^{-1}$ Mpc$^{-1}$, with $h = 0.73$. On the basis of these parameters, we adopt the angular size distance of 5.32 kpc per arcsec at the source redshift of $z = 7.2$ in this paper.

Definition of quasar categories
In this paper, we make a distinction between a reddened type 1 quasar and a type 2 quasar, where we refer to the former as the red quasar. A type 1 quasar is defined to have at least one broad emission line (full-width at half-maximum (FWHM) $\geq 1000–2000$ km s$^{-1}$) in the spectrum, whereas type 2 quasars are defined by those that do not satisfy it, but have too bright narrow UV–optical or IR emission lines, X-ray or radio continuum for a galaxy. In the classical AGN unification models, this difference is generally explained by different viewing angles towards the central accretion disk, where the observer's line of sight in type 2 quasars penetrates through optically thick dusty material owing to the nearly edge-on view of the dust torus that blocks the nuclear broad emission lines. In this context, red quasars are generally defined to have at least one broad emission line in the spectrum, distinguishing them from type 2 quasars, but to be substantially reddened by dust. The extent of the dust reddening has been estimated a number of ways in the literature on the basis of optical, optical–MIR, NIR–radio and MIR.

Uniform processing of archival HST and Spitzer data
GNz7q was identified in a project nicknamed the Complete Hubble Archive for Galaxy Evolution (CHARGE). CHARGE aims to perform uniform processing and analysis of all archival HST and Spitzer data taken away from the Galactic midplane. HST Advanced Camera for Surveys (ACS) optical and the Wide Field Camera 3 (WFC3) NIR and Spitzer/Infrared Array Camera (IRAC) observations covering GNz7q were carried out by a variety of large extragalactic surveys and individual programmes. HST images were obtained in the F435W (6 exposures; 7.2-ks integration), F606W (23 exposures; 9.3 ks), F775W (35 exposures; 19 ks), F814W (42 exposures; 24 ks), F850LP (82 exposures; 37 ks), F105W (6 exposures; 3.3 ks), F125W (8 exposures; 4.4 ks), F140W (6 exposures; 1.2 ks) F160W (8 exposures; 5.4 ks) filters. The IRAC channel 1 (3.6 μm) and channel 2 (4.5 μm) integrations are 345 ks and 330 ks, respectively. We aligned all of the HST exposures to sources in the Gaia Data Release 2 catalogue and created final mosaics in a common pixel frame with 50-mas and 100-mas pixels for the ACS/WFC and WFC3/IR filters, respectively. We aligned the individual Spitzer exposures to the same astrometric frame as the HST frame and generated final drizzled IRAC mosaics with 0.5″ pixels. Further details of the HST (Spitzer) image processing with the grizli (golfir) software will be presented in V. Kokorev et al. (manuscript in preparation). In Fig. 1, we present the HST images of GNz7q.

Archival HST slitless spectroscopy of GNz7q is available with an integration time of 8.8 ks (12.7 ks) in the G02 (G141) grism from the HST General Observer (GO) programme 13420 (i660). Together, the two grisms cover 0.8 μm - λ < 1.7 μm without any gaps (Fig. 1). The slitless spectra are reduced and extracted with the grizli software.

The HST broad-band images and slitless spectroscopy show an ambiguous continuum break at about 1.0 μm. By using an SDSS red quasar template at $z = 3.11$ (SDSS spec-6839-56425-146), we obtain the rest-frame UV redshift at $z_{UV} = 7.23 \pm 0.05$. This is consistent with the [C ii] 158-μm line redshift of $z_{158} = 7.1899 \pm 0.0005$ within the uncertainties (’Multi-band photometry’ section). We fit a power-law ($F(λ) \propto λ^{-\beta}$) model to the rest-frame UV continuum of the G414 slitless spectrum at 1.10–1.66 μm, excluding 1.50–1.60 μm to avoid potential contribution from a C iii] λ1909 line and the noisy edge of the spectrum (Fig. 1), and measure a best-fit power UV continuum slope $\beta = 0.1 \pm 0.3$. By subtracting the best-fit power-law continuum and optimizing the integration range of the spectrum, the broad Lyman α (Lyα) and C i] lines are tentatively detected at 3.76 and 3.46 levels, respectively. Assuming a C i] line width of FWHM – 3,000 km s$^{-1}$ typical among $z > 6$ quasars from the literature, we derive a 3σ upper limit of EW(C IV) – 10 Å from the grism spectrum.

In Extended Data Fig. 1, we compare the rest-frame UV properties of GNz7q with other populations at similar redshifts. The absolute UV luminosity at 1.450 Å ($M_{UV}$) is estimated from the best-fit power-law model. We find that the UV luminosity of GNz7q falls between that of typical quasars and galaxies in the literature, being around ten times fainter and brighter than typical quasars and galaxies, respectively, where several faint quasars and luminous galaxies have been reported. The UV continuum slope of GNz7q is redder than that of any other object in either comparison population.

Extended Data Fig. 2 shows the rest-frame UV morphology in all HST WFC3/IR bands and the radial profile of GNz7q observed with HST/F125W. The instrumental point spread function (PSF) model can fully explain the rest-frame UV morphology/radial profile in all bands. The Sérsic profile fitting with galfit provides almost the same profile as the PSF model in all bands. On the basis of the F125W band, we measure an effective radius of $r_e = 0.06 \pm 0.07$ pixel (pixel scale 0.06”) and adopt a 2σ upper limit of $r_e < 0.02$ pixel = 60 pc. We obtain similar results in the Sérsic profile fitting to the other bands.

NOEMA observations, data reduction and measurements
We observed [C II] with band 3 (1 mm), and CO(7–6), CO(6–5) and [C i] (2–1) lines with band 1 (3 mm) of the Institute Radio Astronomie Millimétrique (IRAM) Northern Extended Millimeter Array (NOEMA). The observations were carried out between 17 June 2020 and 24 February 2021 in various visits with the AC and D array configurations for the 1-mm and 3-mm observations, respectively, using nine or ten antennas. The data were processed in the standard manner with the pipeline using the latest version of the GILDAS software. We used CASA version 5.6 for the imaging.

For the [C II] observations, the upper side band (USB) of the 1-mm band receiver was tuned to 231.8 GHz in the first execution with the C configuration to cover the [C II] line at the source redshift estimated from the far-ultraviolet (FUV) Lyman continuum break (Fig. 1). After confirming the [C II] line detection, we tuned lower side band (LSB) with the A configuration to cover a wide frequency range for the continuum emission. For the 3-mm observations, the 3-mm band receiver
was tuned to 97.7 GHz to cover CO(7–6) and [C II](2–1) in the USB and CO(6–5) in the LSB. In both observations, 0851+202 served as band-pass phase calibrator. Additional targets 1300+580 and 1044+719 were used for the phase and amplitude calibrations. We calibrated the absolute flux scale against MWC349 whose flux is regularly monitored at NOEMA. We adopt conservative uncertainties on the absolute scale of 20% and 10% in the 1-mm and 3-mm observations, respectively. The total integration time on-source was 6.8 h and 13.5 h in the 1-mm and 3-mm bands, respectively.

To maximize sensitivity, we used natural weighting for the imaging. The resulting 1-mm and 3-mm maps have a synthesized beam FWHM of \(0.64\times0.44'\) and \(4.7'\times4.1'\), with 3σ sensitivities of 21 μJy per beam and 6.3 μJy per beam for the continuum, and 0.25 μJy per beam and 0.17 μJy per beam for the line per 60 km/s cell, respectively. We produce the 1-mm and 3-mm continuum map from the all line-free channels, except for noisy channels around the central frequency channels of LSB and USB, and the line cubes with several velocity bins in the range of 40–60 km/s. The central wavelengths of the 1-mm and 3-mm continuum maps are 1.284 mm and 3.276 mm, respectively.

The continuum is detected both from the 1-mm and 3-mm maps with the peak intensity at 16σ and 39σ, respectively. The [C II] line is robustly detected at 232.060 ± 0.013 GHz with FWHM = 280 ± 40 km/s and 17σ peak intensity at 16σ. The central wavelengths of the 1-mm and 3-mm continuum maps from the all line-free channels, except for noisy channels around the central frequency channels of LSB and USB, and the line cubes with several velocity bins in the range of 40–60 km/s. The central wavelengths of the 1-mm and 3-mm continuum maps are 1.284 mm and 3.276 mm, respectively.

The obtained 1-mm and 3-mm maps have a synthesized beam FWHM of \(0.64\times0.44'\) and \(4.7'\times4.1'\), with 3σ sensitivities of 21 μJy per beam and 6.3 μJy per beam for the continuum, and 0.25 μJy per beam and 0.17 μJy per beam for the line per 60 km/s cell, respectively. We produce the 1-mm and 3-mm continuum map from the all line-free channels, except for noisy channels around the central frequency channels of LSB and USB, and the line cubes with several velocity bins in the range of 40–60 km/s. The central wavelengths of the 1-mm and 3-mm continuum maps are 1.284 mm and 3.276 mm, respectively.

The resulting 1-mm and 3-mm maps have a synthesized beam FWHM of \(0.64\times0.44'\) and \(4.7'\times4.1'\), with 3σ sensitivities of 21 μJy per beam and 6.3 μJy per beam for the continuum, and 0.25 μJy per beam and 0.17 μJy per beam for the line per 60 km/s cell, respectively. We produce the 1-mm and 3-mm continuum map from the all line-free channels, except for noisy channels around the central frequency channels of LSB and USB, and the line cubes with several velocity bins in the range of 40–60 km/s. The central wavelengths of the 1-mm and 3-mm continuum maps are 1.284 mm and 3.276 mm, respectively.

The continuum is detected both from the 1-mm and 3-mm maps with the peak intensity at 16σ and 39σ, respectively. The [C II] line is robustly detected at 232.060 ± 0.013 GHz with FWHM = 280 ± 40 km/s and 17σ peak intensity at 16σ. The central wavelengths of the 1-mm and 3-mm continuum maps from the all line-free channels, except for noisy channels around the central frequency channels of LSB and USB, and the line cubes with several velocity bins in the range of 40–60 km/s. The central wavelengths of the 1-mm and 3-mm continuum maps are 1.284 mm and 3.276 mm, respectively.

The obtained 1-mm and 3-mm maps have a synthesized beam FWHM of \(0.64\times0.44'\) and \(4.7'\times4.1'\), with 3σ sensitivities of 21 μJy per beam and 6.3 μJy per beam for the continuum, and 0.25 μJy per beam and 0.17 μJy per beam for the line per 60 km/s cell, respectively. We produce the 1-mm and 3-mm continuum map from the all line-free channels, except for noisy channels around the central frequency channels of LSB and USB, and the line cubes with several velocity bins in the range of 40–60 km/s. The central wavelengths of the 1-mm and 3-mm continuum maps are 1.284 mm and 3.276 mm, respectively.

The resulting 1-mm and 3-mm maps have a synthesized beam FWHM of \(0.64\times0.44'\) and \(4.7'\times4.1'\), with 3σ sensitivities of 21 μJy per beam and 6.3 μJy per beam for the continuum, and 0.25 μJy per beam and 0.17 μJy per beam for the line per 60 km/s cell, respectively. We produce the 1-mm and 3-mm continuum map from the all line-free channels, except for noisy channels around the central frequency channels of LSB and USB, and the line cubes with several velocity bins in the range of 40–60 km/s. The central wavelengths of the 1-mm and 3-mm continuum maps are 1.284 mm and 3.276 mm, respectively.
photometry. We estimate the expected 450-μm flux density of NDI by assuming the typical MBB ($T = 35 K$ and $\beta = 1.8$) at $z = 7.2$. In the same manner, we also subtract the contribution from NDI in the 850-μm photometry. We then obtain the 450-μm and 850-μm photometry of $8.0 \pm 0.5$ mJy and $1.80 \pm 0.39$ mJy, respectively, which are also listed in Extended Data Table 1. Note that we confirm the consistency between the results with and without the tentative detection at the 450-μm band in the following analysis. Note that the contribution of the nearby faint HST objects to these FIR band photometry should be negligible owing to the absence of the detection in the deep NOEMA 1-mm map. Although NDI is detected in the deep NOEMA 1-mm map, a higher resolution 3-mm map with the Briggs weighting (robust $= 0.0$) whose beam size is smaller than the offset of NDI from GNz7q shows $-4 \pm 9$ μJy at the position of NDI. Thus, the 3-mm photometry of GNz7q is not affected by NDI.

In X-rays, there are zero events in the relevant pixel of GNz7q, even with the Chandra 2-Ms integration, some of the deepest X-ray data ever taken. The Chandra 2-Ms data have 0.171 mean background counts in the full band. On the basis of the continuous Poisson distribution with the mean of 0.171, we compute an upper limit on the net counts of $<1.1$ at the 99% confidence level. Assuming an average photon index $\Gamma = 2.0$ obtained among high-redshift quasars up to $z = 7.5$ (refs. 4, 76, 77), we use the online Portable Interactive Multi-Mission Simulator (see ‘Code availability’) and estimate upper limits for the X-ray luminosity to be $L_{\nu,2kev} < 5.1 \times 10^{27}$ erg s$^{-1}$ Hz$^{-1}$ at 2 keV and $L_{\nu,2kev} < 3.9 \times 10^{27}$ erg s$^{-1}$ at 2–10 keV, including a correction for the Galactic absorption in this direction with the hydrogen column density of $N_H = 9.64 \times 10^{21}$ cm$^{-2}$ (ref. 78). It is noted that the upper limit estimate depends on the choice of $\Gamma$. The typical range of spectral indices for X-ray AGN at this redshift is $\Gamma = 1.7$–2.3 (ref. 7). Assuming that even an extremely soft spectrum $\Gamma = 2.3$ increases the luminosity upper limit by about 30%, still well below the expected value.

Following the definition of the optical to X-ray spectral index $\alpha_{\text{ox}} = \log (L_{\nu,2kev}/L_{\nu,2500}) / \log (\nu_{2kev}/\nu_{2500})$ (2)

we then obtain the upper limit of $\alpha_{\text{ox}} < -2.23$. It is noted that here we use the dust-corrected $L_{\nu,2500}$ value for $L_{\nu,2500}$. In Extended Data Fig. 6, we show the tight correlation between $\alpha_{\text{ox}}$ and $L_{\nu,2500}$ previously observed for local and high-z quasars (76, 80, 82). The stringent upper limit of the X-ray luminosity makes GNz7q deviate from this correlation by more than 5σ. In Fig. 3a, we show another tight correlation between $\alpha_{\text{ox}}$ and $L_{\nu,2500}$ known to exist among local and high-z quasars (80, 81, 83–85). The black shows the best-fit relation estimated by Lusso et al. (86), and the gray shaded region represents the 68th percentile of the relation evaluated in the following analysis. Note that the contribution of the nearby faint HST objects to these FIR band photometry should be negligible owing to the absence of the detection in the deep NOEMA 1-mm map. Although NDI is detected in the deep NOEMA 1-mm map, a higher resolution 3-mm map with the Briggs weighting (robust $= 0.0$) whose beam size is smaller than the offset of NDI from GNz7q shows $-4 \pm 9$ μJy at the position of NDI. Thus, the 3-mm photometry of GNz7q is not affected by NDI.

Interpretations for GNz7q

On the basis of the multiwavelength observation results, there are two possible interpretations for GNz7q: a type 1 red quasar or a very compact UV luminous starburst region. The quasar interpretation is supported by the compact and luminous UV emission and the bright detection at rest-frame 3 μm (MIPS 24 μm). The starburst interpretation is motivated by the stringent upper limit on the X-ray luminosity and the absence of the clear detection of broad FUV emission lines between Ly$\alpha$ and C III] λ1909.

In Extended Data Fig. 7, we compare the rest-frame UV size and luminosity of GNz7q with those of galaxies at $z > 5.5$ and UV compact galaxies at $2 \leq z \leq 3$ (refs. 36, 49, 90–92). For a more direct comparison, we show the observed UV luminosity without any dust correction. If the UV emission of GNz7q is interpreted as arising from hot, recently formed stars, we find that the implied SFR surface density reaches $\sim 5000 M_{\odot} yr^{-1} kpc^{-2}$, exceeding that of even the UV compact galaxies by two orders of magnitude; any dust correction will make this more extreme still. Such a luminous and compact object can more reasonably be explained by emission from a hot accretion disk in an active nucleus. In this case, the prominent FUV emission and its red continuum slope suggest that GNz7q is a type 1 red quasar. The full SED analysis (see ‘UV–millimetre SED fitting’ section) indicates an optical colour excess $E(B-V) = 0.11 \pm 0.03$, which would satisfy the colour threshold for red quasars used in the literature (32, 33).

Extended Data Fig. 8 shows NIR–MIR SED and colour properties of GNz7q, galaxies, and both local and high-redshift quasars. The most striking feature of the GNz7q SED is the red colour between the observed Spitzer IRAC 8-μm and MIPS 24-μm band-passes, which probe rest frames of about 1 μm and 3 μm, respectively, at $z = 7.2$. A galaxy stellar population fit to the GNz7q photometry at $\lambda_{\text{filt}} < 10 \mu m$ is shown in the yellow line in Extended Data Fig. 8, along with additional stellar population templates that generally span the galaxy colour space and that include highly obscured starbursts. Also shown is the average MIR spectrum of local quasars and a collection of broad-band SEDs of quasars at $z = 6$ (ref. 78). The flux enhancement in the MIPS 24-μm band cannot be explained by reasonable galaxy stellar population models, which are relatively blue between rest-frame wavelengths 1–3 μm largely independent of star formation history and dust attenuation (that is, the 1.6 μm bump feature). However, the NIR colors of GNz7q are exactly consistent with the typical SEDs of quasars and active nuclei, where the rest-frame 3-μm emission is thought to arise from hot dust associated with the nucleus.

Although the broad UV emission lines are not clearly detected (Fig. 1), a notable group of quasars with exceptionally weak UV broad emission lines have been identified at lower redshifts (90, 102). Moreover, the X-ray observations show that these weak emission line quasars also have weak X-ray emission with higher X-ray spectra and high-ionization lines that are more blueshifted than those of normal quasars (21, 101, 102). This suggests that the X-ray absorption is due to Compton-thick material covering the inner part of the accretion disk, consistent with the small-disk scenario (see ‘Multi-band photometry’ section). A similar implication of the small, Compton-thick absorber has also been obtained from the weak X-ray emission in one of the nearest quasars embedded in the ULIRG-class dusty starburst Mrk 231 (103, 104), which also shows weak high-ionization lines and a very high nuclear outflow velocity of $\sim 8000 \text{ km s}^{-1}$ (refs. 103, 104). Therefore, the extremely faint X-ray luminosity and the lack of broad UV emission lines do not necessarily
It is noted that the uniquely deep X-ray data and general $L_\text{SFR}$ and SFR relations\textsuperscript{114} expect the X-ray detection from such an enormous SFR of the host galaxy, whereas the non-detection of X-ray could be explained by the metallicity dependence of the $L_\alpha$ and SFR relation. $L_\text{SFR}$ at a given SFR decreases in high-metallicity systems\textsuperscript{83,84}. On the basis the recent calibration of Fornasini et al.\textsuperscript{116}, we find that at least the solar value is required for the gas-phase metallicity of the host galaxy to meet the X-ray upper limit (see ‘Multi-band photometry’ section). As the SFR estimate for the host galaxy of GNz7q is not much changed regardless of its interpretation, the non-detection of X-ray thus suggests that the host galaxy has experienced a rapid metal enrichment and reached the solar metallicity even at $z = 7.19$. This is consistent with recent Atacama Large Millimeter/submillimeter Array (ALMA) results for a similarly distant quasar at $z = 7.54$ that the interstellar medium gas-phase metallicity of the host galaxy is comparable to the solar value via FIR line diagnostics\textsuperscript{87}.

$M_{\text{gas}}$ and $M_{\text{dyn}}$ estimates

We obtain molecular gas mass $M_{\text{gas}}$ estimates from five empirical calibrations; the metallicity-dependent $\delta_{\text{GDR}}$ method\textsuperscript{118} ($M_{\text{gas(dust)}}$), the monochromatic Rayleigh–Jeans (RJ) dust continuum approach\textsuperscript{119} ($M_{\text{gas(dust)}}$), the CO line luminosity, the $\text{[C\scriptsize{II}]}$ line luminosity\textsuperscript{120} ($M_{\text{gas(CIR)}}$), and the $\text{[C\scriptsize{II}]}/(2\rightarrow1)$ line luminosity\textsuperscript{120} ($M_{\text{gas(CIR)}}$). First, following the method in the previous studies\textsuperscript{120}, we convert the inferred $M_{\text{gas}}$ to $M_{\text{dyn}}$, adopting a typical gas-to-dust ratio at solar metallicity, $\delta_{\text{GDR}} = 92$. This yields $M_{\text{gas}}/M_{\text{dyn}} = (1.4 \pm 1) \times 10^{10}$, which agrees well with the estimate inferred from the RJ approach, $M_{\text{gas}}/M_{\text{dyn}} = (2.0 \pm 1.2) \times 10^{9}$. For the latter, we adopted a RJ luminosity-to-mass ratio $a_r = L_{\text{gas}}/M_{\text{gas}} = 6.7 \times 10^{10} \text{ erg s}^{-1} \text{ Hz}^{-1} M_{\odot}^{-1}$ calibrated with star-forming galaxies including local spiral and $z = 2$ SMGs following Scoville et al.\textsuperscript{115}. Moving to the line tracers, we first estimate the area-integrated CO(1–0) intensity $L_{\text{CO}}\rightarrow\text{d}$ = (1.3 ± 0.6) $\times 10^{10}$ Jy km s$^{-1}$ pc$^{-2}$ from the CO(7–6) line detection, assuming that $L_{\text{CO}}\rightarrow\text{d}$ = (1.5 ± 0.2) $\times 10^{10}$ estimated in dusty starburst galaxies at $z > 6$ in the literature\textsuperscript{121,122}. We then estimated $M_{\text{gas,CO}}/M_{\text{CO}}$ = (5.0 ± 3.0) $\times 10^{9}$ assuming $L_{\text{CO}}\rightarrow\text{d} = 4.6 M_{\odot}$ (km s$^{-1}$ pc$^{-2}$)\textsuperscript{123} (eq. 16). To convert the $\text{[C\scriptsize{II}]}$ line to $M_{\text{gas}}$, we use the $a_{\text{IC,\scriptsize{CII}}} = M_{\text{gas}}/L_{\text{IC,\scriptsize{CII}}} = 22M_{\odot}/L_{\odot}$ conversion factor, as calibrated on starburst galaxies at $z = 2$–6 by ref. 120 and, adopting a 0.2-dex uncertainty, we estimate $M_{\text{gas(CIR)}} = 3.2 \pm 1.8 \times 10^{10} M_{\odot}$. Finally, we consider the measured 30 upper limit of the $\text{[C\scriptsize{II}]/(2\rightarrow1)}$ line that for $a_{\text{IC,2\rightarrow1}} = M_{\text{gas}}/L_{\text{IC,2\rightarrow1}} = 34 M_{\odot}$ (km s$^{-1}$ pc$^{-2}$) and a 0.32-dex uncertainty\textsuperscript{10,121}, we obtain an upper limit of $M_{\text{gas,CIR}}/M_{\odot} \leq 1.6 \times 10^{10}$. These independent $M_{\text{gas}}$ estimates are in excellent agreement with each other within the uncertainties. For the purposes of this work, we determine $M_{\text{gas}} = (2.0 \pm 1.2) \times 10^{10} M_{\odot}$ by adopting the median value among $M_{\text{gas(\text{dust})}}$, $M_{\text{gas(\text{CO})}}$, and $M_{\text{gas(CIR)}}$. Note that the $M_{\text{gas(\text{dust})}}$ and $M_{\text{gas(\text{CO})}}$ estimates could be decreased by factors of several based on another assumptions of $\delta_{\text{GDR}} = 30$ and $\alpha_r = 0.5$ in the super-solar metallicity case.

We estimate the dynamical mass of the system $M_{\text{dyn}}$ of the $\text{[C\scriptsize{II}]}$ line results. Given the absence of the clear velocity gradient in GNz7q, we interpret $\text{[C\scriptsize{II}]}$ Q as host as a dispersion-dominated system and assume a virialized body with a radius $R$ kpc and one-dimensional velocity dispersion $\sigma$ km s$^{-1}$, which yields\textsuperscript{120}

$$ M_{\text{dyn}}/M_{\odot} = 1.56 \times 10^{4} R. $$(3)

For consistency with previous studies\textsuperscript{127–129}, we use $r_{\text{IC,\scriptsize{CII}}}$ for $R$ after applying a correction factor of 1.5 to recover the contribution of the diffuse emission. We then obtain $M_{\text{dyn}} = (4.5 \pm 0.9) \times 10^{10} M_{\odot}$, which satisfies the requirement that it should be larger than the $M_{\text{gas}}$ estimate. Owing to the negligible dark-matter contribution to $M_{\text{dyn}}$ within a compact scale of $1.5 \times r_{\text{IC,\scriptsize{CII}}}$, we subtract $M_{\text{gas}}$ from $M_{\text{dyn}}$ and derive $M_{\text{star}}$ of $(2.5 \pm 1.4) \times 10^{10} M_{\odot}$. If we apply a typical dust-to-stellar mass ratio of 0.01 to $M_{\text{star}}$, we obtain another estimate of $M_{\text{gas,IR}}$ of $(1.6 \pm 1.1) \times 10^{9} M_{\odot}$, which is consistent with the above $M_{\text{star}}$ estimate within the uncertainties.
Comparison with other populations

Compared with type 2 quasars that are almost completely obscured in the UV/optical owing to the nearly edge-on view of the dust torus, the reddening of red quasars is more moderate than that of type 2 quasars, where the sight lines to red quasars may graze the dusty material surrounding the accretion disk. In this context, red quasars are thought to represent an early phase of the quasar life cycle: an obscured phase before the energy output from radiation, winds and/or jets from the AGN and central star formation expels the obscuring material and transitions to an unobscured blue quasar. This is consistent with hydrodynamical simulations of galaxy mergers and quasar feeding\(^\text{4}\), and supportive observational results have been also reported at \(z = 1 - 3\) (refs. \(13\text{a,13b} - 13\text{d}\)). To investigate whether GNz7q at \(z = 7.2\) is also consistent with this scenario, we compare its physical properties with those of dusty starbursts, red quasars and blue quasars in the literature.

In Extended Data Fig. 9, we compare \(L_{\text{CII}}/L_{\text{in}}\) and \(L_{\text{in}}/L_{\text{IR}}\) for red quasars and blue quasars at \(z > 6\), which is used in the DL07 model. We assume \(T_d = 47\) K and \(\beta_d = 1.6\) when the source has been observed only with a single submillimetre or millimetre band, otherwise we use the longest wavelength measurements available and adopt the \(T_d\) and \(\beta_d\) estimates in the literature\(13\text{a,13b,143,144}\). As a ±10-K change in the \(T_d\) assumption produces a roughly 0.2–0.3 dex difference in the SFR and \(M_{\text{dust}}\) estimates for the sources whose \(T_d\) and \(\beta_d\) are assumed to be 47 K and 1.6, respectively, we add a 0.2 dex uncertainty to the measurement uncertainty in their error bars in Extended Data Fig. 10. We find that the \(M_{\text{dust}}\) and \(M_{\text{gas}}\) values of GNz7q fall in the range probed by blue quasars at the same epoch, whereas the implied SFR is the highest among \(z > 7\) objects so far observed. This indicates that the intense starburst is taking place in the host galaxy of GNz7q with a very short depletion timescale of about 10 Myr, which is consistent with the scenario that the red quasar is forming in the dusty starburst. The higher SFR of GNz7q’s host galaxy than the hosts of lower-redshift red quasars may indicate that GNz7q is experiencing an early stage of its transition phase from the dusty starburst to the blue quasar. In fact, the \(M_{\text{dust}}\) values of the lower-z red quasars are estimated to fall in the super-massive regime of \(\log(M_{\text{dust}}/M_\odot) = 9.3–9.6\) (refs. \(12\text{b}\)). This may suggest that these lower-z red quasars are found at the end phase of the SMBH evolution and that the super-Eddington accretion in W2246−0526 is caused by an active quasar duty cycle even at the end phase. Although there is a possibility that the SFR values in the blue quasars are also increased if their \(T_d\) values are as high as GNz7q, previous studies of blue quasars at \(z > 6\) with multiband FIR photometry in ALMA bands 6 and 9 generally show the FIR SED with \(T_d = 40–50\) K (refs. \(13\text{a,13b,143,144}\)). Furthermore, the rest-frame IR regime of the blue line in Fig. 2 implies that the AGN contribution to \(L_{\text{in}}\) could be much larger in these luminous quasars than that of GNz7q, which reduces their SFR estimates.

In Extended Data Fig. 11, we present \(M_{\text{BH}}\) and \(M_{\text{dyn}}\) properties. For GNz7q, we show the Eddington-limited \(M_{\text{BH}}\) estimate in the red circle and the potential \(M_{\text{BH}}\) range indicated by its extremely faint X-ray property in the red shaded regions whose colour scale and vertical range of each red shade region correspond to those of Fig. 3. For blue quasars at \(z = 6 – 7\), we show \(M_{\text{dyn}}\) measurements based on a systematic kinematic modeling with the ALMA data\(16,17\). We include \(M_{\text{dyn}}\) measurements for \(z > 6\) quasars on the basis of the assumption of the rotating disk geometry and the axial ratio of [C ii] flux map as proxy of the disk inclination angle\(12\text{d}-12\text{f})\). We also show (1) the best-fit relation between the stellar mass in the bulge \(M_{\text{bulge}}\) and \(M_{\text{BH}}\) obtained in local quiescent galaxies\(18\), where we use \(M_{\text{bulge}}\) as \(M_{\text{dyn}}\) and (2) the \(M_{\text{BH}}\) and \(M_{\text{bulge}}\) relation for red quasars at \(z = 2\) that generally fall below the local relation\(19\). We find a relatively low fraction of \(M_{\text{BH}}/M_{\text{bulge}} < 0.2%\) that falls below the local relation\(19\), similar to the general relation of the red quasars at \(z = 2\). In contrast to ideas of an ‘over-massive’ SMBH relative to the host galaxy reported in previous optically luminous quasars at \(z > 6\) (refs. \(12\text{d,12e})\), the ‘under-massive’ SMBH of GNz7q at \(z = 7.2\) offers an intriguing path to the co-evolution between the SMBH and its host in the early Universe: the host galaxies grow earlier than the SMBHs, which is aligned with the predictions of the merger-driven SMBH evolution models\(1\). The ‘under-massive’ SMBH is also argued in recent reports of less luminous quasars\(19,16\), but generally their central BHS are already massive \(M_{\text{BH}} = 10^6 – 10^7\) M_\odot with low \(\lambda_{\text{abs}} < 0.1–0.2\) (refs. \(16,18\)), and thus could be placed at the end-phase of the SMBH evolution after the blue-quasar phase\(18\).

We note that it is unclear whether the quasar host galaxies at \(z > 6\) are the bulge-dominated systems similar to the local quiescent galaxies. We thus also show another best-fit relation between the stellar mass of the entire system and \(M_{\text{BH}}\) among local AGNs\(19\), which the \(M_{\text{BH}}\) range of GNz7q still falls below or on the best-fit relation.

The IR/radio correlation

The correlation between the IR luminosity and the radio emission has been empirically known for several decades. On the basis of the radio detection of GNz7q at 20 cm/1.5 GHz (ref. \(7\)), we evaluate the IR and
radio correlation. From previous studies, the IR and radio correlation is typically evaluated with the parameter $q_{\text{IR}}$ given by

$$q_{\text{IR}} = \log \left( \frac{1.01 \times 10^{48} L_{\text{IR}}}{4.0D^2_{\text{L}}(1+z)\alpha_{\text{IR}}} \right) - \log \left( \frac{10^{32} F_{\alpha_{\text{IR}}}}{(1+z)^2 L_{\text{IR}}} \right),$$

(5)

where $F_{\alpha_{\text{IR}}}$ is the observed flux density at 1.4 GHz and $\alpha_{\text{IR}}$ is the radio spectral index which is defined by $F_{\nu} \propto \nu^{\alpha_{\text{IR}}}$. Owing to the non-detection in a deep 10-GHz map, we obtain a constraint of $\alpha_{\text{IR}} < -1.0 \pm 0.6$. Given the large uncertainty for the $\alpha_{\text{IR}}$ constraint, we adopt a typical value of $\alpha_{\text{IR}} = -0.75$ (refs. 74, 154), convert the observed 1.5-GHz flux density to the 1.4-GHz flux density and estimate a $q_{\text{IR}}$ value of 2.1 \pm 0.3. This is consistent with a typical value range of local starburst galaxies and high-redshift SMGs153,156 and a recent report of the redshift trend among high-redshift star-forming galaxies157,158. We thus conclude that the majority of the radio emission of GNz7q is caused by the star-formation and classify the GNz7q as a radio-quiet object. This property agrees with the young quasar interpretation of GNz7q, because the radio loudness is a strong function of $M_{\text{BH}}$ and the radio-loud quasars generally have massive $M_{\text{BH}} > 10^{8} M_{\odot}$ (ref. 159).

**Comparison with simulations**

We compare our observational results with predictions from a data-constrained, semi-analytic model GAME-QSOdust (GQd) aimed at studying the formation and evolution of high-redshift quasars and their host galaxies in a cosmological framework152,159–161. Here we have analysed the hierarchical merger histories of ten massive dark-matter halos with $M_{\text{halo}} = 10^{13} M_{\odot}$ at $z = 6.4$, designed to reproduced the observed properties of the optically luminous quasar SDSSJ1148 at $z = 6.4$ to investigate whether we could identify—among its progenitors at $z = 7.2$—systems with physical properties similar to GNz7q.

We first produce the ten merger trees for a $10^{13}$- $M_{\odot}$ dark-matter halo, decomposing it into its lower-mass progenitors backwards in time from $z = 6.4$ to $z = 24$ using a Monte Carlo algorithm based on the extended Press–Schechter formalism. Then GQd follows the evolution of the baryonic component within each progenitor halo along a merger tree, from $z = 24$ down to $z = 6.4$. At each redshift, in each halo, we follow the formation of stars and BHs (light and heavy seed formation channels are simultaneously implemented in the model) according to the environmental properties (that is, metallicity of the interstellar medium and the level of illuminating external ionizing and H$_{\text{II}}$ photodissociating radiation field). Black holes in the centre of galaxies can then grow via gas accretion and mergers with other black holes during major halo–halo mergers (dark-matter halos pair mass ratio $>1:4$) whereas in minor ($<1:4$) halo–halo mergers the least massive of the two black holes is ‘ejected’, it is considered as a ‘satellite’ and we do not further follow its evolution. We account for the effect of stellar- and AGN-driven feedback in the form of energy-driven winds and include calculations for the IR luminosity from the host galaxy and the X-ray luminosity from accreting black holes, considering the primary component of the hot corona and the reflection component of the surrounding neutral medium.

For each 10^{13}- $M_{\odot}$ halo merger tree GQd generates a catalogue of progenitor galaxies. Each catalogue contains the properties (for example, the mass of BH, gas, stars, dust, SFR, $L_{\text{IR}}$ and $L_{\text{X}}$) of all the progenitor systems (galaxy + black holes). In Fig. 4a, we show all the progenitors at redshift slices of $z = 7.1$, $z = 7.2$ and $z = 7.3$ in the catalogue. We mark four progenitors with black circles whose X-ray, optical and host galaxy properties are close to GNz7q with criteria of $L_{\text{X}} < 10^{44.5}$ erg s$^{-1}$, $\alpha_{\text{IR}} < -1.9$ and SFR $> 100 M_{\odot}$ yr$^{-1}$. The assembly histories of the nuclear black holes for these four progenitors are shown in Fig. 4b. We find that one of the four progenitors is a direct progenitor which evolves into a luminous quasar harbouring a SMBH with $M_{\text{BH}} > 10^{8} M_{\odot}$ at $z = 6.4$. We also confirm that this progenitor resides in one of the most massive dark-matter halos at $z = 7.2$ with a dark-matter halo mass of about $10^{12.7} M_{\odot}$. In the assembly histories, the remaining three progenitors are subsequently ejected from the centre or become satellites of more massive black holes as a consequence of a minor merger experienced by their host galaxies. Therefore, these black holes are not the direct progenitors of the final SMBHs, although their entire systems also form the SMBHs with $M_{\text{BH}} = 10^{9.5–10} M_{\odot}$ at $z = 6.4$.

**Classical colour selection for high-z quasar search**

A remarkable aspect is that GNz7q is discovered in a relatively small-area coverage of the entire HST archive (about 3 deg$^2$), compared with previous wide-area surveys used in the high-redshift quasar search. Mazzucchelli et al.156 used Panoramic Survey Telescope And Rapid Response System (Pan-STARS)154 and the UKIRT Infrared Deep Sky Survey (UKIDSS)155 data and selected the quasar candidates at $z > 6.5$ with the optical colour criteria of

$$z - y > 1.4$$

(6)

$$y - J < 1.0.$$  

(7)

Integrating the best-fit SED of GNz7q through the Pan-STARRS1 $z$ and UKIRT $y$ and $J$ filter bandpasses, we find it has $z - y = 5.8$ and $y - J = 0.5$, which comfortably satisfies the optical–NIR quasar selection criterion. This indicates that the quasar population similar to GNz7q could be identified in previous high-z quasar surveys if the data are sufficiently deep, such as the Canada–France High-z Quasar Survey154 and Subaru High-z Exploration of Low-luminosity Quasars150. GNz7q also meets the optical–NIR colour criteria used in recent discoveries of the luminous quasars at $z = 7.5$ (refs. 14, 159), although the optical–NIR data of the wide-area surveys used in these discoveries is almost two orders magnitude shallower than that of the GOODS North field.

These colour selection results indicate that the identification of GNz7q at $z = 7.2$ in the relatively small area of the entire HST archive might be just explained by chance, although the expected probability is less than 1% from the quasar luminosity function160 and the red quasar fraction at $z = 6$ (ref. 139). There are two other possibilities. The first is that the transitioning young quasar more frequently emerges at $z > 7$ than at $z = 6$. The second is that a quasar population similar to GNz7q has been identified in the previous surveys, but not regarded or classified as a quasar due to its faintness in the rest-frame UV, MIR, X-ray and radio continuum in the follow-up spectroscopy and/or multi-wavelength analyses. In fact, the presence of the deep HST and MIPS data is crucial for the interpretation for GNz7q (see ‘Interpretations for GNz7q’ section). Without them, the uniquely faint properties of GNz7q in the rest-frame UV emission lines and X-ray generally conclude its classification as a luminous galaxy. Recent studies have also suggested, both observationally and theoretically, a potential high abundance of the dust-rich quasar population at $z > 7$ (refs. 139, 160). A systematic deep, high-resolution optical–MIR imaging campaign for all luminous high-z galaxy candidates could lead to additional discoveries similar to GNz7q. Given the relatively robust calibration160 and lesser effects from the slim disk, detecting broad Balmer emission lines could provide a decisive conclusion for the quasar classification, which will soon become possible even at $z > 7$ with the launch of the James Webb Space Telescope. Moreover, even if we do not detect the broad lines with the James Webb Space Telescope, the results will suggest further exciting possibilities: the existence of an extraordinary UV luminous and compact star-forming region (Extended Data Fig. 7), or, that is, exactly what the first quasars look like.

**Data availability**

This paper makes use of HST data from the programmes 9583, 9727, 9728, 10189, 10339, 11600, 12442, 12443, 12444, 12445, 13063, 13420 and 13779, available at https://archive.stsci.edu/. The reduced HST and Spitzer image mosaics are available at https://doi.org/10.5281/
zenodo.4469734. Other products from the CHARGE project are available at https://github.com/brammer/grizli and https://github.com/brammer/gofir, respectively. The HST F125W image was analysed with galfit, which is available at https://users.obs.carnegiescience.edu/peng/work/galfit/galfit.html. The NOEMA data were reduced using the GILDAS software. The CASA pipeline version of 5.6 is also used for imaging the NOEMA interferometric data. These are available at https://casa.nrao.edu/casa_obtaining.shtml and https://www.nordic-alma.se/software-tools.php. The online Portable Interactive Multi- Mission Simulator is available at https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl.

Code availability

The HST and Spitzer data were processed with grizi and golfi, available at https://github.com/gbrammer/grizli and https://github.com/gbrammer/gofir, respectively. The NOEMA data are available at https://dr12.sdss.org/spectrumDetail?plateid=6839 mjd=56425 fiber=146. The datasets of local quasar and starburst are available from the SWIRE template website at http://www.iasf-milano.inaf.it/~polletta/templates/swire_templates.html. The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Matsuoka, Y. et al. Discovery of the first low-luminosity quasar at z=7. Astrophys. J. Lett. 872, L1 (2019).

Matsuoka, Y. et al. Subaru High-z Exploration of Low-luminosity Quasars (SHELLQs). X. Discovery of 35 quasars and luminous galaxies at 5.7<z<10. Astrophys. J. 883, 2 (2019).

Onoue, M. et al. Subaru High-z Exploration of Low-luminosity Quasars (SHELLQs). VIII. Black hole mass measurements of six quasars at 6.1<z<6.7. Astrophys. J. 880, 2 (2019).

Schouw, S. et al. Significant dust-obscured star formation in luminous Lyman-break galaxies at z<7–8. Preprint at https://arxiv.org/abs/2105.12313 (2021).

Peng, C. Y. et al. Detailed decomposition of galaxy images. II. Beyond axisymmetric models. Astron. J. 139, 2097–2129 (2010).

McMullin, J. et al. CASA architecture and applications. Astron. Data Anal. Softw. Syst. XVI 376, 127 (2007).

Marti-Vidal, I.et al. Over-resolution of compact sources in interferometric observations. Astron. Astrophys. 541, A135 (2012).

Fujimoto, S. et al. Demonstrating A New Census of Infrared Galaxies with ALMA (DANCING-ALMA). I. FIR size and luminosity relation at z=0–6 revealed with 1034 ALMA sources. Astrophys. J. 850, 1 (2017).

Franco, M. et al. GOODS-ALMA: the slow downfall of star formation in z=2–3 massive galaxies. Astron. Astrophys. 620, A152 (2018).

Franco, M. et al. GOODS-ALMA: the slow downfall of star formation in z=2–3 massive galaxies. Astron. Astrophys. 643, A30 (2020).

Wang, T. et al. A dominant population of optically invisible massive galaxies in the early Universe. Nature 572, 211–214 (2019).

Fudamoto, Y. et al. Normal, dust-obscured galaxies in the epoch of reionization. Nature 597, 489–492 (2021).

Cortzen, I. et al. Deceptively cold dust in the massive starburst galaxy GNO2 at z=4. Astron. Astrophys. 634, L14 (2007).

Jin, S. et al. Discovery of four apparently cold dusty galaxies at z=3.62–5.85 in the COSMOS field: direct evidence of cosmic microwave background impact on high-redshift galaxy redshifts. Astron. J. 887, 2 (2019).

Da Cunha, E. et al. An ALMA survey of sub-millimeter galaxies in the extended Chandra Deep Field South: physical properties derived from ultraviolet-to-radio imaging. Astron. J. 150, 110 (2015).

Kajisawa, M. et al. MOIRCS Deep Survey. IX. Deep near-infrared imaging data and source catalog. Publ. Astron. Soc. Jpn. 63, 379 (2011).

Magnelli, B. et al. Evolution of the dusty infrared luminosity function from z=0 to z=2.3 using observations from Spitzer. Astron. Astrophys. 528, 35 (2011).

Cowie, L. et al. A submillimeter perspective on the GOODS fields (SUPER GOODS). I. An ultra deep SCUBA-2 survey of the GOODS-N. Astrophys. J. 837, 139 (2017).

Owen, F. Deep I2LA Imaging of GOODS-N at 20 cm. Astrophys. J. Suppl. Ser. 235, 2 (2016).

Liu, D. et al. Super-deblended dust emission in galaxies. I. The GOODS-North catalog and the cosmic star formation rate density out to redshift 6. Astrophys. J. 853, 172 (2018).

Oliver, S. et al. The Herschel Multi-tiered Extragalactic Survey: HerMES. Mon. Not. R. Astron. Soc. 424, 1614–1645 (2011).

Murphy, E. et al. The GOODS-N Jansky VLA 10-GHz pilot survey: sizes of star-forming radio sources. Astrophys. J. 839, 1 (2017).

Geach, J. et al. The SCUBA-2 Cosmology Legacy Survey: 850 μm maps, catalogues and number counts. Mon. Not. R. Astron. Soc. 465, 1788–1806 (2017).

Nanni, R. et al. The X-ray properties of z=6 luminous quasars. Astron. Astrophys. 603, A128 (2017).

Vito, F. et al. Heavy X-ray obscuration in the most luminous galaxies discovered by WISE. Mon. Not. R. Astron. Soc. 474, 4528–4540 (2018).

HI4PI Collaboration. HI4PI: A full-sky H I survey based on EBHIS and GASS. Astron. Astrophys. 594, A116 (2016).

Wang, F. et al. Revealing the accretion physics of supermassive black holes at redshift 7–7.7 in four distant galaxy areas. Mon. Not. R. Astron. Soc. 489, L1 (2019).

Lusso, E. et al. The tight relation between X-Ray and ultraviolet luminosity of quasars. Astrophys. J. 819, 2 (2016).

Vito, F. et al. The X-ray properties of z=6 quasars: no evident evolution of accretion physics in the first Gyr of the Universe. Astron. Astrophys. 630, A118 (2019).

Shemmer, O. et al. Chandra observations of the highest redshift quasars from the Sloan Digital Sky Survey. Astrophys. J. 644, 1 (2006).

Charaluce, E. et al. The X-ray/UV ratio in active galactic nuclei: dispersion and variability. Astron. Astrophys. 619, A95 (2018).

Zou, F. et al. X-ray properties of dust-obscured galaxies with broad optical/UV emission lines. Mon. Not. R. Astron. Soc. 499, 1823–1840 (2020).

Kim, Y. et al. High star formation rates of low Eddington ratio quasars at z>6. Astrophys. J. 870, 1 (2019).

Iwasawa, K. et al. C-GOALs: Chandra observations of a complete sample of luminous infrared galaxies from the IRAS Revised Bright Galaxy Survey. Astron. Astrophys. 529, A106 (2011).

Veilleux, B. et al. A deep Hubble Space Telescope H-band imaging survey of massive gas-rich mergers. II. The QUEST QSOs. Astrophys. J. 701, 1 (2009).

Ni, Q. et al. Connecting the X-ray properties of weak-line and typical quasars: testing for a geometrical thick accretion disk. Mon. Not. R. Astron. Soc. 480, 5184–5202 (2018).

Muller-Sanchez, R. et al. The discovery of the most UV-luminous star-forming galaxy: the dusty, metal- and metal-poor starburst with QSO-like luminosities. Mon. Not. R. Astron. Soc. 499, 1 (2020).

Shibuya, T. et al. Morphologies of 190,000 galaxies at z>10–11 revealed with HST legacy data. Mon. Not. R. Astron. Soc. 480, L64 (2018).

Conroy, C. et al. The propagation of uncertainties in stellar population synthesis modeling. I. The relevance of uncertain aspects of stellar evolution and the initial mass function to the derived physical properties of galaxies. Astrophys. J. 699, 486 (2009).

Conroy, C. & Gunn, J. The propagation of uncertainties in stellar population synthesis modeling. III. Model calibration, comparison, and evaluation. Astrophys. J. 712, 833 (2010).
93. Brammer, G. et al. EAZY: A fast, public photometric redshift code. Astrophys. J. 686, 2 (2008).
94. Polletta, M. et al. Spectral energy distributions of hard X-ray selected active galactic nuclei in the XMM-Newton medium deep survey. Astrophys. J. 663, 1 (2007).
95. Gilfanov, M., Piro, L. & Revnivtsev, M. A near-infrared spectral template for quasars. Astrophys. J. 640, 2 (2006).
96. Leipski, C. et al. Spectral energy distributions of QSOs at z > 5: common active galactic nuclei-heated dust and occasionally strong star-formation. Astrophys. J. 785, 2 (2014).
97. Neri, R. et al. AGN dust tori. I. Handling of clumpy media. Astrophys. J. 658, 147 (2008).
98. Leja, J. et al. Hot dust in panchromatic SED fitting: identification of active galactic nuclei and improved galaxy properties. Astrophys. J. 864, 62 (2018).
99. Diamond-Stanic, A. & Jackson, D. High-redshift SDSS quasars with emission line widths. Astrophys. J. 699, 1 (2009).
100. Andikia, I. et al. Probing the nature of high-redshift emission line quasars: a young quasar with a starburst host galaxy. Astrophys. J. 903, 1 (2020).
101. Wu, J. et al. X-ray and multicolor images: insights from ALMA. Astrophys. J. 747, 1 (2012).
102. Vito, F. et al. Chandar and Magellen/FIRE follow-up observations of PGC06173: an X-ray weak QSO at z = 6.535. Astron. J. 649, A133 (2022).
103. Gallagher, S. et al. X-raying the ultra-luminous infrared starburst galaxy and broad absorption line QSO Markarian 231 with Chandra. Astrophys. J. 569, 655 (2002).
104. Braito, V. et al. The XMM-Newton and BeppoSAX view of the ultraluminous infrared galaxy MKN21. Astron. J. 420, 79 (2004).
105. Lipari, S., Colina, L. & Macchetto, F. Galaxies with extreme infrared and Fe II emission. I. Markarian 231: the signature of a young infrared QSO. Astrophys. J. 472, 1544 (1994).
106. Veilleux, S. et al. The complete ultra-violet spectrum of the archetypal "wind-dominated" quasar Mkn 231: absorption and emission from a high-speed dusty nuclei outflow. Astron. J. 825, 2 (2007).
107. Kokorev, V. et al. The evolving interstellar medium of star-forming galaxies, as traced by stellar dust. Astrophys. J. 921, 1 (2021).
108. Draine, B. & Li, A. Infrared emission from interstellar dust. IV. The silicate-graftite-PAH model on the post-Spitzer era. Astrophys. J. 657, 2 (2007).
109. Mullany, J. et al. GOODS-Herschel: the far-infrared view of star formation in active galactic nucleus host galaxies since z = 3. Mon. Not. R. Astron. Soc. 419, 91–115 (2012).
110. Shen, Y. et al. The Sloan Digital Sky Survey Reification Mapping Project: velocity shifts of quasar emission lines. Astron. J. 143, 51–63 (2012).
111. Murphy, E. et al. Calibrating extinction-free star formation rate diagnostics with 33 GHz free-free emission in NGC 6946. Astrophys. J. 737, 67 (2011).
112. Kroupa, P. On the variation of the initial mass function. Mon. Not. R. Astron. Soc. 322, 231–246 (2001).
113. Simpson, J. et al. The SCUBA-2 Cosmology Legacy Survey: ALMA resolves the rest-frame 850 μm emission in a high-redshift quasar host galaxy. Mon. Not. R. Astron. Soc. 438, 1581–1590 (2014).
114. Fazio, G. et al. The infrared properties of submillimeter and optically faint radio sources from the Green Bank Telescope. Mon. Not. R. Astron. Soc. 410, L53–L57 (2010).
115. Ibar, E. et al. Deep multi-frequency radio imaging in the Lockman Hole—II. The spectral index of sub-millimeter sources. Mon. Not. R. Astron. Soc. 410, 1976–1999 (2011).
116. Valiante, R. et al. The origin of the dust in high-redshift quasars: the case of SDSS J1449+5251. Mon. Not. R. Astron. Soc. 416, 1918–1935 (2011).
117. Hashimoto, T. et al. Detections of [O II] and [C II] emission in a high-redshift galaxy detected [O II] > 88 μm, [C II] > 158 μm, and dust continuum with ALMA. Astrophys. J. 854, 1 (2020).
118. Marrone, D. et al. Galaxy growth in a massive halo in the first billion years of cosmic history. Nature 553, 51–54 (2018).
119. Laporte, N. et al. Dust in the reionization era: ALMA observations of a z = 8.38 gravitationally lensed galaxy. Astrophys. J. Lett. 837, L21 (2017).
120. Izumi, T. et al. Subaru High-resolution Imaging Camera on Subaru Spitzer Space Telescope: selected dusty, star-forming galaxies at high redshifts. Astrophys. J. 826, 2 (2016).
121. Crocker, A. et al. [C II](1–0) and [C II](2–1) high-redshift observations. Mon. Not. R. Astron. Soc. 476, 881–897 (2018).
122. Balog, K. et al. Evidence for low radiative efficiency or highly biased view of the early co-evolution of black holes and host galaxies. Mon. Not. R. Astron. Soc. 475, 1 (2018).
123. Acknowledgements We thank M. Onoue, K. Ichikawa, Y. Harkiane and Y. Ono for discussions on the physical properties of GNeq7 and the AGN fraction among the brightest Lyman-break galaxies at z > 7. E. Murphy and F. Owen for sharing their I/ALA data. D. Marrone for sharing the best-fit SED model of SPT0311-58W; K. Whisler for a helpful advice on writing the manuscript. This work is based on the archival data of Hubble Space Telescope, Spitzer, Chandra, Subaru, Herschel, James Clerk Maxwell Telescope and the Karl G. Jansky Very Large Array, and the observations of IRAM/NOEMA interferometer (programme ID: E19AD and W20EO). We acknowledge support from the Danish National Research Foundation under grant number 140.015-0012 (DetoxE) and the Danish National Research Foundation through the DetoxE Consolidator Grant funding scheme (project ConText, grant number 648179, Independent Research Fund Denmark grants DFF-7014-00007 and DFF-8021-00130, the Villum Fonden research grant 37440, ‘The Hidden Cosmon’).
**Article**

**Author contributions** G.B.B. reduced and analysed the optical–NIR data of HST and Spitzer and discovered GNz7q. S.F., G.B.B., S.T., G.E.M., D.W., F.V., C.L.S., J.P.U.F., L.C., R.M.-C. M.V. and F.W. discussed and planned the follow-up observing strategy and the data analysis. G.B.B., G.E.M. and V.K. conducted the SED analysis and wrote the relevant Methods section. G.B.B. produced Figs. 1, 2, Extended Data Figs. 2, 8. D.W. analysed the X-ray properties from the Chandra data and wrote the relevant Methods section. T.R.G. reduced and analysed the SCUBA2 data, and M.K. and I.C. reduced the NOEMA data. R.V., M.G. and R.S. performed the cosmological semianalytical simulation GAMETE/QSOdust and wrote the relevant Methods section. F.R. worked on the three-dimensional modelling for the NOEMA [C II] line data cube. P.A.O. investigated the properties of the dust-continuum object identified near GNz7q. All authors discussed the results and commented on the manuscript. S.F. led the team, being principal investigator of the follow-up NOEMA programmes, analysed the NOEMA data, wrote the main text and the Methods section, and produced Figs. 3, 4, Extended Data Tables 1, 2, Extended Data Figs. 1, 3–7, 9–11.

**Competing interests** The authors declare no competing interests.

**Additional information**
**Supplementary information** The online version contains supplementary material available at https://doi.org/10.1038/s41586-022-04454-1.
**Correspondence and requests for materials** should be addressed to S. Fujimoto.
**Peer review information** Nature thanks the anonymous reviewers for their contribution to the peer review of this work. Peer reviewer reports are available.
**Reprints and permissions information** is available at http://www.nature.com/reprints.
Extended Data Fig. 1 | Rest-frame UV properties of GNz7q. The rest-frame 1,450 Å luminosity as a function of redshift (a) and the UV continuum slope (b). GNz7q falls between the typical luminosity ranges of quasars and galaxies in the literature\(^2,6,47,48\), where both faint quasars and luminous galaxies have been also identified\(^49-51,56\). GNz7q shows the reddest UV continuum slope among both galaxies and quasars at \(z > 6\). The galaxies without spectroscopic redshifts and the quasars without a UV continuum slope measurement are displayed in the open symbols. The error bars denote the 1\(\sigma\) measurement uncertainty.
Extended Data Fig. 2 | Point-source morphology of GNz7q. a, HST 4" × 4" cutout in the HST WFC3/IR filters of F105W, F125W, F140W, and F160W (left), instrumental point spread function (PSF) models (centre), and PSF fit residuals (right). b, Radial profile for the rest-frame UV continuum of GNz7q observed in F125W. The black circles show the observed values, while the dark and light red squares and lines present the PSF and the best-fit Sérsic models (Methods). The error bars denote the 68th percentile in each annulus, and the dotted line indicates the standard deviation of the pixel.
Extended Data Fig. 3 | NOEMA 1-mm observation results. a, 1.3-mm continuum (left) and the velocity-integrated [C II] maps (middle) with the natural weighting. We identify a nearby continuum object with a ~3″ offset from GNz7q at the northern east part, dubbed “ND1”. The intensity of the 1.3-mm continuum and the velocity integrated [C II] is shown in the right panel in green and red contours, respectively, overlaid on the HST/F160W 4″ × 4″ cutout. The solid contours are drawn at 3σ, 5σ, and 7σ levels, while the dashed white contours are drawn at −3σ level. The NOEMA synthesized beam is presented at the left bottom. b, [C II] line spectrum within a 1″0 radius aperture. The blue curve is the best-fit Gaussian for the [C II] line. The yellow shaded indicates the velocity range of [−200: +200] km s⁻¹ used for the velocity-integrated map in panel a. c, [C II] line kinematics. The top and bottom panel present the velocity-weighted and the velocity-dispersion maps (4″ × 4″), respectively.
Extended Data Fig. 4 | NOEMA 3-mm observation results. Left: 3.3-mm continuum (top) and the velocity-integrated CO(7–6) maps with the natural weighting. The black (white) contours are drawn at 3σ, 4σ, and 5σ (−3σ).

Right: NOEMA 3-mm band spectrum for LSB (top) and USB (bottom) with a 2″0 radius aperture. The dashed vertical line indicates the observed frequency of the expected far-IR lines based on the source redshift of z = 7.1899 determined by the [C ii] line. The blue curve is the best-fit Gaussian for the CO(7–6) line. The yellow shade indicates the velocity range used for the velocity-integrated map in the left panel.
Extended Data Fig. 5 | 1.3-mm continuum (top) and [C II] (bottom) size measurement results. Left: Observed map, which is the same as Extended Data Fig. 3a. Middle: Residual map by subtracting the best-fit model visibility obtained with uvmodelfit. For the dust continuum, we subtract the best-fit model visibility by fixing the major-axis effective radius as the upper limit value of $r_{e,FIR} = 0.48$ kpc. The visibility of ND1 is subtracted by assuming its profile as a point source before running uvmodelfit. Right: Amplitude as a function of $uv$ distance. The black circles show the observed visibility. The error bars show the standard error of the mean in each $uv$ distance bin. The red curve denotes the best-fit $uv$ model for the [C II] line, while the red dashed curve for the dust continuum indicates the $uv$ model with the upper limit size.
**Extended Data Fig. 6 | Optical luminosity vs. α_{ox} correlation.** The black and blue squares denote SDSS quasars (z~0–4) and blue quasars (z>5) respectively, taken from the literature. The arrows present the upper limits. The black line represents the best-fit relation based on 1544 quasars taken from the literature. The gray shaded region denotes the 68th percentile derivation, evaluated by propagating the 1σ uncertainties of the parameters that define the best-fit relation. The α_{ox} upper limit of GNz7q (99% confidence level) is estimated after the extinction correction and deviated from the best-fit relation by more than 5σ.
Extended Data Fig. 7 | Rest-frame UV size and luminosity relation. The black and blue circles show the rest-frame UV size measurements in the literature for galaxies at \( z > 5.5 \) and for compact galaxies reported at \( z < 2 \)–3, respectively, but no objects similarly compact and luminous to GNz7q have been identified. The error bar denotes the 1\( \sigma \) measurement uncertainty, and the sources whose errors exceed the measurements are not presented. The dashed line indicates the SFR surface density (\( \Sigma_{\text{SFR}} \)) by converting the UV luminosity to SFR\(^{\text{[59]}\). If the compact UV emission in GNz7q is attributed to the star-forming activity, \( \Sigma_{\text{SFR}} \) reaches \( \geq 5,000 \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2} \). Note that the UV luminosity is the observed value, and thus \( \Sigma_{\text{SFR}} \) of GNz7q after dust correction will be more extreme in the star-forming scenario.
Extended Data Fig. 8 | NIR–MIR SED of GNz7q. Left: Observed-frame SED of GNz7q traced by the Spitzer IRAC and MIPS 24 μm bands. The dark blue curve is the best-fit galaxy template (stellar continuum plus nebular emission from ionized gas in HII regions) constrained at $\lambda_{\text{obs}} < 10$ μm. The thin light blue curves are additional galaxy templates that largely span the galaxy color space at lower redshifts\(^9\), and the thicker light blue curves are templates of nearby dusty starbursts M82 and Arp220\(^9\). The thick green curves are templates of Type 1 and 2 quasars\(^9\), and the brown curve is a composite spectrum of nearby quasars\(^9\). The light green curves show the broad-band SEDs of high-redshift quasars at $5 < z < 6.4$\(^9\) interpolated to the redshift of GNz7q. Other than the galaxy fit, all SEDs and templates are normalized to the observed 8 μm flux density of GNz7q. Right: Observed-frame MIR flux ratio diagram for the flux densities at 5.8 μm, 8 μm, and 24 μm as observed for GNz7q and integrated from the SEDs displayed in the left panel. No templates from stars and star formation alone (blue curves and points) can reproduce the flux enhancement at 24 μm (rest-frame 3 μm) of GNz7q, which is fully consistent with the colors of luminous quasars at both low and high redshifts and likely arises from hot dust associated with an active nucleus. The error bars are obtained by propagating the measurement uncertainty of each photometry.
Extended Data Fig. 9 | \(L_{\text{[CII]}}/L_{\text{IR}}\) and \(L_{\text{IR}}\) properties compared with other populations. We show \(L_{\text{[CII]}}/L_{\text{IR}}\) as a function of \(L_{\text{IR}}\) (a) and \(\Sigma L_{\text{IR}}\) (b). For comparison, we also show observational results of local composite systems of AGN and starburst (black square), dusty starbursts at \(z \sim 0–7\) (orange diamond), blue quasars at \(z \sim 6–7\) (blue square), and red quasars at \(z \sim 3–5\) (magenta square) taken from the literature.\(^6,42,122,124,131,133,170\). GNz7q is at the extreme end of the relationship painted by known starbursts and quasars. The \(L_{\text{IR}}\) values of the blue quasars are calculated by assuming the single modified blackbody (\(T_d = 47\) K; \(\beta_d = 1.6\)), where the blue bar at the bottom left of the left panel shows a potential error scale with a change of \(T_d\) by \(\pm 10\) K from the assumption. For GNz7q, the error bar is obtained by propagating the 1\(\sigma\) uncertainties of \(L_{\text{[CII]}}\) and \(L_{\text{IR}}\).
Extended Data Fig. 10 | Host galaxy properties compared with other populations at $z > 6$. a–d, We show (a) SFR, (b) $M_{\text{dust}}$, (c) $M_{\text{gas}}$, (d) and $\tau_{\text{depl}}$ as a function of redshift. For comparison, we also show other galaxy populations with spectroscopic redshifts: blue quasars (blue square), red quasars (magenta circle and shaded region), Lyman-break galaxies (green triangle), and a dusty starburst galaxy (orange circle) that are taken from the literature. The magenta shade represents the 68th percentile of the host galaxy properties of the super-Eddington accretion red quasar, W2246−0526, at $z = 4.64^{+1.0}_{-1.0}$. The host galaxy of GNz7q show the most vigorously star-forming system at $z > 7$ with the large gas reservoir. The filled and open symbols in c denote $M_{\text{gas}}$ estimates from CO and [C\text{\textsc{ii}}] lines, respectively. The error bars of SFR and $M_{\text{dust}}$ are estimated by propagating the 1σ measurement uncertainty and a 0.2 dex uncertainty of the $T_d$ assumption, when they are derived from a single submm-mm band (Section 8). The error bars of $M_{\text{gas}}$ and $\tau_{\text{depl}}$ are estimated with the 1σ measurement uncertainty and the propagation from both SFR and $M_{\text{dust}}$ uncertainties, respectively. For all populations, the different assumptions of the initial mass function and the dust opacity coefficient among the literature are corrected.
**Extended Data Fig. 11 | $M_{\text{BH}}$ and $M_{\text{dyn}}$ relation.** The colour scale and the vertical range of red-shade regions correspond to those of Fig. 3. The red circle and the red-shade regions show the potential $M_{\text{BH}}$ range of GNz7q suggested by its faint $L_{\text{bol}}$ and extremely faint X-ray property, respectively. The horizontal range of the red-shade regions indicates the 68th percentile of the $M_{\text{dyn}}$ estimate from the [C ii] line. For comparison, we also present $M_{\text{BH}}$ and $M_{\text{dyn}}$ (or $M_{\text{star}}$) estimates for blue quasars at $z \sim 6-7$ (blue squares)\cite{127,128,146-148,150,151} and red quasars at $z \sim 2$ (magenta circles)\cite{132}. The error bars denote the 1σ uncertainties taken from the literature. The $M_{\text{dyn}}$ values from the kinematic analysis based on the 3D modeling are shown in the filled blue squares with the 1σ error bars\cite{146,147}. The $M_{\text{dyn}}$ measurements based on the rotation-disk assumption in the literature are shown by the open blue squares. The best-fit relation for the filled blue squares is shown by the blue line\cite{146}. The black solid line represents the best-fit relation between the bulge mass and $M_{\text{BH}}$ among local quiescent galaxies\cite{152}. The black dashed line denotes the best-fit relation between the stellar mass of the entire system and $M_{\text{BH}}$ among local AGNs\cite{153}. The shaded regions present the 1σ confidence level for the best-fit relations.
| Observed $\lambda$ [\(\mu\text{m}\)] | Flux density [\(\mu\text{Jy}\)] | Uncertainty [\(\mu\text{Jy}\)] | Telescope | Instrument | reference |
|-------------------------------------|-------------------------------|-------------------------------|-----------|------------|-----------|
| 0.44                               | 0.000                         | 0.008                         | HST       | ACS/F435W  | This work (CHArGE) |
| 0.61                               | 0.006                         | 0.005                         | HST       | ACS/F606W  | "           |
| 0.78                               | 0.007                         | 0.005                         | HST       | ACS/F775W  | "           |
| 0.81                               | −0.011                        | 0.007                         | HST       | ACS/F814W  | "           |
| 0.85                               | 0.056                         | 0.010                         | HST       | ACS/F850LP | "           |
| 1.05                               | 0.683                         | 0.036                         | HST       | WFC3/F105W | "           |
| 1.25                               | 1.307                         | 0.067                         | HST       | WFC3/F125W | "           |
| 1.40                               | 1.783                         | 0.092                         | HST       | WFC3/F140W | "           |
| 1.60                               | 2.103                         | 0.107                         | HST       | WFC3/F160W | "           |
| 2.15                               | 2.778                         | 0.044                         | Subaru    | MORICS/Ks  | Kajisawa et al. 2011 |
| 3.6                                | 3.574                         | 0.180                         | Spitzer   | IRAC/ch1   | This work (CHArGE) |
| 4.5                                | 3.907                         | 0.197                         | Spitzer   | IRAC/ch2   | "           |
| 5.8                                | 4.138                         | 0.546                         | Spitzer   | IRAC/ch3   | "           |
| 8.0                                | 4.553                         | 0.471                         | Spitzer   | IRAC/ch4   | "           |
| 24                                 | 28.1                          | 6.6                           | Spitzer   | MIPS       | Magnelli et al. 2011 |
| 100                                 | < 1050                        | 350                           | Herschel  | PACS       | Liu et al. 2018 |
| 160                                 | < 2850                        | 950                           | Herschel  | PACS       | "           |
| 250                                 | < 17,100                      | 5,700                         | Herschel  | SPIRE      | Oliver et al. 2012 |
| 350                                 | < 18,300                      | 6,100                         | Herschel  | SPIRE      | "           |
| 500                                 | < 12,300                      | 4,100                         | Herschel  | SPIRE      | "           |
| 450                                 | 8,000                         | 5,500                         | JCMT      | SCUBA2     | This work |
| 850                                 | 1,800                         | 390                           | JCMT      | SCUBA2     | Cowie et al. 2017 |
| 1,284                               | 460                           | 94†                           | NOEMA     | Band 3     | This work |
| 3,276                               | 24.6                          | 6.9†                          | NOEMA     | Band 1     | This work |
| 30,000                              | 0.8                           | 1.1                           | JVLA      | X Band     | Murphy et al. 2017 |
| 200,000                             | 22.4                          | 6.4                           | JVLA      | L Band     | Owen 2018 |

†The potential contributions from nearby objects are subtracted, or confirmed to be negligible (Section 5).

‡The additional uncertainty of the absolute flux calibration is included by 20% and 10% at 1-mm and 3-mm band, respectively.
| Parameter      | Value                          | Description                                                                 |
|---------------|--------------------------------|-----------------------------------------------------------------------------|
| R.A.          | 12:36:16.9195                  | Right Ascension (J2000) in HST                                              |
| Decl.         | 62:12:32.127                   | Declination (J2000) in HST                                                 |
| $z_{\text{UV}}$ | 7.23 ± 0.05                    | Redshift from HST grism spectrum                                           |
| $z_{\text{[CII]}}$ | 7.1899 ± 0.0005              | Redshift from [C II] line                                                  |
| $\alpha_\lambda$ | 0.1 ± 0.3                    | Rest-frame UV continuum slope                                              |
| L$_{2,500}$   | $(2.1 \pm 0.1) \times 10^{30}$ erg s$^{-1}$ Hz$^{-1}$ | Monochromatic optical luminosity at rest-frame 2,500Å                      |
| L$_{2,500}$   | $(3.2 \pm 0.1) \times 10^{30}$ erg s$^{-1}$ Hz$^{-1}$ | Dust corrected L$_{2,500}$                                                 |
| L$_{\text{bol}}$ | $1.7 \pm 0.1 \times 10^{46}$ erg s$^{-1}$ | AGN bolometric luminosity (rest-frame 1216Å–20 cm)                        |
| A$_{V,\text{QSO}}$ | 0.3 ± 0.1                    | Dust attenuation for the quasar component                                  |
| A$_{V,\text{host}}$ | > 6                      | Dust attenuation for the host galaxy component                             |
| L$_{X}$       | $< 3.9 \times 10^{42}$ erg s$^{-1}$ | Rest-frame X-ray (2–10 keV) luminosity                                    |
| L$_{2\text{keV}}$ | $< 5.1 \times 10^{24}$ erg s$^{-1}$ Hz$^{-1}$ | Monochromatic X-ray luminosity at rest-frame 2 keV                       |
| $\alpha_{\text{ox}}$ | $< -2.23$                  | Optical to X-ray spectral index                                            |
| L$_{\text{IR}}$   | $(1.2 \pm 0.6) \times 10^{13}$ L$_{\odot}$ | Rest-frame IR (8–1,000 µm) luminosity                                     |
| L$_{\text{IR, SF}}$ | $(1.1 \pm 0.5) \times 10^{13}$ L$_{\odot}$ | Rest-frame IR luminosity for the host galaxy component                     |
| L$_{\text{IR, AGN}}$ | $(1.0 \pm 0.3) \times 10^{12}$ L$_{\odot}$ | Rest-frame IR luminosity for the AGN component                             |
| f$_{\text{AGN}}$   | 8 ± 5%                        | AGN contribution to L$_{\text{IR}}$                                       |
| $T_d$         | 80 ± 21 K                      | Peak dust temperature                                                      |
| L$_{\text{[CII]}}$ | $(1.1 \pm 0.3) \times 10^{9}$ L$_{\odot}$ | [C II] line luminosity                                                    |
| L$_{\text{CO}(7 - 6)}$ | $(1.3 \pm 0.7) \times 10^{8}$ L$_{\odot}$ | CO(7-6) line luminosity                                                   |
| FWHM$_{\text{[CII]}}$ | 280 ± 40 km s$^{-1}$              | FWHM of the [C II] line                                                  |
| FWHM$_{\text{CO}}$ | 770 ± 230 km s$^{-1}$              | FWHM of the CO(7-6) line                                                  |
| L$_{\text{CO}(6 - 5)}$ | $< 5.0 \times 10^{7}$ L$_{\odot}$ | CO(6-5) line luminosity ([C II] line width assumed)                        |
| L$_{\text{[CI]}2 - 1}$ | $< 7.9 \times 10^{7}$ L$_{\odot}$ | [C I](2-1) line luminosity ([C II] line width assumed)                     |
| SFR           | 1,600 ± 700 M$_{\odot}$ yr$^{-1}$ | SFR of the host galaxy                                                   |
| M$_{\text{dust}}$ | $(1.6 \pm 1.1) \times 10^{8}$ M$_{\odot}$ | Dust mass of the host galaxy                                              |
| M$_{\text{gas}}$   | $(2.0 \pm 1.2) \times 10^{10}$ M$_{\odot}$ | Gas mass of the host galaxy                                               |
| M$_{\text{dyn}}$   | $(4.5 \pm 0.9) \times 10^{10}$ M$_{\odot}$ | Dynamical mass                                                           |
| M$_{\text{star}}$   | $(2.5 \pm 1.4) \times 10^{10}$ M$_{\odot}$ | Stellar mass of the host galaxy from M$_{\text{dyn}}$ - M$_{\text{gas}}$ |
| q$_{\text{IR}}$    | 2.1 ± 0.3                      | IR/radio correlation                                                       |
| $\alpha_{\text{radio}}$ | $< -1.0 \pm 0.6$                   | Radio spectral index                                                      |
| r$_{\text{e, FIR}}$  | < 0.48 kpc                     | Effective radius of the rest-frame FIR continuum                          |
| r$_{\text{e, [CII]}}$ | 1.4 ± 0.2 kpc                  | Effective radius of the [C II] line                                       |