

VIGOROUS STAR FORMATION WITH LOW EFFICIENCY IN MASSIVE DISK GALAXIES AT $z = 1.5^1$

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ABSTRACT

We present the first detection of molecular gas cooling CO emission lines from ordinary massive galaxies at $z = 1.5$. Two sources were observed with the IRAM Plateau de Bure Interferometer, selected to lie in the mass–star formation rate correlation at their redshift, thus being representative of massive high- z galaxies. Both sources were detected with high confidence, yielding $L'_{\text{CO}} \sim 2 \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$. For one of the sources we find evidence of velocity shear, implying CO sizes of ~ 10 kpc. With an infrared luminosity of $L_{\text{FIR}} \sim 10^{12} L_{\odot}$, these disklike galaxies are borderline ULIRGs but with star formation efficiency similar to that of local spirals, and an order of magnitude lower than that in submillimeter galaxies. This suggests a CO to total gas conversion factor similar to local spirals, gas consumption timescales approaching 1 Gyr or longer, and molecular gas masses reaching $\sim 10^{11} M_{\odot}$, comparable to or larger than the estimated stellar masses. These results support a major role of in situ gas consumption over cosmological timescales and with relatively low star formation efficiency, analogous to that of local spiral disks, for the formation of today’s most massive galaxies and their central black holes. Given the high space density of similar galaxies, $\sim 10^{-4} \text{ Mpc}^{-3}$, this implies a widespread presence of gas-rich galaxies in the early universe, many of which might be within reach of detailed investigations of current and planned facilities.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation — galaxies: high-redshift — galaxies: starburst

1. INTRODUCTION

Galaxies in the distant universe were forming stars with much higher rates than today (Madau et al. 1996; Elbaz et al. 2002; Le Floc’h et al. 2005). For galaxies of a fixed stellar mass, e.g., of the order of $M^* \sim 10^{10} - 10^{11} M_{\odot}$, the typical star formation rate (SFR) has been steadily increasing with respect to local values, up to ~ 30 times higher at $z = 2$ (Daddi et al. 2007a, hereafter D07a). This increase can be accounted for either by postulating a higher gas content or a higher star formation efficiency, or both. Galaxy mergers and interactions, expected to be much more common in the distant universe than today, can increase the density of gas in galaxies, and thus help transform gas into stars more rapidly and with a higher star formation efficiency. The relative importance for massive galaxy formation and assembly of the hierarchical merging of small subgalactic units, versus the in situ formation of stars through gas consumption, is largely unknown observationally.

The molecular gas content of galaxies is best probed through the detection of redshifted cooling emission lines of CO. Combining observations for local and distant galaxies, all the way from spirals to (ultra) luminous infrared galaxies (LIRGs, $L_{\text{FIR}} \gtrsim 10^{11} L_{\odot}$; and ULIRGs, $L_{\text{FIR}} \gtrsim 10^{12} L_{\odot}$), a nonlinear correlation is observed (e.g., Solomon & Vanden Bout 2005) between CO luminosity (proportional to molecular gas content) and FIR luminosity (proportional to the SFR), with more luminous sources having higher FIR-to-CO luminosities, i.e.,

higher efficiencies than spiral disks in converting gas into stars, likely due to their higher gas densities (Tacconi et al. 2006; Downes & Solomon 1998). Mapping the physics of molecular gas in representative galaxies at high redshifts would be a major step forward in understanding the processes regulating galaxy formation, and is a key target of future astrophysical facilities such as ALMA.

However, if the local correlations hold at high redshifts, current techniques and sensitivities allow us to detect CO lines, and thus study the molecular gas content, only for extreme objects such as bright ($S_{850 \mu\text{m}} > 5 \text{ mJy}$) submillimeter-selected galaxies (SMGs; Genzel et al. 2004; Neri et al. 2003; Greve et al. 2005), quasars (Walter et al. 2003; Maiolino et al. 2007), or in the case of strong gravitational lensing. Indirect evidence has been mounting very recently that this might not be the general case. Vigorous starbursts at high redshift appear to be the ordinary star formation mode in massive galaxies. The existence of tight correlations between SFRs and galaxy masses (Elbaz et al. 2007; Noeske et al. 2007; D07a) and the predominance of ULIRGs inside mass-limited samples of $M \gtrsim 5 \times 10^{10} M_{\odot}$ galaxies (Daddi et al. 2005; D07a; Caputi et al. 2006) suggests that vigorous starbursts were typically long lasting among ordinary massive galaxies in the distant universe, which therefore might be hosting large amounts of gas.

2. CO OBSERVATIONS OF BzK GALAXIES

Motivated by this evidence, we observed two representative massive galaxies at high redshift with the IRAM Plateau de Bure Interferometer, searching for the redshifted emission lines from the CO(2–1) transition at rest frame 230.539 GHz, with the aim of constraining their molecular gas content. The two galaxies, $BzK-4171$ (J123626.53+620835.3, VLA radio frame) and $BzK-21000$ (J123710.60+622234.6), at redshift $z = 1.465$ and $z = 1.522$, respectively (measured from Keck DEIMOS spectroscopy), were selected in the Great Observatories Origins Deep Survey northern field (GOODS-N) using the BzK technique (Daddi et al. 2004b), which provides complete K -limited samples of normal, massive galaxies at $1.4 < z < 2.5$.

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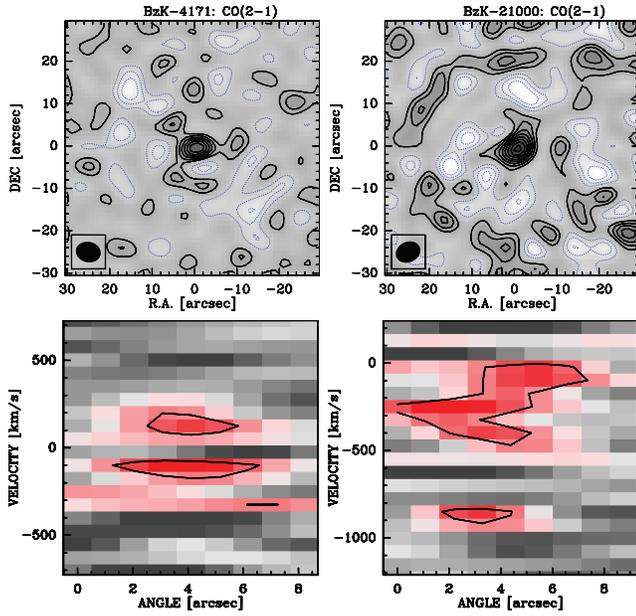


FIG. 1.—*Top*: CO(2–1) emission-line detections in two ordinary, massive high- z galaxies. We show (uncleaned) velocity-averaged spatial maps of CO emission, from -350 to 425 km s^{-1} (BzK -4171; *left*) and between -575 and -25 km s^{-1} and from -950 to -800 km s^{-1} (BzK -21000; *right*). The contours are from -3 to $+6$ σ , in steps of 1 σ (~ 0.1 mJy beam^{-1}). The field of view is $1'$. The size of the beam is shown on the lower left. *Bottom*: Position-velocity maps, extracted along the major-axis direction measured on the HST + ACS UV rest frame imaging. The spatial field of view is $\sim 9''$. Red/white colors are for positive pixels. Contours are at the level of 1 mJy beam^{-1} .

SFRs of about 100 – 150 $M_{\odot} \text{ yr}^{-1}$ were derived by averaging estimates based on the VLA radio detections of 40 ± 5 μJy and 49 ± 7 μJy (using the radio- L_{FIR} correlation; Condon 1992) and UV estimates (correcting for dust reddening using the Calzetti et al. [2000] law), which agree within 0.2 dex or better. For BzK -4171 the 24 μm estimate (based on the Chary & Elbaz [2001] luminosity-dependent templates) also agrees within this factor, while for BzK -21000 the 24 μm estimate of the SFR is 2 – 2.5 larger than the radio and UV ones, mild evidence for possible mid-IR excess usually linked to obscured AGN activity (Daddi et al. 2007b, hereafter D07b). Stellar masses of $(0.5$ – $0.8) \times 10^{11}$ M_{\odot} were derived from optical and UV rest frame photometry, following the method of Daddi et al. (2004b). SFRs and stellar masses are given here for the Chabrier (2003) stellar initial mass function. The two target galaxies lie on the mass-SFR correlation established at their redshifts (D07a), and are thus ordinary massive high- z sources with ongoing star formation.

The sources were observed using newly refurbished receivers for 5.7 and 7.5 hr during 2007 April 24–25 for BzK -4171 and BzK -21000, respectively, during stable and high quality conditions. A compact configuration D with six antennas was used. An additional 7.5 hr of poorer quality weather data in configuration D and with five antennas only were obtained for BzK -4171 on 2007 August 1, reducing the noise by only 25% . Standard data reduction was performed using the GILDAS software. Both sources observed were detected in CO with high confidence (Fig. 1, *top panels*), with a significance of 6.8 and 8.9 σ . Fluxes are 0.60 ± 0.09 Jy km s^{-1} and 0.85 ± 0.10 Jy km s^{-1} for BzK -4171 and BzK -21000, respectively. Figure 2 shows the CO spectra of the two BzK galaxies. The CO line wavelengths are in agreement with the Keck redshifts, within

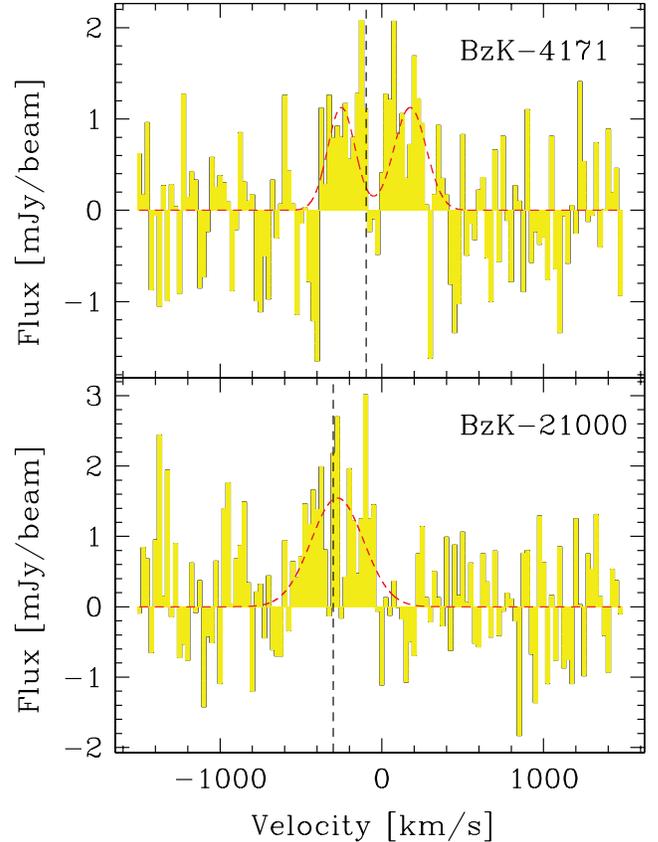


FIG. 2.—We show the CO spectra in velocity space, with respect to the zero velocity offsets (*dashed vertical lines*) defined from the optical redshift measured from the [O II] emission lines (we assume an intensity-weighted wavelength of 3727.3 \AA for the doublet). Best-fitting Gaussian profiles are shown for the emission of the two targets.

50 km s^{-1} or better. The CO positions agree with the VLA positions within $\approx 0.5''$. BzK -4171 is best fitted by a double horn profile, indicative of a rotating disk and consistent with the UV morphology of a nearly edge-on disk. BzK -21000 shows a narrower velocity profile with only a hint of double horns. Figure 1 (*bottom panels*) shows the position-velocity diagram derived using a pseudoslit oriented along the major axis defined in the HST + ACS imaging. BzK -4171 is unresolved, while BzK -21000 shows evidence for shear, consistent over all with rotation in a disk. As a cross-check, we separately fitted velocity channels bluer and redder than the systemic velocities. For BzK -4171 the positions of the blue and red horns are separated by $0.5'' \pm 0.5''$. For BzK -21000 we find $1.3'' \pm 0.3''$ separation (11 ± 2.5 kpc; 4.3 σ), defining a position angle of $-10^{\circ} \pm 17^{\circ}$, in very good agreement with the UV position angle, confirming that the CO emission is extended.

3. GAS-RICH MASSIVE GALAXIES AT $z \sim 1.5$

These results unveil a new and different galaxy formation mode for the most luminous sources such as LIRGs and ULIRGs. In Figure 3 we compare CO-to-FIR luminosities of our BzK galaxies to local and distant sources. We adapted published luminosities for local (Solomon et al. 1997; Yao et al. 2003) and distant sources (Greve et al. 2005) to $WMAP$ cosmological parameters (Spergel et al. 2007). We assume here roughly constant brightness temperature (see Braine & Combes 1992) and thus conversion ratios among the different CO tracers to be of order

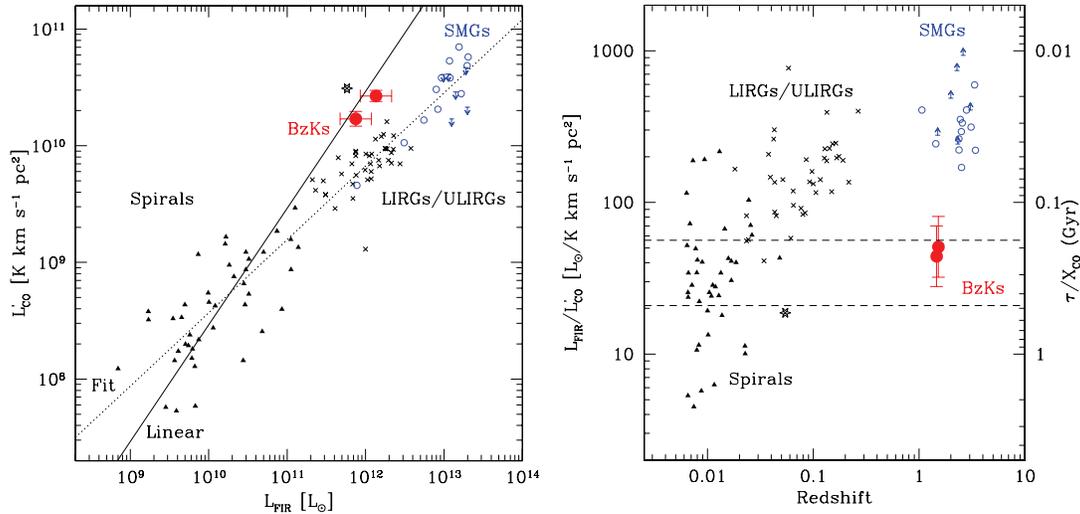


FIG. 3.—Comparison of molecular CO luminosity (L_{CO}) to far-infrared luminosity (L_{FIR} ; integrated between 40 and 500 μm). Quantities for the two *BzK* galaxies presented in this work are shown as large filled circles. The left panel shows the comparison of the two luminosities. The dotted line is the best-fit relation to spirals (triangles), LIRG/ULIRGs (crosses), and distant SMGs (open circles). The solid line is for a linear L_{CO} -to- L_{FIR} correlation normalized to the ratio of local spirals. The local LIRG with high L_{CO} content, behaving similarly to distant *BzK*s, is VII Zw 31 (plotted as an asterisk; Downes & Solomon 1998), which interestingly also has fairly cold 60 μm /100 μm color ratios and larger CO size compared to other ULIRGs. The right panel shows the L_{FIR} -to- L_{CO} ratio as a function of redshift. The dashed horizontal lines show the semi-interquartile range of local spirals.

unity, i.e., $\text{CO}(1-0) \sim \text{CO}(2-1) \sim \text{CO}(3-2)$ (Weiß et al. 2005). Compared to local ULIRGs, these ordinary massive $z = 2$ galaxies have similar bolometric luminosities but larger CO luminosities by a factor of 3–5. On the other hand, SMGs have estimated $L_{\text{FIR}} \geq 10^{13} L_{\odot}$ and therefore (Kennicutt 1998) $\text{SFR} \geq 1000 M_{\odot} \text{yr}^{-1}$, 1 order of magnitude higher than our two targets, but the observed CO luminosities are comparable. The two *BzK* galaxies are outliers of the L_{FIR} versus L_{CO} correlation defined by local spirals, LIRGs/ULIRGs, and distant SMGs (Fig. 3). Instead, they lie close to a linear L_{FIR} -to- L_{CO} relation normalized to local spirals. The observed ratio in the two massive *BzK* galaxies is an order of magnitude lower than that of SMGs at similar redshifts, implying much lower star formation efficiency. This is consistent with the fact that SMGs are outliers of the mass-SFR correlation (D07a), probably due to the higher efficiency in forming stars, for a similar stellar mass and CO luminosity. The L_{FIR} -to- L_{CO} ratios of the two *BzK* galaxies are within the semi-interquartile range of values from local spirals (Fig. 3, right panel). No object with a similar L_{FIR} -to- L_{CO} ratio and large L_{FIR} was previously known in the distant universe (Fig. 3). This implies that these distant *BzK* galaxies behave as *scaled-up* versions of local spirals, with proportionally higher SFR and molecular gas content for a fixed galaxy stellar mass.

We use a conversion rate (Kennicutt 1998) $L_{\text{FIR}}/L_{\odot} = 0.8 \times 10^{10} \text{SFR} (M_{\odot} \text{yr}^{-1})$, adapted to a Chabrier (2003) stellar initial mass function and on the assumption, appropriate for these galaxies, that L_{FIR} is about 80% of the bolometric luminosity. In general, we can write $L_{\text{CO}} = M_{\text{H}_2}/X_{\text{CO}}$, where M_{H_2} is the total molecular gas mass (including He) and the conversion factor (Downes & Solomon 1998; Solomon & Vanden Bout 2005) is $X_{\text{CO}} = 4.6 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ for the Milky Way and as low as $X_{\text{CO}} = 0.8 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ for ULIRGs and likely for SMGs. The high detected CO luminosities imply that giant molecular gas reservoirs are present, of the order of $2 \times 10^{10} M_{\odot}$ for a ULIRG-like $X_{\text{CO}} \sim 1$, comparable to SMGs and larger than in local ULIRGs. The typical gas consumption timescales (Fig. 3) are about $(2-4) \times 10^7$ yr for SMGs, a factor of ≈ 2

larger for local ULIRGs, and reach $(2-3) \times 10^8$ yr for the massive *BzK* galaxies at $z = 1.5$, in the case of $X_{\text{CO}} \sim 1$. The SFR could last for even longer than that, as further gas accretion will be substantial during such long timescales. Hydrodynamical simulations from Kereš et al. (2005) predict gas accretion rates of about $10-70 M_{\odot} \text{yr}^{-1}$ for similarly massive galaxies at $1.4 < z < 2.5$ (i.e., for dark matter halo masses of $\sim 10^{12}-10^{13} M_{\odot}$; Hayashi et al. 2007). This is of the same order of magnitude as the estimated SFR in massive $z \sim 2$ galaxies. These are likely lower limits to the SFR duration and gas masses as we are entirely neglecting atomic gas. As the star formation efficiencies are consistent with those of local spirals, in analogy to the latter it might be that $X_{\text{CO}} > 1$ or even that the Milky Way conversion factor applies to these massive *BzK* sources.

This is further supported by the evidence that, unlike local ULIRGs (Downes & Solomon 1998) and distant SMGs (Tacconi et al. 2006), these two *BzK* galaxies, like $z > 1.4$ massive star forming galaxies (Daddi et al. 2004a; Bouche et al. 2007) in general, are not compact merger-induced starbursts. From detailed Sérsic fitting of their UV rest frame light profiles from *Hubble Space Telescope* imaging data obtained with Advanced Camera for Surveys (Giavalisco et al. 2004), we derive half-light radii of 4.4 and 5.5 kpc (proper size, or about $0.5''$, accurate to better than 5%). Both galaxies have disklike (exponential) morphology with Sérsic index $n = 1.3$ and 0.6 (accurate to better than 20%). *BzK*-4171 appears indeed as a nearly edge-on disk, consistent with the Sérsic fitting. *BzK*-21000 has a clumpy structure, still consistent with a disk but also with the possible presence of minor merging events. The UV rest frame sizes are likely reasonably accurate measurements of the starbursts' sizes, because for these sources reliable SFR measurements can be obtained from the UV (Daddi et al. 2005; D07a; Dannerbauer et al. 2006; Reddy et al. 2005); i.e., their UV emission is not entirely opaque, while local ULIRGs and distant SMGs are optically thick in the UV (Champan et al. 2005; Goldader et al. 2002). This is confirmed by the evidence for extended CO emission, at least for *BzK*-21000. The inferred sizes are a factor of 2–3 larger than distant SMGs (Tacconi et al.

2006) and 10 times larger than local ULIRGs (Downes & Solomon 1998). This converts to 1–2 orders of magnitude lower gas densities and justifies the relatively modest star formation efficiencies. Independent estimates of the molecular gas masses and thus SFR timescales can also be obtained. First, if we apply the Schmidt-Kennicutt law (using also its latest derivation from Bouche et al. [2007], which also includes distant SMGs), using the (UV and/or CO) size for the typical gas and SFR size, we estimate $M_{\text{gas}} \sim (0.5\text{--}1) \times 10^{11} M_{\odot}$ for each galaxy. Second, from the CO velocity widths and (UV and/or CO) size measurements of the galaxies, we estimate dynamical masses of about $(1\text{--}1.5) \times 10^{11} M_{\odot}$, within the half-light radii, including gas, stars, and dark matter. Given the estimated total stellar masses of $\sim(0.5\text{--}0.8) \times 10^{11} M_{\odot}$, roughly half of which presumably lies within the half-light radii, it seems plausible that $\approx 10^{11} M_{\odot}$ of gas can be present. We conclude that it would take up to 1 Gyr to consume all of the gas in these typical, massive high-redshift galaxies, assuming the SFR remained roughly constant. Clearly, the star formation episodes could last longer since additional gas is accreted over such long timescales.

4. DISCUSSION

In order to evaluate the implications of these results for massive galaxy formation, recall that the two observed galaxies are representative of massive galaxies at high redshifts. They were selected for CO observations simply due to the availability of known spectroscopic redshifts. The two galaxies lie on the SFR-to-stellar mass correlation inferred at $1.4 < z < 2.5$, and their colors and morphologies are fully typical of massive $z \sim 2$ galaxies. Star-forming galaxies in that redshift range with similar stellar masses are common in the distant universe, with space densities of the order of 10^{-4} Mpc^{-3} , quite a bit larger than the $(2\text{--}6) \times 10^{-6} \text{ Mpc}^{-3}$ observed for SMGs by Chapman et al. (2003). Clearly, these results point to the existence of a much larger population of gas-rich galaxies in the distant universe than previously thought.

We note that the far-IR luminosity estimates for our objects are based on the UV, radio, and mid-IR luminosities, and are solid given that self-consistent measurements of SFR activity have been shown to be obtainable for these kinds of objects at high redshift (D07a). It is very unlikely that we are strongly

underestimating their star formation activity (which would lead us to overestimate the duration timescales). Instead, the L_{FIR} for SMGs from Greve et al. (2005) is based only on the $850 \mu\text{m}$ flux and is likely more uncertain. Using radio and *Spitzer*, Pope et al. (2006) suggest lower L_{FIR} for SMGs. This could imply that SMGs are closer in their SFR modes to massive *BzK* galaxies, but would change little about our conclusion because it is the latter which represent the dominating star formation mode at high redshift.

The large molecular gas fraction in these galaxies, possibly up to 50% or more, would likely give rise to large-scale instabilities, with the formation of clumps (e.g., Immeli et al. 2004; Bournaud et al. 2007). This could explain the clumpy structure of these two galaxies, and in general of a large fraction of the high- z massive galaxies (e.g., Daddi et al. 2004a), and the high velocity dispersions observed in many of the high- z massive disk galaxies (e.g., Genzel et al. 2006; Forster Schreiber et al. 2006).

The long duration timescale for star formation activity implies, as a corollary, long duration activity for the galactic nuclei. In fact, it has been recently unveiled by D07b that up to 20%–50% of massive galaxies in $1.4 < z < 2.5$ likely contain strongly obscured but relatively luminous AGNs. Some of the large gas reservoir is likely slowly funneled, in some way, into the central black hole with timescales similar to star formation, at a rate roughly consistent with what is required to assemble the correlation between stellar and black hole masses that we observe today (D07b). Our results underline the major role of gas consumption over long timescales and with low efficiencies, as opposed to rapid and strong merger-driven bursts, as a major growth mode for both stellar mass and black holes in the distant universe.

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