

Tentative detection of neutral gas in a Little Red Dot at $z = 4.46$

HOLLIS B. AKINS,^{1,*} CAITLIN M. CASEY,^{2,3} JOHN CHISHOLM,¹ DANIELLE A. BERG,¹ OLIVIA COOPER,^{1,*} MAXIMILIEN FRANCO,⁴
SEIJI FUJIMOTO,^{1,†} ERINI LAMBRIDES,^{5,‡} ARIANNA S. LONG,⁶ AND JED MCKINNEY^{1,†}

¹*Department of Astronomy, The University of Texas at Austin, Austin, TX 78712, USA*

²*Department of Physics, University of California, Santa Barbara, CA 93106, USA*

³*Cosmic Dawn Center (DAWN), Denmark*

⁴*Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, 91191 Gif-sur-Yvette, France*

⁵*NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA*

⁶*Department of Astronomy, University of Washington, Seattle, WA 98195, USA*

ABSTRACT

JWST has revealed a population of broad-line active galactic nuclei at $z > 4$ with remarkably red colors, so-called “Little Red Dots.” Ubiquitous Balmer breaks suggest that they harbor old stellar populations in massive, compact host galaxies. We present ALMA observations of three LRDs at $z = 3.10, 4.46$, and 7.04 , targeting molecular and neutral gas via CO(7–6) and [C I](2–1), respectively. We do not detect CO in any target, placing conservative limits on the host molecular gas mass $\lesssim 1\text{--}5 \times 10^{10} M_{\odot}$. We report the tentative (4.9σ) detection of the [C I](2–1) line in A2744-45924 ($z = 4.46$), one of the brightest known LRDs. The [C I] line is narrow (FWHM $\sim 80 \text{ km s}^{-1}$), implying a dynamical mass $\lesssim 10^{10} M_{\odot}$, adopting conservative limits for the galaxy size. The dynamical mass limit is significantly lower than expected from the local $M_{\text{BH}}\text{--}M_{\text{dyn}}$ relation, and is an order of magnitude below the stellar mass derived from SED fitting, potentially supporting a non-stellar origin of the Balmer break. These results, while tentative, paint a picture of LRDs that is markedly different than typical high- z quasars, which live in massive, gas-rich, and actively star-forming host galaxies.

1. INTRODUCTION

The formation of the first supermassive black holes (SMBHs), and their co-evolution with galaxies, remains a key question of modern astrophysics (Kormendy & Ho 2013). The existence of luminous quasars as early as $z \gtrsim 7$ likely requires the existence of massive black hole seeds or accretion rates beyond the Eddington limit (Agarwal et al. 2012; Pezzulli et al. 2016; Inayoshi et al. 2020; Fan et al. 2023). However, conducting a complete census of early SMBH growth is made complicated by the fact that active galactic nuclei (AGN) at $z > 7$ are likely highly obscured (e.g. Ni et al. 2020; Gilli et al. 2022), limiting optical/near-IR observations. This is supported by quasar proximity zone measurements (Eilers et al. 2020, 2021; Davies et al. 2019) and the identification of several remarkably luminous obscured AGN at $z \gtrsim 7$

(Fujimoto et al. 2022; Endsley et al. 2022a,b; Lambrides et al. 2023) in relatively small survey areas.

A key result from *JWST* is the discovery of an abundant population broad line AGN at $z > 4$ (Harikane et al. 2023; Taylor et al. 2024). Among these are the “Little Red Dots” (LRDs), first identified as broad-line H α emitters in NIRC2/WFSS data (Matthee et al. 2024). The LRDs are characterized by a unique SED shape: blue in the rest-UV, but with a sharp turnover to a very red optical slope, suggesting significant dust attenuation (Labbé et al. 2023). They appear contribute significantly to the overall AGN population, and bolometric luminosity function, at $z \sim 4\text{--}9$ (Greene et al. 2024; Kokorev et al. 2024; Kocovski et al. 2024; Akins et al. 2024). While generally fainter than the UV-bright quasars, their black hole masses and bolometric luminosities can approach the regime of low-luminosity quasars ($L_{\text{bol}} \gtrsim 10^{45} \text{ erg s}^{-1}$), despite their apparently high abundance.

The nature of the LRDs, however, remains unclear. In particular, they lack several key features common in AGN: they are generally weak in the mid-IR, indicating minimal hot dust emission from the torus (Williams et al.

Corresponding author: Hollis B. Akins
hollis.akins@gmail.com

* NSF Graduate Research Fellow

† Hubble Fellow

‡ NPP Fellow

Table 1. Summary of ALMA observations.

Target	Redshift	Band	Frequency Tuning [GHz]	T_{int} [min]	Beam ["×"]	RMS (cube) [μJy/beam]	RMS (cont) [μJy/beam]
RUBIES-BLAGN-1	3.1034	5	194.1–197.7, 205.9–209.5	190.3	0.92×0.68	102.5	9.7
A2744-45924	4.4655	4	134.8–138.4, 146.9–150.5	98.5	1.56×1.27	96.7	7.5
A2744-QSO1	7.0367	3	87.6–91.2, 99.5–103.1	149.6	2.50×1.85	68.3	5.3

2023; Wang et al. 2024a; Akins et al. 2024; Li et al. 2024). They are also X-ray weak, with non-detections in deep X-ray stacks (Ananna et al. 2024; Yue et al. 2024; Maiolino et al. 2024; Lambrides et al. 2024), and only two objects (out of hundreds) detected individually with *Chandra* (Kocevski et al. 2024). Moreover, the host galaxies of LRDs are not well characterized; many LRDs exhibit Balmer breaks in their spectra (Wang et al. 2024a; Labbe et al. 2024; Furtak et al. 2024), which typically serves as a signature of an old stellar population. If the optical continuum in LRDs is dominated by an old stellar population, the implied stellar masses are large ($\gtrsim 10^{10-11} M_{\odot}$), and given their characteristic compactness, the required stellar mass *densities* approach that of the densest nuclear star clusters (Baggen et al. 2023, 2024; Akins et al. 2024). Curiously, the wavelength of the turnover from blue-to-red appears to occur consistently at the Balmer limit, $\sim 3800 \text{ \AA}$ (Setton et al. 2024), which is unexpected if the SED shape arises from a composite of galaxy+AGN components.

It has also been suggested that the Balmer break may arise not from old stars, but instead from absorption from nuclear gas with sufficient density to continuously populate the $n = 2$ state via collisional excitation (Inayoshi & Maiolino 2025). In this scenario, the observed Balmer break is purely a product of the AGN structure. This is somewhat supported by the observations of velocity-offset Balmer absorption lines (e.g. $H\alpha$, $H\beta$) in the spectra (e.g. Matthee et al. 2024; Taylor et al. 2024), as well as the X-ray weak nature of the LRDs, which can originate from Compton-thick gas absorption (Maiolino et al. 2024). However, current *JWST* spectroscopy is not sufficiently deep to directly probe the spectrum around the break at high spectral resolution, limiting the possibility of any robust conclusions.

In this letter, we present ALMA spectroscopic observations of three LRDs at $z = 3.10\text{--}7.04$, targeting the CO(7–6) and [C I](2–1) lines at 806.65 and 809.34 GHz. These far-infrared lines, tracing the molecular and atomic gas in the host galaxy interstellar medium (ISM), are routinely observed in high- z quasars and dusty star-forming galaxies. While CO and [C I] are typically fainter than

[C II] $158 \mu\text{m}$, their similar frequencies make it possible to simultaneously trace multiple gas phases to better characterize the host galaxies of LRDs.

2. ALMA OBSERVATIONS AND DATA REDUCTION

We targeted three LRDs with existing (spectroscopic) redshifts from *JWST*: RUBIES-BLAGN-1 at $z = 3.1034$ (Wang et al. 2024b, hereafter W24b), A2744-45924 at $z = 4.4655$ (Labbe et al. 2024, hereafter L24), and A2744-QSO1 at $z = 7.0367$ (Furtak et al. 2024, hereafter F24). These objects were selected for their relative brightness and accessibility to ALMA. RUBIES-BLAGN-1 and A2744-45924 are among the brightest LRDs known, and A2744-QSO1, while intrinsically fainter and at much higher redshift, is strongly lensed, with images A ($\mu = 6.2$) and B ($\mu = 7.3$) fitting into the same ALMA pointing.

The ALMA observations (PID 2024.1.01085.S) were tuned to detect CO(7–6) and [C I](2–1) at rest-frame frequencies of 806.65 and 809.34 GHz, respectively. Integration times were determined by scaling the measured black hole masses to host galaxy bulge masses assuming local relations (Kormendy & Ho 2013), converting to CO luminosities, and scaling down by a conservative factor. The Common Astronomy Software Applications package (CASA; McMullin et al. 2007) was used for reduction, calibration, and imaging. We adopt the standard ALMA pipeline results and perform custom imaging using the `tclean` task in CASA. We use the `auto-multithresh` automasking algorithm (Kepley et al. 2020) using the standard recommended parameters.¹ We also explored manually masking in a circular aperture around the known positions of each target, and find consistent results using this method. All images are made using natural weighting to maximize sensitivity, and datacubes are produced at the native channel width

¹As detailed in Section 9.39 of the ALMA pipeline User’s Guide: https://almascience.nrao.edu/documents-and-tools/cycle10/alma-pipeline-users_guide.2023

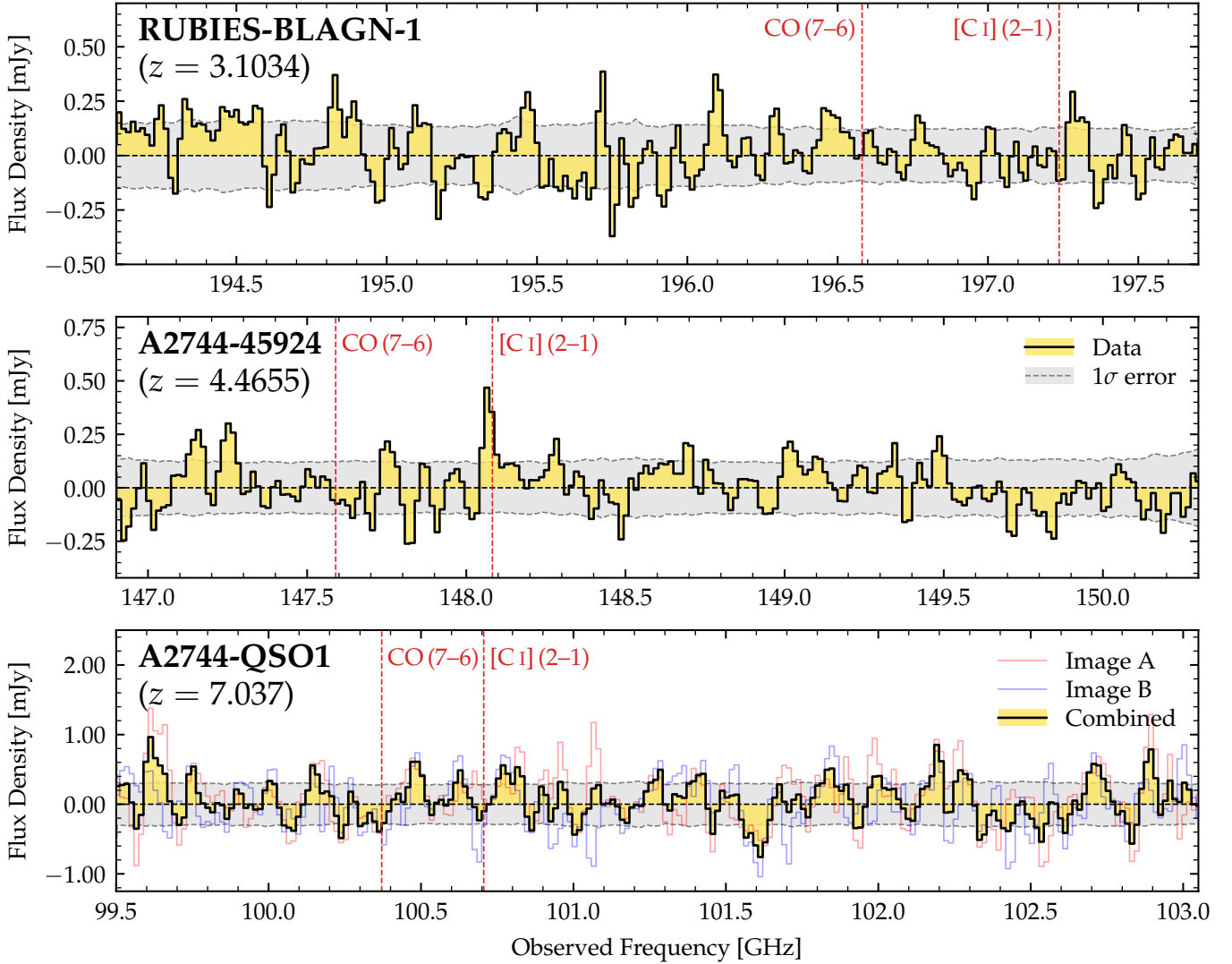


Figure 1. Extracted spectra covering CO(7–6) and [C I](2–1) for the three LRD targets. Spectra are extracted from $r = 0''.5$ apertures and corrected to account for the total beam. The grey shaded region shows the 1σ error, measured from random apertures in each channel of the cube. For A2744-QSO1, we show the extracted spectra at the positions of image A and B, as well as the co-added spectrum. CO(7–6) is not detected in any of these three LRDs; however, we identify a tentative feature at the wavelength of [C I](2–1) for A2744-45924.

of each observation. All maps are primary beam corrected.

Table 1 summarizes the ALMA observations of the three LRDs. Between the three observations in bands 3, 4, and 5, the beam size ranges from $\sim 0''.9$ – $2''.5$, and the RMS ranges from 68–103 $\mu\text{Jy}/\text{beam}$ (measured in the primary beam *uncorrected* datacubes).

3. RESULTS

3.1. CO(7–6) and [C I](2–1) line spectra

Figure 1 shows the extracted 1D spectra for the three targets. We mark the expected positions of the CO(7–6) and [C I](2–1) lines in red, based on the *JWST*-derived redshifts. We note that we adopt the redshifts derived

from NIRSpec medium or high-resolution spectroscopy ($R \sim 1000$ – 2700) or NIRCам WFSS ($R \sim 1600$). These redshifts should be accurate to $\lesssim 30 \text{ km s}^{-1}$; this is not necessarily true for redshifts derived from the PRISM, which can have a systematic offset up to $\sim 300 \text{ km s}^{-1}$ (D’Eugenio et al. 2025), making ALMA line identification difficult. For the multiply-imaged object A2744-QSO1, we show the extracted spectra at the positions of images A and B, and the coadded spectrum.

No lines are detected at the expected wavelength of CO(7–6) in the three targets. We identify a tentative feature at the position of [C I](2–1) in A2744-45924, though we do not see a similar feature in RUBIES-BLAGN-1 or A2744-QSO1.

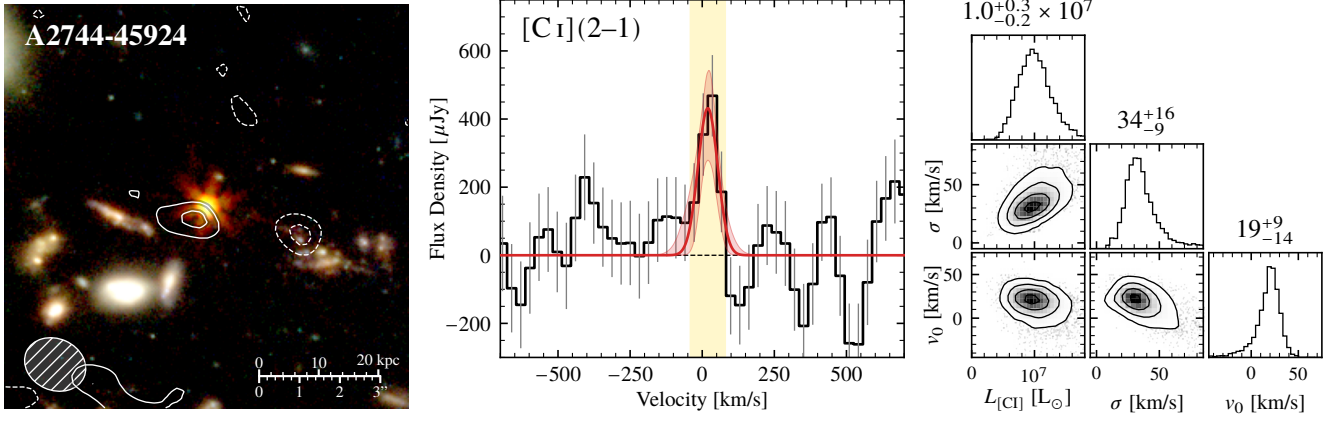


Figure 2. The tentative [C I](2–1) detection in A2744-45924. **Left:** 10'' × 10'' *JWST*/NIRCam RGB cutout around A2744-45924 from the UNCOVER survey (Bezanson et al. 2022). We overlay the [C I] moment-0 map as white contours (−3, −2, 2, and 3σ). The beam size (1''.56 × 1''.27) is indicated by the ellipse in the bottom left. **Center:** The extracted 1D spectrum of [C I](2–1) at the peak position in the moment-0 map. Error bars show the 1σ uncertainty derived from random aperture measurements across each channel in the cube. The red line and shaded region shows our best-fit Gaussian line profile fit with *emcee*. **Right:** Corner plot of the posterior line properties from our MCMC fit.

3.2. Dust continuum

We do not detect any target in the continuum observations, consistent with the overall LRD population, which are undetected at far-infrared wavelengths (Labbé et al. 2023; Akins et al. 2024). We derive upper limits on the dust mass in the optically-thin, Rayleigh-Jeans tail of the SED, following the methodology of Scoville et al. (2016). Assuming a mass-weighted dust temperature $T_{\text{dust}} = 25$ K and dust emissivity index $\beta = 1.8$, we estimate dust mass limits of $M_{\text{dust}} < 7 \times 10^7$, $< 1.4 \times 10^8$, and $< 6 \times 10^7 M_{\odot}$ for RUBIES-BLAGN-1, A2744-45924, and A2744-QSO1, respectively.

3.3. Detection of [C I](2–1) in A2744-45924

We identify a $\sim 3.9\sigma$ peak in the spectrum at the expected frequency of [C I](2–1) in A2744-45924. Figure 2 shows the moment-0 map integrated over the four channels at this peak and the 1D spectrum extracted at the peak position. The integrated signal-to-noise over these channels is 4.9σ .

The peak position of the [C I](2–1) detection is located $\sim 0''.4$ to the SE of A2744-45924. Given the slight positional offset, we consider the possibility that the detection is spurious. Following Ivison et al. (2007), we estimate the positional uncertainty of the ALMA observations from the beam size θ and signal-to-noise ratio. Random positional offsets of distance r will occur following the probability distribution $P(r) = r \exp(-r^2/(2\sigma^2))$, where σ is the typical offset in RA/Dec, given by $\sigma = 0.6\theta(S/N)^{-1} \approx 0''.25$. Following this probability distribution, the expectation value of r is $\approx 0''.32$, and offsets greater than $0''.4$ will occur $\sim 30\%$ of the time. We

therefore consider the positional offset to be negligible, statistically consistent with emission from phase center.

We fit the spectrum with a Gaussian line profile using the *emcee* Python package. The right panel of Figure 2 shows the resulting posterior estimates of the line luminosity, width, and velocity offset from the nominal redshift of $z = 4.4655$. We measure a total line flux of $I_{[C I]} = 36.9^{+10.6}_{-8.4}$ mJy km s $^{-1}$ and a luminosity of $L_{[C I]} = 1.0^{+0.3}_{-0.2} \times 10^7 L_{\odot}$. The line center is offset 19^{+9}_{-14} km s $^{-1}$ from the nominal redshift, consistent with 0, and we derive a line FWHM of 80^{+38}_{-22} km s $^{-1}$. The line width is remarkably narrow, and in fact is unresolved; the velocity resolution for the ALMA observations is ~ 70 km s $^{-1}$. The narrow line width implies a remarkably low dynamical mass, which we return to in §3.5.

3.4. Molecular gas mass

We estimate the molecular gas masses (or upper limits) of the three LRDs using the CO(7–6) and [C I] lines. Molecular gas masses are commonly derived from CO observations, though the use of high- J CO lines imparts additional uncertainty from the CO excitation ladder. The [C I] lines have proven effective tracers of the total molecular gas when low- J CO is inaccessible (Carilli & Walter 2013). This is thought to be due to the stratified chemical structure in photodissociation regions (PDRs), in which C 0 occupies a very narrow transition layer between C $^+$ and CO (Wolfire et al. 2022). We perform both calculations in order to place conservative limits on the H $_2$ mass in the LRDs.

For CO, we provide two estimates of the upper limit on the H $_2$ mass. First, we adopt a standard set of assumptions for quasar host galaxies: a CO-to-H $_2$ mass conversion

factor $\alpha_{\text{CO}} = 0.8 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ and a relatively steep CO SLED, such that $L'_{\text{CO}(7-6)}/L'_{\text{CO}(1-0)} = 0.60$, similar to Venemans et al. (2017). We assume CO line widths of 300 km s^{-1} to translate the upper limits in terms of flux density to luminosity. These assumptions give us 3σ molecular gas mass limits of $M_{\text{H}_2, \text{CO}} < 4 \times 10^8$, $< 9 \times 10^8$, and $< 2 \times 10^9 M_{\odot}$ for RUBIES-BLAGN-1, A2744-45924, and A2744-QSO1, respectively. Adopting a more conservative set of assumptions for CO-to- H_2 conversion factor of $\alpha_{\text{CO}} = 4.5 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$, the canonical value for the Milky Way, and a shallower CO SLED such that $L'_{\text{CO}(7-6)}/L'_{\text{CO}(1-0)} = 0.1$, approximately the lower bound observed for SMGs (Casey, Narayanan, & Cooray 2014), yields larger molecular gas mass limits by a factor of ~ 30 . Specifically, we derive $M_{\text{H}_2, \text{CO}} < 10^{10}$, $< 3 \times 10^{10}$, and $< 5 \times 10^{10} M_{\odot}$ for RUBIES-BLAGN-1, A2744-45924, and A2744-QSO1, respectively.

For [C I], we adopt a [C I]-to- H_2 conversion factor of $\alpha_{[\text{C I}](2-1)} = 34$ from Crocker et al. (2019). For A2744-45924, we derive a [C I] luminosity of $L'_{[\text{C I}]} = 5.8^{+1.7}_{-1.4} \times 10^8 \text{ K km s}^{-1} \text{pc}^2$, which corresponds to a molecular gas mass of $M_{\text{H}_2} = 2.0^{+3.1}_{-1.2} \times 10^{10} M_{\odot}$. We note that this accounts for uncertainty in $\alpha_{[\text{C I}]}$ at the level of 0.4 dex. For RUBIES-BLAGN-1 and A2744-QSO1, we derive 3σ limits of $M_{\text{H}_2, [\text{C I}]} < 10^{10}$ and $< 4 \times 10^{10} M_{\odot}$. These limits are similar to the conservative limits from CO(7–6) but depend only on the empirically-derived $\alpha_{[\text{C I}](2-1)}$ conversion factor, and not on the (highly uncertain) CO line SLED.

3.5. Dynamical mass

We estimate the dynamical mass in A2744-45924 based on the [C I] line kinematics. The dynamical mass is estimated as

$$M_{\text{dyn}} = \frac{5R_e\sigma^2}{G} \quad (1)$$

where G is the gravitational constant, R_e is the effective radius, and σ is the velocity dispersion of the gas, in this case from the [C I] line, $\sigma_{\text{gas}} = 34^{+16}_{-9} \text{ km s}^{-1}$. However, the relevant radius is not obvious, as the [C I] line is spatially unresolved. Labbe et al. (2024) fit 2D Sersic models to the *JWST*/NIRCam imaging and estimate the effective radius $R_e \lesssim 70 \text{ pc}$. However, if the [C I] originates from larger scales than the NIRCam emission (which may be predominantly from the AGN), this size would be too small. Labbe et al. (2024) also find evidence for a faint, extended ($R_e \sim 700 \text{ pc}$) structure alongside the dominant unresolved component. We adopt this size for our fiducial measurement of the dynamical mass, for which we derive $M_{\text{dyn}} = 1.4^{+1.7}_{-0.6} \times 10^9 M_{\odot}$. We note that this accounts for the unknown inclination angle via a factor

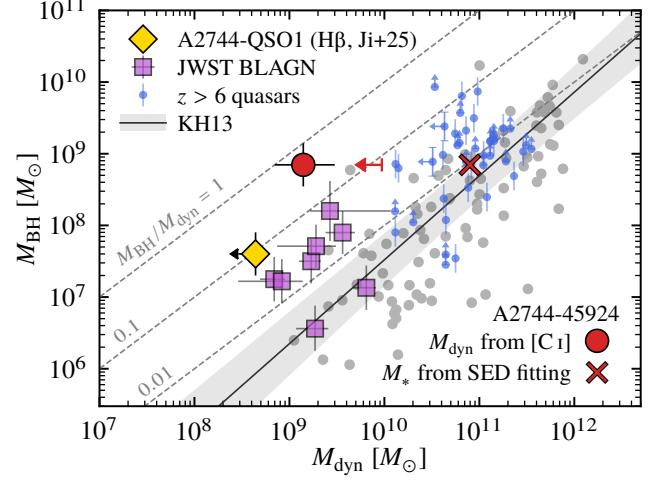


Figure 3. Black hole mass vs. dynamical mass *JWST* AGN at $z > 4$, including A2744-45924, compared to local SMBHs and $z > 6$ quasars. We plot local SMBHs and the best-fit relation from Kormendy & Ho (2013) in grey. We show $z > 6$ quasars in blue, with ALMA [C II] dynamical mass measurements (Izumi et al. 2019). We also show other *JWST* BLAGN with dynamical masses measured from high-resolution spectroscopy (Maiolino et al. 2023; Übler et al. 2023), including A2744-QSO1 (Ji et al. 2025). Our dynamical mass measurement for A2744-45924 is comparable to the black hole mass, and significantly above the local relation.

of $3/2$, which is the reciprocal of the expectation value of $\sin^2 i$.

Given the unknown size of the [C I]-emitting gas, we also conservatively quote an upper limit on the dynamical mass assuming a size of $R_e < 4.8 \text{ kpc}$, which corresponds to the half-width at half-maximum of the ALMA beam. This yields a dynamical mass limit of $M_{\text{dyn}} < 9.4^{+11.4}_{-4.9} \times 10^9 M_{\odot}$. The dynamical mass limit, even adopting a conservative limit on the size, is at least an order of magnitude below the stellar mass for A2744-45924 derived by Labbe et al. (2024) from SED fitting to the Balmer break, which we discuss further in Section 4.

4. DISCUSSION

4.1. Implications for the host galaxies of LRDs

The limits we place on the host galaxy dynamical and molecular gas masses allow us to better place the three targeted LRDs in context among high- z galaxies and quasars. It has been suggested that the LRDs represent the obscured phase of quasar evolution (Schindler et al. 2024; Arita et al. 2025) or are actually massive, compact galaxies (Baggen et al. 2024). In fact, the large black hole masses reported for two of our targets ($M_{\text{BH}} \sim 1\text{--}4 \times 10^8 M_{\odot}$ and $\sim 10^9 M_{\odot}$ for RUBIES-BLAGN-1 and A2744-45924, respectively) already suggests some similarity to quasars, and the strong Balmer break in both

objects indicates the presence of a massive stellar population. However, the CO and [C I] observations imply low gas fractions: adopting typical assumptions for quasar host galaxies, our derived gas mass limits imply $f_{\text{gas}} = M_{\text{gas}} / (M_{\star} + M_{\text{gas}}) < 20\%$ for RUBIES-BLAGN-1 and $< 1\%$ for A2744-45924. This is in sharp contrast to high- z quasars (Venemans et al. 2017; Decarli et al. 2018; Izumi et al. 2019) and luminous obscured AGN (Fujimoto et al. 2022; Endsley et al. 2022b; Lambrides et al. 2023) which live in massive, gas-rich, and actively star-forming host galaxies.

The dynamical mass estimate for A2744-45924 is remarkably low, comparable to the black hole mass derived from the broad $H\alpha$ line (L24). This suggests that the SMBH in A2744-45924 is overmassive relative to the host, even in terms of the dynamical mass. Figure 3 shows black hole mass vs. dynamical mass for A2744-45924 alongside local SMBHs (Kormendy & Ho 2013), high- z quasars (Izumi et al. 2021) and recent JWST-discovered AGN (Maiolino et al. 2023; Übler et al. 2023). We also show A2744-QSO1; though not detected in [C I] or CO, the dynamical mass has recently been measured from the narrow component of $H\beta$ via high-resolution JWST IFU spectroscopy (Ji et al. 2025). They derive a black hole-to-dynamical mass ratio of $\gtrsim 0.1$, similar to this work. Our dynamical mass measurement positions A2744-45924 significantly above the local $M_{\text{BH}}-M_{\text{dyn}}$ relation. The existence of such overmassive black holes may be a signature of high-mass seeds (e.g. Agarwal et al. 2012) or super-Eddington growth (e.g. Hu et al. 2022).

Moreover, our derived dynamical mass for A2744-45924 is more than an order of magnitude below the stellar mass derived in L24 ($M_{\star} \sim 8 \times 10^{10} M_{\odot}$), which is based on the assumption that the strong Balmer break observed in the NIRSpec spectrum is associated with an old stellar population. Provided the [C I] detection traces the overall kinematics of the host galaxy, our results suggest that the Balmer break in A2744-45924 *cannot* originate from stellar emission. Instead, it seems plausible that the Balmer break originates from extremely dense gas close to the AGN (e.g. Inayoshi & Maiolino 2025). This is somewhat corroborated by the detection of velocity-offset $H\alpha$ absorption lines, as well as remarkably strong $\text{O I } \lambda 8446$ emission in A2744-45924 (L24). The latter can arise from resonance fluorescence of $\text{Ly}\beta$ in extremely dense gas, due to the similar energy levels between O I and H I (see further discussion in Inayoshi & Maiolino 2025).

4.2. Origin of the [C I] emission

The detection [C I] in A2744-45924, without a corresponding detection of CO(7–6), is distinct from high- z

quasars (e.g. Venemans et al. 2017), dusty star-forming galaxies (e.g. Yang et al. 2017), and even main-sequence galaxies at lower-redshift (e.g. Valentino et al. 2020). Moreover, the molecular gas mass as estimated from the [C I] line is more than an order of magnitude larger than the dynamical mass measured from the same line, perhaps suggesting that the mechanism exciting [C I] in A2744-45924 may be different than in the local galaxies used to calibrate the [C I]-to- H_2 relation (e.g., PDRs; Papadopoulos et al. 2004). Such conditions have been observed in the circumnuclear disk of the local radio galaxy Centaurus A: Israel et al. (2014) measure $[\text{C I}](2-1)/\text{CO}(7-6) \gtrsim 6$, a ratio larger than any known AGN or starburst galaxy and inconsistent with their PDR modeling.

There are a number of possible scenarios that could produce elevated [C I] relative to CO, particularly at high redshift, where extreme ISM conditions occur more frequently (e.g. Cameron et al. 2023; Katz et al. 2023). The interpretation of this result depends in part on whether the [C I] indeed traces H_2 gas, as is thought to be the case in PDRs, or primarily H I gas. In the former scenario, the H_2 gas must be “CO-dark,” as in translucent clouds (Magnani et al. 1998; Bolatto et al. 2013). One possibility is a super-solar C/O abundance, which would leave more of the carbon in its atomic phase, unable to form into CO, therefore increasing the C/CO column density ratio. A super-solar C/O has been tentatively reported in another LRD at $z = 7$ (Akins et al. 2025), though no robust abundance measurements have been made. At the same time, the C/CO column density ratio can be increased by dissociation of the CO molecules. CO dissociation can occur in shocks, driven by outflows from the AGN (e.g. Saito et al. 2022), or in X-ray dominated regions (XDRs; Meijerink & Spaans 2005; Meijerink et al. 2007; Wolfire et al. 2022). However, we note that A2744-45924 is undetected in deep (2.14 Ms) *Chandra* X-ray observations (PID 23700107; PI: A. Bogdan), consistent with the majority of LRDs and JWST-selected AGN at $z > 4$, (e.g. Ananna et al. 2024; Maiolino et al. 2024; Lambrides et al. 2024). If the strong [C I] is indeed driven by XDRs, it would have to be in regions of very high density, sufficient to absorb the X-rays as well.

It is also possible that the [C I] primarily traces H I gas rather than H_2 . Indeed, the non-stellar Balmer break interpretation *requires* abundant H I gas, at very high density, sufficient to continuously populate the $n = 2$ state via collisional excitation (Inayoshi & Maiolino 2025). At these extreme densities ($n_{\text{H}} > 10^9 \text{ cm}^{-3}$) and temperatures ($T > 8000 \text{ K}$), H_2 is dissociated via collisions with H I gas. However, the critical density of the [C I](2–1) line is $< 1000 \text{ cm}^{-3}$, far below the density required to

produce the Balmer absorption. The [C I] would therefore, in this scenario, arise from a lower-density component of the H I gas responsible for producing the observed Balmer break and H α absorption lines in A2744-45924. The formation of these lower density atomic clouds, without a significant molecular component, may be aided by strong FUV Lyman-Werner radiation fields, which can dissociate H₂ (Stecher & Williams 1967); this argument is often invoked to prevent cooling and fragmentation in models of primordial gas clouds forming into “direct collapse black holes” (e.g. Bromm & Loeb 2003). X-ray radiation can have a similar effect by heating gas (Jeon et al. 2014), but it is less clear-cut: by also ionizing H I, X-rays can in fact promote H₂ formation (Glover & Brand 2003).

While it is certainly possible to envision connections between the [C I] emission and the Balmer break/dense gas absorption, confirming such a scenario will require more comprehensive characterization of the gas conditions in A2744-45924 and other LRDs. Other far-infrared lines such as [O I] 63 μ m or 145 μ m, which have larger critical densities than [C I], could prove a useful tracer of dense neutral gas (e.g. Ishii et al. 2025). Molecular transitions in the rest-frame near-infrared, which trace warm/hot molecular gas, may be accessible with MIRI (e.g. Costa-Souza et al. 2024). Higher resolution spectra in the rest-frame UV could provide constraints on the carbon abundance (e.g. Hsiao et al. 2024), Ly β pumping scenario (via O I λ 1304, e.g. Rodríguez-Ardila et al. 2002; Matsuoka et al. 2007), and even potential detect H₂ fluorescence (e.g. Johnson et al. 2025). Understanding the extreme and peculiar gas conditions in LRDs will be key to characterizing their overall role in galaxy/SMBH formation.

5. SUMMARY

Our observations of [C I] and CO suggest that the LRDs do not live in particularly gas-rich host galaxies. This is in sharp contrast to high- z quasars/obscured AGN, which have been found to reside in intensely star-forming host galaxies, routinely detected in CO, [C I], [C II], and dust continuum (Venemans et al. 2017; Decarli et al. 2018; Izumi et al. 2019; Endsley et al. 2022b; Fujimoto et al. 2022; Lambrides et al. 2023). Even A2744-45924, despite hosting a nearly $10^9 M_{\odot}$ black hole, appears to live in a $< 10^{10} M_{\odot}$ host galaxy. Perhaps most intriguing, the dynamical mass of A2744-45924 is significantly lower than the stellar mass derived from SED fitting, potentially corroborating the proposed non-stellar origin of the Balmer break in LRDs.

However, given the relatively low SNR (4.9σ), it remains possible that the [C I] detection in A2744-45924

is spurious, or that it traces only a part of the overall host galaxy ISM, impacting the interpretation of the dynamical mass measurement. These results remain tentative; future deeper and/or higher resolution observations will be needed to confirm the dynamical mass measurement in A2744-45924, and reveal the host galaxy properties of other LRDs.

ACKNOWLEDGEMENTS

The authors wish to thank Kohei Inayoshi and Junehyoung Jeon for useful discussions that greatly improved this letter. H.B.A. acknowledges the support of the UT Austin Astronomy Department and the UT Austin College of Natural Sciences through Harrington Graduate Fellowship, as well as the National Science Foundation for support through the NSF Graduate Research Fellowship Program. This paper makes use of the following ALMA data: ADS/JAO.ALMA#2024.1.01085.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), NSTC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Authors from UT Austin acknowledge that they work at an institution that sits on indigenous land. The Tonkawa lived in central Texas, and the Comanche and Apache moved through this area. We pay our respects to all the American Indian and Indigenous Peoples and communities who have been or have become a part of these lands and territories in Texas.

Table 2. Summary of measurements.

Property	Units	RUBIES-BLAGN-1	A2744-45924	A2744-QSO1 [†]
$I_{\text{CO}(7-6)}$	mJy km s^{-1}	< 35	< 43	< 37
$L'_{\text{CO}(7-6)}$	$10^8 \text{ K km s}^{-1} \text{ pc}^2$	< 3.2	< 6.9	< 11.5
$I_{[\text{C I}](2-1)}$	mJy km s^{-1}	< 41	$36.9^{+10.6}_{-8.4}$	< 37
$L'_{[\text{C I}](2-1)}$	$10^8 \text{ K km s}^{-1} \text{ pc}^2$	< 3.6	$5.8^{+1.7}_{-1.4}$	< 11.5
$M_{\text{H}_2, \text{CO}}$	$10^{10} M_{\odot}$	< 1.4	< 3.1	< 5.1
$M_{\text{H}_2, [\text{C I}]}$	$10^{10} M_{\odot}$	< 1.1	$2.0^{+3.1}_{-1.2}$	< 3.9
M_{dyn}	$10^9 M_{\odot}$	...	$1.4^{+1.7*}_{-0.6}$	...
$S_{370 \mu\text{m}}$	μJy	< 29.1	< 22.5	< 2.4
M_{dust}	$10^7 M_{\odot}$	< 6.8	< 13.9	< 5.9

* Dynamical mass estimated from the [C I] line for A2744-45924, see text for details.

[†] All measurements for A2744-QSO1 are corrected for lensing magnification.

NOTE—All upper limits are 3σ .

REFERENCES

- Agarwal, B., Khochfar, S., Johnson, J. L., et al. 2012, *Monthly Notices of the Royal Astronomical Society*, 425, 2854, doi: [10.1111/j.1365-2966.2012.21651.x](https://doi.org/10.1111/j.1365-2966.2012.21651.x)
- Akins, H. B., Casey, C. M., Lambrides, E., et al. 2024, arXiv e-prints, 2406.10341, doi: [10.48550/arXiv.2406.10341](https://doi.org/10.48550/arXiv.2406.10341)
- Akins, H. B., Casey, C. M., Berg, D. A., et al. 2025, *The Astrophysical Journal*, 980, L29, doi: [10.3847/2041-8213/adab76](https://doi.org/10.3847/2041-8213/adab76)
- Ananna, T. T., Bogdán, Á., Kovács, O. E., Natarajan, P., & Hickox, R. C. 2024, arXiv e-prints, 2404.19010, doi: [10.48550/arXiv.2404.19010](https://doi.org/10.48550/arXiv.2404.19010)
- Arita, J., Kashikawa, N., Onoue, M., et al. 2025, *Monthly Notices of the Royal Astronomical Society*, 536, 3677, doi: [10.1093/mnras/stae2765](https://doi.org/10.1093/mnras/stae2765)
- Baggen, J. F. W., van Dokkum, P., Labbé, I., et al. 2023, *The Astrophysical Journal*, 955, L12, doi: [10.3847/2041-8213/acf5ef](https://doi.org/10.3847/2041-8213/acf5ef)
- Baggen, J. F. W., van Dokkum, P., Brammer, G., et al. 2024, arXiv e-prints, 2408.07745, doi: [10.48550/arXiv.2408.07745](https://doi.org/10.48550/arXiv.2408.07745)
- Bezanson, R., Labbe, I., Whitaker, K. E., et al. 2022, arXiv, 2212.04026, doi: [10.48550/arXiv.2212.04026](https://doi.org/10.48550/arXiv.2212.04026)
- Bolatto, A. D., Wolfire, M., & Leroy, A. K. 2013, *Annual Review of Astronomy and Astrophysics*, 51, 207, doi: [10.1146/annurev-astro-082812-140944](https://doi.org/10.1146/annurev-astro-082812-140944)
- Bromm, V., & Loeb, A. 2003, *The Astrophysical Journal*, 596, 34, doi: [10.1086/377529](https://doi.org/10.1086/377529)
- Cameron, A. J., Saxena, A., Bunker, A. J., et al. 2023, *Astronomy and Astrophysics*, 677, A115, doi: [10.1051/0004-6361/202346107](https://doi.org/10.1051/0004-6361/202346107)
- Carilli, C. L., & Walter, F. 2013, *Annual Review of Astronomy and Astrophysics*, 51, 105, doi: [10.1146/annurev-astro-082812-140953](https://doi.org/10.1146/annurev-astro-082812-140953)
- Casey, C. M., Narayanan, D., & Cooray, A. 2014, *Physics Reports*, 541, 45, doi: [10.1016/j.physrep.2014.02.009](https://doi.org/10.1016/j.physrep.2014.02.009)
- Costa-Souza, J. H., Riffel, R. A., Souza-Oliveira, G. L., et al. 2024, *The Astrophysical Journal*, 974, 127, doi: [10.3847/1538-4357/ad702a](https://doi.org/10.3847/1538-4357/ad702a)
- Crocker, A. F., Pellegrini, E., Smith, J. D. T., et al. 2019, *The Astrophysical Journal*, 887, 105, doi: [10.3847/1538-4357/ab4196](https://doi.org/10.3847/1538-4357/ab4196)
- Davies, F. B., Hennawi, J. F., & Eilers, A.-C. 2019, *The Astrophysical Journal*, 884, L19, doi: [10.3847/2041-8213/ab42e3](https://doi.org/10.3847/2041-8213/ab42e3)
- Decarli, R., Walter, F., Venemans, B. P., et al. 2018, *The Astrophysical Journal*, 854, 97, doi: [10.3847/1538-4357/aaa5aa](https://doi.org/10.3847/1538-4357/aaa5aa)
- D'Eugenio, F., Cameron, A. J., Scholtz, J., et al. 2025, *The Astrophysical Journal Supplement Series*, 277, 4, doi: [10.3847/1538-4365/ada148](https://doi.org/10.3847/1538-4365/ada148)
- Eilers, A.-C., Hennawi, J. F., Davies, F. B., & Simcoe, R. A. 2021, *The Astrophysical Journal*, 917, 38, doi: [10.3847/1538-4357/ac0a76](https://doi.org/10.3847/1538-4357/ac0a76)
- Eilers, A.-C., Hennawi, J. F., Decarli, R., et al. 2020, *The Astrophysical Journal*, 900, 37, doi: [10.3847/1538-4357/aba52e](https://doi.org/10.3847/1538-4357/aba52e)

- Endsley, R., Stark, D. P., Fan, X., et al. 2022a, *Monthly Notices of the Royal Astronomical Society*, 512, 4248, doi: [10.1093/mnras/stac737](https://doi.org/10.1093/mnras/stac737)
- Endsley, R., Stark, D. P., Lyu, J., et al. 2022b, arXiv, 2206.00018, doi: [10.48550/arXiv.2206.00018](https://doi.org/10.48550/arXiv.2206.00018)
- Fan, X., Bañados, E., & Simcoe, R. A. 2023, *Annual Review of Astronomy and Astrophysics*, 61, 373, doi: [10.1146/annurev-astro-052920-102455](https://doi.org/10.1146/annurev-astro-052920-102455)
- Fujimoto, S., Brammer, G. B., Watson, D., et al. 2022, *Nature*, 604, 261, doi: [10.1038/s41586-022-04454-1](https://doi.org/10.1038/s41586-022-04454-1)
- Furtak, L. J., Labbé, I., Zitrin, A., et al. 2024, *Nature*, 628, 57, doi: [10.1038/s41586-024-07184-8](https://doi.org/10.1038/s41586-024-07184-8)
- Gilli, R., Norman, C., Calura, F., et al. 2022, *Astronomy and Astrophysics*, 666, A17, doi: [10.1051/0004-6361/202243708](https://doi.org/10.1051/0004-6361/202243708)
- Glover, S. C. O., & Brand, P. W. J. L. 2003, *Monthly Notices of the Royal Astronomical Society*, 340, 210, doi: [10.1046/j.1365-8711.2003.06311.x](https://doi.org/10.1046/j.1365-8711.2003.06311.x)
- Greene, J. E., Labbe, I., Goulding, A. D., et al. 2024, *The Astrophysical Journal*, 964, 39, doi: [10.3847/1538-4357/ad1e5f](https://doi.org/10.3847/1538-4357/ad1e5f)
- Harikane, Y., Zhang, Y., Nakajima, K., et al. 2023, *The Astrophysical Journal*, 959, 39, doi: [10.3847/1538-4357/ad029e](https://doi.org/10.3847/1538-4357/ad029e)
- Hsiao, T. Y.-Y., Topping, M. W., Coe, D., et al. 2024, arXiv e-prints, 2409.04625, doi: [10.48550/arXiv.2409.04625](https://doi.org/10.48550/arXiv.2409.04625)
- Hu, H., Inayoshi, K., Haiman, Z., et al. 2022, *The Astrophysical Journal*, 935, 140, doi: [10.3847/1538-4357/ac7daa](https://doi.org/10.3847/1538-4357/ac7daa)
- Inayoshi, K., & Maiolino, R. 2025, *The Astrophysical Journal*, 980, L27, doi: [10.3847/2041-8213/adaebd](https://doi.org/10.3847/2041-8213/adaebd)
- Inayoshi, K., Visbal, E., & Haiman, Z. 2020, *Annual Review of Astronomy and Astrophysics*, 58, 27, doi: [10.1146/annurev-astro-120419-014455](https://doi.org/10.1146/annurev-astro-120419-014455)
- Ishii, N., Hashimoto, T., Ferkinhoff, C., et al. 2025, *Publications of the Astronomical Society of Japan*, 77, 139, doi: [10.1093/pasj/psae105](https://doi.org/10.1093/pasj/psae105)
- Israel, F. P., Güsten, R., Meijerink, R., et al. 2014, *Astronomy & Astrophysics*, 562, A96, doi: [10.1051/0004-6361/201322780](https://doi.org/10.1051/0004-6361/201322780)
- Ivison, R. J., Greve, T. R., Dunlop, J. S., et al. 2007, *Monthly Notices of the Royal Astronomical Society*, 380, 199, doi: [10.1111/j.1365-2966.2007.12044.x](https://doi.org/10.1111/j.1365-2966.2007.12044.x)
- Izumi, T., Onoue, M., Matsuoka, Y., et al. 2019, *Publications of the Astronomical Society of Japan*, 71, 111, doi: [10.1093/pasj/psz096](https://doi.org/10.1093/pasj/psz096)
- Izumi, T., Matsuoka, Y., Fujimoto, S., et al. 2021, *The Astrophysical Journal*, 914, 36, doi: [10.3847/1538-4357/abf6dc](https://doi.org/10.3847/1538-4357/abf6dc)
- Jeon, M., Pawlik, A. H., Bromm, V., & Milosavljević, M. 2014, *Monthly Notices of the Royal Astronomical Society*, 440, 3778, doi: [10.1093/mnras/stu444](https://doi.org/10.1093/mnras/stu444)
- Ji, X., Maiolino, R., Übler, H., et al. 2025, arXiv e-prints, 2501.13082, doi: [10.48550/arXiv.2501.13082](https://doi.org/10.48550/arXiv.2501.13082)
- Johnson, M., Burkhart, B., D'Eugenio, F., et al. 2025, A Tentative Detection of Molecular Hydrogen (H₂) Emission Lines at Cosmic Dawn, arXiv, doi: [10.48550/arXiv.2502.19484](https://doi.org/10.48550/arXiv.2502.19484)
- Katz, H., Saxena, A., Cameron, A. J., et al. 2023, *Monthly Notices of the Royal Astronomical Society*, 518, 592, doi: [10.1093/mnras/stac2657](https://doi.org/10.1093/mnras/stac2657)
- Kepley, A. A., Tsutsumi, T., Brogan, C. L., et al. 2020, *Publications of the Astronomical Society of the Pacific*, 132, 024505, doi: [10.1088/1538-3873/ab5e14](https://doi.org/10.1088/1538-3873/ab5e14)
- Kocevski, D. D., Finkelstein, S. L., Barro, G., et al. 2024, arXiv e-prints, 2404.03576, doi: [10.48550/arXiv.2404.03576](https://doi.org/10.48550/arXiv.2404.03576)
- Kokorev, V., Caputi, K. I., Greene, J. E., et al. 2024, arXiv e-prints, 2401.09981, doi: [10.48550/arXiv.2401.09981](https://doi.org/10.48550/arXiv.2401.09981)
- Kormendy, J., & Ho, L. C. 2013, *Annual Review of Astronomy and Astrophysics*, 51, 511, doi: [10.1146/annurev-astro-082708-101811](https://doi.org/10.1146/annurev-astro-082708-101811)
- Labbé, I., Greene, J. E., Bezanson, R., et al. 2023, arXiv, 2306.07320, doi: [10.48550/arXiv.2306.07320](https://doi.org/10.48550/arXiv.2306.07320)
- Labbe, I., Greene, J. E., Matthee, J., et al. 2024, arXiv e-prints, doi: [10.48550/arXiv.2412.04557](https://doi.org/10.48550/arXiv.2412.04557)
- Lambrides, E., Chiaberge, M., Long, A., et al. 2023, arXiv, 2308.12823, doi: [10.48550/arXiv.2308.12823](https://doi.org/10.48550/arXiv.2308.12823)
- Lambrides, E., Garofali, K., Larson, R., et al. 2024, arXiv e-prints, 2409.13047, doi: [10.48550/arXiv.2409.13047](https://doi.org/10.48550/arXiv.2409.13047)
- Li, Z., Inayoshi, K., Chen, K., Ichikawa, K., & Ho, L. C. 2024, arXiv e-prints, 2407.10760, doi: [10.48550/arXiv.2407.10760](https://doi.org/10.48550/arXiv.2407.10760)
- Magnani, L., Onello, J. S., Adams, N. G., Hartmann, D., & Thaddeus, P. 1998, *The Astrophysical Journal*, 504, 290, doi: [10.1086/306062](https://doi.org/10.1086/306062)
- Maiolino, R., Scholtz, J., Curtis-Lake, E., et al. 2023, arXiv, 2308.01230, doi: [10.48550/arXiv.2308.01230](https://doi.org/10.48550/arXiv.2308.01230)
- Maiolino, R., Risaliti, G., Signorini, M., et al. 2024, arXiv e-prints, 2405.00504, doi: [10.48550/arXiv.2405.00504](https://doi.org/10.48550/arXiv.2405.00504)
- Matsuoka, Y., Oyabu, S., Tsuzuki, Y., & Kawara, K. 2007, *The Astrophysical Journal*, 663, 781, doi: [10.1086/518399](https://doi.org/10.1086/518399)
- Matthee, J., Naidu, R. P., Brammer, G., et al. 2024, *The Astrophysical Journal*, 963, 129, doi: [10.3847/1538-4357/ad2345](https://doi.org/10.3847/1538-4357/ad2345)
- McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, 376, 127
- Meijerink, R., & Spaans, M. 2005, *Astronomy and Astrophysics*, 436, 397, doi: [10.1051/0004-6361:20042398](https://doi.org/10.1051/0004-6361:20042398)

- Meijerink, R., Spaans, M., & Israel, F. P. 2007, *Astronomy and Astrophysics*, 461, 793, doi: [10.1051/0004-6361:20066130](https://doi.org/10.1051/0004-6361:20066130)
- Ni, Y., Di Matteo, T., Gilli, R., et al. 2020, *Monthly Notices of the Royal Astronomical Society*, 495, 2135, doi: [10.1093/mnras/staa1313](https://doi.org/10.1093/mnras/staa1313)
- Papadopoulos, P. P., Thi, W. F., & Viti, S. 2004, *Monthly Notices of the Royal Astronomical Society*, 351, 147, doi: [10.1111/j.1365-2966.2004.07762.x](https://doi.org/10.1111/j.1365-2966.2004.07762.x)
- Pezzulli, E., Valiante, R., & Schneider, R. 2016, *Monthly Notices of the Royal Astronomical Society*, 458, 3047, doi: [10.1093/mnras/stw505](https://doi.org/10.1093/mnras/stw505)
- Rodríguez-Ardila, A., Viegas, S. M., Pastoriza, M. G., Prato, L., & Donzelli, C. J. 2002, *The Astrophysical Journal*, 572, 94, doi: [10.1086/340192](https://doi.org/10.1086/340192)
- Saito, T., Takano, S., Harada, N., et al. 2022, *The Astrophysical Journal*, 927, L32, doi: [10.3847/2041-8213/ac59ae](https://doi.org/10.3847/2041-8213/ac59ae)
- Schindler, J.-T., Hennawi, J. F., Davies, F. B., et al. 2024, arXiv e-prints, doi: [10.48550/arXiv.2411.11534](https://doi.org/10.48550/arXiv.2411.11534)
- Scoville, N., Sheth, K., Aussel, H., et al. 2016, *The Astrophysical Journal*, 820, 83, doi: [10.3847/0004-637X/820/2/83](https://doi.org/10.3847/0004-637X/820/2/83)
- Setton, D. J., Khullar, G., Miller, T. B., et al. 2024, arXiv e-prints, 2402.05664
- Stecher, T. P., & Williams, D. A. 1967, *The Astrophysical Journal*, 149, L29, doi: [10.1086/180047](https://doi.org/10.1086/180047)
- Taylor, A. J., Finkelstein, S. L., Kocevski, D. D., et al. 2024, arXiv e-prints, 2409.06772, doi: [10.48550/arXiv.2409.06772](https://doi.org/10.48550/arXiv.2409.06772)
- Übler, H., Maiolino, R., Curtis-Lake, E., et al. 2023, *Astronomy and Astrophysics*, 677, A145, doi: [10.1051/0004-6361/202346137](https://doi.org/10.1051/0004-6361/202346137)
- Valentino, F., Daddi, E., Puglisi, A., et al. 2020, *Astronomy and Astrophysics*, 641, A155, doi: [10.1051/0004-6361/202038322](https://doi.org/10.1051/0004-6361/202038322)
- Venemans, B. P., Walter, F., Decarli, R., et al. 2017, *The Astrophysical Journal*, 845, 154, doi: [10.3847/1538-4357/aa81cb](https://doi.org/10.3847/1538-4357/aa81cb)
- Wang, B., Leja, J., de Graaff, A., et al. 2024a, arXiv e-prints, 2405.01473, doi: [10.48550/arXiv.2405.01473](https://doi.org/10.48550/arXiv.2405.01473)
- Wang, B., de Graaff, A., Davies, R. L., et al. 2024b, arXiv e-prints, 2403.02304, doi: [10.48550/arXiv.2403.02304](https://doi.org/10.48550/arXiv.2403.02304)
- Williams, C. C., Alberts, S., Ji, Z., et al. 2023, arXiv, 2311.07483. <https://arxiv.org/abs/2311.07483>
- Wolfire, M. G., Vallini, L., & Chevance, M. 2022, *Annual Review of Astronomy and Astrophysics*, 60, 247, doi: [10.1146/annurev-astro-052920-010254](https://doi.org/10.1146/annurev-astro-052920-010254)
- Yang, C., Omont, A., Beelen, A., et al. 2017, *Astronomy and Astrophysics*, 608, A144, doi: [10.1051/0004-6361/201731391](https://doi.org/10.1051/0004-6361/201731391)
- Yue, M., Eilers, A.-C., Ananna, T. T., et al. 2024, arXiv e-prints, 2404.13290, doi: [10.48550/arXiv.2404.13290](https://doi.org/10.48550/arXiv.2404.13290)