Evidence for extended gaseous reservoirs around AGN at cosmic noon from ALMA CO(3-2) observations

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ABSTRACT

Gaseous outflows are key phenomena in the evolution of galaxies, as they affect star formation (either positively or negatively), eject gas from the core or disk, and directly cause mixing of pristine and processed material. Active outflows may be detected through searches for broad spectral line emission or high-velocity gas, but it is also possible to determine the presence of past outflows by searching for extended reservoirs of chemically enriched molecular gas in the circumgalactic medium (CGM) around galaxies. In this work, we examine the CO(3-2) emission of a set of seven z ~ 2.0 – 2.5 AGN host galaxies, as observed with ALMA. Through a three-dimensional stacking analysis we find evidence for extended CO emission of radius r ~ 13 kpc. We extend this analysis to the HST/ACS i-band images of the sample galaxies, finding a complex small-scale (r < 10 kpc) morphology but no robust evidence for extended emission. In addition, the dust emission (traced by rest-frame FIR) shows no evidence for significant spatial extension. This indicates that the diffuse CO emission revealed by ALMA is morphologically distinct from the stellar component, and thus traces an extended reservoir of enriched gas. The presence of a diffuse, enriched molecular reservoir around this sample of AGN host galaxies at cosmic noon hints at a history of AGN-driven outflows that likely had strong effects on the star formation history of these objects.

Key words: galaxies: high-redshift - galaxies: evolution - ISM: jets and outflows

1 INTRODUCTION

The diffuse circumgalactic medium (CGM) surrounding a galaxy is a record of its recent past and an indicator of its future. This spatially extended (O[10 – 100 kpc]; e.g., Prochaska et al. 2017; Tumlinson et al. 2017; Fujimoto et al. 2019) material, which acts as a major reservoir of fuel for star formation, may include streaming gas from large-scale gaseous filaments (e.g., Arrigoni Battaia et al. 2018; Umehata et al. 2019), as well as processed materials ejected from the galaxy itself. Gas may be expelled from the central source by starburst-driven winds (e.g., Gallerani et al. 2018; Spilker et al. 2018; Jones et al. 2019) or by feedback from an active galactic nucleus (AGN; e.g., Fluttsch et al. 2019; Bischetti et al. 2019; Lutz et al. 2020; Travascio et al. 2020; Vayner et al. 2021), hinting at energetic processes in the center of the galaxy or its disk. This expelled gas may form an extended gaseous reservoir, which can be explored using multiple tracers (e.g., HI 21 cm, Lyα, optical nebular lines, [CII] 158 μm, CO rotational transitions).

The most direct has been the HI line, which traces the atomic medium. Using MeerKAT and its predecessor, studies have revealed a diffuse component of HI gas in local starburst galaxies that extends beyond the stellar disk (e.g., Lucero et al. 2015; Ianjamasimanana et al. 2022). The kinematics of these extended gaseous reservoir differ from those of the disk, suggesting that the gas was expelled by past starburst-driven winds.

In addition to the several detections via absorption features towards the line of sight of quasars in the background of the CGM of galaxies (Werk et al. 2016; Tumlinson et al. 2017), some of the most robust detections of the CGM in emission have been through VLT/MUSE observations of Lyα emission in z > 2 AGN (e.g., Ginolfi et al. 2018; Drake et al. 2020; Sanderson et al. 2021), where halos up to ~ 170 pkpc have been discovered. However, the resonant nature of Lyα makes the process of extracting the morphology and kinematics of the underlying CGM non-trivial. In addition, a significant fraction of the CGM mass may be in the cold phase. Therefore, in order to trace the true gas distribution, including the cold component, it is necessary to use other direct tracers, such as [CII] (e.g., Zanella et al. 2018) or CO (e.g., Bolatto et al. 2013).

Due to its low excitation energy, [CII] emerges from a number of gas phases (i.e., warm ionized, warm/cold diffuse atomic, and warm dense molecular; Pineda et al. 2013). Local observations have revealed a weak, diffuse component of [CII] emission around some
galaxies (e.g., Madden et al. 1993) which likely trace the gas in the atomic HI disk rather than the molecular distribution. At high-redshift, extended gas reservoirs have been detected in both individual sources and stacks of [CII] emission in star-forming main sequence (MS; e.g., Noeske et al. 2007) galaxies at $z > 4$ (e.g., Fujimoto et al. 2019, 2020), suggesting significant enrichment of the CGM after only $<1.5$ Gyr. This [CII] emission is clearly larger than the ALMA synthesized beam, and may extend further than the underlying rest-frame UV emission (tracing young stars). The extended red gas reservoirs are taken as evidence for starburst-driven outflows (e.g., Pizzati et al. 2020; Ginolfi et al. 2020; Herrera-Camus et al. 2021), which could eject processed material into the CGM (e.g., Heckman et al. 1990). The galaxies in these [CII] studies were chosen to exclude galaxies with type 1 AGN, and the extended [CII] emission was found to be more evident in sources with higher star formation rates (SFRs), strengthening the star formation-driven outflow hypothesis.

While evidence for gaseous outflows and extended red gas reservoirs in SFGs at $z > 4$ have been well-studied with ALMA, it is important to also search for these signatures in AGN host galaxies at cosmic noon (i.e., $z > 2$; Ginolfi et al. 2017; Li et al. 2021; De Breuck et al. 2022). One recent survey in this epoch is SUPER (a SINFONI Survey for Unveiling the Physics and Effect of Radiative feedback; Circosta et al. 2018), which used VLT/SINFONI to target 39 x-ray–detected AGNs. These sources were then observed in CO(3-2) emission with ALMA (Circosta et al. 2021), resulting in 11 detections (from 27 targets) over 2019. These sources were then observed in CO(3-2) emission with ALMA (Circosta et al. 2021), resulting in 11 detections (from 27 targets).

In this work, we perform a stacking analysis of the ALMA CO(3-2) data in order to investigate whether these energetic, outflowing sources exhibit extended reservoirs of molecular gas. We begin by describing the properties of the observations and our data reduction and image creation process in Section 2. The stacking analysis, radial profile extraction technique, and radial fitting details are presented in Section 3. These ALMA CO(3-2) findings are discussed in Section 4. We conclude in Section 5.

We assume a standard concordance cosmology $(\Omega_m, \Omega_{\Lambda}, h) = (0.7, 0.3, 0.7)$ throughout. Between $z = 2.0 - 2.5$, 1” corresponds to 8.370-8.071 kpc, respectively.

### 2 OBSERVATIONS AND DATA REDUCTION

In this project, we wish to examine $z \sim 2.1 - 2.5$ QSO host galaxies observed in CO(3-2) emission as part of ALMA projects 2016.1.00798.S and 2017.1.00893.S (PI: V. Mainieri; Circosta et al. 2021).

Of the 28 sources observed as part of the two ALMA programs, we exclude all sources not detected in CO(3-2) emission (17 sources) and those with evidence of close companions based on ALMA CO(3-2) and rest-frame FIR images (3 sources: CID_971, CID_1215, and CID_1253). Following Circosta et al. (2021), we exclude CID_1057 due to an uncertain redshift. While a weak detection of CO(3-2) from X_N_6.27 is reported in Circosta et al. (2021), deeper observations show that the emission is intrinsically fainter, and at a different redshift (see Appendix A). Because of this, we exclude X_N_6.27, leaving a final sample of seven galaxies. The reported properties of these galaxies are presented in Table 1.

This subsample features a small redshift range ($2.2 \leq z \leq 2.5$) and only contains broad line (BL) AGN. When available, the SFRs and stellar masses of each object place them around the star-forming main sequence (SFR $\sim 48-686$ $M_\odot$ year$^{-1}$, log$_{10} (M_*/M_\odot) \sim 10.30-11.21$; Circosta et al. 2021).

Each of these ALMA projects was executed in Cycle 4 or 5, so their data are now public. Since our science goals require homogeneity of the data, we chose to reanalyze each dataset, beginning at the visibility level. The raw science data models (SDMs) were passed through a calibration pipeline created by ALMA staff, resulting in calibrated measurement sets (MSs) for each individual observation. These included multiple sources: flux/bandpass calibrators, phase calibrators, the target source, and occasionally a pointing calibrator. Because of this, we created new MSs containing only calibrated visibilities of the target source (CASAsplit). Some sources were observed over two executions, so their individual MSs were joined into one (CASACONCAT). With the calibrated MSs of each source in hand, we created an imaging pipeline, in order to ensure homogeneity of the resulting images.

The first step of the imaging pipeline is to determine which channels may contain CO(3-2) emission. While we may adopt the CO(3-2) FWHM as derived from previous ALMA data (Circosta et al. 2021), it is possible that the spatially extended emission features a different spectral width. That is, since these AGN host galaxies feature small-scale outflows (Kakkad et al. 2020), they may feature a spectral component that is low-amplitude but broad in velocity space, as seen in other AGNs with outflows (e.g., Bischetti et al. 2019).

To take this idea into account, we first assumed the CO(3-2) redshift reported by Circosta et al. (2021) ($z_{CO}$ in Table 1) and took a range of $\pm$800 km s$^{-1}$. This value is based on the largest CO(3-2) full-width at half-maximum (FWHM) reported in Circosta et al. (2021): 810 $\pm$ 93 km s$^{-1}$ for CID_1253 (a triple-component system excluded from this work). This conservative estimate ensures that we exclude all CO(3-2) emission from our ‘line-free’ channels.

We then use the CASA task UVCONTSUB to fit the source visibilities with a first order model using all line-free channels and to subtract this model from the data, resulting in a ‘continuum-free’ MS. These continuum-free visibilities are imaged using CASA tclean in ‘cube’ mode with natural weighting and 0.2” cells to create a ‘dirty’ line cube. The channel width is kept to its intrinsic value of $\sim 7.812 $ MHz (roughly 25 km s$^{-1}$). Using the CASA task IMSHAPER, we then trim the channel range to only include the sideband containing CO emission and to exclude the uncalibrated channels at the edge of each SPW. The RMS noise level of the channel of this cube is calculated using sigma clipping (using astropy sigma_clipped_stats with $\sigma/\sigma_{upper} = 3$; Astropy Collaboration et al. 2013, 2018). The tclean task is then repeated, but the image is cleaned down to 3× the RMS of the ‘dirty’ image, creating a final ‘clean’ line cube. The rest frequency of the line is set to the value found by Circosta et al. (2021).

This process resulted in seven continuum-free data cubes with similar synthesized beam sizes ($\sim 1''$) and RMS noise levels ($\sim 0.3 - 0.6$ mJy beam$^{-1}$; see Table 1).

### 3 CO CUBE ANALYSIS

With seven homogeneous CO(3-2) data cubes in hand, we proceed by stacking them in image-space and creating moment zero maps.
of each stacked cube (Section 3.1). The brightness distribution of each map is then analyzed by extracting radial profiles (Section 3.2). We use a simple 2-D Gaussian model to determine whether there is greater evidence for a single resolved source or a compact source surrounded by an extended component (Section 3.3).

### 3.1 Stacking Method

While each of the sources in our subsample have been detected in CO(3-2) emission, most of them have relatively low significance (i.e., less than 5σ in integrated intensity). Since we wish to search for low-level emission, we require higher S/N, and thus must perform stacking of each data cube.

To begin, we initialize an empty cube with spatial dimensions of 100×100 pixels (20′′×20′′, with 0.2′′/pixel) and a spectral axis that covers -300<v<3000 km s⁻¹ in 240 channels of width 25 km s⁻¹. These spatial and spectral pixel scales are chosen to replicate those of the input cubes. Each CO(3-2) cube is then read, and a 3-D cutout is made of the central 100×100 spatial pixels.

We consider four possible weighting schemes when stacking our sample of data cubes:

**Inverse Variance (InvV):** The mean RMS of each cube is found, and the weight of cube in the stacked cube with a central velocity of \( v \) and width \( \Delta v \) is taken from Circosta et al. (2021), and each median beam is given the same weight as its corresponding data cube. Using a similar equation as above we find the 2-D PSF of the stack:

\[
PSF_{\text{stack}}(x, y; v) = \frac{\sum_{n=1}^{N} PSF_n(x, y) w_n}{\sum_{n=1}^{N} w_n} \tag{3}
\]

This stacked PSF is then fit with a 2-D Gaussian, and the best-fit major axis, minor axis, and position angle are set as the PSF (i.e., synthesized beam) for each channel of the stacked cube.

We use each of the four weighting schemes to create a separate stacked cube (CASA immoments). These cubes are then collapsed over five velocity ranges (±100 × [1, 2, 3, 4, 5] km s⁻¹), resulting in 20 moment zero maps (see left panels of Figure 1).

Note that we do not attempt to stack sources undetected in CO(3-2) emission. This is due to large differences between previously determined \( z_{\text{spec}} \) values and the redshift of CO emission of SUPER sources (i.e., up to ~1500 km s⁻¹, see Table 1). Since the true systemic redshift of CO emission is not known for these sources, their CO emission could be significantly offset in velocity space.

### 3.2 Radial Profile Extraction

#### 3.2.1 Method

Since our goal is to search for low-level, extended CO emission (tracing a molecular gas reservoir), we extract radial brightness profiles of each moment zero map. We begin by finding the brightness-weighted spatial center by fitting a 2-D Gaussian to this emission. We then examine the emission in circular bins of width 1 pixel centered on this spatial position. The values within each radial bin are collected, and the mean value in each bin is calculated.

In order to determine the uncertainty on the mean in a bin, we take the maximum value of two values: the standard deviation in the bin and a beam-dependent RMS noise level (see Appendix B for full details).

Both the mean values and uncertainty are then normalized by dividing by the maximum value of the mean values. These normalized values are shown as the brown errorbars in the right panels of Figure 1. The radial profile of the effective synthesized beam (shown as the cyan line in the right panels of Figure 1) is derived in a similar fashion.

In order to determine which results are physically significant, we
consider the hypothetical case where the flux values contained within a radial bin are all distributed around 0, with a standard deviation equal to $\text{RMS}_{\text{M0}}$. This is the ideal case of pure noise, and in this case the mean value would be 0. Considering an alternative case where the mean value is a positive value, the significance is more difficult to determine. This is because the emission is not necessarily circular, due to convolution with the beam, noise peaks, and a possibly complex intrinsic source morphology. Indeed, previous works (e.g., Fujimoto et al. 2019, 2020; Herrera-Camus et al. 2021) did not include a significance limit on their radial brightness profiles (although Ginolfi et al. 2020 presented a Poisson noise level). Since it is not possible to state a definite limit of significance in these radial profiles, we adopt the case where the mean value in a bin is equal to $0.5 \times \text{RMS}_{\text{M0}}$ as an illustrative limit. Radial bins with mean values below this limit may still be significant, but as seen in Figure 1, this is rarely the case. In addition, this limit allows us to see the peak significance of the detection (i.e., a stronger detection will result in a lower grey zone). Note that this choice is for data presentation only, and does not affect the analysis in the following sections.

When extracting the radial brightness profile of the moment zero map, the average S/N of each annulus decreases with increasing radius, so each profile features a point where noise dominates the signal ($r_{\text{max}}$). Since the average intensity of annuli at this radius and beyond are not physically meaningful, we wish to exclude them from plots and further analysis. To determine this $r_{\text{max}}$, we determine the smallest bin that features a negative intensity (i.e., $r_n$), and set $r_{\text{max}}$ to the radius of the previous bin (i.e., $r_{n-1}$). As seen in Figure 1, this results in radial profiles with different maximum radii.

### 3.2.2 Initial Results

Before examining the radial profiles in the right panels of Figure 1 in a quantitative manner, we may examine their general appearance. If the emission is purely point-like, the brown and cyan profiles would line up exactly. On the other hand, an extended component smaller than the maximum recoverable scale (MRS) of the instrument will appear as a constant value (e.g., the grey uncertainty region) while pure noise or a diffuse component larger than the MRS would result in a value of 0 and would not be visible on these plots (i.e., log$_{10}(x)$ approaches $-\infty$ as $x$ approaches 0). If the source is resolved, then the slope of the brown line will be slightly shallower than the cyan. But perhaps the most interesting case is if the source may be decomposed into a central source and an extended component. In this case, we expect the extracted radial profile to show non-Gaussian behaviour due to the presence of multiple components.

For moment zero maps created with the same velocity range but different weighting schemes (i.e., plots in the same row), the spatial distribution of emission shows only slight variations between weighting schemes. This highlights the small intrinsic diversity of the sample. Since the sample of CO(3-2) data cubes we included in these stacks were all detected in line emission, it is not surprising that all 20 moment 0 maps show strong central detections. While most are in agreement with the PSF, some show significant extensions. Because of this, we proceed by characterizing the relative contributions of the central and extended components.
Figure 1. Moment zero maps (left) and radial brightness profiles (right) for each weighting technique (columns) and integrated velocity range (rows). The collapsed emission is shown with contours $\pm (2, 3, 4, \ldots) \sigma$. The effective restoring beam is shown by the white ellipse to the lower left. For the right panels, the normalized radial profile of the moment 0 emission is shown in brown, with 1$\sigma$ error bars, while that of the PSF is shown in cyan. The shaded region depicts a normalized mean intensity of $\langle$RMS noise level of the moment 0 map$\rangle$. The $\chi^2$ value representing how well the PSF profile matches the observed profile are presented in the upper right of each right panel. The legend label ‘M0 (CS)’ stands for ‘Moment 0, Cube Stack’, to differentiate these profiles from the Moment 0 stacking analysis presented in Section 4.1.2.
To examine how these radial profiles deviate from the point source response, we examine the uncertainty-weighted chi-squared:

$$\chi^2 = \sum_{i=1}^{N} \left( \frac{D_i - M_i}{\delta D_i} \right)^2$$

(4)

where $D_i$ is the observed normalized mean intensity for a radial bin, $\delta D_i$ is the associated uncertainty, and $M_i$ is an associated model value. Here, we treat the radial profile of the PSF as the ‘model’ value and calculate the $\chi^2$ between the observed radial profile and the PSF. These values are shown in the upper right of each panel in Figure 1.

As seen in this Figure, the radial profile of the ‘$\text{InvV}$’-weighted data cube over ±100 km s$^{-1}$ presents the largest $\chi^2$ value and thus deviates from a point-like source most strongly. The corresponding moment 0 map is clearly extended, and the radial profile shows complex behavior which suggests the presence of a second component. Since the average FWHM$^2$ of the stacked sources is 336 ± 199 km s$^{-1}$ (see Table B.1 of Circosta et al. 2021), this represents integrating over the low-velocity, high-S/N emission near the line peak.

Since the moment zero map of this data cube stack shows the strongest deviation from a point-like source, it represents the best case for the existence of an extended component. While it is possible that a stronger deviation could be found using a different velocity bin (e.g., ±150 km s$^{-1}$), we will proceed with this image. In the next subsection, we explore whether this radial profile is better explained by a single resolved source or a central source with a low-level extended component.

### 3.3 Radial Profile Fitting

#### 3.3.1 Methods

Here, we explore whether the radial brightness profile of the moment zero image of the SUPER CO(3-2) stacked emission is better represented by a single resolved source or the combination of a central source and a diffuse component.

While it would be possible to assume a general elliptical Gaussian (or 2-D Sérsic profile; Sérsic 1963) and determine the intrinsic axis ratio and intrinsic position angle of the moment 0 map, we simply wish to search for the existence of diffuse emission, and thus proceed with a simpler 2-D circular Gaussian model. In addition, the stacking procedure averages these non-axisymmetric features.

To begin, we create a 2-D circular Gaussian model with arbitrary amplitude and set width (FWHM$_{G1}$). This model is convolved with the representative PSF of a moment 0 map, and a radial profile of the convolved image is extracted. After normalizing the central value of this radial profile to unity, we compare the radial profiles of the moment 0 map and the convolved model. By using the Bayesian inference code MultiNest (Feroz et al. 2009) and its python wrapper (PyMultiNest; Buchner et al. 2014), we find the best-fit intrinsic FWHM of the model so that the difference between the radial profiles is minimized.

In this case, we only have one variable: the intrinsic width of the model source. We wish to explore a range of intrinsic widths, so we fit for log$_{10}$(FWHM$_{G1}$) (where the FWHM is in units of arcseconds) and set the prior to a uniform distribution between [-2,0.5], corresponding to angular scales [0.01”, ~ 3”]. We adopt the likelihood function of Nikolic (2009):

$$\log_{10} L(\theta) = -\frac{1}{2} \sum_{i} \left[ \frac{D_i - M_i}{\delta D_i} \right]^2 + \log_{10} \left( 2\pi\delta D_i^2 \right)$$

(5)

where each parameter is the same as in equation 4.

To test whether this radial profile could be explained by two components, we expand the initial model to include three parameters: the intrinsic width of a central source (log$_{10}$(FWHM$_{G2}$)), the width of a more diffuse component (log$_{10}$(FWHM$_{G2}$)), and the relative amplitudes of these two sources (log$_{10}$(f$_{12}$)). The prior distributions for the two log$_{10}$(FWHM) variables are set to uniform distributions: [-2.0] (or [0.01”, 1”]) for log$_{10}$(FWHM$_{G1}$) and [0.0, 0.5] (or [1”, ~ 3”]) for log$_{10}$(FWHM$_{G2}$). We adopt a uniform distribution between [-3.5, 0] for log$_{10}$(f$_{12}$).

#### 3.3.2 Results

The results of fitting the one-component and two-component models to the ±100 km s$^{-1}$ moment 0 map of the InNo-weighted ALMA SUPER CO(3-2) stacked cube are shown in the top and bottom panels of Figure 2, respectively. The radial profiles of the moment 0 map, beam, and uncertainty are the same as in Figure 1. However, we now denote the best-fit intrinsic FWHM by a solid black vertical line, and show its convolved radial profile with a magenta line. The residual between the model and data is shown by a green line. The returned best-fit parameters are listed in Table 2, while the corner plots of each model are presented in Appendix C.

While the single-component fit captures the $r < 10$ kpc behaviour quite well, there are slight residuals above the 0.5xRMS level at both small and large radius (Figure 2). By adding a second component, the best-fit model radial profile is a better match, and the residuals at large radius are much reduced. These results argue that the stacked emission is best explained by a central source with a low-level, diffuse component. However, this interpretation is primarily qualitative, so we now turn to a quantitative analysis of the relative goodness of fit for each model.

#### 3.3.3 Goodness of Fit

This goodness of fit may be made quantitative in several ways. The most simple is to use an uncertainty-weighted $\chi^2$ (Equation 4). The two-component model is preferred, as $\chi^2$ is lower by a factor of ~ 7 (see Table 2). We note that the two-component model has a $\chi^2$ value that is sub-unity, which usually indicates overfitting. However, this is likely due to our conservative uncertainty limits (see Appendix B).

While this value reflects how well the data and model agree, it does not encapsulate the complexity of the respective models. Indeed, when comparing models with different numbers of fit variables, it is crucial to take degrees of freedom into account to avoid overfitting. Because of this, we also use the reduced $\chi^2$ (e.g., Webb et al. 2021):

$$\chi^2_{\text{red}} = \frac{\chi^2}{N_{\text{data}} - N_{\text{variables}}}$$

(6)

where $N_{\text{data}}$ is the number of fit data points and $N_{\text{variables}}$ is the number of free parameters in the model. This value informs us if the improvement in goodness of fit in more complex models is significant. Again, the two-component model is preferred, suggesting that we are not overfitting.

We may also use the Bayesian evidence of each fit (as output by PyMultiNest) to judge the quality of each fit. MultiNest operates on the principle of Bayes’ theorem (e.g., Feroz et al. 2009):
Evidence for extended gaseous reservoirs at $z \sim 2$

$Pr(D, H)$ is the Bayesian evidence (also written as $Z$). When considering two models, we may use their relative Bayesian evidences to calculate the Bayes factor:

$$K = \frac{Z_1}{Z_2}$$

where we assume that neither model is preferred a priori. The resulting value of $K$ informs us of which model is favored: $K \sim 1 - 10$ is weak evidence towards model 1, $K \sim 10 - 30$ is strong evidence towards model 1, and $K > 30 - 100$ is very strong evidence for model 1 (Jeffreys 1961). The resulting Bayesian evidence values are listed in Table 2. We find that the Two Gaussian model is strongly favored ($K \sim 27$).

These three tests agree that the two-component model is preferred over an unresolved source or the single-component model, with little evidence for overfitting and slight evidence for overestimated uncertainties. This best fit model includes a compact, barely resolved source with an amplitude of unity and HWHM = 0.09$^{+0.19}_{-0.06}$ kpc, and a more diffuse component with an amplitude of 0.005$^{+0.004}_{-0.002}$ and HWHM = 1.66$^{+0.58}_{-0.43}$ kpc. Note that these values were fit in log-space, and so the listed uncertainties are 1σ errors on the logarithm of each parameter. Each value is PSF deconvolved. In the next Section, we discuss the implications of this result.

4 DISCUSSION

4.1 Additional Stacking Analyses

The primary analysis of this work has been based on a three-dimensional stack of seven ALMA CO(3-2) images of $z \sim 2 - 2.5$ AGN host galaxies from the SUPER sample. In addition, we may examine multiple 2-D stacks of these sources. In this subsection, we detail stacking analyses of HST data (Section 4.1.1), CO(3-2) moment 0 maps (Section 4.1.2), and rest-frame FIR continuum maps (Section 4.1.3).

4.1.1 HST stacking

If the extended emission found in the previous Section is tied to the inner CGM, its radial brightness distribution should differ from that of stars and the gas around them (i.e., the interstellar medium; ISM). Here, we analyze rest-frame UV images (tracing the young stellar distribution) of SUPER galaxies in order to test this hypothesis.

The majority of the sample examined by Circosta et al. (2021) (21/28 sources) lie in the COSMOS field, and thus benefit from a host of multiwavelength observations (Scoville et al. 2007a,b). We choose to analyze the HST/ACS F814W (i-band) data for each of these sources. As the reddest broad optical filter for ACS, F814W reveals the morphology of the young stellar population (e.g., Popescu et al. 2011) with higher sensitivity than other filters (e.g., F775W; Koekemoer et al. 2007).

Each i-band image was downloaded from the IPAC COSMOS

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1 Due to the low number of data points, we are not able to use the Bayesian Information Criterion (BIC) or Akaike Information Criterion (AIC; e.g., Liddle 2007; Concas et al. 2019).

2 The remaining seven sources are from the XMM-XXL north field, which lacks suitable HST observations.
These images have cell sizes of ~0.03″, and we assume a circular PSF of FWHM 0.095″ (Koekemoer et al. 2007). We exclude the three sources observed to have close companions or disturbed morphologies (CID_971, CID_1215, CID_1253; see Section 2).

While the CO data were stacked in three dimensions, the i-band images must be stacked in two dimensions. Thus, we use equation 3 with the ‘inverse variance’ weighting scheme (InvV). We fit a 2-D Gaussian to the central emission of each input image and set the centre of each galaxy as the best-fit centroid, in order to account for offsets between gas and stellar emission. A radial profile is then taken, using annuli that are 2 pixels wide.

The results of stacking all 21 HST/ACS i-band images and taking the radial brightness profile of the resulting image is shown in Figure 3. Since the PSF is much smaller than the ALMA observations (i.e., 0.095″ rather than ~1″), the radial profile is much less affected by convolution effects. The emission is clearly detected and resolved, with a clear divergence from what is expected from a simple single-component source. To illustrate this, we performed a two-component Gaussian fit to the observed brightness profile (using scipy curve_fit()).

If this profile is compared to the best-fit intrinsic HWHM values of the CO(3-2) moment 0 map (yellow lines and shaded uncertainty regions), we see that the significant emission barely reaches the scale of the larger CO HWHM, while the smaller CO HWHM agrees with the <0.25″ behaviour of the HST radial profile, which likely represents the host galaxy. Since the CO emission shows emission beyond 10 kpc, this suggests that the molecular gas extends beyond the stellar component.

The sample of SUPER sources with HST/ACS i-band photometry includes both NL and BL AGN, where BL AGN were classified by the presence of broad (FWHM> 10^3 km s^-1) emission lines in optical spectra. Since in the case of BL AGN the continuum image may be dominated by the nuclear AGN, it is important to test whether there are any differences between the two sub-sample and, in particular, whether the NL sample presents the same compact emission. Therefore, we may divide the 21 sources into these groups (11 NL and 10 BL sources). The results of stacking these groups and extracting radial profiles are shown in Figure 4. We may see that the NL stack has similar small-scale behaviour as the total stack, but with a lower S/N. The BL sample features stronger i-band detections, resulting in a much higher central S/N of the lower radial profile in Figure 4.

Despite the differences between the two groups, each radial profile shows the same qualitative behaviour as the full sample: a steep decrease from the central radial bin to ~0.2″ and a bump between ~0.2 – 0.5″. While the initial decrease may easily be fit with a convolved Gaussian source, the outer radial profile quickly deviates from this simple fit. Since the ALMA data have much coarser resolution (i.e., ~1″), we may not state whether this complex behaviour is due to stacking galaxies with a diversity of small-scale properties or the effect of outflows or complex source morphologies (e.g., disturbed disk, close-separation mergers). However, we may state that the stacked HST/ACS i-band data shows no evidence for significant extended emission beyond ~7.5 kpc, unlike the ALMA CO(3-2) data. This suggests that the gaseous reservoir traced by CO(3-2) is morphologically separate from the stellar distribution, and thus may trace the inner CGM rather than the ISM. On the other hand, the fact that the molecular gas has a greater extent than the young stellar population may simply indicate an inside-out growth of stellar mass (e.g., Frankel et al. 2019). This gas would then be directly associated with the host galaxy, and would be used in future star formation.

In order to compare these results more directly with those of the 3-D CO stacking analysis, we repeat this analysis using the four galaxies included in the 3-D stacking analysis that have i-band images. Since all of these are BL AGN, the resulting radial profile is nearly identical to the profile of the full BL sample shown in Figure 4, and is therefore not included.

Finally, we follow a similar approach to past comparisons of ALMA and HST data (e.g., Fujimoto et al. 2019) and explore the effect of convolving the high-resolution HST data (PSF~0.095″) with the ALMA beam (1.38 × 1.24 at 0.58″). The result of this convolution is shown in the left panel of Figure D1. We also fit the radial profile of this convolved map, finding that a single Gaussian component (∼2 kpc) is a better fit than the PSF, and a double Gaussian component (∼1 kpc and ∼18 kpc) returns the best fit (based on χ^2 and χ^2_red statistics).

At first glance, the fact that the best-fit model includes a spatially extended component that is comparable in size to that of the CO emission may imply that the gas and stellar component are well-linked, and that the earlier disagreements were simply a matter of resolution. In this light, the ‘extended’ CO component may simply be a result of a complex compact gas morphology that is convolved with a large beam.

Table 2. Best-fit values for a point source (PSF), one-Gaussian model, and two-Gaussian model applied to SUPER galaxies: the ±100 km s^-1 CO(3-2) moment 0 map of the InNo-weighted stacked cube (‘Cube Stack’, see Section 3.3), the InNo-weighted stacked CO(3-2) moment 0 map (‘Moment 0 Stack’, Section 4.1.2), and the InNo-weighted stacked FIR continuum map (‘Continuum Stack’, see Section 4.1.3). We also note the χ^2 and χ^2_red, and Bayesian evidence for each.

server\(^3\), using the central positions given by Circosta et al. (2021) as the centre of a 15″ × 15″ cutout. Due to the AGN nature of this sample, all 21 sources feature strong central i-band detections. In order to compare these results more directly with those of the 3-D CO stacking analysis, we repeat this analysis using the four galaxies included in the 3-D stacking analysis that have i-band images. Since all of these are BL AGN, the resulting radial profile is nearly identical to the profile of the full BL sample shown in Figure 4, and is therefore not included.

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The second way to interpret this, however, is to first examine the intrinsic (i.e., deconvolved) stacked HST image (Figure 3). This emission is clearly extended past the PSF, but also features multiple discrete companions that are \( \sim 1 - 2'' \) away from the central source. These may be true satellite galaxies, or low-redshift interlopers. These other sources will naturally cause an effect on the radial profile, and may be to blame for the deviation from a single resolved source.

In summary, our test of convolving the HST stacked image to the ALMA resolution reveals a radial brightness distribution is deviates from a single resolved source, but it is not clear if this is due to resolution effects or the presence of foreground galaxies.
4.1.2 Moment 0 map stacking

The three-dimensional stacking of this work is dependent on a number of assumptions, including a lack of diversity between sources (see Section 4.5 for a more complete discussion). Indeed, Circosta et al. (2021) found that the CO(3-2) profiles of the SUPER sample feature different linewidths. In order to account for this, we may first create a CO(3-2) moment zero map for each source, using all channels identified to contain line emission. As seen in Table 3, the emission in these maps is either unresolved or poorly resolved (i.e., each size estimate is within 3\(\sigma\) of zero).

These moment 0 maps may then be stacked in 2-D space, using equation 3. We explore each of the four weighting schemes introduced in Section 3.1, finding that the ‘InvV’ scheme results in the greatest divergence from a point source (as quantified by the \(\chi^2\) comparison between the beam and data profiles).

To explore the presence or absence of an extended component, we repeat the analysis of Section 3.3 (i.e., using a one- and two-component model to fit for the intrinsic spatial scale of the emission), but now using the stacked moment zero map rather than a moment zero map created using a stacked data cube.

The resulting map, radial profile, and best-fit models are presented in Figure 5, and the best-fit parameters and goodness of fit are listed in Table 2. It is clear that this emission is best-fit by a two-Gaussian model, as quantified by a smaller \(\chi^2\) and \(\chi^2_{red}\). However, the SFO factor does not show a preference for either model (Z\(\chi^2\)) approaches is due to the fact that the first approach (‘Cube Stack’) does not show a preference for either model (Z\(\chi^2\)) to contain line emission (\(\chi^2\) comparison between the beam and data profiles).

The different appearance of the radial profiles between these two approaches is due to the fact that the first approach (‘Cube Stack’) includes only the high-signal channels at \(|v| \leq 100\,\text{km\,s}^{-1}\), while the second approach (‘Moment 0 Stack’) includes all channels identified to contain line emission (\(|v| \leq 100 – 600\,\text{km\,s}^{-1}\), depending on source). Since a moment 0 map is proportional to the sum of the values in each pixel:

\[
M_0(x, y) = \Delta_v \sum_{ij} S(x, y, v_i)
\]

the inclusion of low-S/N data at high \(|v|\) will wash out the low-amplitude extended signal.

On the other hand, if we create and stack moment zero maps using a uniform range of \(|v| \leq 100\,\text{km\,s}^{-1}\), we recover a nearly identical image to the ‘Cube Stack’ result. This is because both approaches combine data from a set of 3-D data cubes into a single image, but use different orders of operation.

4.1.3 FIR Continuum stacking

We have now examined the distribution of CO(3-2) (tracing molecular gas) and HST/ACS i-band emission (tracing the stellar distrubution). It is also possible to examine the rest-frame FIR continuum emission (\(\nu_{rest} \sim 870\,\mu\text{m}\)). Other works found that in a number of high-redshift sources (e.g., \(z \sim 4 – 9\) SFGs detected in FIR continuum emission; Fujimoto et al. 2020; Fudamoto et al. 2022, a \(z \sim 6\) QSO host galaxy; Meyer et al. 2022), the dust emission featured a slightly smaller spatial extent, but was comparable to that of the [C II] emission.

There are four sources in our sample of 28 ALMA-observed sources that show signatures of mergers or close companions (< 10\(\arcsec\)) in CO and/or continuum images (CID_1215, X_N_6_27, CID_1253, and CID_971) which we exclude. For the remaining 24 sources in our sample (see Table 1), we create continuum maps by using the CASA task tmap in ‘MFS’ mode, selecting the line-free channels (see Section 2). The RMS noise level in this ‘dirty’ image is identified, and a ‘clean’ image is made by cleaning down to 3\(\times\) this RMS noise level.

Due to significant differences in \(z_{\text{spec}}\) and \(z_{\text{CO}}\), the CO line emission stacks (both 2-D and 3-D) only included CO-detected sources. This was done in order to maximize our S/N and avoid including a line-less spectrum. Unlike the CO stack, the continuum stack may include continuum-undetected sources, as there is no concern with redshifts. Each continuum image was made by excluding CO emission based on either \(z_{\text{CO}}\) (if it was known) or \(z_{\text{spec}}\). So for the CO-undetected sources, there may be low-level line emission that adds extra flux to the continuum images. This is not a concern for this work, as any line emission would be quite weak (i.e., it is not significant enough to be detected in the cube).

Since many of these sources are not detected in FIR continuum emission, we may only consider the ‘None’ and ‘InvV’ weighting schemes. Of these two, ‘InvV’ shows a more significant divergence from a point-source profile. Again, we apply the fitting routine detailed in Section 3.3 to the stacked continuum map, resulting in the fits shown in Figure 6 and the parameters listed in Table 2. We find that a point source returns the best fit, implying that the emission is unresolved. Using the average redshift of this sample (\(z \sim 2.3\)), this implies an upper limit on the continuum size of \(\leq 0.6\arcsec \sim 5\,\text{kpc}\).

A separate analysis of six FIR-detected SUPER sources (Lamperti et al. 2021) found a mean FIR size of \(R_e = 1.16 \pm 0.11\,\text{kpc}\). The observations in this previous work featured a higher spatial resolution (~ 0.2\(\arcsec\) – 2 kpc) and sampled a brighter region of the FIR SED (i.e., ALMA band 7 rather than band 3), so it is encouraging that our results are in agreement. This highlights the utility of high-resolution continuum observations for characterizing the morphology of the host galaxy.

4.1.4 Summary of stacking results

Thus far, we have analyzed the spatial extent of cold gas (traced by CO(3-2)), the stellar component (traced by HST/ACS i-band), and dust (traced by rest-frame FIR continuum emission). When the CO(3-2) emission is stacked in three-dimensional space and then collapsed in a small velocity bin (i.e., [-100,+100\,\text{km\,s}^{-1}]), we find strong evidence for two components: a compact (\(r \sim 1\,\text{kpc}\) centre and an extended (\(r \sim 13\,\text{kpc}\) but much weaker (i.e., peak amplitude \sim 0.005 that of the centre) component. A similar fit is found if we first create CO(3-2) moment zero maps of each source and then stack them.

A different behaviour is found for the stellar distribution, as the radial profile of the high-resolution HST stack may be decomposed into a point source, a ‘bump’ at \(r \sim 3\,\text{kpc}\), and a third component that extends to a maximum radius of \(r \sim 5 – 10\,\text{kpc}\). The complex stellar distribution may indicate small-scale merger or outflow activity that
Evidence for extended gaseous reservoirs at $z \sim 2$

Figure 5. Intensity map (left) and best-fit radial brightness profile for stacked CO(3-2) moment 0 maps using InV-weighting and a one-component (centre) or two-component model (right). The collapsed emission is shown with contours $\pm (2, 3, 4, \ldots) \sigma$. The synthesized beam is shown by the ellipse to the lower left. In the centre and right panels, the normalized radial profile of the intensity map is shown in brown with $1\sigma$ error bars, while that of the PSF is shown in cyan. The grey shaded region depicts a normalized mean intensity of $< 0.5\times$ (RMS noise level of the intensity map).

Figure 6. Intensity map (left) and best-fit radial brightness profile for stacked rest-frame FIR continuum maps using InV-weighting and a one-component (centre) or two-component model (right). The collapsed emission is shown with contours $\pm (2, 3, 4, \ldots) \sigma$. The synthesized beam is shown by the ellipse to the lower left. In the centre and right panels, the normalized radial profile of the intensity map is shown in brown with $1\sigma$ error bars, while that of the PSF is shown in cyan. The grey shaded region depicts a normalized mean intensity of $< 0.5\times$ (RMS noise level of the intensity map).

is not detectable in the relatively low-resolution ALMA observations. Alternatively, this could be a result of dust screening (e.g., Fudamoto et al. 2021). Since the CO emission is found to feature a HWHM $\sim 13$ kpc (not a maximum radius), the extended gaseous component has a much larger spatial extent than the stellar component. The difference in radial extents indicates that the extended CO emission is separate from the young stellar component, and thus may trace the inner CGM rather than the ISM. Alternatively, this extended reservoir could represent an extended disk or infalling gas from past outflows or a diffuse large-scale filament (see Section 4.2).

Finally, the dust emission is best-modeled by a unresolved central source, with little evidence for an extended component. This stack includes 24 sources (both continuum-detected and continuum-undetected), making it sensitive to weak emission. Despite this, it only shows two low-significance extensions that are likely noise.

When combined, these analyses indicate a multi-layered structure of AGN host galaxies at Cosmic Noon: a compact core of dust, stars, and cold gas ($r \lesssim 1$ kpc), a complex stellar distribution that extends to $r \sim 3$–$10$ kpc, and an underlying diffuse gas reservoir with HWHM $\sim 13$ kpc. This agrees with previous observations of SUPER sources, which found half-light radii of $r \sim 1$–$4$ kpc for ionized gas ([OIII] $\lambda 5007$) and star formation (H$\alpha$; Lamperti et al. 2021). The bulk motion of high-velocity ionized outflows in these sources were detected out to $r \sim 3$ kpc (Kakkad et al. 2020). Other works found that high-mass star-forming galaxies around cosmic noon should feature stellar radii of $r_{50} \sim 5$ kpc (Mosleh et al. 2020). Since the $r \sim 13$ kpc CO emission is beyond the stellar, dust, and star forming regions, we posit that it represents an extended gaseous reservoir.

4.2 How was the extended gaseous reservoir formed?

The extended CO emission revealed by this stacking procedure may be caused by multiple possibilities: a number of discrete satellites, a low-level enriched gaseous reservoir, or single gaseous filaments (see discussion of Fujimoto et al. 2019).

In order for the satellite explanation to be viable, the stellar contribution of these companions should contribute to the stack of stellar emission, and so we should also see weak extended emission in the F814W stack. We do not (Section 4.1.1), so we conclude that satellites have little contribution to the diffuse emission.

Instead, it is possible that the extended CO emission represents a gaseous reservoir created by outflowing gas. Indeed, a detailed analysis of SUPER galaxies as observed in [OIII] $\lambda 5007$ line emission with SINFONI (Kakkad et al. 2020) found evidence for out-
flows of ionized gas with high velocities (~ 650 – 2700 km s⁻¹). Assuming the redshift-dependent stellar mass-halo mass relation of Girelli et al. (2020), the SUPER galaxies should reside in halos of mass ~ 10²¹–10²² M⊙. Thus some of this outflowing gas detected in SINFONI observations is travelling faster than the escape velocity (~ 10⁴ km s⁻¹ for a ~ 10¹⁸ M⊙ halo; Miller et al. 2018). Some of this gas may escape the halo, while the rest could be deposited into a gaseous reservoir or fall back into the galaxy (e.g., Spitoni et al. 2013).

While the outflows feature high enough velocities to escape the galaxy, it is not clear if they are sufficient to create an extended CO component with HWWM ~ 13 kpc at z ~ 2.0 – 2.5 (t_H = 3.2 – 2.6 Gyr, respectively). As a sanity check, in the extreme case that the outflows began at Cosmic Dawn (z ~ 15; e.g., Wise et al. 2014), the minimum outflow velocity required for the gas to reach this radius is only < 10 km s⁻¹, which is much less than the currently observed ionized outflow velocities. Instead, we may consider how long it would take the gas to reach the observed radius, considering a mean outflow velocity of 1000 km s⁻¹. In this case, only ~ 13 Myr would be required. In reality, AGN outflows are expected to be highly episodic (e.g., Hickox et al. 2014; Sun et al. 2014), so an assumption of constant velocity is not physical. But we are not able to rule out the possibility that outflows populated the extended component with molecular gas.

Cosmological simulations showed that bright galaxies at high redshift were likely encased in diffuse filaments of gas (e.g., Pallottini et al. 2017; Kohandel et al. 2019). In this case, the detected extended emission would not represent gas that emerged from the galaxy, but instead would signify infalling gas from the circumgalactic environment. However, this gas is expected to have densities ≤ 3 orders of magnitude lower than the central galaxy, making its detection difficult. It is also expected to have very low metallicity, and thus would be hardly visible in CO emission.

Finally, it is possible that these galaxies are undergoing ‘inside-out growth’ (e.g., Frankel et al. 2019), where the star formation rate decreases with radius. The extended CO emission detected here would then represent a gaseous reservoir surrounding the galaxy that will contribute to future star formation. But since a CO detection implies that the gas is not pristine, the CO-traced gas must have had some past star formation, making this scenario less likely. This type of galactic feature is better detected in HI maps (e.g., Lucero et al. 2015).

In summary, we find it unlikely that the extended emission is caused by a gaseous filament or individual satellite galaxies. The observed outflows feature sufficient velocities to populate an enriched gaseous reservoir at the observed radius. Additionally, the emission could be caused by an extended reservoir with a a low level of past star formation.

### 4.3 Gas Mass

Ideally, these results would be used to calculate the gas mass of the host galaxies and their associated extended components by converting L′_{CO} to M_{H₂} (see review by Bolatto et al. 2013). However, there are several issues that make this currently impossible for our dataset.

Primarily, the conversion of CO(3-2) flux density to molecular gas density is dependent on two values: the ratio of L′_{CO(3-2)}/L′_{CO(1-0)} = r_{31} and the ratio of M_{H₂}/L′_{CO(1-0)} = a_{CO}. A common approach is to take an r_{31} value for the galaxy type from literature (e.g., Carilli & Walter 2013) and assume either a metallicity-based a_{CO} (e.g., Narayanan et al. 2012) or the common values for starbursts and Milky Way-like sources (~ 0.8 & ~ 4.3 M⊙ K⁻¹ km⁻¹ s⁻¹ pc⁻² respectively; e.g., Bolatto et al. 2013). While values of r_{31} for integrated CO luminosities only vary by ~ 0.5 dex, local observations have revealed that this quantity may vary by an additional ~ 0.25 dex between the central value and that at r_{proj} (e.g., Leroy et al. 2022). Since this value is truly dependent on the temperature and density of the gas (e.g., van der Tak et al. 2007), it is reasonable to expect that it should differ greatly for the host galaxy and the much less dense, colder CGM. Similarly, observations and simulations suggest that a_{CO} may vary by up to an order of magnitude within a galaxy (e.g., Teng et al. 2022; Hu et al. 2022), as it is dependent on metallicity, density, and optical depth (Madden et al. 2020).

Because r_{31} and a_{CO} have not been derived for the CGM of AGN host galaxies at cosmic noon, we are not able to place precise constraints on M_{H₂,CGM}. As a very basic estimate of the host galaxy gas mass, we may consider a representative L′_{CO(3-2)} ~ 10¹⁰ K km s⁻¹ pc² (Circosta et al. 2021), r_{31} ~ 0.97 (Carilli & Walter 2013), and a_{CO} ~ 0.8 M⊙ K⁻¹ km⁻¹ s⁻¹ pc⁻² (appropriate for high-z QSO host galaxies; Decarli et al. 2022). This results in log_{10}(M_{H₂,CGM}/M⊙) ~ 8.99. Taking the best-fit FHWMs and relative peak intensity from Table 2, we find that the integrated flux density (S_{ΔV_{CO}}) of the extended component is ~ 2× that of the host galaxy. Using the Milky Way-like values of r_{31} = 0.27 (Carilli & Walter 2013) and a_{CO} ~ 4.3 (Bolatto et al. 2013), we find log_{10}(M_{H₂,CGM}/M⊙) ~ 10.4. However, we emphasize that this value is highly uncertain because of the issues discussed above.

### 4.4 Comparison to other detections of extended gas emission

Studies in recent years have revealed a number of high-redshift sources with extended [CII] emission by using radial brightness profiles. Both [CII] and CO are used as tracers of cold gas (e.g., Bolatto et al. 2013; Zanella et al. 2018), so their spatial extension may be used as evidence for a gaseous reservoir. However, the interpretation of [CII] is complicated by a strong dependence on gas conditions (e.g., Madden et al. 2020) and a variety of emission media (e.g., molecular and atomic gas; Pineda et al. 2013). Here, we outline some of these discoveries and compare the results with our findings.

The first study to show evidence for high-z extended gas components from ALMA [CII] observations was Fujimoto et al. (2019), who studied 18 galaxies at z ~ 5 – 7. Each dataset was trimmed to only include [-50,+50] km s⁻¹ from z_{CII}, the visibilities were combined, the weighting was adjusted using the CASA task stiltnt, and a final stacked image was created. A radial profile from this image shows signal out to ~ 10 kpc and evidence for two components (i.e., host galaxy and extended gas reservoir). But since beam convolution is not taken into account when analyzing the radial profile, it is difficult to say what the intrinsic extension of the [CII] emission is. While the small velocity range was selected to minimize the effects of close companions, the sample still includes two sources with close companions at the same velocity (HZ8 Capak et al. 2015 which is also known as DEIMOS_COSMOS_873321 Béthermin et al. 2020; Jones et al. 2021, and WMH5 Jones et al. 2017), making the origin of the extended emission ambiguous (i.e., an extended component or close companions).

The study of [CII] emitters at high-z was greatly progressed by the ALPINE survey (Le Fèvre et al. 2020; Béthermin et al. 2020; Faist et al. 2020), which used ALMA to observe [CII] emission from 118 SFGs between z ~ 4 – 6 at ~ 1″ resolution (~ 6 – 7 kpc). Fujimoto et al. (2020) examined the [CII] moment maps and radial brightness profiles of the 46 individual sources that were detected at
Evidence for extended gaseous reservoirs at z ~ 2

$S/N_{[CII]} > 5$, claiming evidence for extended emission to ~ 10 kpc. However, as before, if the beam convolution is taken into account, the true sizes are only $r \sim 1 - 3$ kpc. Because of this, it is unlikely that the individual sources exhibit reliable evidence for true extended gas components, based only on ALPINE data.

In a separate analysis, Ginolfi et al. (2020) examined the 50 ALPINE galaxies that were detected at 3.5μm and showed no signs of merging (according to the morpho-kinematic classification of Le Fèvre et al. 2020, but see further discussions of morpho-kinematic classification difficulty for low-resolution data in ALPINE: Jones et al. 2021; Romano et al. 2021). This sample is further split for classification difficulty for low-resolution data in ALPINE: Jones et al. 2020, but see further discussions of morpho-kinematic classification difficulty for low-resolution data in ALPINE: Jones et al. 2021; Romano et al. 2021. This sample is further split into galaxies with SFR < 25 $M_\odot$ year$^{-1}$ (30 objects) and SFR > 25 $M_\odot$ year$^{-1}$ (20 objects; based on ALPINE DR1). The data cubes of the high-SFR subsample are stacked in three dimensions in a nearly identical way to this work, and a moment 0 map is made for [-200,+200] km s$^{-1}$. A radial profile of this map reveals a distinct discontinuity, with a compact inner component and a low-level extended component with an intrinsic radius of $\sim$ 10 kpc. This extended component is likely created by SF-driven outflows, as the low-SFR subsample does not show evidence for such a component and the ALPINE sample was chosen to exclude type 1 AGN.

The ALPINE survey has now been followed by the RELBELS survey, which is observing [C II] from 40 SFGs at $z \sim 6.5-9.0$ (Bouwens et al. 2022). The spatial extent of [C II] emission in 28 well-detected galaxies in this survey has been examined by Fudamoto et al. (2022). By stacking moment 0 maps and extracting radial profiles, they find little evidence for two spatial components, as the emission is well fit with a single component with $r_e \sim 2.2$ kpc. This analysis is repeated with ALPINE data, revealing a similar result for the $z \sim 4-6$ galaxies. The lack of an extended component may be due to the stacking of moment maps rather than data cubes (see discussion in Section 4.1.4), the inclusion of both high- and low-SFR sources, or may be an intrinsic lack of extended emission. However, in all cases the [C II] emission was found to be $\sim$ 2x as extended as the rest-frame UV and FIR dust continuum emission.

The $z \sim 5.5$ SFG HZ4 was observed at high resolution (0.3′′ ≈ 2 kpc) and high sensitivity (0.15 mJy beam$^{-1}$ RMS noise level in 16 km s$^{-1}$ channels) in [C II] emission by Herrera-Camus et al. (2021). This source is similar to those of the ALPINE sample (i.e., a $z \sim 4-6$ SFG with no evidence for type 1 AGN), and the high-resolution observations yielded a similar extended [C II] brightness profile with an intrinsic [C II] radius of $r \sim 6$ kpc, which extended past the dust and UV emission.

At slightly higher redshift, Meyer et al. (2022) observed the $z = 6.42$ QSO J1148+5251 in [C II] emission with ALMA. The resulting radial brightness profile revealed extended emission with an intrinsic radius of $\sim 10$ kpc.

Very recently, Akins et al. (2022) analyzed the spatial distributions of [C II], [O III] 88μm, FIR dust, and rest-frame UV emission in the $z = 7.13$ SFG A1689-zD1. While the [O III] 88μm and UV profiles show single, resolved components, the FIR and [C II] both show evidence for two components. This extended emission is significant out to a convolved radius of $\sim 12$ kpc, but the deconvolved HWHM of the extended emission is not apparent. In addition, the source features two spatial peaks in UV continuum emission and a disturbed morphology in the other tracers, suggesting either an ongoing merger or a ‘clumpy’ morphology. The interpretation of this extended [C II] emission is thus made more difficult.

At lower redshifts, CO transitions have also been used to investigate extended emission around a few high-z galaxies. Ginolfi et al. (2017) mapped CO(3-4) in a galaxy at $z=3.5$ and found evidence for emission extending to a radius of about 20 kpc, well beyond the stellar disc. CO observations of powerful radio loud AGNs have found extended molecular gas on even larger scales of several tens of kpc (Emonts et al. 2016; Li et al. 2021).

ACA observations of one of the SUPER galaxies in CO(3-2) emission revealed evidence for a large amount of molecular gas out to $r \sim 200$ kpc (CID_346; Cicone et al. 2021), implying an enormous history of outflows that enriched the CGM out to large radii. Unfortunately a deeper ACA CO(3-2) observation of this source does not reveal evidence for any significant emission beyond $r \sim 10$ kpc (Jones et al. submitted). However, the concept of outflows creating such a large gaseous reservoir is intriguing. As noted by the authors, a definitive detection of this gas component will require a new instrument (e.g., AtLAST; Klaassen et al. 2020).

To summarize this past work, a number of [C II] and CO observations of higher-redshift ($z \sim 3-6$) SFGs and a QSO show that the individual sources exhibit larger extensions in [C II] than rest-frame UV (Ginolfi et al. 2017; Fujimoto et al. 2020; Herrera-Camus et al. 2021; Meyer et al. 2022). On the other hand, a stack of high-SFR SFGs (Ginolfi et al. 2020) and a strongly lensed $z \sim 7$ SFG show evidence for a second spatial component on a scale of $\sim 10$ kpc. This is the same scale as we find in this work for a stack of CO(3-2) AGN host galaxies at cosmic mean ($z \sim 2$).

While the comparison sample features galaxies with different outflow-driving engines (i.e., star formation winds rather than AGN feedback) and is in a different cosmological era (i.e., $t_H \lesssim 1$ Gyr rather than $t_F \lesssim 3$ Gyr), the common size scale of the extended components suggests a link of some sort. Indeed, the ALPINE sources and a number of SUPER host galaxies are located on the main sequence for their redshift (i.e., they are neither starbursts or quiescent galaxies), which may indicate a similar evolution. Since enriched reservoirs could either be created by AGN or starburst-driven outflows (e.g., Maiolino et al. 2012; Fiore et al. 2017; Spilker et al. 2018; Fliege et al. 2019; Jones et al. 2019; Schneider et al. 2020; Lutz et al. 2020), both AGN and starbursts are episodic events (e.g., Novak et al. 2011; Arata et al. 2020; Talbot et al. 2022), and some galaxies host both starbursts and AGN (e.g., Sanders & Mirabel 1996; Banerji et al. 2017), these reservoirs were likely created by a combination of past AGN and starburst activity for all sources.

4.5 Stacking Assumptions

Throughout this work, we have utilized image stacking to increase the S/N of our data and explore low-brightness emission. Stacking is a powerful tool that allows us to increase the S/N of our data without requiring more observing time. But its use rests on several assumptions.

Sample Uniformity: Primarily, the input sample is assumed to be relatively uniform in intrinsic properties (e.g., size, luminosity), observational characteristics (e.g., beam size, RMS noise level), and imaging parameters (e.g., cell size, phase centre).

By adopting a combined stack weighting scheme of inverse variance, we are able to account for variations in intrinsic RMS noise level, but not CO line strength. Since our goal is to search for extended emission, it is reasonable to allow strong sources to dominate the stack. Our imaging pipeline ensures that the cell size of each image is uniform, while the beam size and phase center of each data cube is similar since the stacked data was taken from the same observing programs. While the beam properties (major axis length, axis ratio, and position angle) do vary slightly between data cubes (see

\url{https://cesam.lam.fr/a2c2a/dr1}
Table 1), we account for this by stacking the beams of each cube in the same way as the data.

**Physical Scale:** Our CO(3-2) sample includes sources in the redshift range \( z = 2.219 - 2.450 \), implying a angular scale of \( 8.253 - 8.105''/\text{kpc} \). This ~2% spread has no serious effect on our conclusions. Similarly, while we find that the HST/ACS i-band spatial centroids of each source may differ from the ALMA CO(3-2) positions (Circosta et al. 2018, 2021) by up to 0.24" (or ~1 pixel in the CO cubes), this has little effect on the large-scale (i.e., >1'') emission that we detect.

**PSF Sidelobes:** The above approach does not alleviate all of the issues associated with analysing interferometer-based data in the image plane. The true PSF of these data is not just a 2-D Gaussian, but features complex variations over the field of view (i.e., sidelobes of \( \lesssim 10\% \)). The cleaning process (i.e., CASA tclean) acts to reduce the effects of these sidelobes by iteratively identifying the brightest pixel, convolving it with the true PSF, and subtracting this from the original ("dirty") map. However, this does not remove the sidelobes entirely, as it only cleans down to a user-provided cleaning threshold, which is usually set to 3\( \times \) the RMS noise level (e.g., Spilker et al. 2016; Bischetti et al. 2019; Ginolfi et al. 2020; Yu et al. 2021). \(^5\) While a lower threshold (e.g., 0r) would ensure that the effects of the sidelobes are minimized, this would introduce a number of artifacts due to noise peaks. On the other hand, a higher threshold (e.g., 5r) would ensure that there are no artifacts caused by noise, but also would result in high-level sidelobes. Since we use a threshold of 3\( \sigma \) (see Section 2), it is possible that we have not fully subtracted the sidelobes of the PSF.

This is of importance for our work because we wish to search for low-level (\( \lesssim 10\% \)) at large spatial separations from our sources. Luckily, there are two properties of our analysis that minimize the effects of these sidelobes. First, an inspection of the PSFs show that they are not azimuthally symmetric Airy disks, but feature some isolated peaks and troughs. Second, our stacking analysis smears these PSFs together, minimizing the effects of local extrema. By then extracting radial profiles, the effects of the sidelobes are again lessened.

While these factors result in a greatly lessened effect of sidelobes in our analysis, we note that the best way to ensure their absence is to switch from the image plane to visibility-based analysis (e.g., Fujimoto et al. 2019, Scholtz et al. submitted).

**Visibility or Image Stacking:** Working in the visibility plane has several strengths over the image plane, as there is no need to consider weighting schemes (e.g., natural, uniform, Briggs ‘robust’; Briggs 1995), cell size, or cleaning parameters (e.g., threshold, iterations, primary beam limit). In short, the visibilities are the “pure” data seen by the interferomer without any further (Fourier) transformation, processing or interpolation of the data, and are hence more reliable for detecting and characterising (simple) signals (e.g., Fujimoto et al. 2019; Fudamoto et al. 2022).

But only simple morphologies may be assumed (generally only point sources or Gaussians) and faint companions (which appear as low-level sinusoidal contributions to the real part of the visibilities) may be difficult to detect. This is where image-plane stacking is useful, as we may examine the full 2-D distribution of flux and search for discrete emission that may signal a satellite galaxy.

With this in mind, image- and visibility-plan analyses are complementary. While we will utilize the latter method in future works to analyze the distribution of emission (Jones et al. submitted, Scholtz et al. submitted), we posit that the beam-deconvolved analysis in this work is self-sufficient.

5 Although other studies use a threshold of 1.5 – 2.0\( \sigma \) (e.g., Kaasinen et al. 2020; Algea et al. 2021; García-Vergara et al. 2022).

5 CONCLUSIONS

In this work, we have analyzed ALMA CO(3-2) data from a set of \( z \sim 2.0 - 2.5 \) AGN host galaxies from the SUPER survey, with the intent of searching for extended gaseous components that may hint at past outflows.

- By performing a three-dimensional stacking analysis and extracting radial profiles of surface brightness, we find qualitative evidence for extended emission that deviates from the PSF.
- To examine these profiles in more depth, we create a brightness model that consists of one or two circular Gaussians, which we convolve with the observed PSF. These model profiles are then compared with the observed brightness profiles, and the intrinsic properties are fit for using the Bayesian inference code MultiNest. The single-Gaussian model returns an intrinsic (i.e., deconvolved) source radius of HWHM= 0.47±0.07'' = 3.89±0.58 kpc, while the two-Gaussian model returns a bright central source (HWHM= 0.09±0.15'' = 0.76±0.19 kpc) and a weaker extended component (HWHM= 1.66±0.58'' = 13.49±4.71 kpc). The two-Gaussian model returns a better goodness of fit (i.e., \( \chi^2 \), \( \chi^2_{\text{red}} \) and Bayes factor).
- A similar stacking and radial profile analysis is run on HST/ACS i-band SUPER galaxies, finding evidence for complex behaviour for \( r \lesssim 10 \text{kpc} \) but no emission at the CO-derived radius of \( r \sim 13 \text{kpc} \). If the sample is split into NL and BL AGN, then this behaviour is present for both subsamples.
- We repeat the stacking analysis in two dimensions by using the CO moment 0 maps and rest-frame FIR continuum maps for the sample. For the former, we find similar results to the ‘cube stack’ analysis, although at lower significance. The continuum emission is best fit by a point source, implying a size limit of \( r \lesssim 5 \text{kpc} \).
- Various causes of this extended emission are explored, including enriched outflows caused by AGN feedback, satellite galaxies, and a background filament of low-density gas. Based on our analyses of the ALMA CO(3-2) and HST/ACS i-band emission, we conclude that the most likely case is that this emission represents processed material ejected from the host galaxy by past outflows. However, we note that other explanations (e.g., inside-out star formation) are also possible, and further data (e.g., high-sensitivity ACA observations) are required for a robust conclusion.
- Since it is not currently possible to convert the observed CO(3-2) luminosity in the extended component to a molecular gas mass, we discuss the assumptions that would have to be made.
- A comparison of our results to those of other high-redshift sources reveals a similar extent of molecular gas around a diverse sample of galaxies (\( r \sim 10 \text{kpc} \)). Due to the diverse sample properties (i.e., SFGs, AGN host galaxies, QSO host galaxies) and large redshift range (\( z \sim 2 - 7 \)), this is interpreted as evidence for a common series of star formation- and AGN-driven outflows over a large timescale.

Altogether, these analyses suggest that the molecular gas in SUPER galaxies exhibit a central peak, surrounded by an extended gaseous reservoir. That this extended component is not detected in a stack of the HST/ACS i-band images implies that it is caused by expulsion of gas by AGN feedback.
Following the success of the SUPER-ALMA programs (2016.1.00798.S, 2017.1.00893.S; PI V. Mainieri), a new ALMA program was proposed to perform deeper observations of the CO(3-2) emission of the nine sources previously detected in Circosta et al. (2021) (2021.1.00327.S; PI: R. Maiolino). These observations are ongoing, and will be presented in later works (Jones et al. submitted, MNRAS 2022). The data from these observations were downloaded from the ALMA archive, and were calibrated using the scripts provided by ALMA staff. As a first step, we produce a data cube with no primary beam correction or cleaning. Emission is not detected at the original redshift (z = 2.2640, corresponding to v_\text{obs} = 105,942 GHz). However, we do detect emission at 105,405 GHz (z = 2.2806), or ~1500 km s^{-1} from the redshift expected from previous spectroscopic redshifts. This offset is large, but comparable to the offset of other SUPER sources (e.g., ~1100 km s^{-1} for CID_166, ~1400 km s^{-1} for X_N_44_64).

The resulting moment zero map and spectrum are shown in Figure A1. A ~4\sigma source is present at the phase centre, while a much stronger source lies to the west. Both feature similar central frequencies and linewidths. The amplitude of the central detection is quite low (~0.1 mJy), and would fall within the noise of previous observations (~0.5 mJy, see figure D.1 of Circosta et al. 2021).

While further analysis of these sources (including a more thorough cleaning process) is deferred to a future work, we may state that the CO(3-2) emission line of this source is not detected in the original SUPER-ALMA data, so we do not include it in our analysis.

APPENDIX B: UNCERTAINTY IN RADIAL SURFACE BRIGHTNESS PROFILES

While it is now common practice to use radial profiles to characterize surface brightness distributions, there are slightly different approaches to determine the appropriate uncertainties in each radial bin. For example, some use the RMS noise level of the image (e.g., Meyer et al. 2022), while others use the standard deviation of values in each annulus (e.g., Ginolfi et al. 2020; Fujimoto et al. 2019). Users use bootstrap analyses to determine the background noise level (e.g., Fujimoto et al. 2020) or use the variance of their sample (e.g., Fujimoto et al. 2019). It is also possible to present the Poisson noise (i.e., the RMS noise level of the image divided by the square root of the number of pixels in each annulus; Ginolfi et al. 2020).

This variety of approaches arises from complexities of noise in interferometric images. Primarily, the noise per pixel is not independent, but is spatially correlated on the scale of the beam. Since annuli sample pixels from multiple beams, the appropriate uncertainty for the average value is not quite clear.

To determine the true behaviour of noise, we created a test image of 100x100 pixels (0.24''/px) of pure Gaussian noise (noise level RMS_1), and convolved this with the 2-D Gaussian beam of ±100 km s^{-1}, InvV-weighted moment zero map of Figure 1 (1.38'' x 1.24'' at 0.82''). The convolved image exhibits a lower RMS noise level (RMS_2), so we adjust RMS_1 so that RMS_2 agrees with an observed value (RMS_{MO}) to within 5%. Radial profiles of this convolved image are then taken, and the RMS in each annulus is calculated. This process is repeated 100 times.

The resulting RMS profiles are depicted as colored lines in Figure B1. It is clear that the scatter in RMS decreases with increasing radius, due to the increasing number of pixels in larger annuli. However, the average RMS profile (dashed line) increases slightly at small radii before levelling off at a slightly higher value than RMS_{MO} (solid line).

From this, it is clear that a Poisson error or standard error (which are dependent on the number of pixels in each annulus) are not appropriate. The RMS noise level of the image (RMS_{MO}) is a reasonable approximation, as it lies within the scatter of RMS profiles. Our full treatment of the beam-dependent RMS per annulus is more precise.

We note that this analysis assumes a signal-free environment. In reality, the map will also include a source that is convolved with the beam, without azimuthal symmetry. To take this into account, the radial profile uncertainty in this work is the maximum of the beam-dependent RMS and the standard deviation in the radial profile.

APPENDIX C: COVARIANCE PLOTS

APPENDIX D: CONVOLVED HST PROFILE TEST
Evidence for extended gaseous reservoirs at $z \sim 2$

**Figure A1.** Initial results from further observations of CO(3-2) emission in X_N_6_27 (Project 2021.1.00327.S). Emission is detected both at the phase centre and from a source to the west. The moment zero map of this emission is shown in the top panel, while the spectra of each source (using the $2\sigma$ contours as apertures) are shown below. Contours begin at $\pm 2\sigma$ and are in steps of $1\sigma = 0.027 \text{ Jy beam}^{-1} \text{ km s}^{-1}$. The new redshift is shown as a vertical line at $v = 0 \text{ km s}^{-1}$, while the originally reported redshift (Circosta et al. 2021) is shown at $\sim -1500 \text{ km s}^{-1}$. For both spectra, the collapsed channels are highlighted.

**Figure B1.** Results of radial profile uncertainty test. Colored lines show RMS noise level in annuli for 100 individual noise simulations. The average noise level in each bin is shown by the dashed black line. All noise levels are normalized to the RMS noise level of the image (solid black line).

**Figure C1.** Posterior probability distribution for the best-fit intrinsic HWHM of the analyzed moment zero map when assuming a single 2-D Gaussian component (see top panel of Figure 2; Section 3.3). Vertical lines correspond to the best-fit value and $\pm 1\sigma$. 

$log_{10}(\text{HWHM}_{G1}/[\text{kpc}]): 0.58+/-0.06$
Figure C2. Corner plots for the best-fit source parameters when assuming two 2-D Gaussian components (see bottom panel of Figure 2; Section 3.3). Top panels of each column show posterior probability distributions for each variable, while the coloured plots are covariance distributions. Vertical and horizontal lines correspond to the best-fit value and $\pm 1\sigma$.

Figure D1. Results of fitting models to the stacked image of HST/ACS i-band emission using 21 SUPER galaxies (see Section 4.1.1). In each panel, the brown and cyan lines show the normalized mean radial profiles of the stacked map and beam, while the shaded region depicts $< 0.5\times$(RMS noise level of the moment 0 map). For the one-Gaussian model (central panel), we present the best-fit model radial profile (magenta) and intrinsic (i.e., unconvolved) profile (black solid curves), as well as the intrinsic HWHM value of the best-fit model (vertical black line). For the two-Gaussian model (right panel), the intrinsic and convolved components of the best-fit model are shown by dashed black and magenta lines, respectively. The vertical lines show the best-fit intrinsic HWHMs of each component. Note that in this case, the residual and intrinsic extended component lie below the lower y-limit. Each profile is normalized to its maximum value.