The [CII] 158 µm emission line as a gas mass tracer in high redshift quiescent galaxies

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ABSTRACT

A great deal of effort has been made in recent years to probe the gas fraction evolution of massive quiescent galaxies (QGs); however, a clear picture has not yet been established. Recent spectroscopic confirmations at z>3 offer the chance to measure the residual gas reservoirs of massive galaxies a few hundred Myr after their death and to study how fast quenching proceeds in a highly star-forming Universe. Even so, stringent constraints at z>2 remain hardly accessible with the Atacama Large Millimeter/submillimeter Array (ALMA) when adopting molecular gas tracers commonly used for the quenched population. In this letter we propose overcoming this impasse by using the carbon [CII] 158 µm emission line to systematically probe the gaseous budget of un lensed QGs at z>2.8. when these galaxies could still host non-negligible star formation on an absolute scale and when the line becomes best observable with ALMA (Bands 8 and 7). Predominantly used for star-forming galaxies to date, this emission line is the best choice to probe the gas budget of spectroscopically confirmed QGs at z > 3, reaching 2-4 and 13-30 times deeper than dust continuum emission (ALMA band 7) and CO(2-1)-(1-0) (Very Large Array, VLA, K-Ka bands), respectively, at fixed integration time. Exploiting archival ALMA observations, we place conservative 3σ upper limits on the molecular gas fraction (f_{mol}=M_{H_2}/M_*) of ADF22-QG1 (f_{mol}<21%) and ZF-COS-20115 (f_{mol}<3.2%), two of the best-studied high-z QGs in the literature, and GS-9209 (f_{mol}<72%), the most distant massive QG discovered to date. The deep upper limit found for ZF-COS-20115 is three times lower than previously anticipated for high-z QGs suggesting, at best, the existence of a large scatter in the f_{mol} distribution of the first QGs, Lastly, we discuss the current limitations of the method and propose ways to mitigate some of them by exploiting ALMA bands 9 and 10.

Key words. Quiescent galaxies – Galaxy evolution – Quenching

1. Introduction

Disentangling the different processes that lead to the formation of massive quenched galaxies is one of the most complex tasks in galaxy evolution (Man & Bell 2018). A common aspect to all quenching mechanisms is that they directly affect the amount of cold gas available for star formation. A deep characterisation of the interstellar medium in quiescent galaxies (QGs) is therefore necessary. If near-infrared spectroscopic campaigns allowed the stellar component of QGs to be studied up to z~4-7 with impressive data quality (Carnall et al. 2022), our view of their gaseous reservoir becomes increasingly less clear already beyond the local Universe due to the general faintness of this galaxy population to commonly adopted H2 probes, such as dust continuum emission or low-J CO transitions (Sargent et al. 2015; Bezanson et al. 2019; Williams et al. 2021). To date, no general consensus has been reached on the residual cold gas fraction of massive QGs at 1<z<3, which is broadly constrained from a few per cent to around 10-20%, primarily due to rather limited statistics, in addition to uncertainties in different conversion factors, sample selection criteria, and intrinsic scatter (Williams et al. 2021; Whitaker et al. 2021a; Blánquez-Sesé et al. 2023). At higher redshifts, our chances to study the gaseous component of individual unlensed QGs drop due to the loss in depth of these gas tracers. Perhaps the most attainable task is constraining the relevance of bulge growth, which is expected to decrease the star formation efficiency of galaxies whose cold gas fraction dropped below ~20% keeping them not entirely devoid of cold gas (Martig et al. 2009; Gobat et al. 2018). However, this requires tracers bright enough to break such a threshold as a function of redshift at reasonable observational costs. Critically, ALMA’s sensitivity in band 6 would make it impractical to probe the dust mass or low-J CO transitions at depths comparable to those reached in Whitaker et al. (2021a) in high-z unlensed galaxies until the advent of the next-generation VLA. Notably, low-J CO transitions in QGs will also be difficult to detect against the increasing cosmic microwave background (CMB): assuming local thermal equilibrium and following the results of Magdis et al. (2021) at z=2, the kinetic temperature of CO can be expected to follow the decrease in size of QGs with redshift (Lustig et al. 2021), which would lead to T_{kin} ~24K at z~3. In this case, from Eq. (32) in da Cunha et al. (2013) the recoverable fraction of CO(1-0) flux would be ~60% the intrinsic one at z=3. The loss of contrast is even worse in the case of no intrinsic gas temperature evolution with redshift. To date, therefore, understanding whether fast-quenching channels at z>3 efficiently deplete more than 80-90% of the gas of massive galaxies remains limited to the availability of lensed galaxies or far-IR stacks (Whitaker et al. 2021a; Gobat et al. 2020).
In this letter we propose probing the residual gas content of QGs at z > 3 by extending to this galaxy population the use of the [CII] emission line at 157.74 μm as a cold gas tracer, to date primarily adopted for star-forming galaxies at z > 4. We discuss the advantages of the method in Sect. 2. We apply this method to the three massive QGs at z > 2.8 with publicly available coordinates and archival [CII] ALMA coverage in Sect. 3, yielding upper limits on their cold gas fraction. Finally, in Sect. 4 we interpret the results obtained and discuss the potential caveats related to using this tracer for the quenched population. We assume a ΛCDM cosmology with H_0 = 70 km s^{-1} Mpc^{-1}, Ω_M = 0.27, Ω_Λ = 0.73, and a Chabrier (2003) initial mass function (IMF). Magnitudes are given in the AB photometric system.

### 2. Studying high-z quiescent galaxies through [CII]

In order to secure robust spectroscopic confirmations with JWST telescopes, QGs at z > 3 have been generally selected with a magnitude cut in either H or K band (22 and 23 AB mag, respectively), thus primarily selecting recently quenched or transitioning systems with modest dust reddening (Schreiber et al. 2018; Valentino et al. 2020; D'Eugenio et al. 2020; Forrest et al. 2020; Saracco et al. 2020). Their specific star formation rate (sSFR) is typically required to be less than 10% that of the coeval main sequence (MS), and therefore, as the normalisation of the MS increases towards high-z, the sSFR of many high-z QGs can be comparable to that of local MS galaxies (e.g. Wuyts et al. 2011), while still being quenched compared to the typical coeval star-forming galaxy. This alone suggests that they likely host [CII] emission. Notably, redder UVJ or NUVrJ QGs could host significantly more dust at fixed stellar age, increasing the pool of sources detectable with [CII].

Several studies have argued that the bulk of 2P_{3/2} – 2P_{1/2} [CII] fine structure emission originates from photo-dissociation regions (PDRs) in the external layers of molecular clouds heated by the far-UV radiation emitted from hot stars (e.g. Stacey et al. 1991; Cormier et al. 2015; Woffle et al. 2022). Zanella et al. (hereafter Z18) first proposed adopting this emission line as a molecular gas tracer, having shown that the [CII] luminosity (L_{[CII]}) tightly correlates with the molecular gas mass of star-forming galaxies from z = 0 up to z = 6 regardless of their elevation on the MS. This correlation holds over 4 dex in luminosity and with an L_{[CII]} to H_2 conversion factor (α_{[CII]} ≈ 31 M_⊙/L_{α}) that varies by a factor of two at most when galaxies of different star formation efficiencies (SFE = SFR/M_\text{mol}) are considered (Z18; Sommovigo et al. 2021).

Lapham et al. (hereafter L17) show a power-law correlation between the CO(1-0) and [CII] fluxes in a sample of 20 nearby gas-rich early-type galaxies (ETGs) from the Atlas3D sample (Young et al. 2011). This correlation shares a similar slope and scatter as for late-type galaxies (LTGs), showing a trend that holds over almost 3 dex in line luminosities. This demonstrates the existence of a correlation in the local Universe between [CII] and CO(1-0) luminosities in galaxies with sSFRs as low as sSFR < 3 \cdot 10^{-11} yr^{-1} and sSFRs less than a few M_⊙ yr^{-1}. This supports the hypothesis for which the Z18 relation would also hold for high-z QGs because the correlation in L17 arises from galaxies with SFRs lower than what can be expected from the bulk of massive QGs z > 2.8. Moreover, this correlation ensures the presence of [CII] emission also in galaxies with severely suppressed star formation at high-z. Remarkably, this also implies that LTGs and ETGs share, on average, the same α_{[CII]}/α_{CO} ratio, supporting the use of [CII] as a molecular gas mass tracer also in the quenched population.

If the exact contribution of different gaseous components to L_{[CII]} is still discussed, at least 45% of its luminosity is arising from the molecular component (e.g. Z18; Tarantino et al. 2021), allowing us to place conservative upper limits. In this regard, L17 also notes that the average fraction of L_{[CII]} arising from PDRs and not from purely ionised regions is 63.5-70.9% for their sample ETGs, which is the vast majority. Ionisation fractions larger than one-half were found in 25% of their sample, possibly associated with active galactic nucleus (AGN) activity. This average fraction is similar to that of spiral galaxies in their work and to other fractions previously reported in the literature for star-forming galaxies (e.g. Stacey et al. 1991; Cormier et al. 2015).

The reliability of the Z18 calibration between L_{[CII]} and M_\text{H_2} at z = 4 has recently been further tested by Dessauges-Zavadsky et al. (2020) by using 11 ALPINE galaxies at 4 < z < 6. By converting L_{[CII]} into L_{CO(1-0)} using the Z18 relation and an α_{CO} = 4.36 M_⊙/(K m s^{-1} pc^{2})^{-1}, all the galaxies considered were found to lie within the 0.38 dex dispersion of the expected relation between L_{CO(1-0)} and L_{IR} for MS and starburst galaxies in place between z = 0 and z = 5.3. An average systematic overestimation by a factor of 2 was found when comparing L_{[CII]} to single-band dust continuum measurements. This offset was reported to be dependent on the scaling used for dust continuum emission and its origin remains difficult to attribute to either one of the two tracers. The average α_{[CII]} from Z18 and Dessauges-Zavadsky et al. (2020) are consistent with those of massive galaxies (M_⋆ > 10^11 M_⊙) at z > 6 from the SIMBA simulations, where the [CII] emission is almost entirely arising from the molecular phase (Vizgian et al. 2022a). Although the relative contributions from HI and H_2 to L_{[CII]} are still under debate (e.g. Heintz et al. 2021) and the calibration between [CII] and other molecular gas tracers still suffers from limited statistics at z > 2, we note that CO and dust continuum emission as H_2 proxies are also affected by increasingly larger uncertainties with increasing redshift (i.e. surface brightness dimming, decrease in gas-phase metallicity, uncertainty on the dust temperature and emissivity evolution with redshift, loss of contrast against the CMB), thus making [CII] a reasonable alternative option to explore the gas content of QGs.

Here we argue that the multi-phase origin and striking brightness of [CII] can be capitalised to probe the gaseous component of faint high-z QGs. This can be assessed in Fig. 1 where we quantify and compare the depths on different UV and near-IR bands with dust template (e.g. Gobat et al. 2021). The VLA Exposure Calculator whenever necessary. The corresponding flux density of the QGs dust template from Gobat et al. (2021) is considered appropriate for high-z QGs (D'Eugenio et al. 2020). For dust continuum measurements, this offset was reported to be dependent on the scaling used for dust continuum emission and its origin remains difficult to attribute to either one of the two tracers. The average α_{[CII]} from Z18 and Dessauges-Zavadsky et al. (2020) are consistent with those of massive galaxies (M_⋆ > 10^11 M_⊙) at z > 6 from the SIMBA simulations, where the [CII] emission is almost entirely arising from the molecular phase (Vizgian et al. 2022a). Although the relative contributions from HI and H_2 to L_{[CII]} are still under debate (e.g. Heintz et al. 2021) and the calibration between [CII] and other molecular gas tracers still suffers from limited statistics at z > 2, we note that CO and dust continuum emission as H_2 proxies are also affected by increasingly larger uncertainties with increasing redshift (i.e. surface brightness dimming, decrease in gas-phase metallicity, uncertainty on the dust temperature and emissivity evolution with redshift, loss of contrast against the CMB), thus making [CII] a reasonable alternative option to explore the gas content of QGs.
rescaled at a given z and assuming a gas-to-dust ratio (G/D) of 92 (Magdis et al. 2021). Being a relative comparison, here we neglect the effect of the CMB. As can be seen, [CII] yields by far the best performance across almost the entire range from z = 3 to 6 for non-lensed galaxies, reaching deeper limits than what is allowed by dust continuum (2-4 × deeper) and CO(2-1)/(1-0) (13-30 × deeper). This translates into faster observations at fixed targeted \( f_{\text{mol}} \cdot \) up to 16 x faster than dust continuum and 170-1000 x faster than CO(2-1) and CO(1-0), respectively. We note that by using excitation ratios of regularly star-forming galaxies at \( z > 1.6 \) (Daddi et al. 2015), the depths of CO(2-1) and CO(3-2) would improve by 50%, but would still not go below \( f_{\text{mol}} \cdot \) 10% at \( z \geq 3 \) (CO(3-2)). As a result, these numbers would reduce the need for strongly lensed sources to probe gas fractions down to a few per cent in the high-z universe. Interestingly, [CII] would perform equally well as CO(3-2), CO(2-1), and dust continuum (band 7) at \( z \approx 1.8 \), which would serve as a sweet spot to calibrate the amount of \( \text{L}_{\text{CII}} \) arising from cold gas on lower redshift QGs.

Lastly, should [CII] observations reveal robust detections, it would open up to dedicated follow-ups aimed at accessing the kinematics of cold gas in QGs, to be compared to that of their stellar component from JWST IFU spectroscopy in search of potential signatures of past merger events or external accretion, if any (Kahla et al. 2022; Raimundo et al. 2023). Additionally the gas kinematics could be compared to that of plausible progenitors at higher redshifts (Rizzo et al. 2020; Lelli et al. 2021).

3. High-z QGs with [CII] coverage: Analysis and results

The ALMA archive contains three high-z QGs with publicly available coordinates and [CII] coverage: ADF22-QG1 (Programme: 2013.1.00159.S, PI: H. Umehata), a recently quenched galaxy in the SSA22 protocluster (Kubo et al. 2021); ZF-COS-20115 (Programme: 2015.A.00026.S, PI: C. Schreiber), one of a pair with a dust-obscured star-forming galaxy (dubbed the Jekyll and Hyde system; Schreiber et al. 2018b); and GS-9209 ( Programme: 2015.1.01074.S., PI: H. Inami), the most distant massive QG spectroscopically confirmed to date (Carnall et al. 2023). A description of these sources and their ALMA data sets can be found in Appendix A.

We reduced the ALMA data following the standard CASA calibration script. The calibrated visibilities were converted to UVFITS data to allow for uv-plane source fitting with the UV_FIT task of the GILDAS/MAPPING software package used for the spectral extraction. Whenever necessary, we imposed the target’s coordinates as the phase centre and we corrected the extracted spectrum for the corresponding primary beam (PB) attenuation, as described below. No detection was present in the spectra of our three galaxies (Fig. 2). We computed upper limits from the velocity integrated RMS taken as the RMS measured from the whole spectrum, multiplied by the square root of the number of channels within the expected FWHM of the line and by the channel width in km s\(^{-1}\). For ZF-COS-20115 and GS-9209 their FWHM was fixed to the value arising from their high-resolution stellar spectra (i.e. 665 km s\(^{-1}\)) and GS-9209 their FWHM was fixed to the value arising from the line and by the channel width in km s\(^{-1}\). For ADF22-QG1 based on the latest measurements of Forrest et al. 2022 (3σ, \( \sim 300 \text{ km s}^{-1} \)) for similarly massive high-z QGs. For each source we first converted the integrated RMS into \( \text{L}_{\text{CII}} \) and then into \( \text{M}_{\text{mol}} \) by adopting the \( \alpha_{\text{CII, mol}} = 31 \text{M}_\odot / \nu \text{GHz} \) from Z18. We computed upper limits on \( \text{f}_{\text{mol}} \) by conservatively adopting the lowest stellar mass value for each source given the uncertainties quoted in the respective reference papers.

ADF22-QG1: The spectrum of this galaxy was extracted using a Spergel profile with parameters fixed to the published properties of the source (see Appendix A). Spergel index \( \nu = 0.0 \) (corresponding to a Sersic index of 25), size of \( r_e \approx 0.13'' \), and position angle of \( -5^\circ \) (Kubo et al. 2017). The centre of its ALMA pointing is offset by 5.6'' in the north-west direction compared to the position of the target. At the expected observed-frame frequency of [CII] the half power beam width (HPBW) is 13.6'' from which we obtain a PB correction of \( \times 1.6 \) applied to the extracted spectrum. As expected, the sensitivity reached for ADF22-QG1 only results in a 0.6 significance. The corresponding 1σ velocity integrated RMS is \( \text{S}_{\text{CII}} = 1.10 \text{ Jy km s}^{-1} \), which translates into a 3σ upper limit of \( \text{M}_{\text{mol}} < 5.2 \times 10^6 \text{M}_\odot \) and a molecular gas fraction of \( \text{f}_{\text{mol}} < 21\% \). Converting the value of the rms outside the expected line channels divided by the square root of the number of channels, we obtain 1.05 mJy. This value is about eight times higher with respect to the dust SED from Goebel et al. 2018 rescaled to a \( z_{\text{spec}} = 3.092 \) and to the same stellar mass.

GS-9209: Due to its very compact nature, its spectrum was extracted as a point source. The centre of its ALMA pointing is offset by 6.5'' in the south-west direction compared to the position of the source, from which, given the HPBW of 17.3'', we obtain a PB correction of \( \times 1.5 \) applied to the extracted spectrum. The 1σ velocity integrated RMS over the expected frequency of [CII] is \( \text{S}_{\text{CII}} < 0.467 \text{ Jy km s}^{-1} \), which translates into a 3σ upper limit of \( \text{M}_{\text{mol}} < 2.8 \times 10^7 \text{M}_\odot \). This corresponds to a molecular gas fraction upper limit of \( \text{f}_{\text{mol}} < 72\% \).}

ZF-COS-20115: At the position of the QG, the ALMA spectrum is still dominated by the star-forming neighbour. We tested whether any signal could be ascribed to the QG by subtracting Hyde’s [CII] emission (and underlying continuum) in the uv plane. We fitted the quiescent and star-forming components simultaneously, by fixing the coordinates of the QG and letting the position of the star-forming galaxy vary in each channel. We adopted several models for Hyde’s subtraction: elliptical Gaussians, exponential profiles, and elliptical Spergel profiles with varying parameters (source size and position angle). The spectrum of the QG was extracted using the parameters listed in Appendix A with a Spergel profile of index \( \nu = -0.6 \) corresponding to \( \text{S}_{\text{CII, spec}} = 4 \). The resulting detection is only tentative (significance levels ranging from 0.7σ to 3.0σ) since the noise properties of the residual spectrum are dependent on Hyde’s subtraction scheme. The highest significance is reached using a Spergel profile for ZF-COS-20115 and an elliptical Spergel profile for Hyde. As our main interest is to provide a proof of concept, we compute our gas fraction upper limit from the spectrum with the largest RMS (\( \text{S}_{\text{CII}} < 0.0775 \text{ Jy km s}^{-1} \)) and using the corresponding integrated value to place a 3σ upper limit. We obtain \( \text{M}_{\text{mol}} < 3.6 \times 10^7 \text{ M}_\odot \) corresponding to \( \text{f}_{\text{mol}} < 3.2\% \) assuming that the entire [CII] luminosity arises from cold molecular gas (see Fig. 1). The upper limit increases to \( \text{f}_{\text{mol}} < 4.5\% \), when adopting the largest value of \( \text{f}_{\text{CII, mol}} \) allowed by the uncertainties in Z18. We note that this is one of the most stringent individual constraints on the molecular gas mass of QGs at \( z > 2 \) to date. The ALMA band 8 continuum RMS outside of the expected [CII] line (\( < 0.04 \text{ mJy beam}^{-1} \)) yields a dust continuum-driven
f_{mol} upper limit of $\sim 15\%$, five times shallower than what can be done with [CII] at fixed time investment, further supporting the method proposed here.

A discussion on the assumptions behind our spectral analysis can be found in Appendix B.

4. Discussion and conclusions

In this letter we proposed a new method for constraining the cold gas budget of high-z QGs by extending to this galaxy population the use of the [CII] emission line, routinely used for star-forming objects. We then explored the ALMA archive to do the exercise of applying the $L_{\text{[CII]}}$-to-$H_2$ conversion by Z18 on those high-z QGs covered with already existing [CII] observations. Since this is the first time that such a method has been adopted for QGs, we mention some caveats that make the conversion not straightforward, and we discuss the implications of a low strict upper limit for ZF-COS-20115.

4.1. Caveats

The $\alpha_{\text{[CII]}}$_{mol} conversion factor: In Fig. 9 in Z18, the $\alpha_{\text{[CII]}}$_{mol} conversion factor appears to be fairly independent on the sSFR of galaxies down to $\sim 0.3$ sSFR/sSFR$_\text{MS}$. For less star-forming or quenched objects, however, the points systematically shift to larger values of $\alpha_{\text{[CII]}}$_{mol}. If the trend is real, $\alpha_{\text{[CII]}}$_{mol} might increase by a factor of 2-3 for galaxies ten times below the MS, leading to a systematic underestimation of integration times or molecular gas fractions at fixed depth when adopting the average $\alpha_{\text{[CII]}}$_{mol} from Z18. In order to test whether a value of $\alpha_{\text{[CII]}}$_{mol} significantly higher than $31 \, M_\odot/L_\odot$ would be more appropriate for QGs, a suitable experiment is to follow-up, with deep [CII] observations, QGs already detected in either dust continuum or CO transitions. This would provide a first constraint on the $L_{\text{[CII]}}$ that would correspond to the previously derived molecular gas mass ($M_{\text{H}_2}$) albeit still dependent on $\alpha_{\text{CO}}$ or on the G/D conversion factors. Non-detections would be an indication that $\alpha_{\text{[CII]}}$_{mol} would need to be revised for QGs or that a low G/D ratio would apply (Donevski et al. 2023). As can be seen in Fig. 1 QGs with $M_{\text{H}_2}$ measurements all lie at $z<2.5$. Those at $1.0<z<1.4$ and $1.68<z<2.17$ would thus be ideal targets because they are in redshift windows for which [CII] coverage is still provided by ALMA bands 10 and 9, respectively.

**Contribution to $L_{\text{[CII]}}$ by ionised and atomic gas:** In the case of detections, it will be necessary to assess whether ionised gas has a larger contribution to $L_{\text{[CII]}}$ in high-z QGs. One solution would be to target the [NII] emission line at 205 $\mu$m, which has the same critical density as [CII]$_{158}$, but higher ionisation potential (11.3 vs 14.5 eV Carilli & Walter 2013). Comparing the observed [CII]$_{158}$/[NII]$_{205}$ line ratio with the expected theoretical ratio if both [CII] and [NII] originated from purely ionised
regions, it is possible to obtain a direct measure of the fraction of [CII] arising from the neutral medium (atomic and molecular, L17; Schreiber et al. 2021). This line ratio is relatively insensitive to the electron density ($n_e$) and can vary, at most, by a factor of 1.6 over 3 dex in $n_e$. We caution, however, that current theoretical values available in the literature are mostly dependent on the assumed n([CII])/n$_e$ and n([NII])/n$_e$ gas-phase abundance (Obrechowski et al. 2006, L17). Competitive integration times to reject ionised fractions higher than 40-50% can be reached with [NII] at $z>2.9$, when the [NII]$_{520}$ emission line enters in ALMA band 7, and thus compensating for the lower luminosity of [NII] with ionisation fractions higher than 40-50% can be reached with [NII] (Oberst et al. 2006, L17). Competitive integration times to reject molecular gas expected to be dominant in the central regions of galaxies due to enhanced hydrostatic pressure, as observed in local star-forming galaxies (Blitz & Rosolowsky 2006) and ETGs (Serra et al. 2012; Baby et al. 2023). Due to the increasing stellar density of QGs with redshift, molecular gas may thus be expected to be the primary gaseous component when limiting observations over spatial scales comparable to stellar sizes. Further studies are needed to accurately decompose the mass contribution of atomic versus molecular gas (and their mass-to-light ratio with respect to L$_{[CII]}$) over different spatial scales. Finally, we recall here that the uncertainty on the H$_2$/HI mass ratio affects the G/D ratio as well, being formally a tracer of the total gas $M_{gas}=M_{HI}+M_{H_2}$.

**Effects of the CMB:** The increasing CMB temperature is expected to heat the gas of galaxies and to introduce an additional component that would reduce the contrast of both dust continuum and line emissions. Vallini et al. 2015 and Lagaiche et al. 2018 argue that the effect of the CMB on the cold neutral medium (CNM, n<50 cm$^{-3}$) should be negligible up to $z=4.5$. Beyond this redshift, as the CMB temperature would rapidly reach the excitation temperature of [CII] at $z=6.5$ in the CNM, the recoverable [CII] emission from this component would be <10% and only [CII] from PDRs would be recovered. The limiting redshift depends on the exact excitation temperature of [CII] in different ISM components, and hence on the kinetic temperature and density of the gas and the source of ionisation. Following da Cunha et al. 2013 and Vallini et al. 2013 we compute the fraction of recoverable [CII] flux against the CMB for our galaxies. We conservatively assume the excitation temperature of the CNM from Vallini et al. 2015 ($T_{CNM}=22 K$, not too distant from $T_{CMB}=21 K$ in Magdis et al. 2021). The recovered fractions for our galaxies are 0.98, 0.95, and 0.82 for ADF22-QG1, GS-9209 bottom panel). The positions of the QGs are shown as black crosses. The contours show 1, 2, 3, and 4 times the RMS of the image.

![Fig. 2: [CII] coverage for our sources. Left column: Spectra extracted at the position of our targets. The dashed and dotted green lines are, respectively, the expected $v_{obs}$ and its uncertainty. The red curves show the MPFIT Gaussian fits at fixed frequency and FWHM. Channels where a significant contribution from hydrogen could be expected were masked, as shown by the grey vertical area. Right column: Dirty images averaged over the stellar FWHM of our sources: ZF-COS-20115, before and after hydrogen’s subtraction (top two panels); ADF22-QG1 (mid panel); GS-9209 (bottom panel). The positions of the QGs are shown as black crosses. The contours show 1, 2, 3, and 4 times the RMS of the image.

### 4.2. What can be inferred on quenching from deep upper limits

Under the assumption that the $\alpha_{[CII],mol}$ in Z18 applies to high-z QGs, an $f_{mol} < 3\%$ for ZF-COS-20115 is approximately three times lower than the extrapolation of trends reported in Gobat et al. 2018 and Magdis et al. 2021 (although within the scatter of Blánquez-Sesé et al. 2023) see Fig. 1). Such a low value reinforces the existence of extremely gas-poor objects at high-z (as highlighted by previous works; e.g. Whittaker et al. 2021b) and possibly of a large scatter in the gas content of the early quenched population. With 1.2 hours of integration, it highlights the daunting possibility that future [CII] observations might also yield non-detections, requiring large statistics and observational efforts to assess the scatter. Moreover, although the galaxy has recently been quenched, its gas fraction is 3-5 times lower than has been observed for lower redshift post-starburst galaxies with a similar age (Bell et al. 2021; Suess et al. 2017; Zanella et al. 2023). This implies that the initial gas fraction of newly quenched galaxies at high-z may not be constant, and that additional parameters such as stellar mass may be needed when modelling the effect of progenitor bias into the gas fraction evolution.
lution of QGs (Gobat et al. 2020). According to the star formation history inferred for ZF-COS-20115 in S18b, the galaxy has been evolving passively for $t_{\text{quench}}=0.5^{+0.2}_{-0.1}$ Gyr. An $f_{\text{drop}}<3\%$ after 0.5 Gyr from the last substantial drop in star formation implies that the galaxy did not experience substantial gas accretion after quenching and that bulge stabilisation (Martig et al. 2009) is not the main maintenance mechanism for its quiescence. ZF-COS-20115 is associated with a moderately star-forming galaxy with $M_* \sim 0.34 \cdot 12.8 \cdot 10^{10} M_\odot$ and $SFR_{\text{tot}} \sim 50 M_\odot$ yr$^{-1}$, about a factor of 4 below the MS at its redshift (Schreiber et al. 2021). Summing their stellar masses, we obtain a maximum $M_{\text{tot}} \sim 2.6 \cdot 10^{11} M_\odot$, which, assuming that the two galaxies belong to the same dark matter halo, leads to a maximum halo mass of $M_{\text{DM}} \sim 10^{15} M_\odot$, according to the stellar-to-halo mass relation at 3.5$<z<4.5$ (Shuntov et al. 2022). At this redshift and halo mass, cold accretion in a hot medium is expected to take place (Dekel & Birnboim 2006; Daddi et al. 2022). An absence of detectable gas down to $\sim 3\%$ in ZF-COS-20115, and a suppressed star formation activity in its companion galaxy, suggest that a mechanism other than virial shock heating is operating to prevent further accretion. This suggests that efficient heating of the surrounding circumgalactic medium to temperatures high enough to have a cooling time in excess of $t_{\text{quench}}$ is needed. A viable internal mechanism to starve galaxies (Croton et al. 2006), which is qualitatively consistent with the increasing strength of radio-mode AGN activity in QGs towards higher redshifts (D'Eugenio et al. 2021; Magdis et al. 2021; Ito et al. 2022), Deep radio observations are needed to quantitatively test this scenario.

In summary, we argue that at $z>3$ and for fixed ALMA time commitment, [CHI] can push much deeper than other molecular gas tracers (see Fig. 1) providing stringent constraints on which quenching processes are operating, thus representing an obvious choice for studying the gaseous component of QGs at high redshift.

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References

Appendix A: Sources

ADF22-QG1 is a massive QG at $z_{\text{spec}} = 3.092_{-0.004}^{+0.008}$ (Kubo et al. 2021), located at the core of the SSA22 protocluster (Umehata et al. 2015). Its stellar mass, size, and Sersic index have been constrained to $M_\star = 1.66 - 3.72 \times 10^{11} M_\odot$, $r_e = 1.01 \pm 0.04$ kpc (0.13$''$), and $n_{\text{sersic}} = 2.5 \pm 0.2$, respectively (Kubo et al. 2017, 2021). No measurement on its stellar velocity dispersion is currently available. The integration on this source is 4.5 min, and thus likely insufficient for our purposes.

ZF-COS-20115 is located at $z_{\text{spec}} = 3.715_{-0.002}^{+0.002}$ and its stellar mass, size, Sersic index, and stellar velocity dispersion are $M_\star = 1.15_{-0.16}^{+0.10} \times 10^{11} M_\odot$, $r_e = 0.66 \pm 0.08$ kpc (0.09$''$), $n_{\text{sersic}} = 4.1 \pm 1.0$, and $\sigma_\star = 283 \pm 52$ km s$^{-1}$, respectively (Schreiber et al. 2018b, Esdaile et al. 2021). ZF-COS-20115 has been extensively studied as it is one of a pair with a moderately star-forming companion galaxy (Hyde), undetected in H band, located at a distance 3.1 kpc (inferred from the 0.43$''$ offset from the HST and ALMA images and the $\Delta z = 0.008$, Schreiber et al. 2018a,b hereafter S18a and S18b respectively). Hyde is detected in [CII] emission showing a very broad double-peaked profile associated with a rotating disk ($v_{\text{rot}} = 781_{-36}^{+218}$ km s$^{-1}$, S18a) and offset from the QG by $-550$ km s$^{-1}$ in frequency space. Its [CII] spectrum is shown in blue in Fig. 2. The integration on this source is 1.2 hours.

GS-9209 is located at $z_{\text{spec}} = 4.6582_{-0.0002}^{+0.0002}$ and its stellar mass, size, Sersic index, and stellar velocity dispersion are $M_\star = 4.1_{-0.2}^{+0.2} \times 10^{10} M_\odot$, $r_e = 215 \pm 20$ pc (0.033$''$), $n_{\text{sersic}} = 2.3 \pm 0.3$, and $\sigma_\star = 247 \pm 16$ km s$^{-1}$, respectively (Carnall et al. 2023). The integration on this source is 52 s.

The QGs considered here have been spectroscopically confirmed with an accuracy of $\delta z/(1 + z) \sim 0.001, 0.0004$, and 0.00004, respectively. This translates into an uncertainty on the position of the [CII] line of $\pm 440$ km s$^{-1}$, $\pm 159$ km s$^{-1}$, and $\pm 11$ km s$^{-1}$, respectively. None of the galaxies is resolved at the resolution of these data sets (beam sizes of 0.27"$\times$0.26", 0.54"$\times$0.43", and 0.19"$\times$0.16", respectively).

The QGs considered here have rest-frame optical spectral properties consistent with being post-starbursts. This category can contain misclassified dusty starbursts, galaxies still transitioning towards full quiescence, and recently quenched but rather passive systems. The most robust indicator of any dust-obscured star formation activity is their IR-based SFRs (SFR$_{\text{IR}}$; Poggianti & Wu 2000, Baron et al. 2022). ADF22-QG1 has an SFR$_{\text{IR}} < 20 M_\odot$ yr$^{-1}$ ($\sim$19 times below the coeval MS) based on its 1.2mm flux (Kubo et al. 2021), ZF-COS-20115 has an SFR$_{\text{IR}} < 13 M_\odot$ yr$^{-1}$ ($\sim$40 times below the coeval MS) based on its ALMA Band 8 continuum flux, conservatively assuming a dust temperature range of 20-35K (Schreiber et al. 2018a). No SFR$_{\text{IR}}$ is currently available for GS-9209. The most stringent constraint available comes from the narrow component of its H$\alpha$ emission line (Carnall et al. 2023), which yields SFR$_{\text{H}\alpha} = 1.9 \pm 0.1$ M$_\odot$ yr$^{-1}$ ($\sim$50 times below the MS at its redshift). Although these SFRs are inherently model-dependent (ADF22-QG1 and ZF-COS-20115) or biased towards short wavelengths (GS-9209), we note that appropriate ALMA coverage for high-$z$ QGs is still missing.

Appendix B: Assumptions and limitations of the spectral analysis

We explicitly note here that we assumed that the [CII] emission shares the same spatial distribution and velocity dispersion as the stars. However, [CII] halos more extended than the stellar component have been found in several samples of star-forming galaxies at high redshift. We note that the beam sizes for ZFCOS-20115 and GS-9209 already reach 2.5-3 times their rest-frame optical $r_e$, which is the typical ratio of the [CII] sizes to the optical–UV sizes of both ALPINE and REBELS galaxies (Fujimoto et al. 2020, Fudamoto et al. 2022). Extracting the spectrum of ZF-COS-20115 over the entire beam (using a point source model) leaves our results unchanged. Applying UV tapering (tapered beam FWHM$=0.93 \times 0.86''$, i.e. $\approx 2 \times 3 \times r_e$) and performing a point source extraction for ADF22-QG1 still leads to an undetecion with consequent upper limit of 50% due to the increase in noise.

Moreover, although molecular gas may not strictly follow the stellar kinematics, we note that large line widths are conservative and that these upper limits scale with velocity interval as $\sqrt{\Delta v}$ (Williams et al. 2021). We also note that by performing Gaussian fitting on each spectrum with MPFIT (Markwardt 2009) at fixed expected observed-frame frequency and FWHM, imposing the continuum level to zero and rescaling the error spectrum to obtain a reduced $\chi^2$ of unity, our upper limits increase by 20%, leaving our conclusions unaffected.

Lastly, we note that the spectral coverage at our disposal for ADF22-QG1 and GS-9209 is incomplete. This prevents us from ruling out the potential presence of outflows that would offset the [CII] emission line from the near UV–optically derived $z_{\text{spec}}$ (e.g. Carniani et al. 2017, Fujimoto et al. 2020). Ruling out any potential presence of dust-obscured star formation and/or the presence of strong outflows will require additional targeted ALMA observations.

https://www-astro.physics.ox.ac.uk/~cappellari/software/