Widespread QSO-driven outflows in the early Universe

M. Bischetti\textsuperscript{1,2,3,4}, R. Maiolino\textsuperscript{3,4}, S. Carniani\textsuperscript{3,4}, F. Fiore\textsuperscript{5,1}, E. Piconcelli\textsuperscript{1}, and A. Fluetsch\textsuperscript{3,4}

\textsuperscript{1} INAF - Osservatorio Astronomico di Roma, Via Frascati 33, I–00078 Monte Porzio Catone (Roma), Italy
\textsuperscript{2} Università degli Studi di Roma "Tor Vergata", Via Orazio Raimondo 18, I–00173 Roma, Italy
\textsuperscript{3} Cavendish Laboratory, University of Cambridge, 19 J. J. Thomson Avenue, Cambridge CB3 0HE, UK
\textsuperscript{4} Kavli Institute for Cosmology, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
\textsuperscript{5} INAF - Osservatorio Astronomico di Trieste, via G.B. Tiepolo 11, I–34143 Trieste, Italy

ABSTRACT

We present the stacking analysis of a sample of 48 QSOs at 4.5 < z < 7.1 detected by ALMA in the [CII]158\,\mu m line to investigate the presence and the properties of massive, cold outflows traced by broad [CII] wings. We reveal very broad [CII] wings tracing the presence of outflows with velocities in excess of 1000 km s\(^{-1}\). We find that the luminosity of the broad [CII] emission increases with \(L_{\text{AGN}}\), while it does not significantly depend on the SFR of the host galaxy, indicating that the central AGN is the main driving mechanism of the [CII] outflows in these powerful, distant QSOs. From the stack of the ALMA cubes, we derive an average outflow spatial extent of \(\sim 2\) kpc. The average mass outflow rate inferred from the whole sample stack is \(\dot{M}_{\text{out}} \sim 170\, M_\odot\, \text{yr}^{-1}\), while for the most luminous systems it increases to \(\sim 340\, M_\odot\, \text{yr}^{-1}\). The associated outflow kinetic power is about 0.1% of \(L_{\text{AGN}}\), while the outflow momentum rate is about \(L_{\text{AGN}}/c\) or lower, suggesting that these outflows are either driven by radiation pressure onto dusty clouds or, alternatively, are driven by the nuclear wind and energy conserving but with low coupling with the ISM. We discuss the implications of the resulting feedback effect on galaxy evolution in the early Universe.

Key words. galaxies: active – galaxies: high-redshift – galaxies: nuclei – quasars: emission lines – quasars: general – techniques: interferometric

1. Introduction

The growth of super-massive black holes (SMBH) at the centres of galaxies and the properties and evolution of the interstellar medium (ISM) in their hosts are expected to be connected (e.g. Dr Matteo et al. 2005; Hopkins et al. 2008). There are in fact well established correlations observed between the black hole mass and the physical properties of the host galaxy (Kormendy & Ho 2013) such as the bulge mass or velocity dispersion, suggesting that the energy output of the accretion onto SMBH may be communicated to the surrounding ISM and affect star formation (SF). Indeed, AGN feedback onto their host galaxies is expected to proceed via galaxy-wide, quasi-spherical outflows (Menec\textsuperscript{[2]} et al. 2008; Faucher-Giguère & Quataert 2012), capable of heating and removing gas, therefore suppressing SF. AGN feedback is one of the main mechanisms invoked in cosmological simulations to prevent an excessive growth of massive galaxies and make gas-rich starburst galaxies quickly evolve to quiescence.

Growing observational evidence of massive AGN-driven outflows has been collected, involving different gas phases (ionised, atomic and molecular) extending from sub-pc to kpc scales. While recent works, based on local AGNs, use a multi-phase study of outflows to quantify their impact on the host galaxy (Feruglio et al. 2015; Tombesi et al. 2015; Fluetsch et al. 2018), at high redshift (\(z \sim 1 – 3\)) studies of outflows are still mostly limited to the ionised phase (see Fiore et al. 2017 and references therein). There are only few detections of fast molecular gas observed in OH absorption or CO high-J rotational transitions (Carniani et al. 2017; Feruglio et al. 2017; Brusa et al. 2018). However massive, quiescent systems and old (aged 2–3 Gyr) galaxies have been observed already at \(z \sim 2 – 3\) (Cimatti et al. 2004; Glazebrook et al. 2017), indicating that a feedback mechanism must have been in place even at very early epochs, around \(z \sim 5 – 6\).

Observations of AGN-driven outflows at high redshift have targeted the [CII] line-structure emission line at 158 \mum, which is generally the strongest emission line in galaxies. Typically [CII] is a tracer of both the neutral atomic gas, primarily in Photo-Dissociated Regions (PDRs), but can be in part emitted also from the (partly) ionised medium. Since PDR are produced by the UV radiation emitted by young stars, [CII] has also been used as a tracer of SF (Maiolino et al. 2005; De Looze et al. 2011; Carniani et al. 2013).

Recently, [CII] has also been exploited to trace cold gas in galactic outflows. Indeed, broad wings [CII] emission has been observed in the hyper-luminous QSO J1148+5251 at \(z \sim 6.4\) by Maiolino et al. (2012) and Cicone et al. (2015), releasing outflowing gas extended up to 30 kpc and escaping with velocities in excess of 1000 km s\(^{-1}\). The Herschel Space Observatory has enabled to detect cold outflows through broad wings of the [CII] line also in local active galaxies (Janssen et al. 2016).

The exploitation of the bright [CII] line at high redshift has been increasing in the last few years with the advent of ALMA. In particular, the population of high-\(z\) luminous AGN with detected [CII] emission has been rapidly growing. Previous works have exploited the [CII] emission to investigate the AGN/quasar host galaxy properties, such as the SFR, the dynamical mass, and the presence of merging companions (e.g. Wang et al. 2013; 2016; Kenmans et al. 2016; 2017; Willott et al. 2015; 2017; Trakhtenbrot et al. 2017; Decarli et al. 2017; 2018). In none of these high-\(z\) QSO evidence of [CII] outflows has been reported. However, most of these [CII] observations in distant QSOs are still rather short (10–20 minutes of on-source time), with a sen-
We have collected a sample of 48 QSOs with ALMA [CII] detection to investigate the presence of outflows, as traced by weak [CII] broad wings, by performing a stacking analysis. We will show that the stacked data achieve a sensitivity that is more than an order of magnitude deeper than that reached in previous [CII] outflows detections and enable us to reveal very broad, weak wings tracing cold outflows associated with distant QSOs.

2. Sample and data reduction

We collected all [CII] observations of $z > 4.5$ QSOs on the ALMA archive public as of March 2018 and selected the sources with a [CII] detection significant at $\geq 5\sigma$. Specifically, we used data from ALMA projects 2011.0.00243.S, 2012.1.00604.S, 2012.1.00676.S, 2012.1.00882.S, 2013.1.01153.S, 2015.1.01115.S and 2016.1.01515.S. Details about individual QSOs in our sample, for those which have been published, can be found in Wang et al. (2013), Willott et al. (2013), Willott et al. (2015), Willott et al. (2017), Kimball et al. (2015), Diaz-Santos et al. (2016), Venemans et al. (2016), Venemans et al. (2017), Decarli et al. (2017), Decarli et al. (2018), and Trakhtenbrot et al. (2017); however, we also included some ALMA unpublished archival data. As mentioned, in total we combined ALMA data for 48 QSOs, and equivalent to a total of ~34 hours of on-source observing time.

Observations involve ALMA bands 6 or 7, depending on the host galaxy emission we considered in this work. The distribution of the average rms sensitivity, representative of the [CII] spectral region, and that of the size of the ALMA beam are shown in Fig. [1] Individual values are listed in Table [1]. Except for few outliers, the bulk of the observations have similar sensitivities from ~0.3 to ~0.8 mJy/beam for a 30 km s$^{-1}$ channel. The angular resolutions, computed as average beam axis, range from ~0.3 to 1.2 arcsec.

Data were calibrated using the CASA software (McMullin et al. 2007) in the manual or pipeline mode of the specific CASA version indicated in the README file provided by the ALMA Observatory, as also the default phase, bandpass and flux calibrators provided there. Data cubes were produced by using the CASA task clean with natural weighting, a common pixel size of 0.05″ and a common spectral bin of 30 km s$^{-1}$. Continuum maps were obtained by averaging over all the spectral windows and excluding the spectral range covered by the [CII] emission and possible [CII] broad wings. Continuum flux densities were derived by fitting a 2D Gaussian model to the ALMA maps. Furthermore, to model the continuum emission next to the [CII] line, we combined two adjacent spectral windows (where present) to increase the available spectral range, for a total of ~3.5 GHz. We thus fitted a zeroth order continuum model in the UV plane to all the available channels with a velocity $|v| > 1500$ km s$^{-1}$ with respect to the centroid of the (core) [CII] emission (spectral regions corresponding to an atmospheric transmission < 0.5 for a 1 mm precipitable water vapour were excluded from the fit). We verified that modelling the continuum emission with a first order polynomial did not significantly affect our results, given the limited frequency range covered by our stack by using two adjacent spectral windows.

To determine the properties of the host galaxy emission we extracted the continuum-subtracted [CII] spectra from a region with an area of four beams (see Sect. 3). The line parameters describing the [CII] core emission were derived by fitting each spectrum with one Gaussian component model. Specifically, red-
and a second, higher-

z

with a Full Width Half Maximum (FWHM) in the range be-
in the range Log(L

/

1

shifts (\(\Delta u\)) from the centroid of the best-fit [CII] model (see Table 1).

The main properties of our high-\(z\) QSOs sample are shown in Fig. 2 and listed in Table 1. The QSOs in the sample are distributed in two main redshift bins, i.e. a first group at 4.5 < \(z\) < 5 and a second, higher-\(z\) group at \(z\) > 6. The bulk of the sample characterised by a luminosity of the [CII] core emission in the range Log(L_{CII}/L_{\odot}) ~ 9.0 – 9.5 and [CII] line profiles with a Full Width Half Maximum (FWHM) in the range between 300 and 500 km s\(^{-1}\). We computed the FIR luminosity using an Mrk231-like template (Polletta et al. 2007) normalised to the ALMA continuum flux density. The resulting \(L_{\text{FIR}}\) (see Fig. 2) span almost two orders of magnitude, i.e. Log(\(L_{\text{FIR}}/L_{\odot}\)) = 11.6 – 13.4. The AGN bolometric luminosity (\(L_{\text{AGN}}\)) was derived from the monochromatic luminosity at 1450 Å by applying the bolometric correction from Runnoe et al. (2012). All sources in our sample are luminous and hyper-luminous QSOs with \(L_{\text{AGN}} \geq 10^{46}\) erg s\(^{-1}\), with an average \(L_{\text{AGN}}\) of 6.3 \(\times 10^{46}\) erg s\(^{-1}\).
3. Methods

In order to investigate the presence of high velocity wings of the [CII] emission, we performed a stacking analysis of the distant QSOs in our sample. The stacking technique has the potential to greatly increase the sensitivity of the stacked spectrum or stacked cube and, therefore, favours the detection of even modest outflows traced by weak [CII] wings. As a first step, the cubes were aligned at the [CII] rest frequency (1900.5369 GHz) according to $z_{\text{CII}}$ and spatially centred on the peak of the QSO continuum emission. In this way, spatial or spectral interpolation of the data during the stack was not needed. We did not include in the stack spectral regions corresponding to an atmospheric transmission $<0.5$ for a 1 mm precipitable water vapour. Then, we combined the data from the 48 sources in our sample according to the relation below, defining the weighted intensity $I'_k$ of a generic spatial pixel $(x', y')$ in the stacked cube for each spectral channel $k$, and the relative weight $W'_k$ as follows (Fruchter & Hook 2002):

$$W'_k = \sum_{j=1}^{n} w_{j,k} = \sum_{j=1}^{n} \frac{1}{\sigma_{j,k}^2} = \frac{1}{\sum_{j=1}^{n} \sigma_{j,k}^2}$$  \hspace{1cm} (1)

$$I'_k = \sum_{j=1}^{n} \left( \frac{i_{j,k} \cdot w_{j,k}}{W'_k} \right)$$  \hspace{1cm} (2)

where $i_{j,k}$ is the intensity at the same spatial pixel $(x', y')$ and same spectral channel $k$ of source $j$, and $n = 48$. We applied a standard variance-weighted stacking, i.e. we used a weighting factor $w_{j,k} = 1/\sigma_{j,k}^2$, where $\sigma_{j,k}$ is the rms noise estimated channel by channel from cube $j$. Furthermore, with this method we accounted for the noise variation with frequency in the spectral range covered by the ALMA [CII] spectra, i.e. $\sim 4$ GHz, and considered only the contribution of sources with available spectral coverage in our weighted mean.

We performed the stacking in two alternative, complementary ways: by stacking the 1D spectra extracted from the individual cubes and by stacking the 3D cubes into a single stacked cube. In the first case the continuum-subtracted spectrum of each target was extracted from an elliptical aperture with same position angle of the beam, but over an area four times larger. This approach allows us to collect most of the flux from the QSO (for a point source, $\sim 94\%$ of the flux lies within two beam axes) and limits the contamination of possible companions. The individual spectra were therefore stacked according to Eq. 1 and Eq. 2.

In the second approach, the continuum-subtracted cubes of the single sources were stacked by applying Eqs. 1, 2 to each spaxel. This resulted in a stacked data cube, containing the contribution of each source to the different channels and spatial positions.

Finally, to verify that the presence of broad [CII] wings was not associated with few QSOs but instead a general properties of our sample, we recomputed 1000 times the stack of the integrated spectrum on different subgroups of sources. Each time we excluded a different combination of 5 sources, i.e. $\sim 10\%$ of our sample. The resulting rms variation of the [CII] wings in the velocity range $400 < |v| < 1800$ km s$^{-1}$ corresponds to $\sim 20\%$ of the peak flux density of the broad [CII] wings (presented in Sect. 4.1).

4. Results

4.1. Stacked spectrum

The integrated spectrum resulting from the stack of all 48 QSO individual (1D) spectra in our sample is shown in Fig. 3. The stacked spectrum clearly reveals very broad wings beneath the narrow line core, clearly tracing fast outflows of cold gas. The red line shows the best-fit with two Gaussian components, indicated with blue and green lines. The $\chi^2$ minimisation of the fit was performed by using for each channel the weight $W'_k$ (see Eq. 1) and gives a $\chi^2 = 3.7$, a factor of $\sim 2$ smaller than the $\chi^2_{\text{red}} = 8.6$ resulting from a single Gaussian fit of the spectrum. This reduction in $\chi^2$ indicates that the second, broad Gaussian component is required with very high confidence level ($>99.9\%$). The reduced $\chi^2$ is yet larger than unity, hence suggesting that the line profile might be more complex than two simple Gaussian components. The median rms of the stacked spectrum is $\sim 0.065$ mJy/beam (see Table 2), which is nicely consistent with the noise expected by stacking the original spectra if the noise is Gaussian. To give an idea of the significant improvement in sensitivity obtained with the stack, the sensitivity level reached in this work is a factor of $\sim 14$ lower than that of the J1148+5251 observations of Ciccone et al. (2015), where a massive [CII] outflow was found.

In the stacked spectrum the core emission component has a width of FWHM$^{\text{conv}}_{\text{CII}} = 364 \pm 4$ km s$^{-1}$, while the underlying very
Table 2. Variance-weighted properties of the stacked QSOs samples and the corresponding broad [CII] emission properties. The columns give the following information: (1) identification of the (sub-)sample used for the stack (see Sect. 4.2 for details), (2) rms sensitivity representative of the [CII] spectral region for a channel width of 30 km s\(^{-1}\), (3) average \(L_{\text{AGN}}\) in the (sub-)sample, (4) average FIR-based SFR, (5) average [CII]-based SFR, (6) luminosity of the broad [CII] wings, (7) peak and (9) integrated flux density ratios of the broad [CII] with respect to the core [CII] emission.

| Sample | rms [mJy/beam] | \(L_{\text{AGN}}\) [erg s\(^{-1}\)] | \(SFR_{\text{FIR}}\) \([M_\odot \text{yr}^{-1}]\) | \(SFR_{\text{[CII]}}\) \([M_\odot \text{yr}^{-1}]\) | \(L_{\text{broad}} \text{[CII]}\) \([10^8 \, L_\odot]\) | FWHM\text{broad} \text{[CII]} \([\text{km s}\,\,^{-1}]\) | \(p_{\text{[CII]}}\) | \(f_{\text{[CII]}}\) |
|--------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Whole sample | 0.065 | 47.0 | 790 | 180 | 3.9 \pm 0.7 | 1730 \pm 210 | 0.05 \pm 0.01 | 0.22 \pm 0.04 |
| A | 0.11 | 46.3 | 570 | 140 | 2.4 \pm 0.8 | 850 \pm 160 | 0.05 \pm 0.01 | 0.18 \pm 0.06 |
| B | 0.19 | 47.1 | 540 | 200 | 4.7 \pm 2.0 | 710 \pm 130 | 0.1 \pm 0.03 | 0.23 \pm 0.08 |
| C | 0.18 | 46.7 | 360 | 150 | 3.3 \pm 1.1 | 2360 \pm 640 | 0.05 \pm 0.02 | 0.22 \pm 0.07 |
| D | 0.10 | 47.2 | 1270 | 210 | 6.4 \pm 1.4 | 1920 \pm 250 | 0.07 \pm 0.01 | 0.31 \pm 0.06 |
| E | 0.09 | 46.7 | 260 | 100 | 1.1 \pm 0.3 | 2210 \pm 430 | 0.07 \pm 0.01 | 0.39 \pm 0.09 |
| F | 0.10 | 47.1 | 1750 | 270 | 1.0 \pm 0.1 | 1380 \pm 200 | 0.04 \pm 0.01 | 0.14 \pm 0.02 |

Fig. 4. Stacked integrated spectra for the different QSOs subgroups A, B, C, D (properties of the individual samples are indicated in the top labels). For each plot, the top panel shows the [CII] flux density as a function of velocity, in bins of 60 km s\(^{-1}\). The red curve represents the best-fit 2 Gaussian components model; the two individual component are shown with blue and green lines. Labels indicate the number of stacked sources and the luminosity of the broad [CII] wings. The insets show zooms around the broad components. The bottom panel shows the residuals at different velocities. The 1\(\sigma\) rms of the spectrum is also indicated by the shaded region.

The broad component has a width of FWHM\text{broad} \text{[CII]} = 1730 \pm 210 \text{ km s}^{-1}\)(see Table 2). The broad wings are not symmetric, the blue side being much more prominent than the red side, resulting in the overall broad Gaussian used to fit the broad component being slightly blueshifted (by \(-100 \text{ \, km s}^{-1}\)) with respect to the systemic [CII] emission. This might be an artefact resulting from the asymmetric distribution of the data, with the red wing being contributed by fewer spectra than the blue wing (top panel of Fig. 3). Alternatively, at such early epochs, the host galaxies of these hyper-luminous QSOs may be similar to extreme ultra-
luminous infrared galaxies (ULIRGs), which have been found to be optically thick even at far-IR and submm wavelengths (Papadopoulos et al. 2010; Neri et al. 2014; Gillberg et al. 2015), which may result into absorption of the receding (redshifted) component of the outflow, even at the wavelength of [CII].

The peak flux density of the broad [CII] component is about 5% of that of the core, while the integrated broad-to-narrow [CII] flux density ratio is \( f_{\text{CII}} \approx 0.22 \) (see Table 2). In order to estimate the luminosity of the [CII] broad component representative of our sample, we computed a weighted \( L_{\text{CII}}^{\text{stack}} \) by applying Eqs. (1) and (2) to the individual narrow [CII] luminosities of our targets. We therefore derived the luminosity associated with the broad [CII] wings as \( L_{\text{CII}}^{\text{broad}} = L_{\text{CII}}^{\text{stack}} \times f_{\text{CII}} \).

### 4.2. Outflow relation with QSO-galaxy properties

In this section, we investigate the relation between the presence of cold outflows traced by the [CII] wings and the properties of the QSO-host galaxy system, such as AGN luminosity and SFR. Furthermore, in the stack of the whole sample (Sect. 4.1) we consider sources with [CII] line profiles that are significantly different (FWHM\(_{\text{CII}}\) ~ 200 to 800 km s\(^{-1}\)), we verify that the presence of broad [CII] wings is not an artefact of the stack.

Specifically, we separate the QSOs in two subsamples with FWHM\(_{\text{CII}}\) < 400 km s\(^{-1}\) (median linewidth of the whole sample) and FWHM\(_{\text{CII}}\) > 400 km s\(^{-1}\), respectively. This roughly corresponds to discriminates between less and more massive systems, given that the [CII] linewidth is a proxy of the dynamical mass of the galaxy (modulo disc inclination effects). We further separate our sample in two AGN luminosity bins: specifically \( L_{\text{AGN}} < 10^{46.8} \) erg s\(^{-1}\) (median \( L_{\text{AGN}} \) of the whole sample) and \( L_{\text{AGN}} > 10^{46.8} \) erg s\(^{-1}\). This allowed us to investigate the relation between the [CII] outflow strength and \( L_{\text{AGN}} \). For simplicity, hereafter the different subsamples will be referred to as:

\begin{itemize}
  \item A: FWHM\(_{\text{CII}}\) < 400 km s\(^{-1}\), \( L_{\text{AGN}} < 10^{46.8} \) erg s\(^{-1}\)
  \item B: FWHM\(_{\text{CII}}\) < 400 km s\(^{-1}\), \( L_{\text{AGN}} > 10^{46.8} \) erg s\(^{-1}\)
  \item C: FWHM\(_{\text{CII}}\) > 400 km s\(^{-1}\), \( L_{\text{AGN}} < 10^{46.8} \) erg s\(^{-1}\)
  \item D: FWHM\(_{\text{CII}}\) > 400 km s\(^{-1}\), \( L_{\text{AGN}} > 10^{46.8} \) erg s\(^{-1}\)
\end{itemize}

The stacked spectra for the different subsamples are shown in Fig. 6. Because of lower statistics, the sensitivity improvement is smaller compared to the stack of the whole sample. (see Table 2). With such reduced statistics, the individual source contribution to the stacked spectrum is more evident. This is particularly evident in Fig. 6 for stacks C and D, where the core of the stacked [CII] profile is broadened by few sources exhibiting a rotation pattern in their [CII] spectra. We fit A and B with a two Gaussian components model, while for stack D and E we use a combination of two Gaussians to account for the broadening of the [CII] core, and a third Gaussian to reproduce the [CII] wings. The best fit models are shown in Fig. 4.
A faint broad [CII] emission component is observed in the stacked spectrum of all subgroups, although with lower significance if compared to the whole sample stack presented in Sect. 4.1. In sources with small FWHM of the [CII] core emission (stacks A and B), wings are characterised by FWHM$_{[\text{CII}]}$ up to $\sim 850$ km s$^{-1}$, while broader wings with FWHM$_{[\text{CII}]} \sim 2000$ km s$^{-1}$ are observed in the subsamples with broader [CII] cores (stacks C and D). Similarly to what we found in the whole sample stack, the peak of the broad [CII] wings is 5% to 10% of the core peak flux density, while the integrated flux of the broad component corresponds to 20 – 30% of the core component.

For each subsample, $I_{\text{[CII]}}$ and $L_{\text{AGN}}$ have been computed following the same method of Sect. 4.1 (see Table 2). We observe an increased $I_{\text{[CII]}}$ in the high $L_{\text{AGN}}$ sources (see Fig. 4), despite the limited luminosity range spanned by the sources considered in this work. Fig. 5 shows indeed a positive correlation between $I_{\text{[CII]}}$ and $L_{\text{AGN}}$ in agreement with previous works (Cicone et al. 2014; Fiore et al. 2017; Fluetisch et al. 2018) finding that the outflow strength correlates with the AGN luminosity. This result indicates that the observed [CII] outflows are primarily QSO-driven. Instead, we see only marginal variations of $I_{\text{[CII]}}$ with respect to the width of the line core, indicating that the dynamics of the galactic disc does not significantly affect the detectability of the broad [CII] components associated with the outflow.

An alternative driving mechanism of the fast [CII] emission could be the starburst in the QSO host galaxy through supernovae and radiation pressure. To investigate this possibility in more detail, we considered two subgroups according to their SFR, as inferred from their $L_{\text{FIR}}$ (computed following Kennicutt & Evans (2012)), assuming that the bulk of the far-IR emission is associated with SF in the host galaxy:

- $E$: SFR$_{\text{FIR}} < 600$ M$_\odot$ yr$^{-1}$
- $F$: SFR$_{\text{FIR}} > 600$ M$_\odot$ yr$^{-1}$

The corresponding stacked spectra are shown in Fig. 6. It is evident that the [CII] core emission is mainly associated with SF activity, confirming that [CII] is a tracer of star formation. The [CII] flux density of the core in stack E, characterised by a variance-weighted SFR of 260 M$_\odot$ yr$^{-1}$, is in fact a factor of $\sim 3.5$ lower with respect to the highly star forming sources stacked in F (whose variance-weighted SFR is $\sim 1750$ M$_\odot$ yr$^{-1}$).

However, the broad [CII] wings are well present in both stacks with comparable luminosity $I_{\text{[CII]}} \sim 10^{47.6}$ erg s$^{-1}$, indicating that SF does not significantly contribute to the outflows in the hosts of these powerful QSOs.

### 4.3. Stacked Cube

In this section we present the results from the stacking of the ALMA data cubes for the QSOs in our sample. We produced a stacked cube by applying the stacking technique presented in Sect. 3 i.e. we used Eqs. (1) and (2) to compute the variance-weighted flux density of each spaxel in the final cube. It is a very simple approach primarily aimed at investigating the spatial scale of the [CII] outflows in the high-$z$ QSOs host galaxies. Differently from the analysis of the integrated spectra of Sect. 4.1 here we did not choose an extraction region but only piled up the emission contributions to each pixel of the map.

However, the application of this stacking method to heterogeneous observations may lead to a few issues, as discussed in the following:

- Combining observations with different angular resolutions (see Fig. 1) implies that emission from different physical scales may contribute to the total flux density of a same pixel. Degrading the observations to the lowest angular resolution would allow to stack emission arising from similar physical scales (given that the physical-to-angular scale ratio changes only by a factor $\lesssim 1.3$ in the redshift range of our sources).

However, in interferometric data this would imply tapering the visibilities, i.e. lowering the weight of the extended baselines to the final map, at the expenses of the sensitivity. Therefore, we preferred not to modify the angular resolutions. However, by computing the variance-weighted beam-size of our stacked cube, it is possible to have an indication of the angular scale above which the most of the emission is resolved. For the all-sample stacked cube we computed an average angular resolution $\theta_{\text{res}} = 0.52'' \times 0.68''$. In the case of a point source emission, the flux density contribution to the scale of the beam axes is only $\sim 6\%$. We may therefore safely assess that emission on larger scales is mainly associated to extended, resolved emission.

- Lacking a-priori information about the structure and orientation of possible [CII] extended emission, in particular at high velocities, may cause outflowing anisotropic or clumpy [CII] emission to be diluted in the stack. As a consequence, the true fraction of [CII] emission associated with extended structures may be significantly higher.

- The different angular resolutions of the interferometric observations are the result of different array configurations, which may filter out emission on different large angular scales. As a rough estimate the largest angular scale ($L_{\text{AS}}$) that can be recovered by interferometric observations is $L_{\text{AS}} \sim (4 - 6) \times \theta_{\text{res}}$, where $\theta_{\text{res}}$ is the angular resolution. In the case of our stacked cube the flux loss of extended emission due to filtering starts to become important at $\sim 2$ arcsec.

Aware of these potential issues, Fig. 7 shows the central $6'' \times 6''$ region of the stacked cube obtained by combining all the high-$z$ QSOs in our sample. Specifically, channel maps of the [CII] emission are shown for a velocity range $v \in [-1000, 1000]$ km s$^{-1}$ in bins of 80 km s$^{-1}$. The bulk of the [CII] core emission is in the central $v \in [-390, 390]$ km s$^{-1}$. Compact [CII] emission is observed in almost all channels at $\geq 2\sigma$ up to $\sim 6\sigma$, in addition to the presence of few offset clumps. At $|v| \sim 400-600$ km s$^{-1}$ there is also some indication of extended [CII] emission, although the lower velocity channels might be contaminated from emission associated with the [CII] core.

The channel maps of Fig. 8 suggest that we might be observing [CII] emission clumps moving at different velocities and characterised by a range of velocity dispersions. To build a global picture of the [CII] outflows, we create an integrated luminosity map of the high-velocity [CII] emission by summing the emission contributions, in the 80 km s$^{-1}$ channel maps, detected at $> 3\sigma$ significance for at least three channels (i.e. $\geq 250$ km s$^{-1}$) in the all-sample stacked cube. The result is shown in Fig. 9 where the maps corresponding to the velocity bins $|v| > 400$ km s$^{-1}$, $550$ km s$^{-1} < |v| < 700$ km s$^{-1}$ are displayed. We also plot the associated signal-to-noise ratio maps.

As expected, most of the fast [CII] emission arises from the central regions, where all sources contribute in the stack. At the highest velocities ($\sim 700$ km s$^{-1}$) the nuclear outflow is still present at $\sim 3.5\sigma$ significance. At moderate velocities $|v| \sim 400-550$ km s$^{-1}$, we observe extended emission up to $\sim 1.5$ arcsec, corresponding to $\sim 9$ kpc at $z_{\text{stack}} = 5.8$. Marginally resolved emission is observed also at higher velocities. However, we stress again that we might be losing a significant part of the extended emission in our stack. We compute the spatial scale at...
A & A proofs: manuscript no. CII-stack-submitted

5. Discussion

The luminosity of the broad [CII] wings is linked to the mass of the outflowing atomic gas. It is therefore possible to estimate the typical energetics of [CII] outflows in high-redshift, high-luminosity QSOs, in the central ∼ 2 kpc regions (see Sect. 4.3). Specifically, to compute the outflow mass of atomic neutral gas we use the relation from Hailey-Dunsheath et al. (2010):

\[ \frac{M_{\text{outf}}}{M_\odot} = 0.77 \left( \frac{0.7 L_{\text{[CII]}}}{L_\odot} \right) \left( \frac{1.4 \times 10^{-6}}{X_{\text{C}^+}} \right) \left( 1 + \frac{2e^{-91kT}}{n_{\text{crit}}/n} \right) \]  

where \( X_{\text{C}^+} \) is the C\(^+\) fraction per hydrogen atom, \( T \) is the gas temperature, \( n \) is the gas density and \( n_{\text{crit}} \sim 3 \times 10^3 \) cm\(^{-3}\) is the [CII] \( \lambda158\mu\text{m} \) critical density. We use Eq. (3) in the approximation of \( n \gg n_{\text{crit}} \), thus deriving a lower limit on the outflowing gas mass. Moreover, the [CII] emitting region is in most cases characterised by densities in excess of \( n_{\text{crit}} \sim 3 \times 10^3 \) cm\(^{-3}\) (e.g. De Breuck et al. 2011). Following Maiolino et al. (2012) we consider a conservative \( X_{\text{C}^+} \sim 10^{-4} \), typical of photo-dissociated regions, and a gas temperature of 200 K. Assuming a temperature from 100 K to 1000 K would imply a variation of only 20% in the resulting gas mass. Accordingly, for the stack of the whole sample we infer a mass of the outflowing neutral gas of \( M_{\text{outf}} = (3.7 \pm 0.7) \times 10^8 M_\odot \), see Table 3.

To compute the [CII] outflows energetics of the high-z QSOs in our sample, we assume the scenario of time-averaged expelled shells or clumps (Rupke et al. 2005):

\[ \dot{M}_{\text{outf}} = \frac{v_{\text{outf}} \times \Delta v_{\text{broad}}}{R_{\text{outf}}} \]  

where \( v_{\text{outf}} = \Delta v_{\text{broad}} + \text{FWHM}_{\text{[CII]}}/2 \) (see Table 3) and \( \Delta v_{\text{broad}} \) is the velocity shift of the centroid of the broad [CII] wings with re-
Fig. 8. Top: luminosity maps of the high-velocity [CII] emission derived from the whole sample stacked cube. From left to right, panels correspond to emission at increasing absolute velocities, specifically $|v| > 400 \text{ km s}^{-1}$, $|v| > 550 \text{ km s}^{-1}$ and $|v| > 700 \text{ km s}^{-1}$. Maps were obtained by summing the emission at $> 3\sigma$ in 80 km s$^{-1}$ channel maps for at least three channels (i.e. $> 250 \text{ km s}^{-1}$). The variance-weighted beam of the stacked cube is also indicated in the first map (solid line), together with the smallest beam contributing to the stack (dashed line). The thick solid contour encloses the region from which 50% of $L_{\text{[CII]}}$ arises. Bottom: signal-to-noise maps associated with the different velocity bins.

We calculate the kinetic power associated with the [CII] outflows as:

$$E_{\text{outf}} = \frac{1}{2} M_{\text{outf}} v_{\text{outf}}^2$$  \hspace{1cm} (5)$$

and the momentum load:

$$P_{\text{outf}} / P_{\text{AGN}} = \frac{M_{\text{outf}} v_{\text{outf}}}{L_{\text{AGN}} / c}$$  \hspace{1cm} (6)$$

where $P_{\text{AGN}} = L_{\text{AGN}} / c$ is the AGN radiation momentum rate. This approach allows us to directly compare our findings to the collection of 30 low redshift AGNs by (Fluetsch et al. 2018), for which the energetics of spatially resolved molecular and (in $\sim$ one third of the same sources) neutral [CII] and ionised outflows has been homogeneously calculated.

The resulting outflow parameters for the whole sample stack and the different subsamples considered (see Sect. 4.2) are listed in Table 3. We derive a mass outflow rate of $M_{\text{outf}} = 170 \pm 40 \text{ M}_\odot \text{ yr}^{-1}$ for the stack of the whole sample, while for the large FWHM, high-$L_{\text{AGN}}$ subgroup (stack D) we find $M_{\text{outf}} \sim 340 \text{ M}_\odot \text{ yr}^{-1}$. These outflow rates only refer to the atomic neutral component. Fluetsch et al. (2018) obtained that, for AGN-driven outflows, the molecular mass outflow rates are of the same order as the atomic neutral outflow rates, while the contribution from the ionised gas is negligible, at least in the luminosity range probed by them. They find that the molecular-to-ionised outflow rate increases with luminosity, in contrast with what found by Fiore et al. (2017); the discrepancy may originate from the fact that the latter study investigate disjoint samples, or may originate from the different luminosity ranges sampled. If we assume that the relations found by Fluetsch et al. (2018) also apply to these distant luminous QSOs, then the implied total outflow rate is twice the value inferred from [CII].

Fig. 9a shows the mass outflow rate as a function of the AGN bolometric luminosity. Stars show the atomic neutral outflow rate inferred from the [CII] broad wings for the various stacked spectra, as indicated in the legend. The circles, connected to the star through a dashed line, indicate the inferred outflow rate by accounting also for the molecular gas content in the outflow assuming the relation given by Fluetsch et al. (2018). Blue, green and purple squares show the molecular, ionised and atomic neutral outflow rates measured by Fluetsch et al. (2018) in local AGNs. In the latter case the neutral component is obtained through [CII] observations of local galaxies performed by the Herschel infrared space telescope (Janssen et al. 2016) and purple circles show the effect of correcting the atomic outflow rate as discussed above. Hollow green squares show the ionised outflow rates inferred from Fiore et al. (2017); these are from a disjoint sample (they do not have measurements for the molec-
Table 3. Outflow parameters associated to the different stacked integrated spectra. The columns give the following information: (1) stacked sample, (2) atomic gas mass associated to the broad \([\text{CII}]\) wings, (3) mass outflow rate, computed following [Fluetsh et al. 2018], (4) kinetic power and (5) momentum load factor of the outflow.

| Stack        | \(\nu_{\text{out}}\) | \(M_{\text{out}}\) | \(M_{\text{out}}\) | \(E_{\text{out}}\) | \(P_{\text{out}}/P_{\text{AGN}}\) |
|--------------|------------------------|---------------------|---------------------|---------------------|-----------------------------|
|              | [km s\(^{-1}\)]       | \([10^{8} \text{ M}_{\odot}]\) | [M\(_{\odot}\) yr\(^{-1}\)] | \([10^{43} \text{ erg s}^{-1}]\) |                             |
| Whole sample | 960 ± 130              | 3.7 ± 0.7           | 170 ± 40            | 5.0 ± 1.5           | 0.4 ± 0.1                   |
| A            | \(< 400 \text{ km s}^{-1}\) \(L_{\text{AGN}}\) \(< 10^{46.8} \text{ erg s}^{-1}\) | 530 ± 100           | 2.4 ± 0.9           | 60 ± 25              | 0.6 ± 0.3                   |
| B            | \(< 400 \text{ km s}^{-1}\) \(L_{\text{AGN}}\) \(> 10^{46.8} \text{ erg s}^{-1}\) | 420 ± 90            | 4.6 ± 1.5           | 90 ± 35              | 0.5 ± 0.2                   |
| C            | \(> 400 \text{ km s}^{-1}\) \(L_{\text{AGN}}\) \(< 10^{46.8} \text{ erg s}^{-1}\) | 1180 ± 380          | 3.2 ± 1.0           | 180 ± 50             | 8 ± 3                       |
| D            | \(> 400 \text{ km s}^{-1}\) \(L_{\text{AGN}}\) \(> 10^{46.8} \text{ erg s}^{-1}\) | 1140 ± 150          | 6.2 ± 1.2           | 340 ± 60             | 14 ± 4                      |
| E            | SFR\(_{\text{FIR}}\) \(< 600 \text{ M}_{\odot}\) yr\(^{-1}\) | 1240 ± 250          | 3.9 ± 1.1           | 230 ± 75             | 7.7 ± 1.3                   |
| F            | SFR\(_{\text{FIR}}\) \(< 600 \text{ M}_{\odot}\) yr\(^{-1}\) | 930 ± 140           | 3.6 ± 0.8           | 160 ± 50             | 4.4 ± 1.6                   |

The balance between the various phases is different in these systems. [Bischetti et al. 2017] and [Fiore et al. 2017], however, as illustrated in Fig. 3, even the ionised phase does not seem to be massive and powerful enough to match the requirements of the energy-driven scenario with high coupling.

In alternative, the interferometric data used in our stack of the \(\text{[CII]}\) emission may extend, diffuse emission associated with outflows. Indeed, a large fraction of the data have angular resolution higher than 0.7°, which may prevent them to detect emission on scales larger than \(3 - 4\)°. The lack of sensitivity to extended, diffuse emission may indeed be a major problem in very distant systems, due to the rapid cosmological dimming of the surface brightness, decreasing as \((1 + z)^4\). This scenario may also explain why the \(\text{[CII]}\) outflow rate and kinetic power in the stacked data of distant QSOs do not seem to increase significantly with respect to the local, lower-luminosity AGN (purple square symbols in Fig. 3) whose \(\text{[CII]}\) broad wings were observed with Herschel.

With this context it is interesting to note that in the QSO J1148+5251 at \(z=6.4\) [Maiolino et al. 2012] and Cicone et al. (2015) did detect a very extended outflow on scales of \(6\)″, by exploiting low angular resolution observations. J1148+5251 (black square in Fig. 3) is indeed characterised by a larger outflow rate and higher kinetic power with respect to the stacked measurements. However, even for J1148+5251 the kinetic power and momentum rate appear to be significantly lower than what expected by the simple scenario of energy-driven outflows with high coupling with the ISM.

### 6. Conclusions

In this work we have presented the stacking analysis of a sample of 48 QSOs at \(4.5 < z < 7.1\) detected in \(\text{[CII]}\) by ALMA, equivalent to an observation of ~ 34 hours on-source, aimed at investigating the presence and the properties of broad \(\text{[CII]}\) wings tracing cold outflows. The stack allows us to reach an improvement in sensitivity by a factor of ~ 14 with respect to the previous observation of a massive \(\text{[CII]}\) outflow in J1148+5251 at \(z=6.4\) [Maiolino et al. 2012] and Cicone et al. (2015).

- From the stacked integrated spectra, we clearly detect broad \(\text{[CII]}\) wings, tracing cold outflows associated with these distant QSOs and with velocities exceeding 1000 km s\(^{-1}\). This weak broad component has not been previously detected in single observations (except for the case of J1148+5251) because of insufficient sensitivity. The same limitation applies to the stack recently performed by Decarli et al. (2018) on the sample of 23 PÅN-STARSS QSOs with ALMA \(\text{[CII]}\) detection, which were mostly observed with very short (few...
minutes) exposures. In fact similarly to [Decarli et al. (2018)], we find no significant broad [CII] wings in the stacked spectrum of their PAN-STARRS sources alone.

- The redshifted [CII] wing is fainter than the blueshifted [CII] wing. This may be associated with the asymmetric distribution of the spectral coverage of the spectra used in the stacked spectrum. However, if confirmed with additional data, this asymmetry would suggest that in these systems the dusty gas in the host galaxy has a column density high enough to obscure the receding component of the outflows, with respect to our line of sight. High dust column densities capable of absorbing even at far-IR and submm wavelengths have been observed in local ULIRGs.

- By splitting the sample in AGN luminosity and SFR bins, we observe that the strength of the broad component depends on the AGN luminosity, but does not depend on the SFR. This indicates that the QSOs are the primary driving mechanism of the [CII] outflows in these systems.

- From the stacked cube we infer an average atomic mass outflow rate $M_{\text{outf}} \sim 170 \, M_{\odot} \, yr^{-1}$, which increases to $M_{\text{outf}} \sim 340 \, M_{\odot} \, yr^{-1}$ for the stack of the most luminous sources. By correcting for the atomic-to-molecular gas ratio found by Fluetsch et al. (2018), the former value translates into $\sim 7 \times 10^{3}$ M$_{\odot}$ yr$^{-1}$.

References

Bissetti, M., Piconcelli, E., Viti, G., et al. 2017, A&A, 598, A122
Bourne, M. A., Nayakshin, S., & Hobbs, A. 2014, MNRAS, 441, 3055
Bourne, M. A., Zubovas, K., & Nayakshin, S. 2015, MNRAS, 453, 1829
Brusa, M., Cresci, G., Daddi, E., et al. 2018, A&A, 612, A29
Carniani, S., Marconi, A., Biggs, A., et al. 2013, A&A, 559, A29
Carniani, S., Marconi, A., Maiolino, R., et al. 2017, A&A, 605, A105
Cicone, C., Maiolino, R., Gallerani, S., et al. 2015, A&A, 574, A14
Cicone, C., Maiolino, R., Sturm, E., et al. 2014, A&A, 562, A21
Cimatti, A., Daddi, E., Renzini, A., et al. 2004, Nature, 430, 184
Conn, T., Rosdahl, J., Sijacki, D., & Haehnelt, M. G. 2017, ArXiv e-prints [arXiv:1709.08638]
Costa, T., Sijacki, D., & Haehnelt, M. G. 2015, MNRAS, 448, L30
De Breuck, C., Maiolino, R., Caselli, P., et al. 2011, A&A, 530, L8
De Looze, I., Baes, M., Bendo, G. J., Cortese, L., & Fritz, J. 2011, MNRAS, 416, 2712
Decarli, R., Walter, F., Venemans, B. P., et al. 2017, Nature, 545, 457
Decarli, R., Walter, F., Venemans, B. P., et al. 2018, ApJ, 854, 97
Di Matteo, T., Springel, V., & Hernquist, L. 2005, Nature, 433, 604
Díaz-Santos, T., Assef, R. J., Blain, A. W., et al. 2016, ApJ, 816, L6
Fischer, G., Gabor, J. M., Bournaud, F., et al. 2015, A&A, 583, A99
Fiore, F., Feruglio, C., Shankar, F., et al. 2017, A&A, 601, A143
Fluetsch, A., Maiolino, R., Carniani, S., et al. 2018, ArXiv e-prints [arXiv:1805.05352]
Fruchter, A. S. & Hook, R. N. 2002, PASP, 114, 144
Gabor, J. M. & Bournaud, F. 2014, MNRAS, 441, 1615
Glazebrook, K., Schreiber, C., Labbé, I., et al. 2017, Nature, 544, 71
Gallagher, B., De Breuck, C., Vieira, J. D., et al. 2015, MNRAS, 449, 2883
Hailey-Dunsheath, S., Nikola, T., Stacey, G. J., et al. 2010, ApJ, 714, L162
Hopkins, P. F., Hernquist, L., Cox, T. J., & Kereš, D. 2008, ApJS, 175, 356
Ishibashi, W., Fabian, A. C., & Maiolino, R. 2018, MNRAS, 476, 512
Janssen, A. W., Christopher, N., Sturm, E., et al. 2016, ApJ, 822, 43
Kennicutt, R. C. & Evans, N. J. 2012, ARA&A, 50, 531
Kimball, A. E., Lacy, M., Lonsdale, C. J., & Macquart, J.-P. 2015, MNRAS, 452, 88
Kormendy, J. & Ho, L. C. 2013, ARA&A, 51, 51
Maiolino, R., Cox, P., Caselli, P., et al. 2005, A&A, 440, L51
Maiolino, R., Gallerani, S., Neri, R., et al. 2012, MNRAS, 425, L66
McMullin, J. P., Waters, B. D., Schieder, D., Young, W., & Golap, K. 2007, in Astronomical Society of the Pacific Conference Series, Vol. 376, Astronomical Data Analysis Software and Systems XVI, ed. R. A. Shaw, F. Hill, & D. J. Bell, 127
Menci, N., Fioro, F., Puccetti, S., & Cavaliere, A. 2008, ApJ, 686, 219
Neri, R., Downes, D., Cox, P., & Walter, F. 2014, A&A, 562, A35
Papadopoulos, P. P., van der Werf, P., Isaak, K., & Xilouris, E. M. 2010, ApJ, 715, 775
Polletta, M., Tajer, M., Maraschi, L., et al. 2007, ApJ, 663, 81
Roos, O., Juneau, S., Bournaud, F., & Gabor, J. M. 2015, ApJ, 800, 19
Runnoe, J. C., Brotherton, M. S., & Shang, Z. 2012, MNRAS, 422, 478
Rupke, D. S., Veilleux, S., & Sanders, D. B. 2005, ApJS, 160, 115
Tombesi, F., Meléndez, M., Veilleux, S., et al. 2015, Nature, 519, 436
Trakhtenbrot, B., Lira, P., Netzer, H., et al. 2017, ApJ, 836, 8
Venemans, B. P., Walter, F., Decarli, R., et al. 2017, ApJ, 837, 146
Venemans, B. P., Walter, F., Zschaechner, L., et al. 2016, ApJ, 816, 81
Wang, R., Wu, X.-B., Neri, R., et al. 2016, ApJ, 830, 53
Willott, C. J., Bergeron, J., & Omont, A. 2015, ApJ, 801, 123
Willott, C. J., Bergeron, J., & Omont, A. 2017, ApJ, 850, 108
Willott, C. J., Omont, A., & Bergeron, J. 2013, ApJ, 770, 13
Zubovas, K. & King, A. 2012, ApJ, 745, L34

Future deep ALMA follow-up observations will allow us to confirm the presence of [CII] outflows in individual high-z QSOs. Furthermore, the increasing number of available sources on the ALMA archive will increase the statistics, enabling us to reduce the uncertainties on the cold outflows parameters in the early Universe.
Fig. 9. [CII] outflows parameters. (a): mass outflow rate as a function of $L_{\text{AGN}}$ for the different stacked spectra (stars, see legend for details), compared to the sample of 30 low-redshift AGNs from [Fluetsh et al., 2018] for which spatially resolved molecular (blue) and, in one third of the sample, ionised (green) outflows have been observed. We also included the compilation of ionised outflows (hollow green squares) with spatial information in $z \sim 0.1 - 3$ AGN from [Fiore et al., 2017], recomputed according to Eqs. [10]. Purple squares are local systems for which the outflow has been traced in [CII] through observations with the Herschel Space Observatory [Janssen et al., 2016] [Fluetsh et al., 2018]. By applying the atomic-to-molecular outflowing gas mass correction by [Fluetsh et al., 2018], the molecular+atomic mass outflow rates are shown with circles. (b): Outflow velocity as a function of $L_{\text{AGN}}$. (c): Kinetic power as a function of $L_{\text{AGN}}$. The dotted, dashed, solid and dot-dashed curves indicate kinetic powers that are 10%, 1%, 0.1% and 0.01% of the AGN luminosity. (d): Momentum load factor as a function of the outflow velocity. The horizontal line corresponds to $P_{\text{out}} = P_{\text{AGN}}$. 