



The ALMA-CRISTAL Survey: Weak Evidence for Star-formation-driven Outflows in $z \sim 5$ Main-sequence Galaxies

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Abstract

There is a broad consensus from theory that stellar feedback in galaxies at high redshifts is essential to their evolution, alongside conflicting evidence in the observational literature about its prevalence and efficacy. To this end, we utilize deep, high-resolution [C II] emission-line data taken as part of the [C II] resolved interstellar medium (ISM) in star-forming galaxies with the Atacama Large Millimeter/submillimeter Array (CRISTAL) survey. Excluding sources with kinematic evidence for gravitational interactions, we perform a rigorous stacking analysis of the remaining 15 galaxies to search for broad emission features that are too weak to detect in the individual spectra, finding only weak evidence that a broad component is needed to explain the composite spectrum. Additionally, such evidence is mostly driven by CRISTAL-02, which is already known to exhibit strong outflows in multiple ISM phases. Interpreting modest residuals in the stack at $v \sim 300 \text{ km s}^{-1}$ as an outflow, we derive a mass outflow rate of $\dot{M}_{\text{out}} = 26 \pm 11 M_{\odot} \text{ yr}^{-1}$ and a cold outflow mass-loading factor of $\eta_m = 0.49 \pm 0.20$. This result holds for the subsample with the highest star formation rate surface density ($\Sigma_{\text{SFR}} > 1.93 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$), but no such broad component is present in the composite of the lower-star-formation-rate density subsample. Our results imply that the process of star-formation-driven feedback may already be in place in typical galaxies at $z = 5$, but on average are not strong enough to completely quench ongoing star formation.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); Galaxy kinematics (602); High-redshift galaxies (734); Stellar feedback (1602)

1. Introduction

There is a general consensus that stellar feedback is an important component in galaxy formation models, and that such feedback (alongside AGN feedback) plays a key role in regulating the evolution of galaxies and producing the conditions we observe (e.g., A. Dekel & J. Silk 1986). Massive



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stars inject enormous levels of energy into the interstellar medium (ISM) through supernovae and stellar winds, heating the gas and potentially expelling it from the galaxy altogether, with the possibility of later recycling it to drive further star formation (e.g., B. D. Oppenheimer et al. 2010; B. M. B. Henriques et al. 2013; D. Anglés-Alcázar et al. 2017). Such feedback primarily prevents runaway star formation, regulates the metallicity of the galaxy (e.g., C. A. Tremonti et al. 2004; J. J. Dalcanton 2007; K. Finlator & R. Davé 2008; S. J. Lilly et al. 2013; P. Torrey et al. 2019), and enables quenching. This regulation manifests in the observed mass–metallicity relation (e.g., C. A. Tremonti et al. 2004; M. Curti et al. 2020) and fundamental metallicity relation (e.g., J. Lequeux et al. 1979; S. L. Ellison et al. 2008; F. Mannucci et al. 2010). Massive galaxy-scale outflows are one of the most dramatic consequences of feedback, and therefore have a huge influence on the evolution of galaxies. This process should therefore be understood and accurately implemented in theoretical models.

Observationally, outflow signatures have been detected in multiple phases of the ISM, from cool molecular and cold dust components all the way up to hot X-ray-emitting gas (for a review, see, e.g., S. Veilleux et al. 2020). Therefore, there are various observational indicators that can be used to search for outflow signatures. Efforts to detect outflows in galaxies and characterize their effects on the evolution of the host have been ongoing for decades. However, at high redshifts these observational indicators become fainter and much more difficult to detect. Most studies at $z \sim 5$ and beyond have therefore focused on extreme galaxies and/or quasars (e.g., R. Maiolino et al. 2012; C. Cicone et al. 2015; M. Bischetti et al. 2019). In less extreme galaxies, statistical conclusions about the nature and impact of outflows are fewer and further between (although see, e.g., R. L. Davies et al. 2019; N. M. Förster Schreiber et al. 2019; G. C. K. Leung et al. 2019; A. M. Swinbank et al. 2019; A. Weldon et al. 2024, for studies at intermediate redshifts).

At $z \sim 4$ and beyond, the emission line of singly ionized carbon at $158 \mu\text{m}$, [C II] is one of the strongest lines that can be observed, originating primarily from neutral regions but with a nonnegligible contribution from ionized gas (K. V. Croxall et al. 2017; T. Díaz-Santos et al. 2017; D. Cormier et al. 2019). Importantly for studies at $z \sim 4$ –6, this bright line is redshifted into an atmospheric transmission window accessible from the ground by interferometers such as the Atacama Large Millimeter/submillimeter Array (ALMA). As a consequence, the [C II] emission line has been exploited frequently to study outflows in sources at these epochs, most prominently high- z QSOs (e.g., R. Maiolino et al. 2012; C. Cicone et al. 2015; M. Bischetti et al. 2019; M. Novak et al. 2020) but increasingly for star-forming galaxies in recent years (e.g., S. Gallerani et al. 2018; Y. Sugahara et al. 2019; M. Ginolfi et al. 2020; J. S. Spilker et al. 2020; R. Herrera-Camus et al. 2021; K. Kade et al. 2023). On the contrary, the reliability of the [C II] line as a tracer of outflows was questioned by J. S. Spilker et al. (2020), who found no broad [C II] emission in sources displaying clear OH outflows.

A common thread between high-redshift [C II] studies of outflows in QSOs and star-forming galaxies is the lack of a general consensus on their presence, absence, or ubiquity. Several studies of individual QSOs have found evidence for broad wings, such as R. Tripodi et al. (2022), whose study of the $z \sim 6$ QSO SDSS J2310+1855 was also supported by H₂O

emission line observations, and R. Maiolino et al. (2012) who reported an outflow in SDSS J1148+5251 at $z = 6.4189$ (later followed up and corroborated by C. Cicone et al. 2015). This result was later challenged by R. A. Meyer et al. (2022) using new NOEMA data. However, the QSOs studied in those works are extremely bright, making the detection of weaker broad-line components in the line easier than for fainter star-forming galaxies (although, see R. Herrera-Camus et al. 2021, for an example of an outflow detected in an individual star-forming galaxy at $z \sim 5.5$).

As a result of this limitation, authors have resorted to stacking techniques to improve the signal-to-noise ratio (S/N) of their data, in an attempt to detect broad components in fainter sources (e.g., R. Decarli et al. 2018; M. Bischetti et al. 2019; R. L. Davies et al. 2019; F. Stanley et al. 2019; J.-B. Jolly et al. 2020; M. Novak et al. 2020). This method amplifies weak features in the emission but sacrifices information about individual sources, providing only average properties of the sample as a whole. An additional challenge arises from the intrinsic diversity among galaxies, including differences in size, brightness, and kinematics. These variations must be carefully accounted for when combining spectra to avoid skewing the interpretation toward galaxies with more extreme characteristics.

For QSOs, there is a considerable amount of literature on [C II] stacking analyses, but with differing conclusions. M. Bischetti et al. (2019) stacked a sample of 48 $z \sim 4.5$ –7.1 QSOs and found evidence of outflows with velocities $> 1000 \text{ km s}^{-1}$, corresponding to an atomic gas mass outflow rate of $\dot{M} \sim 100$ – $200 M_{\odot} \text{ yr}^{-1}$. In contrast, R. Decarli et al. (2018) stacked the spectra of 27 $z \sim 6$ QSOs and found no such evidence. M. Novak et al. (2020) came to the same conclusion from a uv -plane stack of a similar sample of 27 $z \sim 6$ QSOs (and a further 20 archival sources observed at lower resolution). As outflows are not likely to be isotropic, F. Stanley et al. (2019) tested the effects of orientation on stacking QSO spectra, after themselves finding only tentative evidence for broad emission from a sample of 26 $z \sim 6$ QSOs.

The various studies employ subtly different techniques, making it difficult to compare and to determine which are most likely to be accurate. Nevertheless, studies of high-redshift star-forming galaxies, particularly those on the star formation “main sequence,” are heavily reliant on stacking simply because the sources are fainter.

In one of the most ambitious attempts to characterize the typical galaxy population at $z \sim 5$, the ALMA Large Program to INvestigate [C II] at Early times (ALPINE; PI Le Fèvre; M. Béthermin et al. 2020; A. L. Faisst et al. 2020; O. Le Fèvre et al. 2020) detected 75 galaxies in [C II] emission, which was later exploited by M. Ginolfi et al. (2020, hereafter G20) to examine outflows at this epoch. G20 carried out a stacking analysis using 50 galaxies from the ALPINE sample, excluding 25 sources morpho-kinematically identified as mergers. They tested three different techniques: stacking the residuals from single-Gaussian fits to the data, stacking the [C II] spectra, and stacking the cubes. They also binned their sample by star formation rate, finding only the composite of galaxies with higher star formation rates to display broad emission, and interpreted this as evidence for star formation driven outflows. This followed a similar analysis by S. Gallerani et al. (2018) of nine $z \sim 5.5$ galaxies, which showed flux excess in the combined residuals extended over $\sim 1000 \text{ km s}^{-1}$.

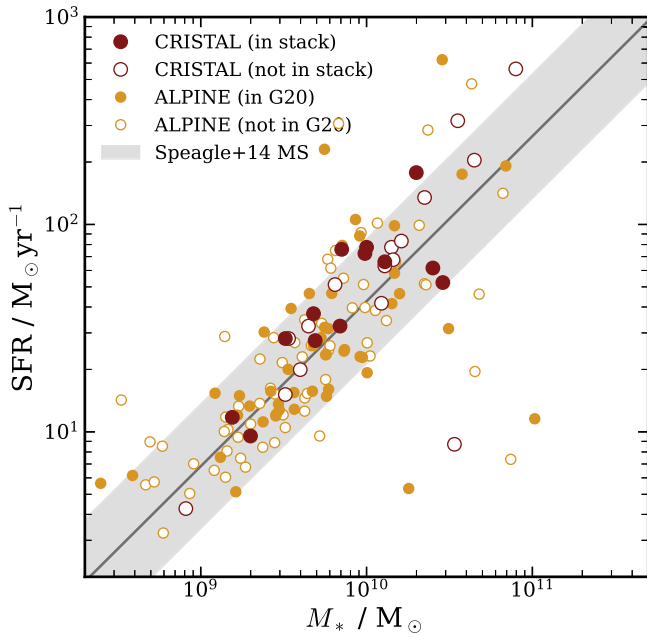


Figure 1. Star formation rate (SFR) as a function of stellar mass for the CRISTAL sample (red) along with its parent sample, ALPINE (yellow). The subset of ALPINE galaxies used in the G20 stack are shown as filled circles. The ALPINE sample was selected to represent sources that are close to the star-forming main sequence (shown for $z=5$ in gray for the J. S. Speagle et al. 2014 prescription).

The work of the ALPINE survey has been naturally extended through the [C II] Resolved ISM in Star-forming Galaxies with ALMA (CRISTAL; R. Herrera-Camus et al. 2025) Large Program that has provided higher spatial resolution (by over a factor of 2 on average) [C II] data of a subsample of ALPINE galaxies, in addition to a supplementary six literature galaxies. The latter includes some galaxies from the samples studied by S. Gallerani et al. (2018) and Y. Sugahara et al. (2019). The deeper data should make it easier to detect outflows, if they exist, and the higher angular resolution will enable us to more robustly identify mergers, and to spatially resolve any outflows that are present on smaller scales.

In this work, we present a stacking analysis of the CRISTAL data, with the aim of building upon the work of G20. The outline of this paper is as follows: in Section 2 we describe the observations carried out along with our data reduction methods, and in Section 3 we describe our analysis of the reduced data. In Section 4 we present the results, and in Section 5 we discuss their implications. In Section 6 we summarize our findings. Throughout this paper, we adopt a flat Λ cold dark matter cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2. Observations and Data Reduction

2.1. The CRISTAL Survey

We utilize Band 7 data from CRISTAL, an ALMA Cycle-8 Large Program (project ID 2021.1.00280.L; PI: R. Herrera-Camus), which is designed to provide spatially resolved [C II] and $158 \mu\text{m}$ dust continuum maps of main-sequence galaxies at $z \sim 5$. The CRISTAL sample consists of 25 main-sequence galaxies at $z \sim 4.4\text{--}5.7$, which were selected from the ALPINE sample (project ID 2017.1.00428.L; PI: O. Le Fèvre) to have

existing rest-frame UV and/or optical Hubble Space Telescope detections, stellar masses greater than $10^{9.5} M_\odot$, and specific star formation rates differing from that of the $z=5$ main sequence by no more than a factor of 3. Figure 1 shows both the ALPINE and CRISTAL samples in the stellar mass-SFR plane, with the sources used in G20 and this work highlighted, respectively. We note that CRISTAL-09b and CRISTAL-23c do not have available spectral energy distribution (SED) fits and are therefore not shown in Figure 1. To account for this in our analysis, we assign them the median M_* and SFR of the remaining 13 galaxies.

The CRISTAL sample comprises 19 ALPINE sources (O. Le Fèvre et al. 2020) along with a further six galaxies in the COSMOS field (HZ4, HZ7, HZ10, DC818760, DC873756, and VC8326), that have ALMA data with similar spatial resolutions and sensitivities as CRISTAL (2018.1.01359.S and 2019.1.01075.S; PI: Manuel Aravena, 2018.1.01605.S; PI: Rodrigo Herrera-Camus, 2019.1.00226.S; PI: Edo Ibar). In the 25 fields observed as part of this sample, a total of 37 galaxies were identified by either resolving the main target into multiple objects or serendipitously detecting other sources. R. Herrera-Camus et al. (2025) presents details of the survey design and observational setup. For this work, we conservatively removed 22 sources that resembled mergers or have significantly disturbed kinematics based on the classification by L. Lee et al. (2025, in preparation; and see Section 3.1), leaving a final sample size of 15 galaxies. The IDs, coordinates, redshifts, star formation rates, and stellar masses of the remaining 15 CRISTAL sources are shown in Table 1.

2.2. ALMA Band 7 Data Reduction

The CRISTAL and ALPINE archival observations were taken using ALMA Band 7, targeting the [C II] line ($\nu_{\text{rest}} = 1900.54 \text{ GHz}$). To detect the targets, ALPINE observations were taken using the most compact configurations (typically C43-1/2), which achieved an average beam size of $0.85 \times 1.13''$ (O. Le Fèvre et al. 2020). As one of the main goals of CRISTAL is to spatially resolve the [C II] emission, the new observations utilize more extended configurations (typically C43-4/5; beam sizes $0.1\text{--}0.3''$) with the existing compact-configuration data being used to capture large-scale structures, such as extended [C II] line emission (more details in R. Herrera-Camus et al. (2025); also see R. Ikeda et al. 2025).

To achieve greater depths, the CRISTAL team combined the ALPINE and CRISTAL raw observations and re-processed them consistently, imaging the visibilities using both natural and Briggs (robust = 0.5) weighting. In this work, we utilize the natural-weighted data to maximize our sensitivity to weak outflow features. The median sensitivity achieved is 0.22 mJy in 20 km s^{-1} channels, and the median synthesized beam FWHM is $0.46 \times 0.40''$ ($2.9 \times 2.5 \text{ kpc}$).

3. Analysis

3.1. Removing Potential Mergers from the Sample

The spectra of merging galaxies can blend multiple velocity components, from the interacting sources, disturbed gas kinematics, and the presence of tidal tails. Ultimately, this results in broader spectral features, which can mimic the appearance of feedback-driven outflows. Therefore, failing to account for mergers can bias the interpretation of broad

Table 1
Basic Properties for the 15 [C II]-detected Galaxies Used in This Work

CRISTAL ID	Alternate ID	R.A. (J2000)	Decl. (J2000)	$z_{[\text{C II}]}$	$\log_{10}(\text{SFR})$ ($M_{\odot} \text{ yr}^{-1}$)	$\log_{10}(M_{*})$ ($M_{\odot}$)
Sources included in G20 composite						
CRISTAL-08	vuds_efdc5_530029038	03:32:19.03	−27:52:37.6	4.430	1.88 ± 0.23	9.85 ± 0.36
CRISTAL-09a	DEIMOS_COSMOS_519281	09:59:00.89	+02:05:27.6	5.575	1.51 ± 0.32	9.84 ± 0.39
CRISTAL-11	DEIMOS_COSMOS_630594	10:00:32.59	+02:15:28.4	4.439	1.57 ± 0.31	9.68 ± 0.33
CRISTAL-12	CANDELS_GOODSS_21	03:32:11.95	−27:41:57.5	5.572	0.98 ± 0.40	9.30 ± 0.47
CRISTAL-19	DEIMOS_COSMOS_494763	10:00:05.11	+02:03:12.2	5.233	1.45 ± 0.36	9.51 ± 0.36
Sources not included in G20 composite						
CRISTAL-02	DEIMOS_COSMOS_848185	10:00:21.50	+02:35:11.0	5.294	2.25 ± 0.42	10.30 ± 0.28
CRISTAL-03	DEIMOS_COSMOS_536534	09:59:53.26	+02:07:05.5	5.689	1.79 ± 0.31	10.40 ± 0.29
CRISTAL-06b	...	10:01:01.00	+01:48:34.9	4.562	1.07 ± 0.33	9.19 ± 0.46
CRISTAL-07a	DEIMOS_COSMOS_873321	10:00:04.06	+02:37:35.8	5.154	1.89 ± 0.26	10.00 ± 0.33
CRISTAL-09b	...	09:59:00.78	+02:05:26.9	5.577	− ± −	− ± −
CRISTAL-10a	DEIMOS_COSMOS_417567	10:02:04.13	+01:55:44.4	5.671	1.86 ± 0.20	9.99 ± 0.31
CRISTAL-15	vuds_cosmos_5101244930	10:00:47.66	+02:18:02.2	4.580	1.44 ± 0.24	9.69 ± 0.33
CRISTAL-20	HZ4	09:58:28.52	+02:03:06.7	5.545	1.82 ± 0.28	10.11 ± 0.35
CRISTAL-23b	...	10:01:54.97	+02:32:31.5	4.562	1.72 ± 1.33	10.46 ± 0.24
CRISTAL-23c	...	10:01:54.68	+02:32:31.4	4.565	− ± −	− ± −

Note. Stellar masses and star formation rates are estimated from spectral energy distribution (SED) fitting with CIGALE, taken from I. Mitsuhashi et al. (2024). We divide the table into those included in, and excluded from, the G20 composite. CRISTAL-09b and CRISTAL-23 c do not have available SED fits; therefore, for the remainder of the analysis, we adopt the median M_{*} and SFR of the rest of the sample in these two cases.

emission, attributing it to outflows when it may simply reflect the dynamics of the merger. This demands a conservative approach to our analysis. G20 identified possible mergers in their sample using the morpho-kinematic classification of ALPINE galaxies by O. Le Fèvre et al. (2020). However, as previously discussed, the angular resolution of the CRISTAL data is over twice as high as the ALPINE data, providing a new opportunity to examine which sources are likely to be mergers with higher precision.

A kinematic analysis of the full CRISTAL sample will be provided in L. Lee et al. (2025, in preparation), and their classifications inform our choices of which sources to include. More specifically, they classified the CRISTAL galaxies as either disk-like, with types “Best disk” and “Disk,” or nondisk. Their classification is based on a combination of kinemetry to identify deviations from orderly velocity gradients and asymmetries in the velocity/velocity dispersion maps, and spectro-astrometry to identify distinct components by utilizing the full 3D information from the cubes.

The “Best disk” category comprises isolated sources with no visible neighbors or signs of perturbations; and the “Disk” category comprises sources that exhibit disk-like kinematics, with minor perturbations in their outskirts. Therefore, there remain sources in the “Disk” category that are interacting with a nearby companion, most prominently CRISTAL-07a and CRISTAL-23b (see Figure 2). Further, separate analyses of CRISTAL-05 and CRISTAL-22 have been presented by A. Posses et al. (2024) and K. Telikova et al. (2024), both of which appear to show complex kinematics.

Considering the above, we retain the 15 sources that are classified as “Best disk” and “Disk” sources from L. Lee et al. (2025, in preparation). Based on the analysis by L. Lee et al. (2025, in preparation), we do not expect interacting sources in the “Disk” category to contribute substantial high-velocity emission originating from these interactions to the stack, hence their inclusion. We remove the sources classified as nondisks,

which lack disk-like characteristics and potentially include both major mergers and poorly resolved sources. We also conservatively remove CRISTAL-05 and CRISTAL-22 due to their complex kinematics. While this approach limits the S/N improvement achieved by stacking, it is a necessary concession to ensure that our conclusions are unbiased. The final sample is shown in Table 1, where we separate sources that were included in/excluded from the G20 stack (see also Figure 1). Interestingly, two-thirds of our sample were excluded by G20 on the basis of their morpho-kinematic analysis. This highlights how the differing resolution of the ALPINE and CRISTAL data sets can affect the interpretation of the same parent sample.

3.2. Spectral Extraction

For the finalized sample of 15 CRISTAL galaxies, we produce [C II] line maps by collapsing the continuum-subtracted cubes within ± 1 FWHM_[C II] of the [C II] redshift (so as to ensure full coverage of the [C II] emission; FWHM_[C II] measured by R. Herrera-Camus et al. (2025), in a $4'' \times 4''$ window centered on the source position. These are shown in Figure 2, in which we can clearly see the morphological complexity of many of the galaxies. This makes simple circular or elliptical apertures less effective for extracting spectra than it would be for pointlike sources. Therefore, for each line map, we generate a mask for all pixels with flux density exceeding 2σ , and sum all emission within the mask to extract 1D spectra for each source. To quantify the uncertainty on the flux densities, we mask channels in the 1D spectra that are within ± 1 FWHM_[C II] of the line centroid, and calculate the rms of the remaining channels (i.e., the signal-free part of the spectrum).

A visual inspection of the spectra (see Figures 3–6 alongside the composites; Section 4) shows that some of the line profiles are complex, with a handful appearing asymmetric. In these cases, fitting Gaussian profiles would not give a representative

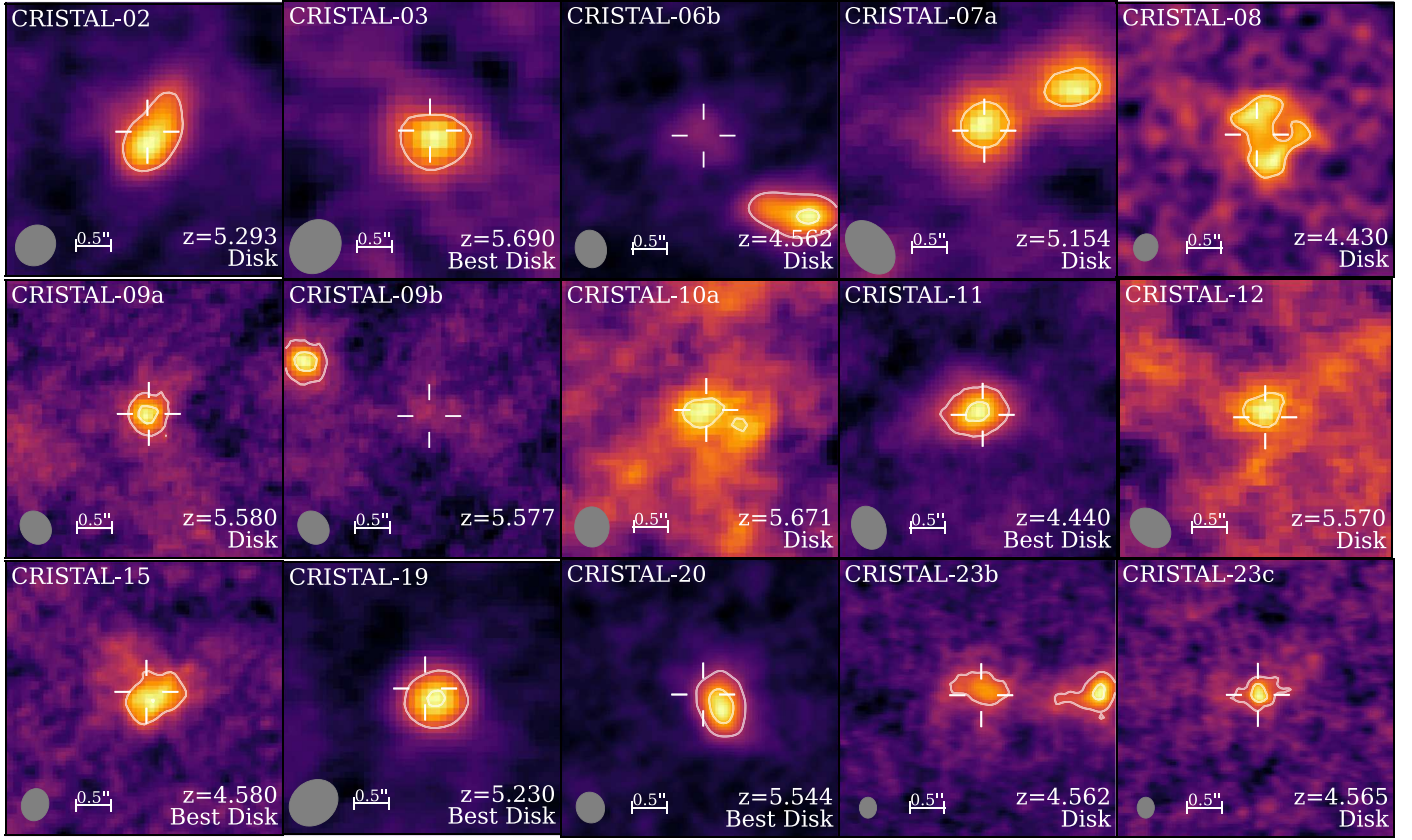


Figure 2. $4'' \times 4''$ [C II] line maps for the 15 CRISTAL galaxies that are included in the main composite. Maps are generated by collapsing the data cubes across channels spanning ± 1 FWHM_[C II] of the [C II] emission line, using the values from R. Herrera-Camus et al. (2025). The contours show [C II] emission at 2σ and above (increasing in 1σ increments). The ALMA synthesized beam is shown in the bottom-left corner of each panel. The kinematic classifications of L. Lee et al. (2025, in preparation) are shown in the bottom-right corner of each panel (CRISTAL-09b was not included in that analysis and is therefore not classified).

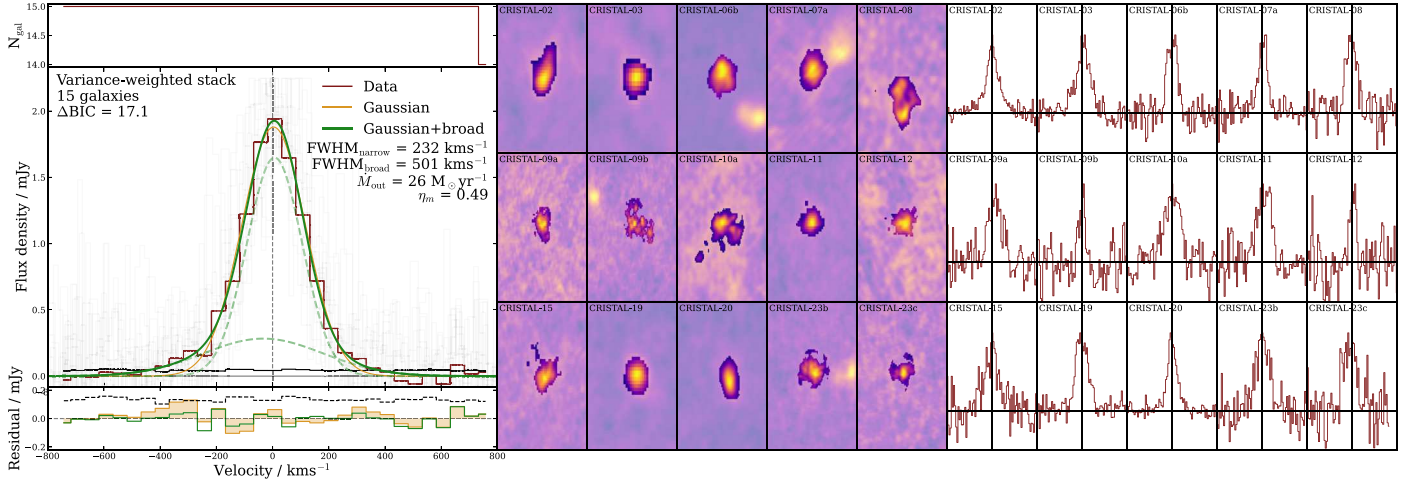


Figure 3. Left panel: stack of the colored regions in the [C II] line maps (red) at 50 km s^{-1} resolution, with both single- (yellow) and double-Gaussian (green) models overlaid. We also decompose the double-Gaussian model into its individual components (green dashed). The individual spectra of the galaxies used in the stack are shown as the faded gray lines. The top panel shows the number of galaxies that contribute to each velocity bin, while the bottom panel shows the residuals from both fits. In the bottom panel, the dashed black line shows the 3σ uncertainty. In this case, the Bayesian information criterion (BIC) test described in Section 3.4 indicates that a broad component is necessary to model the composite emission line. Center panel: [C II] emission-line maps for all CRISTAL galaxies, with bold colored regions indicating the areas from which spectra were extracted. Right panel: individual spectra used in the stack, at 20 km s^{-1} resolution.

model of the [C II] emission, and in general, we prefer to derive the zeroth, first, and second moments of the spectra to estimate line fluxes, centroids and line widths, respectively (e.g., J. E. Birkin et al. 2021). This is particularly important in deriving the velocity centroid, which must be done correctly to

center each emission line before the stack. If the line centers are not aligned before stacking, this could falsely induce broad features in the composite.

We note that uncertainties on the emission centroids were not explicitly included in our analysis. These centroid uncertainties

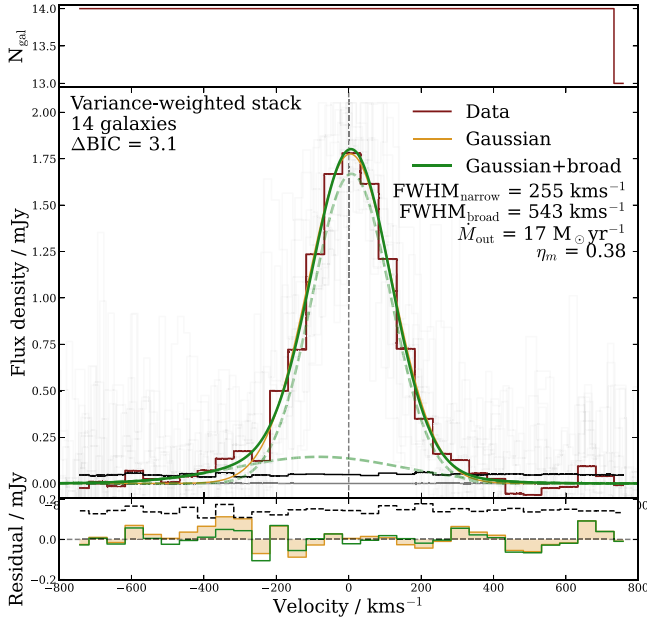


Figure 4. Stack of the same galaxies as shown in Figure 3 except for CRISTAL-02, which has been removed. Given the strong outflows already detected in this source, we test to see how much it drives our results. In this case, the BIC test described in Section 3.4 indicates that a broad component is only marginally significant in the composite spectrum. This would suggest that the outflow components observed in Figures 3 and 6 are largely driven by this individual source.

were found to be small ($<20 \text{ km s}^{-1}$ for the entire sample), substantially smaller than the measured line widths (median 260 km s^{-1}). Nevertheless, to confirm that these uncertainties do not influence our results, we incorporated centroid errors into the Monte Carlo uncertainty analysis described above. We found that our conclusions remained unchanged.

As the S/N of the individual spectra are modest, median $\text{S/N} = 14 \pm 3$, when deriving moments, we first fit an approximate Gaussian to the line profile to establish the FWHM, and then only use channels between $\pm 1.5 \times$ the FWHM of the Gaussian to mitigate the influence of the continuum on the measured centroid (J. E. Birkin et al. 2021). For the 15 CRISTAL galaxies used in the stack, we measure a median $\text{FWHM}_{[\text{C II}]} = 260^{+50}_{-80} \text{ km s}^{-1}$, where the uncertainties reflect the 16th–84th percentile scatter in the sample. To prepare the individual spectra for stacking, we shift each velocity axis by a value equal to the first moment.

3.3. Stacking Analysis

To combine the individual spectra, we sum the flux density in each channel, weighted by the uncertainty σ (as calculated in Section 3.2) as:

$$S_i^{\text{stack}} = \frac{\sum_{k=1}^N S_{i,k} \times w_k}{\sum_{k=1}^N w_k}, \quad (1)$$

where S and $w = 1/\sigma^2$ are the flux density and corresponding weight, i represents the channel index, and k represents the source index (M. Ginolfi et al. 2020). We sample the composite in bins of 50 km s^{-1} , ensuring that each bin contains a reasonable number of channels from the original 20 km s^{-1} data. To estimate the uncertainty in each composite channel, we perturb each flux density value by a random

multiple of its associated error (sampled from the normal distribution) 100 times, then calculate the rms of the resultant values.

It is not obvious what the “correct” method of normalizing the sample is, given the variety of properties, and therefore we attempt several methods:

1. *No normalization.* Purely stacking the spectra as they are. This method aligns most closely with that used by G20.
2. *Scaling the line width by the median.* It has been shown by J.-B. Jolly et al. (2020) that stacking lines with different widths results in a non-Gaussian composite. Therefore, we measure the FWHM of each line profile from the second moment, and then stretch the emission line from each source to match the median of the sample, $\text{FWHM}_{\text{med}} = 260 \text{ km s}^{-1}$, following R. Decarli et al. (2018) and M. Novak et al. (2020). The resultant factors applied to the individual spectral axes are all in the range 0.8–2.0.
3. *Scaling the line width by the median and normalizing the flux density to ensure that the total integrated flux across the emission line is conserved.* Expanding on method 2, but now also adjusting the flux density by the same factor as the line width, so that the total integrated flux is conserved. This method should give less weight to brighter sources.
4. *Scaling the line width to match the median and adjusting the flux density by the peak value.* Similar to method 3, but we instead divide each spectrum by the peak emission flux density. This ensures that we are purely considering the profile of the emission lines. The resultant factors applied to the individual flux densities are all in the range 0.5–5.4.

We perform tests of these four methods to ensure that we understand how they affect our conclusions, which we present in Section 4.3. However, for the analysis presented in the rest of this paper, we mainly utilize the composites derived using method 4.

3.4. Line Fitting

Having produced composite spectra, we search for broad components that may indicate outflows. To do so, we fit two models to the $[\text{C II}]$ emission line, using the Markov Chain Monte Carlo ensemble sampler emcee (D. Foreman-Mackey et al. 2013). The first is a simple single-Gaussian model with free parameters amplitude, mean, and sigma. The second is a double-Gaussian model, one narrow and one broad, each with the same three free parameters. However, in the double-Gaussian model, we place a number of constraints on these parameters:

1. The narrow FWHM is constrained to be between 80 km s^{-1} and 400 km s^{-1} , and the broad FWHM is constrained to be between 400 km s^{-1} and 1500 km s^{-1} ;
2. The central wavelengths of both lines are constrained to be within $\pm 200 \text{ km s}^{-1}$ of the systemic redshift;
3. The narrow amplitude is constrained to be at least twice the broad amplitude (S. Carniani et al. 2024);
4. The broad FWHM is constrained to be at least $1.2 \times$ the narrow FWHM (S. Carniani et al. 2024).

To statistically conclude whether or not broad components are necessary to describe our stacks, we implement a Bayesian

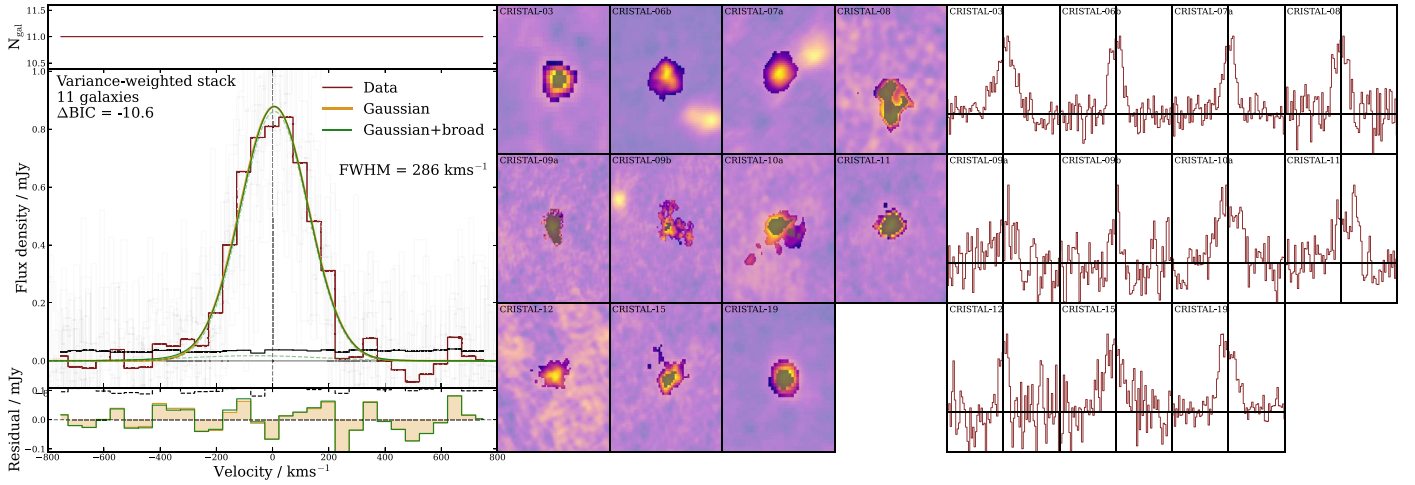


Figure 5. The same as Figure 3, but only including regions of the sample with $\Sigma_{\text{SFR}} < 1.93 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$. The composite is well modeled by a single-Gaussian function.

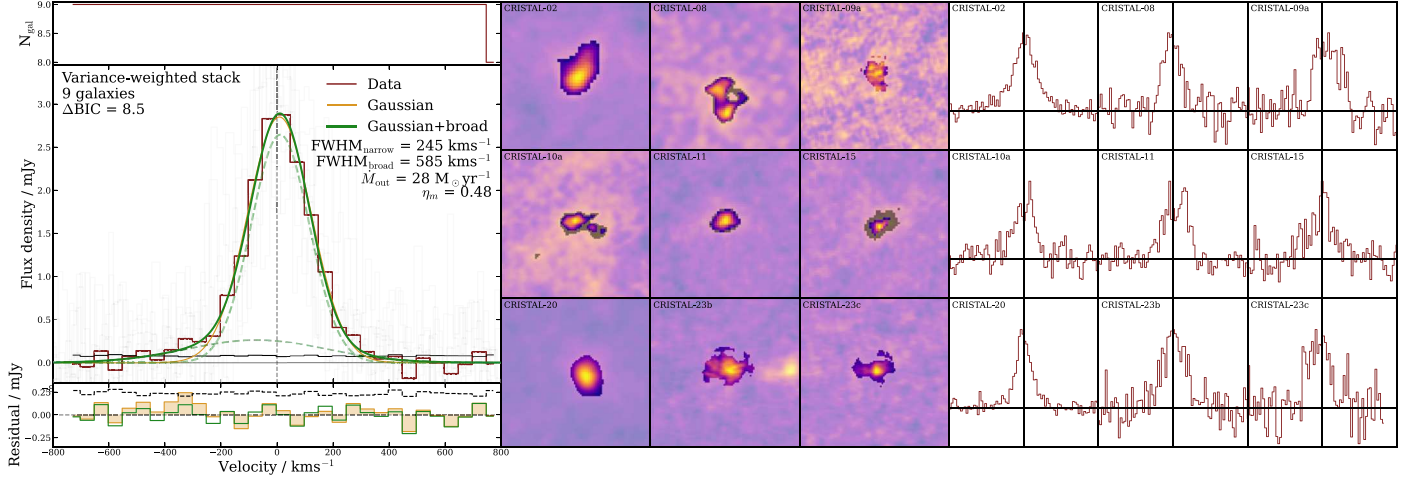


Figure 6. The same as Figure 3, but only including regions of the sample with $\Sigma_{\text{SFR}} > 1.93 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$. With $\Delta\text{BIC} = 9$, the composite requires a broad component to fully describe the emission.

information criterion (BIC) test. Measured as $\text{BIC} = \chi^2 + k \log n$, where χ^2 is the chi-squared value of the model, k is the number of parameters in the model, and n is the number of data points used in the fit, the BIC punishes the model if using many parameters to obtain a good fit. This allows us to quantitatively decide whether adding an additional model component to describe an outflow provides a statistically better description of the data to justify the extra parameters, based on the difference in BIC between the single- and double-Gaussian models, calculated as $\Delta\text{BIC} = \text{BIC}_{\text{single}} - \text{BIC}_{\text{double}}$. Although the ΔBIC test does not give a statistical significance such as a p -value, the general rule of thumb is that $\Delta\text{BIC} > 10$ represents overwhelming evidence for the model with the lowest BIC. In our analysis, we will measure outflow properties if the $\Delta\text{BIC} > 0$, but require $\Delta\text{BIC} > 10$ to securely reject the null hypothesis that the composite [C II] emission is satisfactorily described by a single Gaussian (A. M. Swinbank et al. 2019; C. R. Avery et al. 2021; A. Concas et al. 2022; A. Weldon et al. 2024).

We note that this choice of $\Delta\text{BIC} = 10$ is not a perfect one, in the context of fitting outflows (B. Reichardt Chu et al. 2025), and it was mostly made to ensure comparability with

other similar studies. For full transparency, we include the measured ΔBIC values with our results, and it is left up to the reader to make their own conclusions about the significance of these results.

3.5. Bootstrap/Jackknife Resampling Tests

Previously, we have aimed to remove any obvious individual sources that may mimic outflows in the sample (see Section 3.1). However, we still wish to test whether any of the remaining galaxies could potentially bias our conclusions. For example, CRISTAL-02 is known to drive a powerful outflow from its central regions (R. Davies et al. 2025, in preparation). To account for this, we perform a bootstrap test by resampling with replacement. For each composite, we create 100 resampled sets by randomly selecting from the included galaxies, and then apply the BIC test described in Section 3.4. Further, we perform a separate stack of the full sample without CRISTAL-02, the individual CRISTAL galaxy with the most obvious outflow (R. Davies et al. 2025, in preparation), reducing the sample size to 14. We discuss the results of these tests in Section 4.

4. Results

4.1. Global Stacks

We stack the integrated spectra of all 15 [C II]-detected CRISTAL disk-like galaxies using method 4 (see Section 3.3), the result of which is shown in Figure 3. The majority of the individual line profiles, also shown in Figure 3, do not reveal any obvious outflow signatures, although the double-Gaussian fit appears to better match the outer parts of the composite profile. This can be seen in the single-Gaussian residuals, which show a feature at $\sim -300 \text{ km s}^{-1}$ that is not present in the double-Gaussian model. Indeed, we find $\Delta\text{BIC} = 17$ for the composite indicating that the double-Gaussian model is preferred, which has $\text{FWHM}_{\text{narrow}} = 232 \pm 13 \text{ km s}^{-1}$ and $\text{FWHM}_{\text{broad}} = 501 \pm 62 \text{ km s}^{-1}$. Stacks of the residuals from single-Gaussian fits to each source were found to be consistent with the residuals shown in Figure 3.

Applying the bootstrap test described in Section 3.5, we find that in 55% of cases, broad emission is identified, with only 8% of all cases having $\Delta\text{BIC} > 10$. This implies that a small number of sources, likely including CRISTAL-02, are significantly influencing the need for a broad component when modeling the stacked spectra. Indeed, when purposefully removing CRISTAL-02 from the stack, we find $\Delta\text{BIC} = 3.1$ (shown in Figure 4). Given this result, and the relatively low δb_{ic} , we choose to interpret our global composite as providing only modest support for outflows.

4.2. Resolved Composites

One of the key results obtained by G20 showed that outflows are only present in the stacks of ALPINE galaxies with higher global star formation rates. Other authors have found a similar result (see, e.g., N. M. Förster Schreiber et al. 2019; A. M. Swinbank et al. 2019). This was shown by dividing the sample into low-SFR and high-SFR bins and stacking the resultant subsets. However, in reality, outflows likely occur in specific regions of galaxies rather than uniformly (R. Genzel et al. 2011; S. F. Newman et al. 2012; R. L. Davies et al. 2019).

To test these findings, we build on the G20 result by leveraging the improved resolution of CRISTAL to focus on stacking only resolved low- and high- Σ_{SFR} galaxy regions across the sample. To split the sample into low- and high- Σ_{SFR} galaxy regions, we first convert all (2σ -masked) [C II] maps to Σ_{SFR} maps using the average $L_{[\text{C II}]}$ -SFR trend of G. Lagache et al. (2018):

$$\log\left(\frac{L_{[\text{C II}]}}{L_{\odot}}\right) = (1.4 - 0.07z) \\ \times \log\left(\frac{\text{SFR}}{M_{\odot} \text{ yr}^{-1}}\right) + 7.1 - 0.07z, \quad (2)$$

and dividing by the pixel area in kpc^2 . At this point, each spatial pixel has a corresponding value of Σ_{SFR} . We then choose the median value of all pixels, $\Sigma_{\text{SFR}} = 1.93 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, as the boundary between low- and high- Σ_{SFR} galaxy regions. In this regard, low- and high- Σ_{SFR} are meant not in the absolute sense, but in relation to the sample as a whole. Using data from the SINS/zC-SINF of $z \sim 2$ galaxies, S. F. Newman et al. (2012) identified a threshold of $\Sigma_{\text{SFR}} = 1 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ above which strong

outflows occurred in their sample. As our threshold between low- and high- Σ_{SFR} is higher than this, in theory, we should see outflows in both samples, but in reality, our threshold is dependent on our choice of $L_{[\text{C II}]}$ -SFR calibration. Given this uncertainty, we prefer to interpret the results of stacking the low- and high- Σ_{SFR} subsets in isolation to search for a trend of outflows with Σ_{SFR} , rather than comparing to other studies.

Some galaxies naturally will have pixels that fall into both subsamples, e.g., CRISTAL-08. We impose an additional requirement that to include a galaxy in the low/high- Σ_{SFR} subsample, the number of pixels that fall below/above the Σ_{SFR} threshold must be greater than the number of the pixels within the synthesized beam. This is to ensure that the summed spectra have adequate S/N to be used in the stack. The regions of each [C II] map that are classified as low- Σ_{SFR} and high- Σ_{SFR} are highlighted in Figures 5 and 6.

Figure 5 shows the composite of all regions of the sample with $\Sigma_{\text{SFR}} < 1.93 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$, which includes 11 of the 15 galaxies used in the previous stack. Contrary to Figure 3, we see no evidence for broad components in this composite, with the residuals appearing random for both models and $\Delta\text{BIC} = -11$. On the other hand, Figure 6 shows the composite of all regions of the sample with $\Sigma_{\text{SFR}} > 1.93 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$. This sample includes 9 of the original 15 sources, including CRISTAL-02, which shows a strong broad feature in its integrated spectrum (R. Davies et al. 2025, in preparation). This composite spectrum displays a broad feature with $\text{FWHM}_{\text{narrow}} = 245 \pm 11 \text{ km s}^{-1}$ and $\text{FWHM}_{\text{broad}} = 585 \pm 76 \text{ km s}^{-1}$, broader than the full-sample stack but still consistent within the uncertainties. As with the full-sample stack, the combined residuals from single-Gaussian fits to each were consistent with the residuals from fitting a single-Gaussian model to both the low- Σ_{SFR} and high- Σ_{SFR} samples. We note that it is entirely possible that this observation, namely the higher significance of broad emission in the low- Σ_{SFR} sample, is simply due to the [C II] emission being brighter in those galaxies (as a result of using [C II] to trace SFR). This would make any fainter broad emission easier to detect. Despite this, the low- Σ_{SFR} and high- Σ_{SFR} stacks have similar S/Ns, 39 and 37, respectively. Therefore, both stacks should have a similar ability to yield broad-line detections.

We conducted a similar test by dividing each galaxy into inner and outer regions. This division was achieved by sorting flux density values into two bins on a source-by-source basis, with the fainter bin representing the outer regions, and the brighter bin corresponding to the inner regions. We visually inspected the resulting masks to ensure this division was accurate. In doing so, we found statistically moderate evidence of broad emission in the inner regions ($\Delta\text{BIC} = 5.1$), but not in the outer regions, as shown in Figures 11 and 12. This suggests that outflows predominantly originate from the center of the galaxy (which are also generally the regions with the highest Σ_{SFR}).

4.3. Effects of Using Different Stacking Methods

As discussed in Section 3.3, we chose to test four different methods of normalization when stacking the CRISTAL spectra. The main aim of this test is not to show which method is best, but to characterize how the results vary depending on the choice of normalization. As our goal is to analyze the line profiles in our sample, we have chosen to focus on presenting and analyzing the method 4 stacks, in

Table 2

Properties of Each Stacking Subsample: The Number of Galaxies in the Sample, the Median Redshift, Star Formation Rate and Stellar Mass, the Difference in BIC for Single- and Double-Gaussian Models and Corresponding Conclusion on Model Preference, and the Narrow and Broad Line Widths

Sample	N_{gal}	z_{med}	SFR_{med} ($M_{\odot} \text{ yr}^{-1}$)	$M_{*,\text{med}}$ ($10^9 M_{\odot}$)	$\Delta(\text{BIC})$	Result	$\text{FWHM}_{\text{narrow}}$ (km s^{-1})	$\text{FWHM}_{\text{broad}}$ (km s^{-1})
Method 1: No FWHM normalization, no flux normalization								
Full sample	15	5.230	52^{+24}_{-26}	7^{+13}_{-4}	0.4	<i>Double</i>	229 ± 12	543 ± 71
Low-SFR	11	5.230	35^{+40}_{-16}	6^{+4}_{-3}	-8.8	Single	293 ± 14	
High-SFR	9	4.580	59^{+17}_{-26}	8^{+11}_{-3}	8.2	<i>Double</i>	219 ± 14	492 ± 49
Method 2: FWHM normalization, no flux normalization								
Full sample	15	5.230	52^{+24}_{-26}	7^{+13}_{-4}	-2.3	Single	268 ± 8	
Low-SFR	11	5.230	35^{+40}_{-16}	6^{+4}_{-3}	-10.9	Single	297 ± 18	
High-SFR	9	4.580	59^{+17}_{-26}	8^{+11}_{-3}	-1.3	Single	250 ± 10	
Method 3: FWHM normalization, flux conservation								
Full sample	15	5.230	52^{+24}_{-26}	7^{+13}_{-4}	-7.7	Single	276 ± 11	
Low-SFR	11	5.230	35^{+40}_{-16}	6^{+4}_{-3}	-11.1	Single	289 ± 17	
High-SFR	9	4.580	59^{+17}_{-26}	8^{+11}_{-3}	-0.2	Single	256 ± 7	
Method 4: FWHM normalization, flux normalization								
Full sample	15	5.230	52^{+24}_{-26}	7^{+13}_{-4}	17.1	Double	232 ± 13	501 ± 62
Low-SFR	11	5.230	35^{+40}_{-16}	6^{+4}_{-3}	-10.6	Single	286 ± 19	
High-SFR	9	4.580	59^{+17}_{-26}	8^{+11}_{-3}	8.5	<i>Double</i>	245 ± 11	585 ± 76

Note. Quoted uncertainties on the median SFR and M_* are the 16th–84th percentile ranges. In the result column, “double” is printed in italics if $0 < \Delta\text{BIC} < 10$ (indicating marginal broad emission) and in bold if $\Delta\text{BIC} \geq 10$ (indicating significant broad emission).

which all lines are normalized to the same width and peak flux density. Indeed, we have already shown the results of the method 4 stacks, in which we find only moderate evidence for broad wings in the integrated spectrum of the entire sample and in the high- Σ_{SFR} regions of the sample (predominantly the central regions). Here, we provide and compare the individual results for all four methods, which are shown in Table 2.

If we stack the spectra purely as they are extracted with no changes (method 1), we see moderate evidence for broad emission in both the full sample and high- Σ_{SFR} sample. This makes sense, as not normalizing the line widths can artificially introduce broad features (J.-B. Jolly et al. 2020). In this stack, the full sample shows $\text{FWHM}_{\text{broad}} = 543 \pm 71 \text{ km s}^{-1}$ (broader than using method 4).

After normalizing the line widths, this evidence disappears without any flux normalization (method 2). In this case, we would expect any real broad emission to be more clearly distinguished. The broad emission also remains absent when peak flux is multiplied to conserve the total flux (method 3), a method that should reduce the impact of the brighter sources in the sample. The fact that method 4 gives the clearest indication of broad emission in the stack is interesting because this method gives equal weight to all sources and would therefore imply that there is a real underlying broad signal in the full sample. However, it is also very possible that the low S/N of this data is the cause of this result, and the impact of removing CRISTAL-02 from the sample reinforces this idea.

4.4. Comparisons with G20 Analysis

The detection of broad [C II] emission in high-redshift galaxies offers a potential signature of large-scale outflows driven by star formation. In a key study, G20 stacked the global [C II] spectra of 50 ALPINE galaxies and found that the

composite spectrum is best described by the sum of a narrow Gaussian with $\text{FWHM}_{\text{narrow}} = 233 \pm 15 \text{ km s}^{-1}$ and a broad Gaussian with $\text{FWHM}_{\text{broad}} = 531 \pm 90 \text{ km s}^{-1}$. They also found even broader emission when stacking only galaxies with SFRs above the sample median.

The G20 analysis has informed the work presented in this paper, but there are a number of important differences between the two projects, most notably in the data quality. The CRISTAL data used in this study has a median synthesized beam FWHM of $0''.46 \times 0''.40$, over a factor of 2 improvement on the ALPINE data, which has a median of $0''.85 \times 1''.13$ (O. Le Fèvre et al. 2020). Therefore, our data probe scales of $\sim 3.9 \text{ kpc}$ at $z = 5$, whereas for G20, this value is $\sim 9.1 \text{ kpc}$. This finer resolution enables us to better resolve the internal kinematics of galaxies and mitigate the effects of beam smearing, which can artificially broaden line profiles. Indeed, five sources classified as interacting by L. Lee et al. (2025, in preparation; and therefore excluded from our analysis) were included in the G20 composite.

To test whether the broad features reported by G20 would be recovered under our stacking methodology and data quality, we simulated their composite spectrum using their best-fit Gaussian parameters, added noise consistent with the rms of our data, and stacked the resulting spectra using our method 4. For this comparison, we focus on the full-sample stack from G20 (their Figure 5). Given the deeper sensitivity of the CRISTAL data (R. Herrera-Camus et al. 2025), we expect to be sensitive to faint broad components in the stack.

The results of this stack are shown in Figure 7, showing marginal broad features, slightly less significant than in our full-sample composite. We measure narrow- and broad-line widths of 223 km s^{-1} and 495 km s^{-1} , respectively, lower than the input values of 233 km s^{-1} and 531 km s^{-1} , although this is

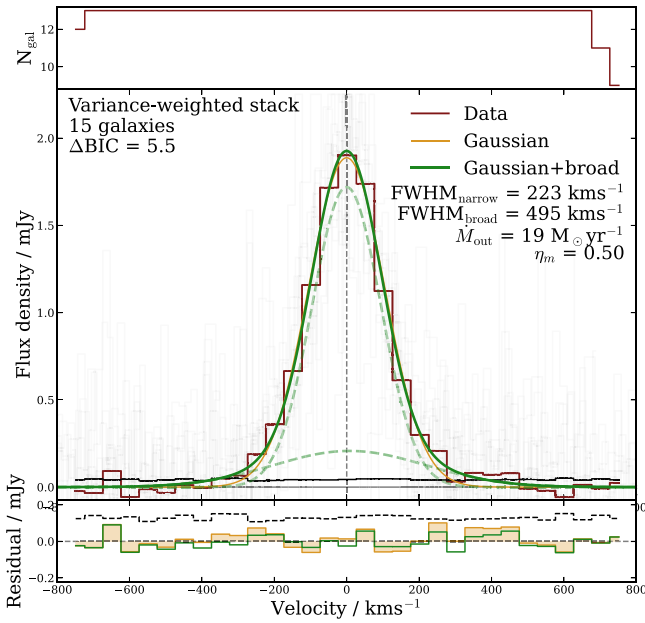


Figure 7. Simulated results obtained from inserting the G20 composite signal into spectra with the rms of the CRISTAL data. The broad emission is detected with $\Delta\text{BIC} = 5.5$, i.e., less significant than our full-sample stack.

simply because we normalized all spectra to the same line width as in our CRISTAL stacks. In general, Figure 7 shows that the outflow signal measured by G20 could be detected with the sensitivity of the CRISTAL data analyzed here. It is difficult, however, to more directly compare this result with Figure 5 in G20, as they do not include ΔBIC values, but in general, we do not see residuals above 3σ , whereas they do. Several differences in sample selection, resolution, and methodology may explain these residual discrepancies between the two analyses.

First, the sample utilized by G20 is much larger than ours, 50 versus 15 (11 and 9 in the low- and high- Σ_{SFR} stacks, respectively). As a result, the S/N gain from stacking should be a factor of ~ 1.8 better in the G20 analysis compared to ours. It is also possible that the ALPINE stacking sample includes sources with stronger outflows on average than those selected by CRISTAL. This seems unlikely if, as G20 suggests, the outflows are primarily driven by star formation, because the CRISTAL sources are among the highest-SFR sources of the full ALPINE sample (see Figure 1). A further possibility is that there remain incorrectly classified mergers in the G20 sample. Given that these sources likely have higher SFRs than nonmerging sources, this could contribute to their interpretation that outflows are star formation driven.

Another difference is that the coarser spatial resolution of the original ALPINE data could artificially induce broad components in the spectra, potentially from mergers. The kinematic analysis of the higher-resolution CRISTAL data provided by L. Lee et al. (2025, in preparation) has allowed us to more accurately exclude mergers from the sample. Unfortunately, this comes at the cost of a reduced sample size, meaning that stacking provides a smaller increase in S/N. Due to the mass-based selection of CRISTAL, the proportion of interacting sources in our sample is expected to be higher than that of ALPINE.

Additionally, the two analyses employ different methodologies. G20 did not normalize the line widths in their

stack (most closely resembling our method 1, which could have artificially introduced broad components into their composite (J.-B. Jolly et al. 2020)). However, we tested this method as part of our analysis (see Section 4.3) and found that the results did not skew significantly toward double-Gaussian when compared to our method 4.

In summary, while differences in resolution, sample selection, and stacking methodology can influence the interpretation of broad emission components, both studies point toward the tentative presence of galaxy-scale outflows in normal star-forming galaxies at $z \sim 5$. A definitive understanding of these outflows will require large, statistically robust samples observed at CRISTAL-like resolution. Such a study is well within the capability of ALMA and would represent a critical next step in understanding feedback processes in the early Universe.

5. Discussion

We now discuss our findings from the various stacks and their implications for the presence or absence of feedback in $z \sim 5$ main-sequence star-forming galaxies.

5.1. Are Outflows Responsible for the Broad Emission?

While we have found modest evidence that a broad component is required to explain the [C II] emission in the CRISTAL sample, this does not preclude scenarios other than outflows. In this section, we discuss other possibilities and justify interpreting the broad component as an outflow.

On the marginality of the broad detection, we address here the possible biasing of our sample selection. Given our conservative approach to rejecting potential mergers, our final sample comprises strictly disk-like sources with measured inclinations in the range 43° – 84° (L. Lee et al. 2025, in preparation), meaning that most are closer to being edge-on disks. If true, outflows perpendicular to the disk will have a relatively low velocity along the line of sight and, therefore, be more difficult to detect. This is briefly discussed further in Section 5.2.

As discussed in Section 3.1, the spectra of merging galaxies can combine multiple velocity components due to interacting sources, disturbed gas kinematics, and tidal tails, resulting in broader spectral features that can mimic feedback-driven outflows. While mergers and interactions are known to produce such broad features, our careful approach ensures these effects are minimized. If indeed there are any mergers remaining in the sample after the selection, they must be close mergers ($< 0''.4$) with a small offset between velocity components ($\sim 100 \text{ km s}^{-1}$). Such a merger would likely involve a minor component (if not visible spatially and kinematically) and/or would not significantly broaden the line given the small velocity offset. A similar argument can be made for tidal tails.

Additionally, AGN feedback can produce very rapid outflows of gas, which, if present, may appear in our composite spectrum. However, AGN-driven winds can often reach thousands of kilometers per second (e.g., M. Bischetti et al. 2019), whereas our stacks only show excess emission at velocities of a few hundred kilometers per second. Additionally, the majority of the sample appears to show [N II]/H α and [O III]/H β ratios that place them within the star formation

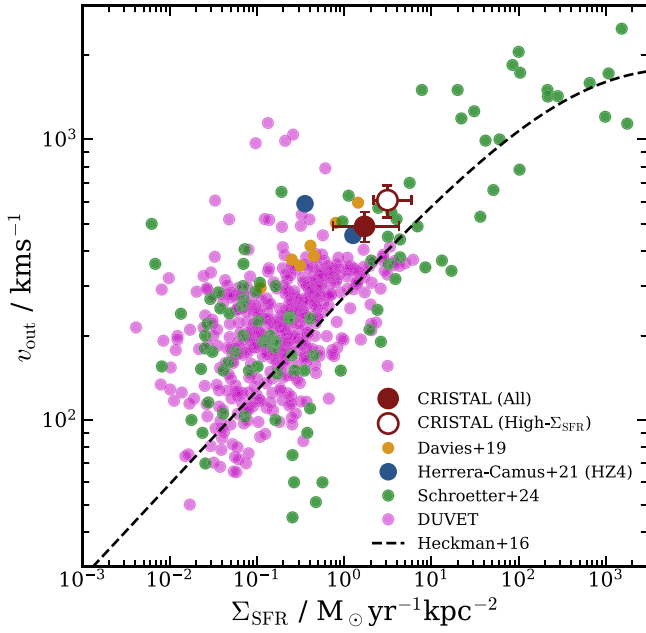


Figure 8. Outflow velocity v_{out} plotted as a function of star formation rate surface density Σ_{SFR} for the two CRISTAL composites displaying broad emission, along with $z \sim 2$ – 2.6 star-forming galaxies from R. L. Davies et al. (2019) and I. Schroetter et al. (2024). We show the best-fit lines derived by T. M. Heckman & S. Borthakur (2016) and B. Reichardt Chu et al. (2025; from the DUVET sample).

section of the classical BPT diagram (A. Faisst et al. 2025, in preparation).

5.2. Outflow Velocity

If we interpret the weak detection of a broad component in the composite spectrum of highly star-forming regions as outflowing gas driven by stellar feedback, we can estimate some basic properties of the potential outflow. Following D. Lutz et al. (2020), we measure the outflow velocity as:

$$v_{\text{out}} = |\Delta v| + 0.5\text{FW}_{10\%}, \quad (3)$$

where Δv is the velocity offset of the broad component, and $\text{FW}_{10\%}$ is the full-width at 10% of the peak flux density. For the method 4 stacks of the full sample, we find $v_{\text{out}} = 490 \pm 59 \text{ km s}^{-1}$, and for the high- Σ_{SFR} sample, we find $v_{\text{out}} = 607 \pm 80 \text{ km s}^{-1}$. This is expected if sources with higher star formation rates drive more powerful outflows, although the two values are consistent within the 1σ uncertainties.

As noted in Section 5.1, our sample selection results in disks that are inclined somewhere roughly in the center of edge-on and face-on. If the apparent outflows are perpendicular to the disk, then some component on the outflow velocity would not be in the line of sight and, therefore, not detectable in our data. In this case, an inclination correction would be required. For the CRISTAL disks, L. Lee et al. (2025, in preparation) measured a median inclination of 54° , implying a median velocity correction of $1/\sin^2(54^\circ) = 1.24$. Applying this would instead yield outflow velocities of $v_{\text{out}} = 608 \pm 73 \text{ km s}^{-1}$ for the full sample and $v_{\text{out}} = 753 \pm 99 \text{ km s}^{-1}$ for the high- Σ_{SFR} sample.

Figure 8 presents the outflow velocity of the two composites as a function of the star formation rate surface density, Σ_{SFR} . Σ_{SFR} is calculated as the median value across all pixels

included in the stack, with the 16th and 84th percentiles indicated by the error bars. Also included are SINFONI $\text{H}\alpha$ measurements by R. L. Davies et al. (2019) for $z \sim 2$ – 2.6 star-forming galaxies, and a literature compilation of $z < 1.5$ star-forming galaxies from I. Schroetter et al. (2024; mostly measured from absorption lines of background QSOs). The CRISTAL composites match well with the literature data, and sit close to the measured trend of increasing outflow velocity with star formation rate surface density measured by both T. M. Heckman & S. Borthakur (2016) and B. Reichardt Chu et al. (2025). Although this is not a highly constraining result, it is useful to see that, if interpreted as outflows, our composite properties are comparable to similar samples in the literature.

5.3. Mass Outflow Rate

Following G20, we estimate the atomic gas mass of the outflowing region using the following relation from S. Hailey-Dunsheath et al. (2010):

$$\frac{M_{\text{out}}^{\text{atom}}}{M_{\odot}} = 0.7 \left(\frac{0.7 L_{[\text{C II}]}}{L_{\odot}} \right) \times \left(\frac{1.4 \times 10^{-4}}{X_{\text{C}^+}} \right) \times \frac{1 + 2e^{-91\text{K}/T} + n_{\text{crit}}/n}{2e^{-91\text{K}/T}}, \quad (4)$$

where the $[\text{C II}]$ luminosity $L_{[\text{C II}]}$ is derived from the integral of the outflowing regions. We assume a C^+ abundance per hydrogen atom of $X_{\text{C}^+} = 1.4 \times 10^{-4}$, a gas density n equal to the critical density $n_{\text{crit}} = 3 \times 10^3 \text{ cm}^{-2}$, and a gas temperature of 100 K (M. Ginolfi et al. 2020). To derive the mass of the outflowing material, we consider the entire broad component of the fit for consistency with G20. For an alternative measurement, we use Equation (4) only including velocity channels where the broad component accounts for at least half of the total flux density, following D. Lutz et al. (2020). This latter approach is more conservative, as it aims to exclude flux density contributions from the main component of the galaxy. In Figures 9 and 10, the downward-pointing red arrows indicate the extent to which this approach reduces the measured values.

We then compute the mass outflow rate as (S. Gallerani et al. 2018):

$$\dot{M}_{\text{out}} = \frac{v_{\text{out}} M_{\text{out}}}{R_{\text{out}}}, \quad (5)$$

where M_{out} is derived using Equation (4). We adopt $R_{\text{out}} = 6 \text{ kpc}$, following G20.

The resulting mass outflow rates are $\dot{M}_{\text{out}} = 26 \pm 11 M_{\odot} \text{ yr}^{-1}$ for the full sample and $\dot{M}_{\text{out}} = 28 \pm 10 M_{\odot} \text{ yr}^{-1}$ for the low- Σ_{SFR} sample, although it is important to note that these values assume that only the atomic phase contributes to the outflows. To account for the other ISM phases, we follow recent work by A. Fluetsch et al. (2019), applying a factor of 3 to the atomic outflow rates, yielding total outflow rates of $\dot{M}_{\text{out}} = 78 \pm 33 M_{\odot} \text{ yr}^{-1}$ for the full sample and $\dot{M}_{\text{out}} = 85 \pm 31 M_{\odot} \text{ yr}^{-1}$ for the low- Σ_{SFR} sample. We stress that such a correction is based on CO observations of local galaxies, over half of which are Seyferts and LINERs, and therefore may not be applicable to our $z \sim 5$ sample. Further, an analysis of multiphase outflows in M82 by R. C. Levy et al. (2023) found that the corresponding factor would only be ~ 2 (see also work

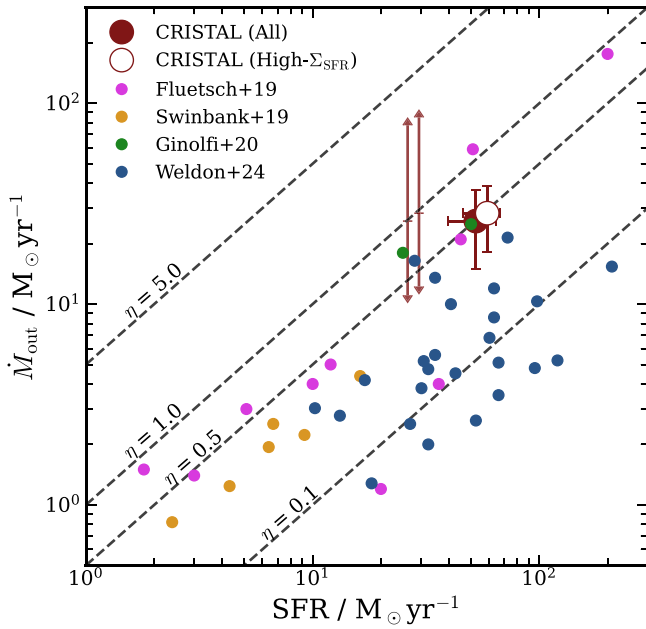


Figure 9. Mass outflow rate $\dot{M}_{\text{out}}$ vs. star formation rate for both CRISTAL composite spectra that show evidence for broad emission, along with samples from A. M. Swinbank et al. (2019), G20, and A. Weldon et al. (2024). The vertical arrows show how much the two CRISTAL points would move up if we were to adopt a correction factor of 3 to estimate the total mass outflow rate, and how much they would move down if we were to compute the mass outflow rate from only emission in the wings, as opposed to the entire broad component (see Section 5.3).

by A. K. Leroy et al. 2015; P. Martini et al. 2018). In Figures 9 and 10, the upward-pointing red arrows indicate the extent to which applying the factor of 3 increases the values.

Our mass outflow rate measurements are shown as a function of star formation rate in Figure 9. Data from the CRISTAL survey are plotted as filled red circles for the entire sample and open red circles for regions with high star formation rates. Additional outflow measurements from A. Fluetsch et al. (2019) and G20 are shown, along with ionized outflow measurements from A. M. Swinbank et al. (2019) and A. Weldon et al. (2024; at slightly lower redshifts of $z \sim 1-4$); we note, however, that the latter trace a hotter phase of outflowing material, coming from regions more directly impacted by energetic feedback processes, like supernovae and stellar winds. This is in contrast with our [C II] data, which traces colder outflows. $\dot{M}_{\text{out}}$ and SFR are generally positively correlated, and indeed our sample shows higher outflow rates than lower-SFR literature samples. The high- Σ_{SFR} subset of CRISTAL also shows a marginally higher $\dot{M}_{\text{out}}$ than the full sample, although the two composites are consistent within their uncertainties. Further, our measured $\dot{M}_{\text{out}}$ are consistent with those measured by G20. Compared to the other samples, particularly A. Weldon et al. (2024), our composites imply higher mass-loading factors than star-forming galaxies at lower redshifts, if indeed the broad emission we detect is driven by outflows. We discuss this further in the next section.

5.4. Mass-loading Factor

The efficiency of a star formation driven outflow is typically quantified by the mass-loading factor $\eta_m = \dot{M}_{\text{out}}/\text{SFR}$, which

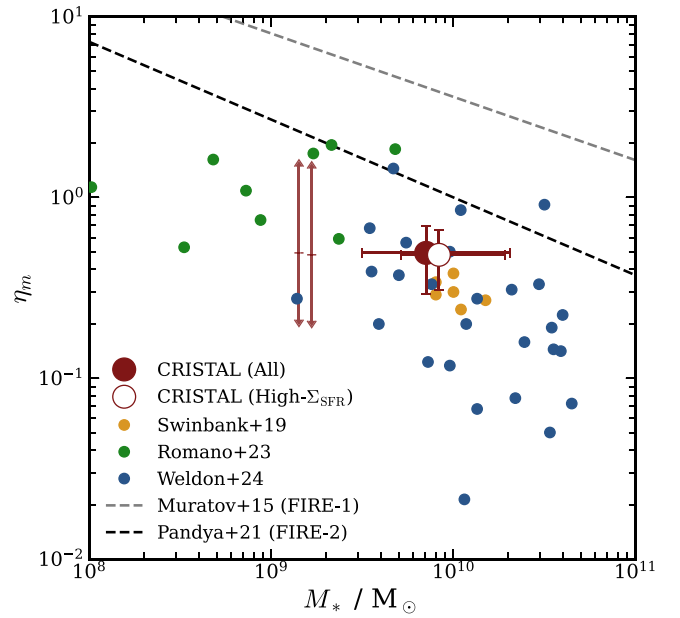


Figure 10. Mass-loading factor η_m plotted as a function of stellar mass. For CRISTAL, we show estimates for both the full-sample composite and the high- Σ_{SFR} subsample. The arrows are the same as in Figure 9. For comparison with lower-redshift sources, we include results from A. M. Swinbank et al. (2019), A. Concas et al. (2022), M. Romano et al. (2023), and A. Weldon et al. (2024; most of which were inferred from H α data). Predictions from both FIRE-1 and FIRE-2 suggest higher η_m than implied by CRISTAL, but we are largely in agreement with the observational data shown.

can be intuitively understood as the amount of mass removed per stellar mass newly formed.

For the integrated stack presented in Figure 3, we adopt the median SFR of the sample, $52 M_{\odot} \text{ yr}^{-1}$. This gives a mass-loading factor of $\eta_m = 0.49 \pm 0.20$, indicating the mass is lost at a slower rate than new stars are formed. When conservatively multiplying this number by a factor of 3 to account for multiphase outflows (A. Fluetsch et al. 2019), this would give $\eta_m = 1.48 \pm 0.61$, consistent with scenarios ranging from no significant overall mass loss to moderate mass loss with time. Given that the A. Fluetsch et al. (2019) calibration factor is conservative, we suggest that the former scenario is more likely. For the higher- Σ_{SFR} sample, we find a similar mass-loading factor of $\eta_m = 0.48 \pm 0.18$, implying comparable feedback efficiency between the two samples.

In Figure 10, we show the relationship between stellar mass and the mass-loading factor. Data from the CRISTAL survey are plotted as filled red circles for the entire sample and open red circles for regions with higher star formation rates, both exhibiting moderate uncertainties around $\eta_m = 0.5$. Additional data points from A. M. Swinbank et al. (2019), A. Concas et al. (2022), and A. Weldon et al. (2024) are shown, although we again note that these additional data are derived from ionized gas, which traces a hotter phase of the ISM.

For a closer comparison with our data, we include results from M. Romano et al. (2023) in Figure 10, which were measured from observations of the [C II] emission line in local dwarf galaxies. These systems have stellar masses that are around an order of magnitude lower than the CRISTAL sample, but they generally have comparable mass-loading factors to CRISTAL, and both data sets lie close to the A. Weldon et al. (2024) relation. This alignment implies that the feedback efficiency, as represented by η_m , scales with

stellar mass in a consistent manner across cosmic time for the two galaxy types, even though the two samples differ significantly in redshift and galaxy properties.

Theoretical predictions from the FIRE-1 (A. L. Muratov et al. 2015) and FIRE-2 (V. Pandya et al. 2021) simulations are indicated by the dashed gray and black lines, both of which predict a decrease in the mass-loading factor as stellar mass increases. This can be interpreted to mean that stellar feedback is more efficient at driving gas outflows in low-mass systems due to their shallower gravitational potential wells. The predictions from FIRE-2 in particular match our full-sample composite reasonably well, but only when adjusted to account for contributions from other phases of outflowing gas.

5.5. Contribution of Outflows to Observed Extended [C II] Emission

A recent development in the study of high-redshift galaxy evolution is the discovery of apparent extended [C II] halos on scales of ~ 10 kpc. By stacking ALMA data from 18 galaxies at $z \sim 5-7$, S. Fujimoto et al. (2019) provided the first evidence for this phenomenon, along with several potential driving mechanisms. Currently, there is very little consensus on which mechanism is most important, but perhaps the most discussed is outflows removing gas to large radii from the galaxy without it escaping the halo entirely. E. Pizzati et al. (2020, 2023) developed a semianalytic model in which supernova-driven outflows can reproduce the [C II] halos. In their stacking analysis, G20 used the observed detection of broad emission to suggest that the baryon cycle is already in place in the CGM of normal star-forming galaxies at $z \sim 5$.

However, utilizing the CRISTAL sample, R. Ikeda et al. (2025) found that the [C II] line emission is well described by a single extended disk component, implying that the aforementioned halos are not as significant as previously thought. Further, they found no correlation between the ratio of $R_{e,[C II]}/R_{e,UV}$ and SFR or $\Sigma_{SFR,IR}$, which they interpreted to suggest that [C II] outflows are not the cause of extended emission in the sample. This is clearly consistent with the lack of strong outflows in our full-sample stack (when excluding CRISTAL-02).

6. Conclusions

We have carried out a stacking analysis of ALMA Band 7 data from the CRISTAL survey of $z \sim 5$ main-sequence star-forming galaxies. The data cover the forbidden line from singly ionized carbon [C II] (rest-frame $158 \mu\text{m}$), which we use to search for outflow signatures in the form of broad wings. Our main conclusions are as follows:

1. We adopt a conservative stacking approach, leveraging kinematic analysis of the higher-resolution CRISTAL data (compared to ALPINE) to remove 22 systems that are potentially interacting/merging, leaving a final sample size of 15. When included in a stack, these sources can easily mimic broad wings. Given that CRISTAL-02 is already known to drive a prominent outflow, we perform our stacking analysis both with and without this source.
2. Given the different redshifts, masses, and luminosities of the CRISTAL sources, we test several methods for aggregating the emission-line profiles when stacking, including standardizing all line widths. We find that the chosen method can meaningfully affect the conclusion

on whether or not outflows are present, and therefore extreme care must be taken. We prefer to normalize both the line widths and peak flux densities to a constant value, to ensure that we are probing only the average *shape* of the emission-line profiles.

3. After excluding potential mergers from the sample and combining the integrated spectra, the resultant composite shows weak evidence for outflows with $\Delta\text{BIC} = 17$. Evidence with this significance is *only* present when normalizing the line widths and peak flux densities—all other stacking methods show little-to-no evidence of broad emission in the composites. We measure an outflow velocity (not corrected for inclination) of $v_{\text{out}} = 490 \pm 59 \text{ km s}^{-1}$, which is consistent with literature measurements for galaxies with similar Σ_{SFR} . The result is also almost entirely driven by CRISTAL-02, without which the significance drops to $\Delta\text{BIC} = 3.1$.
4. We compare our stacking results with those obtained from the ALPINE survey by G20, aiming to identify any systematic differences related to data quality. Although the CRISTAL data offer higher resolution and therefore allow for more effective identification and removal of mergers, our stack reveals less significant broad emission than that reported by G20. Moreover, when we inject rms noise comparable to the CRISTAL data into their composite signal, the resulting stack also shows less significant residuals than those presented in G20. We suggest that sample size, selection, and methodology all contribute to these differences.
5. We find a mass outflow rate of $\dot{M}_{\text{out}} = 26 \pm 11 M_{\odot} \text{ yr}^{-1}$ and mass-loading factor of $\eta = 0.49 \pm 0.20$, indicating feedback that, while relatively weak and unlikely to quench star formation, could still regulate the system over long timescales by moderating the gas supply available for star formation.
6. We exploit the high resolution of the CRISTAL data to generate [C II] luminosity maps, which we use as a proxy for star formation maps. By defining a threshold in star formation rate, we stack the individual spatial pixels from the sample that are most highly star-forming. When only considering the [C II]-brightest regions of the sample (again excluding mergers), which should broadly represent the most highly star-forming, the resultant composite spectrum also shows moderate evidence for outflows, $\Delta\text{BIC} = 9$, with $v_{\text{out}} = 607 \pm 80 \text{ km s}^{-1}$, $\dot{M}_{\text{out}} = 28 \pm 10 M_{\odot} \text{ yr}^{-1}$, and $\eta = 0.48 \pm 0.18$. This could suggest that the potential outflows are driven by star formation.

Few sources in the CRISTAL sample individually show evidence for outflows. The analysis presented here indicates that any further evidence would need to be revealed with deeper [C II] observations and/or larger stacking samples. JWST/NIRSpec data covering H α , [N II], H β , and [O III] has recently become available that will push forward our picture of the CRISTAL sample, namely allowing for the ruling out of any substantial AGN activity using line ratio diagnostics, the measurement of metallicities, and searching for outflows in the ionized phase.

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Facility: ALMA.

Software: astropy (Astropy Collaboration et al. 2018), CASA (J. P. McMullin et al. 2007).

Appendix Inner and Outer Galaxy Stacks

Figures 11 and 12 show the stacks of the regions within the sample divided into the outer and inner parts of the galaxies, respectively as described in Section 4.2. These are presented in the same format as Figures 5 and 6, and show that broad emission is predominantly detected in the inner regions of the CRISTAL galaxies.

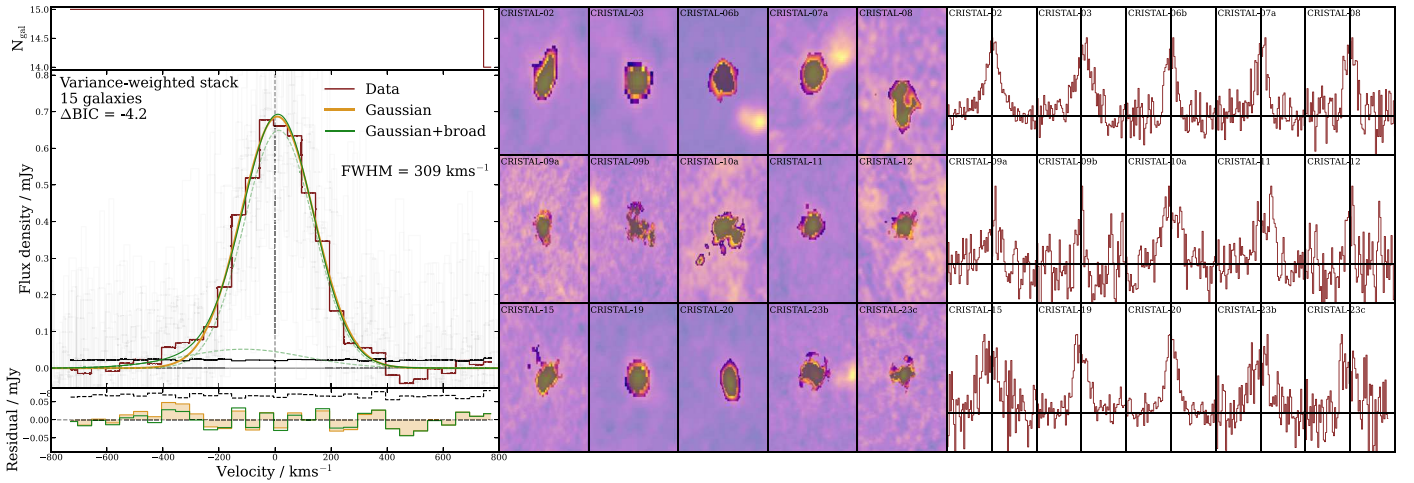


Figure 11. The same as Figure 3, but only including the outer regions of each galaxy, selected as $\Sigma_{\text{SFR}} < \Sigma_{\text{SFR,med}}$. The composite is well modeled by a single-Gaussian function.

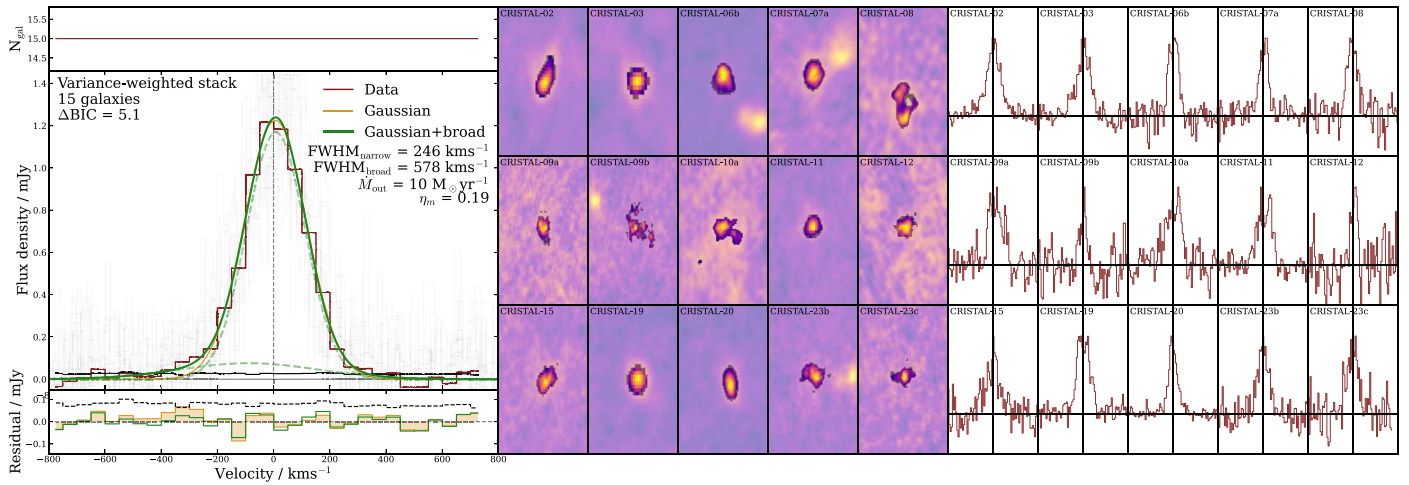


Figure 12. The same as Figure 3, but only including the inner regions of each galaxy, selected as $\Sigma_{\text{SFR}} > \Sigma_{\text{SFR,med}}$. The composite is marginally better-modeled when including a broad component.

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