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COALAS: I. ATCA CO(1-0) survey and luminosity function in the Spiderweb protocluster at $z = 2.16$

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ABSTRACT

We report a detailed CO(1-0) survey of a galaxy protocluster field at $z = 2.16$, based on 475 hours of observations with the Australia Telescope Compact Array. We constructed a large mosaic of 13 individual pointings, covering an area of 21 arcmin² and ± 6500 km/s range in velocity. We obtain a robust sample of 46 CO(1-0) detections spanning $z = 2.09 - 2.22$, constituting the largest sample of molecular gas measurements in protoclusters to date. The CO emitters show an overdensity at $z = 2.12 - 2.21$, suggesting a galaxy super-protocluster or a protocluster connected to large-scale filaments with ~ 120 cMpc size. We find that 90% CO emitters have distances $> 0'.5 - 4'$ to the center galaxy, indicating that small area surveys would miss the majority of gas reservoirs in similar structures. Half of the CO emitters have velocities larger than escape velocities, which appears gravitationally unbound to the cluster core. These unbound sources are barely found within the R_{200} radius around the center, which is consistent with a picture in which the cluster core is collapsed while outer regions are still in formation. Compared to other protoclusters, this structure contains relatively more CO emitters with relatively narrow line width and high luminosity, indicating galaxy mergers. We use these CO emitters to place the first constraint on the CO luminosity function and molecular gas density in an overdense environment. The amplitude of the CO luminosity function is 1.6 ± 0.5 orders of magnitude higher than observed for field galaxy samples at $z \sim 2$, and one order of magnitude higher than predictions for galaxy protoclusters from semi-analytical SHARK models. We derive a high molecular gas density of $0.6 - 1.3 \times 10^9 M_{\odot} \text{cMpc}^{-3}$ for this structure, consistent with predictions for cold gas density of massive structures from hydro-dynamical DIANOGA simulations.

Key words. Galaxies: evolution – Galaxies: formation – Galaxies: clusters: individual: Spiderweb – Galaxies: high redshift – Galaxies: survey – interstellar medium: CO transition

1. Introduction

Galaxy protoclusters (see Overzier 2016 for a review) are expected to contribute significantly to the star formation rate density (SFRD) at high redshifts (Chiang et al. 2017), e.g., 20–50% at $z > 2$. Thus understanding how clusters assembled their mass is of critical importance. Molecular gas is the reservoir where the stars form. Measuring the molecular gas content and distribution in galaxies as a function of environment and epoch is crucial for developing our understanding of how galaxies form and evolve. Moreover, since the potential impact of environment can be large on galaxy evolution as evidenced by the tightness of the color-luminosity sequence in local clusters and the morphology-density relation (Dressler 1980; Davies et al. 2014), constraining the evolution of the gas galaxy in clusters/protoclusters offers us key tests of galaxy evolution models.

As a proxy for the cold molecular gas content, CO surveys of random fields (e.g., Walter et al. 2016; Riechers et al. 2019; Decarli et al. 2019, 2020; Riechers et al. 2020a) have been revealing the evolution of the molecular gas density over cosmic history. The ASPECS survey (Walter et al. 2016) conducted the first blind CO search with Atacama Large Millimeter Array (ALMA) in the Hubble Ultra Deep Field (HUDF). This survey revealed an elevated CO luminosity function at $z \sim 2$ with respect to the local Universe and an evolution of cosmic molecular gas density within galaxies as a function of redshift (Decarli et al. 2016).

Using the Karl G. Jansky Very Large Array (VLA) observations, the COLDz project (Riechers et al. 2019) provided detailed measurements of the CO luminosity function and molecular gas density at $z = 2-3$ and $z = 5-7$ via CO(1-0) and CO(3-2) detections, respectively. Recently, based on the reported CO detections by González-López et al. (2019) and Aravena et al. (2019), Decarli et al. (2019, 2020) constructed the CO luminosity function out to $z \sim 4$ and found that the observed evolution of the molecular gas density tracks the evolution of the cosmic star formation rate density. This finding is confirmed by the PHIBSS2 survey (Lenkić et al. 2020) with CO observations with the Plateau de Bure Interferometer (PdBI). These CO surveys focus on field galaxy samples while the molecular gas density in dense environments such as galaxy (proto)clusters has not yet been constrained.

Over the last few years, there have been significant efforts to observe CO in high-redshift (proto)cluster environments (e.g., Emonts et al. 2016, 2018; Hayashi et al. 2017; Noble et al. 2017, 2019; Casey 2016; Wang et al. 2016, 2018; Dannerbauer et al. 2017; Rudnick et al. 2017; Stach et al. 2017; Oteo et al. 2018; Coogan et al. 2018; Miller et al. 2018; Tadaki et al. 2019; Gómez-Guijarro et al. 2019; Lee et al. 2019; Castignani et al. 2019; Hill et al. 2020; Ivison et al. 2020; Spérone-Longin et al. 2020). However, due to the frequency coverage, ALMA line surveys mostly target high-J CO(J , $J - 1$) transitions ($J \geq 2$) that could introduce uncertainties into the total molecular gas

mass due to unknown gas excitation (e.g. Dannerbauer et al. 2009; Daddi et al. 2015; Liu et al. 2015; Yajima et al. 2020). The ground-state CO transition (rest-frame 115.27 GHz, $J=1$) is extensively used as the best tracer of the total cold molecular gas mass (e.g., Ivison et al. 2011; Emonts et al. 2013). Using deep CO(1-0) observations with the VLA, Rudnick et al. (2017) revealed two gas-rich cluster members at $z = 1.62$ and found that cluster members have comparable gas fractions and star-formation efficiencies (SFEs) with respect to field galaxies, consistent with field scaling relations between the molecular gas content, stellar mass, SFR and redshift. In the $z = 2.5$ CL J1001 (proto)cluster field, Wang et al. (2016, 2018) conducted VLA observations of the CO(1-0) transition. They found low gas content and elevated SFEs in cluster members compared to field galaxies, presenting evidence for impact of the environment on the molecular gas reservoirs and SFEs of $z = 2$ cluster galaxies. However, the above mentioned CO(1-0) observations in high- z galaxy clusters targeted either individual cluster members or the central region of a (proto)cluster core (e.g., Emonts et al. 2016, 2018; Dannerbauer et al. 2017; Wang et al. 2018; Champagne et al. submitted) and thus introduced a bias in their interpretation in the context of galaxy formation and evolution, as protoclusters can be extended up to $30'$ on the sky (resp. up to 15 Mpc in physical units; Muldrew et al. 2015; Casey 2016) and superstructure has been found with a size of ~ 120 cMpc in comoving size at $z > 2$ (Cucciati et al. 2018). Clearly, surveys covering the large volume of a galaxy protocluster in the distant universe are still missing and would allow us to characterize the CO luminosity function and molecular gas density in such an environment.

To this end, the Spiderweb protocluster field at $z = 2.16$, being a prominent and well-studied example of a cluster in formation, is an ideal laboratory for such a study (Miley et al. 2006). This protocluster has been continually observed and resulting in rich, multi-wavelength datasets. It hosts a significant overdensity of Ly α emitters (LAEs; Pentericci et al. 2000; Kurk et al. 2000), H α emitters (HAEs) (Kuiper et al. 2011; Koyama et al. 2013; Shimakawa et al. 2014, 2018), extremely red objects (ERO; Kurk et al. 2004), and submillimeter galaxies (SMGs) (Rigby et al. 2014; Dannerbauer et al. 2014). A 10 Mpc scale filament traced by HAEs has been identified across this region (Koyama et al. 2013; Shimakawa et al. 2018). Meanwhile, the SFRD based on far-infrared/submillimeter measurements appears high, $\sim 1500 M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$ (Dannerbauer et al. 2014). Recently, massive gas reservoirs in this structure have been revealed via CO(1-0) observations with the ATCA. Emonts et al. (2016) found a large reservoir of molecular gas extending across 70 kpc around the central starbursting radio galaxy MRC 1138–262. This reservoir of molecular gas fuels in-situ star formation (Hatch et al. 2008) and drives the growth of a massive central-cluster galaxy, suggesting that the brightest cluster galaxies could form out of extended, recycled gas at high redshift. This work demonstrated the power of ATCA to detect the most extended CO(1-0) emission. Subsequently, Dannerbauer et al. (2017) discovered an extended rotating disk (40 kpc) with a massive molecular gas mass $M_{\text{mol}} = 2 \times 10^{11} M_{\odot}$ in a normal star-forming galaxy in this protocluster, and found no evidence of environmental impact on the star-formation efficiency (SFE). More recently, one more protocluster galaxy was found in CO(1-0) in the region between the radio galaxy and HAE229 (Emonts et al. 2018). As these CO(1-0) observations target only a small area around the center radio galaxy, the very limited number of detections cannot constrain the CO luminosity function and total gas density in co-moving volume. On the other hand, the physical scale of the protocluster is unknown. This is due to the

narrowness of the redshift range probed in narrow-band imaging surveys and the rest-frame UV/optical lines of dusty member galaxies can be severely attenuated, making the identification of cluster membership difficult to complete. A large scale CO survey with a broad bandwidth will help to find additional cluster members that are missed by optical/near-infrared surveys and could be able to reveal wider structure. Moreover, the SFRD found in Dannerbauer et al. (2014) is well above the predictions of simulations and semi-analytical models (e.g., Bassini et al. 2020; Lim et al. 2020). It is unclear if the molecular gas density compared to the field sample is similarly overdense as the SFRD, and would be of great interest to compare the observed gas density to predictions from cosmological simulations (e.g., Lagos et al. 2020; Bassini et al. 2020). Thus, a dedicated CO(1-0) survey is urgently needed in order to constrain the molecular gas density in this structure and help to clarify these issues.

In the present study, we report the first result of the COALAS (CO ATCA Legacy Archive of Star-forming galaxies) project, focusing on the ATCA CO(1-0) observations of the Spiderweb cluster field at $z = 2.16$. In section 3, we discuss the source extraction and construct the CO-emitter catalogue. In section 4, we present the results of the catalogue. In addition, we constrain the CO(1-0) luminosity function and molecular gas density of this structure. We close the paper with a discussion in section 5 and present the major conclusions of this study in section 6. We adopt a flat Λ CDM cosmology with $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$, $\Lambda_0 = 0.73$ (Spergel et al. 2003, 2007), and a Chabrier IMF (Chabrier 2003).

2. Observations and data reduction

The CO ATCA Legacy Archive of Star-Forming Galaxies (COALAS) project¹ is a large program (ID: C3181, PI: H. Dannerbauer) with the Australia Telescope Compact Array (ATCA). The observations took place during April 2017 until March 2020. A major goal of this project is to study the impact of environment on the cold molecular gas content via the CO(1-0) transition. In total, we obtained 820 hours observing time with the ATCA (including compensation for bad weather). The COALAS large program consists of well-covered ‘field’-targets from the Extended Chandra Deep Field-South (ECDFS) and ‘cluster’-targets from the Spiderweb protocluster ($z = 2.16$). In this work, we present only the results in the Spiderweb protocluster field, while the work in ECDFS will be presented in Thomson et al. (in prep.).

In addition, we included observations of several LABOCA-selected sources (ID: 2014OCTS/C3003 and 2016AO-PRS/C3003; PI: H. Dannerbauer, high resolution pointings focusing on DKB01-03 ID: 2017APRS/C3003, PI: B. Emonts), the center radio galaxy and the HAE229 (Emonts et al. 2016; Dannerbauer et al. 2017). These observations were finished before the large program started, which were conducted in the same Spiderweb field at the same frequency as the large program. In total, we have observed the Spiderweb protocluster field for 475 hours (including bad weather). We stress that currently, ATCA is the only facility in the southern hemisphere that can target the lowest CO transition of $z \sim 2$ galaxies. The situation will change with the installation of ALMA band 1.

As shown in Fig. 1, including data from Emonts et al. (2016, 2018) and Dannerbauer et al. (2017), 13 pointings in total have been observed at 36.5 GHz (the redshifted CO(1-0) transition) with a 2 GHz bandwidth. The pointings have been designed in

¹ <http://research.iac.es/proyecto/COALAS/pages/en/home.php>

Table 1. Overview of observations

Pointing	Phase center	Beam	PA [deg]	Integrated time [hours per config.]	RMS [b]	Configuration ^a
MRC1138	11:40:48.3,-26:29:11	4.8'' \times 3.5''	45.5	5, 18, 30, 26, 11	0.13	H75, H168, H214, 750A/D, 1.5A
HAE229	11:40:46.6,-26:29:11	4.9'' \times 3.7''	-2.7	40, 42	0.13	H214, 750C
DKB01-03	11:40:59.2,-26:30:43	4.7'' \times 4.3''	29.6	24, 24	0.14	H214, 750D
DKB12	11:40:57.6,-26:29:36	5.1'' \times 4.3''	-86.3	23	0.20	H214
DKB15	11:40:54.7,-26:28:21	5.9'' \times 4.5''	77.0	22, 10	0.15	H214, H168
DKB16	11:41:02.4,-26:27:45	5.3'' \times 4.3''	80.0	18	0.23	H214
SWpoint1	11:40:37.7,-26:30:20	9.8'' \times 7.6''	69.0	15, 16	0.18	H168, H75
SWpoint2	11:40:43.1,-26:29:20	6.5'' \times 5.9''	66.0	15, 5	0.18	H168, H75
SWpoint3	11:40:44.1,-26:28:32	7.0'' \times 6.2''	74.0	20, 6	0.19	H168, H75
SWpoint4	11:40:52.5,-26:29:30	13.8'' \times 10.7''	-84.9	8, 22	0.24	H168, H75
SWpoint5	11:41:00.1,-26:28:56	12.6'' \times 9.8''	-83.9	9, 20	0.22	H168, H75
SWpoint6	11:40:40.1,-26:29:47	13.8'' \times 13.1''	-87.0	27	0.19	H75
SWpoint7	11:40:39.7,-26:28:45	12.7'' \times 9.8''	-86.7	8, 15	0.29	H168, H75

Notes. ^a See www.narrabri.atnf.csiro.au/operations/array_configurations/configurations.html for details on the array configurations.

^b In unit of mJy bm^{-1} in 40 km s^{-1} channel width.

that way to maximize the number of known sources (with spectroscopic redshifts from the rest-frame UV/optical) per pointing. Therefore, the spacing between the pointing varies, and the depth of the mosaic is not homogeneous. The pointings cover primarily submillimeter galaxies detected with LABOCA that are most probably physically related to the protocluster (Dannerbauer et al. 2014), secondarily the HAEs confirmed in the same structure (Koyama et al. 2013; Shimakawa et al. 2014). We observed at different configurations for about 8 hours per night, mostly using the most compact array configuration as H75, H168 or H214 (see details in Table 1), and the beam size varies between 4'' to 14''. Therefore, in principle we do not expect to resolve sources in the data cube. However, because of the very compact array configurations (baselines < 100 m), our ATCA observations are very sensitive to low-surface-brightness emission from extended molecular gas reservoirs, ensuring that we obtain reliable mass estimates. We summarize the observations of the 13 individual pointings in Table 1, in which 11 of them are from the COALAS large program. The data of the pointings of MRC1138 and HAE229 are taken from previous studies of Emonts et al. (2016, 2018) and Dannerbauer et al. (2017). For the remaining 11 pointings, the phases are calibrated every 15 minutes with a short (~ 2 min) scan on a nearby calibrator 1124–186. 1124–186 is also used for bandpass calibration which calibrated out a uniform sensitivity over the frequency range covered. Flux calibration was done on PKS 1934–638. Following Emonts et al. (2014), a conservative 20% uncertainty in the measured fluxes is assumed to account for the uncertainty in absolute flux calibration. However, this does not affect the source extraction via signal-to-noise-ratio (SNR) in the data cube, see section 3.

We use the software packages MIRIAD (Sault et al. 1995) and Karma (Gooch 1996) for the data reduction and visualization, following the strategy described in detail in Emonts et al. (2014, 2016) and Dannerbauer et al. (2017). We imaged the ATCA data cube with natural weighting using the task INVERT for each individual pointing. The FWHM of the ATCA primary beam is 70'' at 7mm. We imaged each individual pointing with a radius of 0.9' so that adjacent pointings significantly overlap. The total sky coverage of the 13 ATCA pointings is 25.8 arcmin^2 , while sources are only detected in regions with rms noise < 1 mJy per beam which corresponds to an area of 21.3

arcmin^2 . The data cubes are imaged using pixel size of 1.5'' and channel width of 40 km s^{-1} . We applied a Hanning smooth, resulting in a resolution of 80 km s^{-1} . The continuum was separated from the line by fitting a straight line to the line-free channels in the uv-domain. Velocities are in the optical frame relative to $z = 2.1612$, spanning ± 7000 km/s .

We linearly combined the 13 pointings using the task LINMOS after correcting for primary beam attenuation. The rms level of individual pointing are 0.13 – 0.29 mJy per beam (in 40 km s^{-1} channel) on the phase center of each pointing as listed in Table 1, while the SNR in the overlapping regions got improved, with an rms of 0.1 – 1 mJy over the whole field after primary beam correction. The deepest area has an rms of 0.09 mJy per beam, and is centered on the radio galaxy MRC1138-262 and HAE229 that are covered by 3 – 4 individual pointings. Because none of the new CO signals in our survey is strong enough to have significant sidelobes, we did not deconvolve our images, and therefore performed our analysis on the ‘dirty’ cube, following the previous studies in Emonts et al. (2016, 2018) and Dannerbauer et al. (2017).

3. Line search

We adopted two major methods to search for CO lines in the ATCA data cube: (i) our code MaxFinder, which is an algorithm searching for the maximum SNR of candidate lines on each pixel and matching counterparts in optical images (Sec.3.1); and (ii) the Source Finding Application (SoFiA) which is a blind source finding pipeline intended to find and parametrize lines in data cubes (Serra et al. 2015), see details in Sec. 3.2. As a complementary approach, we search for CO lines using the reshifts of the HAEs in this field. We summarize the selection of the final catalogue in Sec. 3.3. The statistical properties of the catalogue (e.g., completeness and flux boosting) will be described in Sec. 3.4.

3.1. MaxFinder

The MaxFinder code is inspired by previous work on manual extraction of CO(1-0) emission from ATCA cubes (Emonts et al. 2014, 2016; Dannerbauer et al. 2017; Emonts et al. 2018). Equivalently, the MaxFinder source extraction code will search for the

most probable line candidate on every position (i.e., pixel) and look for their optical/near-infrared counterparts afterwards. We run the MaxFinder on the large mosaic made of all 13 pointings. This large mosaic contains the best SNR in regions overlapped by multiple pointings albeit with variation in resolution, enabling us to search for the most probable line candidates in the data cube. First, MaxFinder extracts the spectrum on each pixel and calculates the weighted average over any two channels. Given that the sensitivity is uniform over the full ATCA spectral range, the flux uncertainty is defined as the standard deviation of the full spectrum without Hanning smoothing. We compute the weighted average over each two arbitrary channels, and select the two channels n_i and n_j that maximize the weighted average. Second, we define the range of line as channels lying in the FWZI (full width at zero intensity) that contains the channels n_i and n_j . The MaxFinder will determine the FWZI range by searching for the first negative channel on the left (right) side of channel n_i (n_j). Adopting Eq. 2 in Emonts et al. (2014), the line flux is integrated over the FWZI range, and uncertainty of the line flux is calculated as $\Delta I_{\text{co}} = \sigma \Delta v \sqrt{\text{FWZI}/\Delta v}$. Thus the SNR is

$$\text{SNR} = \frac{\int_{\text{FWZI}} S dv}{\sigma \Delta v \sqrt{\text{FWZI}/\Delta v}} \quad (1)$$

where σ is the root-mean-square (rms) noise, Δv is the channel width and FWZI the range over which the line flux was integrated. In this way we keep the calculations consistent with previous work by our team. Then we calculate signal and noise of candidate line on each pixel and make a large mosaic SNR mosaic, as shown in Fig 1. Note that the radio galaxy MRC 1138-262 (Emonts et al. 2013, 2016) and the HAE229 (Emonts et al. 2013; Dannerbauer et al. 2017) are solidly detected in the SNR mosaic where the peak-SNR on their positions are $\text{SNR}_{\text{peak}} = 7.5$ and 8.1, respectively. This verifies the robustness of our search method. At last, we select all sources with $\text{SNR}_{\text{peak}} > 5$ in the large mosaic. For candidates with $\text{SNR}_{\text{peak}} = 4-5$, which have a high possibility of being spurious, we require a counterpart in either the HST F814W (i.e., the I band, Miley et al. 2006) or the VLT/HAWK-I K_s images (Dannerbauer et al. 2014). Such approach was already applied on ALMA data to exclude spurious sources (see e.g., Dunlop et al. 2017). We searched for counterparts within a circle centering on the pixel with peak SNR and with a radius of $3''$ (i.e., 2 pixels). In order to avoid bad channels on the edge of the sideband, we take only the spectral data within velocity range ± 6500 km/s. In this way, we select 75 $\text{SNR} > 4$ sources with optical counterparts.

3.2. SoFiA

In order to obtain a secure catalogue, we also applied the blind source extraction method SoFiA (Serra et al. 2015)² on the ATCA data cubes. SoFiA is a flexible source finder tool for 3D spectral line data. SoFiA is designed for application on any data cube, which is independent of the type of emission line or telescope. SoFiA allows the user to search for spectral line signal on multiple scales on the sky and in frequency, and it takes into account noise level variations across the data cube and the presence of errors and artefacts which are crucial to detect and parametrize 3D sources in a complete and reliable way. Finally, SoFiA is able to estimate the reliability of individual detection. To quantify the

confidence of line detection, SoFiA defines a parameter *reliability*

$$R = \frac{T}{T + F} \quad (2)$$

where T and F are the number of true and false detections, respectively, and are estimated based on the combined statistics of sources with positive and negative total flux (Serra et al. 2012). Thus the *reliability* is identical to the *fidelity* parameter defined in González-López et al. (2019) (Eq. 1) and the *purity* parameter defined in Béthermin et al. (2020) (Eq. 1). In this study, we run SoFiA with threshold of $\text{SNR} = 1.15$ to generate sufficient negative detections to constrain the *reliability*. Given that the 13 ATCA pointings are observed with different configurations, the large mosaic — with varying/inconsistent spatial resolution — is not suitable for blind source finder algorithm like SoFiA. Therefore, we produced four mosaics via linearly combining pointings with comparable beam sizes using LINMOS, i.e., MRC1138+HAE229, DKB12+15+16, SWpoint2+3, SWpoint4+5 and SWpoint6+7. As DKB01–03 and SWpoint1 have different spatial resolutions compared to their neighbouring pointings, SoFiA is applied individually on them. The same SoFiA recipe is applied on above mosaics and individual pointings with tailored *reliability.f_{min}*³ to their beam sizes. This parameter is defined as $\text{reliability.f}_{\text{min}} = \text{SNR}_t \sqrt{A_{\text{beam}}}$, where the SNR_t is the SNR threshold and A_{beam} is the area of the beam in unit of pixel. It is scaled with the square root of the beam area, ensuring that the integrated SNR threshold is identical for all cubes. On the other hand, as detections are not likely resolved in the ATCA beam, we only smooth the spectra in velocity space, and require *reliability* > 0.5 and line width of at least 3 channels (i.e., > 120 km/s). In this way, we detect 187 sources with SoFiA, of which 74 have $\text{SNR}_{\text{peak}} > 4$ within their beams in the SNR map generated by MaxFinder.

3.3. Source Catalogue

The above two methods have both pros and cons. The blind line search generally suffers from a high spurious rate, while searching with priors appears to be more reliable but could still include spurious sources. In detail, although MaxFinder is prior-based, a weakness is that some detections could be spuriously boosted by noise and counterparts can be found by chance on position of the noise peak as MaxFinder is searching for signal on individual pixels and the ATCA beam sizes are 3–8 times larger than the pixel size. However, such spurious detections can be filtered out by SoFiA because it is searching for signal in an area of the beam rather than individual pixels, so that spurious sources with a strong negative peak nearby will be excluded from the detection list.

In order to create a catalogue of reliable line detections, we combine the two methods, preferentially selecting sources extracted by both the MaxFinder and SoFiA. We match MaxFinder and SoFiA sources according to spatial positions and line velocities, where the tolerance of spatial offset is half of the beam size in SoFiA mosaic and the velocity difference is less than the width of two FWZIs. We find 42 sources detected by both the MaxFinder and SoFiA having a $\text{SNR} > 4$ (MaxFinder) and *reliability* > 0.5 (SoFiA). We classify these sources as category A. In category A, all known CO(1-0) detections of this protocluster from the literature such as MRC1138–262 (Emonts

² https://www.atnf.csiro.au/people/Tobias.Westmeier/tools_software_sofia.php

³ See SoFiA control parameter at <https://github.com/SoFiA-Admin/SoFiA/wiki/SoFiA-Control-Parameters>

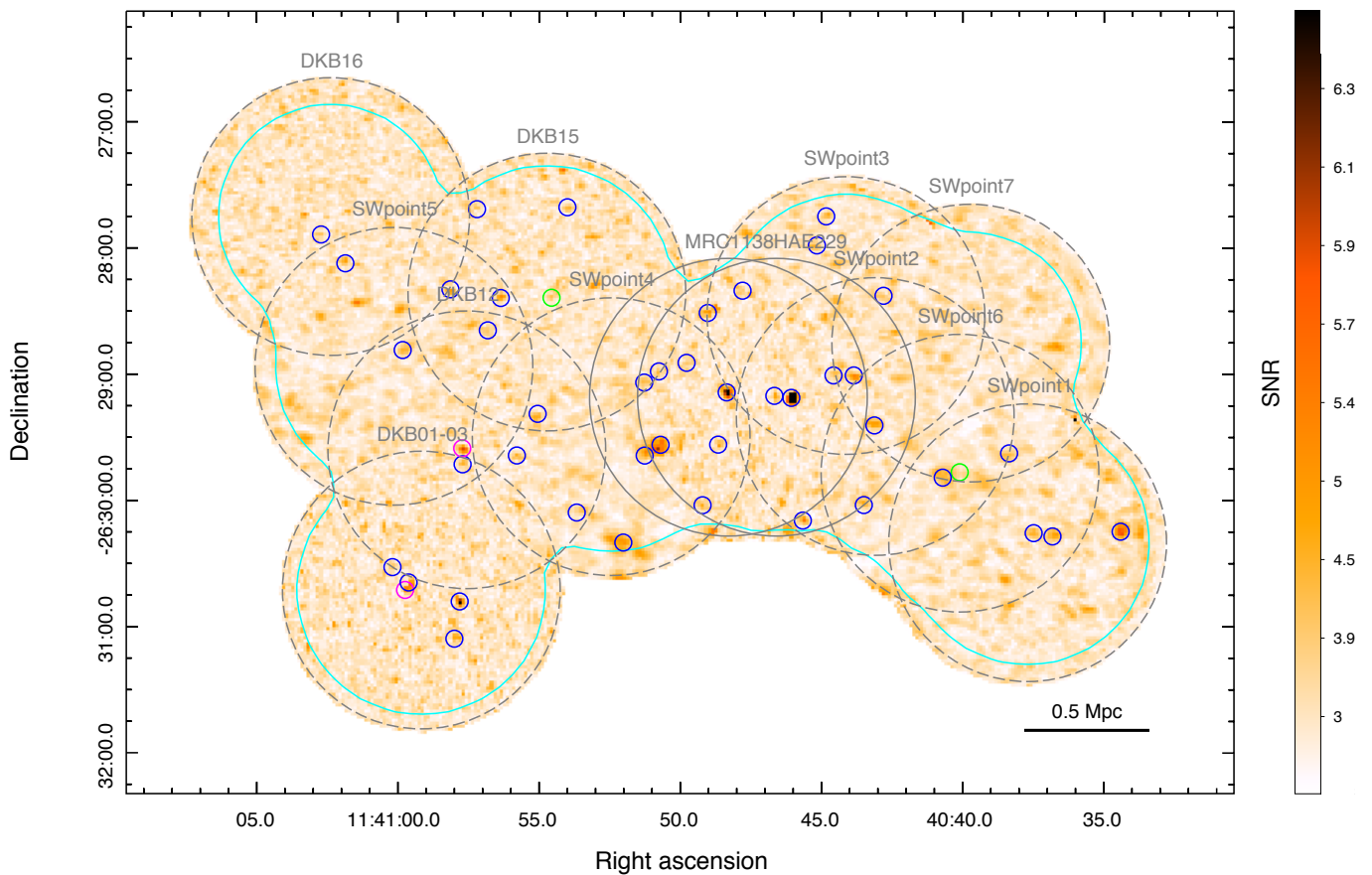


Fig. 1. The SNR map of line candidates (Sec. 3.1) in the ATCA mosaic. The SNR is the maximum signal-to-noise ratio computed in the 1D spectrum on each pixel by our algorithm MaxFinder (see details in Sec. 3.1). The color bar values are limited in $1.5 < \text{SNR} < 6.5$ for fair visibility of detections. ATCA pointings are shown in grey circles with a radius of $0.9'$. Grey solid circles mark the pointings MRC1138 in Emonts et al. (2016) and HAE229 in Dannerbauer et al. (2017), respectively. Cyan contour encloses the area with $\text{rms} < 1 \text{ mJy bm}^{-1}$. Detected sources are marked by solid circles in colors, blue: category A; magenta: category B; green: category C (see details in Sec. 3.3).

et al. 2013, 2016), HAE229 (Emonts et al. 2013; Dannerbauer et al. 2017) and an additional detection by Emonts et al. (2018) are re-discovered by our source extraction, giving credibility for our method. The line intensities of these detections agree well with the results in Emonts et al. (2018). We obtain higher SNRs for MRC1138–262 and HAE229 than the detections presented previously in Emonts et al. (2018) as they used two pointings, whereas in this work we add more visibilities to these sources from overlapped pointings SWpoint2, 3 and 4. On the other hand, these two galaxies are spatially resolved (Emonts et al. 2016; Dannerbauer et al. 2017) and we adopted a large pixel size ($1''.5$) in imaging which also slightly boosted the SNRs.

The majority of SoFiA sources ($\text{SNR} > 3.5$) are not included in category A, either because of low SNR (< 4) or because they lacked an optical/NIR counterpart. On the other hand, the SoFiA line search is conducted in mosaics of data with comparable resolutions, i.e., MRC1138+HAE229, DKB12+15+16, SWpoint2+3, SWpoint4+5 and SWpoint6+7 which have lower SNR in overlapping areas than that in the large mosaic of 13 pointings. Therefore, compared to MaxFinder which was applied on the fully combined mosaic, SoFiA could miss detections in overlapping area due to higher noise level. Thus we include sources that are solidly detected by MaxFinder but missed by SoFiA. We find that two sources selected in MaxFinder with $\text{SNR} > 5$ are missed by SoFiA. One source is the LABOCA-detected SMG DKB12 (Dannerbauer et al. 2014). SoFiA missed

this source due to a negative noise peak near the source in the low SNR mosaic. The second source is an HAE with a possible counterpart of the LABOCA-selected SMG DKB01a (Dannerbauer et al. 2014). The reason that SoFiA missed this source could be that it is blended with the nearby source DKB01b (Dannerbauer et al. 2014). We classify the two sources as category B.

In addition, we also search for CO detections based on HAE priors from Koyama et al. (2013) and Shimakawa et al. (2018). This approach re-discovers 12 HAEs with $\text{SNR} > 4$ that have been included in category A and B (Tables 3) which further credit to our search methods MaxFinder and SoFiA. Moreover, we find two CO detections on HAE positions that are not included in category A and B. The two sources are detected with 3.8σ and 4.4σ respectively while are not selected by SoFiA. However, their CO spectroscopic redshifts are consistent with $\text{H}\alpha$ spectroscopy (Shimakawa et al. 2018), hence they are securely detected and we classify them to category C. To summarize, we show the definition of categories in Table 2. In total, 46 reliable CO detections are included in this catalogue, as listed in Table 3 and shown in Fig. 1. We note that other SNR peaks in Fig. 1 are not identified as detections, because they lack a reliable counterpart or are not selected by SoFiA.

The MaxFinder and HAE prior-based extraction use $3''$ tolerance for all pointings when matching counterparts, being appropriate for counterpart search in high-resolution pointings (e.g., MRC1138 and HAE229) but could be too strict for low resolu-

Table 2. Detection category

Category	Number	Criteria
A	42	Detected by SoFiA & MaxFinder
B	2	MaxFinder SNR>5 & not detected by SoFiA
C	2	HAEs with matched z_{spec} , neither in category A nor B

tion pointings. However, using a larger search beam would introduce high spurious rate as the deep HST I band image contains a large amount of faint sources that could be associated to spurious detections by chance. As a trade off, we decide to apply the 3'' tolerance for all pointings to obtain a conservative detection list, albeit some detections in low resolution pointings could be missed. We refer to a detailed analysis on false positive rates within the search radius in Sec. 3.4. We also note that the recently found optically-dark dusty galaxies (Jin et al. 2019; Wang et al. 2019; Smail et al. 2020) would be not included in this catalogue as we conservatively request a optical counterpart for each detection.

3.4. Flux boosting, completeness and false positive rate

To constrain the CO luminosity function in this protocluster, it is important to measure the completeness of the line detection, and the effects of flux boosting. We therefore performed Monte Carlo simulations in the ATCA large mosaic, analogous to the methods applied in COLDz (Pavesi et al. 2018), ASPECS (Decarli et al. 2019) and PHiBSS2 (Lenkić et al. 2020) projects. Given that detections are not expected to be resolved in the ATCA beam, we assume that the probability of line detection (i.e., completeness) only depends on the integrated line flux, on the line width and on the depth of the data cube (i.e., rms level). As the MaxFinder algorithm works on the spectrum of individual pixels, we perform simulations on 1D spectra extracted on randomly selected positions. We inject mock lines in the data cube, spanning a range of values for various parameters (line flux, FWHM and rms level), then search for lines via the MaxFinder algorithm and check the fraction of lines recovered. In detail, the mock line with a Gaussian profile (integrated line flux, FWHM) is co-added to the 1D spectrum on a random pixel selected in an area with given rms value. To cover the parameter space of our line detections and variable depths of ATCA mosaic, we designed 11 rms bins spanning 0.08 – 1 mJy/beam, 20 injected line fluxes evenly spanning 0.03 – 1 Jy km/s in log space and 16 FWHMs spanning 125–1200km/s in linear space. In each rms bin, we co-added a mock line (in fixed line flux and FWHM) to a 1D spectrum for 100 times where each time the 1D spectrum is extracted on a random position that has an rms value within the rms bin and no line detection on the position. Afterwards, we run MaxFinder on the co-added spectrum to search for lines with maximum SNR, and identify the lines as recovered lines if matching the two criteria: (1) the central velocity of the output line has a distance from the input line center less than the injected FWHM, and (2) the output line has SNR > 4.

The flux factor f_{flux} is defined as the ratio of the median of the recovered line fluxes to the injected ones, and the completeness C is inferred as the ratio between the number of recovered and injected lines. Simulations are performed 3200 times with varying the values of injected line properties, enabling us to associate the measured line properties to their intrinsic values for all lines that can be detected in the ATCA mosaic. For each detected can-

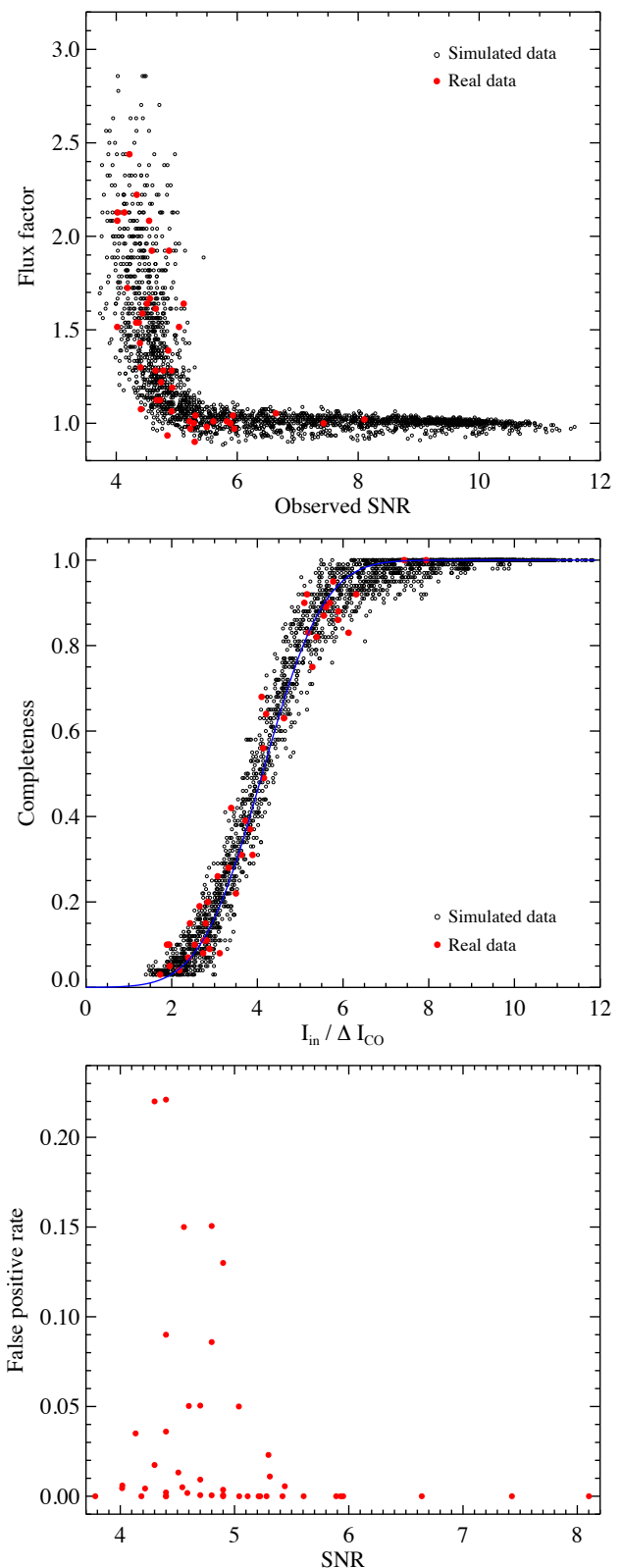


Fig. 2. *Top panel:* The flux boosting factor vs. observed SNR for simulated data (open circle) and real detections (red filled circle). *Central panel:* The completeness as a function of the injected line flux I_{in} over the measured flux uncertainty ΔI_{CO} . The I_{in} for real detections are line fluxes that have been corrected for flux boosting factors in the top panel. The blue curve shows the best fit to the simulated data (see Eq. 3). The completeness decreases with decreasing integrated flux normalized by noise, indicating that sources are more difficult to detect at low SNR. This analysis allows us to correct CO luminosity functions for the completeness of our search algorithm. *Bottom panel:* The false positive rate vs. SNR for CO detections in this study.

didate, based on the measured velocity-integrated intensity I_{CO} , line width FWHM and the rms level σ on its position, we obtained the flux factor and completeness C via matching the line properties to the recovered ones in the simulations, thus associating to a discrete grid of intrinsic properties. We note that the radial variations of depths caused by the primary beam corrections and different integration have accounted for the completeness, as different rms levels (depths) have been fully mimicked in the simulations. The flux boosting factors in this detection catalogue are spanning 0.9 – 2.4 with a median of 1.2. The simulations also provide us with the deviation of the recovered flux density 5 – 28% with a median of 20% which is in excellent agreement with the 20% uncertainty that have been assumed to the observed line fluxes in order to account for uncertainty in flux calibration (Emonts et al. 2014). The completeness is tightly related to the line properties as a function of $I_{\text{in}}/\Delta I_{\text{CO}}$, as shown in Fig. 2-central where I_{in} is the injected line flux and the ΔI_{CO} is the measured flux uncertainty. This relation has a similar expression to the Eq.5 in Lenkić et al. (2020) which is

$$C(x) = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{x - A}{B} \right) \right] \quad (3)$$

where $x = I_{\text{in}}/\Delta I_{\text{CO}}$. The best fit shows $A = 4.1$ and $B = 1.6$ in this study, which is shown in blue curve in Fig. 2. Given this tight correlation, we assign completeness and flux factor for each detection by matching to a simulated source with the closest SNR, line flux and rms level which are shown in Table 3. In the following analysis, we scale down the observed CO luminosities in all figures by the flux factors to account for flux boosting while still presenting flux factors and the observed flux and luminosities in tables. We do not scale down the uncertainties in the flux and luminosity to have more conservative results.

Given that the simulations are computed for secure sources with a known position, this appears to be appropriate for the category A and B sources in our catalogue. Note that one source in category C is detected with $\text{SNR} = 3.8$ that is lower than the $\text{SNR} > 4$ threshold applied in the simulations, we thus do not have constraints on its flux factor and completeness. We verified that including this source or not does not impact on the following statistical analysis. Thus we adopt the completeness and flux factors for category A & B sources and one source with $\text{SNR} > 4$ in category C.

In Fig. 2-bottom, we show the false positive rate of this sample. Among the 46 CO detections (Table 3), nine sources have well-matched optical spectroscopical redshifts to their CO redshifts which are solidly confirmed and false detection case can be excluded. The rest of the sources have no optical redshifts known. Some of them could be false positives, and counterparts can be found by chance within the $3''$ searching radius. The probability of false line detection can be conservatively estimated as $1 - R_{\text{SoFiA}}$, where the R_{SoFiA} is the *Reliability* computed from SoFiA. As the R_{SoFiA} is computed from mosaics with similar resolutions, shallower than the large mosaic, the *Reliability* of detection is actually higher than the SoFiA output and the probability of false line detection ($1 - R_{\text{SoFiA}}$) appears conservative. To constrain the probability of false counterparts, P_c , we run simulations via randomly generating mocked sources with the same sky density of HST I and VLT Ks sources in this field, and searching for counterparts using a $3''$ radius on a random position. We find that the false positive rate of HST I band counterparts is $P_c = 0.46$, and false Ks counterpart is $P_c = 0.06$. The false positive rate of HAE counterparts is entirely negligible, as the HAE sky density is lower than the HST I source density by two orders of magnitude, thus we assigned the false rate of HAE

counterparts to 0. Therefore, the false positive rate P_{false} , i.e., the probability of a counterpart found by chance for a false line detection, is $P_c \times (1 - R_{\text{SoFiA}})$. As shown in Fig. 2-bottom, all sources in this sample have false positive rate < 0.24 , and only sources with $\text{SNR} < 5.5$ have $P_{\text{false}} > 0$. The total false detection number (i.e., $\sum P_{\text{false},i}$) in this sample is less than 1.

4. Molecular gas content of the Spiderweb protocluster

Based on the source catalogue presented in section 3.3, we show the individual spectrum for each detection. Furthermore, we study the cold molecular gas properties of our sample including the determination of the CO(1-0) luminosity function of this high-density field.

4.1. Spectra and integrated CO maps

For all sources, we present the 1D-spectra and contours of the integrated CO maps overlaid on optical/near-infrared images, see Fig. 3 and Appendix A. The integrated CO images are created by summing up the data cube between the channel n_i and n_j determined by MaxFinder (see Sec. 3.1), maximizing the SNR of the line and the visibility of the detection in integrated images. We emphasize that all detections are unresolved in the integrated CO images in which the contours are only used to highlight the SNR level and the optical counterpart. The non-Gaussian contours of some sources are due to stacking of pointings with different resolutions which are not indicative for morphologies and do not affect the peak flux measurements on which the following analysis is based.

In Fig. 3, we present spectra of the 17 sources with $\text{SNR} > 5$ and their optical images overlaid with line intensity contours in which 16 of them have explicit counterparts in the optical/near-infrared imaging. The remaining source, i.e., COALAS-SW.05, is serendipitously found at the edge of pointing SWpoint1 with CO(1-0) $\text{SNR} = 5.9$ at $z_{\text{spec}} = 2.189$. This source is not covered by the VLT nor by HST imaging. However, we find a tentative counterpart in the Subaru z -band image (Koyama et al. 2013). Although there is high noise level at the edge of the pointing, it is unlikely to be spurious given the high SNR, thus we include it in the catalogue.

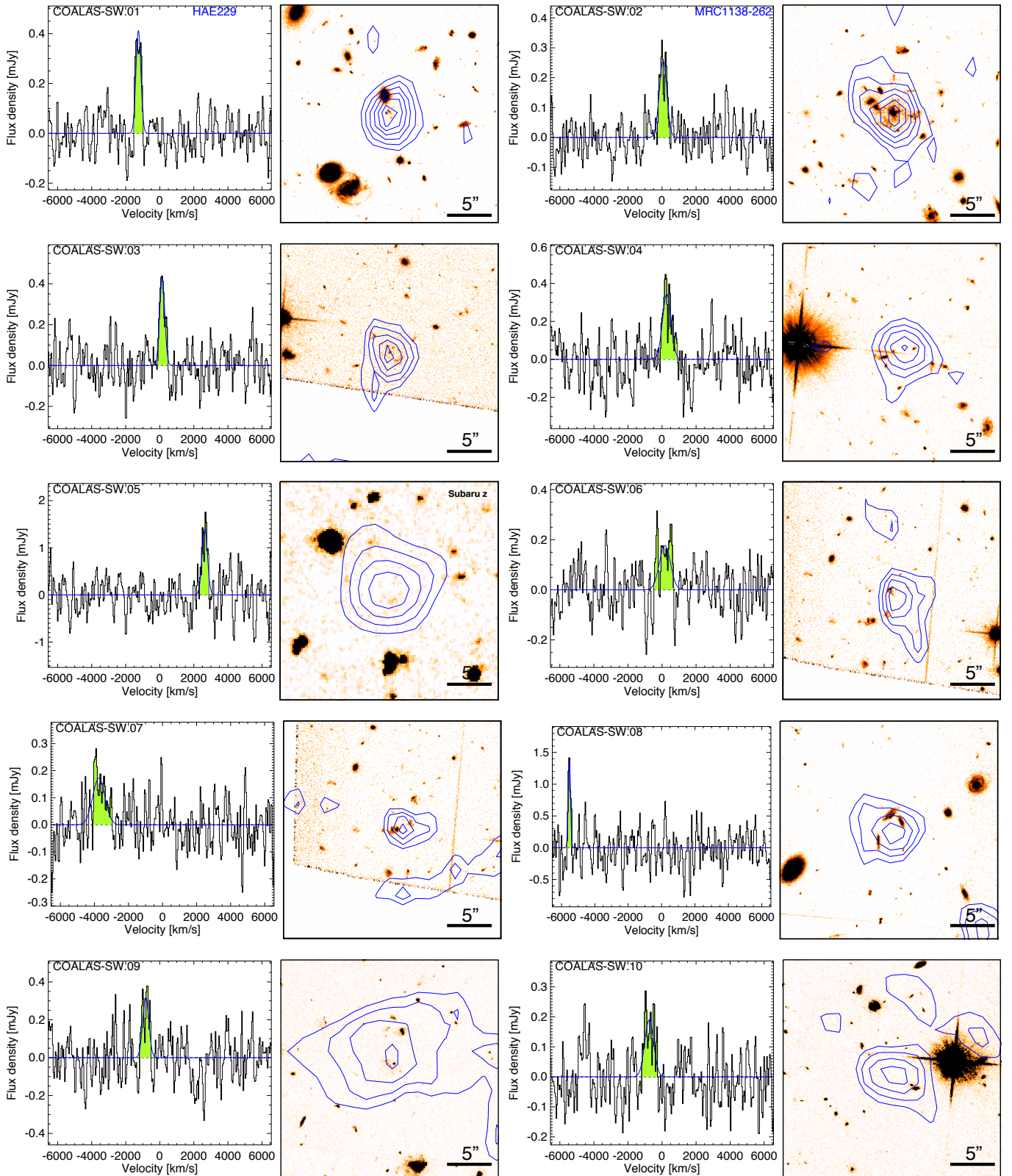


Fig. 3. The ATCA spectra and integrated CO maps for detections with $\text{SNR} > 5$. *Spectra panels:* CO(1-0) lines are highlighted in green and fitted by a single Gaussian profile shown in red curve. Reference names in Emonts et al. (2016) and Dannerbauer et al. (2017) are highlighted in blue when available. *Image panels:* Optical images in $25'' \times 25''$ size overlaid with CO(1-0) intensity contours. In general, images are taken from the HST F814W data (Miley et al. 2006), while VLT K_s (Dannerbauer et al. 2014) and Subaru z-band images (Koyama et al. 2013) are indicated as text on upper-right corner. Contours start at 2σ in steps of 1σ .

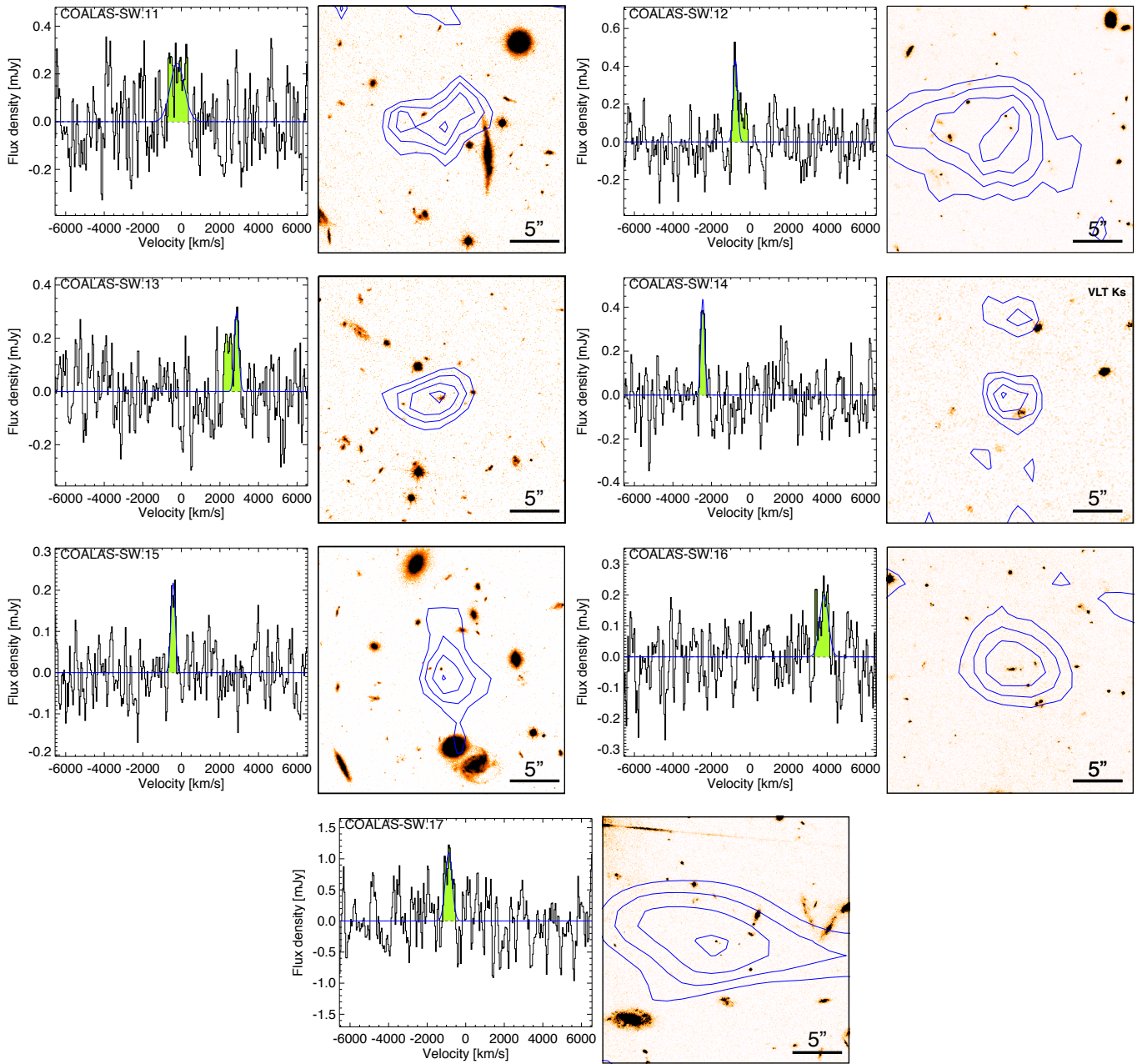


Fig. 3. Continued.

Table 3. ATCA CO(1-0) detections

ID	$z_{\text{spec,opt}}$	z_{CO}	I_{CO} [Jy km s ⁻¹]	SNR_{peak}	FWHM [km s ⁻¹]	$L'_{\text{CO}(1-0)}$ [10 ¹⁰ K km s ⁻¹ pc ²]	Counterpart	f_{flux}	C	R_{SoFIA}	Category
COALAS-SW.01	2.1478	2.1480	0.15±0.02	8.1	339±41	3.5±0.5	I,Ks,HAE	1.0	1.0	1.0	A
COALAS-SW.02	2.1612	2.1618	0.13±0.02	7.5	515±67	3.1±0.5	I,Ks,HAE	1.0	1.0	1.0	A
COALAS-SW.03	2.1618	2.1627	0.16±0.03	6.6	353±52	3.8±0.7	I,Ks,HAE	1.1	0.9	1.0	A
COALAS-SW.04	2.1701	2.1642	0.22±0.04	6.0	588±94	5.1±1.0	I,HAE	1.0	0.8	–	B
COALAS-SW.05	–	2.1890	0.51±0.10	5.9	371±62	12.5±2.5	z^*	1.0	0.9	1.0	A
COALAS-SW.06	2.1670	2.1630	0.17±0.03	5.9	759±159	3.9±0.8	I,Ks,HAE	1.0	0.9	1.0	A
COALAS-SW.07	–	2.1218	0.14±0.03	5.6	852±162	3.3±0.7	I,Ks,HAE	1.0	0.9	–	B
COALAS-SW.08	–	2.1033	0.28±0.06	5.4	213±30	6.5±1.5	I,Ks	1.0	1.0	0.9	A
COALAS-SW.09	2.1510	2.1530	0.15±0.03	5.4	422±83	3.5±0.8	I,Ks,HAE	1.0	0.8	1.0	A
COALAS-SW.10	–	2.1533	0.13±0.03	5.3	615±120	3.1±0.7	I,Ks	1.0	0.9	0.8	A
COALAS-SW.11	–	2.1590	0.22±0.05	5.3	868±185	5.3±1.2	I	0.9	0.9	1.0	A
COALAS-SW.12	–	2.1532	0.17±0.04	5.3	260±47	4.1±0.9	I,Ks,HAE	1.0	0.9	1.0	A
COALAS-SW.13	–	2.1892	0.16±0.04	5.2	656±44	3.9±0.9	I,Ks,HAE	1.0	0.8	0.9	A
COALAS-SW.14	–	2.1354	0.10±0.02	5.2	227±43	2.4±0.5	Ks	1.0	0.9	1.0	A
COALAS-SW.15	KMOS	2.1567	0.06±0.02	5.1	268±49	1.4±0.4	I,Ks,HAE	1.6	0.1	1.0	A
COALAS-SW.16	–	2.2017	0.12±0.03	5.0	544±114	2.8±0.7	I,Ks,HAE	1.2	0.6	1.0	A
COALAS-SW.17	–	2.1519	0.50±0.12	5.0	413±83	11.7±2.8	I	1.5	0.3	0.9	A
COALAS-SW.18	–	2.1801	0.20±0.05	4.9	757±156	4.8±1.2	I	1.6	0.1	1.0	A
COALAS-SW.19	–	2.1674	0.11±0.03	4.9	845±195	2.6±0.6	I	1.3	0.4	0.7	A
COALAS-SW.20	–	2.1282	0.27±0.07	4.9	648±142	6.4±1.6	I,Ks	1.1	0.6	1.0	A
COALAS-SW.21	–	2.1237	0.30±0.07	4.9	1274±290	6.9±1.7	Ks	1.4	0.2	0.9	A
COALAS-SW.22	–	2.1702	0.21±0.05	4.8	762±168	5.0±1.2	I	1.3	0.4	0.8	A
COALAS-SW.23	–	2.1629	0.17±0.04	4.8	471±101	4.0±1.0	I	0.9	0.8	0.7	A
COALAS-SW.24	–	2.1395	0.16±0.04	4.8	313±71	3.6±0.9	I	1.9	0.1	1.0	A
COALAS-SW.25	–	2.1680	0.16±0.04	4.7	623±87	3.8±1.0	I	1.1	0.5	0.9	A
COALAS-SW.26	–	2.1897	0.22±0.06	4.7	334±70	5.4±1.4	I,Ks	1.2	0.3	1.0	A
COALAS-SW.27	–	2.1691	0.25±0.06	4.7	333±72	5.9±1.5	I	1.1	0.6	1.0	A
COALAS-SW.28	–	2.0950	0.31±0.08	4.6	322±65	6.9±1.8	I	1.6	0.1	0.9	A
COALAS-SW.29	–	2.2125	0.12±0.03	4.6	283±58	2.9±0.8	I,Ks	1.7	0.1	1.0	A
COALAS-SW.30	–	2.1315	0.14±0.04	4.6	326±68	3.2±0.9	I	1.1	0.8	0.9	A
COALAS-SW.31	–	2.2034	0.12±0.03	4.5	279±60	3.0±0.8	I,Ks	2.1	0.1	1.0	A
COALAS-SW.32	–	2.1750	0.09±0.03	4.5	219±47	2.3±0.6	I,Ks	1.6	0.1	0.8	A
COALAS-SW.33	–	2.1824	0.11±0.03	4.4	204±44	2.6±0.7	I	1.5	0.2	0.9	A
COALAS-SW.34	–	2.1205	0.14±0.04	4.4	686±171	3.2±0.9	I	1.9	0.1	0.6	A
COALAS-SW.35	–	2.1912	0.10±0.03	4.4	245±52	2.4±0.6	I	1.6	0.2	1.0	A
COALAS-SW.36	–	2.1558	0.08±0.02	4.4	217±46	1.8±0.5	I	1.3	0.4	1.0	A
COALAS-SW.37	–	2.1355	0.13±0.03	4.4	447±108	3.0±0.8	Ks	1.1	0.7	0.7	A
COALAS-SW.38	–	2.1462	0.21±0.06	4.3	1313±302	4.9±1.4	Ks	1.5	0.1	1.0	A
COALAS-SW.39	–	2.2148	0.24±0.07	4.3	189±42	6.1±1.7	I	2.2	0.1	0.6	A
COALAS-SW.40	–	2.1229	0.08±0.02	4.2	442±120	1.8±0.5	I	2.4	0.1	1.0	A
COALAS-SW.41	–	2.1617	0.18±0.05	4.2	290±65	4.2±1.2	I,HAE	1.7	0.2	0.6	A
COALAS-SW.42	–	2.1431	0.10±0.03	4.1	219±47	2.4±0.7	I	2.1	0.1	0.9	A
COALAS-SW.43	–	2.1284	0.13±0.04	4.0	229±57	3.0±0.9	I,Ks	1.5	0.2	1.0	A
COALAS-SW.44	–	2.1906	0.13±0.04	4.0	557±158	3.2±1.0	I,Ks	2.1	0.1	0.9	A
COALAS-SW.45	2.1606	2.1603	0.06±0.02	4.4	168±37	1.4±0.4	I,Ks,HAE	0.3	1.2	–	C
COALAS-SW.46	KMOS	2.1621	0.10±0.03	3.8	567±154	2.4±0.8	I,Ks,HAE	–	–	–	C

Note: $z_{\text{spec,opt}}$: optical redshifts from Shimakawa et al. (2018), KMOS: VLT/KMOS redshift from Pérez-Martínez et al. (in prep.); Counterpart: I (HST F814W), Ks (VLT), z (Subaru), HAE (Koyama et al. 2013; Shimakawa et al. 2018); f_{flux} and C are flux factor and completeness, respectively; R_{SoFIA} : *Reliability* from SoFIA. * Tentative counterpart. The horizontal line highlights sources with with $\text{SNR}>5$.

4.2. Line identification and redshift distribution

In this study, all detected lines are identified as CO(1-0) at $z \sim 2.2$. As shown in Table 3, nine sources are found with consistent redshifts to $z_{\text{CO}(1-0)}$ from near-infrared spectroscopy presented in Shimakawa et al. (2018) and/or the VLT/KMOS observations in Pérez-Martínez et al. (in prep., private consultation). Regarding the remaining sources without a secure spectroscopic redshift, in case of higher-J CO transitions, e.g., CO(2-1) at $z = 5.3$, we inspected Herschel/SPIRE images for all CO detections and found no red colors that could suggest redshifts beyond $z = 4 - 5$ (e.g., Riechers et al. 2017). On the other hand, adopting the number density of $z > 5$ submillimeter galaxies in COLDz survey (Riechers et al. 2020b), the expected number of $z > 5$ galaxies is less than 1 in this field. Thus, the detection of CO(2-1) appears very unlikely and thus cannot be used to constrain CO(2-1) space density at $z = 5.3$. We compute the CO(1-0) luminosities $L'_{\text{CO}(1-0)}$, following Solomon et al. (1997), namely,

$$L'_{\text{CO}(1-0)} = 3.25 \times 10^7 S \Delta \nu \frac{D_L^2}{(1+z)^3 v_{\text{obs}}^2} \text{ K km s}^{-1} \text{ pc}^2 \quad (4)$$

where $S \Delta \nu$ is the integrated flux of the line in Jy km s^{-1} (corrected for flux boosting, see Section 3.4), D_L is the luminosity distance in Mpc, and v_{obs} is the observed frequency.

In Fig. 4, we show the redshift and CO(1-0) luminosity distribution, respectively. The detections spread over the redshift range $z = 2.09 - 2.22$ with CO(1-0) luminosity up to $L'_{\text{CO}(1-0)} = 2 \times 10^{11} \text{ K km s}^{-1} \text{ pc}^2$. Previous membership was based on H α narrow-band imaging and subsequent near-infrared spectroscopy. Thus, the HAE redshift range of $z = 2.146 - 2.170$ is a selection effect of the narrow band filter NB_{2071} (Shimakawa et al. 2018) which is limited within the redshift range of $z = 2.15 \pm 0.2$ and unable to probe the wider structure of Spiderweb cluster. Strikingly, the CO emitters show an overdensity from $z = 2.12 - 2.21$, a factor of 3.8 wider in velocity than the range traced by the HAEs. Such an overdensity remains at $z = 2.12 - 2.21$ even if we limit the z_{CO} histogram to only those sources with $\text{SNR} > 5$. It is independent of the rms level, line width and other properties, which are robust and unlikely to be impacted by selection effects or miss-identifications. Therefore, this indicates that this structure has a scale of 120 co-moving Mpc (cMpc), suggesting a filament and/or a super structure. We discuss this further in Sec. 5.1.

4.3. Spatial distribution of CO emitters

In Fig. 5, we show the footprints of previous studies, including HST I band image, Subaru MOIRCS Ks band image (Koyama et al. 2013; Shimakawa et al. 2014) and LABOCA $870 \mu\text{m}$ continuum map. In this work, using ATCA we observed an area slightly larger than the HST F814W image, covering the majority of LABOCA sources in Dannerbauer et al. (2014) and HAEs in Koyama et al. (2013) and (Shimakawa et al. 2014). As the R_{200} shown in green circle, the central cluster core around MRC1138 is well covered by all observations, while the large filamentary structure traced by HAEs is still not fully observed with ATCA.

In Fig. 6, we show the sky and velocity distributions of CO emitters in this study. Respectively, the left panel shows the velocity of CO emitters to their sky distance to the central radio galaxy MRC1138-262 while the right panel presents the normalized version. In Fig. 6-left, the CO emitters scatter largely in view of the observer, i.e., line-of-sight velocity range of ± 6500

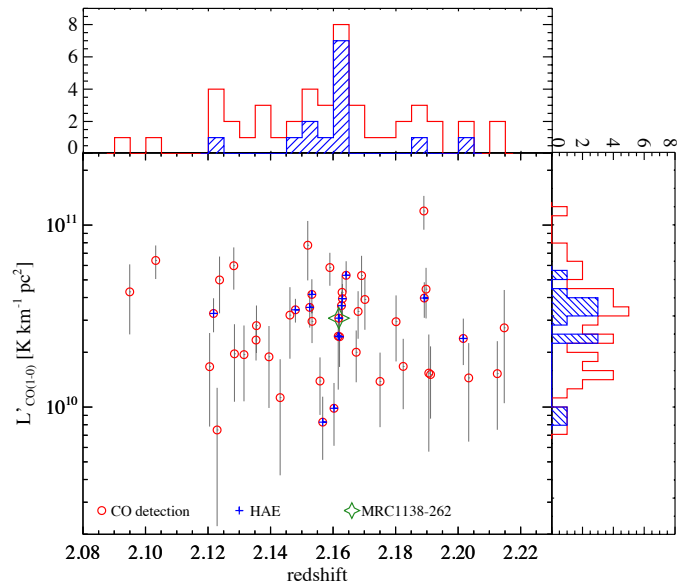


Fig. 4. CO luminosities vs. redshifts for CO detections in this study. Top and right panels show the redshift and CO luminosity distribution of our detections, respectively. In histograms, all CO emitters are shown in red, and HAEs with CO detections are shown in blue.

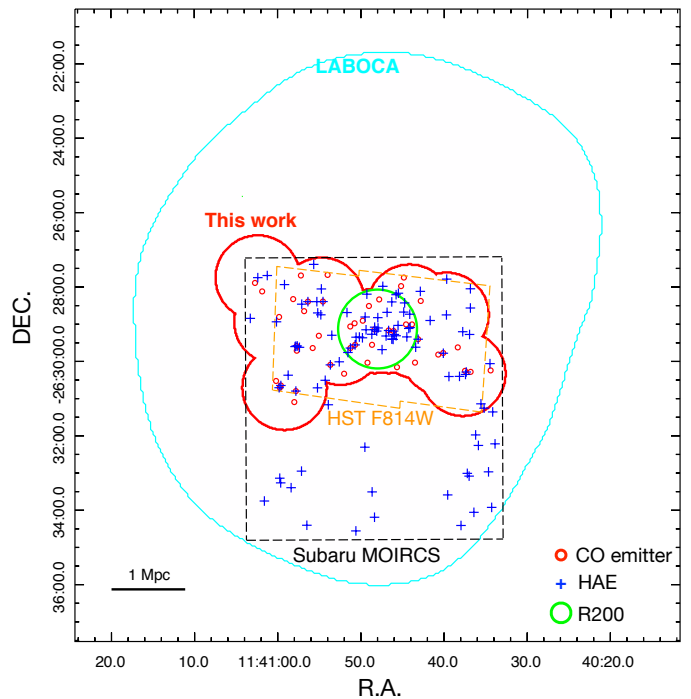


Fig. 5. The footprints of this work and previous studies, overlaid by CO sources (red circles) in this work and HAEs (blue crosses) in Koyama et al. (2013) and Shimakawa et al. (2018). The R_{200} radius (Shimakawa et al. 2014) is shown in a green circle centering on the MRC1138-262.

km s^{-1} and sky distances of $0'.3 - 4'.0$ to the central galaxy. Robust sources ($\text{SNR} > 5$) are also found at large velocity (e.g., 5500 km/s) and large distance (up to $3'.7$) to the center, which further strengthens the large structure indicated by the large redshift range $z = 2.12 - 2.21$ of the CO overdensity (Sec. 4.2). Meanwhile as indicated by the histogram in Fig. 6-left, 90% of the CO emitters are found to have large distances $0'.5 - 4'$ to the central radio galaxy. Thus the single pointings of VLA or ATCA observations at 7mm focusing on the center radio galaxy only

covers 10% of CO sources presented in this work. Regarding the field of view of ALMA, only the ALMA compact array (ACA) at 3 mm can have comparable primary beam (FWHM $\sim 1'.7$) as the VLA and ATCA ones. Thus it is also impractical to discover large structures similar as the Spiderweb protocluster in single pointing mode. Therefore, surveys with large area (> 20 arcmin²) are essential to discover the majority of CO emitters in similar structures as found in this study. On the other hand, narrow-band imaging can cover large area (Koyama et al. 2013; Shimakawa et al. 2018) but the redshift range probed covers only 18% of the velocity range observed by ATCA which is thus unable to discover such large structure.

Given the large velocity and spacial offsets from the center galaxy, some CO sources do not appear to be gravitationally bound to the center galaxy. In Fig. 6-right, we present the normalized velocity and distances to the center for CO emitters in this work and HAEs with spectroscopic redshifts (Shimakawa et al. 2018). Shimakawa et al. (2014) calculated a mass of $1.71 \times 10^{14} M_{\odot}$ for the Spiderweb protocluster assuming virialization in the core. Using this mass, galaxies with velocities that fall within the region enveloped by the two curves (Rhee et al. 2017) are expected to be gravitationally bound. We find that 21 CO emitters have velocities inside the region enclosed by the two curves. In contrast, the remaining CO sources scatter largely in the diagram with velocities faster than the escape velocities which are thus unlikely to be bound with the cluster core. They concluded that the two groups are not gravitationally bound to the core system and will remain distributed within the overall galaxy cluster. In this work, the velocities of CO emitters out of the bound region are 1–5 times larger than the escape velocities. Meanwhile, these unbound CO emitters are mostly at large distance (88% have $R > R_{200}$), only four sources (including the center radio galaxy) are found within the R_{200} radius. This is in line with the picture drawn in Shimakawa et al. (2014) where the center is already collapsed and nearly virialized. The outer regions appears still highly structured and some CO emitters could be at the early phase of assembly towards the protocluster core.

4.4. Comparison to previous surveys

This catalogue contains 46 robust CO(1-0) detections which is the largest catalogue of CO emitters in a galaxy cluster field, and among the largest ones published for one contiguous field ever. In Table 4, we compared this catalogue to CO surveys from the literature in both high- z galaxy (proto)clusters and blank fields. To keep consistency, we show only the number of detections that are found with counterparts in high resolution images (e.g., HST, ALMA and VLA). In terms of the observed area, the 21 arcmin² covered by ATCA is the largest one ever observed in protocluster fields to date while the observed area of other surveys in protocluster fields are smaller by factors of 3–10. The number of 46 detected sources in Spiderweb field is larger than the numbers presented in other protocluster work by a factor of 2–15. Thus the CO emitter sample in this study constitutes the largest CO sample in a protocluster to date. We note that CO emitters in other protoclusters could be underestimated. As mentioned in Sec. 4.3, it is possible that other high- z protoclusters also contain a large number of CO emitters but the majority of them would be missed due to the small area observed. This sample size is also comparable with respect to surveys in blank fields, e.g., COLDz (Pavesi et al. 2018; Riechers et al. 2020a), ASPECS (González-López et al. 2019; Decarli et al. 2019) and PHIBSS2 (Lenkić et al. 2020). These CO surveys in blank fields have been used to constrain the CO luminosity function. Similarly, the large num-

ber of CO emitters with a significant overdensity in the Spiderweb cluster enables us to constrain the CO luminosity function and molecular gas density in an overdense region for the first time.

4.5. CO(1-0) line width versus luminosity

The relationship between CO luminosity, and CO line width is an analogue of the Tully-Fisher relation (Tully & Fisher 1977) which can be interpreted as a relationship between the molecular gas mass and the velocity necessary for centrifugal support of a rotating disk (Bothwell et al. 2013). Although showing a large scatter, this relation is a practical tool that enables us to indicatively diagnose the size and mass of gas reservoirs without high resolution imaging.

In Fig. 7-top, we show the CO(1-0) luminosity L'_{CO} versus the full-width-half maximum (FWHM) of our detections. In addition, we include low- J CO observations, tracing the cold molecular gas, of high- z galaxy (proto)clusters: CO(2-1) observations of a cluster at $z = 1.46$ (Hayashi et al. 2017), CO(1-0) observations of two clusters at $z = 1.62$ and 2.51 (Rudnick et al. 2017; Wang et al. 2018), respectively. The CO(2-1) luminosities are converted into CO(1-0) luminosities using the brightness temperature ratio $r_{21}=0.76$ (Daddi et al. 2015). CO emitters in Wang et al. (2018) and Hayashi et al. (2017) cover a wide parameter space on the plot, while other samples are limited to smaller luminosity and FWHM range due to small sample size and shallow depths. We show the parametrization of the $L'_{\text{CO}(1-0)}$ vs. FWHM relationship for few representative cases: the relation for SMGs between these two parameters established by Bothwell et al. (2013) (radius = 7 kpc and $\alpha_{\text{CO}} = 1$), a disk model with a radius of 13 kpc from Dannerbauer et al. (2017), a disk galaxy and a spherical model described in Aravena et al. (2019). The four lines have the same slope but different normalizations due to the assumption of different disk radius and α_{CO} . The relation of spherical models (i.e., with small radius and low α_{CO}) is above other models in larger disk size and high α_{CO} . Compact galaxies with low α_{CO} (e.g., starbursts) tend to have higher CO luminosity at fixed FWHM while the $L'_{\text{CO}(1-0)}$ –FWHM relation of typical disk galaxies tend to be lower than the relation of compact starbursts.

Interestingly, we find that a dozen of CO sources show higher ratios of CO luminosity to line width compared to other galaxy cluster samples which are above the solid line for disk model (Fig. 7-top) from Bothwell et al. (2013). Some members of the Spiderweb protocluster lie close and/or even above the ‘spherical’ model line presented in Aravena et al. (2019). Compared to other high- z cluster members, our cluster members have a larger CO luminosity at specific line width than the samples from Hayashi et al. (2017), Rudnick et al. (2017) and Wang et al. (2018). Overall, we find larger CO luminosities at fixed line width than all other previous surveys. We note that the optical/near-infrared images (see Fig 3 and Appendix A) show that the morphologies of our cluster members are complex and almost half of them appear irregular. The fit to the spherical CO gas models and their irregular morphology together suggest that these galaxies are merger-like systems, consistent with the expected high merger rate in galaxy cluster environments at high redshift (Coogan et al. 2018). Therefore, their L'_{CO} appears similar to SMGs suggesting that this cluster is rich of SMGs (and mergers) with respect to other high- z clusters. This further strengthens the conclusion presented in Dannerbauer et al. (2014).

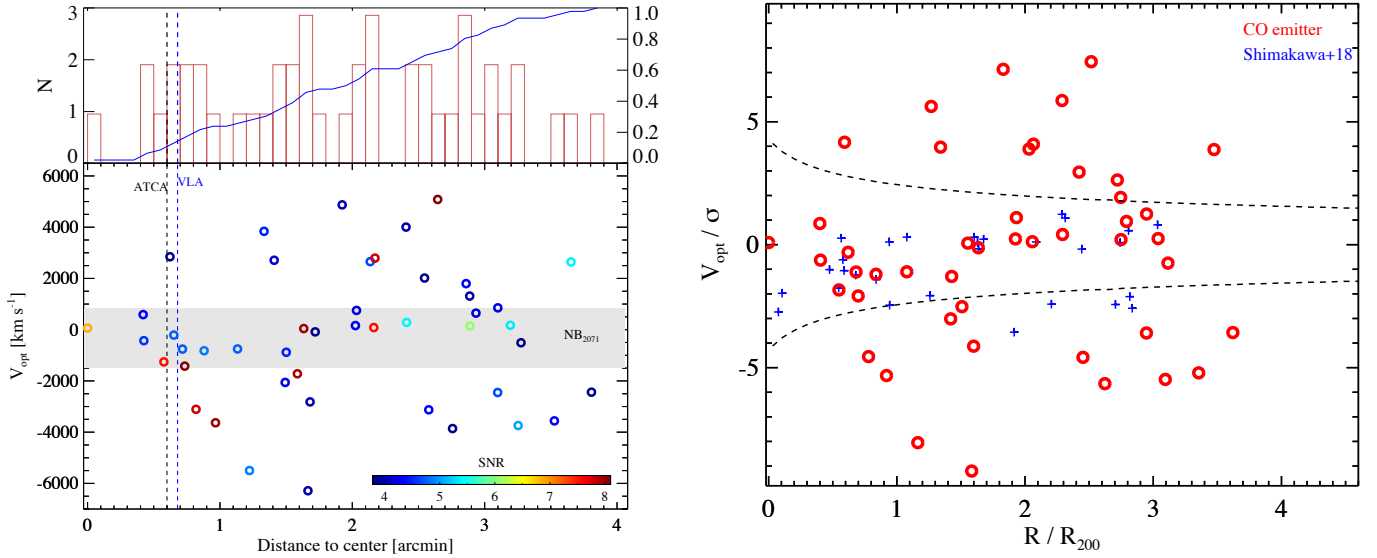


Fig. 6. *Left panel:* Distribution of CO emitters vs. their sky distances to the central radio galaxy MRC1138-262. Top panel shows histogram (red) and cumulative fraction (blue) of CO emitters as a function of the distances to the center galaxy. In the bottom panel, CO emitters are color-coded with their SNR. Grey shaded area marks the redshift range observed by the narrow band N_{2071} (Shimakawa et al. 2018) of MOIRCS at Subaru. Blue and black dashed lines mark the field of view of VLA and ATCA single pointing, respectively. *Right panel:* Normalized velocity vs. distance to center galaxy for CO emitters in this study and HAEs with a spectroscopic redshift (Shimakawa et al. 2018). The normalization factors are $\sigma = 683 \text{ km s}^{-1}$ and $R_{200} = 0.53 \text{ Mpc}$ (Table 2 in Shimakawa et al. 2014). The two dashed curves show the escape velocity (positive and negative) as a function of distance from the cluster mass $1.71 \times 10^{14} M_{\odot}$ (Shimakawa et al. 2014) using prescription in Rhee et al. (2017). Half of the CO emitters in this work have velocities outside of the region enclosed by these two curves which are not expected to be gravitationally bound to the central mass.

Table 4. CO surveys in high- z clusters and blank fields

Project	Facility	Field	z	CO transition	$N_{\text{det,ctp}}$	Area [arcmin ²]	Reference ^d
(High-z clusters)							
COALAS	ATCA	Spiderweb	2.16	J=1	46	21.3	This study
–	VLA	CL J1001 ^b	2.51	J=1	14	1.3	W16,18
–	ALMA	XMMXCS J2215.9-1738 ^c	1.46	J=2	17	2.3	H17
–	ALMA	SpARCS-J0225	1.60	J=2	13	2.6	N17,19
–	ALMA, VLA	Cl J1449+0856	1.99	J=1,3,4	8	1.5	C18
–	ALMA	DRC	4.00	J=6	10	1.0	O18
–	ALMA	SPT2349-56	4.30	J=4	8	0.2	M18
–	ALMA	Spiderweb	2.16	J=3	4	0.6	T19
–	ALMA	USS1558-003	2.53	J=3	6	0.6	T19
–	ALMA	4C23.56	2.49	J=3	6	0.6	T19
–	ALMA, VLA	HXMM20	2.60	J=1,3	5	0.8	GG19
–	ALMA	HELAISS02	2.17	J=3	3	0.6	GG19
–	ALMA	4C23.56	2.49	J=4	11	0.5	L19
–	ALMA	SPT2349-56	4.30	J=4, [CII]	24	7.2	H20
(Blank fields)							
ASPECS-pilot	ALMA	HUDF	–	J=2–4,7,8	9	1.2	D16
COLDz	VLA	GOODS-N,COSMOS	–	J=1,2	17	59.8	P18, R19
ASPECS	ALMA	HUDF	–	J=2–4	18	4.6	GL19, D19
PHIBSS2	PdBI	<i>d</i>	–	J=2–6	43	130.0	L20

Notes. $N_{\text{det,ctp}}$: Number of detection with counterpart.

^a W16,18: Wang et al. (2016, 2018); H17: Hayashi et al. (2017); N17,19: Noble et al. (2017, 2019); C18: Coogan et al. (2018); O18: Oteo et al. (2018); M18: Miller et al. (2018); T19: Tadaki et al. (2019); GG19: Gómez-Guijarro et al. (2019); L19: Lee et al. (2019); GL19: González-López et al. (2019), D16: Decarli et al. (2016); D19: Decarli et al. (2019); L20: Lenkić et al. (2020), H20: Hill et al. (2020).

^b Gómez-Guijarro et al. (2019) identified six of the 14 emitters as tentative detections. Champagne et al. (submitted) indicate a different explanation for the CO emitters using new VLA observations.

^c This cluster is also studied by Stach et al. (2017) who found 6 CO(2-1) emitters with shallower ALMA observations.

^d COSMOS, GOODS-N and EGS.

In Fig. 7-bottom, we normalized the CO luminosity by FWHM^2 as an indicator of starburstiness, and show their sky distance to the center galaxy. Intriguingly, the most starburst-like galaxies, i.e., sources above the spherical model in Aravena et al. (2019), locate at $> 0'.5 - 3'.7$ away from the center galaxy. These galaxies would be totally missed in single pointing observations at 7mm with ATCA and VLA, if the phase center is focusing on the center cluster galaxy. Given that other surveys in protocluster fields are all observing a small area, the majority of starbursting members in protoclusters would be missed if the starbursting members are also far away from the center as in the Spiderweb. In this case, the starburst/merger rates in high- z protoclusters could be significantly underestimated due to the limited field of view. This work indicates that conventional single pointing observations could have severe bias in protocluster fields that missed the bulk of starbursting members.

4.6. CO(1-0) luminosity function

Our large CO(1-0) sample enables us to establish the CO luminosity function and study the molecular gas density in a galaxy protocluster environment for the first time. We construct the CO luminosity function adopting Eq. 2 from Decarli et al. (2016):

$$\Phi(\log L_i) = \frac{1}{V_c} \sum_{j=1}^{N_i} \frac{R_j}{C_j} \quad (5)$$

where N_i is the number of galaxies that fall within the luminosity bin $\log L_i - 0.25$ and $\log L_i + 0.25$, V_c is defined as the observed co-moving volume, C_j is the completeness described in Section 3.4 and R_j is the reliability. Note that Lenkić et al. (2020) introduced two association probabilities to weight each detection which are the probability of an optical counterpart associated with a particular CO transition $P_{z,j}$ and the probability of a line detection spatially associated with an optical counterpart $P_{a,j}$. However, in this study, $P_{z,j}$ equals to 1 as all lines are identified as CO(1-0), and $P_{a,j}$ is close to 1 because we used tolerance $< 3''$ to match any optical counterpart and the uncertainty of spatial association is negligible with respect to 5–13'' beam sizes. Thus we stick to the equation by Decarli et al. (2019). We adopt $R = 1$ for a source with a counterpart and a matching of a previously known/obtained spectroscopic redshift. In cases of sources without a spectroscopic redshift, we conservatively treat the reliability from SoFiA as upper limits. In each luminosity bin, the CO space densities are created 1000 times, each time the reliability R_j is distributed to a random value that is uniformly distributed between 0 and such upper limit (see also González-López et al. 2019; Pavese et al. 2018; Riechers et al. 2019). Line candidates are kept in our analysis only if the random value is below the reliability threshold. The final CO luminosity functions are the medians of all the CO LF realizations and the uncertainty is computed as Poissonian uncertainty $\sqrt{N_i}$.

In order to calculate the volume, first we define the redshift range of this cluster as $z = 2.146 - 2.17$ (i.e., 33 co-moving Mpc or ± 1200 km/s) being determined by the redshift range of the HAEs in this cluster (Fig.4). This redshift range is also consistent with the $z = 2.15 - 2.17$ used in Dannerbauer et al. (2014) for calculating the SFRD, which enable us to consistently compare the CO space density to the SFRD. The total sky coverage of the ATCA mosaic is 25.8 arcmin². We exclude shallow areas that have rms noise > 1 mJy per beam where no source is detected there, thus we adopt 21.3 arcmin², i.e., 53 cMpc². We also compute the CO luminosity function for detections at the redshift range $z = 2.12 - 2.21$ (124 cMpc) as

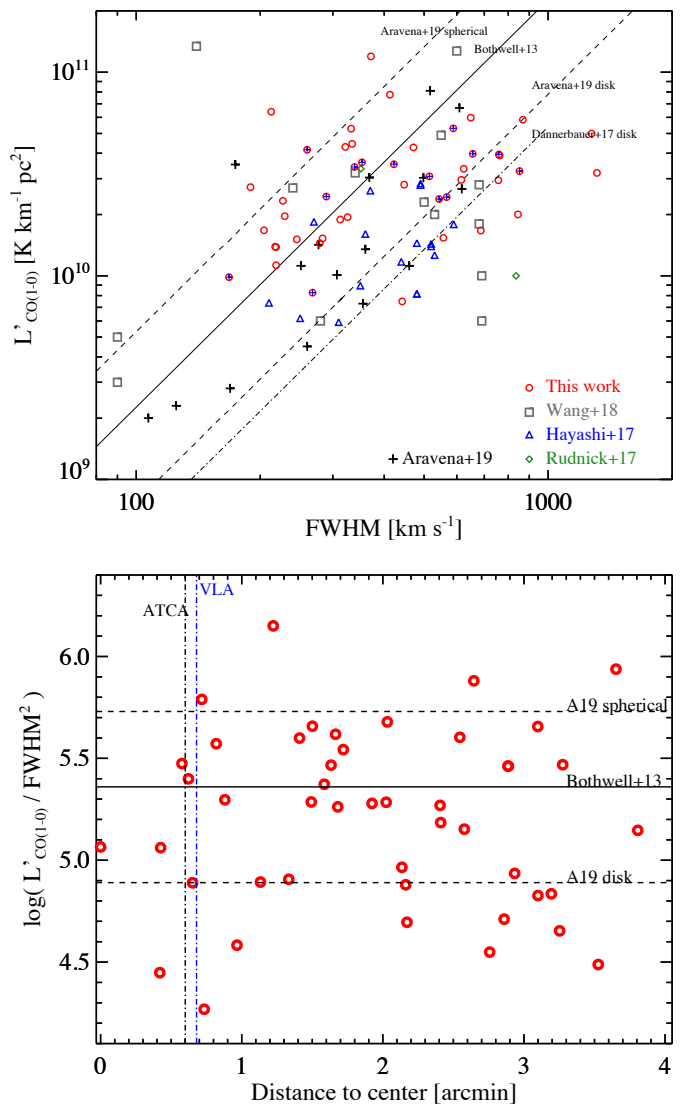


Fig. 7. *Top panel:* CO luminosity vs. FWHM. CO detections in this study are shown in red circles with HAEs marked by blue crosses. The dashed lines are from Aravena et al. (2019) where the upper line represents a spherical model and the bottom line a disk model. ASPECS galaxies (Aravena et al. 2019) are shown in black pluses which lie mostly along the disk model line. The solid line shows the relation from Bothwell et al. (2013), dot dashed line presents the disk model from Dannerbauer et al. (2017). *Bottom panel:* CO luminosity normalized by FWHM^2 vs. distance to the center galaxy. Vertical lines mark the half FWHM of ATCA (black) and VLA (blue) primary beams, respectively. This figure shows that CO emitters in Spiderweb cluster are more likely to be starbursts (mergers) compared to other high- z clusters, and these starbursts are beyond the FoV of the single pointing focusing on the central galaxy.

an overdensity of CO emitters is also seen within this redshift range (Fig. 4). Therefore, the observed co-moving volume is ~ 6600 cMpc³ for the redshift range $z = 2.12 - 2.21$, and ~ 1650 cMpc³ for $z = 2.146 - 2.17$, respectively. We show the CO number densities for the two redshift ranges in Fig. 8 and Table 5. The CO luminosity function is calculated in luminosity bins of 0.5 dex width to compare consistently with the COLDz LF, starting $\log(L'_{\text{CO}} / \text{K km s}^{-1} \text{pc}^2) = 10.1$ in steps of 0.1 dex. The $\log(L'_{\text{CO}} / \text{K km s}^{-1} \text{pc}^2) < 10.1$ bins are ignored because of the small sample size and high incompleteness. The CO space density at $z = 2.146 - 2.17$ is consistent with the ones at

Table 5. CO(1-0) luminosity function

$\log L'_{\text{CO}}$	$z = 2.146\text{--}2.17$		$z = 2.12\text{--}2.21$	
	N	$\log\Phi_{\text{CO}}$	N	$\log\Phi_{\text{CO}}$
10.1–10.6	12	[-2.12, -2.48]	28	[-2.04, -2.13]
10.2–10.7	13	[-2.08, -2.42]	27	[-2.15, -2.27]
10.3–10.8	16	[-2.02, -2.32]	26	[-2.25, -2.53]
10.4–10.9	14	[-2.08, -2.43]	22	[-2.37, -2.56]
10.5–11.0	12	[-2.09, -2.42]	18	[-2.49, -2.73]
10.6–11.1	6	[-2.40, -3.01]	10	[-2.71, -2.06]
10.7–11.2	4	[-2.52, -3.25]	6	[-2.99, -2.64]
10.8–11.3	1	< -2.95	2	< -3.49

$z = 2.12\text{--}2.21$ within error bars (Fig. 8-right). Note that the narrow redshift range $z = 2.146\text{--}2.17$ is also comparable with the gravitationally bound region in Fig. 6-right, the similar amplitudes of CO LFs in the two redshift ranges indicate that the CO space density is not enhanced in the gravitationally bound region of the cluster core. Given that the larger number of sources found in the wide redshift range can better constrain the CO luminosity function than done with the narrower redshift range, we thus adopt the CO luminosity function at $z = 2.12\text{--}2.21$ for further analysis.

Furthermore, we verified the CO luminosity function for robust sources ($\text{SNR} > 5$) at $z = 2.12\text{--}2.21$. We found that the median amplitude of CO LF would be scaled down by 0.5 dex due to having less galaxies per luminosity bin but still one order of magnitude higher than that for COLDz and agrees with the density of the full sample within error bars. On the other hand, given that $\text{SNR} > 5$ sources are robustly detected, using their *Reliability* as upper limits appears too conservative and would overkill, we thus directly adopt their *Reliability* from SoFiA as the R_j in Eq. 5, and found that the resulted CO LF for $> 5\sigma$ sources is in excellent agreement with the best fit (Fig. 8-left). Therefore, These confirms that our results of CO luminosity function are robust and even conservative.

We fit the observed CO(1-0) luminosity function (LF) of $z = 2.12\text{--}2.21$ with a Schechter function (Schechter 1976), in the logarithmic form used in Riechers et al. (2019),

$$\log\Phi = \log\Phi_* + \alpha \log \frac{L'}{L'_*} - \frac{1}{\ln 10} \frac{L'}{L'_*} + \log(\ln 10) \quad (6)$$

where Φ_* is the scale number of galaxies per unit co-moving volume, in units of $\text{cMpc}^{-3} \text{dex}^{-1}$, L'_* is the scale line luminosity in units of $\text{K km s}^{-1} \text{pc}^2$ (the ‘‘knee’’ of the luminosity function) and α is the slope of the faint end. We show the best fitting results for CO LF at $z = 2.12\text{--}2.21$ in Table 6, including one fit with free parameters and two with fixed slopes. The best fit with free Schechter parameters has $\alpha = -0.21 \pm 1.13$, $\log(L'_*/\text{K km s}^{-1} \text{pc}^2) = 10.48 \pm 0.38$ and $\log\Phi_* = -2.16 \pm 0.49$. We note that the slope of the faint end of the LF, α , is very uncertain due to the limited number of galaxies. This parameter is sensitive to the corrections we applied for reliability and completeness.

In order to consistently compare our result with studies from the literature, we fit the CO LF with fixed values of α in our analysis, adopting $\alpha = 0.08$ from the COLDz CO(1-0) LF (Riechers et al. 2019) and $\alpha = -0.2$ from the ASPECS project (Decarli et al. 2019), respectively. As listed in Table 6, the best fit

Table 6. Schechter function fit parameter constraints to CO(1-0) luminosity function at $2.12 < z < 2.21$

α	$\log L'_*$	$\log\Phi_*$
-0.21 ± 1.13	10.48 ± 0.38	-2.16 ± 0.49
0.08*	10.39 ± 0.06	-2.06 ± 0.07
-0.20^*	10.48 ± 0.07	-2.16 ± 0.09

* The value is fixed in the fitting procedure.

with fixed $\alpha = 0.08$ shows $\log(L'_*/\text{K km s}^{-1} \text{pc}^2) = 10.39 \pm 0.06$ and $\log\Phi_* = -2.06 \pm 0.07$. The $\log L'_*$ is close to the COLDz $\log(L'_*/\text{K km s}^{-1} \text{pc}^2) = 10.7$ (50th percentile) while the CO number density Φ_* in this study is 2.6 ± 0.5 dex higher than COLDz number density. If we adopt $\alpha = -0.2$ as in Decarli et al. (2019), we would get $\log(L'_*/\text{K km s}^{-1} \text{pc}^2) = 10.48 \pm 0.07$ and $\log\Phi_* = -2.16 \pm 0.09$, – the density is still more than one order of magnitude higher than the estimated one in COLDz. Comparing with number densities Φ_* from ASPECS (Decarli et al. 2019), our results are higher than ASPECS CO(3-2) density at $z \sim 2.6$ by 1.4 ± 0.5 dex. To summarize, the fits with fixed slopes show a consistent scaled line luminosity $\log(L'_*/\text{K km s}^{-1} \text{pc}^2) \sim 10.5$ and number density ($\log\Phi_* \sim -2.2$) to the fit with free parameters. All fits on our sample show more than 1.5 dex higher number density of CO emitters than the COLDz and ASPECS surveys.

For comparison, we add data from the literature: the observed CO LFs from the field galaxy sample COLDz (Riechers et al. 2019) and Vallini et al. (2016). The CO luminosity density in the Spiderweb cluster is remarkably higher than that in field galaxy samples, e.g., 1.3–1.6 orders of magnitude higher than the median value in COLDz survey at $\log(L'_{\text{CO}}/\text{K km s}^{-1} \text{pc}^2) \sim 10.5$, and 3.4 orders of magnitude higher than the results from Vallini et al. (2016). Recently, Zavala et al. (2019) provided a constraint on gas content in protoclusters at $z \sim 2.0\text{--}2.5$ based on ALMA continuum observations which show enhanced gas density in protocluster environment. Our results agree well with the lower limits in Zavala et al. (2019), only the extrapolation of the Schechter function at $\log(L'_{\text{CO}}/\text{K km s}^{-1}) > 11$. Furthermore, we compare with results from the semi-analytic models in Lagos et al. (2012) and Lagos et al. (2020) predicted for both the random field and the overdense environment. We refer to a detailed discussion on the comparison in Sec. 5.2.

4.7. Molecular gas density in the Spiderweb protocluster

In general, the cold molecular gas density can be obtained via integrating the CO(1-0) luminosity functions and applying a fixed CO to H_2 conversion factor α_{CO} for all CO emitters. However, the α_{CO} of these CO emitters are uncertain. Some CO emitters appear to be starbursts (see Sec 4.5) which have lower α_{CO} than that applied for field galaxies (e.g., $\alpha_{\text{CO}} = 3.6 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ in Riechers et al. 2019 and Decarli et al. 2019). In order to have a reasonable conversion to cold molecular gas mass, we apply two typical α_{CO} values for starbursts and normally star-forming galaxies that are diagnosed by the L'_{CO} –FWHM diagram, respectively. For the 19 CO sources above the Bothwell et al. (2013) line in Fig 7, we adopt a starburst-like $\alpha_{\text{CO}} = 0.8 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ (Emonts et al. 2018), and adopt $\alpha_{\text{CO}} = 3.6 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ (Daddi et al. 2010) for the rest of sources that appear to be disk-like. Given that Wang et al. (2018) adopted $\alpha_{\text{CO}} \gtrsim 4.0 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ in the $z = 2.5$ starburst-

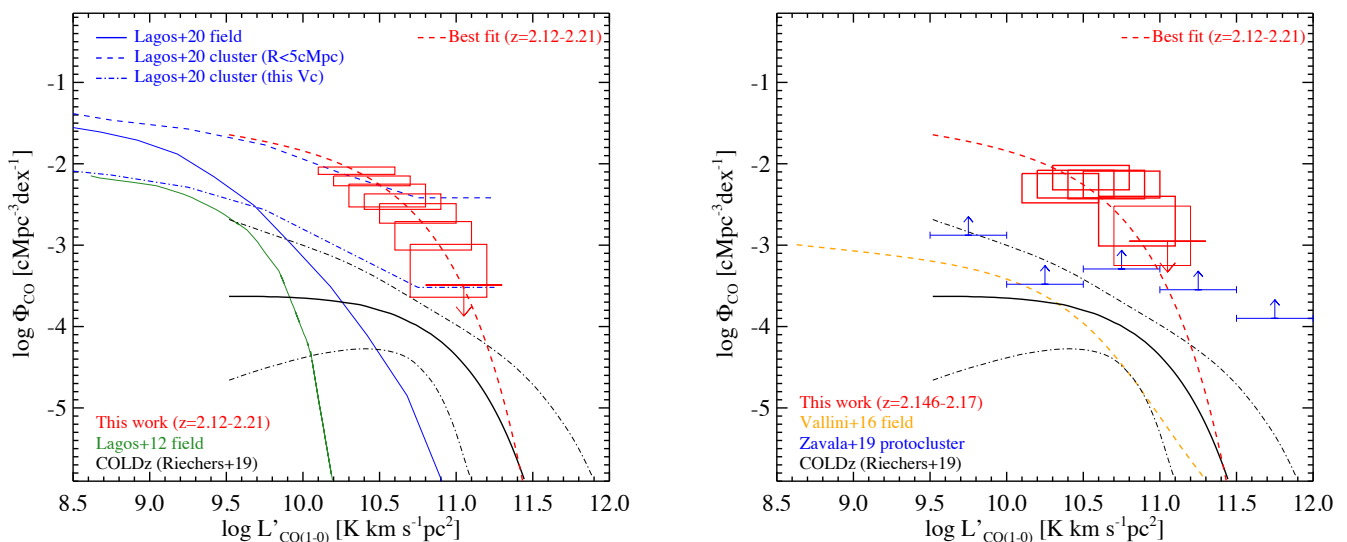


Fig. 8. The CO(1-0) luminosity functions for the Spiderweb cluster and samples from the literature. *Left:* CO(1-0) luminosity density in each luminosity bins at $z = 2.12\text{--}2.21$ in this work, compared with the results at $z \sim 2$ from the COLDz (Riechers et al. 2019), and predictions from semi-analytic SHARK models (Lagos et al. 2012, 2020). The dotted-dashed black lines mark the 5th and 95th percentile of the COLDz LF. Red dashed curve shows the best fit to our data. We show CO luminosity functions for protoclusters derived from SHARK models within two different volumes. One (blue dashed curve) is calculated in a spherical volume with radius $R < 5$ cMpc and the other one (blue dot-dashed curve) is in the identical volume to where the observed CO LF is measured, respectively. *Right:* Same as the left panel, but boxes are shown for CO luminosity density in a narrow redshift range $z = 2.146\text{--}2.17$. Blue arrows mark the lower limits for protoclusters in Zavala et al. (2019), and orange curve shows the results from Vallini et al. (2016).

ing cluster (which are determined following Genzel et al. 2015), the values applied in this work are conservative.

In order to calculate the cold molecular gas density, we followed three different methods: (1) We simply sum up the CO(1-0) luminosity of all detections at $z = 2.12\text{--}2.21$ in our catalogue (taking into account the flux boosting) and convert it into the cold molecular gas using α_{CO} described above. By dividing the total cold molecular gas mass by the co-moving volume, we obtain a cold molecular gas density $\rho(\text{H}_2) = 5.9 \times 10^8 M_{\odot} \text{Mpc}^{-3}$; (2) We derive the cold molecular gas density by adopting a similar method presented in Decarli et al. (2016), summing up and weighting gas mass of each CO detection by completeness and reliability same as we did for the calculation of the CO luminosity function (Section 4.6), i.e.,

$$\rho(\text{H}_2) = \frac{1}{V} \sum_{j=1}^{N_i} \frac{M_j R_j}{C_j} \quad (7)$$

where M_j is the gas mass the j th galaxy calculated as $M_j = \alpha_{\text{CO},j} L'_{\text{CO}(1-0),j}$. We obtain a high value for the cold molecular gas density $\rho(\text{H}_2) = 9.0_{-3.4}^{+3.6} \times 10^8 M_{\odot} \text{Mpc}^{-3}$ with uncertainties of 5th and 95th percentiles; (3) Assuming the same CO LF slope as the COLDz work, we derive the cold gas density by scaling up the COLDz CO(1-0) LF to our work. The COLDz project (Riechers et al. 2019) reported a cold molecular gas density of $1.1 - 5.6 \times 10^7 M_{\odot} \text{Mpc}^{-3}$ at $z \sim 2$ assuming $\alpha_{\text{CO}} = 3.6 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$. The COLDz CO(1-0) LF (50th percentile) shows $\log(L'_{*}/\text{K km s}^{-1} \text{pc}^2) = 10.7$, $\log\Phi_{*} = -3.87$ and $\alpha = -0.08$. Comparing to our Schechter function fit with the same slope (Table 6), our CO LF is 1.7 ± 0.06 dex higher in scaled number density and 0.2 ± 0.05 dex lower in scaled luminosity. The integrated Schechter function is $L_{\text{int}} = \Phi_{*} L'_{*} \Gamma(\alpha + 2)$. Thus, the cold molecular gas density in this protocluster would be 1.5 magnitude higher than that in the COLDz survey, i.e., $\rho(\text{H}_2) = 1.06_{-0.24}^{+0.31} \times 10^9 M_{\odot} \text{Mpc}^{-3}$ adopting the same $\alpha_{\text{CO}} = 3.6$.

This calculation will be scaled down by a factor of 1.3 using the specified α_{CO} described above. We note that the calculations (1) and (2) are based on only the observed part of the luminosity function, undetected galaxies in lower luminosity bins are not accounted for the given large uncertainties in the individual luminosity bins and the unknown intrinsic shape of the CO luminosity function. The three calculations agree well with each other while the estimate (2) appears conservative but consistent with the results of (1) and (3). We thus adopt the calculation (2) and estimate the H_2 density $\rho(\text{H}_2) = 0.56\text{--}1.26 \times 10^9 M_{\odot} \text{Mpc}^{-3}$ in the Spiderweb galaxy protocluster.

In Fig. 9, we compare the cold molecular gas density with results from the COLDz (Riechers et al. 2019) and ASPECS (Decarli et al. 2016, 2019) surveys. Similar to the CO luminosity function, the H_2 density in the Spiderweb cluster is two orders of magnitude higher than that determined in field galaxy samples like COLDz and ASPECS. We note that the ASPECS H_2 densities (Decarli et al. 2019) based on CO(3-2) with assumed $r_{31} = 0.42 \pm 0.07$ should be scaled down by a factor of two on average as calibrated by VLA CO(1-0) followups (Riechers et al. 2020a) which has been recently updated in Decarli et al. (2020) adopting $r_{31} = 0.84 \pm 0.26$ from Riechers et al. (2020a). The H_2 density in this galaxy protocluster is completely based on CO(1-0), the best tracer of the cold molecular gas and free from CO excitation issues.

An important caveat here is that the H_2 density strongly depends on the adopted α_{CO} . Here, we adopted a bimodal α_{CO} . Although this is a good representation of the full sample, the value of α_{CO} for individual galaxies can be highly uncertain.

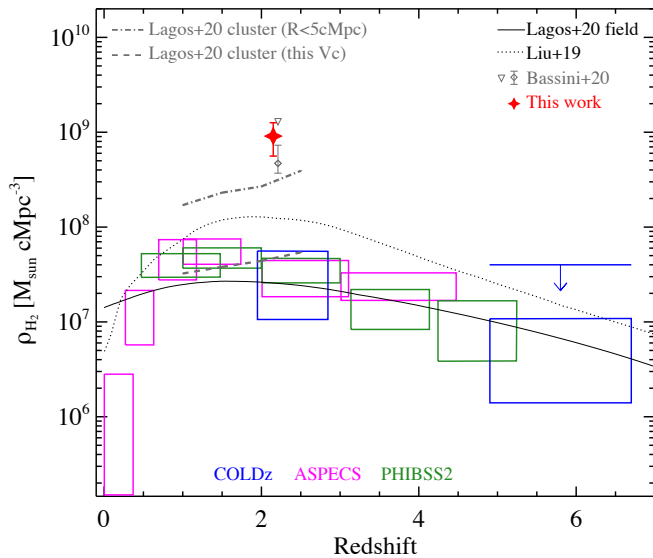


Fig. 9. H_2 density of this study (the red star) compared to results from COLDz (Riechers et al. 2019), ASPECS (Decarli et al. 2020) and PHIBSS2 (Lenić et al. 2020) overlaid by fitting of field galaxy samples from Liu et al. (2019) and Lagos et al. (2020). Gas density in galaxy clusters from simulations are shown in gray curves for SHARK (Lagos et al. 2020) in two volumes, and gray diamond with a bar for DIANOGA (Bassini et al. 2020), respectively. The gray diamond with error bar shows the median, and the downward triangle marks the maximum values for cluster structures in DIANOGA simulations. The gas density in this work is significantly higher than observed in blank fields and also higher than predictions for clusters in simulations.

5. Discussion

5.1. Is the Spiderweb a super-protocluster?

The redshift range of the CO emitters ($z = 2.12 - 2.21$) is a factor of four wider than the redshift range of HAEs and LAEs in this field and indicates a size of 124 Mpc in co-moving distance along the line of sight. Kurk et al. (2000) conducted narrow band $Ly\alpha$ imaging in this field using the VLT/FORS. They used a narrow band filter with a central wavelength of 381.4 nm and a FWHM of 6.5 nm, covering a redshift range of $z = 2.111 - 2.164$. Pentericci et al. (2000) followed up the LAEs selected from Kurk et al. (2000) with the VLT/FORS in MOS mode. They confirmed redshifts of $Ly\alpha$ emitters mostly at $z = 2.14 - 2.17$ except one quasar at $z = 2.183$ with a $Ly\alpha$ absorption feature. Kuiper et al. (2011) discovered a sample of satellite galaxies around the center galaxy MRC1138-262 via detecting $H\alpha$, [O II] and [O III] emissions with SINFONI spectroscopy. Their redshifts span $z = 2.13 - 2.17$, larger than the redshift range of narrow-band-selected HAEs (Koyama et al. 2013; Shimakawa et al. 2018). Both the LAEs and HAEs selected in this field are limited on a narrow redshift range due to use of narrow band filters. The velocity distribution of the confirmed satellite galaxies shows a broad, double-peaked velocity structure with $\sigma = 1013 \pm 87 \text{ km s}^{-1}$ which is proposed to be a result of the merger of two subclusters (Kuiper et al. 2011). Including all spectroscopically confirmed HAEs and LAEs, Shimakawa et al. (2014) measured a velocity dispersion of 683 km s^{-1} in the cluster core with a $R_{200} = 0.53 \text{ Mpc}$ in physical distance. However, in this study, the CO emitters show a much larger spread in redshifts and sky which can not be interpreted as an effect of pure velocity dispersion of cluster galaxies as it would lead to a unrealistically large dispersion exceeding 4000 km s^{-1} . Furthermore,

since robust sources ($\text{SNR} > 5$, Fig. 6) are found to be at large velocity (e.g., 5500 km s^{-1}) and large distance (e.g., $3'.7$), the large spread of velocities and distances to the center cannot be explained as a selection effect. Thus we argue that the large redshift range of CO emitters is tracing a large scale structure that is significantly wider than the assumed previously one. Overall, the CO emitters provide us a very different view of the protocluster structure than that of $Ly\alpha$ and $H\alpha$ emitters, and appear to be better tracers of the large scale matter density.

The $\sim 120 \text{ Mpc}$ co-moving size is significantly larger than the scale of any known galaxy (proto)clusters at low and high redshift, beside the supercluster Hyperion (Cucciati et al. 2018) that is found with a radial size of 150 cMpc . Note that the overdensity of CO emitters at $z = 2.12 - 2.21$ is only slightly higher than the density of the remaining redshift range covered by the ATCA. This structure could be larger than what we observed and more comparable to the radial scale of the Hyperion. This might indicate that we observe a galaxy super-protocluster similar as the Hyperion (Cucciati et al. 2018). However, given that the 53 cMpc^2 area covered by ATCA is 72 times smaller than the $60 \times 60 \text{ cMpc}^2$ size of the Hyperion, possibly this structure could be a protocluster connected to a large scale filamentary structure along line of sight. We are not able to distinguish if this structure is a filament or a super-protocluster with the current data in hand. In case of a super-protocluster, such large structure appears unlikely to totally collapse by $z = 0$, given that half of the CO emitters in this study appears not bound with the central mass (Fig. 6-right). This also holds for the Hyperion. However, filaments can act as highways to fuel the inner regions of clusters with gas and galaxies, as indicated by the ThreeHundred simulations (Rost et al. 2020). There, filaments around clusters can extend out to five R_{200} that are comparable with the distances between the CO emitters and the center core in this study. Thus the collapse of the gas and dark matter would be accelerated if it is a protocluster connected to a large scale filament.

The volume observed in this work is very elongated, $\sim 6 \times 9 \times 120 \text{ cMpc}^3$, thus it is difficult, with such a narrow field of view, to decide whether the structure may be filamentary. In order to confirm the filamentary or super-protocluster structure, a comprehensive redshift survey covering large area is highly desired. Emonts et al. (2018) report 6 CO(4-3) and 4 [CI](1-0) detections using ALMA observations around the MRC1138-262. These observations took only 106 minutes integration time (in a single ALMA pointing). Very recently, Valentino et al. (2020) show the impressive capabilities of ALMA to obtain CO and [CI] transitions in a few minutes of on-source integration time for a sample of a few tens high- z IR-selected galaxies. In the Spiderweb protocluster field, high resolution ALMA observations of alternative molecular gas tracer, e.g., [CI] (accompanying CO(4-3) line emission), would be invaluable to constrain SFEs of individual galaxies and the gas excitation via constructing CO SLEDs. The detection rate in Spiderweb field would be more complete with ALMA given the high brightness of CO(4-3) with respect to CO(1-0). The bandwidth of ALMA band 4 is twice wider than the 2 GHz bandwidth of ATCA. However, given that the CO(4-3) line is at a $4 \times$ higher frequency than CO(1-0), the redshift range probed by ALMA band 4 is just half of the range probed by ATCA, thus being less efficient to probe the large scale of this structure. Therefore, benefiting from its large field of view and broad bandwidth, ATCA is still the best facility for CO line surveys with the largest volume. In the near future, the upgraded

Graphics Processor Units⁴ on ATCA will double the amount of bandwidth that can be observed, thus future ATCA observations of the Spiderweb field will be crucial to unveil the edge of this large structure.

5.2. Comparison to simulations

In Fig. 8, we compared our results with CO LFs in the SHARK semi-analytic models for both field and cluster environment (Lagos et al. 2020). For the field, we compare with GALFORM (Lagos et al. 2012) and SHARK (Lagos et al. 2018, 2020). To compare with our protocluster, we search for halos with masses $> 10^{13.5} M_{\odot}$ in the latest SHARK simulations Lagos et al. (2020) and select the CO(1-0) emitters that fall within the same volume (and geometry) of the Spiderweb protocluster. We find that the CO LF of this protocluster is characterized by a higher number density than the SHARK predictions for both the field and clusters. Compared to the COLDz CO LF, SHARK (Lagos et al. 2020) predicts a CO LF with a different shape, which has a lower number density at bright luminosities, $> 10^{10.5} \text{ K km s}^{-1} \text{ pc}^2$ and higher number density at low luminosities. The CO LF of Spiderweb has a more similar shape that resembles the SHARK one for the field but with a remarkably higher number density by 2.3 dex at $\log(L_{*}/\text{K km s}^{-1} \text{ pc}^2)=10.5$. To make a fairer comparison with the Spiderweb, we investigated the CO LF of high mass halos in SHARK using two different volumes: (1) a spherical volume of $R < 5 \text{ cMpc}$, which is representative of cluster cores, marked by the blue dashed curve; and (2) the identical volume and geometry of the observed co-moving volume (6600 cMpc^3) in this work, marked by blue dot-dashed curve. As shown in Fig. 8-left, the CO LF of SHARK in the small volume ($R < 5 \text{ cMpc}$ core) is comparable to the observed one in the Spiderweb protocluster but appears to have a slightly too high number density at the brightest end (though with poor statistics it is hard to assess whether this is a true tension with the prediction). However, when we study the CO LF adopting the same comoving volume as we use for the Spiderweb, the number density decreases by 0.6 dex across all luminosities. This indicates that cold molecular gas reservoirs in the simulated SHARK clusters are overdense in center cluster cores while much lower in the outer regions. This could indicate that this protocluster is in a higher density region of the Universe than the average halo of mass $> 10^{13.5} M_{\odot}$ at $z = 2$ in SHARK.

In Fig. 9, we compared our cold molecular gas densities with predictions for clusters from the SHARK semi-analytical models (Lagos et al. 2020) and the DIANOGA hydrodynamical simulations (Bassini et al. 2020), respectively. The core region ($R < 5 \text{ cMpc}$) of massive halos in SHARK shows a median gas density of $2.51^{+0.76}_{-0.75} \times 10^8 M_{\odot} \text{ cMpc}^{-3}$ at $z = 2$ with a median α_{CO} of 1.23, indicating a high density of starburst-like members in the center core. This gas density in core region is still lower than the bottom limit of our result by a factor of 2. In the identical volume and geometry to the one analyzed in this paper (this V_c), the SHARK models predict a molecular gas density of $\rho(\text{H}_2) = 4.40^{+0.76}_{-0.75} \times 10^7 M_{\odot} \text{ cMpc}^{-3}$ at $z = 2$, which is lower than the observed one by 1.3 dex even accounted for uncertainties of α_{CO} . In the DIANOGA simulations, which consist of a set of 12 cosmological simulations of massive galaxy clusters (see Bassini et al. 2020 for further details), there is no direct information on the molecular gas content. We thus compare to the cold gas content that directly fuel the star formation

of cluster galaxies. Between the 12 simulations, we selected the one with the highest gas density at $z \sim 2$. This is a simulation of a massive cluster with a mass $M_{200} > 10^{15} M_{\odot}$ at $z = 0$. Therefore, this simulation is suitable for this comparison, since numerical simulations suggest that the Spiderweb complex is the progenitor of a very massive galaxy cluster at $z = 0$ (e.g., Saro et al. 2009). For this simulated cluster, we chose the snapshot nearest to the redshift of the Spiderweb protocluster, and computed the gas density considering all the cold gas bound to the galaxies within the same volume and geometry. By employing ~ 10000 randomly chosen lines of sight, we find a median density of $\rho = 4.7^{+2.6}_{-1.0} \times 10^8 M_{\odot} \text{ cMpc}^{-3}$ (16th and 84th percentiles) with a maximum of $1.29 \times 10^9 M_{\odot} \text{ cMpc}^{-3}$ for massive structures with $M_{500} > 10^{15} M_{\odot}$ at $z = 2.16$ (Saro et al. 2009). The median gas density agrees with the observed one within error bar and the maximum density is very comparable with the upper limit of our results.

Most of the simulations and semi-analytical models under-predict the star formation rate in protoclusters at $z \sim 2$ and 4 (e.g., Granato et al. 2015; Bassini et al. 2020; Lim et al. 2020). This work shows that the molecular gas density in protoclusters can be also underestimated in the SHARK simulations. Regarding the tension between the observations and the SHARK models, one possibility would be that the Spiderweb protocluster is a much higher density than the one typically traced by halos of masses $> 10^{13.5} M_{\odot}$ in simulations and hence we are not comparing like with like. In the future we will investigate if any of the massive halos in these simulations can produce the correct density of star-forming galaxies (and which cosmological volume is required to see such high densities). After isolating whether those systems exist in the simulations, follow-up investigations will focus on comparing star formation efficiencies and their spatial distribution within the protocluster environment. On the other side, the DIANOGA simulations contain more massive structures similar to the Spiderweb protocluster providing very comparable gas density predictions with respect to our observations. We note that even though the total gas densities are comparable, the gas mass function could be different between the observations and simulations. A detailed study on gas mass function requires a deeper inspection which is beyond the scope of this study. To summarize, this comparison shows that observed high- z super-protocluster and large filamentary structures do exist in cosmological simulations and the consistency with observations provide encouraging prospects for future simulation studies.

5.3. SFRD vs. gas density

Based on submm imaging with APEX-LABOCA, Dannerbauer et al. (2014) report that the SFRD of this structure is $1500 M_{\odot} \text{ yr}^{-1} \text{ Mpc}^{-3}$ in physical volume, corresponding to a $\text{SFRD} = 47 M_{\odot} \text{ yr}^{-1} \text{ cMpc}^{-3}$ in co-moving volume after applying a scaling factor of $(1+z)^3$. This SFRD is higher than the CSFRD in random fields (see a review in Madau & Dickinson 2014) by 2.6 dex.

Intriguingly, our observations suggest that the H_2 density is 1.6 ± 0.5 orders of magnitude higher than in the field which is lower than the 2.6 orders of magnitude excess of SFRD with respect to that in blank fields. The offset could be due to a combination of several reasons: 1) a high SFE of the cluster members as suggested by the high fraction of dusty starbursts in this structure; 2) overestimate of the SFRs due to blending as the dusty SEDs in Dannerbauer et al. (2014) are based on low-resolution

⁴ <https://theconversation.com/a-brain-transplant-for-one-of-australias-top-telescopes-129138>

Herschel and LABOCA (sub)mm photometry that could boost the SFR measurements; 3) the H_2 density could be underestimated due to the lack of constraint at faint end of CO LF; and 4) we might be missing some CO emitters in noisy regions. In order to better constrain the L_{IR} and SFRs of individual galaxies, deblended photometry (e.g., Jin et al. 2018; Liu et al. 2018) and wide and deep spectral-line imaging (by ATCA and ALMA) would be essential to identify the main contributors to the difference between the SFRD and the H_2 density of this structure.

5.4. The importance of large area surveys with wide velocity range

As listed in Table 4, previous cold molecular gas surveys often observed a small area around the protocluster (core). In contrast, the Spiderweb protocluster exhibits large distances between the most CO emitters and the center galaxy (Fig. 6), indicating that such large structures can be only revealed by large area line surveys. Other high- z protoclusters could have similarly large spread of gas reservoirs as the Spiderweb protocluster, however, most of CO emitters in such structures would be missed by surveys that covers small area and narrow velocity range, resulting in an underestimate of the total gas mass and gas density. Clearly, large area surveys ($>10 \text{ armin}^2$) are indispensable to unveil complete cluster members and unbiased gas content in high- z protoclusters. The area needs to be even larger for super structures like the Spiderweb and the Hyperion. However, blind line survey appears to be inefficient and risky, as the existence of CO emitters is unknown in outskirts of protocluster. To improve the efficiency, the single dish (sub)mm observations are valuable, e.g., APEX/LABOCA, JCMT/SCUBA2, IRAM 30m/NIKA2 and the upcoming LMT/TolTEC. All these instruments can trace the dust content in protoclusters with large field of view. As demonstrated in this work and Hill et al. (2020), the ATCA and ALMA followup of LABOCA submillimeter sources around the cluster core will increase the efficiency of line survey. On the other hand, the CO(1-0) detection rate of HAEs in this field is 17%, which is comparable with that reported by Tadaki et al. (2014). Thus CO line followup observations covering most of the rest-frame UV/optical line emitters appear also a good strategy for future surveys. A detailed analysis on CO(1-0)-detected HAEs in this field will be presented in future work (Jin et al. in prep.).

6. Conclusion

We present new ATCA CO observations of the $z = 2.16$ Spiderweb galaxy protocluster field. We find 46 robust CO(1-0) emitting sources at the redshift of the Spiderweb protocluster. For the first time we place constraints on the CO luminosity function and the cold molecular gas density on a galaxy protocluster environment in the distant Universe. Our findings can be summarized as follows:

- 475 hours integration time was spent on observations of the CO(1-0) transition of members of the Spiderweb protocluster at $z = 2.16$. We produce a large mosaic of 13 pointings at 7mm, covering an area of 25 armin^2 and velocity range of $\pm 7000 \text{ km/s}$. Using multiple source extraction methods, we reveal 46 solid CO(1-0) detections with $\text{SNR} > 4$ and counterparts in HST optical and/or VLT near-infrared images.
- The CO emitters span a redshift range of $z = 2.09 - 2.22$. We find a CO overdensity at $z = 2.12 - 2.21$ which is four times larger than the velocity range traced by HAEs in previous

studies and suggesting a large scale filament or a galaxy super-protocluster in this field.

- We find that 90% of the CO emitters are $> 0'.5 - 4'$ distant from the central radio galaxy, indicating that line surveys with small area would miss the bulk of CO sources in similar structures. Meanwhile, half of the CO emitters are found to have velocities larger than the escape velocities in assumption of virialization of the cluster core, which appears not gravitationally bound with the center mass. These unbound CO emitters extend to $4 \times R_{200}$ but are barely found within the R_{200} radius, which is consistent with the picture that the cluster core has been virialized and the outer regions are still in formation.

- Comparing to high redshift protoclusters known in the literature, this structure contains more CO emitters with relatively narrow line width and high luminosity being consistent with SMGs samples and indicating starburst/merger activities. The most starburst-like members have large sky distances to the center galaxy with $> 0'.5 - 4'.0$, which is beyond the FoV of single pointings of VLA and ATCA. This indicates that small area observations could have severe bias in protocluster fields missing a bulk of starbursting members.

- We construct the CO luminosity function in this cluster, and find a high overdensity of luminous CO sources. The amplitude of the luminosity function, $\log(\Phi_{*}/\text{cMpc}^{-3} \text{ dex}^{-1}) = -2.16 \pm 0.49$, is 1.6 ± 0.5 orders of magnitude higher than the CO luminosity density in blank fields, and also higher than the prediction from semi-analytical SHARK models by one order of magnitude. This indicates a high density of cold molecular gas $0.6 - 1.3 \times 10^9 M_{\odot} \text{ cMpc}^{-3}$, significantly higher than probed for field galaxy samples by more than one order of magnitude. This gas density is also higher than predictions by semi-analytical SHARK models for protoclusters while it is comparable with the cold gas density in the hydrodynamical DIANOGA simulations. We attribute the underprediction of SHARK partially to the lack of very high density regions in their simulated box, $\sim (300\text{Mpc})^3$.

To summarize, this study shows that molecular line surveys in high- z protocluster are more efficient than surveys in blank fields, and line surveys with large area and wide velocity range are of virtual importance to provide us an unbiased view of large structure and gas content in protocluster environment and thus testing our understanding of galaxy formation and numerical simulations.

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Appendix A: Gallery of CO(1-0) detections

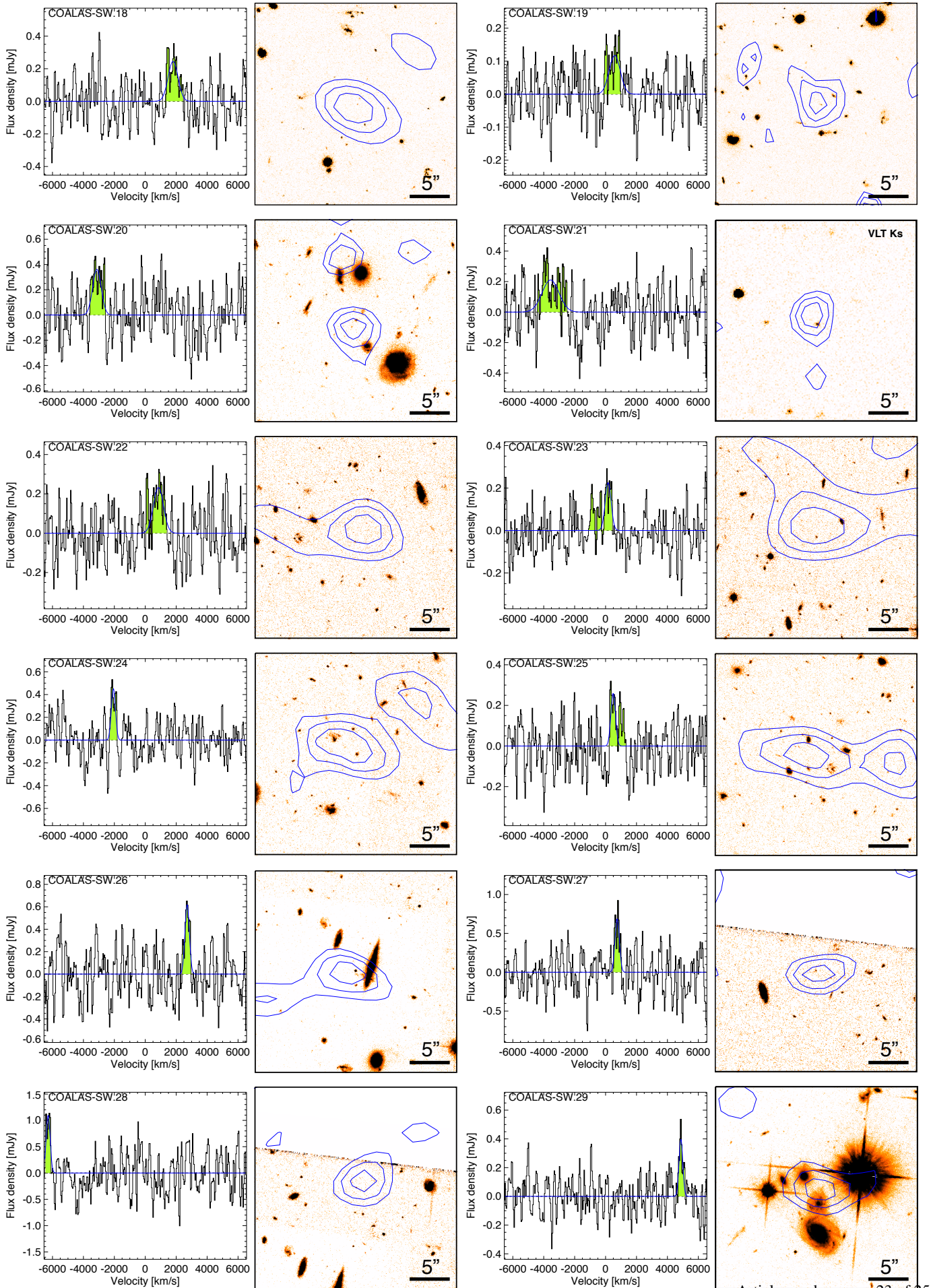


Fig. A.1. Spectra of SNR= 4–5 detections in category A. This figure shares caption in Fig. 3.

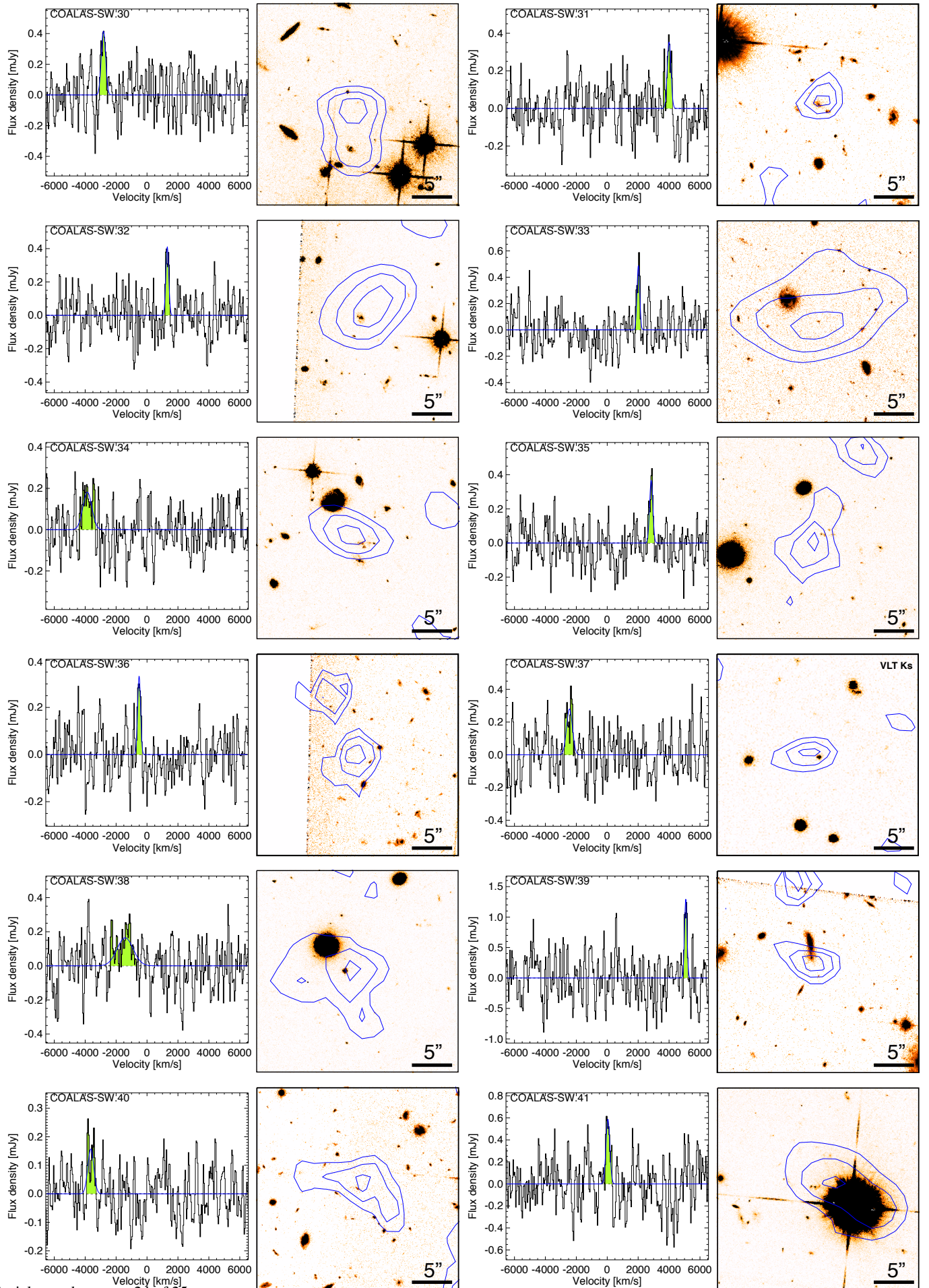


Fig. A.1. Continued.

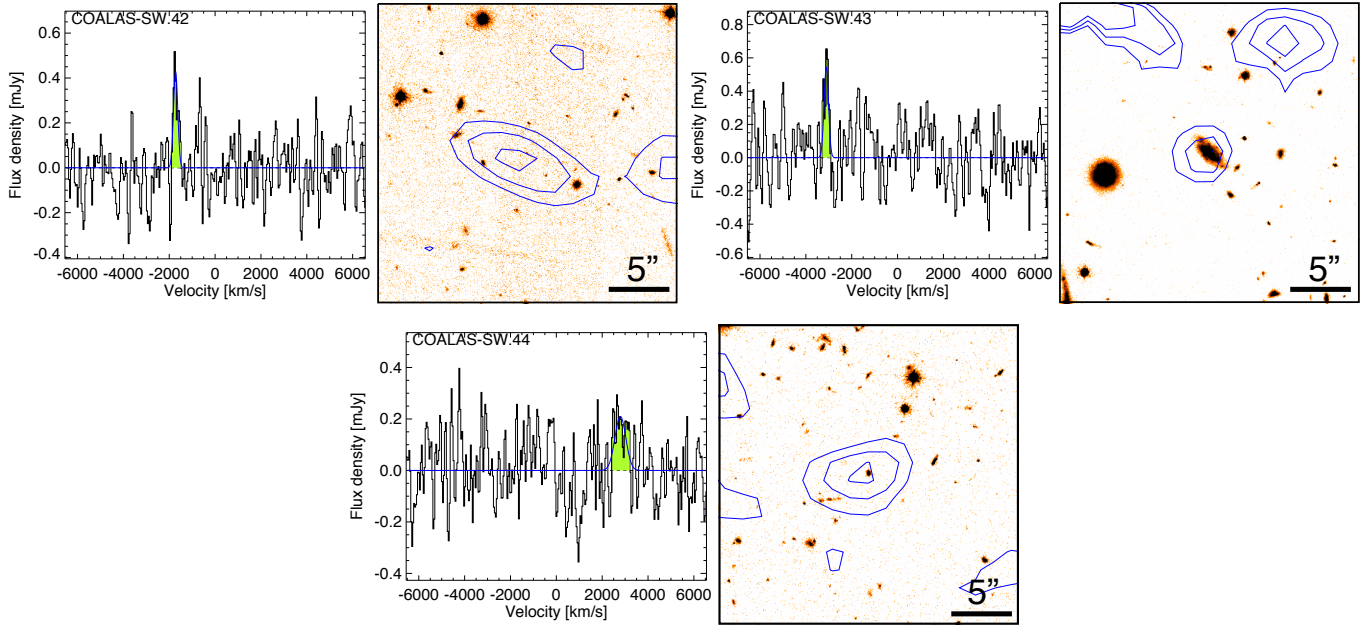


Fig. A.1. Continued.

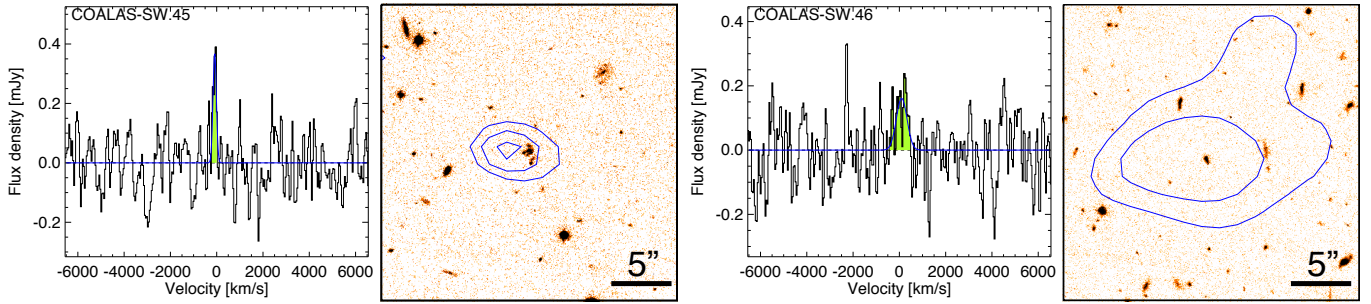


Fig. A.2. Spectra and intensity maps of category C detections.