

VALES I: The molecular gas content in star-forming dusty *H*-ATLAS galaxies up to $z = 0.35$

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ABSTRACT

We present an extragalactic survey using observations from the Atacama Large Millimeter/submillimeter Array (ALMA) to characterise galaxy populations up to $z = 0.35$: the Valparaíso ALMA Line Emission Survey (VALES). We use ALMA Band-3 CO(1–0) observations to study the molecular gas content in a sample of 67 dusty normal star-forming galaxies selected from the *Herschel* Astrophysical Terahertz Large Area Survey (*H*-ATLAS). We have spectrally detected 49 galaxies at $> 5\sigma$ significance and 12 others are seen at low significance in stacked spectra. CO luminosities are in the range of $(0.03 - 1.31) \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$, equivalent to $\log(M_{\text{gas}}/M_{\odot}) = 8.9 - 10.9$ assuming an $\alpha_{\text{CO}} = 4.6 (\text{K km s}^{-1} \text{ pc}^2)^{-1}$, which perfectly complements the parameter space previously explored with local and high- z normal galaxies. We compute the optical to CO size ratio for 21 galaxies resolved by ALMA at $\sim 3''.5$ resolution (6.5 kpc), finding that the molecular gas is on average ~ 0.6 times more compact than the stellar component. We obtain a global Schmidt-Kennicutt relation, given by $\log[\Sigma_{\text{SFR}}/(M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2})] = (1.26 \pm 0.02) \times \log[\Sigma_{\text{H}_2}/(M_{\odot} \text{ pc}^{-2})] - (3.6 \pm 0.2)$. We find a significant fraction of galaxies lying at ‘intermediate efficiencies’ between a long-standing mode of star-formation activity and a starburst, specially at $L_{\text{IR}} = 10^{11-12} L_{\odot}$. Combining our observations with data taken from the literature, we propose that star formation efficiencies can be parameterised by $\log[\text{SFR}/M_{\text{H}_2}] = 0.19 \times (\log L_{\text{IR}} - 11.45) - 8.26 - 0.41 \times \arctan[-4.84 (\log L_{\text{IR}} - 11.45)]$. Within the redshift range we explore ($z < 0.35$), we identify a rapid increase of the gas content as a function of redshift.

Key words: galaxies: high-redshift – galaxies: ISM – infrared: galaxies – submillimeter: galaxies – ISM: lines and bands

1 INTRODUCTION

Understanding the way in which galaxies form and evolve throughout cosmic time is one of the major challenges of extragalactic astrophysics. Recently, theoretical models adopting a Λ CDM cosmology have been successful in probing the hierarchical gravitational growth of dark matter haloes, which is then associated to the large-scale structure of the observed baryonic matter (e.g. [Spergel et al. 2003, 2007](#)). On smaller scales, however, the physical processes that control galaxy growth have intricate non-linear dependencies that make its explanation far from trivial (e.g. [Vogelsberger et al. 2014; Schaye et al. 2015; Crain et al. 2015](#)). One of the key observations used to constrain galaxy formation and evolution models is the behaviour of the cosmic star-formation rate density. Understanding the cosmic evolution of the interplay between the observed star formation rate (SFR), molecular gas content (M_{gas}), global stellar mass content (M_*) and gas-phase metallicity (Z) is a major goal in this field of research. We therefore require a detailed knowledge of the origin and the properties of the gas reservoir that ignites and sustains the star formation activity in galaxies at different epochs.

The accretion of gas into the potential wells of galaxies, either from the inter-galactic medium or via galaxy-galaxy interactions, provides the gas reservoir for ongoing and future star formation ([Di Matteo et al. 2007; Bournaud et al. 2009; Dekel et al. 2009](#)). Most stars form in giant molecular clouds (GMCs), in which the majority of the mass is in the form of molecular hydrogen (H_2). The lack of a permanent dipole moment in this molecule means that direct measurements of cold H_2 gas are extremely difficult (e.g. [Papadopoulos & Seaquist 1999; Bothwell et al. 2013](#)). Thus, an alternative approach to study the molecular gas content is through observations of carbon monoxide (CO) line emission of low- J transitions (e.g. $J = 2 - 1$ or $J = 1 - 0$) – the best standard tracer of the total mass in molecular gas ($M_{\text{H}_2} = \alpha_{\text{CO}} L'_{\text{CO}(1-0)}$; e.g. [Bolatto et al. 2013](#)). Even though this tracer has been historically used as a tracer of the molecular gas mass, the $^{12}\text{C}^{16}\text{O}(J = 1 - 0)$ [hereafter CO(1–0)] emission line is optically thick, hence the dynamics of the system becomes critical for converting luminosities into masses ([Solomon & Vanden Bout 2005](#)). For instance, in the case of a merger where dynamical instabilities are large and the system is not virialised, Doppler-broadening could affect the line profiles and the emitting regions could be more dispersed throughout the inter stellar medium (ISM), thus enhancing the CO emission compared to that from a virialised system of the same mass ([Downes & Solomon 1998a](#)). In dense, optically-thick virialised GMCs, it is found that $\alpha_{\text{CO}} \sim 5 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$, whereas $\alpha_{\text{CO}} \sim 0.8 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ in more dynamically disrupted systems, such as in Ultra Luminous Infrared Galaxies

(ULIRGs; [Downes & Solomon 1998b](#)). On the other hand, α_{CO} may be boosted in low-metallicity environments due to a lack of shielding dust that enhances photo-dissociation of the CO molecule ([Wolfire et al. 2010; Narayanan et al. 2012](#)). For instance, [Narayanan et al. \(2012\)](#) find a parametrisation of α_{CO} in terms of gas metallicity, where $\alpha_{\text{CO}} \propto Z^{-0.65}$ (mixing both low and high- z galaxies), similar to that found by [Feldmann et al. \(2012\)](#). A higher redshifts, a flatter slope has been suggested ([Genzel et al. 2012](#)).

Recent observations taken with the *Herschel Space Observatory*¹ ([Pilbratt et al. 2010](#)) of local star-forming galaxies suggest the existence of at least two different mechanisms triggering the star formation. Taking into account the $L_{\text{FIR}}/M_{\text{H}_2}$ ratio (where L_{FIR} is the far-IR luminosity) as a tracer of the star-formation efficiency, [Graciá-Carpio et al. \(2011\)](#) find an unusual point at $\sim 80 L_{\odot} M_{\odot}^{-1}$ at which average properties of the neutral and ionised gas change significantly, this observation is broadly consistent with a scenario of a highly compressed and more efficient mode of star formation that creates higher ionisation parameters that cause the gas to manifest in low line to continuum ratios. This value is similar to the one at which [Genzel et al. \(2010\)](#) and [Daddi et al. \(2010b\)](#) claim a transition to a more efficient star-formation mode, above the so-called ‘main-sequence’ for star-forming galaxies (e.g. [Elbaz et al. 2011](#)). The different mechanisms controlling the star-formation activity are thought to be the product of dynamical instabilities, where higher efficiencies are seen in more compact and dynamically disrupted systems, such as in Ultra Luminous. Over the last few years, significant efforts have been made to characterise the star formation activity of normal and starburst galaxies at low- z (e.g. [Saintonge et al. 2011; Howell et al. 2010; Bauermeister et al. 2013; Bothwell et al. 2014](#)). The construction of large samples of galaxies with direct molecular gas detections (via CO emission) has remained a challenge. Beyond the local Universe, CO detections are limited to the most massive/luminous yet rare galaxies. For example, [Braun et al. \(2011\)](#) report detections of the CO($J = 1 - 0$) transition for 11 ULIRGs with an average redshift of $z = 0.38$. For these ULIRGs, the molecular gas mass as a function of look-back time demonstrates a dramatic rise by almost an order of magnitude from the current epoch out to 5 Gyr ago. In addition, [Combes et al. \(2011\)](#) presented 18 detected ULIRGs at $z \sim 0.2 - 0.6$ for CO(1–0), CO(2–1) and CO(3–2) with an average CO luminosity of $L'_{\text{CO}(1-0)} = 2 \times 10^{10} \text{ K km s}^{-1} \text{pc}^2$, finding that the amount of gas available for a galaxy quickly increases as a function of redshift. Moreover, [Magdis et al. \(2014\)](#) presented the properties of 17 *Herschel*-selected ULIRGs ($L_{\text{IR}} > 10^{11.5} L_{\odot}$) at $z = 0.2 - 0.8$, showing that the previously observed evolution of ULIRGs at those redshifts is already taking place by $z \sim 0.3$. Nevertheless, the observation of ‘normal’ galaxies

¹ *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia with an important participation from NASA.

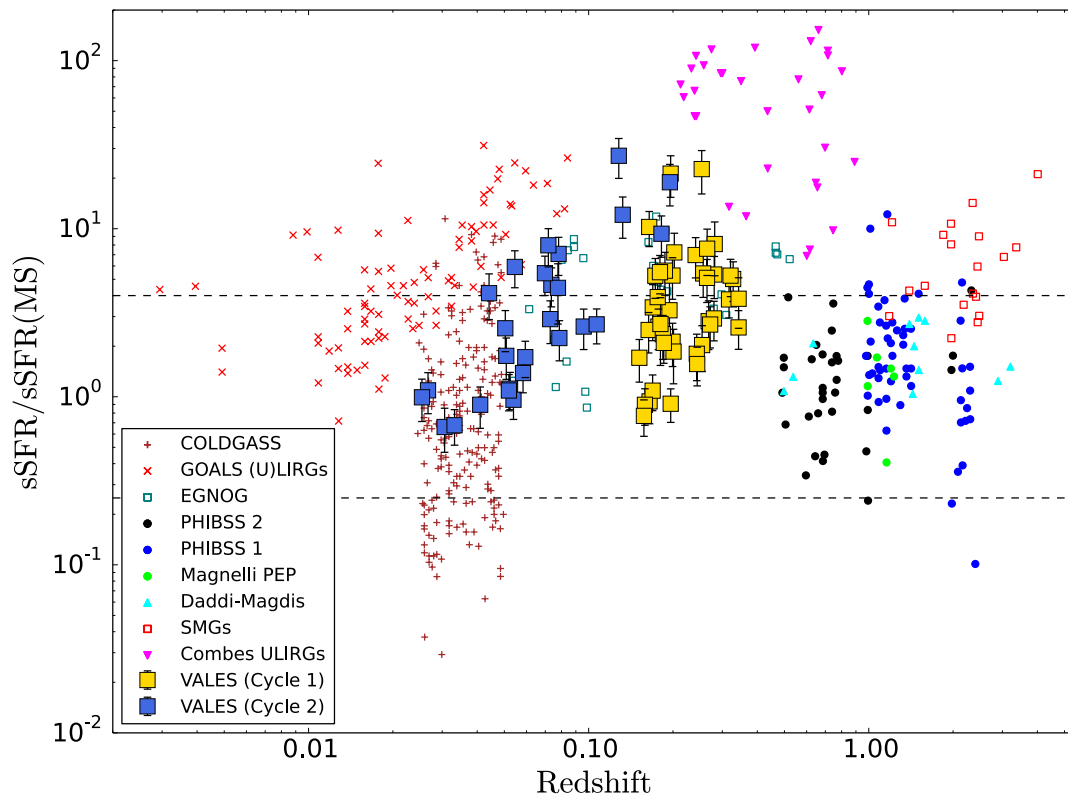


Figure 1. The figure shows the specific Star Formation Rate (sSFR, defined as $\text{sSFR} = \text{SFR}/M_*$), normalised to the one estimated for the ‘main sequence’ (Elbaz et al. 2011; Whitaker et al. 2012) as a function of redshift for different samples of galaxies detected in CO. We use the parametrisation of the ‘main sequence’ made by Genzel et al. (2015) as $\log[\text{sSFR}(\text{MS}, z, M_*)] = -1.12 + 1.14z - 0.19z^2 - (0.3 + 0.13z) \times (\log M_* - 10.5) \text{ Gyr}^{-1}$, where dashed black lines denote 0.6 dex off this equation for star-forming galaxies. Our data is presented in filled squares with error bars taken from our ALMA Cycle-1 (yellow) and Cycle-2 (royal blue) campaigns. We estimate the SFR using $L_{\text{IR}}(8 - 1000 \mu\text{m})$ extracted from the *H*-ATLAS data, stellar masses using MAGPHYS fits (see § 2.4.3) – both using the same IMF, and redshifts taken from the GAMA survey. Dark red crosses are nearby galaxies (Saintonge et al. 2011), red crosses are (U)LIRGs (Howell et al. 2010), light blue unfilled squares are $z = 0.05 - 0.5$ normal galaxies (Bauermeister et al. 2013), pink inverted triangles are ULIRGs at intermediate redshifts (Combes et al. 2011, 2013), blue dots are ‘main sequence’ galaxies at $z = 1 - 1.5$ and $2 - 2.5$ (Tacconi et al. 2010, 2013), black dots are ‘main sequence’ galaxies at $z = 0.5 - 1$ and $z \sim 2$ (Combes & the PHIBSS collaboration 2015), light blue triangles are ‘main sequence’ galaxies at high- z (Magnelli et al. 2012), light green dots are ‘main sequence’ galaxies at $z = 0.5 - 3.2$ (Daddi et al. 2010a; Magdis et al. 2012) and red unfilled squares are sub-millimetre galaxies at $z = 1.2 - 3.4$ (Greve et al. 2005; Tacconi et al. 2006, 2008; Bothwell et al. 2013). Figure adapted from Genzel et al. (2015).

at these redshifts (and beyond) has so far been, at least, restricted.

The advent of the Atacama Large Millimeter/submillimeter Array (ALMA) opens up the possibility to explore the still unrevealed nature of the ‘normal’ star forming galaxies (SFGs) at low/high- z redshift. In this work, we exploit the *Herschel* Astrophysical Terahertz Large Area Survey (*H*-ATLAS²; Eales et al. 2010) and the state-of-the-art capabilities of ALMA to characterise the CO(1 – 0) line emission ($\nu_{\text{rest}} = 115.271 \text{ GHz}$) of ‘normal’ star-forming and mildly starburst galaxies up to $z = 0.35$. This paper is organised as follows. Section 2 explains the sample selection, observing strategy and data reduction. In Section 3, we present the main results and the implications of these new ALMA observations to the global

context of galaxy evolution. Our conclusion is summarised in Section 4. Throughout this work, we assume a Λ CDM cosmology adopting the values $H_0 = 70.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ for the calculation of luminosity distances and physical scales³.

2 OBSERVATIONS

2.1 *H*-ATLAS sample

The galaxies presented in this paper have been selected from the equatorial fields of the *H*-ATLAS survey ($\sim 160 \text{ deg}^2$; Valiante et al. 2016) and observed during ALMA Cycle-1 and Cycle-2 (programs 2012.1.01080.S & 2013.1.00530.S;

² <http://www.h-atlas.org/>

³ We use Ned Wright’s online calculator <http://www.astro.ucla.edu/~wright/CosmoCalc.html>.

| Project ID | Target Names | Observation Date | Flux Calibrator | Bandpass Calibrator | Phase Calibrator | PWV [mm] | Number of Antennas |
|----------------|--|----------------------------------|-----------------|---------------------|------------------|----------|--------------------|
| 2012.1.01080.S | HATLASJ090633.6+001526, HATLASJ090223.9−001639, HATLASJ091157.2+014453, HATLASJ091420.0+000509, HATLASJ090120.7+020223, HATLASJ085616.0+005237, HATLASJ085957.9+015632, HATLASJ085750.1+012807, HATLASJ091956.9+013852, HATLASJ092232.2+002708, HATLASJ085623.6+001352, HATLASJ085828.4+012211 | January 1 st , 2014 | Calisto | J0522−3627 | J0811+0146 | 4.217 | 27 |
| | HATLASJ113858.4−001630, HATLASJ121206.2−013425, HATLASJ114343.9+000203, HATLASJ121141.8−015730, HATLASJ114540.7+002553, HATLASJ114625.0−014511, HATLASJ121427.3+005819, HATLASJ113740.6−010454, HATLASJ121908.7−010159, HATLASJ114702.7+001207, HATLASJ115141.3−004240, HATLASJ121446.4−011155, HATLASJ121253.5−002203, HATLASJ115317.4−010123, HATLASJ115039.5−010640 | December 27 th , 2013 | Mars | J1229+0203 | J1229+0203 | 6.084 | 26 |
| | | December 29 th , 2013 | | | | 5.757 | |
| | HATLASJ142517.1+010546, HATLASJ141008.0+005107, HATLASJ142057.9+015233, HATLASJ144218.7+003615, HATLASJ141925.3−011129, HATLASJ141522.0+004413, HATLASJ141908.5+011313, HATLASJ144515.0+003907, HATLASJ140649.0−005646, HATLASJ142208.8+005428, HATLASJ140912.3−013454, HATLASJ144129.5−000901, HATLASJ144116.2+002723 | March 9 th , 2014 | Ceres, Titan | J1337−1257 | J1410+0203 | 2.223 | 25 |
| 2013.1.00530.S | HATLASJ085356.4+001255, HATLASJ085828.6+003813, HATLASJ085340.7+013348, HATLASJ090005.0+000446, HATLASJ085405.9+011130, HATLASJ085112.9+010342, HATLASJ083745.1−005141, HATLASJ090949.6+014847, HATLASJ090532.6+020222, HATLASJ085346.4+001252, HATLASJ083601.5+002617, HATLASJ084428.4+020350, HATLASJ091205.8+002655 | January 24 th , 2015 | J0750+125 | J0750+1231 | J0909+0121 | 2.223 | 40 |
| | HATLASJ084139.6+015346, HATLASJ084350.8+005534, HATLASJ084305.1+010855, HATLASJ085450.2+021208, HATLASJ083831.8+000044, HATLASJ085111.4+013006, HATLASJ084428.4+020659, HATLASJ084907.1−005138, HATLASJ085234.3+013419, HATLASJ085748.0+004641 | | J0750+125 | J0739+0137 | J0901−0037 | 5.463 | 40 |
| | HATLASJ084217.9+021223, HATLASJ085836.0+013149, HATLASJ084630.9+005055, HATLASJ090750.0+010141 | | Ganymede | J0909+0121 | J0901−0037 | 5.553 | 39 |

Table 1. The table shows the way in which our targets were observed during the Cycle 1 and Cycle 2 campaigns.

P.I. E. Ibar). All galaxies have a $> 3\sigma$ detection with both the Photoconductor Array Camera and Spectrometer (PACS) at $160\mu\text{m}$ and the Spectral and Photometric Imaging Receiver (SPIRE) at $250\mu\text{m}$, i.e. they are detected near the peak of the spectral energy distribution (SED) of a normal and local star-forming galaxy. All galaxies have been unambiguously identified in the Sloan Digital Sky Survey (SDSS; [Adelman-McCarthy et al. 2008](#)) presenting a significant probability for association ($\text{RELIABILITY } R > 0.8$; [Smith et al. 2011](#); [Bourne et al. 2016](#)). The optical counterparts to the *Herschel*-detected galaxies all have high-quality spectra from the Galaxy and Mass Assembly survey (GAMA⁴; $Z_{\text{QUAL}} \geq 3$; [Liske et al. 2015](#); [Driver et al. 2016](#)).

Slightly different selection criteria were used in each cycle to construct the list of ALMA targets. In Cycle-1, we selected a representative sample of 41 galaxies with the following criteria: $0.15 < z < 0.35$ (the upper threshold in redshift corresponds to the limits at which the CO(1–0) line moves out of frequency range covered by Band-3 of ALMA); $S_{160\mu\text{m}} > 100\text{mJy}$; SDSS sizes $\text{ISOA} < 10''$; and a reduced $\chi^2 < 1.5$ when fitting the far-IR/submm SED using a modified black body (following a similar approach as in [Ibar et al. 2013](#)). On the other hand, in Cycle-2 we targeted 27 galaxies that have previous *Herschel* PACS [C II] spectroscopy as shown by [Ibar et al. \(2015\)](#) and so added the following criteria: $0.02 < z < 0.2$ (the threshold is defined by the point where the [C II] is redshifted to the edge of the PACS spectrometer); $S_{160\mu\text{m}} > 150\text{mJy}$; Petrosian SDSS radii smaller than $15''$; sources do not have $> 3\sigma$ PACS $160\mu\text{m}$ detections within 2 arcmin (to ensure reliable on-off sky subtraction).

Combining Cycle-1 and Cycle-2 observations, we construct one of the largest samples of CO(1–0) detected galaxies at $0.02 < z < 0.35$ (see Fig. 1). We highlight that some of the main advantages of our sample over previous studies of far-IR-selected galaxies are: (1) we cover fainter $L_{8-1000\mu\text{m}} \approx 10^{10-12} L_{\odot}$ and less massive $M_{\text{dust}} \approx 1.5 \times 10^{7-8} M_{\odot}$ ranges than *IRAS*-selected samples, i.e. our samples are not significantly biased towards powerful ULIRGs that potentially have complex merger morphologies

as those described by [Braun et al. \(2011\)](#) and [Combes et al. \(2011\)](#); (2) the sample selection dominated by the $160\mu\text{m}$ and $250\mu\text{m}$ photometry gives relatively low dust temperature estimates ($25 < T_{\text{dust}}/\text{K} < 60$) and reduces (but not entirely) the well known bias towards high dust temperatures evidenced in $60\mu\text{m}$ -selected *IRAS*-samples (see discussion by [Gao & Solomon 2004](#); [Kennicutt et al. 2009](#)); (3) the wealth of ancillary data already available for all the sources ([Driver et al. 2016](#); [Bourne et al. 2016](#)); and (4) the redshift range puts galaxies far enough so galaxies can be imaged with a single ALMA pointing in Band-3 – it does not require large mosaicking (using the Atacama Compact Array) campaigns as in more local galaxy samples. These reasons enable us to address our science goals using a much simpler but wider parameter space for the diagnostics of interest (see Fig. 1).

2.2 Observational strategy

ALMA Cycle-1 observations were taken in Band-3 between December 2013 and March 2014 (see Table 1), spending approximately 3 to 9 minutes on-source in each source. Scheduling blocks (SBs) were designed to detect the CO(1–0) emission line down to a root mean square (RMS) of 1.5mJy beam^{-1} at 50km s^{-1} channel width and at $\sim 3''$ – $4''$ resolution (the most compact configuration). On the other hand, Cycle-2 observations were taken in Band-3 on January 2015 and SBs were designed to observe the CO(1–0) emission line but down to 2mJy beam^{-1} at 30km s^{-1} . Even though ALMA is not specifically designed as a ‘survey-like’ telescope, we setup our experiment to minimise the number of spectral tunings needed to observe all sources independently. We make use of the fact that our targets come from three equatorial *H*-ATLAS/GAMA fields which are $\sim 4 \times 14\text{deg}^2$ size, providing large numbers of galaxies at similar redshifts. We modified the ‘by-default’ approach provided by the ALMA Observing Tool (OT) by setting source redshifts to zero, but fixing the spectral windows (SPW) manually in order to cover the widest possible spectral range, i.e. redshift range. We optimised the central frequency position of the SPWs (over $\sim 7.5\text{GHz}$) to maximise the number of sources with the CO(1–0) line redshifted into the ranges covered

⁴ <http://www.gama-survey.org/>

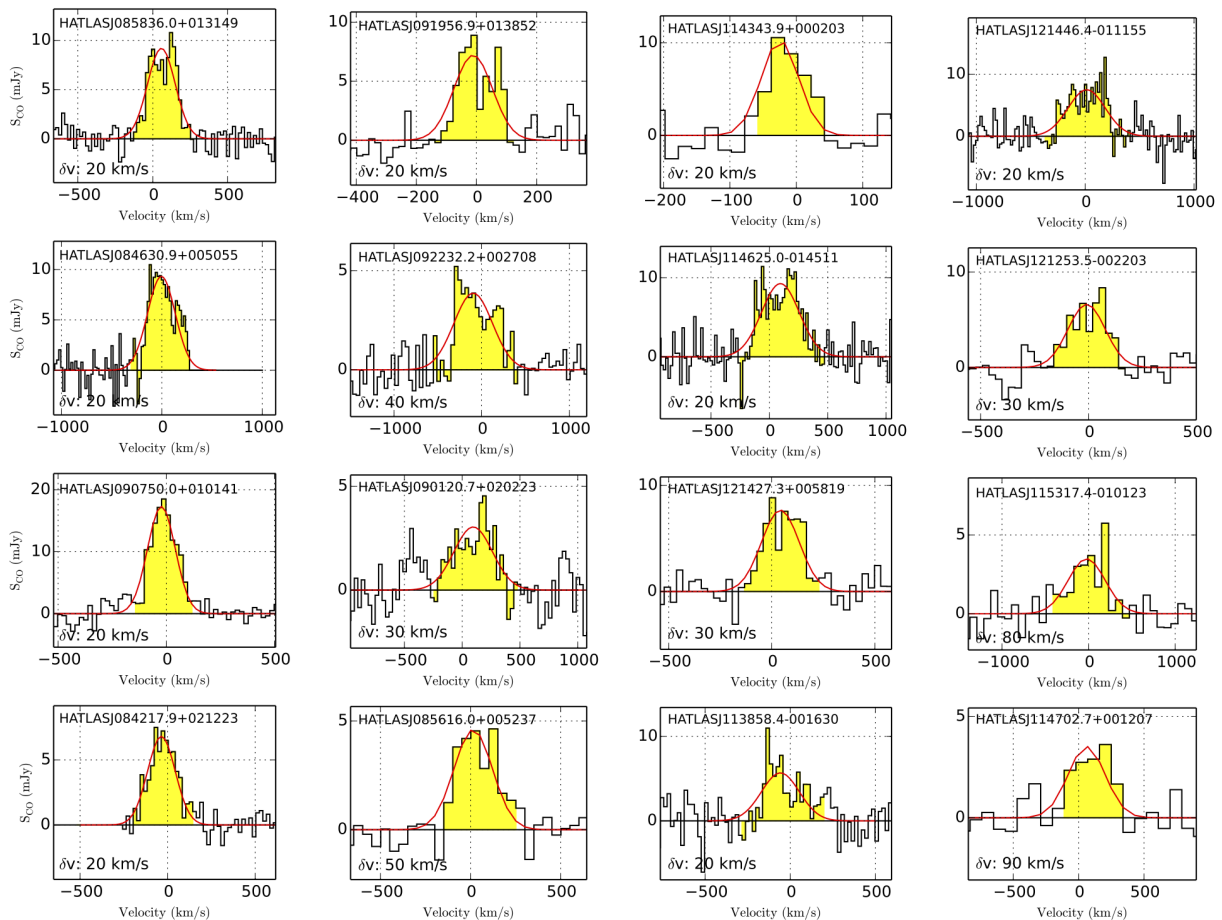


Figure 2. The observed CO(1–0) spectra for spectrally detected galaxies centred on spectroscopic redshifts taken from GAMA. The emission is spectrally binned ($\delta\nu$) differently in order to maximise the number of channels with signal above a 5.0σ significance. The yellow color indicates the spectral range we have used to derive velocity integrated flux densities. The red lines show best-fitting single Gaussian profiles to the spectra (see Table 2).

by our SPWs. This observing strategy allowed us to spectrally resolve the CO(1–0) emission in 49 galaxies (see Fig. 2; $\sim 70\%$ of the whole sample), while in 12 others we see low signal to noise emission in collapsed spectra (moment–0).

2.3 Data reduction

A summary of all ALMA observations are shown in Table 1. To process all observations in a standardised way, we developed a common pipeline within the COMMON ASTRONOMY SOFTWARE APPLICATIONS⁵ (CASA version 4.4.0). Based on the standard pipeline for data processing, we designed our own structured pipeline for calibration, concatenation and imaging. The structure was designed in modules, taking into account the vast amount of data and high flexibility at the time to flag corrupted data. When a science goal has more than one observation, we re-calibrate the phase calibrator to an average flux density (usually variations are seen at $\lesssim 15\%$) and bootstrap this scaling to the targets before con-

catenating the observations. The bandpass, flux and phase calibrators for each data set can be seen in Table 1.

In the first instance, imaging was performed using the task CLEAN at different spectral resolutions (from 20 to 100 km s^{-1} in steps of 10 km s^{-1}). We sought the resolution that provided the highest number of non-cleaned point-like detections $> 5.0\sigma$ within the data-cube (R.A.-Dec.- ν) near the expected source position. If the source was undetected, then we created the cube at 100 km s^{-1} channel width. After choosing the best resolution, we ran task CLEAN again but this time applying a primary beam correction, manually cleaning the CO line emission down to a threshold of 3.0σ , and choosing an image size of 256×256 pixels with roughly 5 pixels (semi-major axis) per synthesised beam full width half maximum (FWHM). We used the optically-derived spectroscopic redshifts (z_{spec}) of each source in a barycentric velocity reference frame. The final cubes were created using natural weighting, resulting in image cubes with typical synthesised beams of $3'' - 4''$. The physical sizes for each source, i.e. the deconvolved major-axes (in kpc) are given in Table 2.

⁵ <http://casa.nrao.edu/index.shtml>

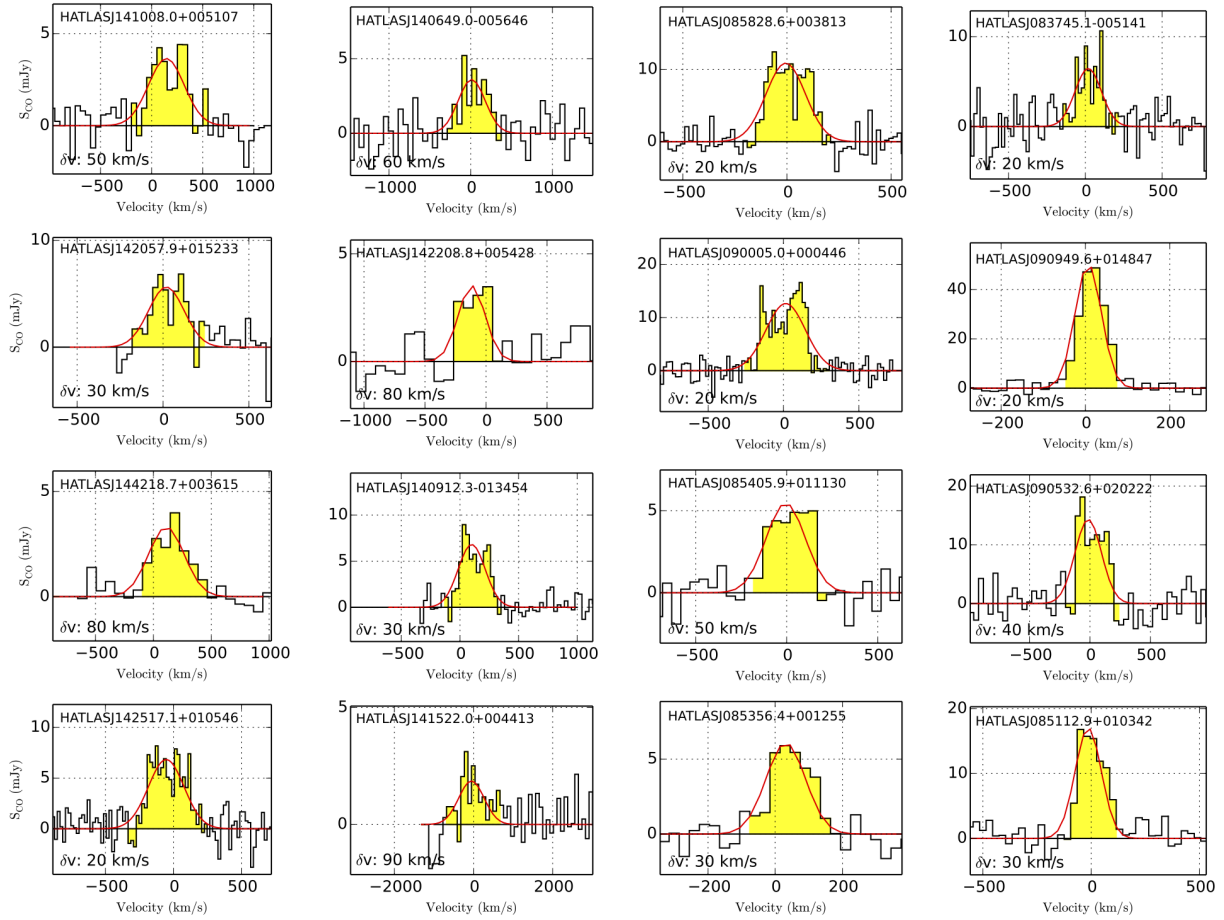


Figure 2. continued

2.4 Source properties

2.4.1 CO emission

We get an average RMS level of $1.6 \text{ mJy beam}^{-1}$ (at 50 km s^{-1}) for both Cycle-1 and Cycle-2. We identify 49 galaxies (out of 67) with a $> 5\sigma$ peak line detection in at least one spectral channel (from 10 to 100 km s^{-1} in all binned). For the 49 spectrally detected galaxies we determine the central frequency (ν_{obs}) of the CO emission line by using a single Gaussian fit to the spectra. We found that central frequencies are in agreement and within the scatter of the expected GAMA's optical redshifts (see column ν_{obs} in Table 2). The fitted FWHM of the CO line in our sample covers a range of $67 - 805 \text{ km s}^{-1}$. All the spectra with spectrally resolved CO signal are displayed in Fig. 2, whereas non-detections are summarised in Table 2.

The velocity integrated CO flux densities ($S_{\text{CO}}\Delta v$ in units of Jy km s^{-1}) were obtained by collapsing the data cubes between $\pm 1 \times \text{FWHM}$ centred on the line (see yellow range shown in Fig. 2). The 2D intensity map is then fitted with a 2D-Gaussian for all detected sources using the task GAUSSFIT within CASA. Errors in these measurements are taken directly from GAUSSFIT's outputs. In seven cases the CO emission is not well fitted by a 2D-Gaussian, so we have used an irregular aperture covering the whole extension of the emission. Errors for those aperture measurements come from the standard deviation of fluxes measured in random

sky regions around the source. We find measurements in the range of $2.2 - 20.8 \text{ Jy km s}^{-1}$, with an average value of $6.9 \pm 0.2 \text{ Jy km s}^{-1}$. We get 21 galaxies which are spatially resolved in CO, based on a fitted semi-major axis $\sqrt{2}$ times larger than the major axis of the synthesised beam.

For non-detections, we collapsed the cubes (moment 0 maps) between $\pm 250 \text{ km s}^{-1}$ centred at the expected observed frequency – a range consistent with the average line width we derive for the whole sample ($251.6 \pm 38.3 \text{ km s}^{-1}$). In these stacked spectra 12 other galaxies show emission (ensuring a corrected optical and redshift association). We provide these measurements in Table 2. These collapsed maps the RMS values range between $0.04 - 5.35 \text{ Jy km s}^{-1}$ (at 100 km s^{-1} channel width) with an average of $1.64 \text{ Jy km s}^{-1}$.

Some spectra show double line profiles providing valuable dynamical information. Our kinematic results will be published by [Molina et al. in prep.](#). We stress, however, that our single Gaussian profiles shown in Fig. 2 are to define the spectral range used to collapse the cubes, from which we obtain the intensity maps to extract the velocity integrated flux densities. We look at how much the velocity integrated flux densities could change if we use double Gaussian profiles to fit the emission lines (in 16 spectra). Collapsing the cubes between the lower and the upper FWHM bound limits (of both Gaussians), and comparing these to those obtained from a single Gaussian fit, we obtain that fluxes decrease by a $\sim 5\%$ (on average), although with a large scatter ($\sim 30\%$).

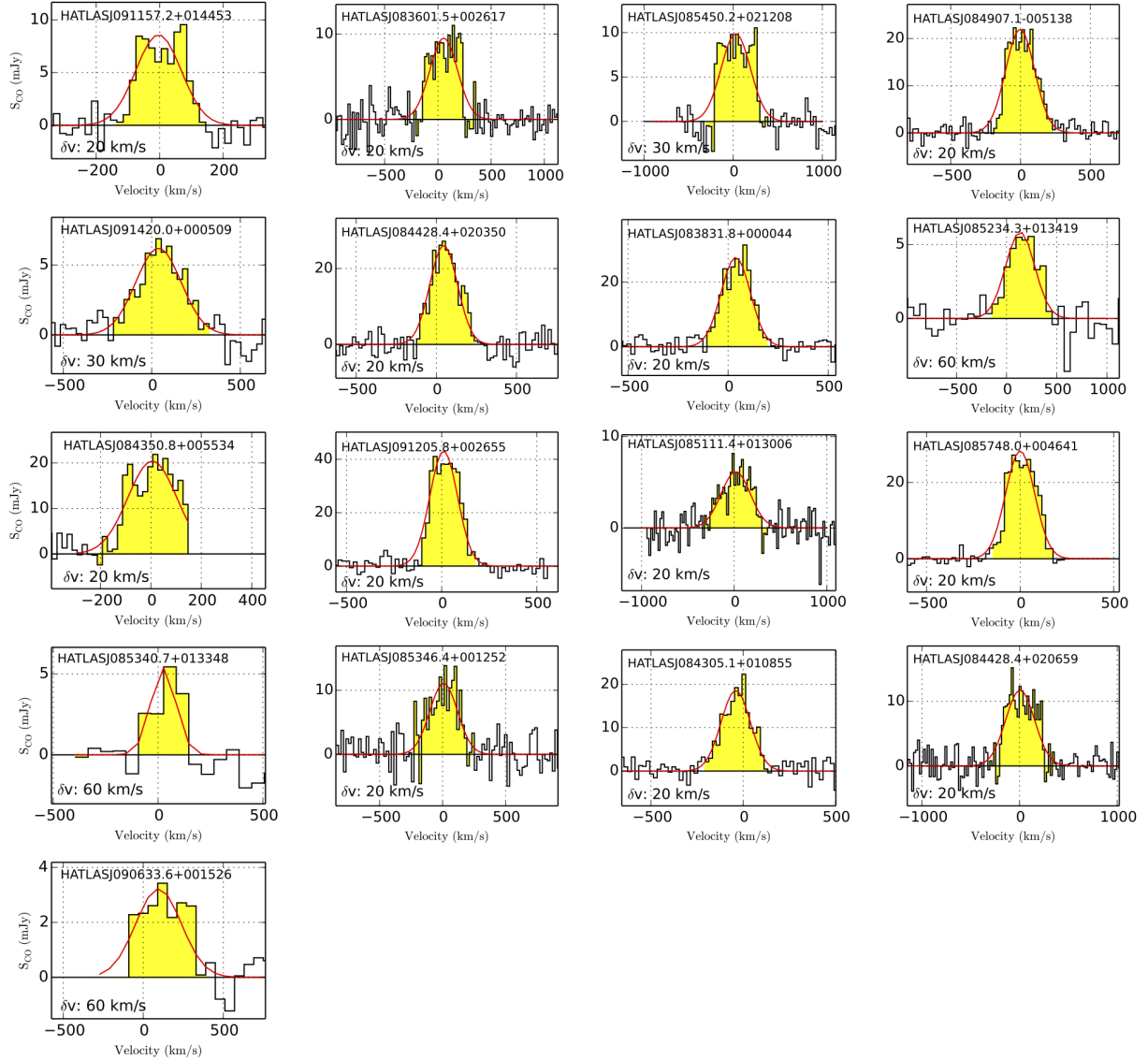


Figure 2. continued

We decide to stick to the single Gaussian fit to estimate the FWHM to collapse the cubes.

2.4.2 IR emission

For each galaxy, we measure the IR luminosity by fitting the rest-frame SED constructed with photometry from *IRAS*, Wide-field Infrared Survey Explorer (WISE), and *Herschel* PACS and SPIRE instruments, using a modified black body that is forced to follow a power law at the high-frequency end of the spectrum. The fit constraints the dust temperature (T_d), the dust emissivity index (β), the mid-IR slope ($\alpha_{\text{mid-IR}}$), and the normalisation. Then we integrate the flux of the best-fitting SED between 8 and 1000 μm to obtain the total IR luminosity (Ibar et al. 2013, 2015), i.e.,

$$L_{\text{IR}}(8 - 1000 \mu\text{m}) = 4\pi D_L^2(z) \int_{\nu_1}^{\nu_2} S_\nu d\nu. \quad (1)$$

The uncertainties on the IR luminosity are obtained

by randomly varying the broadband photometry within the observational uncertainties in a Monte-Carlo simulation (100 times). Our results are listed in Table 2.

We estimate the SFR following $\text{SFR}(M_\odot \text{ yr}^{-1}) = 10^{-10} \times L_{\text{IR}}$ assuming a Chabrier (2003) Initial Mass Function (IMF), where L_{IR} is in units of L_\odot (Kennicutt 1998), and we assume a 1.72 factor to convert from a Salpeter to a Chabrier IMF.

2.4.3 SED fitting

All of our galaxies are present in the GAMA Panchromatic Data Release⁶ (Driver et al. 2016) that provides imaging for over 230 deg² with photometry in 21 bands extending from the far-ultraviolet to far-infrared from a range of facilities that currently includes the GALaxy Evolution eXplorer

⁶ <http://gama-psi.icrar.org>

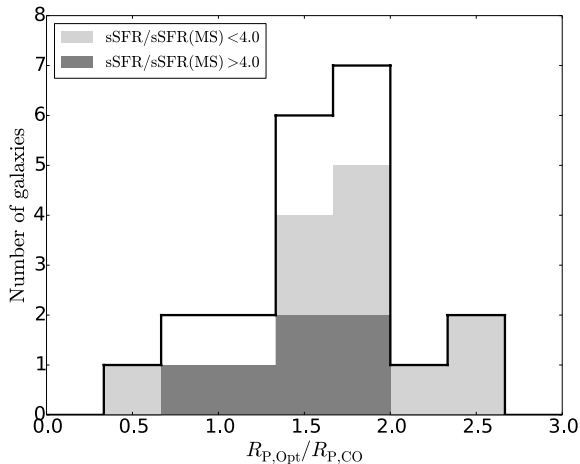


Figure 3. The ratio between the Petrosian radius in r -band ($R_{P,Opt}$) and CO ($R_{P,CO}$) for the 21 ALMA-resolved sources. We separate our sample into two populations based on the relative levels of starburst activity (see Fig. 1). We find that most of our galaxies are distributed around a size ratio $\sim 1.3 - 2.0$.

(GALEX), Sloan Digital Sky Survey (SDSS), Visible and Infrared Telescope for Astronomy (VISTA), WISE, and *Herschel*, meaning that the spectral energy distribution between $0.1-500 \mu\text{m}$ is available for each galaxy. These observed rest-frame SEDs have all been modelled with the Bayesian SED fitting code, MAGPHYS (da Cunha et al. 2008), which fits the panchromatic SED from a library of optical and infrared SEDs derived from a generalised multi-component model of a galaxy, whilst giving special consideration to the dust–energy balance (see Fig. 8). Although Driver et al. (in prep.) will present a complete catalogue and analysis of all the GAMA SEDs modelled with MAGPHYS and the corresponding best-fit model parameters (see also Hughes et al. 2016), in our present study we use the derived stellar masses and their uncertainties, which we calculate from the upper (16th percentile) and lower (84th percentile) limits of the probability distribution function associated with the stellar mass given by the best-fit model, as presented in Table 2.

We briefly assess the quality of the fitting by comparing the stellar masses and IR luminosities derived from MAGPHYS to those estimates from our previous study presented in Ibar et al. (2015). Both of these parameters demonstrate satisfactory agreement with a mean scatter of between 0.15 and 0.2 dex (see Fig. 4). In contrast, our derived star formation rates show a constant systematic offset across the parameter range (of a factor of 2, where MAGPHYS are lower than those estimates from Ibar et al. 2015 using L_{IR}), which likely arises from differences in SFR definition/calibration (see e.g. Kennicutt & Evans 2012). However, removing this systematic offset yields a mean scatter of 0.2 dex.

2.4.4 Morphological properties

In order to explore the morphological properties of our galaxies, we use the GAMA Panchromatic Swarp Imager⁷ to extract multi-wavelength imaging from GALEX, SDSS, VISTA and WISE. We classify each source (based on visual inspection agreed by four members of our team) into three different categories according to the prominence of key morphological features: a Bulge (‘B’), Disk (‘D’) and Merger-Irregular (‘M’). If the source presents more than one morphology, we mark the first letter as the dominant morphology. If the source has multiple neighbouring systems, then we add ‘C’ to denote these ‘companions’. In the following, we refer to our galaxies as ‘B’, ‘D’ or ‘M’ dominated galaxies. We also note that this morphological classification is used to define the most suitable α_{CO} to then compute M_{H_2} (this is discussed in § 3.2).

3 RESULTS AND DISCUSSION

3.1 Morphological description

We have made a census for the different optical/near-IR morphologies present in our sample, according to the morphological classification scheme explained in § 2.4.4. From a total of 49 spectrally detected sources, we have identified 18 as B-dominated, 26 as D-dominated and 5 as M-dominated galaxies (see the morphology column in Table 2). By definition, the 5 M-dominated galaxies present signs of possible morphological disruption: 3 galaxies are clear interacting system (with two or more companions), and 2 show traces of the late stages of merger events. In the case of the spectrally undetected galaxies, we have identified 11 as B-dominated, 4 as D-dominated and 3 as M-dominated galaxies. We do not identify any clear morphological difference between CO-detected and -undetected galaxies.

ALMA observations spatially resolve the CO emission in 21 galaxies (see § 2.4.1). We calculate the deconvolved FWHM of the semi-major axis (R_{FWHM}) using the task GAUSSFIT (within CASA), finding CO sizes in the range of $3''.4 - 15''.2$ ($3.7 - 35.0$ kpc in physical units), usually resolved at a significance of $\sim 7\sigma$ (median value). We compare the optical and CO sizes by using the Petrosian radius in r -band ($R_{P,Opt}$) and the Petrosian radius in CO ($R_{P,CO}$), using Eqn. (1) from Shimasaku et al. (2001). We find values for $R_{P,CO}$ in the range of $1''.9 - 5''.3$ ($2.8 - 14.0$ kpc), with an average of $3''.6$ (6.7 kpc). For our sample, we find that the mean and scatter of the $R_{P,Opt}/R_{P,CO}$ distribution are 1.6 ± 0.5 (i.e. the CO emission is typically smaller than the stellar; see Fig. 3). Previous studies have shown a CO-to-optical ratio of unity for ‘main-sequence’ galaxies, locally (e.g. Young et al. 1995; Regan et al. 2001; Leroy et al. 2008) and at high- z (e.g. Bolatto et al. 2015; Tacconi et al. 2013). In a different luminosity range, Simpson et al. (2015) found that the sizes of Sub-millimetre Galaxies (SMGs) at $z = 2.6 - 4$ in optical *HST* imaging are around four times larger than in CO. Taking into account the typical values of $sSFR/sSFR(MS)$ for our 21 resolved galaxies, we explore if the optical-to-CO ratio changes as a function of $sSFR$.

⁷ <http://gama-psi.icrar.org/psi.php>

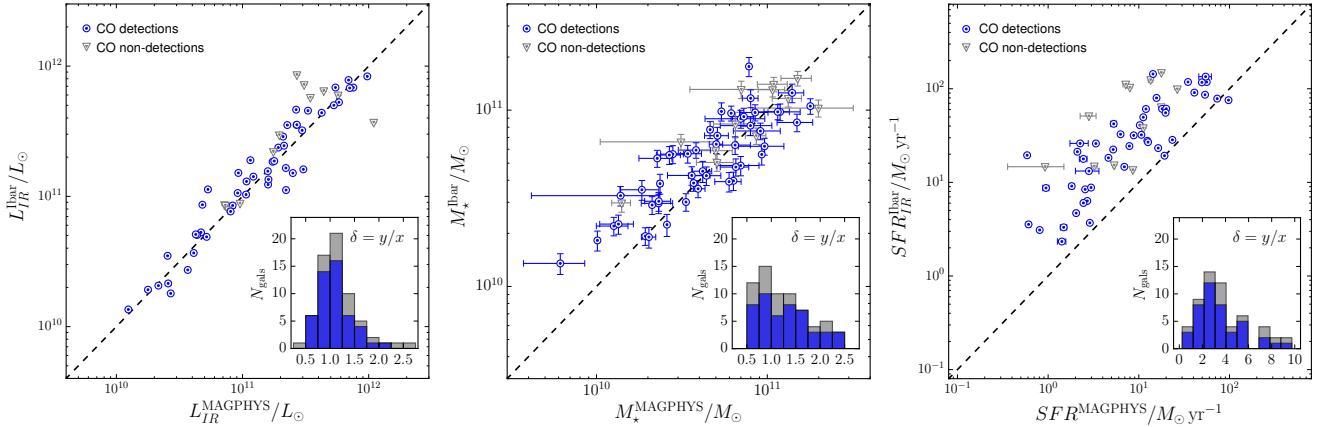


Figure 4. Comparing the infrared luminosity (*left*), stellar mass (*middle*) and star formation rate (*right*) derived from empirical methods (see [Ibar et al. 2015](#)) with those obtained from the MAGPHYS UV–submm SED fitting (see [Driver et al. 2016](#)).

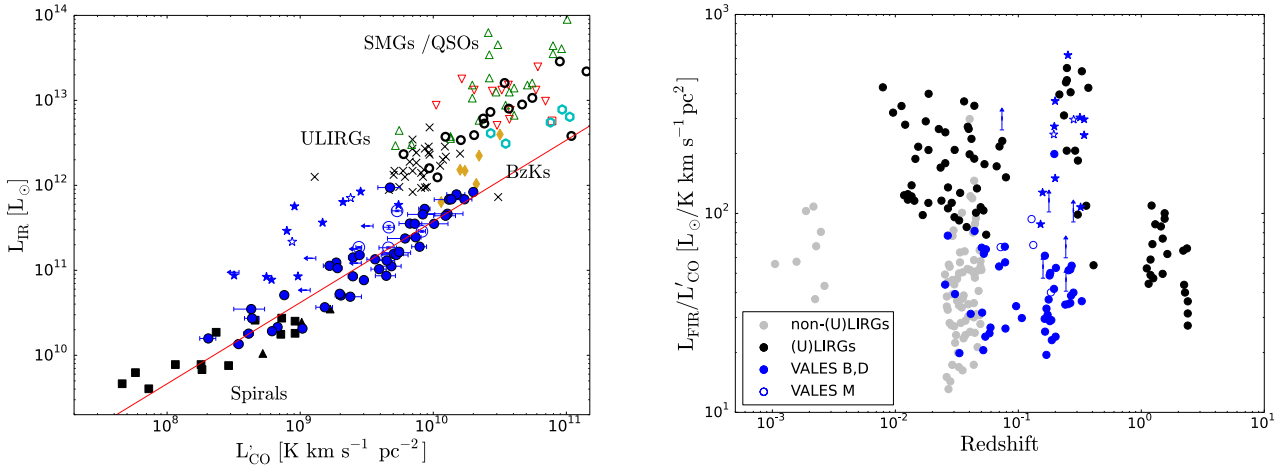


Figure 5. *Left:* Comparison of the CO and IR luminosities for our spectrally detected (blue circles), spectrally undetected but measured with low signal to noise in collapsed cubes (stars), and undetected (blue arrows) CO galaxies. Blue filled symbols are B– and D–dominated, while blue unfilled symbols are M–dominated galaxies. Our sample is compared to other studies taken from the literature, including: colour-selected galaxies (BzK; [Daddi et al. 2010a](#); gold diamonds), submillimeter galaxies (SMGs; [Greve et al. 2005](#), [Daddi et al. 2009a,b](#); red down triangles, [Frayer et al. 2008](#); blue empty square, [Iverson et al. 2011](#); unfilled cyan hexagons), quasi stellar objects (QSOs; [Riechers et al. 2006](#); [Solomon & Vanden Bout 2005](#); green empty triangles), local ULIRGs ([Solomon et al. 1997](#); black crosses), local spirals ([Leroy et al. 2008, 2009](#); black filled squares, [Wilson et al. 2009](#); black filled triangles) and strongly lensed high-redshift dusty galaxies ([Aravena et al. 2016](#); black unfilled circles). The solid line shows the best-fitting L'_{CO} versus L_{IR} relation for the detected B– and D–dominated galaxies presented in this work (see Eqn. 3). *Right:* $L_{\text{IR}}/L'_{\text{CO}}$ as function of redshift. Our galaxies (blue symbols) and other relevant populations classified as (U)LIRGs (black circles) and non-(U)LIRGs (grey circles) taken from [Magdis et al. \(2012\)](#), including: local spirals (COLDGASS [Saintonge et al. 2011](#)); local ULIRGs ([Solomon et al. 1997](#)); $z \sim 0.3$ disks ([Geach et al. 2011](#)), *IRAS* selected $z \sim 0.3$ ULIRGs ([Combes et al. 2011](#)); and high- z star forming galaxies ([Daddi et al. 2010a](#); [Genzel et al. 2010](#)).

We perform a Kolmogorov-Smirnov (KS) for both ‘main sequence’ and ‘starburst’ $R_{\text{P,Opt}}/R_{\text{P,CO}}$ populations (using $\text{sSFR}/\text{sSFR}_{\text{MS}} = 4.0$ as a threshold; see the definition of ‘main-sequence’ in Fig. 1), finding a 90% probability that both populations come from the same parent distribution (see Fig. 3). This little difference might be a product of the small deviation seen from the main sequence (‘starburstiness’) or the six spatially resolved starburst galaxies presented here.

3.2 Correlations between L_{IR} and L'_{CO}

We compute the CO luminosity following [Solomon & Vanden Bout \(2005\)](#),

$$L'_{\text{CO}} = 3.25 \times 10^7 S_{\text{CO}} \Delta v \nu_{\text{obs}}^{-2} D_{\text{L}}^2 (1+z)^{-3} [\text{K km s}^{-1} \text{ pc}^2], \quad (2)$$

where $S_{\text{CO}} \Delta v$ is the velocity-integrated flux density in units of Jy km s^{-1} , ν_{obs} is the observed frequency of the emission line in GHz, D_{L} is the luminosity distance in Mpc, and z is the redshift. We find that the values for L'_{CO} are in the range of $(0.03 - 1.31) \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$, with a median of $(0.3 \pm 0.1) \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$ (see Fig. 5).

We note that our survey expands the parameter space explored before by previous similar studies, such as: (Combes et al. 2011) at $(0.3 - 7) \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$; (Braun et al. 2011) at $(4 - 9) \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$; (Magdis et al. 2014) at $(0.5 - 2) \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$. Based on the IR luminosities derived from the *H*-ATLAS photometry (§ 2.4.2), we find that the ratios between L_{IR} and L'_{CO} are similar to those found in normal local star-forming galaxies (e.g. COLDGASS; Saintonge et al. 2011). However, our galaxies have smaller $L_{\text{IR}}/L'_{\text{CO}}$ ratio than typical (U)LIRGs in the same redshift range by a factor of ~ 10 (see right panel of Fig 5). We compute a linear regression (in log scale) to the L_{IR} versus L'_{CO} relation for our spectrally detected B- and D-dominated galaxies, finding:

$$\log[L_{\text{IR}}/L_{\odot}] = (0.95 \pm 0.04) \times \log[L'_{\text{CO}}/(\text{K km s}^{-1} \text{ pc}^2)] + (2.0 \pm 0.4). \quad (3)$$

This parametrisation is within 1σ of the value previously presented by Daddi et al. (2010b), and supports the clear linearity between these two quantities. However, this slope is steeper compared with that found by Ivison et al. (2011) in high- z SMG, local ULIRGs and LIRGs ($\sim 0.5 - 0.7$). We confirm that most of our detected galaxies (blue circles in left panel Fig. 5) follow the so-called ‘sequence of disks’, associated to a long-standing mode of star-formation. We remark, however, that if we include in the statistics those galaxies which are not spectrally detected in CO (blue stars in left panel Fig. 5), although have low signal to noise emission in collapsed (moment 0 maps), the scatter in the correlation significantly increases. This indicates that deeper observations are required to provide details for the co-existence of different modes of star-formation. We suggest that within the $L_{\text{IR}} = 10^{11-12} L_{\odot}$ range, there might be a break (or a significant increment of the scatter) of the linear relation between the CO and far-IR luminosities (Sargent et al. 2014).

If we add into the statistics all samples presented in Fig. 5) in addition to our B- and D-dominated galaxies, we find in Eqn. 3 a slope and normalisation of (0.99 ± 0.02) and (1.7 ± 0.2) , respectively. Although these parameters are in agreement with previous studies (slope (slope $\sim 1.0 - 1.3$; e.g. Genzel et al. 2010; Daddi et al. 2010b), we should highlight the growing evidence that the star formation efficiencies increase with redshift (e.g. Santini et al. 2014; Rowlands et al. 2014; Genzel et al. 2015; Scoville et al. 2016), therefore combining galaxy samples at different epochs might be an oversimplification of the analysis (see Fig. 5).

For those spectrally identified CO galaxies, we do not identify any clear variation of the $L_{\text{IR}}/L'_{\text{CO}}$ ratio as a function of redshift (up to $z = 0.35$; see right panel of Fig. 5). Our results are consistent with previous works that have shown a constant average $L_{\text{IR}}/L'_{\text{CO}}$ in ‘main-sequence’ galaxies up to $z \sim 0.5$ (e.g. Santini et al. 2014). The scatter on the $L_{\text{IR}}/L'_{\text{CO}}$ ratio, however, increases if non-spectrally detected galaxies are included, an effect which is mainly dominated by the $0.15 < z < 0.35$ galaxy population.

Using L'_{CO} , we compute the molecular gas mass (M_{H_2}) assuming an α_{CO} conversion factor dependent on the morphological classification (see §2.4.4). We adopt $\alpha_{\text{CO}} = 4.6 (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ for the B- and D-dominated galaxies (which includes contribution of He; Solomon & Vanden

Bout 2005), while $\alpha_{\text{CO}} = 0.8 (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ for mergers/interacting galaxies. For B- and D-dominated galaxies, we find M_{H_2} values in the range of $\log(M_{\text{H}_2}/M_{\odot}) = 8.9 - 10.9$ with a median of $\log(M_{\text{H}_2}/M_{\odot}) = 10.31 \pm 0.1$, while for M-dominated galaxies values are in the range of $\log(M_{\text{H}_2}/M_{\odot}) = 9.3 - 9.8$ with a median of $\log(M_{\text{H}_2}/M_{\odot}) = 9.6 \pm 0.2$.

Performing a linear regression to the SFR versus M_{H_2} using our B- and D-dominated galaxies, we obtain:

$$\log[\text{SFR}/M_{\odot} \text{ yr}^{-1}] = (0.95 \pm 0.04) \times \log(M_{\text{H}_2}/[M_{\odot}]) - (8.6 \pm 0.5). \quad (4)$$

In this work, we are significantly increase the number of previously detected galaxies at $\log[M_{\text{H}_2}/M_{\odot}] \sim 9 - 11$. Our sample complements the ‘gap’ between local spirals and ‘normal’ high- z colour-selected galaxies (Fig. 6). We note that our M-dominated galaxies are shifted towards higher SFRs, and closer to the local ULIRGs described by Solomon et al. (1997). At lower redshifts almost all galaxies follow a tight relationship between SFR and M_{H_2} , nevertheless we identify that galaxies at the upper side of the redshift distribution ($0.15 < z < 0.35$) tend to show a higher scatter in this correlation. The scatter is larger when low signal-to-noise detections are included (see stars in left panel of Fig. 6). If we combine our observations with all samples shown in the left panel of Fig. 6), then in Eqn. 4 we obtain a slope of 1.08 ± 0.02 with a normalisation of -9.8 ± 0.2 .

In both cases, one of the main factors controlling the scatter of the correlation is the different α_{CO} conversion factor chosen for M-dominated galaxies. It is worth pointing out that deeper ALMA observations to spectrally detect the CO emission for all of our galaxies would probably confirm a population of optically unresolved ULIRGs-like galaxies with high star formation efficiencies (filling the ‘gap’ between spirals and ULIRGs local galaxies). As shown in left panel of Fig. 5 (see blue stars), this population could significantly affect the slope and the scatter of the correlation.

The major uncertainty in our molecular gas mass estimates originates from the assumption of the α_{CO} conversion factor. Indeed, assuming a different α_{CO} can change M_{H_2} by over a factor of six (around 500 times higher than observational errors). On the other hand, considering the metallicity range of our sample ($12 + \log_{10}(\text{O}/\text{H}) = 8.7 - 9.2$; Ibar et al. 2015) and using the α_{CO} parametrisation for star-forming galaxies made by (Genzel et al. 2015, see their Eqn. 8), we find that the α_{CO} could vary by a factor of four with a tendency to lower values than $4.6 (\text{K km s}^{-1} \text{ pc}^2)^{-1}$. In the left panel of Fig. 6, galaxies can be shifted in position using a different α_{CO} , producing an artificial bimodal behaviour for the star-formation activity in these galaxies. This can clearly affect the reliability for the existence of ‘disk’ and ‘starburst’ sequences. In Molina et al. (in prep.), we use kinematic arguments to confront the bimodality of the α_{CO} conversion factor (e.g. Downes & Solomon 1998b, Sandstrom et al. 2013).

3.3 The Schmidt-Kennicutt relation

We introduce $M_{\text{gas}} = M_{\text{H}_2} + M_{\text{HI}}$ as the total mass content in molecular and atomic gas. As we do not have direct M_{HI}

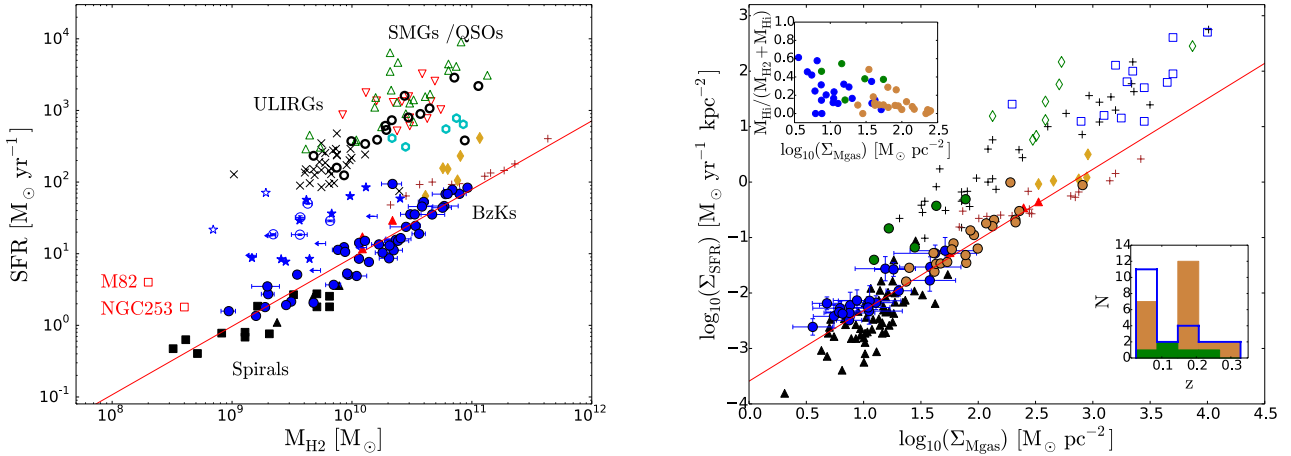


Figure 6. *Left:* The SFR versus M_{H_2} for our galaxies compared to previous works taken from the literature (assuming a Chabrier’s IMF but considering the same α_{CO} used in the original works). We show our spectrally detected (blue circles), spectrally undetected but measured with low signal to noise in collapsed cubes (stars), and undetected (blue arrows) CO galaxies (see § 2.4 for details). Blue filled symbols are B- and D-dominated galaxies, while blue unfilled symbols are M-dominated galaxies. Figure contains BzK galaxies (Daddi et al. 2010a; gold diamonds), $z \sim 0.5$ disk galaxies (Salmi et al. 2012; red filled triangles), $z = 1-2.3$ normal galaxies (Tacconi et al. 2010; brown crosses), SMGs (Greve et al. 2005; Frayer et al. 2008; Daddi et al. 2009a,b; red down triangles, Ivion et al. 2011; unfilled cyan hexagons), QSOs (Riechers et al. 2006; green triangles), local ULIRGs (Solomon et al. 1997; black crosses), strongly lensed high-redshift dusty star forming galaxies (Aravena et al. 2016; black unfilled circles), and local spirals (Leroy et al. 2009; black filled squares; Wilson et al. 2009; black filled triangles). M82 and NGC 253 are also shown (Weiß et al. 2001; Houghton et al. 1997; Kaneda et al. 2009). The solid red line is the best fit for the B- and D-dominated galaxies presented in this work (see Eqn. 4). *Right:* The SFR surface density as a function of the gas mass (atomic and molecular) surface density for the 21 detected sources that can be spatially resolved in CO (blue circles; see § 3.3), 23 detected B- and D-dominated which are unresolved in CO but resolved in R -band (brown circles), and M-dominated unresolved in CO galaxies (green circles). Filled triangles are (U)LIRGs and spiral galaxies from the sample of Kennicutt (1998), brown crosses are $z = 1-2.3$ normal galaxies (Tacconi et al. 2010). The empty blue squares and light green diamonds are SMGs from Bouché et al. (2007) and Bothwell et al. (2009), respectively. The red line is the best linear fit to all of our B- and D-dominated galaxies (see Eqn. 6). The inset figures at the upper left and bottom right corners are: (1) the relative contribution estimated by M_{HI} following Eqn. 5 to the total gas mass ($M_{H_2} + M_{HI}$) versus Σ_{Mgas} . This figure demonstrates the decreasing effect that M_{HI} has at $\Sigma_{Mgas} > 10 M_{\odot} \text{ pc}^{-2}$; (2) the redshift distribution of our VALES galaxies (blue, yellow and green circles), clearly showing that most of the spatially unresolved galaxies are the ones which are more distant.

observations, we estimate these using Eqn. 4 from Zhang et al. 2009:

$$\log[M_{HI}/M_*] = -1.73238(g-r) + 0.215182\mu_i - 4.08451, \quad (5)$$

where g and r are the photometric magnitudes in those filters, and μ_i is the i -band surface brightness (SDSS filters). This approximation provides a 0.31 dex scatter for the estimate. For our sample, using Eqn. 5 we find that the contribution is in general small (although non negligible) with a mean ratio of $M_{HI}/M_{H_2} \sim 0.2$ (see Fig. 6).

Our 49 spectrally-detected CO sources have SFRs in the range of $1-94 M_{\odot} \text{ yr}^{-1}$, with a median value of $15 \pm 1 M_{\odot} \text{ yr}^{-1}$. For those which are spatially resolved in CO (21 in total), we estimate the SFR and M_{gas} surface densities by dividing the measured values by the area of a two-sided disk ($2\pi R_{FWHM}^2$), where R_{FWHM} is the deconvolved FWHM of the semi-major axis measured in ALMA CO images (see Table 2). In Fig. 6 (right), we show the Schmidt-Kennicutt relation (Schmidt 1959; Kennicutt 1998) comparing our samples with previous ones taken from the literature.

For those spectrally detected and spatially resolved CO galaxies, we obtain values for $\log[\Sigma_{SFR}/(M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2})]$ in

the range of -2.61 and -1.23 , with a median of -2.18 ± 0.1 . Most of the spatially resolved ones (16) are D-dominated while the rest (5) are B-dominated galaxies. The B- and D-dominated galaxies have on average 3 times higher Σ_{SFR} than local spiral galaxies, but around 30-70 times lower values than normal BzK galaxies at high- z . On the other hand, for the same spectrally detected CO galaxies, $\log[\Sigma_{Mgas}/(M_{\odot} \text{ pc}^{-2})]$ values range between 0.55 and 1.71, with a median value of 1.04 ± 0.29 . In terms of CO emission, we do not find any remarkable difference between our B- and D-dominated galaxies (although they do have different morphological optical features); the sample has on average 2 times greater Σ_{Mgas} than local spiral galaxies.

According to estimations of the molecular and atomic gas content in nearby galaxies (Bigiel & Blitz 2012), there is a strong evidence that the atomic gas saturates in column gas densities higher than $\sim 10 M_{\odot} \text{ pc}^{-2}$. This is attributed to a natural threshold for the atomic to molecular gas transitions (Krumholz et al. 2009; Sternberg et al. 2014). As shown in Fig. 6, our atomic gas estimates decrease as a function of Σ_{Mgas} (as expected by the M_{HI} saturation), although the large scatter dominating Eqn. 5 still predicts a non-negligible fraction of atomic gas above $\Sigma_{Mgas} > 10^{10} M_{\odot} \text{ pc}^{-2}$.

Something to highlight is that left and right panels of

Fig. 6 should behave similarly, nevertheless we find that most of our galaxies (blue circles) which are lying near the BzK population disappear after considering our spatially resolved CO selection criterion. To explore this further, we compare the median values of M_{H_2} and R_{CO} using resolved galaxies (in CO) at different redshift bins (centred at 0.07 and 0.2) in order to identify a possible evolution in physical size and mass of gas content. Previous studies have shown that at fixed M_* the averaged effective radius vary as $R_{\text{eff}} \propto (1+z)^{-0.8}$ (Magdis et al. 2012). If we assume that the stars and the molecular gas follow the same spatial distribution (which is actually not the case; see Fig. 3), the measured CO sizes are expected to decrease by a factor of 1.1 between $z = 0.07$ and $z = 0.2$. This variation is not sufficient to explain what we observe in Fig. 6.

Considering the results coming from § 3.1 to estimate Σ_{SFR} and Σ_{Mgas} for spatially unresolved CO galaxies, we used the Petrosian optical radius divided by the mean $R_{\text{P,Opt}}/R_{\text{P,CO}} = 1.6$ ratio found for our galaxies (note that R_{FWHM} and $R_{\text{P,CO}}$ differ by only $\sim 2\%$). Brown and green circles in Fig. 6 correspond to CO-unresolved B-/D-dominated and M-dominated galaxies, respectively. The inset panel in Fig. 6 shows clearly that most of the spatially unresolved CO galaxies are those which are more distant (at $0.15 < z < 0.35$). This analysis demonstrates that our sample perfectly complements the parameter space in the Schmidt-Kennicutt relation that joins the local spiral galaxies with those ‘normal’ at high- z .

Using our data, we perform a linear regression in Fig. 6 using all B-/D-dominated galaxies which are spatially resolved in CO (21 sources) and unresolved in CO but resolved in the optical (23 sources). Being aware of the possible biases introduced by our H I estimates, we provide a parametrisation for two cases; M_{H_2} and M_{gas} ,

$$\frac{\Sigma_{\text{SFR}}}{M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}} = \begin{cases} (1.16 \pm 0.05) \times \log[\Sigma_{\text{Mgas}}/M_{\odot} \text{ pc}^{-2}] \\ \quad - (3.3 \pm 0.1) \\ (1.27 \pm 0.05) \times \log[\Sigma_{\text{MH}_2}/M_{\odot} \text{ pc}^{-2}] \\ \quad - (3.6 \pm 0.1) \end{cases} \quad (6)$$

These results are consistent with previously analyses using ensembles of clumps composing galaxies at $z = 1-2$ (e.g. Freundlich et al. 2013; Genzel et al. 2013) and star-forming disks with near-solar metallicities (slope $\sim 1.0-1.3$; e.g. Bigiel et al. 2008; Kennicutt et al. 2008; Schruha et al. 2011; Leroy et al. 2008). Presenting Eqn. 6 for the molecular and total gas helps to see the way the M_{H_2} could affect our results. In particular we find that the slope is flatter when M_{gas} are used. We highlight that given that these galaxies have been selected in the far-IR, our results are not significantly affected by the assumptions in geometrical modelling of the dust as previous in Genzel et al. (2013) and Freundlich et al. (2013) studies.

If we take into account the samples of galaxies belonging to the sequence of disks shown in right panel of Fig. 6 (including $z = 1.0-2.3$ normal galaxies, BzK and $z \sim 0.5$ disks, spiral galaxies and both our spatially resolved and unresolved B-/D-dominated galaxies) in our linear regression of Eqn. 6, we obtain a slope of (1.26 ± 0.02) and a normalisation of (3.6 ± 0.2) . Mentioned before, this should be

taken with caution as there is growing evidence for a cosmic evolution of the star formation efficiency, effective radius and gas content (e.g. Magdis et al. 2012), implying that the combination of samples at different epochs might be mixing intrinsically different populations.

3.4 Star formation efficiency

We define the star formation efficiency as $\text{SFE} = \text{SFR}/M_{\text{H}_2}$ and the M_{H_2} consumption time-scale (τ_{MH_2}) as SFE^{-1} . In the left panel of Fig. 7, we show the SFE vs. L_{IR} for our galaxies including other galaxy samples taken from the literature. Two distinctive types of galaxies are evident: those galaxies that present a long-standing mode of star formation with $\tau_{\text{MH}_2} \sim 1.3$ Gyr; and those affected by a much faster starburst processes with $\tau_{\text{MH}_2} \sim 0.2$ Gyr. We identify a significant number of sources that are located in the ‘transition zone’ between both the sequence of disks and the sequence of starbursts (left panel in Fig. 7), with SFEs in the range of $4.3-11.7 \text{ Gyr}^{-1}$, and with a median of $8.5 \pm 0.1 \text{ Gyr}^{-1}$ (e.g. similar to those SMGs at $z = 0.22-0.25$ presented by Ivison et al. 2011). These sources seem to suggest the co-existence of both modes of star-formation at intermediate efficiencies. We note that 39 of our sources are located in the long-lasting mode, with SFEs in the range of $0.42-4.32 \text{ Gyr}^{-1}$, and with a median of $0.8 \pm 0.1 \text{ Gyr}^{-1}$.

We highlight the evidence for galaxies located in the ‘transition zone’ between ‘normal’ and ‘starburst’ confirming a break in SFE at $L_{\text{IR}} \approx 10^{11-12} L_{\odot}$, which could indicate the possibility of a single evolutionary path (with a large scatter) rather than a sharp bimodal behaviour in evolution (see § 3.2). This is in agreement with previous findings by Sargent et al. (2014). We propose an empirical best-fit parametrisation to describe the dependence of the SFE on L_{IR} (based in all $z < 0.4$ samples included in left panel of Fig. 7):

$$\log[\text{SFR}/M_{\text{H}_2} (\text{yr}^{-1})] = 0.19 \times (\log[L_{\text{IR}}/L_{\odot}] - \phi) + \alpha + \beta \arctan[\rho (\log[L_{\text{IR}}/L_{\odot}] - \phi)], \quad (7)$$

where $\alpha = -8.26$, $\beta = -0.41$, $\rho = -4.84$ and $\phi = 11.45$. This function has a scatter of $\sigma = 0.5$ dex.

In this work we highlight that our method to compute the molecular gas masses is directly using CO(1-0), not assuming any particular conversion for high- J transitions, facilitating the interpretation of the results. Scoville et al. (2016), for example, obtain different star formation modes for normal and starburst/SMG galaxies, which are likely affected by the different methods behind the computation of both gas masses at high redshift (using higher- J CO transitions) and different α_{CO} for each type of galaxy.

In spite of the remaining uncertainties on the assumptions used to derive M_{H_2} , the detection of galaxies in the ‘transition zone’, including spectrally detected/undetected with $\alpha_{\text{CO}} = 4.6 (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ and mergers with a smaller α_{CO} by a factor of six, supports the scenario of a smooth increase of SFE as a function of L_{IR} . This has been hinted before in galaxies at $z = 1.6$ by Silverman et al. (2015), where as they explored sources above the ‘main sequence’ they tentatively concluded a smooth increase of SFE instead of a bimodality in star formation modes.

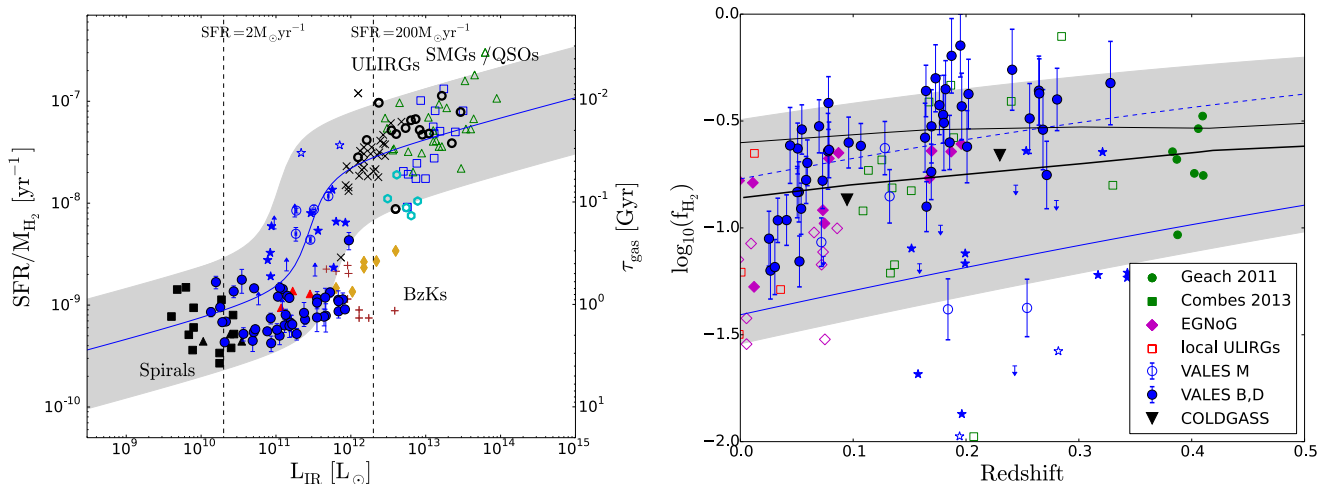


Figure 7. *Left:* SFE versus IR luminosities following the same symbols and colours shown in the left panel of Fig. 5. Blue solid line is the best-fitted parametrisation considering all the galaxy samples at $z < 0.4$ presented in the figure (see Eqn. 7) while the light grey area is the region within a 1σ scatter of 0.5 dex. This parametrisation suggests a break on the star formation efficiency at $L_{\text{IR}} = 10^{11-12} L_{\odot}$. *Right:* Molecular gas fraction (f_{H_2}) versus redshift for different samples of star-forming galaxies. The upside down triangles are the average values from COLDGASS survey. The dashed and solid blue curves are the average behaviour for normal galaxies and the expected location for starburst galaxies by Bauermeister et al. (2013), respectively. The light grey area is the region of the ‘main-sequence’ for star-forming galaxies when adopting an average $\tau_{\text{M}_{\text{H}_2}}$ (MS) ~ 2.2 Gyr (e.g. Bigiel et al. 2008; Leroy et al. 2008). The two black curves show semi-analytic prescriptions for galaxy formation by Lagos et al. (2011), which correspond to mass halo models of $M_{\text{h}} = 10^{11}$ and $10^{12} M_{\odot} \text{ h}^{-1}$, from thinnest to thickest, respectively.

3.5 Evolution of the molecular gas fraction

In this section, we explore the evolution of the molecular gas fraction (f_{H_2}) as a function of redshift. We introduce the molecular gas mass to the stellar mass ratio as:

$$\frac{M_{\text{H}_2}}{M_{\star}} = \tau_{\text{M}_{\text{H}_2}} \times \text{sSFR}, \quad (8)$$

thus, the gas fraction can be calculated as $f_{\text{H}_2} = M_{\text{H}_2}/(M_{\text{H}_2} + M_{\star})$. We find our sample covers a wide range of values $f_{\text{H}_2} \sim 0.04 - 0.71$ (for those sources spectrally CO-detected above 5σ), which are similar to those shown by the Evolution of molecular Gas in Normal Galaxies (EGNoG Bauermeister et al. 2013) survey in normal star-forming galaxies. Compared to local ULIRGs, where f_{H_2} ranges at 3-5% (e.g. Solomon et al. 1997; Gao & Solomon 2004; Chung et al. 2009), our gas fractions are typically higher than those, although if we only consider those M-dominated galaxies we find similar values to those seen in local ULIRGs (lying near the lower f_{H_2} envelope defined for starburst galaxies by Bauermeister et al. 2013). We identify that our f_{H_2} values show a tendency to increase as a function of redshift (see Fig. 7) – probably product of a selection effect induced by the *Herschel* detectability (these are dusty galaxies). Béthermin et al. (2014) suggest a rapid increase of the average fraction of molecular gas with redshift, similarly to what we find in our analysis. Based on recent works (e.g. Dunne et al. 2011; Hardcastle et al. 2016; Wang et al. 2016), there is growing evidence for a rapid galaxy evolution at low redshifts. Particularly, Dunne et al. (2011) find evidence for fast evolution of the dust mass content of galaxies up to $z = 0.5$, a result that suggest that the molecular gas content also rapidly evolves in samples of *Herschel*-selected galaxies. Actually, using galaxies taken from this same work,

Hughes et al. (2016) suggests that this rapid evolution goes together with a significant increment of the gas density (up to $z = 0.2$), aided by predictions from photo-dissociation region modelling.

In the right panel of Fig. 7, the two black curves show semi-analytic prescriptions for galaxy formation and evolution of the molecular ISM computed by Lagos et al. (2011), based on an empirical star formation law to estimate the molecular gas mass. Black solid lines correspond to mass halo models of $M_{\text{h}} = 10^{11}$ and $10^{12} M_{\odot} \text{ h}^{-1}$, from thinnest to thickest, respectively, that trace our B- and D-dominated galaxies. These models suggest that molecular gas mass content and SFR densities increase as a function of redshift, in rough agreement with what we see in our B- and D-dominated galaxies. On the other hand, the M-dominated galaxies are apparently associated to more massive dark matter halos of $\sim 10^{12} M_{\odot}$.

4 CONCLUSIONS

In this paper, we present the VALES survey – one of the largest samples of CO detected normal star-forming galaxies up to $z = 0.35$. We use the ALMA telescope to estimate the molecular gas content via CO(1–0) emission in a sample of 67 dusty star-forming galaxies. Sources are bright far-IR emitters ($S_{160\mu\text{m}} \geq 100 \text{ mJy}$; $L_{\text{IR}} \approx 10^{10-12} M_{\odot}$) selected from the equatorial fields of the *H*-ATLAS survey (with SFRs in the range of $1.4 - 94.2 M_{\odot} \text{ yr}^{-1}$). We have spectroscopically detected 49 galaxies (72% of the sample) with a $> 5\sigma$ CO peak line significance and 12 others are detected in collapsed spectra at low signal to noise. We find that 21 galaxies are spatially resolved in CO (with physical sizes in the range of $3.7 - 35.1 \text{ kpc}$, allowing a multi-wavelength exploration over

a wide parameter space. We summarise our main results as follows:

- Based on a visual inspection to the optical/near-IR photometry of the 49 spectrally CO-detected galaxies, we classify 36% as being dominated by a (B)ulge morphology, 53% as a (D)isk morphology, and 11% show evidence for a (M)erger event or interaction. We spatially resolve 21 galaxies which on average show optical-to-CO size ratios of $\sim 1.6 \pm 0.5$, hence the molecular gas is more concentrated towards the central regions than the stellar component.
- Our sample explores the L'_{CO} luminosity range of $0.3 \times 10^{10} \text{ K km s}^{-1} \text{ pc}^2$ expanding the parameter space to fainter values than previous relevant CO surveys at similar redshifts. Aided by the morphological classification (assuming standard α_{CO} conversion factors for disks and mergers), we estimate a range of $M_{\text{H}_2} = 10^{8.9-10.9} M_{\odot}$ for Bulge- and Disk-dominated galaxies while $10^{9.3-9.8} M_{\odot}$ for Merger-dominated galaxies.
- We explore the Schmidt-Kennicutt relation using values for global Σ_{SFR} and Σ_{Mgas} derived from a combination of CO and optical radii. Our sample perfectly complements the parameter space that joins both, local and high- z ‘normal’ galaxy samples. We find a best linear fit with a power law slope of 1.16 ± 0.05 and 1.27 ± 0.05 when using M_{H_2} and $M_{\text{H}_2} + \text{H I}$, respectively.
- The median SFE of our sample is 8.5 Gyr^{-1} (with values in the range of $0.4 - 11.7 \text{ Gyr}^{-1}$). Even though most of our galaxies follow a long standing mode of star-formation activity, we provide evidence for a population with efficiencies in the ‘intermediate valley’ between normal star formation in disks and more rapid/violent starburst episodes. Within some galaxies there may be a mixture of star-formation modes occurring at the same time. We propose the existence of a continuous transition for the star formation efficiencies as a function of far-IR luminosities.
- We estimate the molecular gas fraction, finding values in the range of $f_{\text{H}_2} = 0.06 - 0.34$. Our observations suggest a strong increment of the gas fraction as a function of redshift (up to $z = 0.35$), faster than semi-analytical models predictions. This rapid evolution might be affected by the selection criteria as we are selecting *Herschel*-detected galaxies with preferentially high dust content.

To conclude, we note that one of the main uncertainties in this work is produced by the different CO conversion factors between CO luminosity and molecular gas mass, which undoubtedly impact our estimates. Two of the most evident drivers of these uncertainties are the dynamical state of the galaxies and the metallicity. We are putting special emphasis on tackling the uncertainty on the molecular gas mass estimates using: dynamical modelling of resolved galaxies (Molina et al. in prep), the physical conditions of the interstellar molecular gas within them (Hughes et al. 2016), and the calibration between the dust continuum luminosity and interstellar gas content (Hughes et al. 2017).

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| GAMA ID | Source | RA (J2000) | Dec (J2000) | z _{spec} | log(L _{IR} /L _⊙) | SFR | log(M _* /M _⊙) | sSFR | ν _{obs} | ν _{obs} | S _{CO} Δν | L _{CO} 10 ¹⁰ | log(M _{H2} /M _⊙) | R _{FWHM} | SFE | Σ _{gas} | Σ _{SFR} | τ _{gas} | Morphology | |
|---------|------------------------|------------|-------------|-------------------|---------------------------------------|------------------------------------|--------------------------------------|----------------------|------------------|-----------------------|--------------------------|---|---------------------------------------|-------------------|----------------------|--|--|------------------|---------------|-----|
| | | | | | | [M _⊙ yr ⁻¹] | | [Gyr ⁻¹] | [GHz] | [km s ⁻¹] | [Jy km s ⁻¹] | [K km s ⁻¹ pc ²] | | [kpc] | [Gyr ⁻¹] | [log M _⊙ pc ⁻²] | [log M _⊙ yr ⁻¹ kpc ⁻²] | [Gyr] | | |
| 214184 | HATLASJ083601.5+002617 | 08:36:01.6 | +00:26:18.1 | 0.0332 | 10.31 ± 0.02 | 2.06 ± 0.1 | 10.59 ± 0.1 | 0.05 ± 0.01 | 111.545 | 54 ± 11 | 306 ± 27 | 20.6 ± 0.85 | 0.104 ± 0.004 | 9.68 ± 0.018 | 10.1 ± 0.8 | 0.43 ± 0.03 | 1.3 ± 0.3 | -2.1 ± 0.3 | 2.318 ± 0.15 | DB |
| 3895257 | HATLASJ083745.1-005141 | 08:37:45.2 | -00:51:40.9 | 0.0306 | 10.13 ± 0.03 | 1.35 ± 0.09 | 10.35 ± 0.12 | 0.06 ± 0.02 | 111.843 | 18 ± 14 | 202 ± 33 | 8.1 ± 0.62 | 0.034 ± 0.003 | 9.2 ± 0.034 | 6.4 ± 0.9 | 0.85 ± 0.09 | 1.3 ± 0.1 | -2.0 ± 0.1 | 1.17 ± 0.119 | D |
| 208589 | HATLASJ083831.9+000045 | 08:38:31.9 | +00:00:45.0 | 0.0781 | 11.15 ± 0.01 | 14.17 ± 0.4 | 10.27 ± 0.11 | 0.77 ± 0.2 | 106.911 | 38 ± 3 | 172 ± 8 | 8.8 ± 0.68 | 0.25 ± 0.019 | 10.06 ± 0.034 | 6.6 ± 0.6 | 1.23 ± 0.1 | -2.1 ± 0.3 | 0.81 ± 0.067 | DBC | |
| 345647 | HATLASJ084139.5+015346 | 08:41:39.5 | +01:53:46.7 | 0.0736 | 10.98 ± 0.01 | 9.48 ± 0.25 | 10.29 ± 0.11 | 0.49 ± 0.13 | 107.561 | | | <1.3 | <0.032 | | | | | | | |
| 417395 | HATLASJ084217.7+021222 | 08:42:17.9 | +02:12:23.4 | 0.096 | 10.93 ± 0.04 | 8.51 ± 0.79 | 10.53 ± 0.11 | 0.25 ± 0.07 | 105.185 | -35 ± 5 | 186 ± 12 | 6.5 ± 0.45 | 0.249 ± 0.02 | 10.059 ± 0.034 | 17.3 ± 1.4 | 0.74 ± 0.09 | 1.1 ± 0.2 | -2.3 ± 0.2 | 1.346 ± 0.163 | DBC |
| 300757 | HATLASJ084305.0+010858 | 08:43:05.1 | +01:08:56.0 | 0.0777 | 11.05 ± 0.03 | 11.31 ± 0.78 | 10.41 ± 0.17 | 0.44 ± 0.17 | 106.975 | -40 ± 4 | 187 ± 11 | 5.9 ± 0.6 | 0.166 ± 0.017 | 9.883 ± 0.044 | | 1.48 ± 0.18 | | | 0.676 ± 0.083 | DBC |
| 371334 | HATLASJ084350.7+005535 | 08:43:50.8 | +00:55:34.8 | 0.0729 | 11.03 ± 0.01 | 10.61 ± 0.27 | 10.64 ± 0.12 | 0.24 ± 0.07 | 107.478 | 30 ± 17 | 285 ± 47 | 7.7 ± 0.64 | 0.191 ± 0.016 | 9.943 ± 0.036 | | 1.21 ± 0.11 | | | 0.826 ± 0.072 | DBC |
| 345754 | HATLASJ084428.3+002949 | 08:44:28.4 | +02:03:49.8 | 0.0254 | 10.25 ± 0.01 | 1.8 ± 0.04 | 10.29 ± 0.12 | 0.09 ± 0.03 | 112.401 | 46 ± 4 | 203 ± 20 | 14.0 ± 1.18 | 0.041 ± 0.003 | 9.276 ± 0.037 | | 1.08 ± 0.08 | | | 1.049 ± 0.091 | DBC |
| 386263 | HATLASJ084428.3+020657 | 08:44:28.4 | +02:06:57.4 | 0.0786 | 11.01 ± 0.03 | 10.33 ± 0.64 | 10.78 ± 0.11 | 0.17 ± 0.05 | 106.865 | 5 ± 10 | 349 ± 25 | 13.6 ± 1.78 | 0.392 ± 0.051 | 10.255 ± 0.057 | | 0.57 ± 0.08 | | | 1.744 ± 0.253 | DC |
| 278475 | HATLASJ084630.7+005055 | 08:46:30.9 | +00:50:53.3 | 0.1323 | 11.51 ± 0.02 | 32.13 ± 1.69 | 10.36 ± 0.12 | 1.42 ± 0.39 | 101.802 | -4 ± 9 | 324 ± 23 | 5.5 ± 0.5 | 0.463 ± 0.042 | 9.569 ± 0.039 | | 8.67 ± 0.91 | | | 0.115 ± 0.012 | M |
| 3264571 | HATLASJ084907.0-005139 | 08:49:07.1 | -00:51:37.7 | 0.0698 | 11.18 ± 0.01 | 15.1 ± 0.33 | 10.48 ± 0.11 | 0.5 ± 0.13 | 107.752 | -3 ± 4 | 244 ± 9 | 12.3 ± 0.98 | 0.279 ± 0.022 | 10.108 ± 0.035 | | 1.18 ± 0.1 | | | 0.85 ± 0.07 | BC |
| 376293 | HATLASJ085111.5+013006 | 08:51:11.4 | +01:30:06.9 | 0.0594 | 10.72 ± 0.02 | 5.29 ± 0.26 | 10.56 ± 0.1 | 0.15 ± 0.04 | 108.805 | 16 ± 15 | 372 ± 35 | 11.2 ± 0.46 | 0.198 ± 0.007 | 9.96 ± 0.016 | 13.9 ± 0.7 | 0.58 ± 0.04 | 1.0 ± 0.3 | -2.1 ± 0.3 | 1.724 ± 0.107 | DB |
| 371789 | HATLASJ085112.9+010342 | 08:51:12.8 | +01:03:43.7 | 0.0267 | 10.2 ± 0.01 | 1.58 ± 0.04 | 10.14 ± 0.12 | 0.11 ± 0.03 | 112.28 | -13 ± 4 | 143 ± 11 | 6.3 ± 0.87 | 0.02 ± 0.003 | 8.972 ± 0.06 | | 1.68 ± 0.24 | | | 0.595 ± 0.083 | DB |
| 323772 | HATLASJ085234.4+013419 | 08:52:34.9 | +01:34:22.7 | 0.195 | 11.92 ± 0.01 | 13.43 ± 2.18 | 10.57 ± 0.12 | 2.25 ± 0.62 | 96.417 | 134 ± 16 | 340 ± 38 | 10.7 ± 0.07 | 1.999 ± 0.012 | 10.963 ± 0.003 | | 0.91 ± 0.02 | | | 1.102 ± 0.03 | BC |
| 323855 | HATLASJ085340.7+013348 | 08:53:40.7 | +01:33:47.9 | 0.041 | 10.28 ± 0.03 | 1.92 ± 0.14 | 10.36 ± 0.12 | 0.08 ± 0.02 | 110.722 | 26 ± 14 | 140 ± 32 | 8.0 ± 0.37 | 0.061 ± 0.003 | 9.451 ± 0.02 | 11.2 ± 2.3 | 0.68 ± 0.06 | 1.9 ± 0.3 | -1.0 ± 0.3 | 1.471 ± 0.125 | DC |
| 600024 | HATLASJ085346.4+001252 | 08:53:46.3 | +00:12:52.4 | 0.0504 | 10.71 ± 0.01 | 1.51 ± 0.15 | 10.31 ± 0.12 | 0.25 ± 0.07 | 109.73 | 8 ± 12 | 259 ± 29 | 6.5 ± 0.13 | 0.076 ± 0.002 | 9.943 ± 0.009 | 5.5 ± 0.7 | 1.46 ± 0.05 | 2.0 ± 0.3 | -1.2 ± 0.3 | 0.684 ± 0.022 | D |
| 600026 | HATLASJ085356.5+001256 | 08:53:56.3 | +00:12:56.3 | 0.0508 | 10.33 ± 0.03 | 2.14 ± 0.16 | 10.01 ± 0.12 | 0.21 ± 0.06 | 109.683 | 31 ± 5 | 138 ± 13 | 8.7 ± 0.14 | 0.068 ± 0.002 | 9.493 ± 0.011 | 9.5 ± 2.5 | 0.69 ± 0.06 | 1.1 ± 0.2 | -2.1 ± 0.2 | 1.45 ± 0.116 | DB |
| 301346 | HATLASJ085406.0+011129 | 08:54:05.9 | +01:11:30.4 | 0.0441 | 10.54 ± 0.02 | 3.5 ± 0.14 | 9.79 ± 0.13 | 0.57 ± 0.17 | 110.405 | -5 ± 17 | 255 ± 41 | 4.8 ± 0.25 | 0.043 ± 0.011 | 9.295 ± 0.113 | 4.5 ± 1.2 | 1.77 ± 0.47 | 0.8 ± 0.2 | -2.6 ± 0.2 | 0.564 ± 0.149 | DBC |
| 386720 | HATLASJ085450.2+021207 | 08:54:50.2 | +02:12:08.3 | 0.0583 | 10.7 ± 0.02 | 5.05 ± 0.27 | 10.66 ± 0.1 | 0.11 ± 0.03 | 108.909 | 29 ± 15 | 387 ± 36 | 12.9 ± 1.23 | 0.202 ± 0.019 | 9.969 ± 0.042 | 8.6 ± 0.8 | 0.54 ± 0.06 | 1.0 ± 0.1 | -2.1 ± 0.1 | 1.842 ± 0.201 | DB |
| 278874 | HATLASJ085611.5+005237 | 08:56:16.0 | +00:52:36.2 | 0.1692 | 10.94 ± 0.01 | 8.62 ± 0.22 | 10.96 ± 0.1 | 0.09 ± 0.02 | 98.588 | 15 ± 13 | 252 ± 32 | 3.2 ± 0.55 | 0.443 ± 0.076 | 10.31 ± 0.075 | 17.1 ± 2.9 | 0.42 ± 0.07 | 1.1 ± 0.2 | -2.5 ± 0.2 | 2.365 ± 0.411 | B |
| 600164 | HATLASJ085623.6+001352 | 08:56:23.7 | +00:13:51.7 | 0.1774 | 11.14 ± 0.01 | 13.86 ± 0.36 | 10.7 ± 0.12 | 0.27 ± 0.07 | 97.305 | | | <0.8 | <0.119 | | | | | | | |
| 622662 | HATLASJ085748.0+004641 | 08:57:48.0 | +00:46:38.7 | 0.0718 | 11.27 ± 0.01 | 18.68 ± 0.33 | 10.37 ± 0.11 | 0.79 ± 0.2 | 107.552 | 0 ± 2 | 182 ± 6 | 11.5 ± 0.58 | 0.276 ± 0.014 | 9.344 ± 0.022 | | 8.46 ± 0.45 | | | 0.118 ± 0.006 | M |
| 376631 | HATLASJ085750.6+012808 | 08:57:50.0 | +01:28:06.7 | 0.1993 | 10.92 ± 0.01 | 8.38 ± 0.21 | 10.49 ± 0.12 | 0.27 ± 0.08 | 96.117 | | | 0.03 ± 0.17 | 0.056 | 9.409 | | 3.26 | | | 0.306 | DB |
| 301648 | HATLASJ085828.4+012211 | 08:58:28.5 | +01:22:11.5 | 0.1992 | 11.46 ± 0.01 | 29.15 ± 0.77 | 10.7 ± 0.12 | 0.58 ± 0.16 | 96.14 | | | 0.04 ± 0.18 | 0.079 | 9.563 | | 7.98 | | | 0.125 | BD |
| 622694 | HATLASJ085828.5+003815 | 08:58:28.6 | +00:38:14.8 | 0.0524 | 10.44 ± 0.02 | 2.72 ± 0.14 | 10.43 ± 0.11 | 0.1 ± 0.03 | 109.538 | -6 ± 8 | 223 ± 19 | 3.4 ± 0.42 | 0.043 ± 0.005 | 9.301 ± 0.053 | 8.2 ± 0.8 | 1.36 ± 0.18 | 1.5 ± 0.3 | -1.4 ± 0.3 | 0.734 ± 0.097 | DBC |
| 376679 | HATLASJ085836.0+013149 | 08:58:36.0 | +01:31:49.0 | 0.1068 | 11.22 ± 0.01 | 16.51 ± 0.43 | 10.9 ± 0.1 | 0.21 ± 0.05 | 104.131 | 57 ± 6 | 217 ± 15 | 10.3 ± 0.2 | 0.554 ± 0.011 | 10.406 ± 0.008 | 24.9 ± 1.2 | 0.65 ± 0.02 | 1.4 ± 0.2 | -1.6 ± 0.2 | 1.544 ± 0.051 | DBC |
| 382034 | HATLASJ085957.9+015632 | 08:59:57.9 | +01:56:34.2 | 0.1943 | 11.34 ± 0.01 | 21.69 ± 0.57 | 10.81 ± 0.2 | 0.33 ± 0.15 | 96.531 | | | 0.5 ± 0.18 | 0.087 | 8.843 | | 31.15 | | | 0.032 | M |
| 299807 | HATLASJ090004.9+000447 | 09:00:05.0 | +00:04:46.8 | 0.0539 | 10.57 ± 0.02 | 3.68 ± 0.15 | 10.7 ± 0.1 | 0.07 ± 0.02 | 109.375 | 14 ± 10 | 308 ± 24 | 11.4 ± 1.64 | 0.153 ± 0.022 | 9.848 ± 0.062 | | 0.52 ± 0.08 | | | 1.916 ± 0.286 | DBC |
| 346900 | HATLASJ090120.7+020224 | 09:01:20.7 | +02:02:24.9 | 0.2009 | 11.28 ± 0.01 | 18.95 ± 0.49 | 11.06 ± 0.15 | 0.16 ± 0.06 | 95.954 | 95 ± 26 | 393 ± 62 | 4.0 ± 0.51 | 0.789 ± 0.101 | 10.56 ± 0.056 | 21.2 ± 5.0 | 0.52 ± 0.07 | 1.9 ± 0.2 | -1.6 ± 0.2 | 1.916 ± 0.25 | DBC |
| 203879 | HATLASJ090223.8-001639 | 09:02:23.8 | -00:16:39.6 | 0.1963 | 10.94 ± 0.01 | 8.72 ± 0.22 | 11.03 ± 0.1 | 0.08 ± 0.02 | 96.338 | | | 0.02 ± 0.17 | 0.032 | 9.166 | | 5.95 | | | 0.168 | BD |
| 382362 | HATLASJ090352.6+020220 | 09:05:32.6 | +02:02:21.9 | 0.0519 | 10.69 ± 0.02 | 4.89 ± 0.17 | 10.8 ± 0.1 | 0.08 ± 0.02 | 109.59 | -13 ± 16 | 256 ± 37 | 19.2 ± 4.08 | 0.238 ± 0.051 | 10.039 ± 0.092 | 6.8 ± 1.4 | 0.45 ± 0.1 | 1.6 ± 0.2 | -1.3 ± 0.2 | 2.24 ± 0.483 | DB |
| 600656 | HATLASJ090633.6+001526 | 09:06:33.6 | +00:15:27.9 | 0.165 | 10.88 ± 0.01 | 7.66 ± 0.19 | 10.98 ± 0.11 | 0.08 ± 0.02 | 98.913 | 95 ± 22 | 334 ± 53 | 2.3 ± 0.1 | 0.301 ± 0.013 | 10.141 ± 0.019 | | 0.55 ± 0.03 | | | 1.807 ± 0.092 | DBC |
| 279387 | HATLASJ090750.6+010141 | 09:07:50.1 | +01:01:41.8 | 0.1281 | 11.7 ± 0.01 | 50.07 ± 1.05 | 10.14 ± 0.12 | 3.62 ± 0.97 | 102.191 | -22 ± 3 | 150 ± 7 | 6.8 ± 0.58 | 0.535 ± 0.045 | 9.631 ± 0.037 | | 11.71 ± 1.02 | | | 0.085 ± 0.007 | M |
| 324842 | HATLASJ090949.6+014847 | 09:09:49.6 | +01:48:46.0 | 0.1819 | 11.84 ± 0.02 | 68.47 ± 2.7 | 10.89 ± 0.12 | 0.88 ± 0.24 | 97.531 | 6 ± 1 | 73 ± 3 | 8.5 ± 0.58 | 1.364 ± 0.093 | 10.788 ± 0.03 | | 1.09 ± 0.09 | | | 0.917 ± 0.072 | BC |
| 324931 | HATLASJ091157.2+014454 | 09:11:57.2 | +01:44:53.9 | 0.1694 | 11.39 ± 0.01 | 24.49 ± 0.64 | 10.9 ± 0.16 | 0.31 ± 0.11 | 98.569 | -3 ± 5 | 168 ± 13 | 5.3 ± 0.52 | 0.737 ± 0.072 | 10.53 ± 0.043 | | 0.72 ± 0.07 | | | 1.384 ± 0.141 | DBC |
| 216401 | HATLASJ091205.8+002655 | 09:12:05.8 | +00:26:55.6 | 0.0545 | 11.09 ± 0.01 | 12.32 ± 0.32 | 10.33 ± 0.11 | 0.58 ± 0.14 | 109.314 | 10 ± 2 | 171 ± 6 | 13.6 ± 0.84 | 0.187 ± 0.011 | 9.934 ± 0.027 | | 1.44 ± 0.09 | | | 0.697 ± 0.044 | BC |
| 210543 | HATLASJ091420.1+000509 | 09:14:20.0 | +00:05:10.0 | 0.2022 | 11.55 ± 0.01 | 35.48 ± 0.94 | 10.62 ± 0.13 | 0.85 ± 0.25 | 95.874 | 37 ± 9 | 302 ± 22 | 3.3 ± 0.57 | 0.667 ± 0.114 | 10.487 ± 0.074 | | 1.16 ± 0.2 | | | 0.864 ± 0.15 | B |
| 378092 | HATLASJ091956.8+013851 | 09:19:57.0 | +01:38:51.6 | 0.1764 | 11.34 ± 0.01 | 13.48 ± 0.35 | 10.45 ± 0.12 | 0.48 ± 0.13 | 97.994 | -10 ± 7 | 151 ± 16 | 2.4 ± 0.32 | 0.365 ± 0.048 | 10.225 ± 0.057 | | 0.8 ± 0.11 | | | 1.246 ± 0.168 | BD |
| 216973 | HATLASJ092232.2+002707 | 09:22:32.0 | +00:27:08.4 | 0.173 | 11.19 ± 0.01 | 15.6 ± 0.4 | 10.36 ± 0.12 | 0.68 ± 0.18 | 98.305 | -96 ± 24 | 518 ± 57 | 3.5 ± 0.64 | 0.504 ± 0.093 | 10.366 ± 0.08 | | 0.67 ± 0.12 | | | 1.487 ± 0.276 | BC |
| 30313 | HATLASJ113740.6-010454 | 11:37:40.7 | -01:04:54.1 | 0.1517 | 10.93 ± 0.01 | 4.49 ± 0.21 | 10.71 ± 0.12 | 0.17 ± 0.05 | 100.123 | | | 0.09 ± 0.11 | 0.096 | 9.646 | | 1.92 | | | 0.521 | DB |
| 53724 | HATLASJ113858.4-001629 | 11:38:58.5 | -00:16:30.2 | 0.1637 | 11.21 ± 0.01 | 16.12 ± 0.42 | 10.84 ± 0.12 | 0.23 ± 0.06 | 99.075 | -58 ± 19 | 261 ± 45 | 4.2 ± 1.0 | 0.546 ± 0.129 | 10.4 ± 0.103 | 18.8 ± 4.2 | 0.64 ± 0.15 | 1.4 ± 0.1 | -2.1 ± 0.1 | 1.559 ± 0.372 | DBC |
| 69661 | HATLASJ114343.9+000203 | 11:43:44.1 | +00:02:02.5 | 0.1872 | 11.05 ± 0.01 | 11.18 ± 0.28 | 10.1 ± 0.12 | 0.89 ± 0.25 | 97.106 | -24 ± 4 | 67 ± 10 | 2.8 ± 0.52 | 0.485 ± 0.089 | 10.348 ± 0.08 | 18.0 ± 4.1 | 0.5 ± 0.09 | 1.5 ± 0.1 | -1.8 ± 0.1 | 1.994 ± 0.369 | BC |
| 84183 | HATLASJ114540.7+002554 | 11:45:41.0 | +00:25:55.3 | 0.3429 | 11.56 ± 0.01 | 36.44 ± 0.97 | 11.04 ± 0.11 | 0.33 ± 0.09 | 85.827 | | | 0.02 ± 0.18 | 0.147 | 9.831 | | 5 | | | | |

This paper has been typeset from a $\text{\TeX}/\text{\LaTeX}$ file prepared by the author.

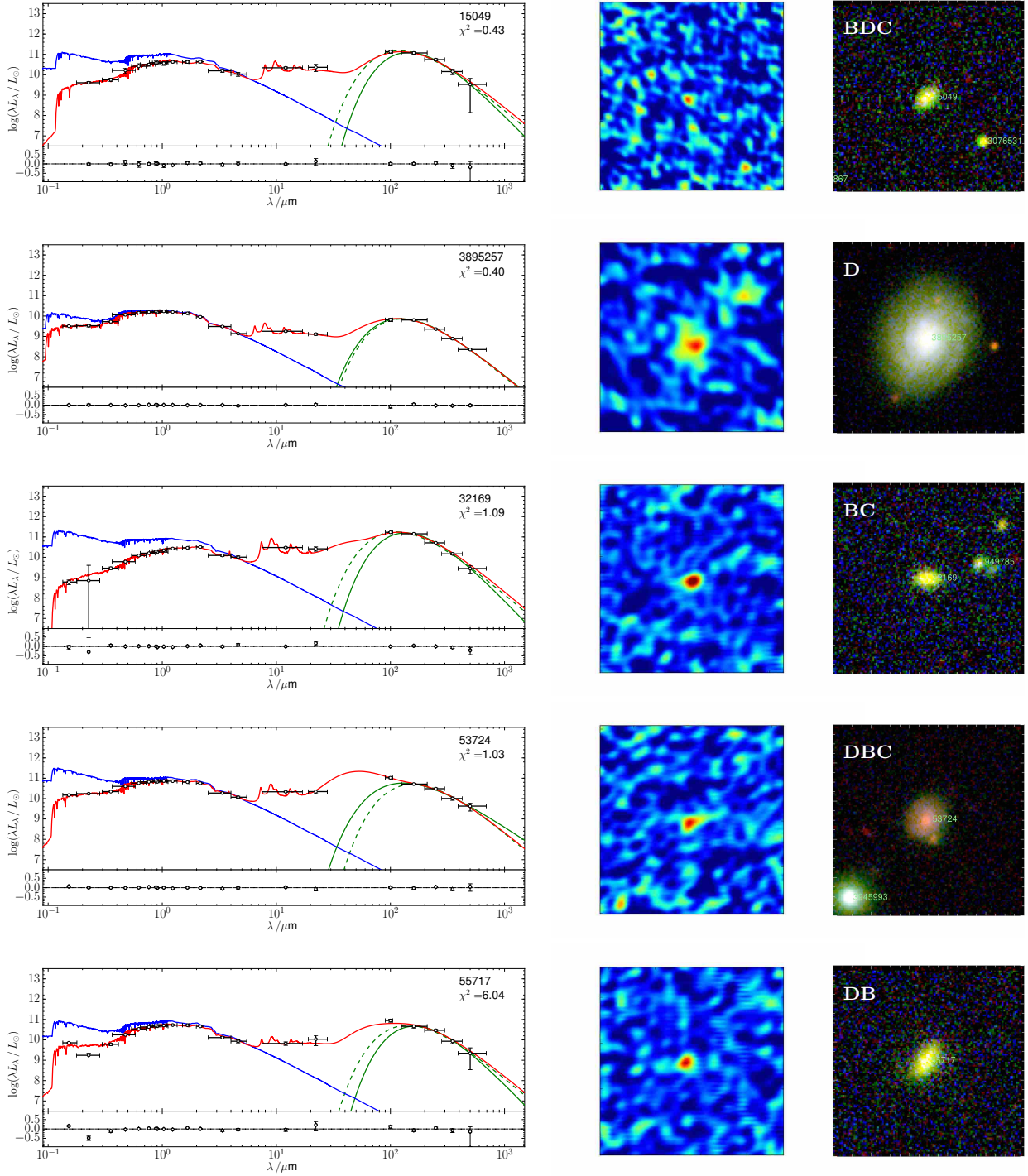


Figure 8. *Left:* Panels show the observed far-UV to submm spectral energy distribution for detected galaxies, constructed from GAMA/*H*-ATLAS photometry (black circles). We model the complete FUV–submm SED using MAGPHYS (da Cunha et al. 2008) to obtain the best-fitting SED (red line) and the unattenuated SED (blue line). We also model the cold dust SED component between 100 to 500 μm by fitting a Hildebrand (1983) one-component modified blackbody model adopting either a fixed emissivity index of $\beta = 1.8$ (green dashed line) or β varying as a free parameter (green solid line). Panels are the residuals between the observed and best-fitting SED model template. Each individual plot is labelled with the GAMA ID of the target and the χ^2 values corresponding to the best-fitting SED template. *Middle:* The collapsed CO cubes. Each panel is $40'' \times 40''$ in size and centred on the source coordinates. *Right:* Multi-band images composed by VISTA *K*-band (red), SDSS *r*-band (green) and SDSS *u*-band (blue) with same size as middle panels. Green numbers are the GAMA ID for the objects present in the field of view.

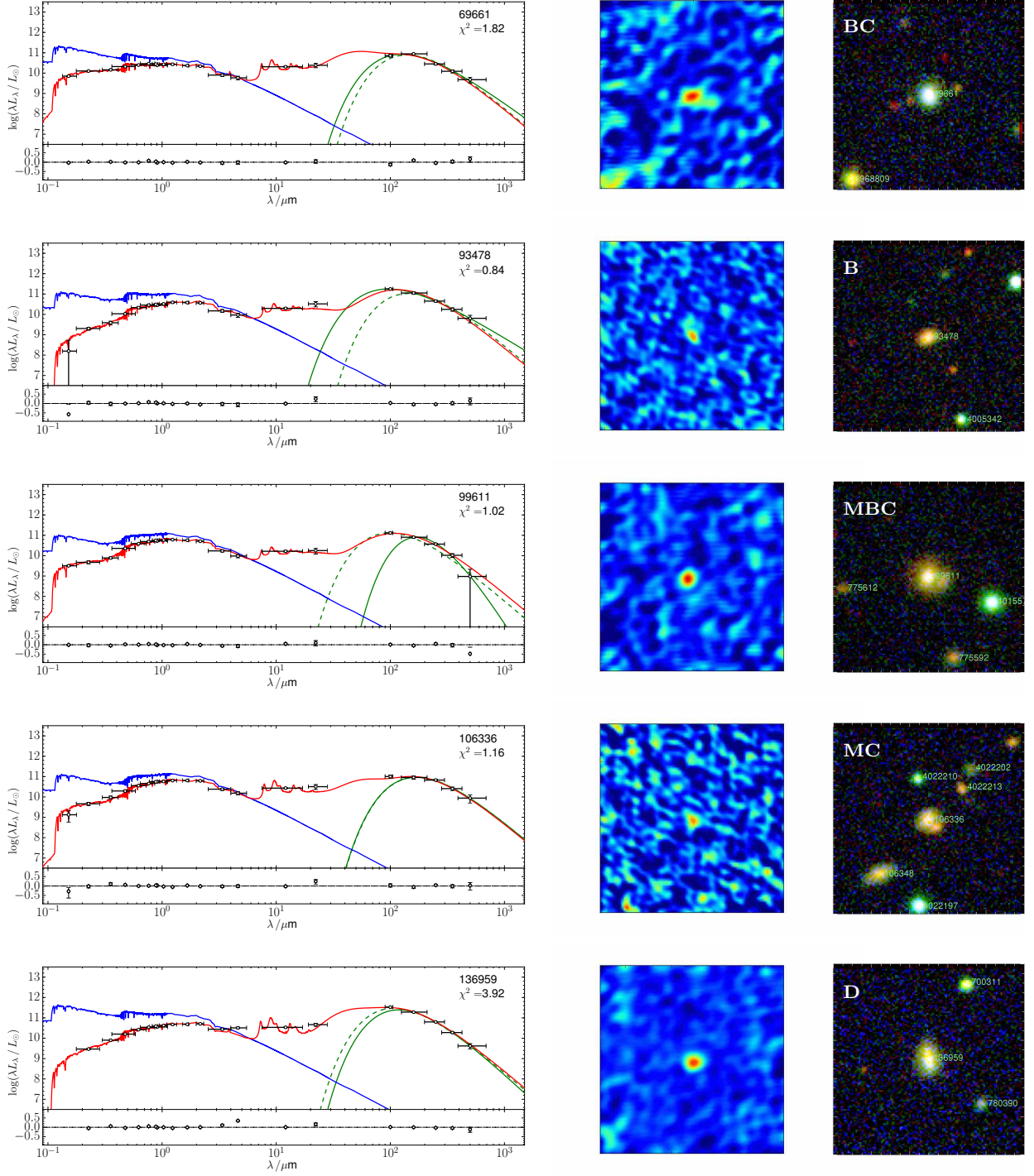


Figure 8. continued

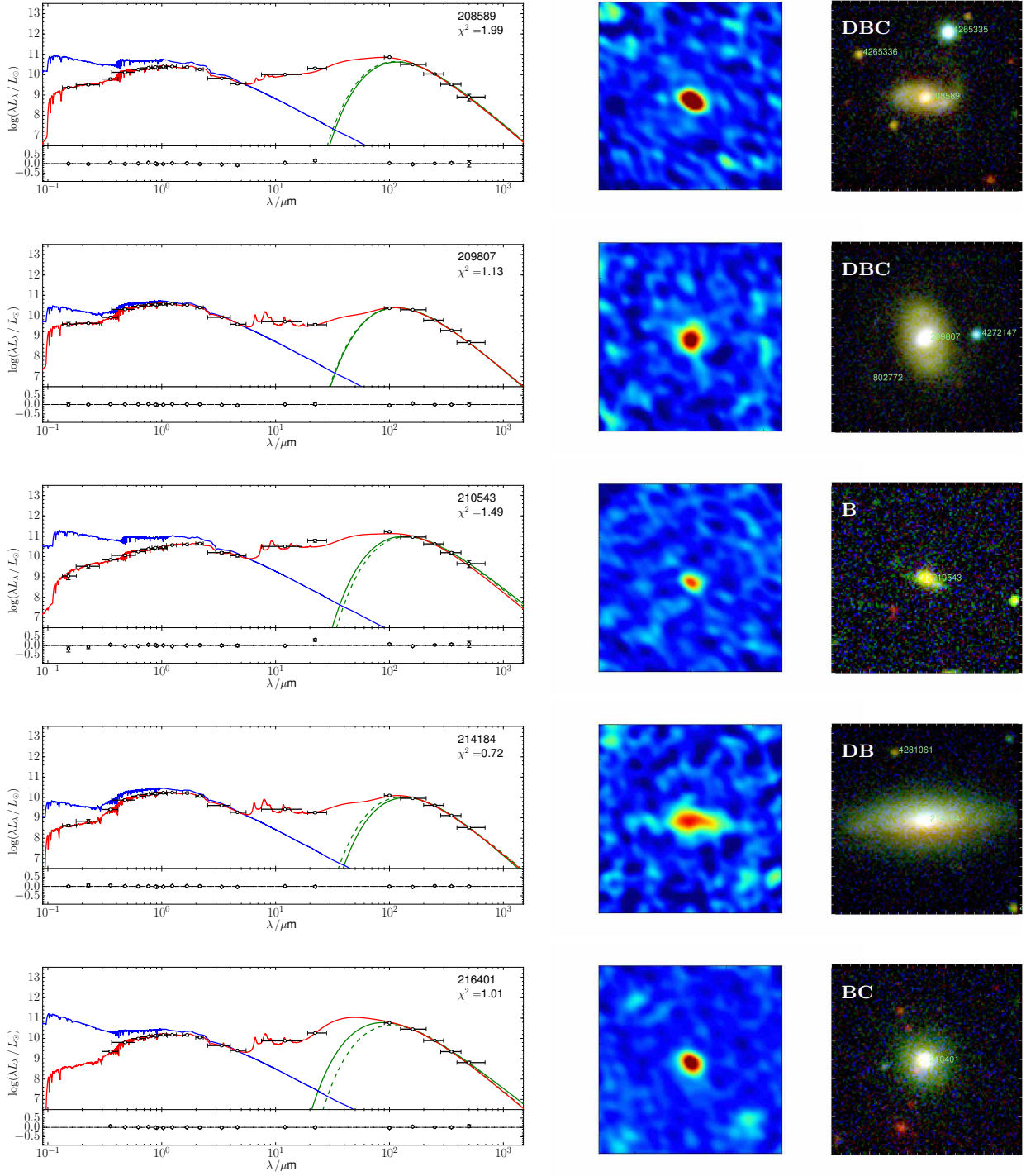


Figure 8. continued

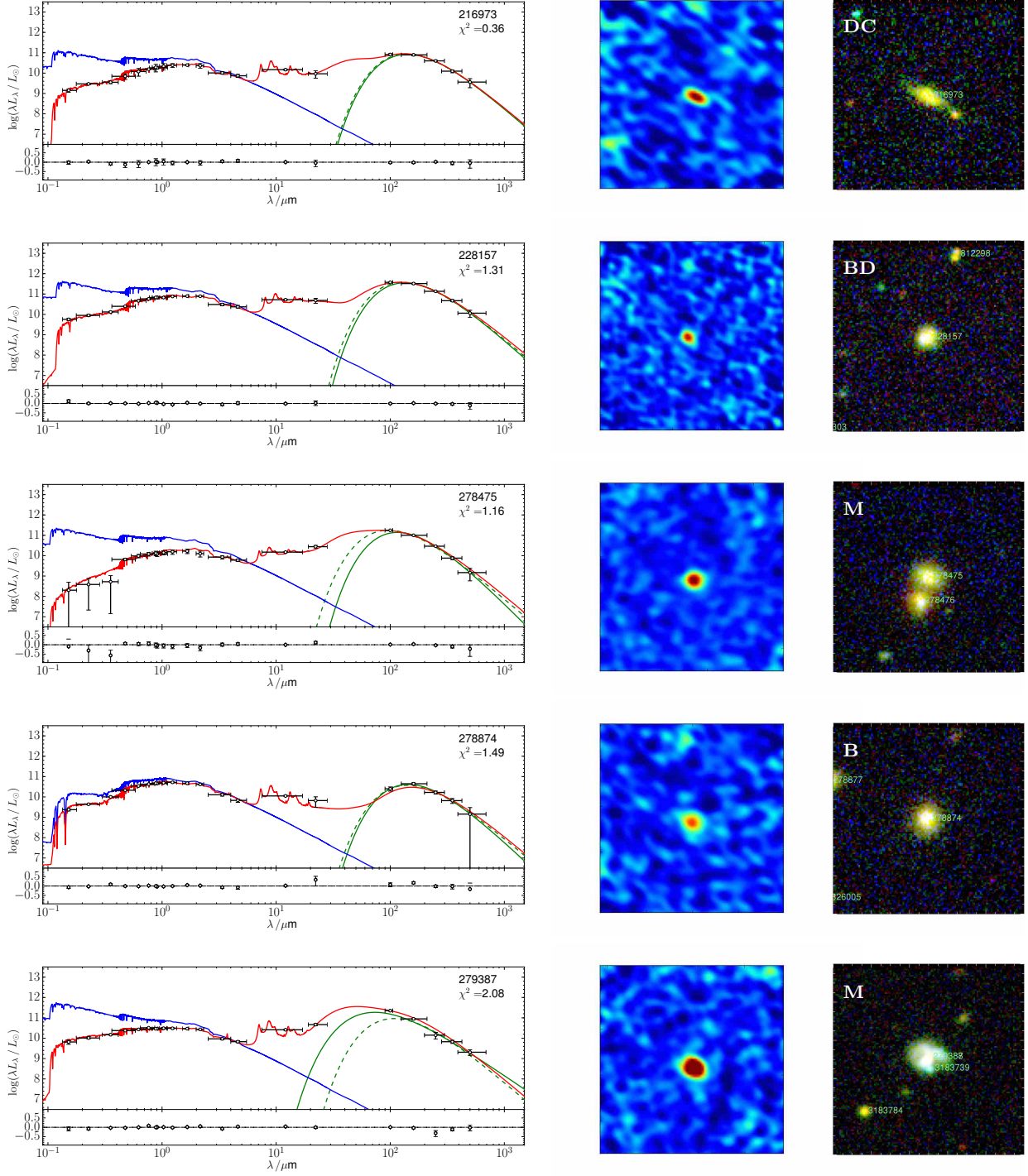


Figure 8. continued

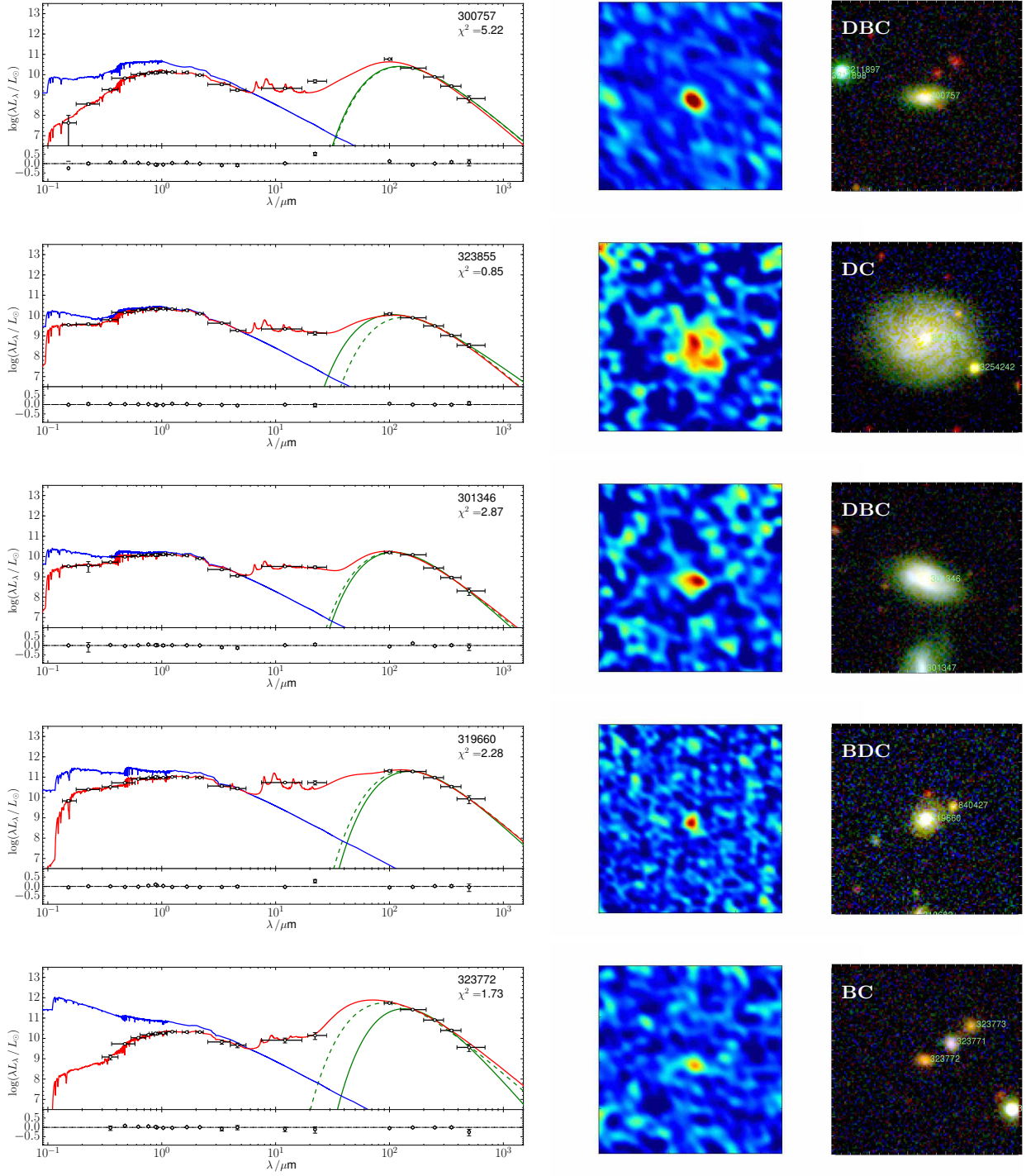


Figure 8. continued

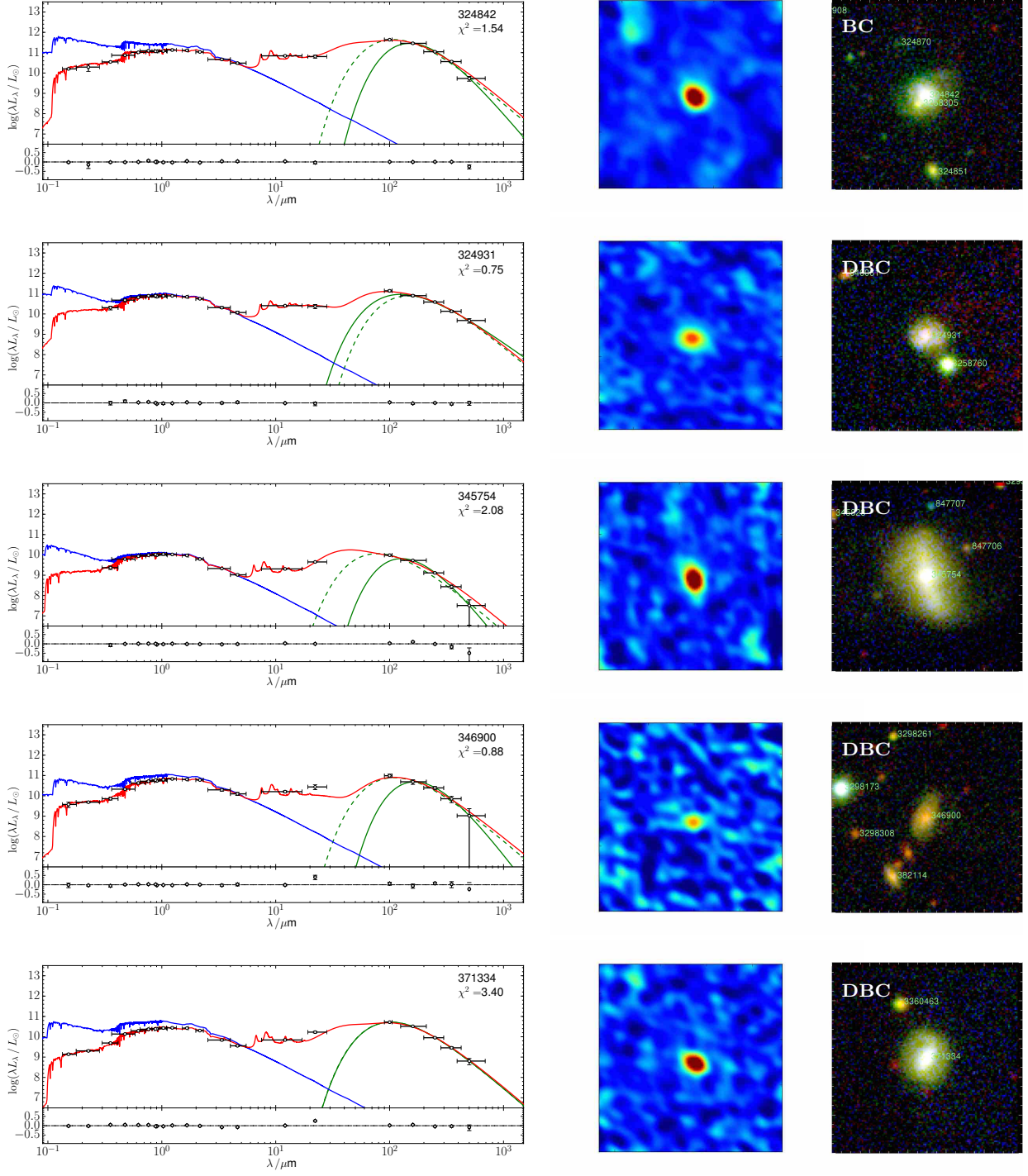


Figure 8. continued

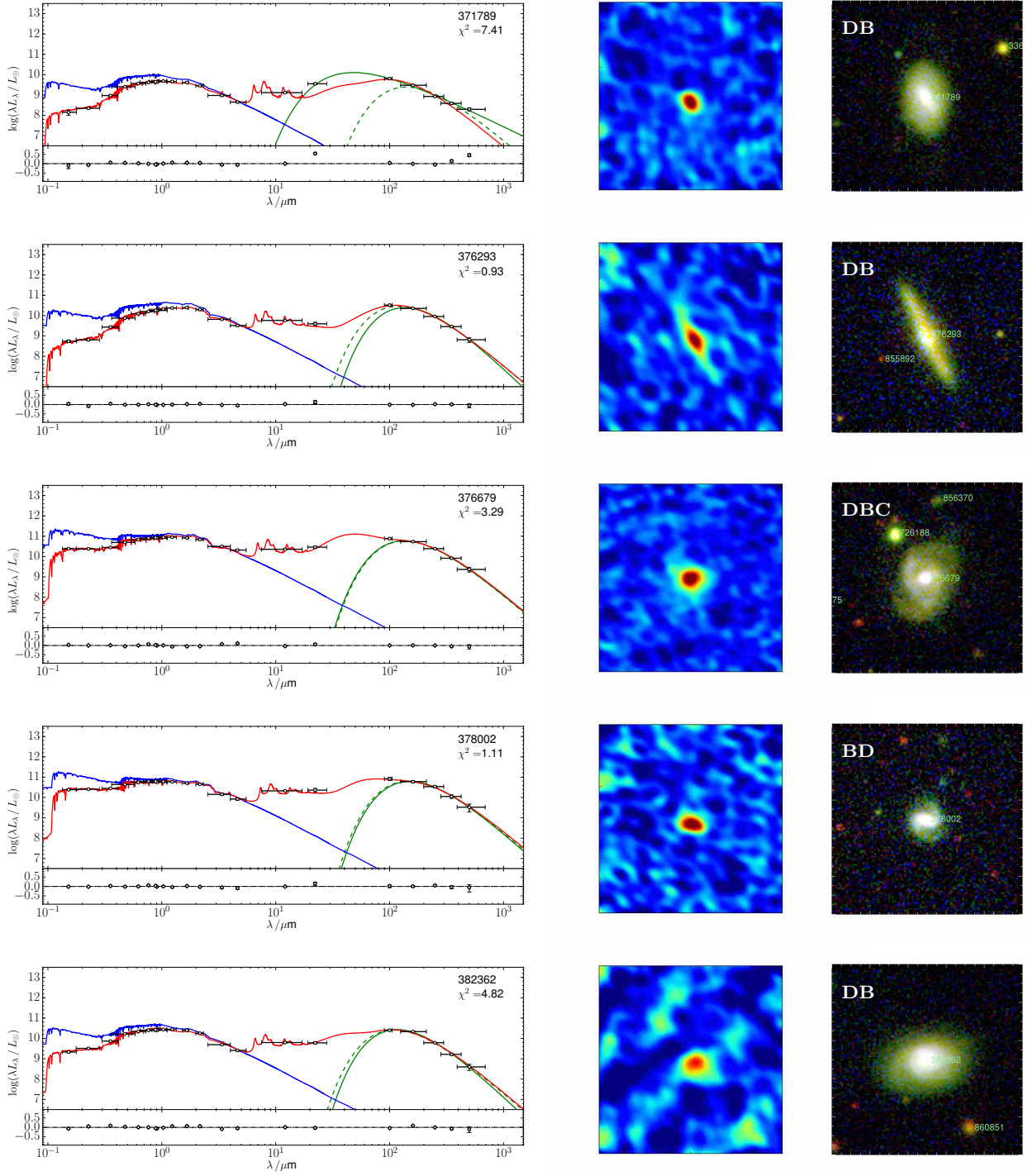


Figure 8. continued

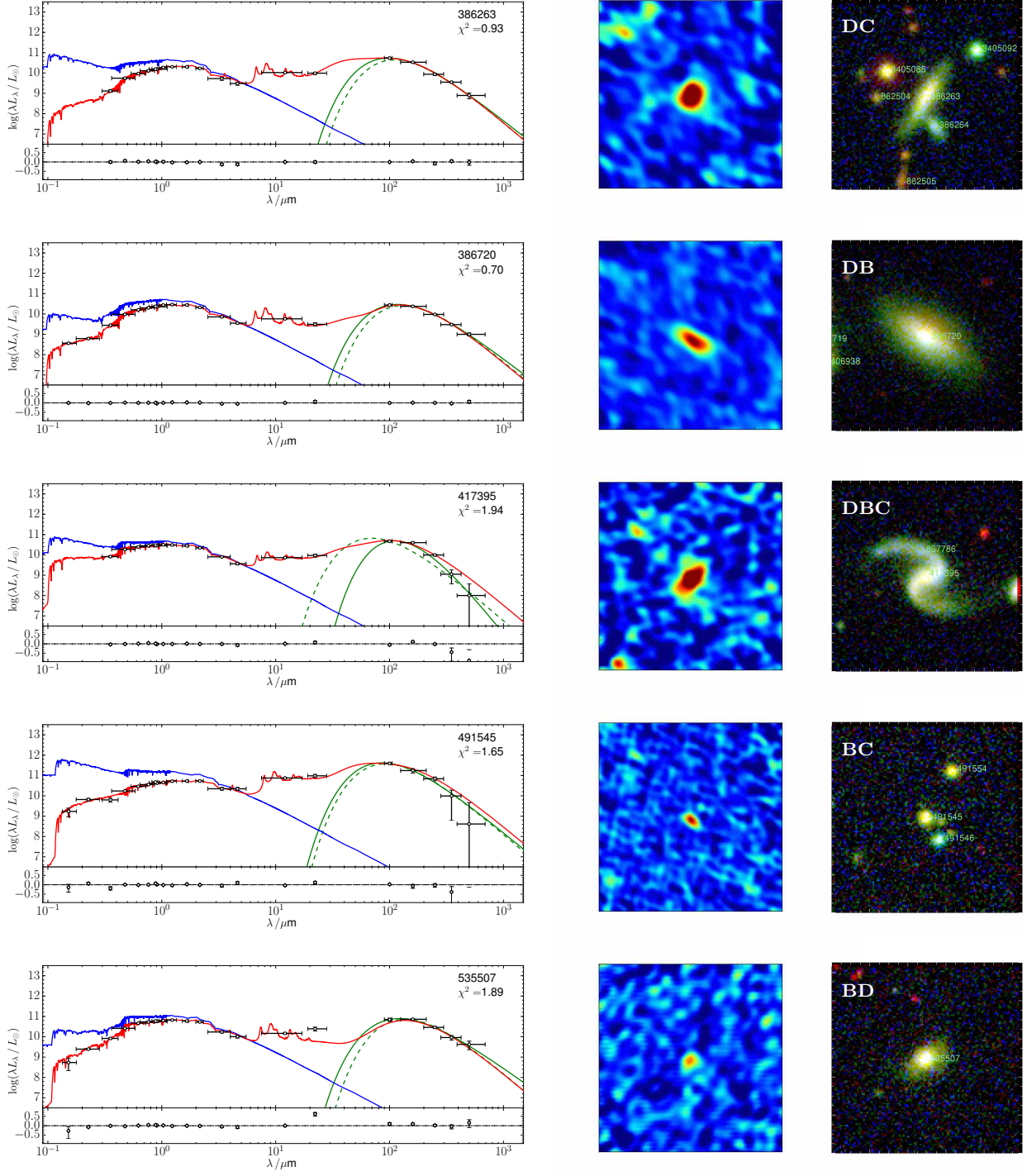
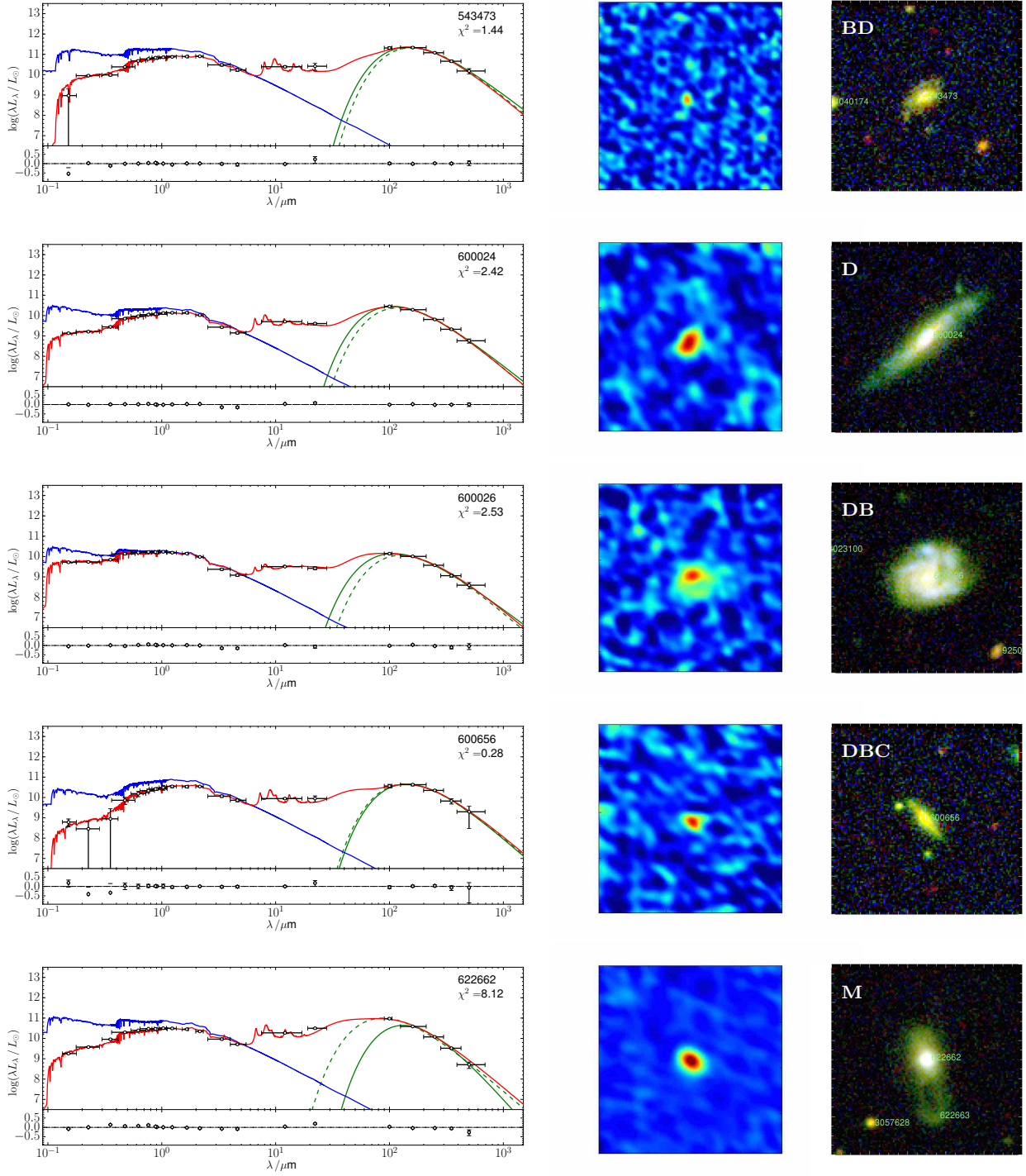


Figure 8. continued



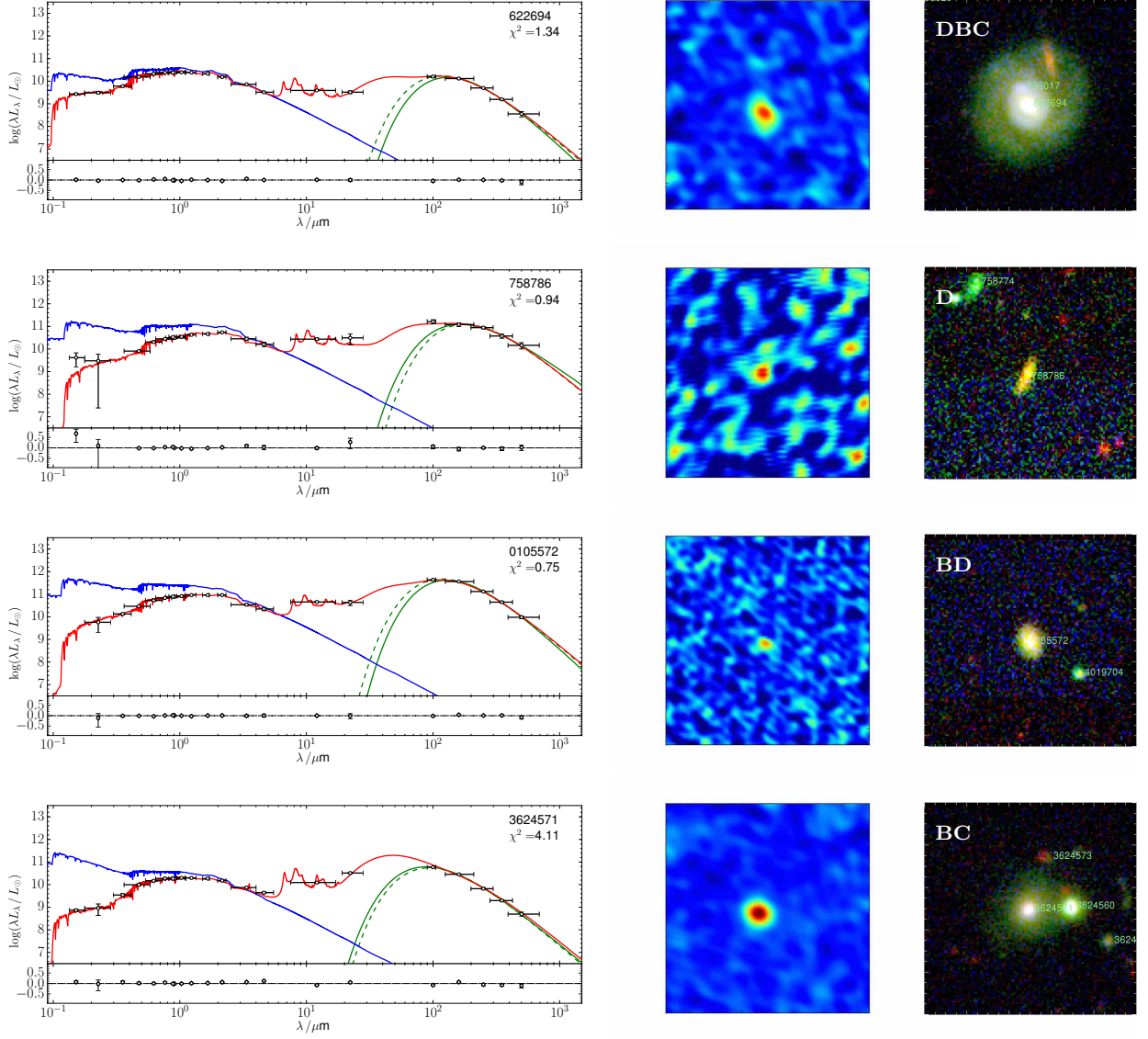


Figure 8. continued

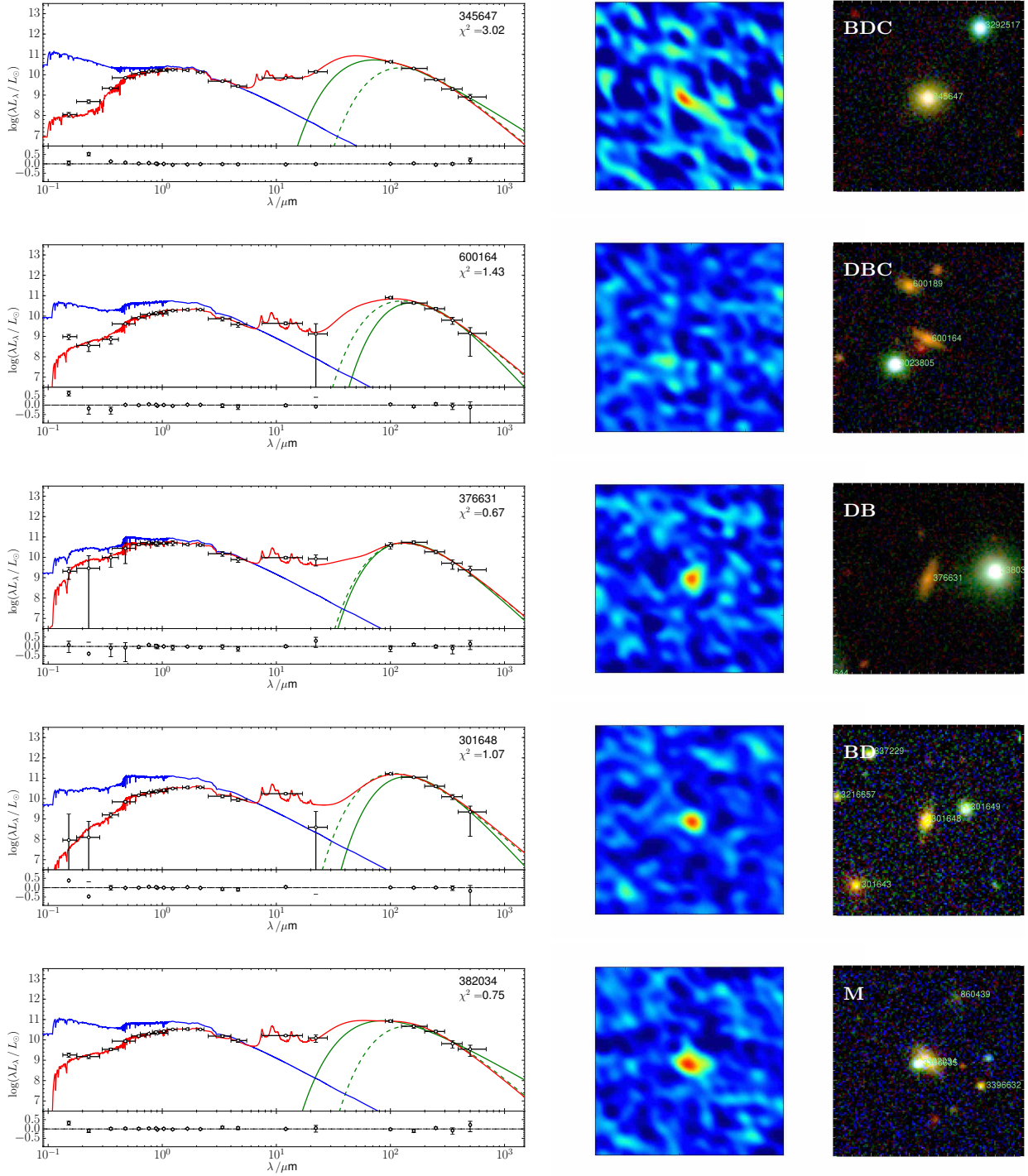


Figure 9. Same as Figure 8 but for spectrally undetected sources. In these cases the CO cubes are collapsed blindly, between $\pm 250 \text{ km s}^{-1}$ from expected observed frequency.

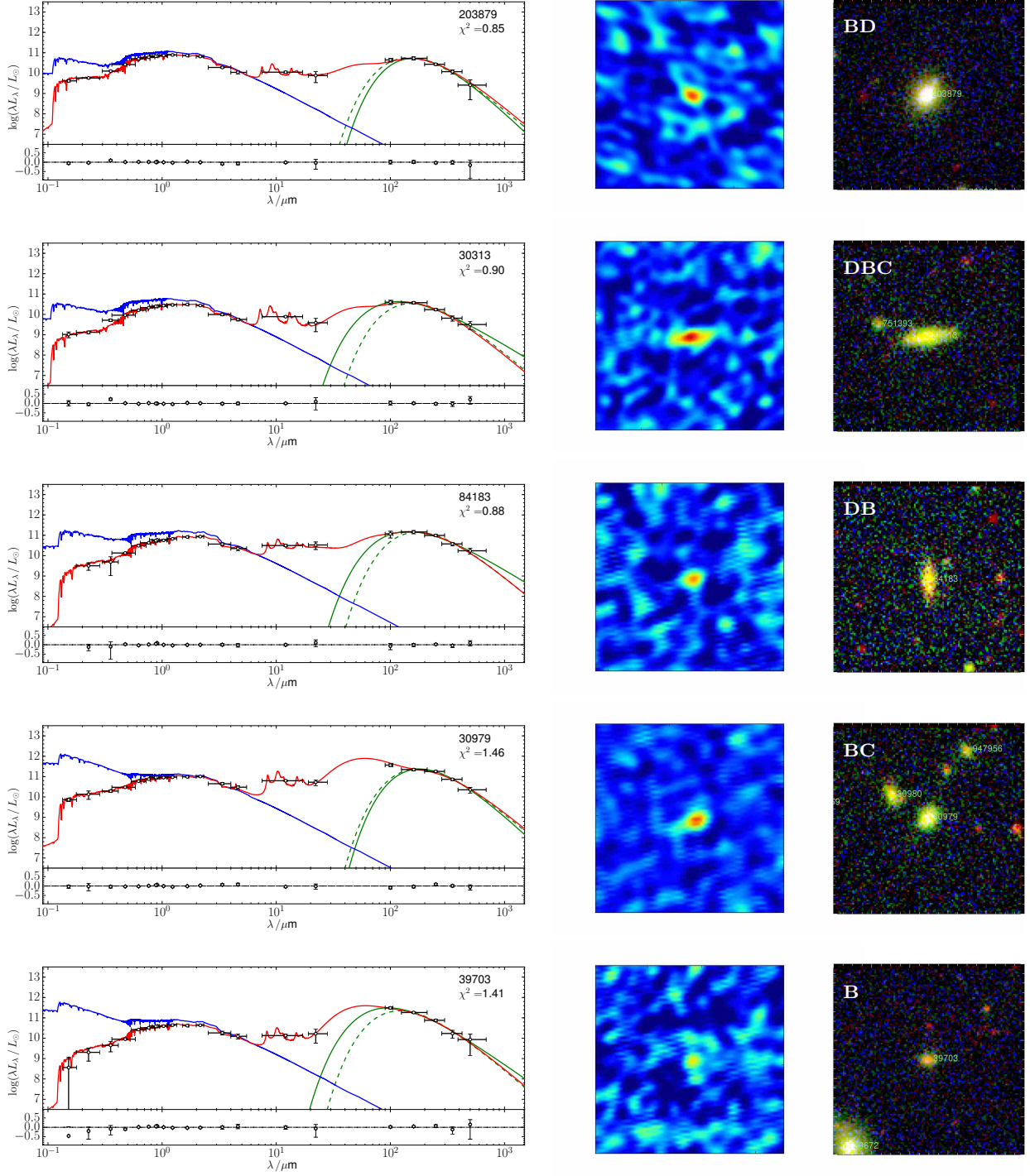


Figure 9. continued

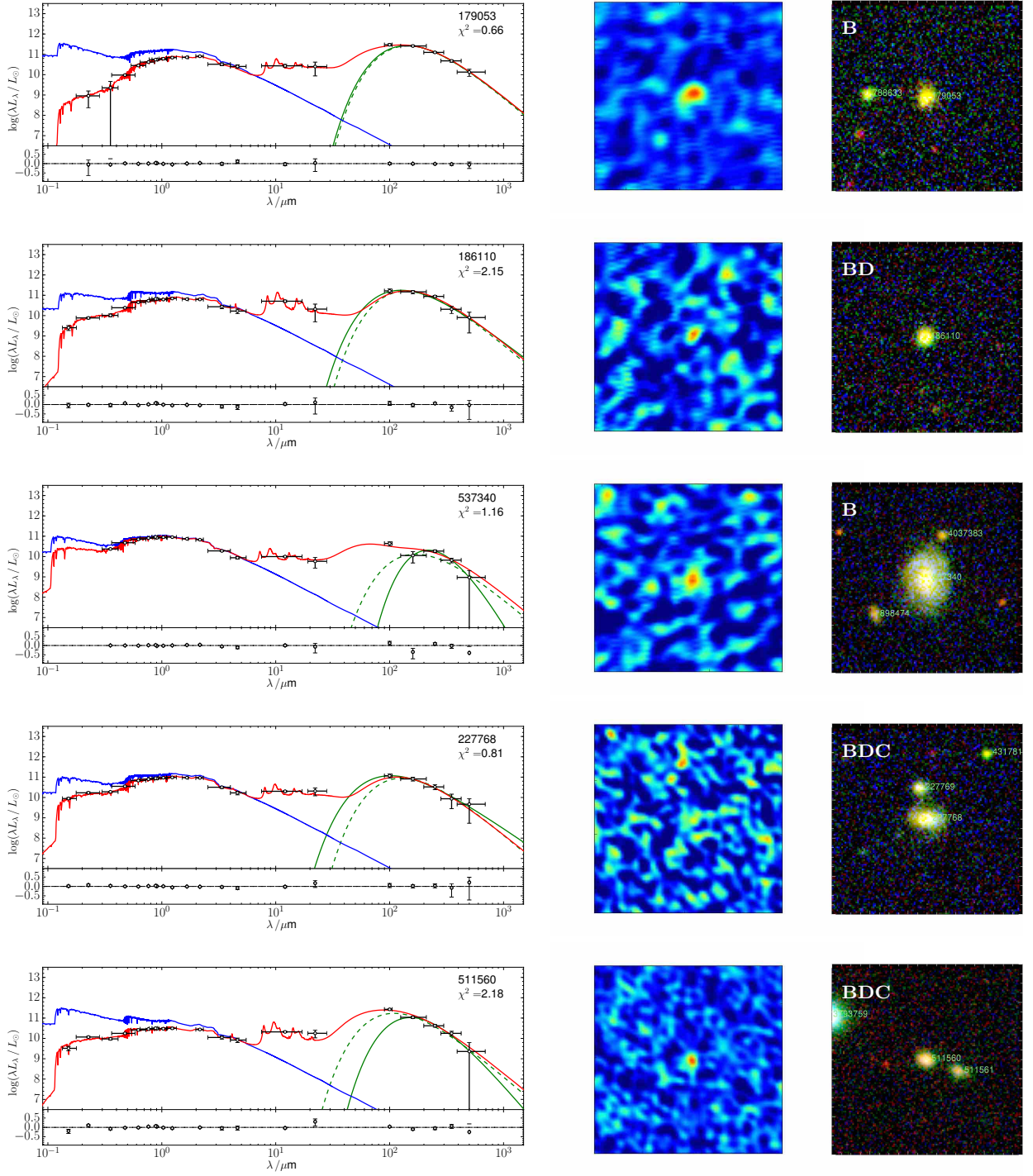


Figure 9. continued

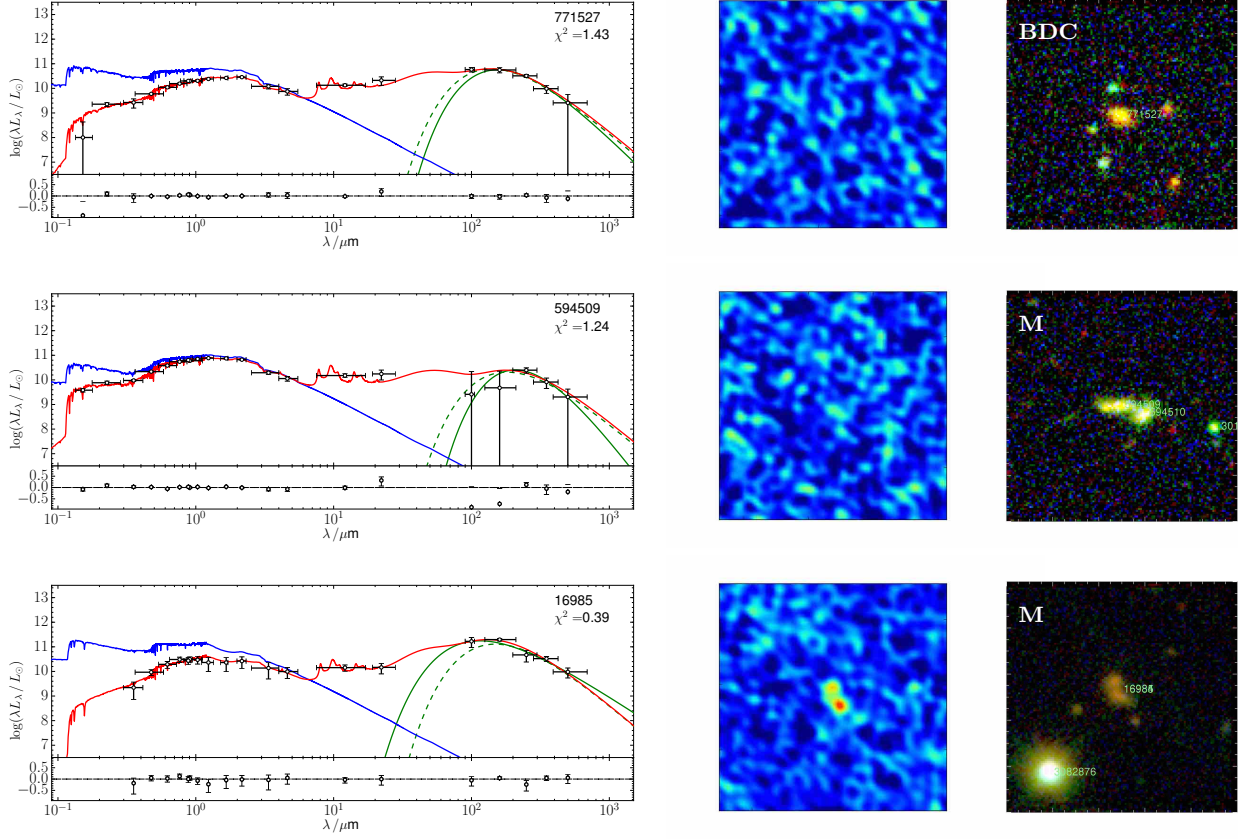


Figure 9. continued