

# The Spatially Resolved Dynamics of Dusty Starburst Galaxies in a $z \sim 0.4$ Cluster: Beginning the Transition from Spirals to S0s

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## ABSTRACT

To investigate what drives the reversal of the morphology–density relation at intermediate/high redshift, we present a multi-wavelength analysis of 27 dusty starburst galaxies in the massive cluster Cl0024+17 at  $z=0.4$ . We combine H $\alpha$  dynamical maps from the VLT / FLAMES multi-IFU system with far-infrared imaging using *Herschel* / SPIRE and millimeter spectroscopy from IRAM / NOEMA, in order to measure the dynamics, star formation rates and gas masses of this sample. Most galaxies appear to be rotationally supported, with a median ratio of rotational support to line-of-sight velocity dispersion  $v/\sigma \sim 5 \pm 2$ , and specific angular momentum  $\lambda_R = 0.83 \pm 0.06$  – comparable to field spirals of a similar mass at this redshift. The star formation rates of  $3\text{--}26\text{ M}_\odot\text{ yr}^{-1}$  and average  $^{12}\text{CO}$ -derived gas mass of  $\sim 1 \times 10^{10}\text{ M}_\odot$  suggest gas depletion timescales of  $\sim 1\text{ Gyr}$  ( $\sim 0.25$  of the cluster crossing time). We derive characteristic dust temperatures (mean  $T_d = 26 \pm 1\text{ K}$ ) consistent with local galaxies of similar far-infrared luminosity, suggesting that the low density gas is yet to be stripped. Taken together, these results suggest that these starbursts have only recently accreted from the field, with star formation rates likely enhanced due to the effects of ram pressure. In order to make the transition to cluster S0s these galaxies must lose  $\sim 40\%$  of their specific angular momentum. We suggest this must occur  $\geq 1\text{ Gyr}$  later, after the molecular gas has been depleted and/or stripped, via multiple tidal interactions with other cluster members.

**Key words:** galaxies: starburst – galaxies: evolution – galaxies: clusters

## 1 INTRODUCTION

Rich clusters present a unique laboratory for studying the interaction between galaxies and their local environment. It has long been established that strong trends exist between the morphology, gas content and star formation of cluster galaxies, and the density of the neighbourhood in which they reside. The populations of rich clusters at  $z=0$  are dominated by passive, gas-poor ellipticals and S0s, with star formation all but extinguished in central regions (the morphology density relation e.g. Dressler 1980; Bower et al. 1992; Lewis et al. 2002; Kodama et al. 2004; Bamford et al. 2009). However, observations of clusters at intermediate redshift show a striking increase in the fraction of blue star-forming

galaxies in cluster cores, from almost zero in the present day to  $\sim 20\%$  by  $z \sim 0.4$  (e.g. Butcher & Oemler 1978). This evolution is accompanied by another key evolutionary change: a sharp decline in the proportion of S0 galaxies (Dressler et al. 1997; Poggianti et al. 2009). Studies of emission line and luminous infrared-selected galaxies out to  $z \sim 1.5$  have confirmed that star-forming galaxies in fact make up the majority of the population in high redshift clusters (Tran et al. 2010; Smail et al. 2014). This increase in the number of star-forming galaxies and decrease of cluster S0s with increasing redshift strongly implies that the two populations are linked in an evolutionary scenario.

An important realisation was that a large fraction of quiescent cluster members have suffered starburst activity in the recent past. Spectroscopic surveys have identified a significant population of k+a or “post-starburst” galaxies

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which appear to be more prevalent with increasing redshift (e.g. Couch & Sharples 1987; Poggianti et al. 1999; Pracy et al. 2005; Tran et al. 2007; Swinbank et al. 2007; De Lucia et al. 2009; Rodríguez Del Pino et al. 2014). Their spectra show strong Balmer absorption lines associated with the recent formation of massive A stars ( $\leq 1$  Gyr ago), but a lack of emission lines suggesting the burst was rapidly quenched (e.g. Poggianti et al. 1999; Poggianti & Wu 2000). However, difficulties arise when attempting to link these galaxies to the formation of S0s. Insufficient numbers of strong starbursts are detected in the optical to explain the post-starburst phase, and the luminosities of S0s are in fact substantially brighter than the proposed progenitor spirals (Poggianti et al. 1999; Kodama et al. 2004; Burstein et al. 2005; Sandage 2005). These problems could both be solved if a considerable fraction of starburst activity is heavily obscured. Indeed, deep mid-infrared observations of intermediate redshift clusters with *Spitzer* and *Herschel* have revealed an abundance of such dusty star-forming galaxies which are missing from optical studies (e.g. Coia et al. 2005; Geach et al. 2006, 2009; Elbaz et al. 2007; Marcillac et al. 2007; Koyama et al. 2008; Oemler et al. 2009; Kocevski et al. 2011; Alberts et al. 2014). In an era in which clusters were still accreting much of their mass, there not only appears to be a significant population of star-forming galaxies, but also many with their star formation temporarily enhanced in this dense environment.

In a model where spirals transition to S0s, the star formation of infalling galaxies must be rapidly quenched, their gas disks stripped, and the dynamics transform from rotationally supported disks (high angular momentum) to dispersion dominated spheroids (low angular momentum). Several authors also suggest that the bulge luminosity luminosity and bulge to disk ratio of S0s is too large for them to have evolved from spirals by disk fading alone (Dressler 1980; Simien & de Vaucouleurs 1986; Kodama & Smail 2001; Christlein & Zabludoff 2004; Cortesi et al. 2013), and spectral decomposition of local lenticulars has revealed that bulges have younger and more metal-rich stellar populations than their adjacent disk (Johnston et al. 2014). It may be that a final, circumnuclear starburst is a critical stage in the transition between infalling spirals and passive S0s. The observational challenge is to identify the processes which may drive this transformation.

Several potential mechanisms are usually invoked to explain galaxy transformations in local clusters: interactions with the intra-cluster medium (ICM) such as ram pressure stripping, strangulation and thermal evaporation (Kenney et al. 2004; McCarthy et al. 2008; Merluzzi et al. 2013; Fumagalli et al. 2014; Peng et al. 2015), and tidal interactions, harassment, minor mergers or halo stripping (Mastropietro et al. 2005; Bekki 2009; Smith et al. 2010; Eliche-Moral et al. 2012; Bialas et al. 2015). What remains elusive is the relative contribution of each process, and an understanding of how the timescales they operate on vary with cluster mass and size (hence redshift), as well as the stellar, halo and gas mass of the infalling galaxy (e.g. Boselli & Gavazzi 2006, 2014).

It is important to study cluster galaxies over a range in redshift to thoroughly explore the mechanisms described above, and to understand what drives the reversal of the morphology–density relation. For example, due to the in-

creased gas fractions of galaxies at high redshift (e.g. Tacconi et al. 2010; Geach et al. 2011), the initial compression of the ISM may be more likely to enhance the star formation (Quilis et al. 2000; Hopkins et al. 2006; Bekki 2014; Sales et al. 2015). Due to the lower mass of typical clusters (compared to those at  $z \sim 0$ ), the lower ram pressure from the intra-cluster medium may also result in the starbursts being both more intense, and long lived. Tidal forces from increased galaxy-galaxy interaction rates in rapidly assembling clusters may also destabilise the gas disks, causing a burst of star formation, and a morphological and dynamical transformation.

Identifying cluster starbursts and measuring their dynamics, star-formation rates and molecular gas properties appears to be key to unravelling the complexities of galaxy evolution in clusters. The short lifetime of the starburst activity provides a snapshot of galaxies which may be undergoing a transition, allowing us to search for potential triggers. For example, asymmetric gas disks may provide evidence for ram pressure stripping (Bekki 2014), high dust temperatures (compared to galaxies in the field) may imply that the cold gas/dust has been stripped (e.g. Rawle et al. 2012), whilst galaxy-galaxy interactions (mergers) may result in complex kinematic signatures (Mihos & Bothun 1998; Colina et al. 2005) depending on the interaction stage and nature of the system (Bellocchi et al. 2013; Hung et al. 2016). Complementing the dynamics with observations of molecular gas also allows us to infer the likely timescales for the starbursts and measure how long the starburst can be maintained.

In this paper we present a multi-wavelength study of 28 spectroscopically confirmed,  $24\mu\text{m}$ -bright galaxies within Cl0024+17. This pilot study forms part of a wider investigation into the properties of cluster starburst galaxies. Analysis of our full sample of  $\sim 150$  galaxies observed with FLAMES/KMOS, from ten massive clusters between  $0.2 < z < 1.5$ , will be presented in paper II. We measure the morphologies and dynamics of the galaxies using *HST* and VLT/FLAMES multi-IFU observations respectively, infer star-formation rates from far-infrared observations with *Herschel*/SPIRE and measure molecular gas masses using  $^{12}\text{CO}(1-0)$  emission from NOEMA. As an original “Butcher & Oemler” cluster, Cl0024+17 has a significant population of blue, star-forming galaxies, and is one of the best studied clusters at intermediate redshift ( $z = 0.395$ ), with a virial mass  $M_{\text{vir}} = (1.2 \pm 0.2) \times 10^{15} M_{\odot} h^{-1}$  (Umetsu et al. 2010), and X-ray luminosity of  $L_{\text{X}} \sim 2.9 \times 10^{44} \text{ erg s}^{-1}$  (Zhang et al. 2005). With a rich variety of star forming galaxies in the cluster, and multi-wavelength ancillary data, Cl0024 provides a useful pilot study for investigating the properties of dusty starbursts in galaxy clusters.

The structure of this paper is as follows. In §2 we describe the target selection, observations and data reduction. In §3 we describe the galaxy integrated properties, such as star formation rates, stellar and gas masses, and dust temperatures. In §4 we describe the internal properties of the galaxies from the IFU observations:  $\text{H}\alpha$  dynamics, two-dimensional maps of star formation, rotation velocity and line of sight velocity dispersion. We then explore the properties of these dusty starbursts in the context of their environment, comparing to field spirals and local lenticulars and searching for trends as a function of cluster radius. We consider which mechanisms may have already acted upon

these galaxies, and discuss what remains to be achieved to complete the transition to S0s, in §5. Finally §6 summarises our main results. Throughout this paper we assume a  $\Lambda$ CDM cosmology with parameters  $\Omega_m = 0.27$ ,  $\Omega_\Lambda = 0.73$  and  $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . The average seeing for our IFU observations,  $0.5''$ , corresponds to a physical scale of 2.6 kpc at  $z \sim 0.4$ . Unless otherwise stated, all magnitudes are quoted on the AB system.

## 2 TARGET SELECTION, OBSERVATIONS & DATA REDUCTION

### 2.1 Cl0024+17

Cl0024+17 is a well studied cluster with extensive archival multi-wavelength imaging and spectroscopy, and its large population of blue star-forming galaxies makes it an ideal environment for exploring the properties of cluster starbursts. In optical wavelengths Cl0024 appears fairly unremarkable, with a well concentrated mass profile and relatively little sub-structure (Fig. 1), but it is thought this disguises a rather eventful dynamical history. Spectroscopic observations reveal two distinct components in the line of sight: a dominant “cluster” which has a velocity dispersion of  $\sim 1000 \text{ km s}^{-1}$ , and a foreground sub-group offset by  $\Delta v \sim 3000 \text{ km s}^{-1}$  which has a velocity dispersion of  $\sim 500 \text{ km s}^{-1}$  (Fig. 2). The sub-group appears to have undergone a high speed collision with the cluster around  $\sim 3 \text{ Gyr}$  ago (Czoske et al. 2001, 2002).

Czoske et al. (2002) explored the proposed cluster - sub-group collision via numerical simulations of dark matter haloes, concluding that this scenario could explain a well documented discrepancy between mass estimates derived from lensing (e.g. Comerford et al. 2006; Hoekstra 2007; Zitrin et al. 2009; Umetsu et al. 2010), velocity dispersion (Diaferio et al. 2005) and X-ray studies (Soucail et al. 2000; Ota et al. 2004; Zhang et al. 2005). Cl0024 has a lower X-ray flux and lower central velocity dispersion than expected for a virialised system, and this leads to some interesting implications. Processes such as galaxy harassment are usually most effective in the outskirts of clusters, or within groups as a method of “pre-processing”, since the lower relative velocity of galaxies leads to longer interaction times. However Moran et al. (2007) suggest that for Cl0024, harassment may be effective down to surprisingly small radii, with ram pressure stripping weak until  $\sim 300 \text{ kpc}$  from the core. Passive spirals appear to be relatively long-lived (1–2 Gyr; Treu et al. 2003) with galaxies experiencing a slower transition due to tidal interactions. In this respect Cl0024 makes a useful analog to higher redshift clusters which are still in the process of assembling.

### 2.2 Target Selection

To identify a sample of dust obscured cluster starbursts suitable for VLT/FLAMES IFU observations, we exploit the *Spitzer*/MIPS  $24\mu\text{m}$  imaging from Geach et al. (2006) and select bright mid-infrared bright sources with  $24\mu\text{m}$  fluxes of  $S_{24\mu\text{m}} = 0.15\text{--}1 \text{ mJy}$  (median  $S_{24\mu\text{m}} = 0.33 \pm 0.03 \text{ mJy}$ ) which have also been spectroscopically confirmed as cluster members (Moran et al. 2005). Approximately two-thirds of the

sample are known  $\text{H}\alpha$  or  $[\text{OII}]$  emitters, as identified from Suprime-Cam narrowband  $\text{H}\alpha$  imaging and DEIMOS spectroscopy (Kodama et al. 2004; Moran et al. 2005). We also include two  $\text{H}\alpha$  emitters of unknown  $24\mu\text{m}$  flux (IDs 9 and 10) which we used to fill vacant IFUs. We find no further distinction between these two galaxies and the rest of the sample, suggesting they are cluster starbursts which are simply not as dust obscured.

As shown by Fig. 1 & 2, our final starburst sample of 28 galaxies is well dispersed throughout the cluster, with projected cluster-centric radii of  $R = 0.2\text{--}3.9 \text{ Mpc}$ . 20 of 28 galaxies lie within the cluster virial radius of  $R_{\text{vir}} = 1.7 \text{ Mpc}$  (Treu et al. 2003). Seven of our targets are associated with the foreground group, which will allow us to assess the effect of an accelerated environment on the galaxy properties.

In Fig. 2 we show the  $(B-R)$  colour for all galaxies within the redshift range  $0.36 \leq z \leq 0.42$  (equivalent to  $\Delta v \sim 9000 \text{ km s}^{-1}$ ). No colour cut was made in selecting our IFU sample, and as can be seen from this figure, the MIPS  $24\mu\text{m}$  detections and our IFU targets tend to lie either in the blue-cloud or between the blue-cloud and the cluster red sequence (which can be identified between  $(B-R) \sim 2.5\text{--}3.2$ ). Some starbursts likely show redder colours due to the influence of dust on a population of intrinsically blue and star-forming galaxies.

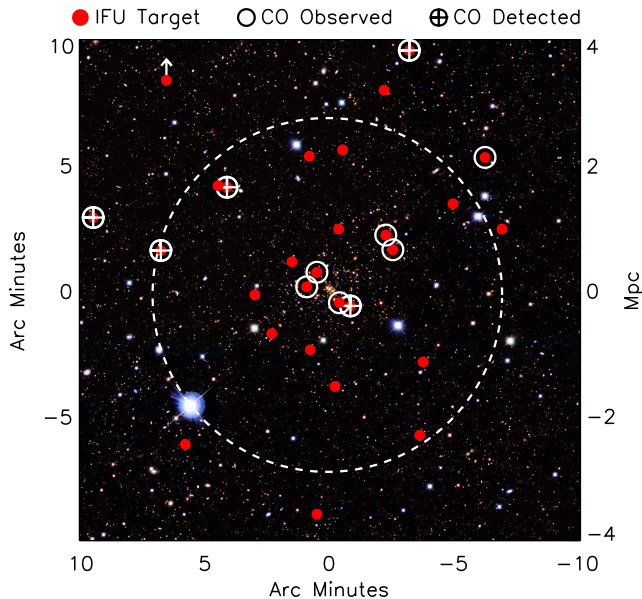
In our analysis we also exploit archival observations of Cl0024+17 which were taken with *HST*/WFPC2 as a 39-point sparse mosaic (Treu et al. 2003). The images were taken with the F814W filter (corresponding to rest-frame 580 nm) and cover approximately one-third of our sample (Fig. A1). We find a high incidence of disks with a range of bulge to disk ratios, and none of the galaxies appear to be undergoing a major merger. We note that there is no obvious trend in morphology with projected cluster-centric radius or association with the cluster or foreground group.

### 2.3 FLAMES IFU Observations

Observations of our 28 starbursts were made using the FLAMES multi-object IFU system on the VLT between December 13 2012 and November 29 2013 as part of ESO runs 089.A-0983 and 092.A-0135. FLAMES employs 15 IFUs across a patrol field of 25 arcmin diameter (Fig. 1) and each of the deployable integral field units consists of a near rectangular array of 20 microlenses (with pixel scale  $0.52'' \times 0.52''$ ), resulting in a total aperture of  $\sim 3'' \times 2''$ . All of the observations were taken in dark time and excellent seeing ( $< 0.5''$ ). We used the GIRAFFE spectrograph with the LR 881.7 filter to cover the  $\text{H}\alpha$  emission line in all of our targets, which at  $z \sim 0.39$  is redshifted to  $\sim 9100\text{\AA}$ . At this wavelength the spectral resolution is  $R = \lambda / \Delta\lambda \sim 9000$  (as measured from skylines), and we correct for this instrumental dispersion in all of our observations. Each observing block was split in to two 1.2 ks observations, with sub-pixel dithers to improve the effective spatial sampling. The total on-source integration time per target was 3–4 hrs.

To reduce the data we used the standard ESO/REX pipeline, which extracts the fibres from each IFU, flatfields and wavelength calibrates to form a set of preliminary datacubes. We reduced each observation individually, before sky subtracting and flux calibrating the spectra. For sky spectra we masked emission lines and continuum from the IFUs and





**Figure 1.** SUBARU SuprimeCam *BVI*-colour image of C10024+17, centred on  $\alpha:00:26:36.0$   $\delta:+17:08:36$  (J2000). The dashed line represents the virial radius of the cluster,  $R_{\text{vir}} = 1.7$  Mpc. We highlight the 28 spectroscopically confirmed dusty starbursts which were observed using the FLAMES multi object IFU. Our targets have projected cluster-centric radii of 0.2–3.9 Mpc. We circle galaxies also observed using IRAM PdBI, with crosses to indicate  $>5\sigma$   $^{12}\text{CO}(1-0)$  detections. It appears that galaxies further from the cluster centre are perhaps more likely to be detected in CO (also see Fig. 2).

then calculated an average sky spectrum which was then removed from all targets.

To create a mosaic for each galaxy we apply the sub-pixel offsets from our dither patterns, which were verified using the centroided continuum emission from the three brightest galaxies in the sample. This resulted in an effective pixel scale of  $0.17''$ . In combining the data cubes we used a  $3\sigma$  clipped average. The final spectra, integrated over each IFU, are shown in Appendix A along with the *HST* (where available; Treu et al. 2003) or Subaru imaging (Kodama et al. 2004). All but one of the targets were detected (and spatially resolved), leaving us with a final sample of 27 cluster starbursts. We note that the undetected target was the galaxy with the weakest  $\text{H}\alpha$  emission in the parent catalog. We exclude this source from the rest of the analysis.

To create the two-dimensional  $\text{H}\alpha$  emission, velocity, and velocity dispersion maps, we first measure the systemic redshift by fitting the  $\text{H}\alpha$  and  $[\text{NII}]\lambda\lambda 6548, 6583$  emission lines in the collapsed spectra. We then repeat this procedure on a pixel-by-pixel basis using a  $\chi^2$  minimisation procedure, inverse weighting the fit using a sky spectrum to account for increased noise at the positions of OH sky lines. We fit the  $\text{H}\alpha$  and  $[\text{NII}]$  doublet emission lines simultaneously, allowing the centroid, intensity and width of the Gaussian profile to vary. The FWHM of the  $\text{H}\alpha$  and  $[\text{NII}]$  lines are coupled and the intensity ratio of the  $[\text{NII}]\lambda\lambda 6548 / \lambda\lambda 6583$  was fixed at 2.98. We require a  $\text{SNR} > 5$  in order to record a detection in each individual pixel. During the fitting, we convolve the line profile with the instrumental dispersion. As such, all measurements are corrected for the instrumental resolution.

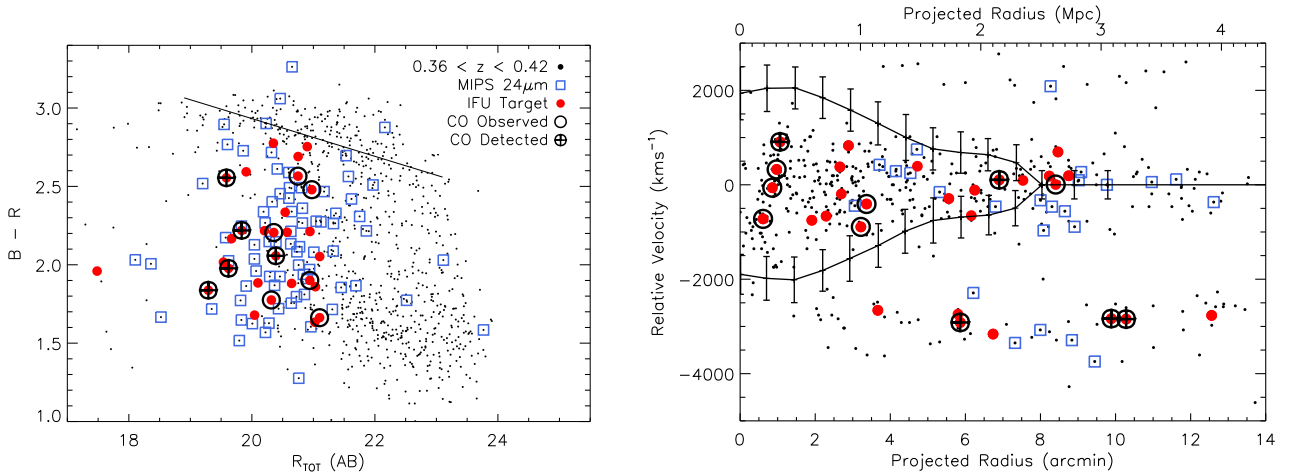
Fig. 6 shows the  $\text{H}\alpha$  velocity field of each of our sample, and in Fig. A1 we show the resolved  $\text{H}\alpha$  emission, dynamics and line-of-sight velocity dispersion maps of all galaxies. Although we observe a range of  $\text{H}\alpha$  morphologies, the majority of the sample appear to have regular (disk-like) velocity fields with velocity dispersions which peak towards the dynamical centre. It is useful to note that in the galaxy integrated one-dimensional spectra (Fig. A2), more than half show emission lines profiles which are double-peaked. This is also indicative of disk-like dynamics, with either increased dust obscuration towards central regions, or ring-like emission. We will return to a more detailed discussion of the dynamics in §4.

## 2.4 Plateau de Bure Observations

To assess the evolutionary state of our target galaxies we have also sought to obtain cold gas masses for a subset. This will allow us to compare the gas properties to field galaxies of a similar mass at the same redshift. We used the IRAM PdBI and its NOEMA upgrade to target the  $^{12}\text{CO} \text{J}(1 \rightarrow 0)$  transition in 11 galaxies, five of which were previously presented in Geach et al. (2009, 2011). These initial targets were predominantly in the outskirts of C10024+17, with cluster-centric radii of 1.8–3.3 Mpc, and so to complement this data we selected a further six galaxies which lie closer to the (projected) cluster core (Fig. 1). Observations took place in 2014 June as part of programme S14BT. Both sets of observations analysed here used the compact “D” configuration using six or seven antennae. We targeted the  $^{12}\text{CO} \text{J}(1 \rightarrow 0)$  115.27 GHz rotational transition, which  $z = 0.395$  is redshifted into the 3 mm band with  $\nu_{\text{obs}} = 82.63$  GHz. The central frequency of the 3 mm receiver was set to coincide with the CO(1-0) line at the spectroscopic redshift. For further details on the setup of the first set of observations, see Geach et al. (2011).

For the most recent sample, since one frequency setup was sufficient to cover all targets we required only one phase calibrator, switching between three pointings. The correlator was set up with 2.5 MHz spacing ( $2 \times 64$  channels, 320 MHz bandwidth), so as to accommodate any potential offset from the systemic redshift or a broad emission line profile. To increase observing efficiency, we chose pointings where two cluster starbursts had sufficiently small on-sky separations that they lay within a single primary beam. Exposure times were 4.15 hr per source pair. The data was calibrated, mapped and analysed using the software GILDAS (Guilloteau & Lucas 2000).

Combining our six new observations with those from Geach et al. (2011), we detect the CO  $\text{J}(1 \rightarrow 0)$  transition in five of eleven targets. We require  $3\sigma$  for a detection, with upper limits on  $L'_{\text{CO}}$  for non-detections based on the rms noise and median line width of the sample. One dimensional spectra are shown in Appendix Fig. A2. For the five detections we find line fluxes in the range  $f_{\text{CO}(1-0)} = (255 - 788) \text{ mJy km s}^{-1}$  and an average line width of  $\sigma_{\text{CO}} = 140 \pm 25 \text{ km s}^{-1}$ . To estimate the average flux of the sample we stack the CO spectra from all 11 galaxies. We find  $f_{\text{CO}(1-0)} = 309 \pm 30 \text{ mJy km s}^{-1}$ , and derive the same flux independent of whether we take an average, a median, or a noise weighted sum. Despite only one new detection, stacking the data allows us to place im-



**Figure 2.** Properties of our starburst sample. *Left:* Colour-magnitude relation for galaxies within a 9 arcmin radius of the Cl0024+17 cluster centre and within  $\Delta z < 0.03$  of the cluster redshift. We identify the cluster red sequence (solid line). Many targets in our sample lie between the red sequence and blue cloud – a consequence of dust-obscured star formation in blue, star-forming galaxies. *Right:* Line of sight velocity with respect to the cluster centre, versus projected cluster-centric radius. Solid lines show the caustics which illustrate the escape velocity of the cluster (Diaferio et al. 2005). The structure at  $\sim -3000 \text{ km s}^{-1}$  appears to be a group in the line of sight, which previously passed through Cl0024+17 (Czoske et al. 2002). Seven of our cluster starbursts lie within this foreground structure.

portant constraints on the gas properties of these starbursts. We will return to this in §3.

### 3 ANALYSIS & DISCUSSION: GALAXY INTEGRATED PROPERTIES

Before discussing the dynamics, star formation and molecular gas properties of our cluster starburst sample, we first derive their stellar masses and star formation rates using the multi-wavelength imaging available for the cluster. This allows the properties (current and final stellar mass, baryon fraction, dynamical state, gas depletion timescale) to be set in context with the field and cluster population at the same redshift.

#### 3.1 Stellar Masses

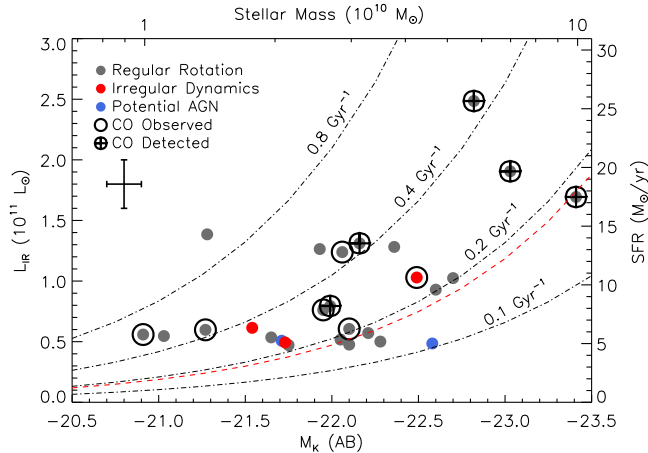
We begin by deriving absolute  $K$ -band magnitudes and stellar masses for the galaxies in our sample, using eight-band photometry from the optical to mid-infrared. The  $BVR$ -band fluxes were taken from Czoske et al. (2002); Treu et al. (2003) (which comprises Canada-France-Hawaii Telescope CFHT12k imaging). The  $J$ - and  $K$ -band photometry is given in Kneib et al. (2003); Smith et al. (2005), and is extracted from observations made with the WIRC camera on the Palomar Hale 200" telescope. In the mid-infrared, we perform aperture photometry using archival *Spitzer* IRAC imaging in the 3.6 and 4.5  $\mu\text{m}$  bands. In all cases, we use 2.5" aperture magnitudes and apply the appropriate aperture corrections to total magnitudes.

To fit the spectral energy distributions (SEDs) of each galaxy and hence infer star-formation histories and stellar masses, we employ the HYPERZ fitting code (Bolzonella et al. 2000). Model SEDs are characterised by their star formation history and parameterised by age, reddening and redshift.

Using spectral templates derived from the Bruzual & Charlot (2003) evolutionary code we consider six star formation histories: a single burst (B), constant star formation (Im), and exponential decays of timescales 3, 5, 15 and 30 Gyr (Sa,b,c,d respectively). We use the Calzetti et al. (2000) reddening law and, given the obscured nature of these cluster starbursts we allow  $A_V = 0.0 - 2.5$  magnitudes in steps of  $A_V = 0.1$ . We find an average extinction across the sample of  $A_V = 1.2 \pm 0.4$  magnitudes. In each case we fix the redshifts of the synthetic templates to match the  $H\alpha$  emission.

We next integrate the best-fit star formation history to calculate the stellar mass of each galaxy, accounting for mass loss from remnants using the STARBURST99 synthesis models (Leitherer et al. 2011). Given the dusty nature of these galaxies, we note that there are degeneracies between age and reddening which results in considerable uncertainty in the stellar mass-to-light ratios, an issue that is likely to be compounded by complex star formation histories. To overcome some of these difficulties, we derive the rest-frame  $K$ -band mass-to-light ratio a galaxy-by-galaxy basis, and then reapply the average value to the entire sample. The average mass to light ratio is  $\langle Y_\star \rangle = M_\odot / L_\odot^K = 0.35$ , and using this technique we find galaxies in our sample to have stellar masses in the range of  $M_\star = (1-10) \times 10^{10} M_\odot$ , with a median of  $M_\star = (2.8 \pm 0.3) \times 10^{10} M_\odot$ . We will use these values in the rest of our analysis. Absolute  $K$ -band magnitudes and stellar masses (using the median  $Y_\star$ ) are given in Table A2 of the Appendix.

To compare the stellar masses to those of field galaxies at the same redshift, we exploit the COSMOS / UltraVISTA survey from Muzzin et al. (2013), who derive a characteristic mass of  $M_\star = (5.8 \pm 0.5) \times 10^{10} M_\odot$  at  $z \sim 0.4$ . This suggests that, on average, the galaxies in our cluster starburst sample have slightly lower stellar masses than the “typical”  $M_\star$  field galaxy at this redshift.



**Figure 3.** Infrared luminosity against  $K$  band absolute magnitude, with additional axes to demonstrate how this relates to star formation rate and stellar mass. We use the median mass to light ratio for our sample of  $M_{\odot}/L_{\odot}^K = 0.35$  (see §3.1). Dashed lines indicate a constant specific star formation rate (sSFR), with a red line used to illustrate the sSFR of the so-called main-sequence at  $z=0.4$ . We highlight galaxies observed using PdBI / NOEMA, and find that detected galaxies tend to be of higher mass and brighter  $L_{\text{IR}}$ . Red points are used to represent galaxies with dynamics which deviate from a rotating disk model, and blue points for galaxies which may have an AGN affect the dynamics (these classifications are assigned in §4). We find no relationship between  $L_{\text{IR}}$ ,  $M_K$  and  $H\alpha$  dynamics.

### 3.2 Star Formation Rates

To estimate the star formation rates of these galaxies we adopt two approaches, using the (reddening corrected)  $H\alpha$  and the far-infrared imaging with *Herschel*. We detect strong  $H\alpha$  emission in the integrated spectra of all but one of our 28 IFU targets (which we have consequently dropped from the sample), with luminosities in the range  $L_{H\alpha} \sim 10^{40.6-41.8} \text{ erg s}^{-1}$  (see Fig. A1 and Table A1). We also make clear detections of the neighbouring  $[\text{NII}]\lambda 6583$  line, with ratios of  $-0.69 < \log([\text{NII}]/H\alpha) < 0.04$  and a median of  $-0.4 \pm 0.02$ . Since two of our sample exhibit  $\log([\text{NII}]/H\alpha) > 0$ , we discuss the possibility of AGN contamination in §4. We note that while the  $H\alpha$  star formation rates of AGN may be unreliable, the far-infrared results are less likely to suffer contamination.

We use the integrated  $H\alpha$  luminosity to calculate star formation rate (SFR) estimates, applying the calibration of Kennicutt (1998) for a Chabrier IMF ( $\text{SFR } M_{\odot} \text{ yr}^{-1} = 4.6 \times 10^{-42} L_{H\alpha} \text{ erg s}^{-1}$ ). Using the attenuation,  $A_V$ , returned by HYPERZ we also apply the dual reddening law of Wuyts et al. (2013) which assumes that the nebular emission is more attenuated than the stellar continuum (since young, ionising stars will typically reside in dustier regions). Therefore applying dust corrections of an average  $A_{\text{gas}} = 1.8 \pm 0.5$  magnitudes, we estimate  $H\alpha$  star formation rates of  $\text{SFR}_{H\alpha} = 0.3 - 16 M_{\odot} \text{ yr}^{-1}$ .

To compare far-infrared star formation rates to those derived from  $H\alpha$  emission, we next exploit the *Herschel* PACS / SPIRE imaging of C10024+17. For PACS, deblended catalogs are available for the cluster core (Lutz et al. 2011), which covers five of the galaxies in our sample. To derive 250, 350 and 500  $\mu\text{m}$  flux densities, we use SPIRE imaging from the HerMES legacy programme (Oliver et al. 2012). We first

align the astrometry of the images by stacking at the 24  $\mu\text{m}$  positions, applying  $<1''$  shifts in  $\Delta\text{RA}$  and  $\Delta\text{Dec}$ , and then deblend following the procedure of Swinbank et al. (2014), using the *Spitzer* 24  $\mu\text{m}$  sources as priors. From our sample of 27 cluster starbursts, 20 are detected above 11 mJy at 250  $\mu\text{m}$ . The median 250, 350 and 500  $\mu\text{m}$  fluxes for the detections in each band are  $20 \pm 3$ ,  $11 \pm 2$  and  $9 \pm 3$  mJy, respectively.

To derive far infrared luminosities we fit the far-infrared flux densities at the spectroscopic redshift, using the far-infrared templates from the Chary & Elbaz (2001), Draine et al. (2007) and Rieke et al. (2009) SED libraries. At the cluster redshift PAH and silicate features lie bluewards of the 24  $\mu\text{m}$  band, and so we include all photometry between 24  $\mu\text{m}$  and 500  $\mu\text{m}$ . Integrating the best fit SEDs we then derive bolometric luminosities of  $L_{\text{IR}} = (0.47 - 2.47) \times 10^{11} L_{\odot}$ , corresponding to star formation rates of  $\text{SFR}_{\text{IR}} = 3 - 26 M_{\odot} \text{ yr}^{-1}$ . Far-infrared luminosities and star formation rates are given in Table A2.

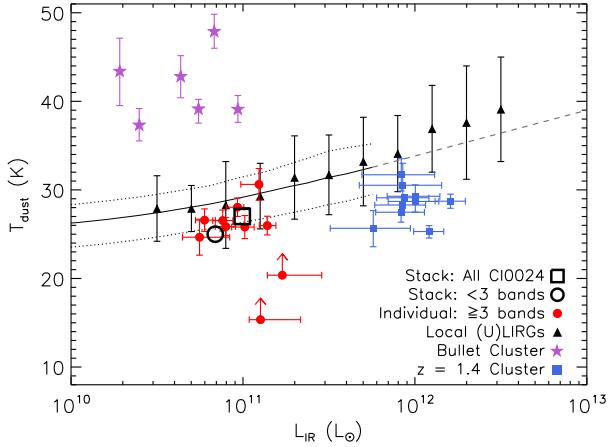
For galaxies with many upper limits on their far-infrared fluxes, we take the  $H\alpha$  star formation rate and multiply this by the average  $\text{SFR}_{\text{IR}}/\text{SFR}_{H\alpha}$  ratio, to estimate  $\text{SFR}_{\text{IR}}$ . On average, the star formation rate derived from the far-infrared is a factor  $2.2 \pm 0.4$  larger than that derived from the  $H\alpha$ , even after applying a dust correction to the  $H\alpha$  luminosity. This is equivalent to an additional  $A_{\text{gas}} = 0.9 \pm 0.2$  (or  $A_V = 1.3 \pm 0.2$ ). This offset may arise due to the differing structures between the dust and stars, particularly if the starbursts are centrally concentrated in an otherwise extended disk. Since the SED fitting provides a luminosity weighted result, the attenuation predicted from HYPERZ will be dominated by the extended disk and so systematically low. As a proxy for the star formation rate, in the rest of our analysis we will use the values derived from the far-infrared fluxes.

In Fig. 3 we plot infra-red luminosity versus absolute  $K$  band magnitude for the galaxies in our sample, converting the values also to star formation rate and stellar mass, respectively. We derive specific star formation rates (sSFR) in the range  $(0.1 - 0.9) M_{\odot} \text{ Gyr}^{-1}$  with a median of  $\text{sSFR} = 0.27 \pm 0.03 \text{ Gyr}^{-1}$ . Our cluster galaxies (excluding one AGN candidate, see §4) lie on or above the so-called “main sequence” at  $z \sim 0.4$  (Elbaz et al. 2007; Noeske et al. 2007; Karim et al. 2011). On average the galaxies are offset from the main-sequence by a factor of  $1.8 \pm 0.2$  at a fixed stellar mass, and hence we adopt the term “starburst”. In §4 we assign each galaxy a dynamical classification – rotationally supported or irregular – based on their velocity map and line of sight dispersion map. In Fig. 3 we split the sample by classifications and do not see any strong trends between the star formation rate and the dynamical state of the galaxy.

### 3.3 Characteristic Dust Temperatures

The far-infrared observations also contain information regarding the characteristic dust temperature. Recently, observations of local clusters have revealed a population of apparently “hot” starbursts, with  $T_d \sim 50 \text{ K}$  and LIRG-like luminosities (Rawle et al. 2012). These galaxies may represent a particular stage in the transition from infalling spiral to cluster S0, where ram pressure has stripped the low density (cold) gas disk but a central starburst is yet to be quenched.





**Figure 4.** Characteristic dust temperature versus far-infrared luminosity for our cluster starburst sample, compared to the relation established for local starburst galaxies (black triangles show  $z < 1$  (U)LIRGs; Symeonidis et al. 2013). Galaxies with detections in three or more infrared bands are shown in red points. We also show stacks of all 27 galaxies (open square) and those with fewer than three detections (open circle). We do not observe a significant offset from the local relation, in either direction. For comparison we plot the “hot” Bullet Cluster starbursts of Rawle et al. (2012) which may have been stripped of their low density gas, and starbursts from a cluster at  $z = 1.4$  (which are consistent with high-redshift field galaxies; Ma et al. 2015).

In order to test whether the cluster starbursts in our sample are more or less evolved, we plot their far-infrared luminosity versus dust temperature in Fig. 4. For consistency with other comparison samples we employ a modified black-body curve of the form  $S_\nu \propto \nu^\beta B_\nu T_d$  to derive the dust temperatures, with an emissivity index of  $\beta = 1.8$ . We only include galaxies with detections in three or more bands, which constitutes approximately a third of the sample. This cut means that a reliable estimate of  $T_d$  can be derived.

On the plot, we include the relationship for local LIRGs / ULIRGs (which is derived from a sample of  $60\mu\text{m}$  selected galaxies at  $z \sim 0$ ; Chapman et al. 2003; Chapin et al. 2009) and SPIRE-selected  $z < 1$  (U)LIRGs (Symeonidis et al. 2013), both of which follow a power-law relation between  $L_{\text{IR}} \sim 10^{10} - 10^{13} L_\odot$ . We also plot similar measurements of high- $z$  submillimeter-selected cluster starburst galaxies in XCS J2215.9–1738 ( $z = 1.4$ ), which show systematically colder dust temperatures at fixed luminosity compared to the local relation (Ma et al. 2015). This is likely to be a result of the more extended gas reservoirs compared to  $z = 0$  galaxies of the same luminosity.

For our sample of cluster starbursts we derive a median dust temperature of  $T_d = 26 \pm 1$  K and far-infrared luminosity  $L_{\text{IR}} = (9.1 \pm 0.9) \times 10^{10} L_\odot$ . These dust temperatures are consistent with those measured for low-redshift field galaxies of similar far-infrared luminosity, and indeed we do not find any starburst galaxies with dust temperatures exceeding 31 K. However, we note that in this analysis we have only included the galaxies with detections in three (or more) bands, and for two of these galaxies we place lower limits on  $T_d$  since we do not resolve the peak of the emission. To infer the average dust temperature of the remaining sample we stack the PACS and SPIRE images in four different ways:

all 27 galaxies, galaxies detected in  $\leq 1$  band, in  $\leq 2$  bands and in  $< 3$  bands. The characteristic dust temperatures of these subsets are all within 2 K of each other (25–27 K), suggesting that the galaxies with well defined blackbody fits are representative of the full of the sample. We plot the temperatures of the full sample stack and the  $< 3$  bands stack on Fig. 4 for comparison.

Finally, we note that although we only selected a small subsample for IFU follow-up, the  $24\mu\text{m}$  MIPS parent sample comprises 60 galaxies in total, approximately one third of which lie in the foreground group. To search for differences between the group and cluster starbursts, we stacked the PACS and SPIRE imaging of the  $24\mu\text{m}$ -detected galaxies in both subsets, but in each case the SPIRE colours and characteristic dust profiles are consistent, with  $T_{d,\text{cluster}} = 23 \pm 2$  K and  $T_{d,\text{group}} = 23 \pm 3$  K respectively.

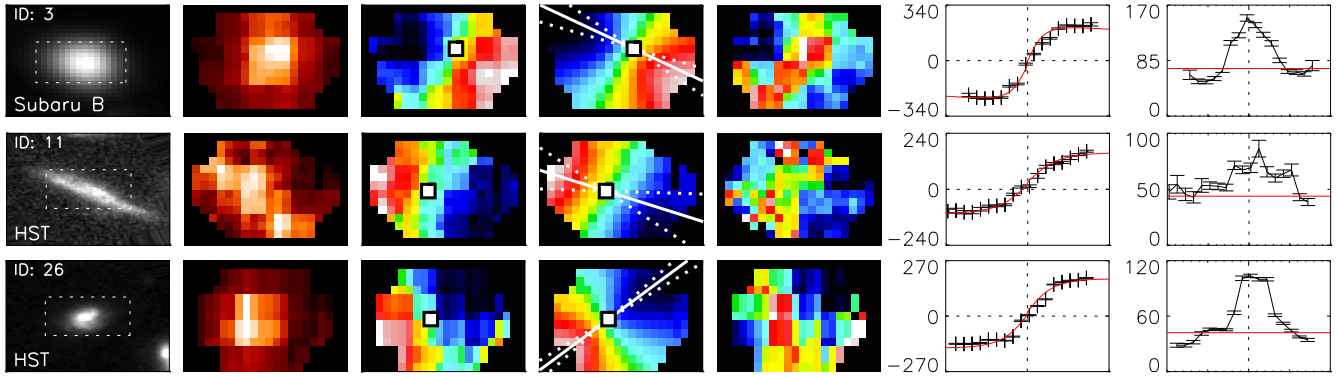
Thus, it appears that the characteristic dust temperatures of cluster starbursts are consistent with a luminosity matched sample of field galaxies. In this respect, our sample appear to be less evolved than the “hot” starbursts seen in some local clusters (Rawle et al. 2012), perhaps indicating that they have been accreted more recently, and have not yet had their low density gas stripped by the ICM.

### 3.4 Molecular Gas Masses

To determine how the molecular gas content of these galaxies compares to similar mass field galaxies, and calculate their likely final stellar mass if all available gas is converted to stars, we use the  $^{12}\text{CO J}(1 \rightarrow 0)$  emission. We overlay the CO spectra on top of the  $\text{H}\alpha$  in Fig. A2, and find that the velocity centroid and line widths are well matched. The two sets of spectra have an average velocity offset of  $50 \pm 10 \text{ km s}^{-1}$ , and an average ratio between the  $\text{H}\alpha$  and CO line widths of  $0.9 \pm 0.2$ . This suggests that the  $^{12}\text{CO}$  traces the same dynamics as the  $\text{H}\alpha$  emission, and that the ionised gas and molecular gas components are similarly distributed throughout the disk.

Fitting each of these  $^{12}\text{CO}$  spectra with a single Gaussian profile, we find line luminosities of  $L'_{\text{CO}} = (2.2 - 6.8) \times 10^9 \text{ K km s}^{-1} \text{ pc}^2$  for the five detected galaxies (Solomon & Vanden Bout 2005), and upper limits of  $L'_{\text{CO}} = (3.9 - 4.9) \times 10^9 \text{ K km s}^{-1} \text{ pc}^2$  for the rest of the sample (see Table A2). To convert to the molecular gas mass we use  $M(\text{H}_2 + \text{He}) = \alpha L'_{\text{CO}}$ . The far-infrared luminosities of our targets are much larger than what is typical of local star-forming galaxies such as the Milky Way (Gao & Solomon 2004), however as discussed in Geach et al. (2011) the choice of  $\alpha = 4.6$  may be the most appropriate given the late-type morphologies of the sample, and that the average  $L_{\text{IR}}/L'_{\text{CO}}$  ratio we measure ( $L_{\text{IR}}/L'_{\text{CO}} = 25 \pm 5$ ) is comparable to local spirals. Using this calibration we estimate molecular gas masses of  $M_{\text{gas}} = (1.0 - 3.0) \times 10^{10} M_\odot$  which equates to gas fractions of  $f_{\text{gas}} = M_{\text{gas}}/(M_{\text{gas}} + M_\star) = 0.11 - 0.39$ . As discussed in §2.4 we also stacked all 11 CO spectra to better characterise the sample as a whole. Using this stack we find a median line luminosity  $L'_{\text{CO}} = (2.7 \pm 0.3) \times 10^9 \text{ K km s}^{-1} \text{ pc}^2$ , which translates to a gas mass of  $M_{\text{gas}} = (1.2 \pm 0.2) \times 10^{10} M_\odot$  (towards the lower end of our detections). We will use this as a representative gas mass for our sample in all of the analysis below.

Our CO sample have an average star formation rate



**Figure 5.** Example broad-band image,  $H\alpha$  morphology and dynamics for three galaxies in our sample (data for the complete sample is shown in Fig. A1). From left to right: Subaru or *HST* broad-band image,  $H\alpha$  intensity map,  $H\alpha$  velocity field, best-fit model velocity field, dispersion map, and the rotation curve and line-of-sight velocity dispersion profile extracted along the primary axis. The dashed outline on the broad-band image illustrates the position and size of the IFU ( $2'' \times 3''$ ). We fit the two dimensional data using a simple inclined disk model. The solid line placed onto the model velocity field shows the position angle, and the dashed lines reflect the  $1-\sigma$  uncertainty of this. The square points indicate the position of the dynamical centre, according to the best-fit model. We fit the one dimensional rotation curve (in red) to find a characteristic rotation velocity. Axes are in units of  $\text{km s}^{-1}$ . The solid red line in the last plot shows the value of  $\sigma_0$ . We find  $\sim 90\%$  of our starburst sample resemble un-disturbed rotating disks, with a characteristic “spider” pattern in the velocity field, and a line of sight velocity dispersion which peaks towards the dynamical centre.

of  $(13 \pm 1) \text{ M}_\odot \text{ yr}^{-1}$  (compared to  $\sim 10 \text{ M}_\odot \text{ yr}^{-1}$  for the wider sample) and so we estimate a gas depletion timescale of  $\sim 1 \text{ Gyr}$ , which is approximately  $\sim 0.25$  of the cluster crossing time. This may explain the non-detections of the  $^{12}\text{CO}$  in the (projected) cluster core. We predict final stellar masses for our sample with an average of  $\sim 4 \times 10^{10} \text{ M}_\odot$ . From a sample of local cluster S0s ( $0.04 < z < 0.07$ ; WINGs survey) Vulcani et al. (2011) find a characteristic stellar mass of  $M_* = 2.2 \times 10^{11} \text{ M}_\odot$ . This implies that our cluster starbursts are destined to be  $\leq M_*$  members of the S0 population. It may be that the most massive  $\leq M_*$  S0s are already in place at this redshift, or that their progenitors are passive spiral galaxies which have already completed their starburst phase.

As shown in Fig. 2, our  $^{12}\text{CO}$  sample includes galaxies of range of cluster-centric radii, and which inhabit both the “main” cluster and sub-group component. While all three galaxies observed in the subgroup are detected in  $^{12}\text{CO}$ , only two of eight galaxies are detected in the larger structure. This could be an environmental trend. However, we also caution that the galaxies which we detect also tend to be more far-infrared luminous, and given the correlation between  $L_{\text{IR}}$  and  $L'_{\text{CO}}$ , this may simply mean the  $^{12}\text{CO}$  is easier to detect. Of course we cannot rule out the possibility that the same sources are brighter in the far-infrared due to some evolutionary effect. Considering our limited sample size it is difficult to draw definitive conclusions with respect to the gas content as a function of cluster radius, but this study motivates a more detailed future study with a larger sample.

To compare the gas masses of these starbursts to galaxies on the star-forming “main-sequence” at this redshift, we use the scaling relations of Genzel et al. (2015). These relations predict that a star-forming galaxy at  $z \sim 0.4$  with a similar stellar mass will have a gas-to-stellar ratio of  $\log(M_{\text{gas}}/M_*) \sim -0.9$ . This implies an average gas mass of  $M_{\text{gas}} \sim 4 - 8 \times 10^9 \text{ M}_\odot$ . The molecular gas masses of our sample therefore appear to be slightly higher (a factor of  $\sim 2$ ) than those of “typical” galaxies of similar stellar mass at

this redshift. The far-infrared and CO luminosities of our sample are consistent with the  $L_{\text{IR}} - L'_{\text{CO}}$  relation fit to low- and high-redshift star forming galaxies (including LIRGs, ULIRGs and SMGs) in Ivison et al. (2013).

Finally, we compare the gas properties of our cluster starbursts to starbursts in the field population, using a sample of ULIRGs ( $L_{\text{IR}} > 10^{12} L_\odot$ ) at  $0.2 < z < 1$  taken from Combes et al. (2013). This comparison sample have star formation rates  $\sim 10\times$  higher than our cluster starbursts, but by mass matching their sample to the median stellar mass of our galaxy sample, we derive an average gas mass of  $M_{\text{gas}} = (1.2 \pm 0.5) \times 10^{10} \text{ M}_\odot$ . This is consistent with the molecular gas masses derived for our cluster starburst sample.

On the basis of our  $^{12}\text{CO}$  observations it appears that these cluster starburst galaxies are richer in molecular gas than typical star forming galaxies at a similar redshift. We derive molecular gas masses which are more closely matched to those of starbursts (ULIRGs) in the field with similar infra-red luminosities. This could suggest a scenario in which the gas of infalling galaxies is compressed upon their encounter with the ICM, converting available  $\text{H I}$  into  $\text{H}_2$  and triggering a burst of star formation. These galaxies may have been typical star forming galaxies upon accretion to the cluster, yet have their molecular gas fraction enhanced through this process. We will return to these results in the final section.

## 4 ANALYSIS & DISCUSSION: IONISED GAS DYNAMICS

### 4.1 Disk Fitting

Now that we have established the integrated properties of our sample, we next investigate the spatially resolved properties as measured from the  $H\alpha$  emission. The galaxies in our sample appear to resemble the field population in terms of



their stellar masses and characteristic dust temperatures (although possibly with higher molecular gas masses), and so our aim in this section is to assess how evolved these galaxies appear in terms of their gas dynamics. We will search for evidence of the mechanisms which may eventually quench the star formation in these galaxies and transform their kinematics from regular, disk-like rotation to pressure-supported S0s.

In Fig. A1 we show the two-dimensional maps of H $\alpha$  emission, velocity, and line of sight velocity dispersion for all 27 targets. In each instance there is a clear velocity gradient with peak-to-peak differences ranging from  $\Delta v = 100 - 500 \text{ km s}^{-1}$ . We note two galaxies (ID 23 and ID 24) exhibit very high  $\log([\text{NII}]/\text{H}\alpha)$  ratios (i.e.  $\gtrsim 0$ ); indicating the presence of an AGN (e.g. Kewley et al. 2013). Additionally, these sources show irregular velocity dispersion profiles, with spatially offset broad emission ( $\gtrsim 150 \text{ km s}^{-1}$ ; Fig. A1), which may indicate that outflows are effecting the gas kinematics in these sources (e.g. Harrison et al. 2016). For these reasons, we omit these two galaxies from the dynamical analysis below, leaving a sample of 25.

Next we assign a dynamical classification to each of the galaxies in our sample (Fig 3; Table A3). We classify 22 of 25 starbursts ( $\sim 90\%$ ) as rotationally supported, since their velocity map is regular (with a characteristic “spider” pattern), their rotation curve smooth, and they possess a line of sight velocity dispersion map which peaks towards the dynamical centre. The optical morphologies of these galaxies also appear smooth (and in some cases disk-like), with no evidence of multiple centres, tidal tails or merger activity. We class the remaining three galaxies as irregular, since they show complex dynamics in their two dimensional maps, rotation curves or dispersion profiles. This fraction of disks is consistent with field surveys at these redshifts, which have suggested that massive galaxies are the most well ordered at all redshifts up to  $z \sim 1.5$  (e.g. Kassin et al. 2012; Wisnioski et al. 2015; Stott et al. 2016; but see also Puech et al. 2007). In Fig. 3 we demonstrate that the kinematics do not appear to be correlated with far-infrared luminosity or  $K$  band magnitude.

To provide a quantitative measure of the dynamics, and derive their basic parameters (such as disk inclination,  $i$  and hence true rotational speed), we fit each each velocity field using a simple disk model with arctan rotation curve (e.g. Courteau 1997). In total we fit for six different parameters: the dynamical centre ( $x_c$ ,  $y_c$ ), asymptotic velocity  $v_c$ , velocity at centre of rotation  $v_0$ , turnover radius  $r_t$ , position angle  $\theta$ , and disk inclination  $i$ . Although all velocity fields show small discrepancies the majority appear to be well fit by this simple model, with  $\langle v_{\text{data}} - v_{\text{model}} \rangle = 26 \pm 15 \text{ km s}^{-1}$ . Example dynamical maps are shown in Fig. 5, and similar images for the full sample are given in appendix Fig. A1. We note that the position angle and dynamical centre returned by the model fit clearly pass through the regions of minimum and maximum rotation velocity. We also compare our inclination values to those derived from the *HST* and Subaru optical morphologies. Although there is some degree of scatter, we find our conclusions in the following sections would be unchanged had we used inclinations derived directly from the images instead. Where the inclination of a particular galaxy is more uncertain, this is reflected in the larger errors assigned to dynamical parameters in Table A3.

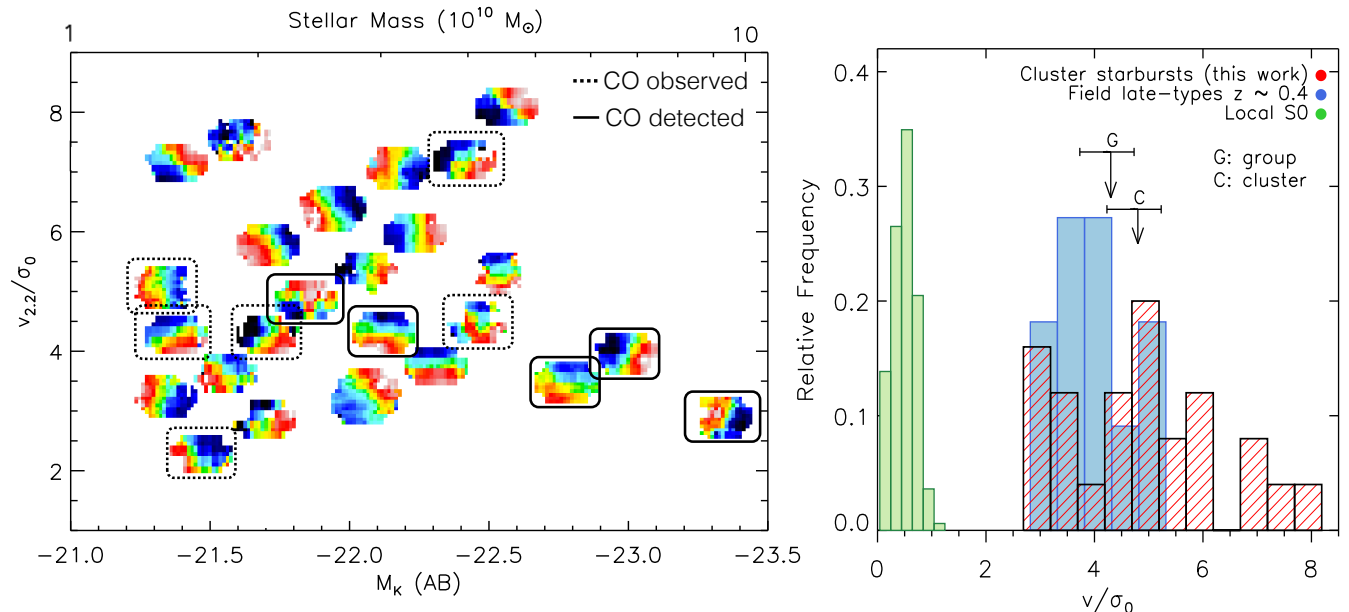
Using the best-fit disk parameters, we extract one-dimensional rotation curves by collapsing the velocity field along the major kinematic axis. It is clear from these data that a number of the rotation curves asymptote and turn over beyond  $\sim 2 \text{ kpc}$ . To fully characterise this shape we fit the rotation curves with a model that includes a dark matter component. The velocity field can therefore be expressed as  $v^2 = v_d^2 + v_h^2 + v_{\text{HI}}^2$ , where the subscripts denote the stellar disk, dark matter halo and HI gas disk respectively. For the stellar disk, we assume the stars follow an exponential surface density (Freeman 1970) which is characterised by a disk mass and radius, and for the dark matter we assume  $v_h^2(r) = G M_h(< r) / r$ , with a dark-matter density profile that is described by a core density and radius. Further details of the modelling used are discussed in Swinbank et al. 2016 (in prep). Although we do not attempt to infer the stellar/dark halo fractions (due to strong degeneracies), this parameterisation allows us to improve our measurement of total rotation speed at the disk radius. While in most cases we could extract this velocity directly from the raw data, a model is useful for when this is not possible. In the following analysis we use inclinations from the two-dimensional disk model and rotation velocities from this one-dimensional rotation curve fit.

As a representative rotation velocity we choose to define  $v_{2.2}$ , the velocity at  $2.2 \times$  the half-light radius, since this typically samples the rotation curve in a region where it is no longer rising steeply. Of our IFU sample, ten are covered by deep *HST* imaging and the remaining 17 by Subaru (see Fig. A1), and we use these images to establish the continuum half light radius ( $r_{1/2}$ ) by fitting a series of ellipses at the galaxy position angle. We deconvolve for the seeing, and use the model rotation curve to estimate the velocity at this radius. We give this rotation speed and the corresponding half-light radius in Table A3.

## 4.2 Turbulence and Rotational Support

To continue to address the question of which physical mechanism(s) drives the star formation in cluster starbursts, we next measure the turbulence in the ISM. By comparing to galaxies in the field with a mass and star formation rate matched sample, this will allow us to quantify the effect of environment on the stability of the disk. To calculate the intrinsic velocity dispersion,  $\sigma_0$ , we first correct for beam-smearing effects using the raw two-dimensional velocity field. For each pixel we consider all neighbouring pixels within the PSF, and calculate the maximum velocity gradient across this element  $\Delta v / \Delta R$ . This contribution to the dispersion is then removed and we calculate the average velocity dispersion across the entire galaxy image (inverse weighting by the noise at each pixel). The final corrected velocity dispersions,  $\sigma_0$ , for each galaxy are given in Table A3 and their values also shown relative to the dispersion profiles in Fig. A1. It can be seen that these  $\sigma_0$  values are comparable to the velocity dispersion in the outer regions of the disk, which is less affected by beam smearing.

We find our cluster starbursts to have a median velocity dispersion of  $\sigma_0 = 50 \pm 15 \text{ km s}^{-1}$ . Dynamical studies between  $0.2 < z < 1.0$  report values in the range  $\sigma_0 = 25 - 60 \text{ km s}^{-1}$  (e.g. Kassin et al. 2012; Wisnioski et al. 2015; Stott et al. 2016), however it is difficult to make direct comparisons since



**Figure 6.** *Left:*  $H\alpha$  dynamics of the 25 galaxies as a function of rotational support ( $v_{2.2}/\sigma_0$ ) and  $K$  band magnitude. We choose to define the characteristic rotation velocity at  $2.2 \times$  the half-light radius, as measured from *HST* and Subaru continuum images. We convert  $M_K$  values to stellar masses, using the average mass-to-light ratio derived from the HYPERZ SED fitting (see §3.1). We circle galaxies for which we have observed the  $^{12}\text{CO}$  transition, with solid lines corresponding to  $> 5\sigma$  detections, and dashed lines elsewhere. Some velocity fields have been shifted a small distance from their original position for clarity, however these values are provided in Tables A2 and A3. The majority of galaxies resemble undisturbed, rotating disks, with no obvious trends between dynamics and galaxy mass or molecular gas content. *Right:* The rotational support of our galaxies compared to local S0s (Emsellem et al. 2011) and field spirals of a similar redshift (Puech et al. 2007). The fact that their  $v/\sigma_0$  values are consistent with field spirals suggests that these galaxies have only recently been accreted. Their disks must be dynamically heated to decrease their  $v/\sigma_0$  values to match S0s. The median  $v/\sigma_0$  of the group does not appear to be significantly different to that of the “main” cluster (‘G’ arrow and ‘C’ arrow respectively).

estimates are highly sensitive to the properties of the sample and the method used (see Stott et al. 2016 for further discussion). To derive  $\sigma_0$  in a consistent way and compare to the turbulence of field galaxies at similar redshift, we exploit the sample of Swinbank et al. (2016, in prep.). This sample consists of  $\sim 500$  [OII] emitters serendipitously identified in a series of commissioning and science verification observations using MUSE. There were 16 “extra-galactic” fields observed, with the science targets largely “blank” fields or studies of high redshift ( $z > 4$ ) galaxies and quasars. We match the redshift, stellar mass and star formation rate of this star-forming sample to our cluster starbursts and find a median of  $\sigma_0 = 50 \pm 10 \text{ km s}^{-1}$ . This suggests that turbulence in the gas disks of our galaxies has not yet been enhanced by the various physical processes acting in this dense environment.

The ratio between inclination corrected rotation velocity and intrinsic velocity dispersion,  $v/\sigma_0$ , is often used as a measure of rotational support against thermal pressure. We therefore calculate this parameter for each galaxy in order to compare their dynamics to the field population and cluster S0s, using the characteristic rotation velocities ( $v_{2.2}$ ) calculated in §4.1. Across our sample we find inclination corrected values between  $v_{2.2}/\sigma_0 = 2.8 - 8.2$ , with a median of  $v_{2.2}/\sigma_0 = 5 \pm 2$ . Given that  $v/\sigma_0 < 1$  is typically used as a cut-off for the classification of “dispersion dominated” galaxies, this further supports our conclusions that the majority of our sample are undisturbed, rotating disks.

In Fig. 6 we compare the rotation of the dusty starbursts to local S0s and spiral galaxies in low density environments

at similar redshift. We plot the  $v/\sigma_0$  values of 32 rotationally supported galaxies at  $0.4 \leq z \leq 0.75$  (also observed using FLAMES). Puech et al. (2007) find a median  $v/\sigma_0 = 3.8 \pm 2$ , which is consistent with our sample. We also see that local S0s (Emsellem et al. 2011) typically have values of  $v/\sigma_0 \leq 1$ . The dynamics of infalling cluster galaxies must evolve significantly if a transformation is to take place between spirals and S0s.

Finally, to search for trends in the dynamics as a function of cluster-centric radius, we divide the sample into galaxies within the (projected) cluster core, in the outskirts, and in the foreground sub-group. However, we do not find any link between whether a galaxy resides in one of these regions and its dynamics (in terms of the observed dynamical state,  $\sigma_0$  or  $v/\sigma_0$ ). We show the median  $v/\sigma_0$  of these two subsamples in Fig. 6. The kinematics also do not appear to be strongly correlated with galaxy mass or star formation rate (see Fig. 3). Although our results may be complicated by projection effects, it appears that the dynamics of the galaxies are not a strong function of location within the cluster. This implies that any dynamical transformation must take place over a longer period than the duration of the starburst ( $\sim 1$  Gyr), or once the starburst has been quenched.

### 4.3 Specific Angular Momentum

Although the ratio of  $v/\sigma_0$  is a useful measure of the dynamical state of a galaxy, a better quantification is the spin,  $\lambda_R$ , since this encodes how the rotational speed and line-of-sight velocity dispersion vary with radius. Dynamical studies

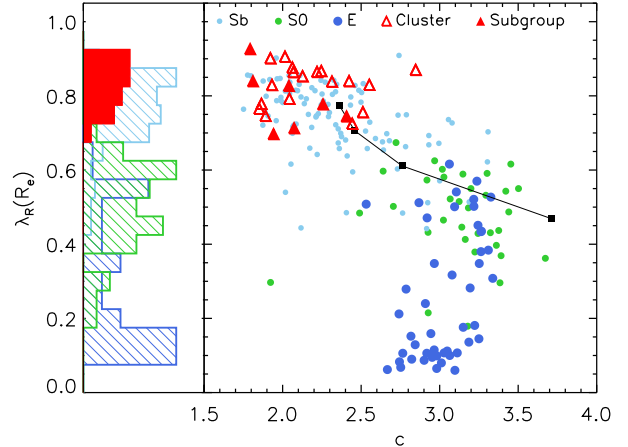
of local galaxies have shown that early-type and late-type galaxies tend to (broadly speaking) have different spin values (Querejeta et al. 2015; Fogarty et al. 2015). Emsellem et al. (2011) define  $\lambda_R$ , which is essentially a proxy for specific angular momentum, as:

$$\lambda_R = \frac{\sum_{i=1}^N F_i R_i |V_i|}{\sum_{i=1}^N F_i R_i \sqrt{V_i^2 + \sigma_i^2}} \quad (1)$$

where  $F_i$ ,  $V_i$ ,  $\sigma_i$ , and  $R_i$  are the flux, velocity, velocity dispersion and radius of the  $i$ th pixel respectively. This spin parameter was initially used in the classification of early-type galaxies, with Cappellari et al. (2011) finding ellipticals and S0s could be split into two regimes – fast rotators and slow rotators – depending on their spin and ellipticity. However more recently the spin has been combined with the concentration of the stellar light profile, as a diagnostic tool to test how galaxies might dynamically evolve from one type to another. Concentration,  $c$ , is defined as the ratio between the radii enclosing 90% and 50% of the Petrosian flux.

In Fig. 7 we compare the spin and concentration of our sample to the properties of spirals and S0s from the CALIFA survey ( $z \sim 0$ ; Querejeta et al. 2015). For consistency with the comparison samples we evaluate  $\lambda_R$  for all pixels within the half light radius, deriving a median  $\lambda_R = 0.83 \pm 0.06$  and concentration of  $c = 2.1 \pm 0.3$  for the cluster galaxies. For this analysis we use *HST* images (F814W filter) where available, and Subaru  $z$ -band images otherwise. As Fig. 7 shows, the dynamics and concentration of our galaxies are consistent with field spirals, implying that the dynamics of our sample are still relatively unaffected by the cluster environment. If these galaxies are to eventually transition to S0s they clearly must undergo a process (or several) which not only dynamically heats the disk and reduces rotational support, but which also increases the bulge to disk ratio (and hence increases the concentration by a factor  $\sim 2$ ).

Interactions with the dense ICM can effectively strip the gas disks of spirals and lead to a rapid truncation of star formation. It was recently suggested that ram pressure stripping may even cause a temporary enhancement of star formation in central regions (Bekki & Couch 2011; Bekki 2014). However, the same numerical simulations predict little effect on the dynamics of these galaxies due to interaction with the ICM. Conversely, tidal interactions are very efficient at disrupting the disk. Repeat galaxy-galaxy encounters can act to increase the velocity dispersion and decrease the spin, potentially channelling gas inwards to fuel episodes of bursty star formation. Indeed, Bekki (2014) predict that a high spin, low concentration late-type galaxy in a high mass group may be transformed via tidal interactions into a low spin, high concentration S0, over a period of 2–4 Gyr. We overlay this evolution in Fig. 7. Although the timescales likely increase in a cluster environment, such a mechanism would simultaneously achieve the two key changes required for a spiral to S0 transition. In this scenario, the concentration is increased gradually via multiple bursts of star formation in the central regions, and we may expect to find starbursts with a range of  $\lambda_R$  and  $c$  values. However, our cluster starburst sample are exclusively high-spin, low-concentration galaxies. We propose instead that the initial encounter with the ICM is responsible for triggering the starbursts observed in this cluster. Repeat galaxy-galaxy interactions may occur after



**Figure 7.** Galaxy spin,  $\lambda_R$  versus concentration,  $c$  for our starburst sample, as compared to galaxies of various morphological types from the CALIFA survey (Querejeta et al. 2015). We also overlay predictions from the numerical models of Bekki & Couch (2011) who simulate the impact of tidal interactions on a typical spiral galaxy in a dense environment. Squares along the tracks represent 0, 2.8, 4.2 and 5.6 Gyr since the beginning of this simulation. The high spin values of our galaxies suggest kinematics that are consistent with recently accreted field spirals. It seems that the mechanism which initiated the current burst of star formation has not had a dramatic effect on the disk dynamics. In order to make a transition between spirals and S0s these galaxies must lose angular momentum and increase their bulge to disk ratio (and therefore concentration).

the bursts have been quenched, to eventually achieve the  $\sim 40\%$  decrease in angular momentum.

#### 4.4 The Beginning of the End?

Overall, the characteristic temperatures, gas masses and dynamics of these dusty starburst galaxies suggest that they have only recently been accreted from the field. The far-infrared star formation rates are on average twice that of a typical star-forming galaxy at this redshift, with our  $^{12}\text{CO}$  observations suggesting there is sufficient cold gas to sustain this activity for another  $\sim 1$  Gyr. In fact we calculate molecular gas masses consistent with local ULIRGs. Dust temperatures in line with the local relation are further evidence that the gas disks have not yet been stripped by the intra-cluster medium.

The dynamics and morphologies of the cluster galaxies appear disk-like, with a large degree of rotational support ( $v/\sigma_0$ ) and a high angular momentum ( $\lambda_R$ ). There is no evidence to suggest that the current bursts of star formation were initiated by mergers. It is possible that they were instead triggered by ram pressure, as an initial encounter with the ICM compresses the ISM of the infalling galaxies. This could also convert available H I into molecular  $\text{H}_2$ , and may explain why these galaxies are so rich in star-forming gas. Such a process is consistent with the small excess of starbursts seen inside the virial radii of some clusters (e.g. Hogg et al. 2006).

As we have seen in Fig. 7, in order for the cluster starbursts to transition from spirals to S0s they must increase their concentration ( $c$ ) and decrease their angular momen-

tum ( $\lambda_R$ ). Multiple galaxy-galaxy interactions (harassment) seem a likely mechanism for the dynamical transformation, however the growth of the bulge does not appear to occur simultaneously. It is more likely that dynamical heating through tidal interactions occurs much later ( $\geq 1$  Gyr), after the molecular gas has been depleted and/or stripped. The current burst looks set to increase the mass of these galaxies by  $\sim 1 \times 10^{10} M_\odot$ , with final stellar masses consistent with sub- $M_*$  S0s. However, how this starburst episode may affect the bulge to disk ratio remains to be seen. To determine how much of the star formation is confined to central regions of the galaxy requires high resolution millimetre/submillimetre observations, for example using ALMA.

## 5 CONCLUSIONS

At low redshift the effects of environment on the morphology, gas content and star formation of galaxies is a well established phenomenon. Yet we know relatively little about the mechanisms which drive these trends, and how they depend on the properties of both the cluster, and the infalling galaxies on which they act. It is vital to develop a greater understanding of these issues if we are to explain the reversal of the morphology–density relation at high redshift.

In this study we investigated the dynamics, star formation and gas properties of 27 cluster starbursts from Cl0024+17 ( $z \sim 0.4$ ), to learn more about the nature of these galaxies, and how dense environments at high redshift can promote star formation in some infalling galaxies. This problem is key to explaining the early and rapid formation of today’s massive cluster galaxies. Our main findings are as follows:

- We use deblended *Herschel* PACS / SPIRE maps to derive bolometric luminosities of  $L_{IR} = (0.47 - 2.47) \times 10^{11} L_\odot$  and star formation rates  $SFR_{IR} = 5 - 26 M_\odot yr^{-1}$ . The enhanced activity of these galaxies places them above the star forming “main-sequence” for this redshift and stellar mass (an average of  $\sim 3 \times 10^{10} M_\odot$ ).
- From the far-infrared photometry, we derive characteristic dust temperatures of  $T_d = 26 \pm 1$  K, consistent with the local  $L_{IR}$ - $T_d$  relation for field galaxies. We do not find any evidence that the cold gas/dust has been stripped by the interaction of the galaxy ISM with the intra-cluster medium. If such an interaction occurs, then it must act on a much longer timescale, or occur after the initial burst.
- We search for the  $^{12}CO$  J(1→0) emission from 11 galaxies in our sample. Of these targets, eight are within Cl0024+17 and three within the foreground sub-group. Only two of eight galaxies are detected in the larger structure, while all three galaxies in the foreground group are detected at  $> 5\sigma$ . We find the average  $^{12}CO$ -derived gas mass of the sample (stacking detections and non-detections) to be  $\sim 1 \times 10^{10} M_\odot$ . A median star formation rate of  $\sim 13 M_\odot yr^{-1}$  suggests gas depletion timescales of  $\sim 1$  Gyr, which is  $\sim 0.25$  of the cluster crossing time. Our galaxies appear to be richer in star forming gas than typical field galaxies at the same redshift.
- We use FLAMES multi-IFU data to study the ionised gas dynamics of these cluster starbursts, as traced by H $\alpha$  emission, and after excluding AGN we find the majority of

the sample ( $\sim 90\%$ ) have dynamics that appear to be consistent with undisturbed, uniformly rotating disks. To quantify the ratio between rotation and pressure support we calculate  $v/\sigma_0$ . The average for our sample is  $v/\sigma_0 = 5 \pm 2$ , in line with spirals of a similar redshift, further demonstrating that these galaxies have only recently accreted from the field.

- We also measure the spin,  $\lambda_R$  (a proxy for specific angular momentum) and concentration,  $c$  of the cluster starbursts. The relation between  $\lambda_R$  and  $c$  provides a useful means to follow the morphological and dynamical evolution of these galaxies. We derive a median spin and concentration of  $\lambda_R = 0.83 \pm 0.06$  and  $c = 2.1 \pm 0.3$ , respectively. These values are consistent with typical field spirals. In order to evolve to S0s, these galaxies must double their concentration (through growth of the bulge) and decrease their angular momentum by a factor of  $\sim 1.5$ .

- Although limited by small numbers, galaxies in the sub-group do not show evidence of an accelerated evolution. The only difference between the “main” cluster and sub-group components is (potentially) in the molecular gas properties, where all three sub-group members are detected in  $^{12}CO$  but only two of eight galaxies are detected in the larger structure.

It appears that these dusty, star-forming galaxies must have only recently been accreted to the cluster, with their dynamics, morphologies and molecular gas consistent with star forming field galaxies. They show no evidence of having yet been significantly disrupted by the dense environment. We conclude that for these  $z \sim 0.4$  cluster galaxies to make the transition to S0s they must undergo a dynamical heating of the disk, and an increase in concentration. While ICM-related processes such as ram pressure stripping will truncate the gas disk, the full transformation from spiral to S0 is unlikely to be achieved by this process alone. Of the various available mechanisms, galaxy-galaxy encounters within the cluster seems most probable. Since  $\sim 90\%$  of our sample display disk-like dynamics, it seems that this must occur after the initial burst has been quenched, and without an associated starburst.

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## REFERENCES

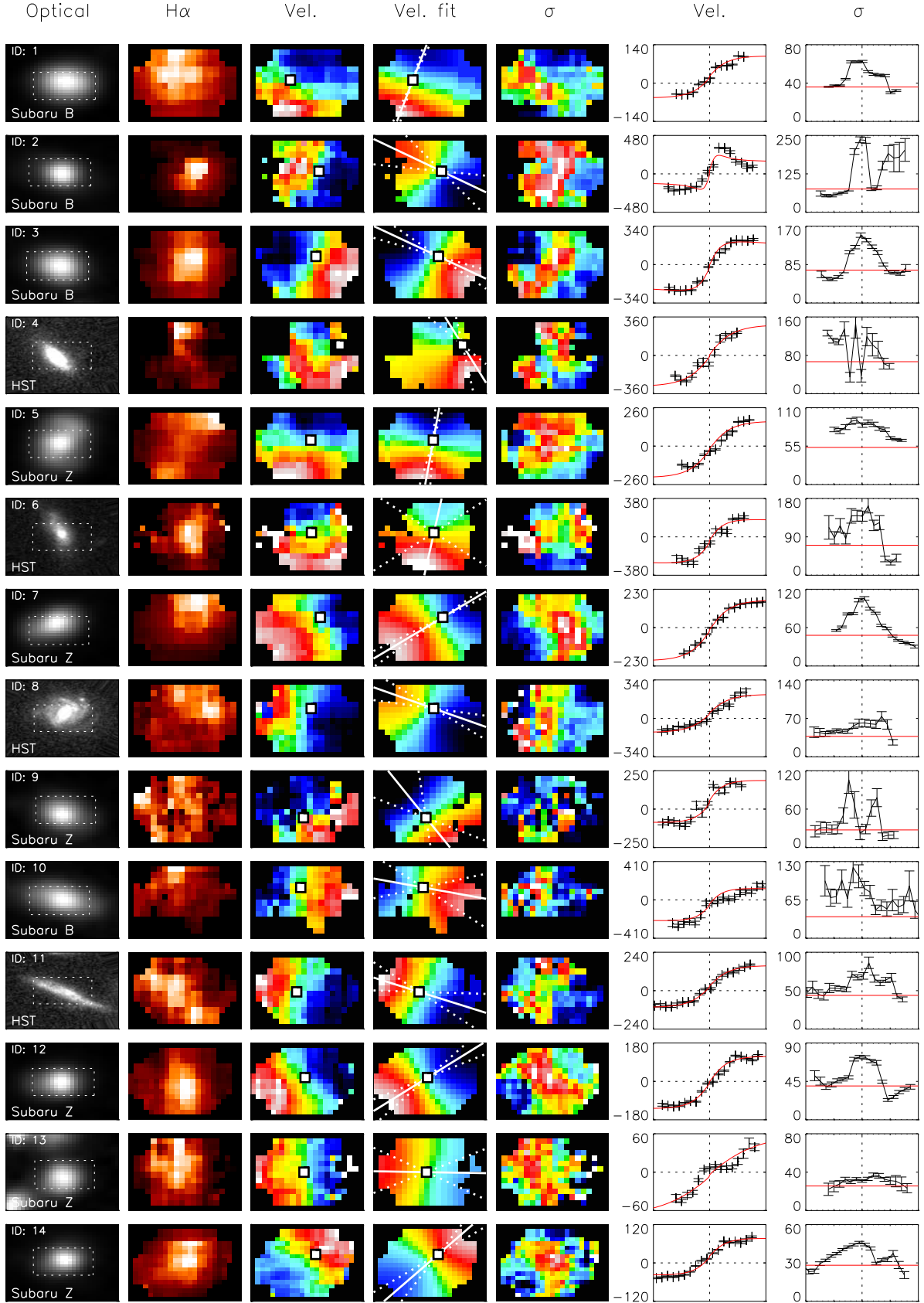
- Alberts S., et al., 2014, *MNRAS*, **437**, 437  
 Bamford S. P., et al., 2009, *MNRAS*, **393**, 1324  
 Bekki K., 2009, *MNRAS*, **399**, 2221  
 Bekki K., 2014, *MNRAS*, **438**, 444  
 Bekki K., Couch W. J., 2011, *MNRAS*, **415**, 1783



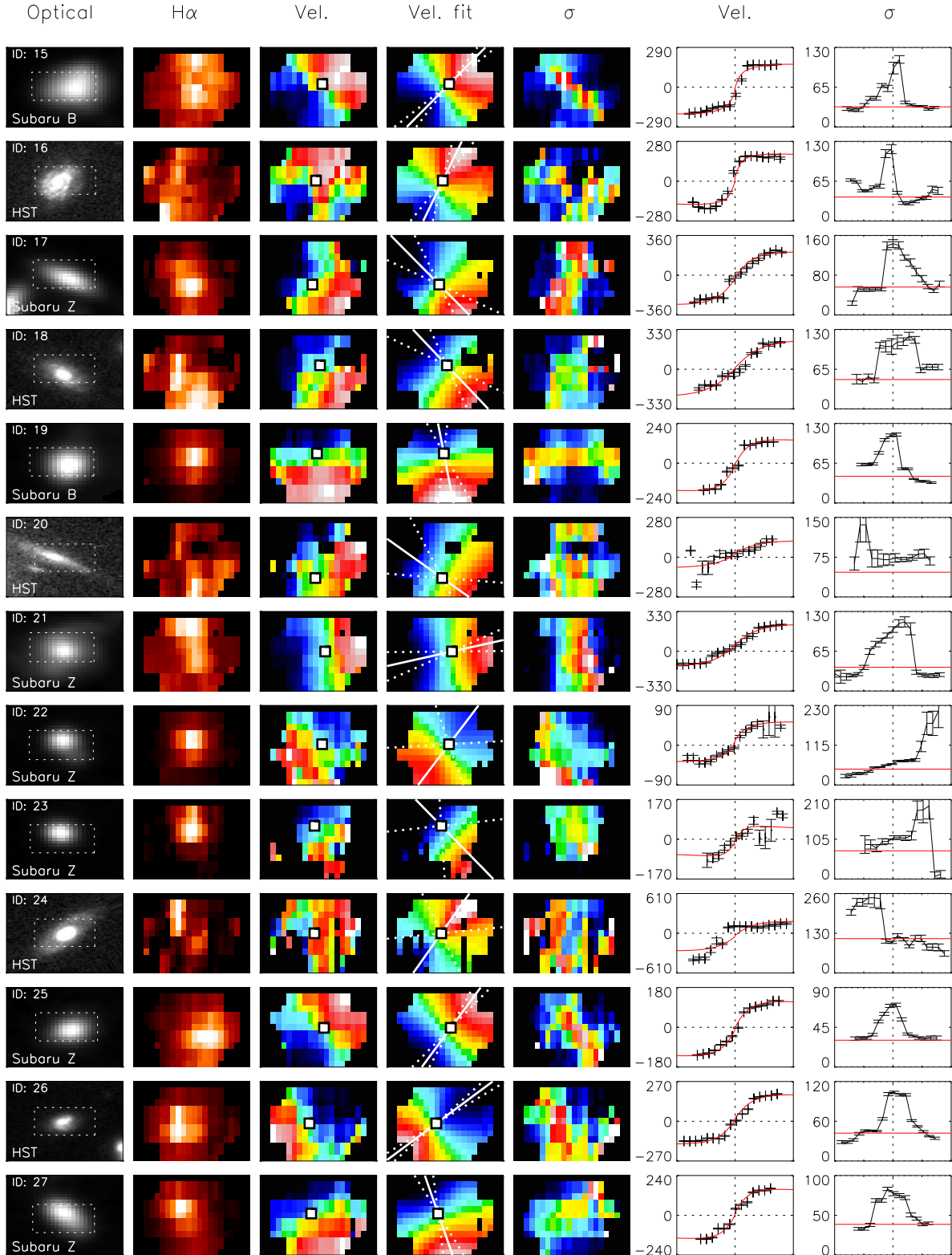
- Bellocchi E., Arribas S., Colina L., Miralles-Caballero D., 2013, *A&A*, **557**, A59
- Bialas D., Lisker T., Olczak C., Spurzem R., Kotulla R., 2015, *A&A*, **576**, A103
- Bolzonella M., Miralles J.-M., Pelló R., 2000, *A&A*, **363**, 476
- Boselli A., Gavazzi G., 2006, *PASP*, **118**, 517
- Boselli A., Gavazzi G., 2014, *A&ARv*, **22**, 74
- Bower R. G., Lucey J. R., Ellis R. S., 1992, *MNRAS*, **254**, 601
- Bruzual G., Charlot S., 2003, *MNRAS*, **344**, 1000
- Burstein D., Ho L. C., Huchra J. P., Macri L. M., 2005, *ApJ*, **621**, 246
- Butcher H., Oemler Jr. A., 1978, *ApJ*, **219**, 18
- Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, *ApJ*, **533**, 682
- Cappellari M., et al., 2011, *MNRAS*, **416**, 1680
- Chapin E. L., Hughes D. H., Aretxaga I., 2009, *MNRAS*, **393**, 653
- Chapman S. C., Helou G., Lewis G. F., Dale D. A., 2003, *ApJ*, **588**, 186
- Chary R., Elbaz D., 2001, *ApJ*, **556**, 562
- Christlein D., Zabludoff A. I., 2004, *ApJ*, **616**, 192
- Coia D., et al., 2005, *A&A*, **431**, 433
- Colina L., Arribas S., Monreal-Ibero A., 2005, *ApJ*, **621**, 725
- Combes F., García-Burillo S., Braine J., Schinnerer E., Walter F., Colina L., 2013, *A&A*, **550**, A41
- Comerford J. M., Meneghetti M., Bartelmann M., Schirmer M., 2006, *ApJ*, **642**, 39
- Cortesi A., et al., 2013, *MNRAS*, **432**, 1010
- Couch W. J., Sharples R. M., 1987, *MNRAS*, **229**, 423
- Courteau S., 1997, *AJ*, **114**, 2402
- Czoske O., Kneib J.-P., Soucaïl G., Bridges T. J., Mellier Y., Cuillandre J.-C., 2001, *A&A*, **372**, 391
- Czoske O., Moore B., Kneib J.-P., Soucaïl G., 2002, *A&A*, **386**, 31
- De Lucia G., Poggianti B. M., Halliday C., Milvang-Jensen B., Noll S., Smail I., Zaritsky D., 2009, *MNRAS*, **400**, 68
- Diaferio A., Geller M. J., Rines K. J., 2005, *ApJ*, **628**, L97
- Draine B. T., et al., 2007, *ApJ*, **663**, 866
- Dressler A., 1980, *ApJ*, **236**, 351
- Dressler A., et al., 1997, *ApJ*, **490**, 577
- Elbaz D., et al., 2007, *A&A*, **468**, 33
- Eliche-Moral M. C., González-García A. C., Aguerri J. A. L., Gallego J., Zamorano J., Balcells M., Prieto M., 2012, *A&A*, **547**, A48
- Emmellem E., et al., 2011, *MNRAS*, **414**, 888
- Fogarty L. M. R., et al., 2015, *MNRAS*, **454**, 2050
- Freeman K. C., 1970, *ApJ*, **160**, 811
- Fumagalli M., Fossati M., Hau G. K. T., Gavazzi G., Bower R., Sun M., Boselli A., 2014, *MNRAS*, **445**, 4335
- Gao Y., Solomon P. M., 2004, *ApJ*, **606**, 271
- Geach J. E., et al., 2006, *ApJ*, **649**, 661
- Geach J. E., Smail I., Moran S. M., Treu T., Ellis R. S., 2009, *ApJ*, **691**, 783
- Geach J. E., Smail I., Moran S. M., MacArthur L. A., Lagos C. d. P., Edge A. C., 2011, *ApJ*, **730**, L19
- Genzel R., et al., 2015, *ApJ*, **800**, 20
- Guilloteau S., Lucas R., 2000, in Mangum J. G., Radford S. J. E., eds, *Astronomical Society of the Pacific Conference Series Vol. 217, Imaging at Radio through Submillimeter Wavelengths*. p. 299
- Harrison C. M., et al., 2016, *MNRAS*, **456**, 1195
- Hoekstra H., 2007, *MNRAS*, **379**, 317
- Hogg D. W., Masjedi M., Berlind A. A., Blanton M. R., Quintero A. D., Brinkmann J., 2006, *ApJ*, **650**, 763
- Hopkins P. F., Hernquist L., Cox T. J., Di Matteo T., Robertson B., Springel V., 2006, *ApJS*, **163**, 1
- Hung C.-L., Hayward C. C., Smith H. A., Ashby M. L. N., Lanz L., Martínez-Galarza J. R., Sanders D. B., Zezas A., 2016, *ApJ*, **816**, 99
- Ivison R. J., et al., 2013, *ApJ*, **772**, 137
- Johnston E. J., Aragón-Salamanca A., Merrifield M. R., 2014, *MNRAS*, **441**, 333
- Karim A., et al., 2011, *ApJ*, **730**, 61
- Kassin S. A., et al., 2012, *ApJ*, **758**, 106
- Kenney J. D. P., van Gorkom J. H., Vollmer B., 2004, *AJ*, **127**, 3361
- Kennicutt Jr. R. C., 1998, *ApJ*, **498**, 541
- Kewley L. J., Dopita M. A., Leitherer C., Davé R., Yuan T., Allen M., Groves B., Sutherland R., 2013, *ApJ*, **774**, 100
- Kneib J.-P., et al., 2003, *ApJ*, **598**, 804
- Kocevski D. D., et al., 2011, *ApJ*, **736**, 38
- Kodama T., Smail I., 2001, *MNRAS*, **326**, 637
- Kodama T., Balogh M. L., Smail I., Bower R. G., Nakata F., 2004, *MNRAS*, **354**, 1103
- Koyama Y., et al., 2008, *MNRAS*, **391**, 1758
- Leitherer C., et al., 2011, *Starburst99: Synthesis Models for Galaxies with Active Star Formation*, Astrophysics Source Code Library (ascl:1104.003)
- Lewis I., et al., 2002, *MNRAS*, **334**, 673
- Lutz D., et al., 2011, *A&A*, **532**, A90
- Ma C.-J., et al., 2015, *ApJ*, **806**, 257
- Marcillac D., Rigby J. R., Rieke G. H., Kelly D. M., 2007, *ApJ*, **654**, 825
- Mastropietro C., Moore B., Mayer L., Debattista V. P., Piffaretti R., Stadel J., 2005, *MNRAS*, **364**, 607
- McCarthy I. G., Frenk C. S., Font A. S., Lacey C. G., Bower R. G., Mitchell N. L., Balogh M. L., Theuns T., 2008, *MNRAS*, **383**, 593
- Merluzzi P., et al., 2013, *MNRAS*, **429**, 1747
- Mihos J. C., Bothun G. D., 1998, *ApJ*, **500**, 619
- Moran S. M., Ellis R. S., Treu T., Smail I., Dressler A., Coil A. L., Smith G. P., 2005, *ApJ*, **634**, 977
- Moran S. M., Miller N., Treu T., Ellis R. S., Smith G. P., 2007, *ApJ*, **659**, 1138
- Muzzin A., et al., 2013, *ApJ*, **777**, 18
- Noeske K. G., et al., 2007, *ApJ*, **660**, L43
- Oemler Jr. A., Dressler A., Kelson D., Rigby J., Poggianti B. M., Fritz J., Morrison G., Smail I., 2009, *ApJ*, **693**, 152
- Oliver S. J., et al., 2012, *MNRAS*, **424**, 1614
- Ota N., Pointecouteau E., Hattori M., Mitsuda K., 2004, *ApJ*, **601**, 120
- Peng Y., Maiolino R., Cochrane R., 2015, *Nature*, **521**, 192
- Poggianti B. M., Wu H., 2000, *ApJ*, **529**, 157
- Poggianti B. M., Smail I., Dressler A., Couch W. J., Barger A. J., Butcher H., Ellis R. S., Oemler A. J., 1999, *ApJ*, **518**, 576
- Poggianti B. M., et al., 2009, *ApJ*, **693**, 112
- Pracy M. B., Couch W. J., Blake C., Bekki K., Harrison C., Colless M., Kuntschner H., de Propriis R., 2005, *MNRAS*, **359**, 1421
- Puech M., Hammer F., Lehnert M. D., Flores H., 2007, *A&A*, **466**, 83
- Querejeta M., et al., 2015, *A&A*, **579**, L2
- Quilis V., Moore B., Bower R., 2000, *Science*, **288**, 1617
- Rawle T. D., et al., 2012, *ApJ*, **756**, 106
- Rieke G. H., Alonso-Herrero A., Weiner B. J., Pérez-González P. G., Blaylock M., Donley J. L., Marcillac D., 2009, *ApJ*, **692**, 556
- Rodríguez Del Pino B., Bamford S. P., Aragón-Salamanca A., Milvang-Jensen B., Merrifield M. R., Balcells M., 2014, *MNRAS*, **438**, 1038
- Sales L. V., et al., 2015, *MNRAS*, **447**, L6
- Sandage A., 2005, *ARA&A*, **43**, 581
- Simien F., de Vaucouleurs G., 1986, *ApJ*, **302**, 564
- Smail I., et al., 2014, *ApJ*, **782**, 19
- Smith G. P., Treu T., Ellis R. S., Moran S. M., Dressler A., 2005, *ApJ*, **620**, 78
- Smith R., Davies J. I., Nelson A. H., 2010, *MNRAS*, **405**, 1723

- Solomon P. M., Vanden Bout P. A., 2005, [ARA&A](#), **43**, 677
- Soucail G., Ota N., Böhringer H., Czoske O., Hattori M., Mellier Y., 2000, [A&A](#), **355**, 433
- Stott J. P., et al., 2016, [MNRAS](#), **457**, 1888
- Swinbank A. M., et al., 2007, [MNRAS](#), **379**, 1343
- Swinbank A. M., et al., 2014, [MNRAS](#), **438**, 1267
- Symeonidis M., et al., 2013, [MNRAS](#), **431**, 2317
- Tacconi L. J., et al., 2010, [Nature](#), **463**, 781
- Tran K.-V. H., Franx M., Illingworth G. D., van Dokkum P., Kelson D. D., Blakeslee J. P., Postman M., 2007, [ApJ](#), **661**, 750
- Tran K.-V. H., et al., 2010, [ApJ](#), **719**, L126
- Treu T., Ellis R. S., Kneib J.-P., Dressler A., Smail I., Czoske O., Oemler A., Natarajan P., 2003, [ApJ](#), **591**, 53
- Umetsu K., Medezinski E., Broadhurst T., Zitrin A., Okabe N., Hsieh B.-C., Molnar S. M., 2010, [ApJ](#), **714**, 1470
- Vulcani B., et al., 2011, [MNRAS](#), **412**, 246
- Wisnioski E., et al., 2015, [ApJ](#), **799**, 209
- Wuyts S., et al., 2013, [ApJ](#), **779**, 135
- Zhang Y.-Y., Böhringer H., Mellier Y., Soucail G., Forman W., 2005, [A&A](#), **429**, 85
- Zitrin A., et al., 2009, [MNRAS](#), **396**, 1985

## APPENDIX A: ADDITIONAL MATERIAL

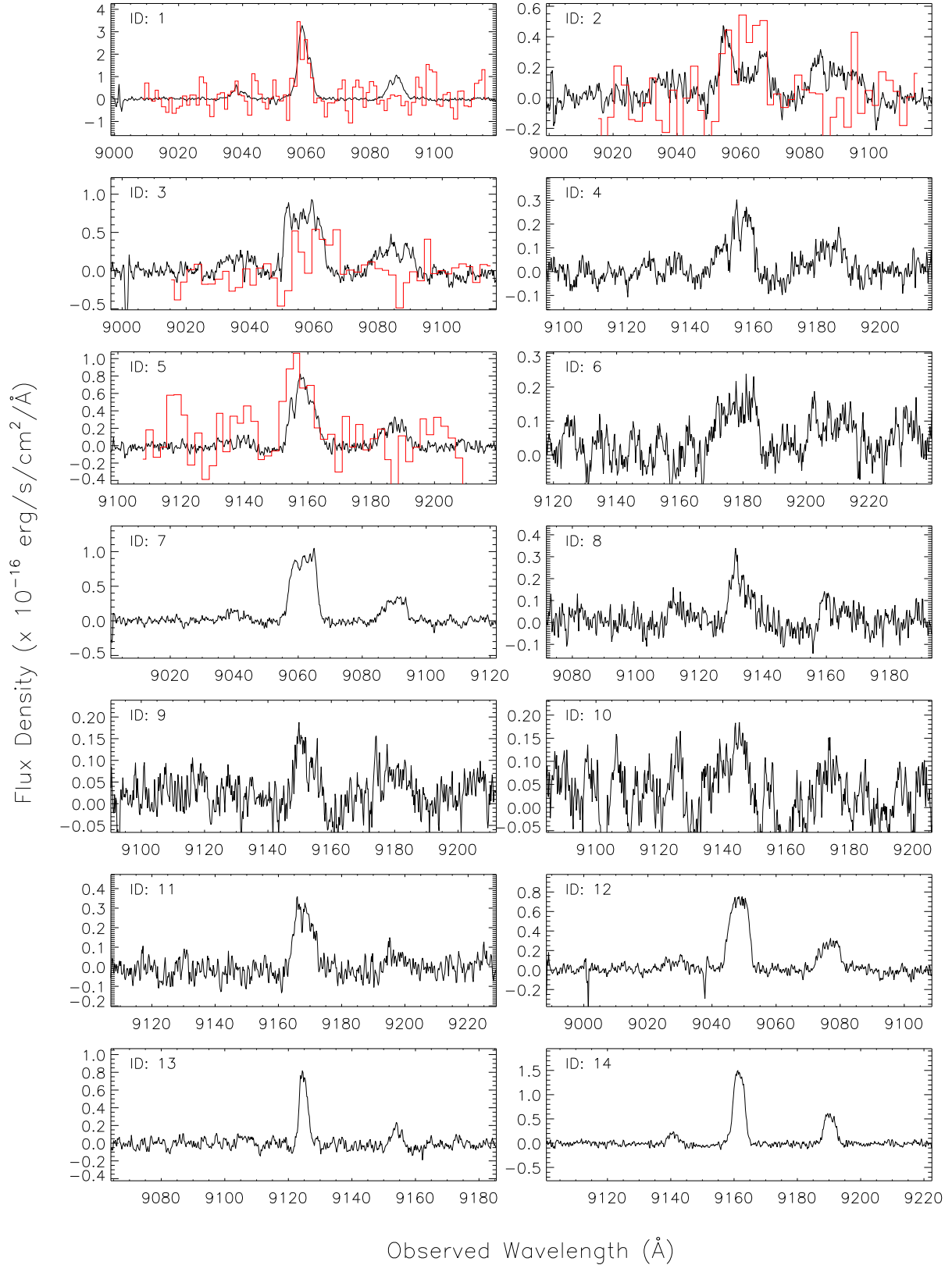


**Figure A1.** Broad-band image, H $\alpha$  morphology and dynamical maps for all 27 galaxies in our cluster starburst sample. Left to right we show: Subaru or *HST* broad-band image (dashed lines illustrate the FLAMES field of view), H $\alpha$  intensity map, velocity field, best-fit model velocity field, dispersion map, and the rotation curve (red line is the model fit) and line of sight dispersion profile (red line is  $\sigma_0$ ) extracted along the primary axis. Axes are in units of  $\text{km s}^{-1}$ . The solid line on the velocity field shows the position angle, with dashed lines illustrating the  $1\sigma$  uncertainty. Square points show the model dynamical centre.

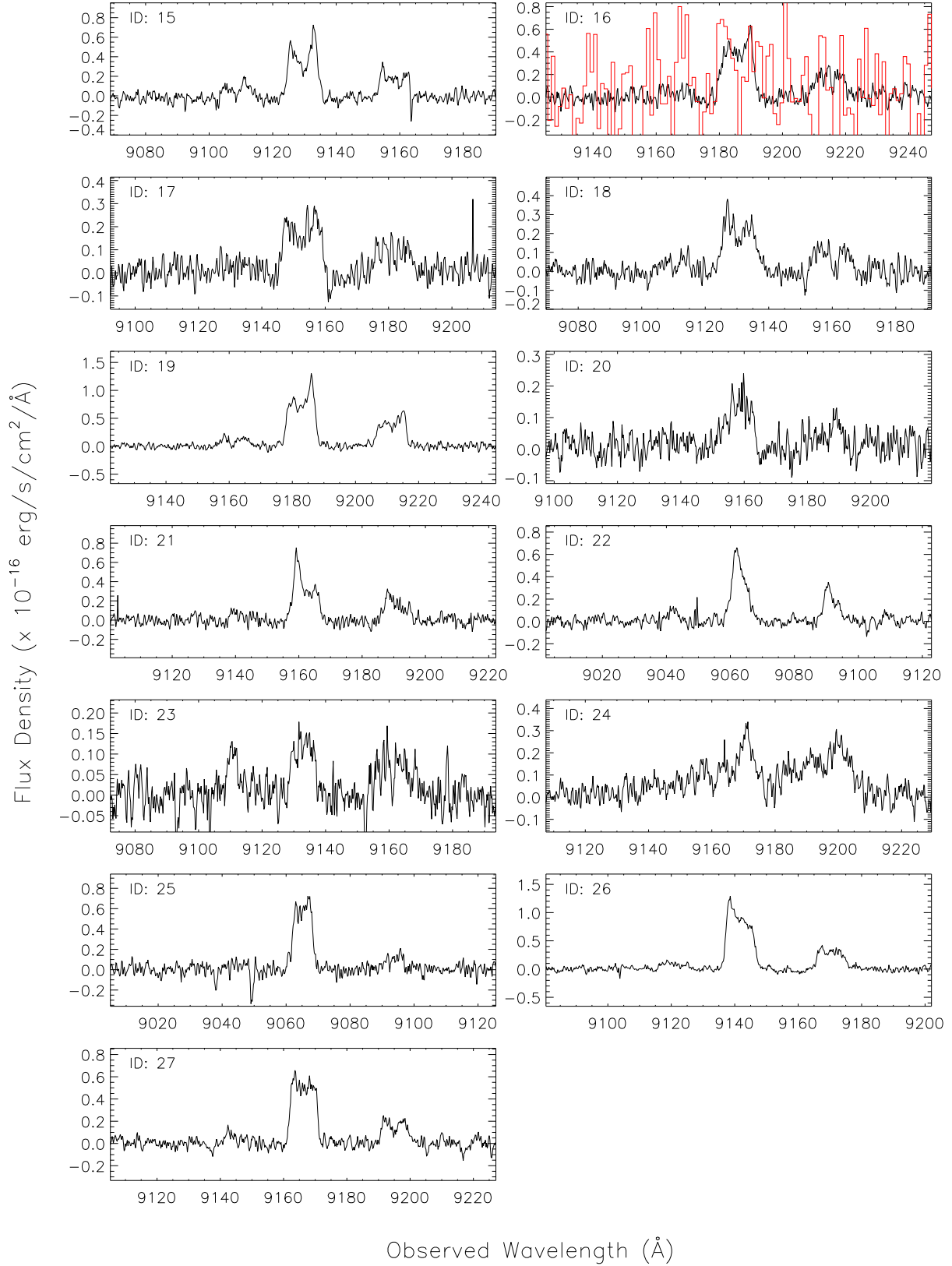


**Figure A1** – *continued* Broad-band image, H $\alpha$  morphology and dynamical maps for all 27 galaxies in our cluster starburst sample. Left to right we show: Subaru or *HST* broad-band image (dashed lines illustrate the FLAMES field of view), H $\alpha$  intensity map, velocity field, best-fit model velocity field, dispersion map, and the rotation curve (red line is the model fit) and line of sight dispersion profile (red line is  $\sigma_0$ ) extracted along the primary axis. Axes are in units of km s $^{-1}$ . The solid line on the velocity field shows the position angle, with dashed lines illustrating the  $1\sigma$  uncertainty. Square points show the model dynamical centre.





**Figure A2.** Integrated spectra around redshifted H $\alpha$  and [NII] (6548,6583) emission lines. Parameters such as redshifts and [NII]/H $\alpha$  ratios are listed in Table A1. Many galaxies show split emission line profiles, indicative of high velocity rotation and possibly strong obscuration towards the dynamical centre. We suspect the dynamics of galaxy IDs 23 and 24 may be affected by an AGN. For IDs 1, 2, 3, 5 and 16 we overlay the CO spectra in red, and find that the velocity centroid and line width are well matched to the H $\alpha$  emission.



**Figure A2** – *continued* Integrated spectra around redshifted  $\text{H}\alpha$  and  $[\text{NII}]$  (6548,6583) emission lines. Parameters such as redshifts and  $[\text{NII}]/\text{H}\alpha$  ratios are listed in Table A1. Many galaxies show split emission line profiles, indicative of high velocity rotation and possibly strong obscuration towards the dynamical centre. We suspect the dynamics of galaxy IDs 23 and 24 may be affected by an AGN. For IDs 1, 2, 3, 5 and 16 we overlay the CO spectra in red, and find that the velocity centroid and line width are well matched to the  $\text{H}\alpha$  emission.

**Table A1.** Observed Properties

ID	RA (J2000)	Dec (J2000)	$z_{\text{H}\alpha}$	$S_{24}$ ( $\mu\text{Jy}$ )	$f_{\text{H}\alpha}$ ( $10^{-16} \text{ erg s}^{-1}$ )	$\log([\text{NII}]/\text{H}\alpha)$	$B$ (AB)	$R$ (AB)	Sub-group
1	6.59050	17.3240	0.3804	$950 \pm 40$	$14.0 \pm 0.2$	$-0.48 \pm 0.01$	21.63	19.80	y
2	6.81270	17.2131	0.3804	$950 \pm 50$	$4.2 \pm 0.2$	$-0.11 \pm 0.03$	22.53	19.98	y
3	6.71870	17.2332	0.3800	$830 \pm 20$	$10.6 \pm 0.3$	$-0.37 \pm 0.02$	22.31	20.10	y
4	6.53730	17.2530	0.3950	$770 \pm 30$	$2.2 \pm 0.1$	$-0.28 \pm 0.04$	23.88	21.32	n
5	6.76520	17.1912	0.3955	$706 \pm 50$	$6.1 \pm 0.1$	$-0.44 \pm 0.02$	22.42	20.45	n
6	6.60820	17.2976	0.3986	$440 \pm 20$	$1.5 \pm 0.1$	$-0.24 \pm 0.06$	24.03	21.34	n
7	6.75580	17.3446	0.3808	$350 \pm 30$	$8.5 \pm 0.2$	$-0.52 \pm 0.01$	22.16	20.48	y
8	6.66020	17.1254	0.3916	$201 \pm 5$	$1.50 \pm 0.08$	$-0.38 \pm 0.06$	22.98	20.76	n
9	6.55990	17.2222	0.3944	$< 150$	$0.83 \pm 0.07$	$-0.29 \pm 0.07$	23.36	21.15	n
10	6.66080	17.2539	0.3935	$< 150$	$0.72 \pm 0.08$	$-0.22 \pm 0.07$	23.28	20.95	n
11	6.64020	17.2055	0.3970	$350 \pm 50$	$2.30 \pm 0.08$	$-0.67 \pm 0.06$	23.57	21.71	n
12	6.58330	17.0687	0.3788	$670 \pm 40$	$5.27 \pm 0.09$	$-0.42 \pm 0.01$	22.86	21.00	y
13	6.60210	17.1917	0.3904	$290 \pm 30$	$2.51 \pm 0.06$	$-0.58 \pm 0.05$	23.09	21.43	n
14	6.65550	17.0162	0.3960	$600 \pm 30$	$6.44 \pm 0.08$	$-0.39 \pm 0.01$	22.40	20.52	n
15	6.67300	17.1838	0.3911	$311 \pm 5$	$4.7 \pm 0.2$	$-0.30 \pm 0.04$	22.26	20.10	n
16	6.63200	17.1545	0.3997	$227 \pm 4$	$5.1 \pm 0.2$	$-0.35 \pm 0.03$	22.86	20.80	n
17	6.66270	17.1672	0.3947	$214 \pm 4$	$2.5 \pm 0.1$	$-0.36 \pm 0.05$	23.91	21.42	n
18	6.63970	17.1566	0.3913	$179 \pm 4$	$3.1 \pm 0.1$	$-0.30 \pm 0.03$	23.01	20.80	n
19	6.69910	17.1619	0.3993	$307 \pm 7$	$8.9 \pm 0.2$	$-0.27 \pm 0.02$	22.13	20.17	n
20	6.52550	17.2054	0.3955	$300 \pm 50$	$1.33 \pm 0.08$	$-0.44 \pm 0.06$	23.92	21.71	n
21	6.74790	17.0626	0.3960	$280 \pm 30$	$3.8 \pm 0.1$	$-0.34 \pm 0.03$	22.53	20.51	n
22	6.63740	17.2581	0.3809	$345 \pm 30$	$3.05 \pm 0.06$	$-0.36 \pm 0.02$	23.35	21.29	y
23	6.72500	17.2343	0.3916	$300 \pm 30$	$1.11 \pm 0.07$	$-0.02 \pm 0.04$	23.79	21.03	n
24	6.58090	17.1174	0.3970	$340 \pm 30$	$3.1 \pm 0.2$	$0.04 \pm 0.03$	23.46	20.69	n
25	6.64270	17.1011	0.3813	$260 \pm 30$	$4.5 \pm 0.1$	$-0.69 \pm 0.04$	22.89	21.26	y
26	6.60710	17.2015	0.3929	$340 \pm 40$	$9.4 \pm 0.2$	$-0.46 \pm 0.03$	22.30	20.53	n
27	6.65550	17.1768	0.3967	$158 \pm 5$	$5.2 \pm 0.1$	$-0.49 \pm 0.03$	23.11	21.21	n

NOTES: The  $B$ - and  $R$ - band magnitudes were extracted at the same aperture, in order to derive the colours plotted in Fig. 2. In the final column we specify whether each galaxy is a member of the “main” cluster (n) or foreground sub-group (y), as discussed in §2.1.

**Table A2.** Derived Properties – Galaxy Integrated

ID	$L_{\text{IR}}$ ( $10^{11} L_{\odot}$ )	$\text{SFR}_{\text{IR}}$ ( $M_{\odot} \text{ yr}^{-1}$ )	$T_{\text{d}}$ (K)	$M_{\text{K}}$ (AB)	$M_{\star}$ ( $10^{10} M_{\odot}$ )	$L'_{\text{CO}}$ ( $10^9 \text{ K km s}^{-1} \text{ pc}^2$ )	$M_{\text{gas}}$ ( $10^{10} M_{\odot}$ )
1	$2.5^{+2}_{-3}$	$26^{+3}_{-13}$	$29 \pm 11$	-22.8	$5.6 \pm 2.5$	$6.8 \pm 0.6$	$3.1 \pm 0.3$
2	$0.5^{+0.9}_{-0.3} *$	$11^{+2}_{-2}$	$> 20$	-23.4	$9.6 \pm 2.9$	$2.6 \pm 0.3$	$1.2 \pm 0.3$
3	$1.4^{+1.5}_{-1.2}$	$14^{+2}_{-1}$	$25 \pm 12$	-23.0	$6.8 \pm 2.0$	$6.4 \pm 0.5$	$2.9 \pm 0.2$
4	$1.3^{+2}_{-1}$	$13^{+9}_{-2}$	$> 18$	-22.5	$4.1 \pm 1.2$	$< 3.9$	$< 1.8$
5	$0.6^{+0.8}_{-0.4}$	$6^{+3}_{-1}$	$> 23$	-22.2	$3.0 \pm 1.4$	$4.3 \pm 0.6$	$2.0 \pm 0.3$
6	$0.5^{+0.9}_{-0.3} *$	$10^{+2}_{-2}$	$31 \pm 22$	-22.4	$3.7 \pm 1.1$	...	...
7	$0.9^{+1.0}_{-0.8}$	$10^{+1}_{-2}$	$> 11$	-21.8	$2.1 \pm 0.8$	...	...
8	$0.8^{+0.9}_{-0.7}$	$8^{+1}_{-1}$	$24 \pm 2$	-22.2	$3.2 \pm 1.0$	...	...
9	$0.8^{+0.9}_{-0.7}$	$8^{+1}_{-1}$	$> 11$	-21.7	$1.9 \pm 0.6$	...	...
10	$0.6^{+0.7}_{-0.5}$	$6^{+1}_{-1}$	$> 11$	-22.1	$2.9 \pm 0.9$	...	...
11	$1.6^{+3}_{-1}$	$17^{+13}_{-3}$	$25 \pm 1$	-21.3	$1.4 \pm 0.5$	...	...
12	$1.0^{+1}_{-0.9}$	$11^{+1}_{-2}$	$> 15$	-21.9	$2.5 \pm 0.9$	...	...
13	$0.5^{+1}_{-0.4} *$	$3^{+1}_{-1}$	$24 \pm 2$	-20.9	$1.0 \pm 0.4$	$< 4.3$	$< 2.0$
14	$0.5^{+1}_{-0.4} *$	$17^{+3}_{-3}$	$> 11$	-22.1	$2.8 \pm 1.1$	...	...
15	$0.6^{+2}_{-0.4} *$	$9^{+2}_{-2}$	$28 \pm 1$	-22.6	$4.6 \pm 2.1$	...	...
16	$0.5^{+1}_{-0.4} *$	$11^{+2}_{-2}$	$26 \pm 1$	-22.0	$2.6 \pm 1.2$	$2.2 \pm 0.7$	$1.0 \pm 0.3$
17	$0.5^{+2}_{-0.1} *$	$12^{+2}_{-2}$	$26 \pm 1$	-22.0	$2.5 \pm 1.2$	$< 4.4$	$< 2.0$
18	$0.5^{+0.9}_{-0.3} *$	$5^{+1}_{-1}$	$27 \pm 2$	-22.1	$2.8 \pm 0.9$	$< 4.1$	$< 1.9$
19	$1.2^{+1}_{-1}$	$13^{+1}_{-3}$	$26 \pm 2$	-22.7	$5.0 \pm 1.8$	...	...
20	$0.9^{+5}_{-1}$	$20^{+31}_{-9}$	$> 11$	-21.7	$2.1 \pm 0.9$	...	...
21	$0.6^{+0.7}_{-0.5}$	$6^{+1}_{-1}$	$> 11$	-22.3	$3.4 \pm 1.7$	...	...
22	$1.0^{+4}_{-0.9}$	$11^{+35}_{-1}$	$> 11$	-21.5	$1.7 \pm 0.8$	...	...
23	$1.3^{+2}_{-1}$	$14^{+7}_{-4}$	$> 11$	-21.7	$2.0 \pm 0.6$	...	...
24	$1.3^{+2}_{-0.6}$	$13^{+7}_{-6}$	$> 11$	-22.6	$4.5 \pm 1.4$	...	...
25	$0.5^{+0.5}_{-0.5} *$	$6^{+2}_{-2}$	$> 11$	-21.0	$1.1 \pm 0.4$	...	...
26	$0.6^{+0.6}_{-0.6}$	$6^{+1}_{-2}$	$30 \pm 2$	-22.1	$2.8 \pm 1.3$	$< 4.9$	$< 2.3$
27	$0.5^{+0.9}_{-0.4} *$	$8^{+2}_{-2}$	$27 \pm 2$	-21.3	$1.3 \pm 0.6$	$< 4.6$	$< 2.1$

NOTES:  $L_{\text{IR}}$  is the bolometric luminosity of the best-fit template SED fit to *Herschel* far-infrared photometry. Star formation rates with an adjacent \* were derived by applying the average  $\text{SFR}_{\text{H}\alpha}/\text{SFR}_{\text{IR}}$  correction factor, since these galaxies have detections in only  $\leq 1$  bands. The characteristic dust temperatures,  $T_{\text{d}}$ , come from a single-temperature blackbody fit, assuming an emissivity index of  $\beta = 1.8$ . Stellar mass estimates were calculated using a constant mass to light ratio of  $M_{\odot}/L_{\odot}^K = 0.35$ .  $L'_{\text{CO}}$  and  $M_{\text{gas}}$  are derived from a Gaussian fit to IRAM / NOEMA CO(1-0) spectra (see §3.4), for which we assume a CO to  $\text{H}_2$  conversion factor of  $\alpha = 4.6$ .



**Table A3.** Derived Properties – Ionised Gas Dynamics

ID	$\sigma_0$ (km s <sup>-1</sup> )	$r_{1/2}$ (kpc)	$v_{2.2}$ (km s <sup>-1</sup> )	$v_{2.2}/\sigma_0$	$\lambda_R$	Class
1	36 ± 5	6.0 ± 0.4	120 ± 10	3.4 ± 0.5	0.71 ± 0.02	R
2	76 ± 8	6.2 ± 0.5	210 ± 40	2.8 ± 0.7	0.74 ± 0.01	R
3	72 ± 5	5.5 ± 0.4	270 ± 20	3.7 ± 0.5	0.77 ± 0.01	R
4	67 ± 5	8.5 ± 0.4	300 ± 20	4.4 ± 0.6	0.82 ± 0.01	I
5	53 ± 5	8.5 ± 0.5	230 ± 10	4.3 ± 0.5	0.82 ± 0.01	R
6	70 ± 9	9.6 ± 0.5	310 ± 20	4 ± 2	0.83 ± 0.01	R
7	48 ± 5	6.0 ± 0.5	280 ± 30	5.7 ± 0.9	0.83 ± 0.02	R
8	37 ± 5	5.8 ± 0.5	260 ± 50	7 ± 2	0.90 ± 0.02	R
9	28 ± 7	5.9 ± 0.4	210 ± 60	8 ± 2	0.85 ± 0.03	R
10	37 ± 7	9.5 ± 0.4	190 ± 20	5.3 ± 0.8	0.87 ± 0.01	R
11	44 ± 5	9.8 ± 0.5	140 ± 10	3.2 ± 0.5	0.83 ± 0.01	R
12	40 ± 5	5.0 ± 0.4	250 ± 50	6 ± 2	0.82 ± 0.07	R
13	26 ± 5	5.4 ± 0.6	130 ± 40	5 ± 2	0.72 ± 0.02	R
14	28 ± 5	6.9 ± 0.2	100 ± 10	3.4 ± 0.6	0.74 ± 0.03	R
15	33 ± 5	6.0 ± 0.4	300 ± 20	8 ± 1	0.90 ± 0.02	R
16	40 ± 4	5.7 ± 0.4	200 ± 10	5.0 ± 0.7	0.77 ± 0.04	R
17	57 ± 7	6.8 ± 0.8	290 ± 30	5.1 ± 0.8	0.86 ± 0.01	R
18	48 ± 5	6.0 ± 0.6	290 ± 30	6 ± 1	0.86 ± 0.05	R
19	44 ± 4	4.2 ± 0.3	220 ± 40	5 ± 1	0.79 ± 0.03	R
20	47 ± 6	8.8 ± 0.7	130 ± 30	2.8 ± 0.7	0.86 ± 0.01	I
21	40 ± 4	9.7 ± 0.4	230 ± 20	5.9 ± 0.8	0.76 ± 0.03	R
22	46 ± 5	5.2 ± 0.5	150 ± 20	3 ± 3	0.69 ± 0.02	I
23	75 ± 6	4.0 ± 0.4	90 ± 30	1.2 ± 0.4	0.47 ± 0.01	I
24	112 ± 7	8.0 ± 0.3	230 ± 20	2.0 ± 0.3	0.47 ± 0.03	I
25	30 ± 5	6.0 ± 0.4	220 ± 20	7 ± 1	0.92 ± 0.05	R
26	42 ± 4	3.7 ± 0.5	190 ± 10	4.5 ± 0.5	0.75 ± 0.06	R
27	38 ± 5	5.8 ± 0.4	200 ± 30	5.2 ± 0.8	0.86 ± 0.04	R

NOTES: To estimate the intrinsic velocity dispersion,  $\sigma_0$ , we correct the two-dimensional  $\sigma$  map for beam smearing and instrumental broadening, then take a pixel-by-pixel mean which is inverse weighted by the error. The rotational support,  $v/\sigma_0$ , is calculated using the value of the rotation curve at  $2.2 \times r_{1/2}$  ( $v_{2.2}$  and  $r_{2.2}$  respectively), corrected for the inclination of the disk. The spin parameter,  $\lambda_R$ , is calculated using all pixels within the half light radius (see §4.3). The final column describes the dynamical class we assign, taking into account the two-dimensional dynamical maps, optical morphology, rotation curve and line of sight velocity dispersion profile – ‘R’ if the galaxy resembles an undisturbed, rotating disk, and ‘I’ if the galaxy shows some sign of irregular kinematics or merger activity.

We note that IDs 23 and 24 likely have an AGN which is disturbing the gas dynamics.