

Hubble Space Telescope H α imaging of star-forming galaxies at $z \simeq 1 - 1.5$: evolution in the size and luminosity of giant HII regions

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ABSTRACT

We present *HST*/WFC3 narrowband imaging of the H α emission in a sample of eight gravitationally-lensed galaxies at $z = 1 - 1.5$. The magnification caused by the foreground clusters enables us to obtain a median source plane spatial resolution of 360pc, as well as providing magnifications in flux ranging from $\sim 10\times$ to $\sim 50\times$. This enables us to identify resolved star-forming HII regions at this epoch and therefore study their H α luminosity distributions for comparisons with equivalent samples at $z \sim 2$ and in the local Universe. We find evolution in the both luminosity and surface brightness of HII regions with redshift. The distribution of clump properties can be quantified with an HII region luminosity function, which can be fit by a power law with an exponential break at some cut-off, and we find that the cut-off evolves with redshift. We therefore conclude that ‘clumpy’ galaxies are seen at high redshift because of the evolution of the cut-off mass; the galaxies themselves follow similar scaling relations to those at $z = 0$, but their HII regions are larger and brighter and thus appear as clumps which dominate the morphology of the galaxy. A simple theoretical argument based on gas collapsing on scales of the Jeans mass in a marginally unstable disk shows that the clumpy morphologies of high- z galaxies are driven by the competing effects of higher gas fractions causing perturbations on larger scales, partially compensated by higher epicyclic frequencies which stabilise the disk.

Key words: galaxies:high-redshift – galaxies:star formation

1 INTRODUCTION

Observations of star-forming galaxies at high- z have shown that a significant fraction of the population have turbulent, clumpy, rotating disks with clump masses of $\sim 10^{8-9}M_{\odot}$, a factor of $\sim 100\times$ the typical Giant Molecular Cloud (GMC) locally (e.g. Cowie et al. 1995; Elmegreen et al. 2004; Elmegreen & Elmegreen 2005; Förster Schreiber et al. 2009; Elmegreen et al. 2009). The clumps are thought to form from gravitational instabilities in gas-rich disks (Elmegreen et al. 2007, 2009; Genzel et al. 2008; Bournaud et al. 2010).

Some recent numerical simulations have suggested that

the majority of massive, high- z galaxies accrete their gas via ‘cold flows,’ in which the gas is accreted smoothly along filaments. These cold flows are less disruptive than a major merger, and hence offer a route to maintain marginally stable disks (Toomre parameter $Q \sim 1$) without disrupting the structure and dynamics. Cold-flow accretion is expected to be a dominant mode of mass assembly above $z \simeq 1$, and thus accounts for the ubiquity of large clumps at high redshift (e.g. Bournaud & Elmegreen 2009; Bournaud et al. 2011; Dekel et al. 2009).

In this picture, the clumps are considered to be transient features, forming in marginally unstable disks at high- z and fed by smooth accretion of gas onto the galaxy. Clumpy galaxies therefore represent a phase in the evolution of present-day spiral disks.

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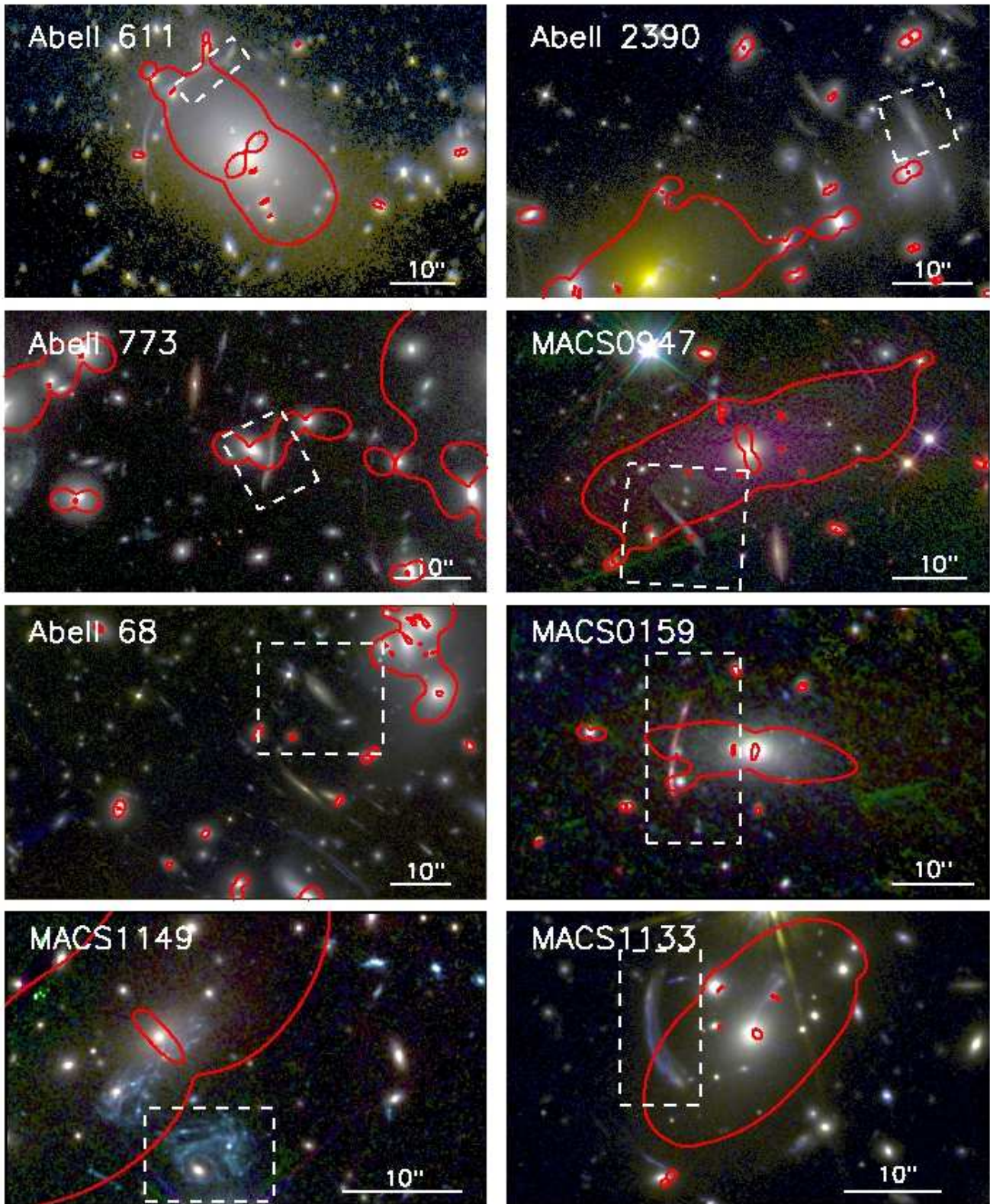


Figure 1. HST/ACS and WFC3 three-colour images of the observed clusters with the critical line at the redshift of the target arc overlaid, showing the positions of the target arcs. The arcs are contained within the white dashed boxes which denote the regions extracted in Figure 2.

There is a need to test the internal physical properties of the interstellar medium (ISM) observationally, to determine whether the clumps are scaled-up analogues of local HII regions or represent a different ‘mode’ of star formation, and whether they can explain the strong evolution of star formation rate density with redshift. However, sufficient spatial resolution is required to resolve the ISM on the scales of star-forming regions. Even with the use of adaptive optics, spatially resolved studies of high-redshift galaxies to date have been limited to a resolution of ~ 1.5 kpc (e.g. Genzel et al. 2006; Förster Schreiber et al. 2009); using the *Hubble Space Telescope* (*HST*), only the largest starburst complexes can be resolved, on scales of ~ 1 kpc (Elmegreen et al. 2007). On these scales, it is possible to probe the dynamics of galaxies on large scales, and Genzel et al. (2011) found evidence that $Q < 1$ in the regions of galaxies where clumps are found, lending observational support to the theory that the clumps form from internal gravitational instabilities. In order to study the clumps in detail, we need to resolve high-redshift disks on the scales of individual star-forming regions; in the local universe, this is ~ 100 pc.

The required spatial resolution can currently only be achieved by exploiting gravitational lensing. By targeting galaxies that lie behind foreground cluster lenses, it is possible to benefit from linear magnification factors (along one direction) of up to $50\times$ (e.g. Swinbank et al. 2007, 2009; Jones et al. 2010), and to isolate HII regions of order ~ 100 pc out to $z \sim 5$ (Swinbank et al. 2009). Regions were found with star formation surface densities $\Sigma_{\text{SFR}} \sim 100\times$ higher than those found locally (Swinbank et al. 2009; Jones et al. 2010). These regions of dense star formation are comparable to the most intensely star-forming interacting systems in the local Universe (Bastian et al. 2006), yet appear to be ubiquitous in non-interacting galaxies at high redshift.

It is not known what drives these regions of intense star formation at high- z , although Jones et al. (2010) suggest a combination of higher gas density, increased star formation efficiency and shorter star-formation timescales. In addition, their data give the appearance of a bimodal distribution of HII region surface brightnesses, although there is no known physical process that might drive this. In order to understand this result further, we require a sample at intermediate redshift ($z \sim 1 - 1.5$) with which we can probe the evolution of star formation density with redshift at higher sensitivity so that regions comparable to those at $z = 0$ are detectable.

Previous work on high- z clumps has made use of Integral Field Units such as *Keck*/OSIRIS (Jones et al. 2010; Wisnioski et al. 2012), *Gemini*/NIFS (Swinbank et al. 2009) and *VLT*/SINFONI (Förster Schreiber et al. 2009). These allow detailed mapping of the nebular emission lines, but at lower sensitivity than is achievable with imaging. An alternative means of identifying star-forming regions with high sensitivity is to take imaging through narrowband filters. The Wide Field Camera 3 (WFC3) on the *HST* presents an opportunity to study the star formation in galaxies at $z \sim 1$ and $z \sim 1.5$, as there are narrowband filters available which correspond to the wavelength of the H α emission line at these redshifts. Combining the sensitivity and high spatial resolution of *HST*/WFC3 with the magnification afforded by gravitational lensing by foreground

clusters, we can map the internal star formation distribution and so identify the frequency and properties of giant HII regions.

In this paper, we therefore study the star formation morphologies of eight galaxies at $z \sim 1 - 1.5$. We present the sample in §2, present the properties of the galaxies and their star-forming clumps in §3, discuss the implications in §4 and present our conclusions in §5. Throughout, we adopt a Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$. Star-formation rates are calculated from H α luminosity $L_{\text{H}\alpha}$ using the prescription of Kennicutt (1998a) adjusted to a Chabrier (2003) IMF.

2 SAMPLE AND OBSERVATIONS

Our sample comprises eight lensed galaxies, each with spectroscopically-confirmed redshifts between $1 < z < 1.5$ such that the H α emission line falls within the high-transmission region of the narrowband filters on WFC3. The associated cluster lenses are massive systems from the X-ray selected BCS and MACS samples (Ebeling et al. 1998, 2001, 2007, 2010) with well-constrained mass models (see references in Table 1), so that the effects of lensing can be accounted for.

The positions and properties of the sample are given in Table 1. We observed each target in the narrowband filter covering H α for a typical exposure time of 6 ks (2 orbits), using a 3- or 4-point linear dithering pattern of ± 5 arcsecs in both directions to improve the detection and removal of cosmic ray hits and bad pixels. At the same time, three of the targets (MACS J0947, MACS J0159 and MACS J1133), which did not have WFC3 data in the archive, were observed in the corresponding broadband filter using the same sequence of observations as their corresponding narrowband data, for a total of 3 ks (1 orbit). The narrowband data and new broadband observations were obtained in Cycle 18 under Program 12197 (PI:Richard), with the exception of Abell 2390, for which the broadband and narrowband data were taken in Cycle 17 under Program 11678 (PI:Rigby). The remaining broadband data were obtained under Cycle 17 Program 11591 (PI:Kneib) or Cycle 18 Program 12065-9 (PI:Postman) as indicated in the notes to Table 1.

All of the WFC3 data were reduced using the multidrizze software (Koekemoer et al. 2002) under PyRAF to perform a cosmic-ray rejection, sky subtraction, and drizzling onto an output pixel scale of $0.05''$. The narrowband and broadband images of the same cluster were aligned using the location of ~ 20 bright stars. A narrowband excess image was constructed by direct pixel-to-pixel subtraction between the narrowband and broadband images, including an arbitrary scaling factor. We calibrated this scaling factor by checking that all bright cluster members, which are featureless elliptical galaxies with no emission lines in the respective filters, became consistent with the background in the excess image. For Abell 773 and Abell 68, the broadband images available in the archive did not directly overlap the H α emission line, so an estimate of the broadband continuum was made by linear interpolation between the adjacent F110W and F160W filters.

The flux calibration of each image was verified using 2MASS stars in the fields, and in all cases was found to

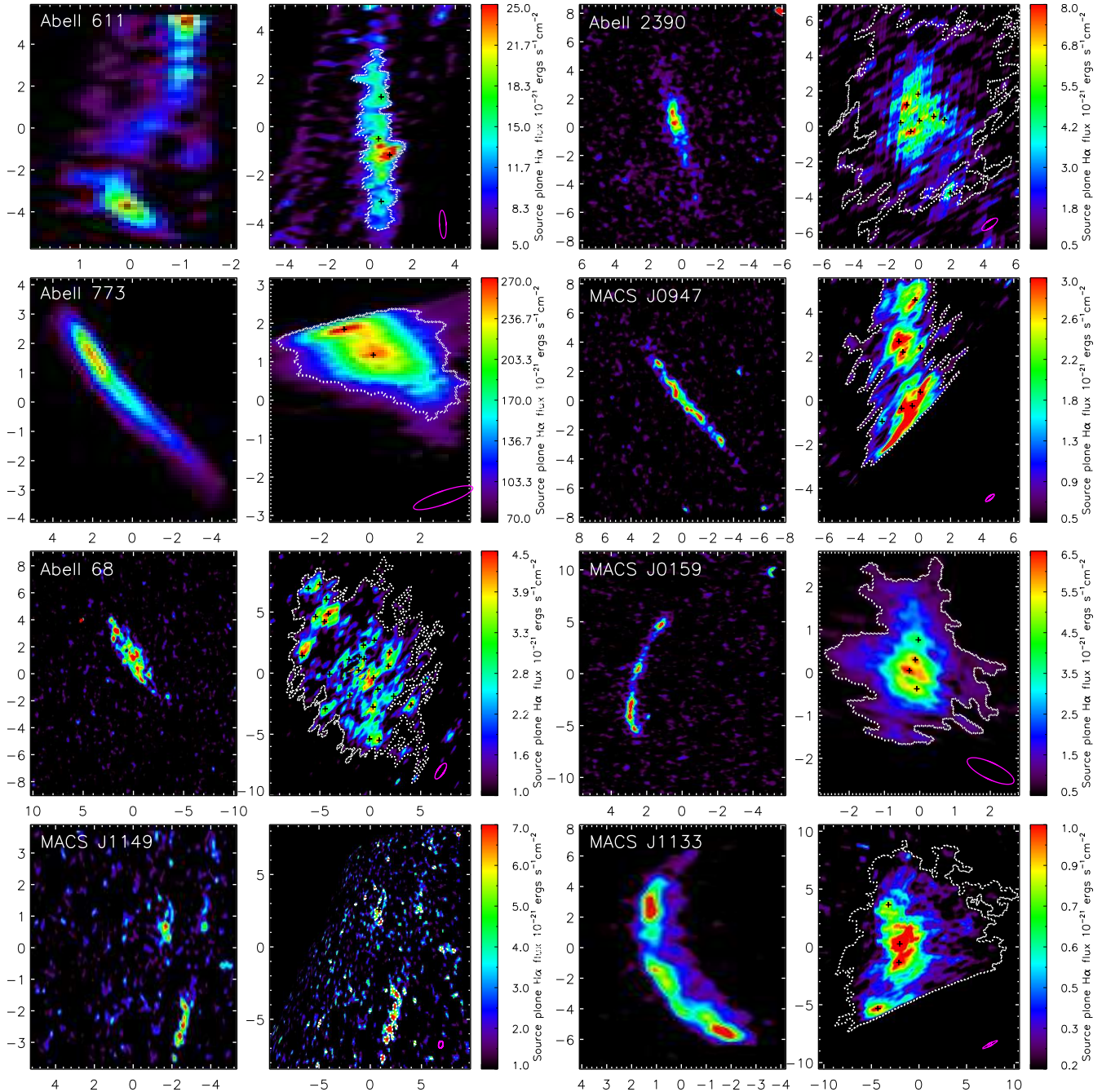


Figure 2. $H\alpha$ excess images in the image plane (left) and reconstructed in the source plane (right). The image scales are in arcseconds in the image plane and in kpc in the source plane. Identified clumps are indicated in the source-plane images by black crosses, and the magenta ellipse shows the FWHM of the effective source-plane PSF, as described in the text.

agree to within 15%, which is sufficient precision for our purposes.

Colour *HST* images of the clusters are shown in Figure 1, with the critical lines at the redshift of the target arc overlaid. We use the transformation between image and source plane mapping from the best-fit cluster mass models (for details of the mass models, see references in Table 1) with LENSTOOL (Kneib 1993; Jullo et al. 2007) to reconstruct the images in the source plane, and show these in Figure 2. In order to reconstruct the source plane morphology, LENSTOOL uses the mapping between the image and source planes on

a cluster-by-cluster basis and ray-traces the galaxy image. The lensing effect is to stretch the galaxy image - in most cases along one direction - and so the reconstruction cannot ‘create’ new HII regions, but rather the lensing has acted to extend them. As surface brightness is conserved by lensing, we then apply this conservation to obtain the intrinsic source plane flux. The total magnification is then simply the ratio of the image- to source-plane flux. To obtain the errors on the magnification, we use the family of best fit lens models which adequately describe the cluster potential, derived by sampling the posterior probability distribution of each

| Target cluster | Arc position | | z | H α flux (intrinsic) (10^{-18} erg/s/cm 2) | Magnification | | Resolution (pc) | Broadband filter | Narrowband filter | Lens model reference |
|-------------------|---------------|----------------|--------------------|--|-----------------------------------|----------------|--------------------|-------------------------------|----------------------|----------------------------|
| | RA (J2000) | Dec (J2000) | | | $\mu_x \times \mu_y$ (PA) | μ | | | | |
| Abell 611 | 08:00:57.30 | +36:03:37.0 | 0.908 | 30 \pm 5 | 10.4×2.7 (1 $^\circ$) | 28 \pm 5 | 338 | F125W ^a | F126N | [1] |
| Abell 2390 | 21:53:34.55 | +17:42:02.4 | 0.912 | 39 \pm 6 | 5.5×2.3 (73 $^\circ$) | 12.6 \pm 1.9 | 435 | F125W ^b | F126N ^b | [2] |
| Abell 773 | 09:17:58.80 | +51:43:42.3 | 1.010 | 274 \pm 49 | 7.0×1.0 (61 $^\circ$) | 7 \pm 1 | 336 | F110W & F160W ^c | F132N | [1] |
| MACS J0947.2+7623 | 09:47:15.26 | +76:23:02.9 | 1.012 ^d | 8.5 \pm 2.2 | 3.0×17.7 (51 $^\circ$) | 53 \pm 14 | 172 | F125W | F132N | [3] |
| Abell 68 | 00:37:04.91 | +09:10:21.0 | 1.017 | 119 \pm 11 | 3.0×1.7 (41 $^\circ$) | 5.1 \pm 0.5 | 615 | F110W & F160W ^e | F132N | [4] |
| MACS J0159.8-0849 | 01:59:04.68 | -34:13:03.4 | 1.488 ^e | 7 \pm 1 | 10.7×3.0 (111 $^\circ$) | 32 \pm 4 | 592 | F160W | F164N | [3] |
| MACS J1149.5+2223 | 11:49:35.30 | +22:23:45.8 | 1.490 ^f | 11 \pm 2 | 4.5×3.5 (140 $^\circ$) | 15 \pm 3 | 315 | F160W ^b | F164N | [5] |
| MACS J1133.2+5008 | 11:33:14.31 | +50:08:39.7 | 1.550 | 8 \pm 1 | 1.1×12.7 (67 $^\circ$) | 14 \pm 2 | 68 | F160W | F167N | [6] |

Table 1. Properties of the redshift-selected sample. Lensing magnifies the image by a factor μ_x at a position angle PA, with a transverse magnification μ_y . The total magnification factor μ is calculated from the amplification of H α flux, and the resolution given is the highest achievable along the most magnified direction, calculated from the FWHM of a star under the same lensing transformation as that applied to the galaxy, as described in the text. All observations were obtained under Program 12197 (Cycle 18, PI:Richard) unless otherwise stated.

^aProgram 12065-9 ^bProgram 11678 ^cProgram 11591 ^dEbeling et al. (2010) ^eEbeling et al. in prep ^fEbeling et al. (2007).

[1] Richard et al. (2010), [2] Pello et al. (1991), [3] Richard et al. in prep, [4] Richard et al. (2007), [5] Smith et al. (2009), [6] Sand et al. (2005)

parameter of the model (see Richard et al. (2010) for more details). For each acceptable lens model, we reconstruct the arc and remeasure the amplification. We give the resulting magnification factors, μ , and associated errors in Table 1.

In cases where the target is multiply-imaged, the images were reconstructed separately and then adjusted for small differences in position and orientation before being combined. For MACS J0159, which consists of five images, only the first three were used due to the high magnification gradients in the fourth and fifth images resulting in high distortion in the source plane reconstructions. In the case of Abell 611, we use only the northernmost arc due to high distortion by a foreground galaxy lying close to the line of sight of the southern arc.

We derive total magnification factors by comparing the total luminosities of the image- and source-plane H α excess images. The intrinsic H α luminosities are in the range $0.45 - 15 \times 10^{41}$ ergs $^{-1}$ corresponding to SFRs of $0.4 - 12 M_{\odot} \text{yr}^{-1}$. These are at the faint end of the H α luminosity function for this redshift range (see Figure 3), and probe fainter galaxies than the $z \sim 2$ sample of Jones et al. (2010), which covers the range $2.5 - 32 \times 10^{41}$ ergs $^{-1}$, although the two samples overlap in luminosity. Due to the increased sensitivity provided by the lensing magnification, both of the lensed samples cover a lower range of intrinsic H α luminosities than the sample of SINGS galaxies studied by Förster Schreiber et al. (2011), which were selected to have bright H α and lie in the range $28 - 43 \times 10^{41}$ ergs $^{-1}$, making them rare, intensely star-forming galaxies. Thus, by harnessing gravitational lensing we are able to probe the more ‘normal’ star-forming population.

Since gravitational lensing can preferentially shear one direction, we estimate the effective source-plane resolution by reconstructing the image of a star from the field repositioned to lie at the centre of the target. The maximum linear resolution, derived from the FWHM of the reconstructed star in the direction of greatest magnification, is 68–615pc with a median of 360pc, sufficient to resolve giant HII regions.

2.1 Comparison samples

In order to interpret our high- z data, we exploit the H α narrowband imaging from the *Spitzer* Infrared Nearby Galaxies Survey (SINGS, Kennicutt et al. 2003), which comprises H α imaging of 75 galaxies with corrected SFRs of up to $11 M_{\odot} \text{yr}^{-1}$. We use the publicly available continuum-subtracted H α narrowband imaging and restrict the sample to those with H α detections with signal-to-noise of > 5 that have no significant defects in the galaxy images (determined by visual inspection). This restricts the SINGS sample to 41 galaxies with $\text{SFR} > 4 \times 10^{-4} M_{\odot} \text{yr}^{-1}$.

To ensure a fair comparison, we rebin the SINGS images so that the resolution is comparable to the high- z data and then threshold to the median surface brightness limit of the $z \sim 1 - 1.5$ observations. It is worth noting that thresholding the images in this manner excludes 10–50% of the total star formation. This should not affect the comparison between samples which have the same surface brightness-limit, but may serve as an indication of the fraction of star formation missed in high- z observations.

To provide a comparison to local galaxies which are

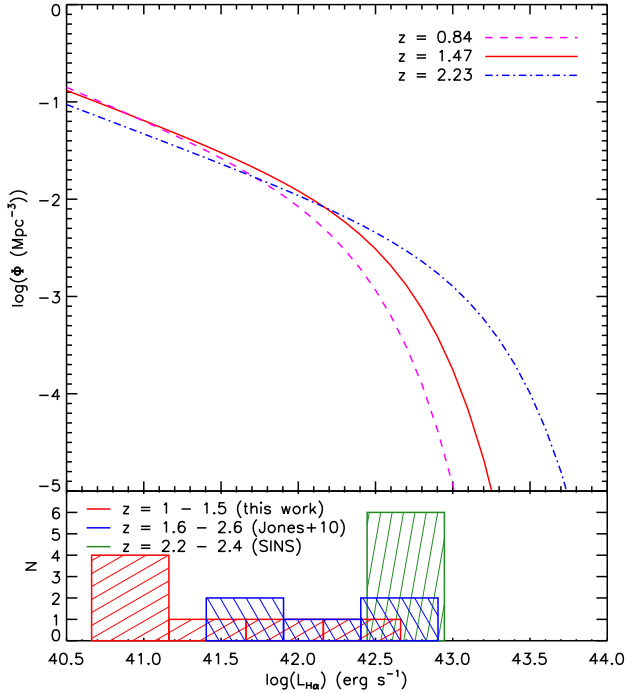


Figure 3. Intrinsic H α luminosities of the high- z samples compared to H α luminosity functions from HiZELS (Sobral et al. 2011). Also shown is the range of H α luminosities of the Förster Schreiber et al. (2011) sample from the SINS survey at $z \sim 2$. The two lensed samples overlap in luminosity and are both at the faint end of the luminosity function, with the median of the $z \sim 1 - 1.5$ WFC3 sample lower than that of the $z = 1.6 - 2.6$ OSIRIS sample by a factor of 6.6 \times , while the unlensed SINS galaxies cover a range of higher H α luminosities.

more actively star-forming, we use the VIMOS H α imaging spectroscopy of Rodríguez-Zaurín et al. (2011), which includes 38 LIRGs and ULIRGs at $z < 0.13$ with spatial resolution of 130 pc – 1.2 kpc and SFR $\lesssim 25 M_{\odot} \text{yr}^{-1}$.

We also compare the $z \sim 1 - 1.5$ sample to the $z \sim 2$ lensed arcs of Jones et al. (2010), which were observed with Keck/OSIRIS. In order to provide a fair comparison, we have constructed narrowband images by summing the OSIRIS cubes over 100 Å either side of the redshifted H α emission line, matching the width of the WFC3 narrowband filters. The resulting images are then corrected for lensing using the same image-to-source plane mapping as Jones et al. (2010) in order to obtain the intrinsic galaxy properties.

2.2 Determination of galaxy properties

The total H α luminosities of the galaxies in all samples are determined by summing all pixels in sky-subtracted images with signal-to-noise of > 3 . In the case of the SINGS galaxies, each image was checked by visual inspection and any foreground sources and defects masked. The resulting luminosities were then compared to the published values and found to agree to within $\sim 20\%$.

We convert H α luminosity to SFR using the Kennicutt (1998a) prescription, corrected to a Chabrier (2003) IMF,

which reduces the SFR by a factor of 1.7 \times . As we do not have constraints on the dust extinction, we adopt an estimate of $A_{H\alpha} = 1$ in all samples. This assumption is widely used in the literature although it is the subject of some disagreement. Garn et al. (2010) suggest a luminosity-dependent $A_{H\alpha}$ is more appropriate; were we to adopt their relation, we would obtain $A_{H\alpha} = 0.7 - 1.6$ with a median $A_{H\alpha} = 1.15$. However, we also note that recent work by Domínguez et al. (2012) suggests that galaxies with $L_{H\alpha} \lesssim 4 \times 10^{41} \text{ erg s}^{-1}$ may be consistent with having $A_{H\alpha} = 0$, and that above this threshold extinction increases in a luminosity-dependent way. Had we adopted this correction instead, the SFRs of the majority of our galaxies would be reduced by a factor of 2.5 \times . The exceptions are the three brightest $z \sim 2$ galaxies, in which the SFRs would increase by factors of 1.3 – 1.8 \times , and the $z \sim 1$ galaxies Abell 68 and Abell 773; the former would be a factor of 1.8 \times lower, while the latter would be unchanged. Qualitatively, there is no significant impact on our results, as adopting either luminosity-dependent extinction relation would serve to increase the evolution we observe in §3.2.2. For simplicity and reproducibility, we adopt $A_{H\alpha} = 1$ throughout.

We define the sizes of the galaxies as twice the half-light radius. The half-light radius is determined using the continuum images to find the shape (i.e. the centre and major to minor axis ratio of an ellipse that best fits the galaxy), and then adjusting the semi-major axis of the ellipse until it encompasses half of the total H α luminosity calculated in the manner described above. The galaxy-averaged star formation surface density, Σ_{SFR} is defined from the total luminosity enclosed within two half-light radii per unit area.

3 RESULTS AND ANALYSIS

3.1 The Spatial Distribution of Star Formation

A common theme in the recent literature is that high redshift galaxies are “clumpier” than galaxies in the local universe. This concept originates from the frequent appearance of “chain” galaxies in the high redshift universe (e.g. Cowie et al. 1995; Elmegreen et al. 2004; Elmegreen & Elmegreen 2005). Even without looking at the properties of individual star forming regions, it is interesting to compare the morphologies of the star-forming regions across the samples.

From visual inspection, it is clear that there are significant differences between the samples. In particular, the surface brightness distributions of the galaxies show distinct differences in the different samples. In Fig. 4, we show the fraction of star formation in pixels above a given Σ_{SFR} for the $z \sim 1 - 1.5$ and $z \sim 2$ samples, with the interquartile range of the thresholded SINGS sample shown for comparison.

To allow for the differing surface brightness limits of the samples, we only show star formation above a surface brightness of $\Sigma_{\text{SFR}} = 0.001 M_{\odot} \text{yr}^{-1} \text{ kpc}^{-2}$. This enables us to compare the star formation occurring in bright regions in a consistent manner. From the peaks - i.e. the points at which the lines tend to zero - we can see that the samples are different, with the $z \sim 2$ galaxies having peak surface brightnesses of around an order of magnitude higher than

the lower- z samples. Similarly, the $z \sim 1 - 1.5$ sample is systematically brighter than SINGS sample, with the exception of MACS J1133, which is similar to the fainter $z = 0$ galaxies, MACS J0947 which is similar to the median of the $z = 0$ sample, and Abell 773 which appears similar to the $z \sim 2$ galaxies.

As a statistical measure of the clumpiness of galaxies, we investigate using the Gini coefficient, G , which is used in economics to measure the inequality of wealth in a population (Gini 1912). It has values from 0 to 1, where at the extremes $G = 0$ for a completely uniform distribution, and $G = 1$ if there is only one non-zero value. Following Förster Schreiber et al. (2011), we use it to quantify the distribution of flux in an image, so a value close to one indicates that the profile has a single peak (in the case of $G = 1$, all of the flux would be in a single pixel), a galaxy with multiple clumps would have a lower G , and at the extreme, a galaxy with completely uniform surface brightness would have $G = 0$.

In the $z \sim 1 - 1.5$ sample, we find a narrow range of $0.25 \leq G \leq 0.39$ with a median of $G = 0.34$. The $z \sim 2$ sample is marginally higher, with $0.42 \leq G \leq 0.56$ and a median of $G = 0.43$. The $z = 0$ SINGS sample has a similar median $G = 0.45$ but a much wider range of $0.05 \leq G \leq 0.82$, and the low- z ULIRGs have $0.38 \leq G \leq 0.85$ with the highest median $G = 0.70$. On the basis of the Gini coefficient there are no clear differences between the samples. Comparing the Gini coefficients with the visual appearance of the galaxies, the lack of distinction reflects the fact that a low Gini coefficient may arise from either a smooth distribution of star formation or from star formation that is concentrated into a large number of distinct clumps. Furthermore, we find no strong correlations between G and any of the properties of the galaxies. Clearly, to progress further we will have to compare the properties of individual clumps. In particular, we will show that the clump luminosity function provides a good means of distinguishing different galaxy star formation morphologies.

3.2 Properties of star-forming clumps

3.2.1 Definition of Clumps

Studies of HII regions or star-forming clumps have used a variety of methods to define and separate clumps from the background emission of the galaxy. Usually an isophote is defined at 3σ above the background noise (e.g. Gonzalez Delgado & Perez 1997; Jones et al. 2010). However, this method is clearly dependent on the noise properties of the image, and thus is problematic when comparing local and high-redshift observations. In particular, as high-redshift galaxy images tend to have high relative noise levels and low dynamic range, the choice of isophote tends to select only the brightest regions in the galaxy, neglecting any lower-surface brightness clumps and underestimating their sizes.

An alternative is the IRAF task `daofind` as employed by Förster Schreiber et al. (2011), which is designed to locate point sources in images. However, we found that it did not perform well on our sample. This is likely to be because `daofind` requires an expected size of features to look for. As the clumps of Förster Schreiber et al. (2011) are largely un-

resolved, they were able to use the PSF of their observations as the expected size. As our clumps are resolved, the routine does not work reliably. For this paper, we therefore use the 2D version of `clumpfind` (Williams et al. 1994), which uses multiple isophotes to define clumps. We defined the contour levels with respect to the rms noise in the image, starting at 3σ and increasing in 1σ intervals until the peak value of the image is reached. The data are first contoured at the highest level to locate clumps, and the algorithm then works down in brightness through the contour levels. Any isolated contours are defined as new clumps, while others extend existing clumps. If a contour surrounds one existing peak, they are allocated to that clump, and any which enclose two or more are divided using a ‘friends-of-friends’ algorithm. The advantages of this approach are that it enables a consistent clump definition to be applied to multiple data sets, lower surface brightness clumps are not excluded, and there is no assumption made about the clump profile.

The clumps identified by `clumpfind` were all confirmed by visual inspection to remove any sources not associated with the target galaxy, of particular importance in the case of the SINGS images where foreground sources lie close to or overlap the target galaxies. The area A of the clump is then obtained from the number of pixels assigned to it, multiplied by the source-plane pixel scale, and from this we define the effective radius $r = \sqrt{A/\pi}$. We only accept clumps where $2r$ is larger than the FWHM of the PSF, so all clumps are resolved.

Due to the manner in which clumps are ‘grown,’ their sizes returned by `clumpfind` tend to be larger than those obtained by other methods. As a comparison, we also fit a 2D elliptical Gaussian profile to each peak and measure the FWHM. A comparison of the clump radii found by the two methods is shown in Figure 5. The rms difference between the two radii is ~ 100 pc, and on average we find that `clumpfind` outputs sizes 25% higher than the FWHM. Wisnioski et al. (2012) note that sizes defined through isophotes can be unreliable due to the level of ‘tuning’ required to select an appropriate isophote level in a given galaxy. This is less significant with `clumpfind` because this tuning is not required; the use of multiple isophote levels in all galaxies allows the levels to be defined in a consistent way across a large sample. We therefore find much lower scatter between the isophotal sizes output by `clumpfind` and the clump FWHM than they do in their sample. Throughout this work, we use the `clumpfind` size for all samples, and give error bars that encompass the FWHM of the clumps.

The sizes and H α -derived SFRs of the $z \sim 1 - 1.5$ clumps are given in Table 2. We analyse these properties in comparison to the other samples below.

3.2.2 Clump properties

One way of quantifying the ‘clumpiness’ of a galaxy is to consider the fraction of a galaxy’s total H α luminosity contained within clumps. We find medians of 31% in SINGS, 36% for the $z < 0.13$ ULIRGs, 50% for the $z \sim 1 - 1.5$ sample and 68% for the $z \sim 2$ sample. Thus, as expected, the higher- z galaxies are clumpier than their local counterparts.

We now consider the properties of the clumps themselves, and first compare the H α -derived SFR to the clump radius, as shown in Figure 6. Locally, there is a well-defined

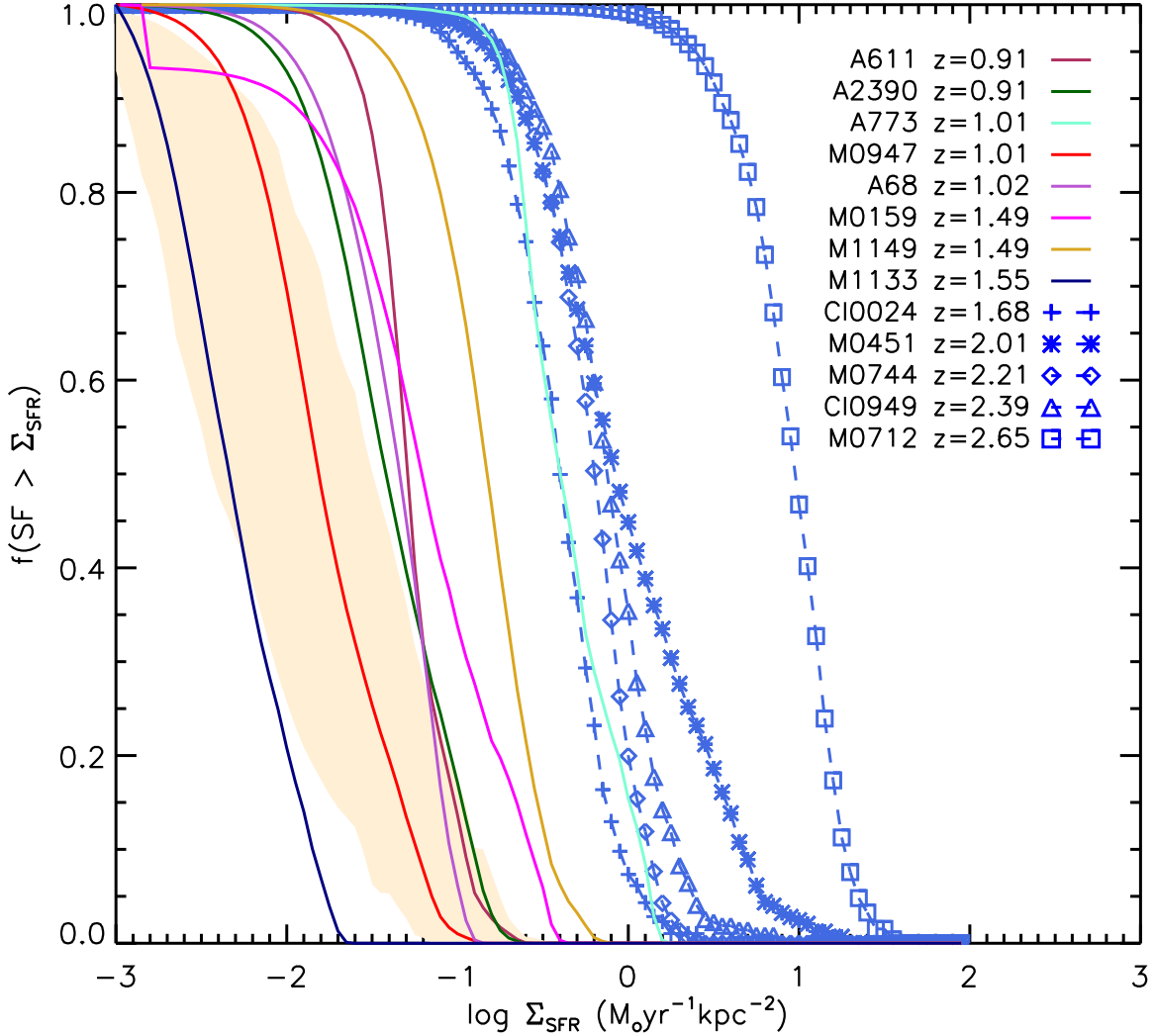


Figure 4. The fraction of star formation within each galaxy occurring above a given surface brightness, for the $z \sim 1 - 1.5$ and $z \sim 2$ samples. The shaded region is the interquartile range of the SINGS $z \sim 0$ sample. There are two galaxies, MACS J1133 and MACS J0947, from the $z \sim 1 - 1.5$ sample with similar surface brightnesses to the $z = 0$ sample, and the remainder are systematically brighter. The $z \sim 2$ sample has significantly higher surface brightnesses. Hence, there is clear evolution in the surface brightnesses of galaxies with redshift.

relationship between these properties, as found by Kennicutt (1988) who found almost constant surface brightness in local HII regions, except in merging and interacting systems (Bastian et al. 2006). The situation at high- z , though, appears different; Swinbank et al. (2009) and Jones et al. (2010) found clumps with SFRs of $\sim 100\times$ higher at a given size than found locally, in systems with no evidence of interactions.

Figure 6 is an updated version of one presented in Jones et al. (2010), where we have re-analysed the $z \sim 2$ and SINGS galaxies using `clumpfind` so that clumps are defined consistently across all samples, and we have added the results from our new $z \sim 1 - 1.5$ data set and the $z < 0.13$ ULIRGS as well as the $z = 1 - 2$ results from SHIZELS (Swinbank et al. in prep.) and WiggleZ (Wisnioski et al. 2012). We show lines of median surface brightness in the

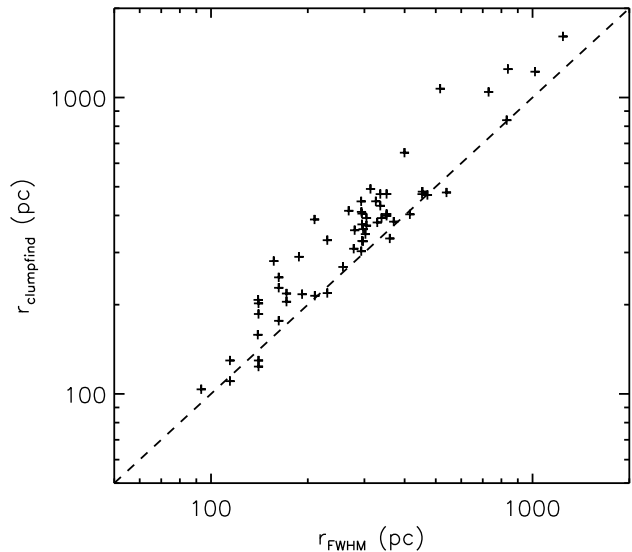
samples, and vertical offsets from these lines represent differences in the surface density of star formation, Σ_{SFR} , in the clumps. We will explore the relation of these offsets to global galaxy properties in Section 4.

We note that the clumps we identify in the SINGS galaxies are derived from images which have been degraded to comparable resolution to the high- z data, and we find the effect of this is to decrease the surface brightness by a factor of $\sim 2\times$, as the size increases more than the luminosity. The points in Figure 6 move along the vector labelled 'A'. Defining clumps in the $z = 0$ sample in this way ensures the fairest possible comparison with the high- z data.

Upon re-analysis using `clumpfind`, we find some lower Σ_{SFR} regions in the Jones et al. (2010) sample, but they all remain separated from the local relation by a factor of $\sim 100\times$. This confirms the large differences between

Table 2. Properties of clumps identified in the $z \sim 1-1.5$ sample, determined as described in §3.2.1.

| Clump | radius (pc) | SFR ($M_{\odot} \text{ yr}^{-1}$) |
|--------------|----------------|-------------------------------------|
| MACS J0947-1 | 350 ± 56 | 0.054 ± 0.010 |
| MACS J0947-2 | 324 ± 22 | 0.0328 ± 0.0086 |
| MACS J0947-3 | 384 ± 48 | 0.045 ± 0.012 |
| MACS J0947-4 | 334 ± 39 | 0.0350 ± 0.0092 |
| MACS J0947-5 | 318 ± 38 | 0.0339 ± 0.0089 |
| MACS J0947-6 | 376 ± 6 | 0.0347 ± 0.0091 |
| MACS J0947-7 | 311 ± 17 | 0.0261 ± 0.0068 |
| MACS J0947-8 | 149 ± 9 | 0.0050 ± 0.0013 |
| MACS J0159-1 | 402 ± 89 | 0.282 ± 0.060 |
| MACS J0159-2 | 370 ± 77 | 0.203 ± 0.043 |
| MACS J0159-3 | 530 ± 130 | 0.355 ± 0.076 |
| MACS J0159-4 | 468 ± 13 | 0.170 ± 0.036 |
| Abell 611-1 | 730 ± 180 | 0.370 ± 0.083 |
| Abell 611-2 | 560 ± 160 | 0.181 ± 0.041 |
| Abell 611-3 | 630 ± 140 | 0.200 ± 0.045 |
| Abell 611-4 | 390 ± 59 | 0.065 ± 0.015 |
| Abell 68-1 | 378 ± 26 | 0.081 ± 0.016 |
| Abell 68-2 | 132 ± 8 | 0.0075 ± 0.0015 |
| Abell 68-3 | 375 ± 24 | 0.076 ± 0.015 |
| Abell 68-4 | 354 ± 25 | 0.070 ± 0.014 |
| Abell 68-5 | 509 ± 31 | 0.114 ± 0.023 |
| Abell 68-6 | 337 ± 33 | 0.062 ± 0.013 |
| Abell 68-7 | 386 ± 61 | 0.099 ± 0.020 |
| Abell 68-8 | 205 ± 42 | 0.0273 ± 0.0055 |
| Abell 68-9 | 348 ± 44 | 0.069 ± 0.014 |
| Abell 68-10 | 299 ± 89 | 0.066 ± 0.013 |
| Abell 68-11 | 328 ± 31 | 0.057 ± 0.012 |
| Abell 68-12 | 312 ± 15 | 0.0476 ± 0.0097 |
| Abell 68-13 | 412 ± 60 | 0.100 ± 0.020 |
| Abell 68-14 | 293 ± 16 | 0.0429 ± 0.0087 |
| Abell 68-15 | 263 ± 5 | 0.0302 ± 0.0061 |
| Abell 68-16 | 280 ± 50 | 0.0454 ± 0.0092 |
| Abell 68-17 | 169 ± 7 | 0.0132 ± 0.0027 |
| Abell 68-18 | 195 ± 33 | 0.0215 ± 0.0044 |
| Abell 68-19 | 224 ± 6 | 0.0199 ± 0.0040 |
| Abell 68-20 | 239 ± 51 | 0.0344 ± 0.0070 |
| Abell 68-21 | 135 ± 5 | 0.0069 ± 0.0014 |
| Abell 68-22 | 163 ± 23 | 0.0142 ± 0.0029 |
| Abell 68-23 | 112 ± 2 | 0.00489 ± 0.00099 |
| Abell 68-24 | 171 ± 31 | 0.0161 ± 0.0033 |
| Abell 68-25 | 98 ± 5 | 0.00416 ± 0.00085 |
| Abell 68-26 | 122 ± 8 | 0.0066 ± 0.0013 |
| Abell 2390-1 | 352 ± 59 | 0.115 ± 0.025 |
| Abell 2390-2 | 404 ± 68 | 0.136 ± 0.030 |
| Abell 2390-3 | 409 ± 6 | 0.086 ± 0.019 |
| Abell 2390-4 | 366 ± 26 | 0.067 ± 0.015 |
| Abell 2390-5 | 463 ± 9 | 0.111 ± 0.024 |
| Abell 2390-6 | 347 ± 13 | 0.059 ± 0.013 |
| Abell 2390-7 | 470 ± 1 | 0.093 ± 0.020 |
| Abell 2390-8 | 341 ± 73 | 0.069 ± 0.015 |
| Abell 773-1 | 1040 ± 200 | 5.6 ± 1.3 |
| Abell 773-2 | 1430 ± 180 | 9.6 ± 2.2 |
| MACS J1133-1 | 1120 ± 100 | 0.118 ± 0.025 |
| MACS J1133-2 | 890 ± 160 | 0.068 ± 0.015 |
| MACS J1133-3 | 790 ± 280 | 0.057 ± 0.012 |
| MACS J1133-4 | 835 ± 4 | 0.0334 ± 0.0072 |
| MACS J1149-1 | 174 ± 34 | 0.084 ± 0.020 |


Figure 5. Comparison of the clump size $r_{\text{clumpfind}}$ output by clumpfind with the size r_{FWHM} obtained by taking the FWHM of a 2D Gaussian profile fit. On average, clumpfind outputs sizes 25% larger than the FWHM. For consistency, we adopt the isophotal size output by $r_{\text{clumpfind}}$ in all samples.

the local and high redshift population already noted by Swinbank et al. (2009) and Jones et al. (2010).

Our new $z \sim 1-1.5$ sample fits in between the SINGS and $z \sim 2$ samples, with the exception of the two regions from the most compact source Abell 773, which have Σ_{SFR} similar to the $z \sim 2$ sample, and the four regions from MACS 1133, which are similar to $z = 0$ clumps. This indicates clear evolution in clump surface brightness, Σ_{SFR} , with redshift.

The surface brightness limit of the $z \sim 2$ data means that we cannot identify the low star formation rate clumps in that sample. We show a dotted line representing the lower limit at which we define clumps in the $z \sim 2$ galaxies. It is likely that there are additional clumps which lie below this limit and are undetected; however, such clumps make only a small contribution to the total SFR, as we shall discuss in Section 3.3.

Selection effects have no impact on the lack of high surface brightness regions in the lower redshift samples, however. The intense star-forming regions are clearly more common in high- z galaxies; they are found only in extreme systems such as the Antennae locally, but exist in all five of the $z \sim 2$ galaxies and one of the eight $z \sim 1-1.5$ sample.

As noted in § 2, the $z \sim 2$ galaxies have ‘normal’ SFRs for their redshift, below the knee of the $\text{H}\alpha$ luminosity function. The offsets seen in the figure emphasise the importance of analysing clumps in terms of their surface brightness. This is even more evident if the clumps belonging to a single galaxies are examined separately. Rather than being distributed across the plot at random, individual galaxies form a much tighter sequence with all the clumps sharing a common surface brightness, particularly in the low redshift sample. Thus the spread in clump properties in Figure 6 appears to be driven by *global* differences in the galaxies.

We therefore next compare the clump Σ_{SFR} to the properties of their host galaxies in Figure 7. In the left-hand

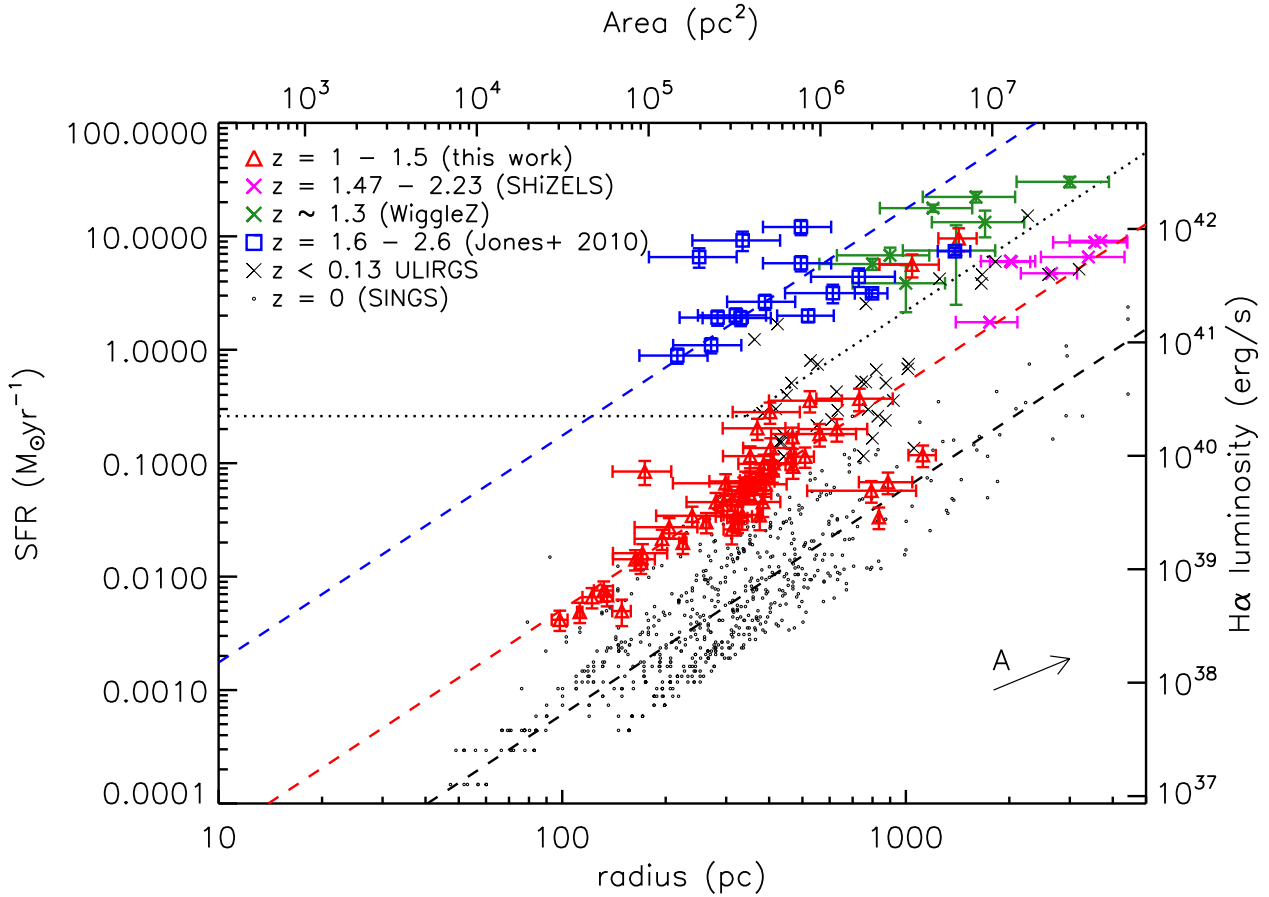


Figure 6. $H\alpha$ SFR for extracted HII regions as a function of size, compared to the lensed $z \sim 2$ sample of Jones et al. (2010), high- z unlensed samples from SHiZELS (Swinbank et al. in prep) and WiggleZ (Wisnioski et al. 2012), low- z ULIRGs from Rodríguez-Zaurín et al. (2011) and the $z = 0$ SINGS galaxies (Kennicutt et al. 2003). Star formation rates are calculated using the Kennicutt (1998a) prescription adjusted for a Chabrier IMF with a dust extinction $A_{H\alpha} = 1$ in all samples, and the error bars of the high- z lensed sources are dominated by the uncertainty in the lensing magnification. Dashed lines show the median surface brightnesses in the SINGS, $z \sim 1 - 1.5$ and $z \sim 2$ samples. The black dotted line indicates the sensitivity limit of the $z \sim 2$ OSIRIS observations. The arrow indicates the effect of degrading the image resolution, as discussed in the text. The four lowest surface brightness clumps in the $z \sim 1 - 1.5$ sample come from one galaxy (MACS J1133), and the two brightest regions are from Abell 773, the most compact galaxy in the sample. The remaining galaxies have clumps with surface brightnesses in between those of the $z = 0$ and $z \sim 2$ samples, similar to local ULIRGs.

panel, we correlate the clump properties with the total star formation rate of the galaxy. For clarity, we plot the median clump Σ_{SFR} in each individual galaxy, and the error bars encompass the central 68% of clumps within each galaxy (i.e. 1σ if they follow a Gaussian distribution). There is evidence for correlation between the clump Σ_{SFR} and the galaxy $H\alpha$ luminosity (which we assume to be proportional to the total SFR); we find a Spearman rank correlation coefficient $\rho = 0.69$, representing a 5.8σ deviation from the null hypothesis of no correlation. This suggests that the star-formation in the high- z sample follows a similar trend to the local sample, and that the differences seen in Fig. 6 may arise from the higher total star formation rates of the high redshift galaxies.

For the majority of the samples, an even stronger relation arises if we compare the clump Σ_{SFR} to the galaxy-averaged Σ_{SFR} . This is shown in the right-hand panel of Figure 7, and has a correlation coefficient $\rho = 0.79$ with 6.6σ significance. The ratio of clump-to-average Σ_{SFR} can be thought of as a measure of the ‘clumpiness’ of the galaxy.

We conclude that the properties of star-forming clumps in a galaxy are strongly dependent on the global Σ_{SFR} of the galaxy. Galaxies with higher overall Σ_{SFR} have higher clump surface densities and are correspondingly offset in the clump size – star formation rate relation. While this accounts for some of the differences seen in Fig. 6, it is also clear that there are more bright clumps in the higher redshift galaxies. We quantify this below.

3.3 HII region luminosity functions

A quantitative measure of the clump brightness is to construct a luminosity function (LF) of HII regions. In the local universe, the HII LF is presented in Kennicutt et al. (1989) and Gonzalez Delgado & Perez (1997). They demonstrate that the LF can be fitted by a broken power-law, or by a power-law with an exponential break. In order to be consistent with our definitions of clump sizes, we reanalyse the local data in order to construct our own LF. The results are shown in Figure 8. The left panel of the figure shows

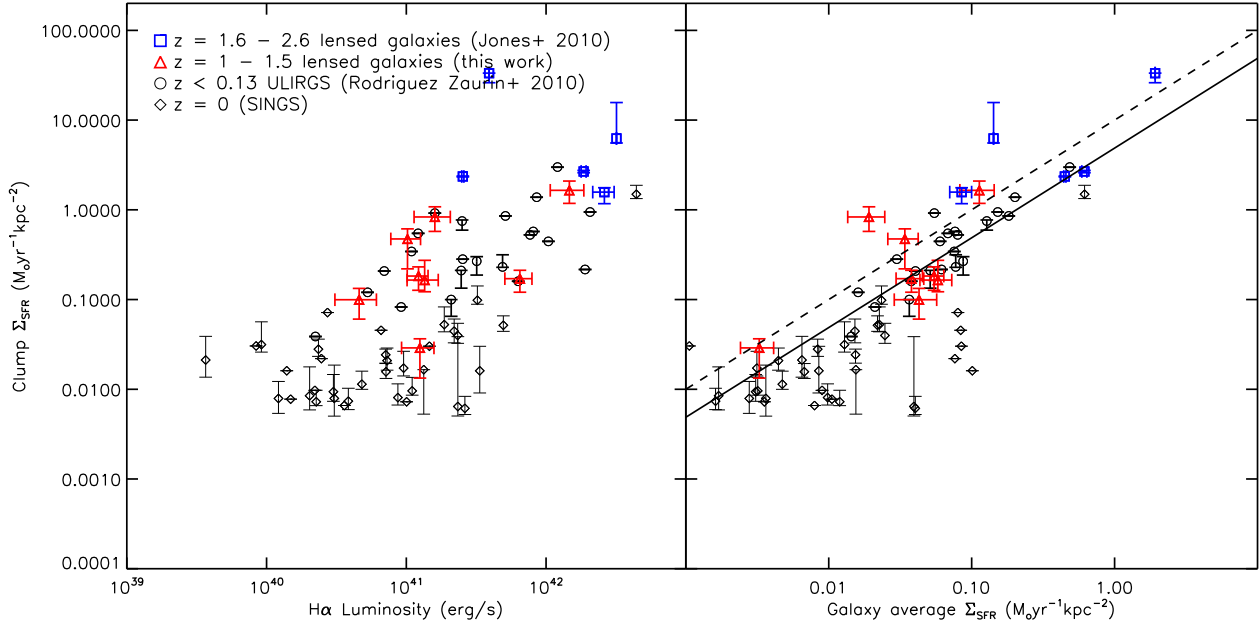


Figure 7. Comparisons between the star formation surface density Σ_{SFR} of star-forming clumps within each galaxy and the intrinsic H α luminosity and galaxy-averaged Σ_{SFR} . The clump Σ_{SFR} shown is the median for each galaxy, with error bars encompassing the full range of Σ_{SFR} for all clumps within each galaxy. The solid line is the best fit to the data, and the dashed line illustrates the clump Σ_{SFR} expected from theory, discussed in Section 4. We find that both are correlated at the 5σ level, implying that we find more high- Σ_{SFR} at high redshift because there are more high-SFR and Σ_{SFR} galaxies at this epoch.

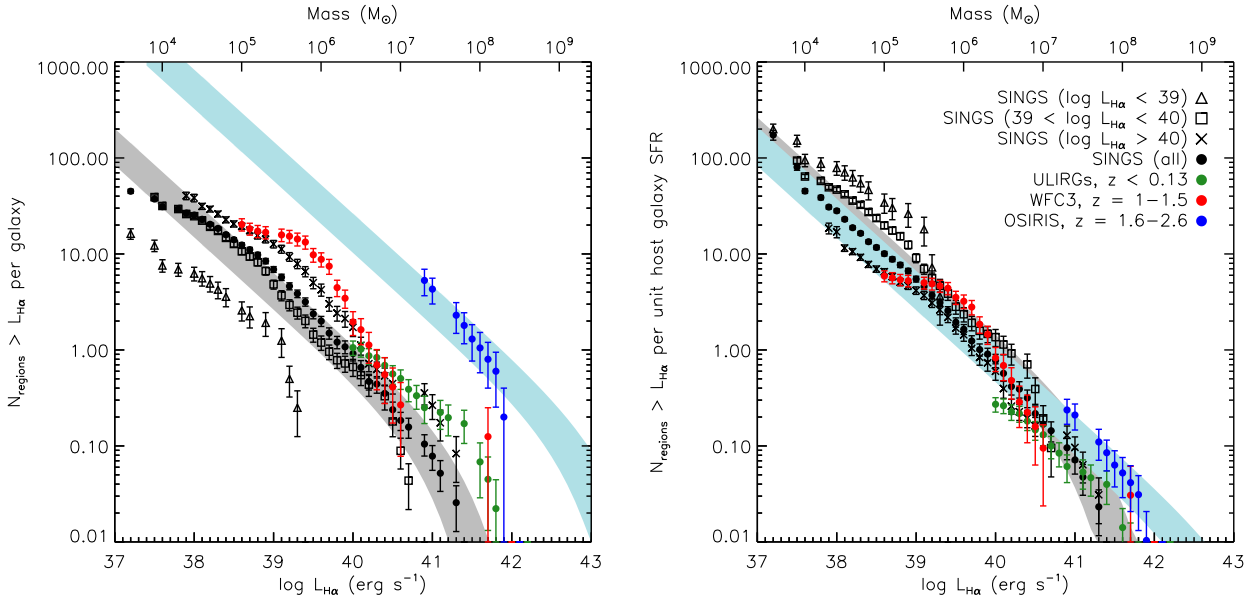


Figure 8. Cumulative luminosity functions of HII regions in the SINGS, $z \sim 1 - 1.5$ and $z \sim 2$ samples, shown as a mean per galaxy (*left*) and normalised by total galaxy H α luminosity (*right*). We plot the SINGS sample as a whole and subdivided into three luminosity bins. The shaded regions illustrate model predictions from the GMC mass functions of Hopkins et al. (2012) for Milky Way-like (grey) and high- z (blue) simulations. We find evolution in the HII region luminosity function, which seems to be driven by the gas fraction of the disk.

the cumulative number of regions per galaxy as a function of H α luminosity. The normalisation of each bin takes into account the different surface brightness limit of the galaxies, with error bars computed from the Poisson error in counting regions. The slope of the power-law part of the mass function is ~ -0.75 , so that although the LF appears steep in this

representation, most of the total luminosity is contributed by the brightest HII regions.

Solid black points show the average of all SINGS galaxies. However, since we will be comparing the galaxies covering a range of luminosities and redshifts, we have separated the galaxies from the SINGS sample into 3 total H α lumi-

nosity bins. At a fixed luminosity, galaxies with lower total emission have fewer regions, but the shape of the luminosity function is similar. In order to emphasise the similarity of the mass function, we normalise each of the curves by the total star formation rate of the host galaxies, and show this in the right-hand panel. The similarity of all the HII region LFs is now clear.

There is a striking similarity between the LF of the $z \sim 1 - 1.5$ sample and that of the highest SFR galaxies in the low- z SINGS sample. The excess of very bright regions ($L \sim 10^{41} \text{ erg s}^{-1}$) is down to one galaxy, Abell 773, which is the same compact galaxy for which we found the clump surface brightnesses to be more typical of the highest redshift galaxies. The low luminosity slope of the LF tends also to be flatter than that seen in the low redshift galaxies, but it is hard to quantify this difference without directly comparable surface brightness limits and is likely to be affected by unresolved regions which are excluded. In any case, these faint regions contribute little to the total flux.

In both panels, the HII region LF for the highest redshift galaxies is strongly offset from the relation seen in the low redshift SINGS sample and from the sample at $z \sim 1 - 1.5$, but is similar to the low-redshift ULIRGs. Although the data do not probe the low-luminosity slope of the LF, these galaxies have much brighter regions than are seen at lower redshift. The right-hand panel emphasises that this is not because they contain many more regions overall.

In order to compare our data to models of mass functions, we must relate the measured H α luminosities to model clump mass, M . As an estimate, we use the H α -derived SFR and adopt $\text{SFR} (M_{\odot} \text{ yr}^{-1}) = 4.6 \pm 2.6 \times 10^{-8} M_{\odot}$ (Lada et al. 2010). This empirical relation is based on local molecular clouds and applies to the high-density gas where $A_K > 0.8$ mag. However, we note that this relation is consistent with the far-infrared-derived star formation rate and CO-derived gas masses of star-forming clumps reported in a lensed $z = 2.3$ galaxy by Swinbank et al. (2011), but clearly more high-resolution CO observations of high- z galaxies are required to confirm this. As a guide, we include this conversion on the upper axis of Figure 8.

The shapes of the LFs can be approximated by a power law with an exponential cut-off at some high luminosity or mass. The difference between the samples' LFs is then best described by a pure luminosity evolution, so that the cut-off shifts to higher luminosity/mass at higher redshift.

To demonstrate this, we include shaded regions representing a Schechter function of the form

$$N(> M) = N_0 \left(\frac{M}{M_0} \right)^{\alpha} \exp \left(\frac{-M}{M_0} \right), \quad (1)$$

where we adopt the median value of $\alpha = -0.75$ from Hopkins et al. (2012). The normalisation N_0 is arbitrary, so we fit N_0 to the $z = 0$ data and then keep it fixed while allowing M_0 to vary in order to find best-fit values of in the different samples. The best-fit values are $M_0 = 4.6_{-2.0}^{+3.1} \times 10^7 M_{\odot}$ at $z = 0$, $M_0 = 8.0_{-4.3}^{+11.0} \times 10^7 M_{\odot}$ at $z \sim 1 - 1.5$ and $M_0 = 1.5_{-1.0}^{+2.2} \times 10^9 M_{\odot}$ at $z \sim 2$, where the errors are found with a bootstrap method. We shade the best-fit Schechter functions at $z = 0$ and $z \sim 2$ in grey and blue respectively in Figure 8. The normalisation of the model in the right-hand panel is obtained by summing the luminosities of the

clumps. The result is in remarkably good agreement with our observations.

Not only do the highest-redshift galaxies have HII regions that are higher surface brightness, but the characteristic luminosity of the regions is higher too. We suggest that the presence of high-luminosity regions may be a good operational definition of the clumpiness of a galaxy.

4 DISCUSSION

In the previous section, we presented an analysis of star forming regions in galaxies at $z = 0$, $z \sim 1 - 1.5$ and $z \sim 2$. We find that the luminosities of the regions in $z = 1$ galaxies are similar to those of bright ($L > 10^{40} \text{ erg s}^{-1}$) galaxies at low redshift, but the surface brightnesses are systematically higher. At higher redshifts, the properties of the galaxies change, with the galaxies having clumps that are both much higher surface brightness and shifted to higher total luminosities. This accounts for the qualitative impression that the most distant galaxies are ‘‘clumpier.’’

We also noted that the increase in the surface brightness of HII regions tracks the increase in the average star formation rate surface density, Σ_{SFR} , of the galaxies. The observations are consistent with the changing properties of the HII regions being driven by changes in the overall Σ_{SFR} of the galaxies. We can link the increase in the observed Σ_{SFR} to an increase in the gas surface density of these galaxies by assuming that the Kennicutt-Schmidt law holds at $z \sim 2$ as well as at $z = 0$. In this case, we have an emerging picture that the changes we see are likely driven by greater gas surface densities at higher redshift.

The connection between the increasing surface density of clumps and the greater peak brightness arises naturally from this picture (Hopkins 2011). The clump mass required for collapse on scale R from a turbulent ISM is given by the Jean’s mass, M_J :

$$\rho_c = \frac{3}{4\pi R^3} M_J \approx \frac{9}{8\pi R^2 G} \sigma_t(R)^2, \quad (2)$$

where $\sigma_t(R)$ is the line of sight turbulent velocity dispersion. Assuming a turbulent velocity power spectrum $E(k)$, the velocity dispersion $\sigma_t(R)$ for wavenumber $k = 1/R$ is

$$\sigma_t^2 = kE(k) \propto R^{p-1}, \quad (3)$$

where $p \approx 2$ for supersonic turbulence appropriate to the ISM (Burgers 1974; Schmidt et al. 2009).

To determine the normalisation of the relation, we assume that the clumps are located in a marginally unstable disk. We note that the available kinematic data for the $z \sim 2$ sample and for MACS J1149 support this assumption, as do larger surveys (Genzel et al. 2011); nonetheless, clearly this is uncertain without dynamical data for the entire sample. However, if we make the assumption that the galaxies are rotating disks with Toomre parameter $Q \approx 1$, we can relate the epicyclic frequency, κ of the disk to its scale height, h : $\kappa \approx \sigma_t(h)/h$.

$$Q = \frac{\kappa \sigma_t(h)}{\pi G \Sigma_0} \approx \frac{\sigma_t(h)^2}{\pi G \Sigma_0 h}. \quad (4)$$

Since the stability of the disk is a global phenomenon, we will associate Σ_0 with the average surface density of the star forming disk, Σ_{disk} , and treat the quantities appearing

in Eq. 4 as appropriate global disk averages. Since the disk is made up of both stars and gas, we must take an appropriate average of the surface densities in the two components. Following Rafikov (2001), and focussing on the largest unstable fluctuations, the appropriate combination of gas and star surface densities (denoted Σ_g and Σ_*) is

$$\Sigma_{\text{disk}} = \Sigma_g + \left(\frac{2}{1 + f_\sigma^2} \right) \Sigma_*, \quad (5)$$

where $f_\sigma = \sigma_*/\sigma_t$ is the ratio of the velocity dispersion of the stellar component to that of the gas.

Assuming $Q \approx 1$, we can write,

$$\sigma_t^2(R) = (\pi G \Sigma_{\text{disk}} h) \left(\frac{R}{h} \right)^{p-1} \approx \pi G \Sigma_{\text{disk}} R, \quad (6)$$

where we have used Eq. 3 to relate $\sigma_t(h)$ to $\sigma_t(R)$. Combining with Eq. 2 gives a critical density for collapse of

$$\rho_c(R) = \frac{9}{8} \Sigma_{\text{disk}} \frac{1}{R}. \quad (7)$$

Assuming that the cloud contracts by a factor ≈ 2.5 as it collapses, the post-collapse surface density is

$$\Sigma_{\text{cloud}} \approx 10 \rho_c R \approx 10 \Sigma_{\text{disk}}. \quad (8)$$

Thus, for the turbulent power spectrum $p \approx 2$, the surface density of collapsed clouds is independent of radius and proportional to the surface density of the disk. The normalisation of the relation follows from the collapse factor and the requirement that the disk is marginally stable. This model provides a good description of clouds in the Milky Way (Larson's laws) as discussed in Hopkins (2011), and predicts that the surface brightnesses of clouds should increase as the gas surface density (and thus overall average star formation rate surface density) increases. If we assume a constant Kennicutt-Schmidt law of the form $\Sigma_{\text{gas}} \propto \Sigma_{\text{SFR}}^{1.4}$ (Kennicutt 1998b), we can compare Eq. 2 to our data; we therefore overplot this line on Figure 7 and find that it is in good agreement with the observations.

Moreover, the model predicts that the most massive clouds should increase in size with the average gas surface density. This follows from the marginal stability condition (Eq. 4), since density structures on scales greater than h will tend to be stabilised by disk rotation.

This can be demonstrated formally by examining the dispersion relation for a finite thickness disk (Begelman & Shlosman 2009). Hopkins (2011) shows that this leads to an exponential cut-off of the clump mass function above a mass

$$M_0 \approx \frac{4\pi}{3} \rho_c(h) h^3 = \frac{3\pi^3 G^2}{2} \frac{\Sigma_{\text{disk}}^3}{\kappa^4}, \quad (9)$$

where we have used Eqs. 3 and 4 to express h as a function of Σ_{disk} and $\kappa = v_{\text{disk}}/R_{\text{disk}}$ (where v_{disk} is the disk circular velocity and R_{disk} is half-mass radius of the disk). Expressing κ in units of $100 \text{ km s}^{-1} \text{ kpc}^{-1}$ we obtain a normalisation of

$$\frac{M_0}{M_\odot} = 8.6 \times 10^3 \left(\frac{\Sigma_{\text{disk}}}{10 M_\odot \text{ pc}^{-2}} \right)^3 \left(\frac{\kappa}{100 \text{ km/s kpc}^{-1}} \right)^{-4}. \quad (10)$$

We can check that this results in a reasonable value

of M_0 in the Milky Way by using a gas surface density $\Sigma_{\text{gas}} \sim 10 M_\odot \text{ pc}^{-2}$ and a gas fraction of 10% with $f_\sigma = 2$ (Korchagin et al. 2003) to obtain an effective $\Sigma_{\text{disk}} \sim 35 M_\odot \text{ pc}^{-2}$. With $\kappa = 36.7 \text{ km s}^{-1} \text{ kpc}^{-1}$ (Feast & Whitelock 1997), this gives $M_0 \sim 10^7 M_\odot$, in good agreement with the characteristic mass of the largest Galactic GMCs (Stark & Lee 2006).

Eq. 10 shows that the mass cut-off depends strongly on the disk surface density — the higher the surface density, the more massive the clumps that are able to form. This trend can, however, be opposed by the stabilising effect of angular rotational speed. For a fixed disk radius, a higher circular velocity tends to reduce the mass of the largest clumps.

For low-redshift galaxies, simple theoretical models suggest that $R_{\text{disk}} \propto v_{\text{disk}}$ since halo spin is weakly dependent on the halo mass (Mo et al. 1998), and thus we should expect the dependence on the disk surface density to be the dominant trend controlling the cut-off clump mass. This is confirmed by analysis of the observed properties of galaxies. For example, Dutton et al. (2011) find

$$\frac{R_{\text{disk}}}{\text{kpc}} \approx 2.5 \left(\frac{v_{\text{disk}}}{100 \text{ km/s}} \right)^{1.2} \quad (11)$$

in the local universe. Combining this with the observed dependence of the disk rotation velocity on galaxy mass

$$\frac{M_*}{10^{10} M_\odot} = 0.25 \left(\frac{v_{\text{disk}}}{100 \text{ km/s}} \right)^{4.5}, \quad (12)$$

we obtain

$$\frac{\kappa}{100 \text{ km/s kpc}^{-1}} \approx 0.38 \left(\frac{M_*}{10^{10} M_\odot} \right)^{-0.04}, \quad (13)$$

which shows that κ is very weakly dependent on the galaxy mass, and the variation in the clump mass functions of local galaxies is driven by the disk surface density.

We also note that in a disk of constant circular velocity, κ scales with radial distance r as $\kappa \propto r^{-1}$, while the gas surface density profiles are shallow, with $\Sigma_{\text{gas}} \propto r^{-4/3}$ (Fu et al. 2010). Thus from Eq. 10 there is no dependence of M_0 on r ; while the surface density is higher towards the centre of the galaxy, this is balanced by the higher rotational frequency. This explains the observations that clump properties appear to be driven by the global properties of their host galaxies rather than by local conditions, and this allows us to use disk-averaged values of κ and Σ .

We have no measurements of the gas contents of our samples, but dynamical information available for the $z \sim 2$ sample permits us to predict the cut-off mass in these galaxies from our model if we estimate Σ_{disk} from the dynamical mass. Using the measurements reported in Jones et al. (2010, see their Table 2), we compute a cut-off mass ranging from $3.3 \times 10^6 - 3.1 \times 10^9 M_\odot$ for the $z \sim 2$ sample. The median value is $5 \times 10^7 M_\odot$, approximately $5 \times$ higher than the Milky Way value. We therefore expect that the $z \sim 2$ sample should contain clumps of higher mass and luminosity, as observed. However, the uncertainty in the cut-off mass for the $z \sim 2$ sample is very large due to uncertainties in Σ_{disk} and κ , which prevents us from making a precise comparison of the cut-off mass in the different samples.

To understand how the clumpiness of galaxies evolves, we must therefore use simulations to estimate the evolution of their scaling relations. Dutton et al. (2011) present

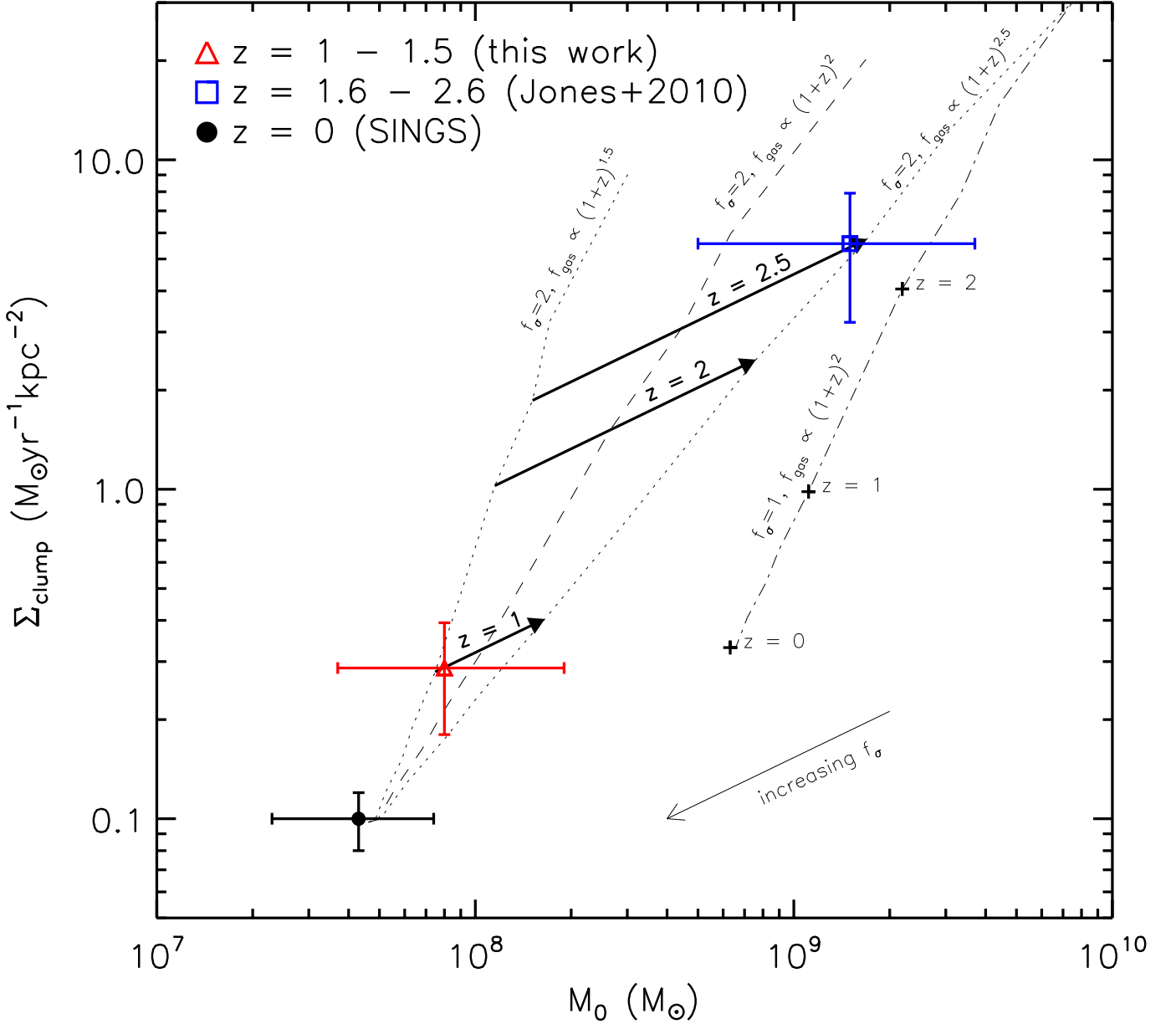


Figure 9. The evolution of cut-off mass M_0 and clump surface density Σ_{clump} in comparison with model predictions (equation 10). The model is strongly dependent on the assumed evolution of gas fraction with redshift; we show tracks for $f_{\text{gas}} \propto (1+z)^{2\pm 0.5}$ and the thick arrows show the effect of increasing the gas fraction. We also show a track for $f_{\sigma} = 1$ - i.e. assuming that the gas and stars have the same velocity dispersion. This makes the disk unstable on larger scales and would lead to higher-mass clumps at low- z than are observed. The impact of this is reduced at higher- z where gas dominates the disk dynamics. As f_{σ} increases, the points move in the direction of the arrow in the lower right corner. The model provides a good fit to the data, demonstrating that larger, higher surface brightness clumps at high- z are a natural consequence of increasing gas fractions, which explains the observed morphologies of high- z galaxies.

a simple analytic model that seems to describe the observational data well (Trujillo et al. 2006; Förster Schreiber et al. 2009; Williams et al. 2010). We use their scaling relations for mass, size and rotational frequency with redshift in combination with Eq. 8 and Eq. 10 to predict how the cut-off mass and clump surface brightness should evolve with redshift. Figure 9 illustrates this evolution for a gas fraction evolution of $f_{\text{gas}} \propto (1+z)^{2\pm 0.5}$ (Geach et al. 2011). The arrows show how altering the assumed gas fraction changes the model. This suggests that the changing clump properties are a natural consequence of increasing gas frac-

tions dominating high- z galaxy dynamics. The high gas fractions probably arise from high gas infall rates at high redshift (Bournaud & Elmegreen 2009; Krumholz & Dekel 2010; Bournaud et al. 2011); however, our observations do not directly rule in or out cold flows. Our results merely require high gas fractions, and cold flows are a method of maintaining the gas supply. Crucially, we note that this effect is tempered by the more compact nature of galaxies, which leads to higher epicyclic frequencies that limit the collapse on larger scales. The need to include the κ term is apparent from our HII region luminosity functions: without

it, a factor 10 increase in disk surface density would correspond to an increase in clump luminosity of $1000\times$, and we do not observe such a large increase.

To summarise, we find that our simple theoretical model is in good agreement with the observations and suggests that the evolving ‘clumpiness’ of galaxies is a manifestation of the different cut-off mass of the HII region luminosity function, which is driven by evolution in the gas fraction with redshift.

5 CONCLUSIONS

We have used *HST/WFC3* to obtain narrowband H α imaging of eight gravitationally lensed galaxies at $z \sim 1 - 1.5$. The magnification provided by the lensing enables us to reach spatial resolutions in the source plane of $68 - 615$ pc. In addition, to provide comparisons we have re-analysed the lensed $z \sim 2$ sample observed with Keck/OSIRIS by Jones et al. (2010), the Rodríguez-Zaurín et al. (2011) sample of $z < 0.13$ (U)LIRGs observed with VLT/VIMOS and the H α narrowband imaging of the $z = 0$ SINGS survey (Kennicutt et al. 2003).

The high- z samples have ‘clumpy’ morphologies, dominated by a few large regions of high H α luminosity, which we use as a proxy for the SFR. We have extracted star-forming clumps from the galaxies in each sample and examined their properties. The clumps follow similar SFR-size scaling relations in all samples, but the normalisation of the relation exhibits systematic offsets to higher surface brightness at higher redshifts. The normalisation appears to be approximately constant within a given galaxy, implying that this relation is driven by global galaxy properties.

On comparison with the properties of the host galaxies, we find that all samples follow approximately the same scaling relations between the clump surface brightness and both the host galaxy’s total H α luminosity, $L_{H\alpha}$, and its average surface density of star formation, Σ_{SFR} , and that they evolve along this relation in decreasing $L_{H\alpha}$ and Σ_{SFR} with decreasing redshift.

We have measured the luminosity function of clumps in the samples, and shown that the $z \sim 1 - 1.5$ sample is similar to the higher- $L_{H\alpha}$ members of the SINGS sample. When normalised by the host galaxies’ total SFR, the SINGS and $z \sim 1 - 1.5$ samples can be fit by the same Schechter function, while the ULIRGs and $z \sim 2$ samples are offset horizontally. This shift can be explained by an increase in the cut-off mass of the HII region luminosity functions of the ULIRGs and $z \sim 2$ disks.

We present a simple theoretical model which shows that the evolution in luminosity and surface brightness are connected, and are driven by the competing effects of disk surface density Σ_{disk} and the epicyclic frequency κ . Galaxies at high redshift tend to have higher Σ_{disk} , which increases the maximum mass of clumps that are able to form; however, this is tempered by the more compact nature of high- z galaxies, implying higher κ , which impedes collapse on the largest scales.

We have shown that this model is consistent with the evolution in clump properties seen in our data. We therefore conclude that the clumps observed in high- z galaxies are star-forming regions analogous to those found locally but with higher masses and surface brightnesses. As HII re-

gions in the distant Universe are larger and brighter, they give rise to the ‘clumpy’ appearance. The increase in clump luminosity is driven primarily by increasing gas fractions at high- z . This clearly motivates further study with ALMA to better quantify the evolution of gas properties in high- z galaxies.

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REFERENCES

- Bastian N., Emsellem E., Kissler-Patig M., Maraston C., 2006, *A&A*, 445, 471
 Begelman M. C., Shlosman I., 2009, *ApJ*, 702, L5
 Bournaud F., Chapon D., Teyssier R., Powell L. C., Elmegreen B. G., Elmegreen D. M., Duc P.-A., Contini T., Epinat B., Shapiro K. L., 2011, *ApJ*, 730, 4
 Bournaud F., Elmegreen B. G., 2009, *ApJ*, 694, L158
 Bournaud F., Elmegreen B. G., Teyssier R., Block D. L., Puerari I., 2010, *MNRAS*, 409, 1088
 Burgers J. M., 1974, *The Nonlinear Diffusion Equation*. D. Reidal Publishing Co.
 Chabrier G., 2003, *PASP*, 115, 763
 Cowie L. L., Hu E. M., Songaila A., 1995, *AJ*, 110, 1576
 Dekel A., Sari R., Ceverino D., 2009, *ApJ*, 703, 785
 Domínguez A., Siana B., Henry A. L., Scarlata C., Bedregal A. G., Malkan M., Atek H., Ross N. R., Colbert J. W., Teplitz H. I., Rafelski M., McCarthy P., Bunker A., Hathi N. P., Dressler A., Martin C. L., Masters D., 2012, *ArXiv e-prints*
 Dutton A. A., van den Bosch F. C., Faber S. M., Simard L., Kassin S. A., Koo D. C., Bundy K., Huang J., Weiner B. J., Cooper M. C., Newman J. A., Mozena M., Koekoemoer A. M., 2011, *MNRAS*, 410, 1660
 Ebeling H., Barrett E., Donovan D., Ma C.-J., Edge A. C., van Speybroeck L., 2007, *ApJ*, 661, L33
 Ebeling H., Edge A. C., Bohringer H., Allen S. W., Crawford C. S., Fabian A. C., Voges W., Huchra J. P., 1998, *MNRAS*, 301, 881

- Ebeling H., Edge A. C., Henry J. P., 2001, *ApJ*, 553, 668
- Ebeling H., Edge A. C., Mantz A., Barrett E., Henry J. P., Ma C. J., van Speybroeck L., 2010, *MNRAS*, 407, 83
- Elmegreen B. G., Elmegreen D. M., 2005, *ApJ*, 627, 632
- Elmegreen B. G., Elmegreen D. M., Fernandez M. X., Lemonias J. J., 2009, *ApJ*, 692, 12
- Elmegreen B. G., Elmegreen D. M., Hirst A. C., 2004, *ApJ*, 612, 191
- Elmegreen D. M., Elmegreen B. G., Ravindranath S., Coe D. A., 2007, *ApJ*, 658, 763
- Feast M., Whitelock P., 1997, *MNRAS*, 291, 683
- Förster Schreiber N. M., Genzel R., Bouché N., Cresci G., Davies R., Buschkamp P., Shapiro K., Tacconi L. J., et al. 2009, *ApJ*, 706, 1364
- Förster Schreiber N. M., Shapley A. E., Erb D. K., Genzel R., Steidel C. C., Bouché N., Cresci G., Davies R., 2011, *ApJ*, 731, 65
- Förster Schreiber N. M., Shapley A. E., Genzel R., Bouché N., Cresci G., Davies R., Erb D. K., Genel S., et al. 2011, *ApJ*, 739, 45
- Fu J., Guo Q., Kauffmann G., Krumholz M. R., 2010, *MNRAS*, 409, 515
- Garn T., Sobral D., Best P. N., Geach J. E., Smail I., Cirasuolo M., Dalton G. B., Dunlop J. S., McLure R. J., Farrah D., 2010, *MNRAS*, 402, 2017
- Geach J. E., Smail I., Moran S. M., MacArthur L. A., Lagos C. d. P., Edge A. C., 2011, *ApJ*, 730, L19+
- Genzel R., Burkert A., Bouché N., Cresci G., Förster Schreiber N. M., Shapley A., Shapiro K., Tacconi L. J., et al. 2008, *ApJ*, 687, 59
- Genzel R., Newman S., Jones T., Förster Schreiber N. M., Shapiro K., Genel S., Lilly S. J., Renzini A., et al. 2011, *ApJ*, 733, 101
- Genzel R., Tacconi L. J., Eisenhauer F., Förster Schreiber N. M., Cimatti A., Daddi E., Bouché N., Davies R., et al. 2006, *Nature*, 442, 786
- Gini C., 1912, *Memorie di metodologia statistica*
- Gonzalez Delgado R. M., Perez E., 1997, *ApJS*, 108, 199
- Hopkins P. F., 2011, *ArXiv e-prints*
- Hopkins P. F., Quataert E., Murray N., 2012, *MNRAS*, 421, 3488
- Jones T. A., Swinbank A. M., Ellis R. S., Richard J., Stark D. P., 2010, *MNRAS*, 404, 1247
- Jullo E., Kneib J., Limousin M., Elíasdóttir Á., Marshall P. J., Verdugo T., 2007, *New Journal of Physics*, 9, 447
- Kennicutt Jr. R. C., 1988, *ApJ*, 334, 144
- Kennicutt Jr. R. C., 1998a, *ARA&A*, 36, 189
- Kennicutt Jr. R. C., 1998b, *ApJ*, 498, 541
- Kennicutt Jr. R. C., Armus L., Bendo G., Calzetti D., Dale D. A., Draine B. T., Engelbracht C. W., Gordon K. D., et al. 2003, *PASP*, 115, 928
- Kennicutt Jr. R. C., Edgar B. K., Hodge P. W., 1989, *ApJ*, 337, 761
- Kneib J., 1993, PhD thesis, Ph. D. thesis, Université Paul Sabatier, Toulouse, (1993)
- Koekemoer A. M., Fruchter A. S., Hook R. N., Hack W., 2002, in S. Arribas, A. Koekemoer, & B. Whitmore ed., *The 2002 HST Calibration Workshop : Hubble after the Installation of the ACS and the NICMOS Cooling System MultiDrizzle: An Integrated Pyraf Script for Registering, Cleaning and Combining Images.* p. 337
- Korchagin V. I., Girard T. M., Borkova T. V., Dinescu D. I., van Altena W. F., 2003, *AJ*, 126, 2896
- Krumholz M. R., Dekel A., 2010, *MNRAS*, 406, 112
- Lada C. J., Lombardi M., Alves J. F., 2010, *ApJ*, 724, 687
- Mo H. J., Mao S., White S. D. M., 1998, *MNRAS*, 295, 319
- Pello R., Sanahuja B., Le Borgne J.-F., Soucail G., Mellier Y., 1991, *ApJ*, 366, 405
- Rafikov R. R., 2001, *MNRAS*, 323, 445
- Richard J., Kneib J.-P., Jullo E., Covone G., Limousin M., Ellis R., Stark D., Bundy K., Czoske O., Ebeling H., Soucail G., 2007, *ApJ*, 662, 781
- Richard J., Smith G. P., Kneib J.-P., Ellis R. S., Sander-son A. J. R., Pei L., Targett T. A., Sand D. J., Swinbank A. M., Dannerbauer H., Mazzotta P., Limousin M., Egami E., Jullo E., Hamilton-Morris V., Moran S. M., 2010, *MNRAS*, 404, 325
- Rodríguez-Zaurín J., Arribas S., Monreal-Ibero A., Colina L., Alonso-Herrero A., Alfonso-Garzón J., 2011, *A&A*, 527, A60+
- Sand D. J., Treu T., Ellis R. S., Smith G. P., 2005, *ApJ*, 627, 32
- Schmidt W., Federrath C., Hupp M., Kern S., Niemeyer J. C., 2009, *A&A*, 494, 127
- Smith G. P., Ebeling H., Limousin M., Kneib J.-P., Swinbank A. M., Ma C.-J., Jauzac M., Richard J., Jullo E., Sand D. J., Edge A. C., Smail I., 2009, *ApJ*, 707, L163
- Sobral D., Best P., Matsuda Y., Smail I., Geach J., Cirasuolo M., 2011, *ArXiv e-prints*
- Stark A. A., Lee Y., 2006, *ApJ*, 641, L113
- Swinbank A. M., Bower R. G., Smith G. P., Wilman R. J., Smail I., Ellis R. S., Morris S. L., Kneib J., 2007, *MNRAS*, 376, 479
- Swinbank A. M., Papadopoulos P. P., Cox P., Krips M., Ivison R. J., Smail I., Thomson A. P., Neri R., Richard J., Ebeling H., 2011, *ApJ*, 742, 11
- Swinbank A. M., Webb T. M., Richard J., Bower R. G., Ellis R. S., Illingworth G., Jones T., Kriek M., Smail I., Stark D. P., van Dokkum P., 2009, *MNRAS*, 400, 1121
- Trujillo I., Förster Schreiber N. M., Rudnick G., Barden M., Franx M., Rix H.-W., Caldwell J. A. R., McIntosh D. H., et al. 2006, *ApJ*, 650, 18
- Williams J. P., de Geus E. J., Blitz L., 1994, *ApJ*, 428, 693
- Williams R. J., Quadri R. F., Franx M., van Dokkum P., Toft S., Kriek M., Labbé I., 2010, *ApJ*, 713, 738
- Wisnioski E., Glazebrook K., Blake C., Poole G. B., Green A. W., Wyder T., Martin C., 2012, *MNRAS*, p. 2831

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