DISCOVERY OF STRONGLY INVERTED METALLICITY GRADIENTS IN DWARF GALAXIES AT Z~2

Xin Wang1, Tucker A. Jones2, Tommaso Treu3, Jesse Hirtenstein2, Gabriel B. Brammer3, Emanuele Daddi4, Xiao-Lei Meng5, Takahiro Morishita6, Louis E. Abramson7, Alaina L. Henry8, Ying-Jie Peng9, Kasper B. Schmidt3, Kerén Sharon10, Michele Trenti10,11, Benedetta Vulcani12

1 Department of Physics and Astronomy, University of California, Los Angeles, CA, USA 90095-1547
2 University of California Davis, 1 Shields Avenue, Davis, CA 95616, USA
3 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD, 21218, USA
4 Laboratoire AIM, CEA/DSM-CNRS-Université Paris Diderot, IRFU/Service d’Astrophysique, Bât. 709, CEA Saclay, F-91191 Gif-sur-Yvette Cedex, France
5 Physics Department and Tsinghua Center for Astrophysics, Tsinghua University, Beijing 100084, China
6 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD, 21218, USA
7 Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China
8 Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16, D-14482 Potsdam, Germany
9 Department of Astronomy, University of Michigan, 1085 S. University Avenue, Ann Arbor, MI 48109, USA
10 School of Physics, University of Melbourne, VIC 3010, Australia
11 ARC Centre of Excellence for All-Sky Astrophysics in 3-Dimensions, Australia and
12 INAF- Osservatorio Astronomico di Padova, Vicolo Osservatorio 5, I-35122 Padova, Italy

Abstract

We report the first sub-kiloparsec spatial resolution measurements of strongly inverted gas-phase metallicity gradients in two dwarf galaxies at z~2. The galaxies have stellar masses \( \sim 10^8 M_{\odot} \), specific star-formation rate \( \sim 20 \text{ Gyr}^{-1} \), and global metallicity \( 12 + \log(O/H) \sim 8.1 \) (1/4 solar). Their metallicity radial gradients are measured to be highly inverted, i.e., \( 0.122 \pm 0.008 \) and \( 0.111 \pm 0.017 \) dex/kpc, which is hitherto unseen at such small masses in similar redshift ranges. From the Hubble Space Telescope observations of the source nebular emission and stellar continuum, we present the 2-dimensional spatial maps of star-formation rate surface density, stellar population age, and gas fraction, which show that our galaxies are currently undergoing rapid mass assembly via disk inside-out growth. More importantly, using a simple chemical evolution model, we find that the gas fractions for different metallicity regions cannot be explained by pure gas accretion. Our spatially resolved analysis based on a more advanced gas regulator model results in a spatial map of net gaseous outflows, triggered by active central starbursts, that potentially play a significant role in shaping the spatial distribution of metallicity by effectively transporting stellar nucleosynthesis yields outwards. The relation between wind mass loading factors and stellar surface densities measured in different regions of our galaxies shows that a single type of wind mechanism, driven by either energy or momentum conservation, cannot explain the entire galaxy. These sources present a unique constraint on the effects of gas flows on the early phase of disk growth from the perspective of spatially resolved chemical evolution within individual systems.

Subject headings: galaxies: abundances — galaxies: evolution — galaxies: formation — galaxies: high-redshift — gravitational lensing: strong

I. INTRODUCTION

Galaxy formation models require inflows and outflows of gas to regulate star formation (Finlator & Davé 2008; Recchi et al. 2008; Bouche et al. 2010; Davé et al. 2012; Dayal et al. 2013; Dekel et al. 2013; Lilly et al. 2013; Dekel & Mandelker 2014; Peng & Maiolino 2014; Pipino et al. 2014), yet this “baryon cycle” is not quantitatively understood. The interstellar medium (ISM) oxygen abundance (i.e. metallicity) and its spatial distribution is fortunately a key observational probe of this process (Tremonti et al. 2004; Erb et al. 2006; Maiolino et al. 2008; Bresolin et al. 2009; Mannucci et al. 2010, 2011; Zahid et al. 2011; Yates et al. 2012; Zahid et al. 2012; Jones et al. 2013; Sánchez et al. 2014; Zahid et al. 2014; Bresolin & Kennicutt 2015; Ho et al. 2015; Sanders et al. 2015; Strom et al. 2016). “Inside-out” galaxy growth implies that initially steep radial gradients of metallicity flatten at later times (higher masses) as disks grow larger, yet other scenarios suggest metallicities are initially well mixed by strong galactic feedback, and then locked into negative gradients as winds lose the power to disrupt massive gas disks (Prantzos & Boissier 2000; Hou et al. 2000; Mollà & Díaz 2005; Kobayashi & Nakasato 2011; Few et al. 2012; Pilkington et al. 2012; Gibson et al. 2013; Ma et al. 2017). What in common between these scenarios is that none of them predict the existence of a steep positive (i.e. inverted) radial gradient such that metallicity increases with galacto-centric radius.

However, there is growing evidence of such phenomenon in both the local and distant Universe (Cresci et al. 2010; Queyrel et al. 2012; Stott et al. 2014; Troncoso et al. 2014; Sánchez et al. 2014; Pérez-Montero et al. 2016; Wuyts et al. 2016; Belfiore et al. 2017; Carton et al. 2018). The key reason for local galaxies possessing inverted gradients is gas re-distribution by tidal force in strongly interacting systems (Kewley et al. 2006, 2010; Rupke et al. 2010; Rich et al. 2012; Torrey et al. 2012). At high redshifts, inverted gradients are often attributed to the inflows of metal-poor gas from the filaments of cosmic web, infalling directly onto galaxy centers, diluting central metallicities and hence creating positive gradients (Cresci et al. 2010; Mott et al. 2013). Given most of the high-z observations are conducted from the ground with
natural seeing, the targets are usually super-L galaxies with stellar mass \((M_* \geq 10^{10} M_\odot)\) (see e.g., Troncoso et al. 2014).

These high-\(z\) inverted gradients are in concert with the “cold-mode” gas accretion which has long been recognized to play a crucial role in galaxies getting their baryonic mass supply (Birnboim & Dekel 2003; Kereš et al. 2005; Dekel & Birnboim 2006; Dekel et al. 2009b; Kereš et al. 2009). Instead of being shock-heated to dark matter (DM) halo virial temperature \((\sim 10^5 K)\) for a \(M_h \sim 10^{12} M_\odot\) halo and then radiating away the thermal energy to form stars (vis-

hot-mode” accretion), gas streams can remain relatively cold \((<10^6 K)\) while being steadily accreted onto galaxy disks\(^2\). This cold accretion dominates the growth of galaxies forming in low-mass halos irrespective of redshifts since a hot permeating halo of virtualized gas can only manifest in halos above \(2-3 \times 10^{11} M_\odot\), at \(z \lesssim 2\) (Birnboim & Dekel 2003; Kereš et al. 2005).

A question thus arises: if cold-mode gas accretion dominates in low-mass systems (with \(M_*\) less than a few \(10^{10} M_\odot\)) and is thought to lead to inverted gradients under the condition that the incoming gas streams are centrally directed, can we observe this phenomenon in dwarf galaxies (with \(M_* \lesssim 10^9\)) at high redshifts? The answer is not straightforward since the effect of ejective feedback (e.g. galactic winds driven by supernovae) is more pronounced in lower mass galaxies, given their shallower gravitational potential wells and higher specific star-formation rate (sSFR) (see e.g. Hopkins et al. 2014; Vogelsberger et al. 2014). On one hand, galactic winds can bring about kinematic turbulence that prevents a smooth accretion of filamentary gas streams directly onto galaxy center, resulting in rapid formation of in-situ clumps (Dekel et al. 2009a). On the other hand, metal-enriched outflows triggered by these powerful winds can help remove stellar nucleosynthesis yields from galaxy center (Tremonti et al. 2004; Erb et al. 2006). Therefore the existence of strongly inverted gradients in dwarf galaxies at high redshifts, ifany, presents a sensitive test of the relative strength of feedback-induced radial gas flows, in the early phase of the disk mass assembly process. There have not been any attempts to investigate such existence, primarily due to the small sizes of these dwarf galaxies and sub-kiloparsec (sub-kpc) spatial resolution required to yield accurate gradient measurements (Yuan et al. 2013). In this work, we present the first effort to secure two robustly measured inverted metallicity gradients in \(z \sim 2\) star-forming dwarf galaxies from the Hubble Space Telescope (\(HST\)) near-infrared (NIR) grism slitless spectroscopy, aided with galaxy cluster lensing magnification. The details of data and sample galaxies are presented in Section 2. We describe our analysis methods alongside main results in Section 3, and conclude in Section 4. Throughout this paper, a flat ΛCDM cosmology \((\Omega_m = 0.3, \Omega_\Lambda = 0.7, H_0 = 70 \text{ km} \text{s}^{-1} \text{Mpc}^{-1})\) is assumed.

2. DATA AND GALAXY SAMPLE

The two galaxies with exceptional inverted gradients are selected from a comprehensive study of \(\sim 300\) galaxies with metallicity measurements at \(1.2 \lesssim z \lesssim 2.3\) (Wang et al. 2017; Wang et al. in prep.). Before we discuss the two systems in detail in Section 2.4, we give for convenience a brief summary of the spectroscopic data (Section 2.1), a concise description of the data reduction procedure (Section 2.2), and the ancillary imaging used in this work (Section 2.3).

2.1. \(HST\) grism slitless spectroscopy

We use the diffraction-limited spatially resolved slitless spectroscopy, obtained using the \(HST\) wide-field camera 3 (WFC3) NIR grisms (G102 and G141), acquired by the Grism Lens-Amplified Survey from Space (GLASS, Schmidt et al. 2014; Treu et al. 2015). GLASS observes the distant Universe through 10 massive galaxy clusters as natural telescopes, exposing 10 orbits of G102 (0.8-1.15 μm, \(R \sim 210\)) and 4 orbits of G141 (1.1-1.7μm, \(R \sim 130\)) per sightline. This amounts to a sum of \(\sim 21\) kiloseconds of G102 and \(\sim 9\) kiloseconds of G141, as well as \(\sim 5\) kiloseconds of F140W+F105W direct imaging for astrometric alignment and wavelength/flux calibrations per field. These exposures distributed over two separate visits per cluster with nearly orthogonal orientations, designed to help disentangle spectral contamination from neighboring objects. So for each source, two sets of G102+G141 spectrum are obtained, covering an uninterrupted wavelength range of 0.8-1.7μm with almost unchanging sensitivity, reaching a 1-σ surface brightness of \(3 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}\) across the entire spectral range. The GLASS collaboration has made the catalogs of their redshift identifications in the 10 fields, based on visual inspections of emission line (EL) features, publicly available at https://archive.stsci.edu/prepds/glass/.

2.2. Grism data reduction

To explore the chemical properties of galaxies at the peak epoch of cosmic chemical enrichment, we select from these catalogs, a parent sample consisting of \(\sim 300\) galaxies with secure redshifts (i.e. redshift quality \(\geq 3\)) in the range of \(1.2 \lesssim z \lesssim 2.3\). This range is chosen for the detection of multiple nebular ELs\(^3\) — in particular the Balmer lines, \([\text{O} \text{ii}] \lambda 5008\) and \([\text{O} \text{ii}] \lambda 3726, 3729\) — enabling the metallicity measurements, as in our earlier work (Jones et al. 2015b; Wang et al. 2017). The GLASS data for these \(\sim 300\) galaxies are reduced using the Grism Redshift and Line analysis (Grzuzi\(^4\); G. Brammer et al. in prep) software. Grzuzi presents an end-to-end processing of the paired grism and direct exposures. The procedure includes five steps: 1) pre-processing of the raw grism exposures, 2) full field-of-view (FoV) grism model construction, 3) 1D grism and direct exposures. The procedure includes five steps: 1) pre-processing of the raw grism exposures, 2) full field-of-view (FoV) grism model construction, 3) 1D spectrum and EL stamps. In step 1), the pre-processing consists of hot-pixel/persistence masking, cosmic ray flagging, flat fielding, astrometric alignment, sky background subtraction, and extraction of visit-source catalogs and segmentation maps. In step 5), the EL stamps are drizzled onto a grid with a pixel scale of 0.065. Nyquist sampling the WFC3 point spread function (PSF). We apply an additional step on the Grzuzi output products to obtain pure 2D maps of \([\text{O} \text{ii}] \lambda 5008\) and \([\text{H} \beta]\) clean from the partial contamination of \([\text{O} \text{ii}] \lambda 4960\) and \([\text{O} \text{iii}] \lambda 3726, 3729\) := \([\text{O} \text{ii}]\).

2.3. \(HST\) imaging: estimating \(M_*\)

\(^2\) Note however that cold-mode accretion does not necessarily enforce that gas has to reach galaxy center first given the large dynamic range of the scales of galaxy disks (~kpc) and cosmic web (~Mpc).

\(^3\) The names of the forbidden lines are simplified as usual, if presented without wavelength numbers: \([\text{O} \text{ii}] \lambda 5008 := [\text{O} \text{ii}], [\text{O} \text{ii}] \lambda 3726, 3729 := [\text{O} \text{iii}].

\(^4\) https://github.com/gbrammer/grzuli/
2.4. Two dwarf galaxies with strongly inverted metallicity gradients

Out of the parent sample of ~300 galaxies, we are able to secure accurate (i.e. at sub-kpc resolution) radial metallicity gradients on 81 sources with suitable spatial extent and high signal-to-noise ratio (SNR) nebular emission. These extended sources typically have half-light radii $R_{50} \gtrsim 0.1$ kpc. In a range of $7 \lesssim \log (M_*/M_{\odot}) \lesssim 10$ given by the analyses in Section 2.3, our sample probes much lower $M_*$ than other surveys of spatially resolved line emission at similar redshifts (Wuyts et al. 2016; Förster Schreiber et al. 2018), thanks to the enhanced resolution from lensing magnification, and high sensitivity of the HST NIR grisms. We have previously described the properties of 10 galaxies in our sample from the cluster MACS1149.6+2223 (Wang et al. 2017); results for the full sample are in preparation.

In most cases, we find that metallicity gradients are approximately flat (i.e. consistent with zero given the typical error of 0.03 dex kpc$^{-1}$) or slightly negative. A majority (10/81) of our sample shows positive (i.e. “inverted”) gradients, which are of interest as they pose a challenge to standard galactic chemical evolution models (e.g., Mollá & Díaz 2005). We have selected the two best examples with strongly inverted gradients for further study in this paper. The two sources are ID03751 ($z = 1.96$, $M_* = 1.12 \times 10^9 M_{\odot}$) in the prime field of Abell 370, and ID01203 ($z = 1.65$, $M_* = 2.55 \times 10^9 M_{\odot}$) in the prime field of MACS0744.9$-$3927.

Table 1 presents their properties. Figure 1 shows the color composite HST images of these two galaxies and their 2D spatially resolved maps of the nebular ELs. Remarkably, they have $M_*$ considerably lower — by one order of magnitude — than those of previous positive gradients measured at similar redshifts (see e.g., Cresci et al. 2010; Queyrel et al. 2012; Stott et al. 2014; Troncoso et al. 2014). To complement the low dispersion grism spectra, we have obtained adaptive optics (AO) assisted kinematic data on our sources using ground-based integral-field unit (IFU) spectrograph when available. The observation of source ID01203 is presented in Appendix A. The

| ID       | 03751  | 01203  |
|----------|--------|--------|
| cluster  | Abell 370 | MACS0744.9$-$3927 |
| R.A. (deg.) | 39.977361 | 116.97585 |
| Decl. (deg.) | -1.91636 | 39.456968 |
| $z_{spec}$ | 1.96 | 1.65 |
| $\mu^b$ | $6.35^{+0.40}_{-0.08}$ | $2.25^{+0.04}_{-0.01}$ |
| Observed emission line fluxes | |
| $EW_{[O\,\text{iii}]}$ | 111.41$^{+0.84}_{-1.17}$ | 111.66$^{+1.17}_{-1.17}$ |
| $EW_{[O\,\text{iii}]}$ | 17.68$^{+0.68}_{-1.06}$ | 17.46$^{+1.06}_{-1.06}$ |
| $EW_{[O\,\text{iii}]}$ | 29.57$^{+0.51}_{-0.96}$ | 34.00$^{+0.96}_{-0.96}$ |
| $EW_{H\beta}$ | 7.21$^{+0.67}_{-0.01}$ | 7.06$^{+0.01}_{-0.01}$ |

Restframe equivalent widths

| $EW_{[O\,\text{iii}]}$ | 406.22$^{+3.52}_{-7.95}$ | 79.14$^{+7.95}_{-7.95}$ |
| $EW_{H\beta}$ | 73.98$^{+2.83}_{-11.28}$ | 118.29$^{+7.18}_{-7.18}$ |
| $EW_{[O\,\text{iii}]}$ | 79.14$^{+1.37}_{-1.37}$ | 123.91$^{+3.50}_{-3.50}$ |
| $EW_{H\beta}$ | 30.18$^{+2.82}_{-2.53}$ | 25.73$^{+3.68}_{-3.68}$ |

Estimated physical parameters

| $M_* [10^9 M_{\odot}]$ | $1.12^{+0.14}_{-0.14}$ | $2.55^{+0.04}_{-0.04}$ |
| $12 + \log (O/H)$ | $8.05^{+0.12}_{-0.12}$ | $8.05^{+0.12}_{-0.12}$ |
| $\Delta \log (O/H)/\Delta [\text{dex/kpc}]$ | $0.122^{+0.008}_{-0.008}$ | $0.111^{+0.017}_{-0.017}$ |
| SFR $[M_*/\text{yr}]$ | $25.39^{+2.19}_{-8.66}$ | $48.86^{+3.04}_{-3.04}$ |
| $A_V$ | $0.84^{+0.13}_{-0.10}$ | $0.90^{+0.16}_{-0.16}$ |
| $i_{90} [10^6 \text{yr}]$ | $7.93^{+0.88}_{-0.88}$ | $3.98^{+0.51}_{-0.51}$ |
| $M_{{gas}} [10^9 M_{\odot}]$ | $4.07^{+1.27}_{-0.23}$ | $22.85^{+7.33}_{-7.33}$ |
| $f_{{gas}}$ | $0.56^{+0.20}_{-0.19}$ | $0.86^{+0.13}_{-0.13}$ |
| $B/T^8$ | $0.36^{+0.14}_{-0.14}$ | $0.14^{+0.07}_{-0.07}$ |

Gas kinematics

| $\sigma [\text{km/s}]$ | $79^{+3}_{-4}$ | $0.8^{+0.1}_{-0.1}$ |
| $V_{\sigma}$ | $49.9^{+14.7}_{-52.1}$ | $52.1^{+20.2}_{-52.1}$ |
| $\Psi [M_*/\text{yr}]$ | $313.3^{+96.2}_{-1700.9}$ | $1700.9^{+681.9}_{-1700.9}$ |

$^a$ The magnification estimates are obtained from the SExtractor & Johnson version 4 model of Abell 370 (Johnson et al. 2014) and the Zitrin PIEMD+ENFW version 2 model of MACS0744.9$-$3927 (Zitrin et al. 2015), for the two sources respectively.

$^b$ Values presented here are corrected for lensing magnification.

$^c$ Values represent global metallicity, inferred from integrated line fluxes.

$^d$ The bulge-disk decomposition, we fix the Sérsic index $n = 4$ (i.e. de Vaucouleurs) for the bulge component, and $n = 1$ (i.e. exponential) for the disk component.

$^e$ Ground-based Keck OSIRIS follow-up observations targeting He or [O iii] gas kinematics for this source are not feasible due to significantly low atmospheric transmission at the corresponding wavelengths.

full data analysis will be included in a separate work (Hirtenstein et al. in prep).

3. METHODS AND RESULTS

In this section, we describe our key methods used to derive radial metallicity gradients (Section 3.1), 2D maps of SFR, average stellar population age, and gas fraction (Section 3.2), as well as spatial distributions of net gaseous outflow rate and mass loading factor (Section 3.3). The main results are presented alongside the corresponding methods.

3.1. Radial metallicity gradients

Since we infer metallicity from strong line flux ratio diagnostics, calibrated by either empirical methods, or theoretical methods, or a hybrid of both, it is essential to make sure that the line emission is not contaminated by active galactic nucleus (AGN) ionization or shock excitation. We check that our targets have a low probability (<10%) of being classified as AGN according to the mass-excitation diagram (Juneau et al. in prep).
Their individual spatial pixels (spaxels) also have excitation states, as revealed in their loci in the [O iii]λλ3726,3729 versus [O ii]λλ3726,3729 diagram, compatible with Hii regions (Lamareille 2010; Rodrigues et al. 2012; Jones et al. 2015a). In the source ID01203 covered by our follow-up OSIRIS observations (see Appendix A), its integrated [N ii]/Hα (≤ 0.1 at 3-σ) also shows no sign of AGN or shocked gas emission.

Our measurements of radial metallicity gradients largely follow the procedures described in our previous work (Wang et al. 2017). We use a Bayesian approach to jointly infer metallicity (12 + log(O/H)), nebular dust extinction (A_V), and de-reddened Hβ flux (f_{Hβ}). We explore the parameter space using the Markov Chain Monte Carlo sampler EMCEE (Foreman-Mackey et al. 2013). The likelihood function is given by $L \propto \exp(-\chi^2/2)$ with

$$\chi^2 = \sum_i \left( \frac{f_{ELi} - R_i \cdot f_{Hβ}}{(\sigma_{ELi})^2 + (f_{Hβ})^2 \cdot (\sigma_{Ri})^2} \right)^2,$$

where EL_i corresponds to each available EL: [O ii], Hβ, [O iii], and Hγ. f_{ELi} and σ_{ELi} are the flux and uncertainty of EL_i, R_i is the flux ratio between EL_i and Hβ, with σ_{Ri} being the intrinsic scatter at fixed physical properties. In the case EL_i = Hγ, R_i is given by the Balmer decrement Hγ/Hβ = 0.47. For EL_i ∈ {[O ii], [O iii]}, R_i and σ_{Ri} are given by strong line metallicity diagnostics calibrated by Maiolino et al. (2008). We also adopt the empirical calibrations by Curti et al. (2016) based on metallicities given by pure electron temperature method, and verified that there is no significant change in our gradient measurements. The same process is applied to both galaxy-integrated fluxes and to fluxes measured at individual spaxels.

To obtain the correct intrinsic de-projected distance scale for each spaxel, we conducted full source plane morphological reconstruction of our sources. We ray-trace the image of each galaxy to its source plane using up-to-date lens models for each cluster: the macroscopic model of Sharon & Johnson version 4 for Abell 370 (Johnson et al. 2014), and the Zitrin version 2 model for MACS0744.9+3927 (Zitrin et al. 2015). Other lens models are available for these clusters (e.g. Diego et al. 2016; Strait et al. 2018) and we verified that the morphology of each source is robust to the choice of model.

For each source, we fit the spectral energy distributions of individual spaxels using the procedures described in Section 2, obtaining the 2D stellar surface density ($\Sigma_*$) map shown in Figure 1. Then we reconstruct $\Sigma_*$ map in the source plane. The axis ratios, inclinations, and major axis orientations are determined from an elliptical Gaussian fit. This procedure provides the intrinsic lensing–corrected morphology, and in particular, the galacto-centric radius at each point of the observed images. The radial scale as black contours in all figures is used to establish the absolute metallicity gradient slope (i.e., in units of dex per proper kpc).

Figure 2 shows the 2D maps of metallicity of our selected two dwarf galaxies at $z \sim 2$. Clearly, the outskirts of our galaxies display highly elevated oxygen abundance ratios. In particular, the outskirts of ID03751 are more metal enriched by ~0.4 dex (i.e. a factor of 2.5) than its center, and more metal-rich by ~0.2 dex than the value inferred based on the fundamental metallicity relation (FMR) given its integrated $M_*$, Mannucci et al. (2010, 2011). For the first time, we are able to detect strongly inverted metallicity gradients in $z \sim 2$ dwarf galaxies at unprecedentedly high confidence: 0.122±0.008 dex/kpc for ID03751 (~ 15.2σ), and 0.111±0.017 dex/kpc for ID01203 (~ 6.5σ).

The question is thus what caused these dwarf galaxies to have such strongly inverted gradients? First of all, our sources show no evidence of major mergers, supported by their regular morphology displayed in the 2D maps of $M_*$ and EL surface brightness in Figure 1. For source ID01203 with OSIRIS data, this statement is further strengthened by the kinematic evidence of disk orderly rotation. Secondly, the fact that the outskirts of our sources show elevated metallicity as compared to the FMR expectations indicates that there are more metals in the outer regions than could be produced by the stars in those regions. This discourages any explanations involving solely low-metallicity gas inflows, not limited to those induced by mergers. In the subsequent sections, we thus gather all available pieces of observational evidence to further investigate the possible cause.

3.2. SFR, stellar population age, and gas fraction

To understand the cause of the strongly inverted metallicity gradients seen in these dwarf galaxies, we combine their EL maps with HST broad-band photometry to derive 2D maps of $M_*$, SFR, stellar population age, and gas surface density
Inverted Metallicity Gradients in High-$z$ Dwarf Galaxies

for each galaxy. The SFR is derived from extinction-corrected Balmer emission line flux. Maps of Hβ and Hγ emission are shown in Figure 1. The Hβ/Hγ line ratio provides a measurement of nebular extinction although it is limited by the modest signal-to-noise of Hγ. We obtain more precise results from HST photometry, by converting $B_{435}-I_{444}$ color maps to spatial distributions of stellar reddening $E_B(B-V)$ (Daddi et al. 2004). Nebular reddening $E_N(B-V)$ is then calculated following Valentino et al. (2017). The nebular reddening maps of both our galaxies show lower dust attenuation in centers than at outskirts, consistent with the inverted metallicity gradients shown in Figure 2.

We calculate extinction in Hβ adopting a Cardelli et al. (1989) dust extinction law (with $R_V=3.1$) and assuming Case B recombination with Balmer ratios appropriate for fiducial Hα region properties (i.e., $Hα/Hβ = 2.86$). Finally, we convert intrinsic Hα luminosity to SFR through the commonly used calibration (Kennicutt 1998a; Moustakas et al. 2010),

$$\text{SFR} = 4.6 \times 10^{-42} \frac{L(Hα)}{\text{erg/s}} \ [M_\odot/\text{yr}],$$

appropriate for the Chabrier (2003) IMF. This provides the instantaneous star formation rate on $\sim 10$ Myr time scales; we note that the ultraviolet continuum probed by HST photometry is sensitive to recent SFR over a longer time span ($\sim 100$-300 Myr). The short timescales probed by Balmer emission are most relevant for determining outflow physical properties, which are highly dynamic on small spatial scales, e.g., at sub-kpc level.

Next we derive average stellar age maps, using the spatial distribution of EL EW as the primary constraint. We calculate Hβ rest-frame EWs from our maps of the emission line flux and stellar continuum flux density. Stellar continuum maps are corrected for emission line contamination as described in Section 2. We correct for stellar Balmer absorption which we estimate to be rest-frame EW $\sim 3$ Å in Hβ based on the derived galaxy properties (Kashino et al. 2013). Maps of Hβ EW are then converted to average stellar age using a series of Starburst99 stellar population synthesis models (Leitherer et al. 1999; Zanella et al. 2015) assuming 1/5 solar metallicity and constant star formation history.

We also compare the age estimates given by our SED fitting (Section 2) and Hβ rest-frame EW using the method described above. The median values given by the former practice are systematically larger than those of the latter by $\sim 0.5$ dex, but we note that the uncertainties by the SED fitting are usually much larger due to the absence of prominent continuum spectral age indicators, e.g., $D_n(4000)$ and H$\alpha$ (Kauffmann et al. 2003). Hence, we adopt the results from Hβ rest-frame EW as the average age for stellar populations throughout our paper, as we consider this a more reliable estimate.

Finally, we calculate the gas fraction defined as $f_{\text{gas}} \equiv M_{\text{gas}} / (M_{\text{gas}} + M_*) = \Sigma_{\text{gas}} / (\Sigma_{\text{gas}} + \Sigma_*)$. Since we do not directly observe the bulk of interstellar gas, we instead estimate gas surface density $\Sigma_{\text{gas}}$ by inverting the Kennicutt-Schmidt
(KS) law (Schmidt 1959; Kennicutt 1998b), i.e., $\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{\alpha}$ together with our measurements of $\Sigma_{\text{SFR}}$ described above. We adopt the more robust extended version of the KS law developed by Shi et al. (2011, 2018) which is especially useful in low density regimes:

$$\frac{\Sigma_{\text{SFR}}}{M_\odot/\text{yr/kpc}^2} = 10^{-4.76} \left(\frac{\Sigma_{\text{gas}}}{M_\odot/\text{pc}^2}\right)^{0.545} \left(\frac{\Sigma_{\text{gas}}}{M_\odot/\text{pc}^2}\right)^{1.09}. \quad (3)$$

This extended KS law has been tested in numerous ensembles of galaxies as well as low surface brightness regions in individual galaxies, and is shown to have relatively small scatter ($\sim 0.3$ dex) over a large dynamic range of gas and SFR surface densities. We have combined in quadrature this systematic uncertainty of 0.3 dex in our estimates of $\Sigma_{\text{gas}}$.

Figure 3 shows the derived 2D maps of SFR, average stellar age, and gas fraction. In general, we observe centrally concentrated star formation, with the most actively star-forming regions having surface densities $\gtrsim 10 M_\odot/\text{yr/kpc}^2$. On average, the central regions also have older stellar populations and smaller gas fractions than the outskirts, indicating that the outer regions are still in the early stages of converting their gas into stars. These features together indicate that we are witnessing the rapid build-up of galactic disks through in situ star formation and strongly support an inside-out mode of galaxy growth (Nelson et al. 2014; Jones et al. 2013).

As in Cresci et al. (2010), we compare our radially averaged $f_{\text{gas}}$ and metallicity measurements against the predictions from the simple chemical evolution model developed by Erb (2008). To separate the effects of gas inflows and outflows, we compute two extreme sets of results, one being pure gas accretion (i.e. with no outflows, $f_o = \Psi$/SFR = 0) and the other corresponding to the leaky box model (i.e. with no inflows, $f_i = \Phi$/SFR = 0). The results are shown in Figure 4. We note that for the pure gas accretion scenario, $f_{\text{gas}}$ cannot decrease beyond a certain value, i.e.,

$$f_{\text{gas}} = 1 - \frac{1 - R}{f_i - f_o},$$

where $f_o = 0$ and $R$ is the instantaneous return fraction. This $f_{\text{gas}}$, implicitly imposed by Eq. (11) of Erb (2008), physically indicates that galaxies cannot exhaust their gas reservoir to below a certain amount without the help of outflows, under the equilibrium condition with steady gas accretion (see Section 3.3 when this equilibrium assumption is relaxed). Therefore, the pure gas accretion scenario cannot explain the observed gas fractions in our source central regions (at $\lesssim 2\text{kpc}$) where metallicities are also lower. The leaky box model, on the other hand, provides a plausible explanation for our observation such that the outflow rate tends to increase towards galaxy center.

### 3.3. Spatially resolved gaseous outflows

The application of simple chemical evolution in Section 3.2 is enlightening but depends on strong assumption, such as that the azimuthal variations are negligible and galaxies live in equilibrium. In reality, these conditions might not be valid, e.g., due to rapid gas flows. To gain a more precise understanding of the physics of galactic winds and the role of gaseous outflows in shaping the observed spatial distribution of metallicity, independent of those assumptions, we can turn to a more advanced framework for galaxy chemical evolution: the gas regulator model (Lilly et al. 2013; Peng & Maiolino 2014). This model provides an informative and coherent view of the full baryon cycle, involving the accretion of underlying DM halos, as well as the instantaneous regulation of star formation by a time-variable gas reservoir. A key feature of this model is that it does not assume that galaxies live in an equilibrium state, where the total amount of gas mass remains constant. The non-equilibrium flexibility is especially important for applying this model to spatially resolved regions within a galaxy, where gas may be transported radially from one region to another. Chemical evolution within the gas regulator model is described by the equations:

$$Z_{\text{gas}} = \left[ Z_0 + \gamma \tau_{\text{eq}} \epsilon \left(1 - \exp\left(-\frac{t}{\tau_{\text{eq}}}\right)\right) \right] \left[ 1 - \exp\left(-\frac{-t}{\tau_{\text{eq}}}\right) \right]. \quad \text{(4)}$$

Here we adopt the convention of symbols itemized in Table 1 of Peng & Maiolino (2014): $Z_{\text{gas}}$ is the mass fraction of metals in the gas reservoir (determined from the observed $12 + \log(O/H)$ as in Peeples & Shankar (2011)), $\epsilon$ is the average stellar population age, $\tau_{\text{eq}}$ is the time scale on which the baryon cycle reaches equilibrium, $\gamma$ is the star-forming efficiency (defined as $\delta = \text{SFR}/M_{\text{gas}} = \Sigma_{\text{SFR}}/\Sigma_{\text{gas}}$), and $\lambda$ is the mass loading factor (defined in terms of the mass outflow rate $\Psi$, such that $\lambda = \Psi/\text{SFR}$). We adopt a stellar nucleosynthesis yield $\gamma = 0.003$ (Dalcanton 2007) with $R = 0.4$ estimated from BC03 (Bruzual & Charlot 2003) stellar population models. Finally, we assume that gas inflows are pristine ($Z_i = 0$).

For each spatial region where we have estimated the metallicity, SFR, gas surface density, and age (Figures 2, 3), we solve the above equations for the mass loading factor $\lambda$ and subsequently calculate the mass outflow rate $\Psi$. The 2D distribution of $\Psi$ is displayed in Figure 5. Taking a gradient of the outflow map, we obtain the direction of the net mass flux on sub-galactic scales, denoted by the red arrows in Figure 5. The results demonstrate that strong galactic winds transport mass from the center to the outskirts, with the net radial transport of heavy elements causing the inverted gradients observed in our targets.

The distribution of mass loading factors $\lambda$ within each of our targets is also shown in Figure 6, revealing higher $\lambda$ (and therefore a higher fraction of metals lost) in the central regions. This preferential removal of metals from the center, and subsequent deposition at larger radii, gives rise to the strong positively sloped metallicity gradients evident in Figure 2. The high values of $\lambda$ have important implications for the role of feedback in galaxy formation. Most fundamentally, our results support feedback as a solution to the “over-cooling” problem in galaxy formation, by ejecting gas and preventing overly condensed baryonic regions at high redshifts (White & Rees 1978; Dekel & Silk 1986). Such strong outflows are also expected to suppress the formation of stellar bulges from low angular momentum gas (Governato et al. 2010; Brook et al. 2012). This is consistent with low bulge fraction in these two galaxies measured from high resolution $HST$ imaging (Table 1).

A key feature in the $\lambda$ distribution is that neither of the wind modes, driven by momentum or energy conservation, can explain the behavior of the mass dependence of $\lambda$ alone.

---

Note that $\lambda$ and $f_o$ in Section 3.2 represent the same quantity but here we are solving for $\lambda$ in a spatially resolved fashion.
Fig. 3.— Maps of SFR surface density, average stellar population age, and gas fraction for our galaxies, derived from our spatially resolved analysis of stellar continuum and nebular emission. The spatial extent and orientation follows that in Figure 1. We see that for both sources compared with their outskirts, their central regions have more active star formation, older stellar population, and lower gas fraction.

Fig. 4.— Gas fraction and metallicity estimated in different radial annuli for galaxy ID03751. The diamond, circle, and star symbols represent measurements derived at a galacto-centric radius of $r \in [0,1)$kpc, $r \in [1,2)$kpc, and $r \geq 2$kpc, respectively. We also overlay the curves calculated from a simple chemical evolution model Erb (2008) under extreme conditions, i.e., pure gas inflow ($f_i = 0$; left) and pure gas outflow ($f_o = 0$; right). Note that the trajectories of pure gas inflow cases cease at the grey squares for high infall rate ($f_i \geq 1$) conditions; any extensions from those grey squares toward low gas fraction (while fixing metallicity) are unphysical. This simple comparison shows that purely gas accretion does not suffice to explain the strong inverted gradients seen in our galaxies.
Fig. 5.— Maps of gaseous outflow rates derived from our analysis combining gas regulator models and empirical star-formation laws. The spatial extent and orientation follows that in Figure 1. Red arrows show the net direction and magnitude of the gaseous outflows driven by galactic winds. We argue that outflows play a key role in effectively transporting stellar nucleosynthesis yields from the inner regions of these two galaxies to their outskirts.

Fig. 6.— Correlation between spatially resolved mass loading factor $\lambda$ (normalized to the value at radius 1 kpc; see Table 1) and stellar surface density $\Sigma_*$, color-coded by metallicity. As in Figure 3, the diamond, circle, and star symbols represent measurements derived at a galacto-centric radius of $r \in [0, 1)$ kpc, $r \in [1, 2)$ kpc, and $r \geq 2$ kpc, respectively. We overlay as an illustration two scaling relations that are commonly assumed to describe integrated measurements: $\lambda \propto \Sigma^{-2/3}_*$ for an energy-driven wind model marked by magenta dotted lines, and $\lambda \propto \Sigma^{-1/3}_*$ for a momentum-driven wind model by cyan dashed lines. Evidently, a single scaling relation is not sufficient to describe the spatially resolved data, demonstrating the need for a more sophisticated approach. The black point in the lower right corner in each panel displays the median uncertainties for these measurements.
within individual galaxies. Outflows are typically parameterized by either a momentum-driven (Oppenheimer & Davé 2006, 2008) or an energy-driven (Springel & Hernquist 2003) wind mode, both of which are physically well motivated (Murray et al. 2005). The energy-driven wind scenario assumes that outflows are launched by the thermal pressure of supernova (SN) explosions and/or winds from massive stars. A portion of this thermal energy provides the outflow kinetic energy, i.e., \( \Psi \propto v_{\text{wind}}^2 \propto \text{SFR} \), where the wind speed \( v_{\text{wind}} \) can mimic the escape velocity from DM halo, i.e., \( v_{\text{esc}} \propto M_1^{1/3} \) given by the virial theorem. This results in the scaling relation of \( \lambda \propto M_2^{2/3} \), assuming the linear correlation between the mass constituents of stellar and dark components. The energy-driven wind model is found successful in explaining the low abundance of satellite galaxies in the Milky Way (Okamoto et al. 2010). The momentum-driven wind model instead relies on the momentum injection deposited by radiation pressure from SN explosions and/or massive stars, leading to \( \Psi \propto v_{\text{wind}} \propto \text{SFR} \) and \( \lambda \propto M_2^{-1/3} \). In this scenario, \( v_{\text{wind}} \) is proportional to \( M_2 \) and SFR, broadly consistent with some observational results (Martin 2005). The transition from energy- to momentum-driven winds is typically thought to be a galaxy-wide phenomenon, resulting in the steepening of the mass-metallicity relation below \( M_2 \approx 10^{9.3} M_\odot \) at \( z \approx 2 \) (Henry et al. 2013). However, our analysis indicates that a single mode is not sufficient to describe spatially resolved data within one galaxy and it is highly likely that the transition from energy- to momentum-driven winds occurs on sub-galactic scales, governed by local gas and star formation properties in addition to the global gravitational potential.

4. SUMMARY AND DISCUSSION

We present the first robust confirmation of the existence of strongly inverted metallicity radial gradient (i.e. \( \gtrsim 0.1 \text{dex/kpc} \)) in star-forming dwarf galaxies (\( M_\star \lesssim 10^9 M_\odot \)) at the peak of star formation and chemical enrichment (\( z \sim 2 \)).

Our synergy of the diffraction-limited imaging spectroscopy from \( HST \) NIR grisms and lensing magnification permits exquisite spatial sampling, i.e., at the scale of 50-100 pc, to securely resolve our \( z \sim 2 \) galaxies with \( \gtrsim 300 \) resolution elements (Figures 1 and 2) to deliver precise radial gradient measurements. To understand the physical origin of these strongly inverted gradients, we obtain high resolution 2D maps of star formation rate, characteristic stellar age (or equivalently star formation timescale), and gas fraction, from \( HST \) observations of source stellar continuum and nebular emission. These 2D maps show that the galactic disks of our sources are rapidly assembling stellar mass through in-situ star formation, in the early phase of inside-out growth (Figure 3). By comparing our observations with simple chemical evolution models, we find that gas accretion alone cannot explain these strongly inverted gradients in our galaxies (Figures 4).

Using a more advanced gas regulator model, we are able to calculate the spatial distribution of mass loss rates from outflows, treating each spixel as an independent star-forming region, and thus map the macroscopic patterns of net gaseous outflows (Figure 5). It turns out that the mass loss rates are highest in the central regions of both galaxies, coincident with the peak star formation surface densities. A natural explanation is that active star formation in galaxy centers gives rise to powerful winds that transport gas and metals away from the center toward larger radii, forming “galactic fountains” (Martin et al. 2002).

Furthermore, our spatially resolved analysis of metals, SFR, and stellar populations shows that a single type of wind mechanism (either energy or momentum driven) cannot explain the entire galaxy (Figure 6). A primary physical parameter that has been proposed to set the transition between the two wind dynamics is the gravitational potential, often parameterized by velocity dispersion \( \sigma \). There exists a critical scale \( \sigma_{\text{crit}} \) (Murray et al. 2005) such that for galaxies with \( \sigma < \sigma_{\text{crit}} \), energy injection by SNe sets a limiting SFR above which interstellar gas is ejected in galactic winds. For galaxies with \( \sigma > \sigma_{\text{crit}} \), momentum deposition limits the maximum SFR above which the ISM is likewise ejected. The presence of both energy- and momentum-driven wind scalings in one galaxy suggests that feedback-triggered winds are connected to physical properties on sub-galactic scales, e.g., local velocity dispersion \( \sigma_{\text{local}} \), which is sensitive to the optical depth of gas flows, the coupling efficiency between gas clouds and dust parcels, etc.. On sub-galactic scales, there exists a strong correlation among velocity dispersion (not necessarily \( \sigma_{\text{local}} \)), surface density and size of molecular clouds (see Ballesteros-Paredes et al. 2011, and references therein). It appears that in our galaxies, the wind-launching mechanism transitions from energy- to momentum-driven as galacto-centric radius increases. This gives rise to a hypothesis that \( \sigma_{\text{local}} \) in our galaxies should increase from inner to outer regions. Our current kinematic data on source ID01203 have high spatial resolution (at 0’05 scale plate) yet narrow FoV so that it is infeasible to map sub-kpc scale velocity dispersion accurately to outer regions at \( r \gtrsim 2 \) kpc, where momentum-driven wind seems to take over. To test this hypothesis conclusively, more spatially resolved data taken under sufficient spatial sampling will be required to robustly derive a full 2D map of velocity dispersion out to the periphery of the galactic disk, using instruments with relatively large FoV, e.g., the \( JWST \) NIRSpec IFU.

Physically, the momentum-driven wind scaling applies to “cool” (\( T \sim 10^4 \) K) ambient interstellar gas entrained in outflows, whereas the energy-driven wind is appropriate when entrained gas is shock heated to temperatures where cooling is inefficient (\( T \sim 10^6 \) K). A plausible scenario for our galaxies is that feedback from an intense burst of star formation in the central regions heats the ejected gas to a highly ionized phase, while gas entrained in outflows from the outer regions remains cool. If this interpretation is correct, then we expect a distinct signature in the absorption properties of outflowing gas. Outflows from the central regions should be dominated by highly ionized species (e.g. O \( \text{vi} \), C \( \text{iv} \), Si \( \text{iv} \)) whereas outflows from the outer regions should have relatively more of the low ions characteristic of \( T \sim 10^4 \) K gas (e.g. Fe \( \text{ii} \), Mg \( \text{ii} \), Si \( \text{ii} \)). Both high and low ion species are commonly observed in outflows from star forming galaxies at \( z \approx 2 \) (Du et al. 2018), although their spatial distributions are not yet well known. Our hypothesis suggests a more central concentration of the high ions in the specific cases where a combination of both outflow scalings results in inverted metallicity gradients. This prediction can be directly tested with spatially resolved spectroscopy of rest-frame ultraviolet absorption lines using instruments such as Keck/KCWI or VLT/MUSE.

This study makes use of Hubble Space Telescope data collected by the GLASS program. We gratefully acknowledge support by NASA through HST grant HST-GO-13459. XW thanks Tuan Do, Suoqing Ji, Dušan Kereš, Roberto Maiolino,
Yong Shi, Enci Wang, Pieter van Dokkum, Anita Zanella, and Dong Zhang for helpful discussions. YP acknowledges support from the National Key Program for Science and Technology Research and Development under grant number 2016YFA0400702, and the NSFC grant no. 11773001.

APPENDIX

A. GAS KINEMATICS FROM Keck OSIRIS OBSERVATIONS

Kinematics of H\textsc{ii} regions are of interest both for determining whether rotating gaseous disks are present, and the overall scale of velocity dispersion which is thought to correlate with the mode of feedback. We have obtained kinematic maps from H\textalpha\ emission for source ID01203 as part of a GLASS followup campaign with the OSIRIS integral field spectrograph (Larkin et al. 2006) on the Keck I telescope. Full details of the observations and analysis will be presented elsewhere (Hirtenstein et al. in prep); here we give a brief summary. Data were obtained on 2016 October 21 using the Hn5 filter, 50 milliarcsecond scale, and laser guide star AO, which provides the excellent spatial sampling needed to resolve velocity structure on the relevant ∼0.7 arcsec.

We obtained 3 exposures of 900 seconds each. The OSIRIS Data Reduction Pipeline was used to process the data, following the standard methods adopted in our previous work (Jones et al. 2013). We fit H\textalpha line emission in each spaxel with a Gaussian function, requiring ≥5\sigma significance for acceptable fits. Gas velocities (V) and velocity dispersions (\sigma) are derived from the Gaussian centroid and width. We correct velocity dispersions for the effects of instrument resolution and beam smearing by subtracting these terms in quadrature from the best-fit Gaussian dispersion. The median beam smearing correction is a 7% level of ISM turbulence. This V curve is in good agreement with the data, with maximum velocity V along the kinematic major axis. We fit this with the circular rotation curve of an exponential disk mass profile. The disk rotation curve is in good agreement with a disk rotation curve despite a high level of turbulence.

Resulting maps of V and \sigma in Figure A1 reveal a sheared velocity field with high local velocity dispersion (≥ 50 km s\textsuperscript{-1}), common among disk galaxies at similar redshift. To quantify the degree of rotational support, we extract a 1D velocity profile along the kinematic major axis. We fit this with the circular rotation curve of an exponential disk mass profile. The disk rotation curve is in good agreement with the data, with maximum velocity V\textsubscript{rot} sin i = 60 ± 6 km s\textsuperscript{-1}. Here i is the disk inclination angle relative to the line-of-sight. The pixel-averaged \sigma\textsubscript{perp} = 79 ± 3 km s\textsuperscript{-1} such that we derive V/\sigma = (0.8 ± 0.1)/sin i indicating a high level of ISM turbulence. This V/\sigma ratio is typical of the galaxy population at similar mass and redshift (Wisnioski et al. 2015; Leethochawalit et al. 2016).

REFERENCES

Ballesteros-Paredes, J., Hartmann, L. W., Vázquez-Semadeni, E., Heitsch, F., & Zamora-Avilés, M. A. 2011, Monthly Notices of the Royal Astronomical Society, 411, 65
Belfiore, F., Maiolino, R., Tremonti, C. A., et al. 2017, Monthly Notices of the Royal Astronomical Society, 469, 151
Bertin, E., & Arnouts, S. 1996, Astronomy and Astrophysics Supplement Series, 117, 393
Bimboin, Y., & Dekel, A. 2003, Monthly Notices of the Royal Astronomical Society, 345, 349
Bouche, N., Dekel, A., Genzel, R., et al. 2010, The Astrophysical Journal, 718, 1001
Bresolin, F., Gieren, W., Kudritzki, R.-P., et al. 2009, The Astrophysical Journal, 700, 309
Bresolin, F., & Kennicutt, R. C. 2015, Monthly Notices of the Royal Astronomical Society, 454, 3664
Brook, C. B., Stinson, G. S., Gibson, B. K., et al. 2012, Monthly Notices of the Royal Astronomical Society, 419, 771
Brzual, G., & Charlot, S. 2003, Monthly Notices of the Royal Astronomical Society, 344, 1000
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, The Astrophysical Journal, 533, 682
Cappellari, M., & Copin, Y. 2003, Monthly Notices of the Royal Astronomical Society, 342, 345
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, The Astrophysical Journal, 345, 245
Carton, D., Brinchmann, J., Contini, T., et al. 2018, Monthly Notices of the Royal Astronomical Society, 480, 1431
Chabrier, G. 2003, Publications of the Astronomical Society of the Pacific, 115, 763
Cresci, G., Mannucci, F., Maiolino, R., et al. 2010, Nature, 467, 811
Curti, M., Cresci, G., Mannucci, F., et al. 2016, eprint arXiv:1610.06939, stw2766
Daddi, E., Cimatti, A., Renzini, A., et al. 2004, The Astrophysical Journal, 617, 746
Dalcanton, J. J. 2007, The Astrophysical Journal, 658, 941
Davé, R., Finlator, K., & Oppenheimer, B. D. 2012, Monthly Notices of the Royal Astronomical Society, 421, 98
Dayal, P., Ferrara, A., & Dunlop, J. S. 2013, Monthly Notices of the Royal Astronomical Society, 430, 2891

Software: Astropy (Price-Whelan et al. 2018), APLpy (Robitaille & Bressert 2012), ASTRODrizzle (Gonzaga & al 2012), EMCEE (Foreman-Mackey et al. 2013), FAST (Kriek et al. 2009), Galfit (Peng et al. 2002), SExtractor (Bertin & Arnouts 1996), VorBin (Cappellari & Copin 2003).
Treu, T., Schmidt, K. B., Brammer, G. B., et al. 2015, The Astrophysical Journal, 812, 114
Troncoso, P., Maiolino, R., Sommariva, V., et al. 2014, Astronomy and Astrophysics, 563, A58
Valentino, F., Daddi, E., Silverman, J. D., et al. 2017, Monthly Notices of the Royal Astronomical Society, 472, 4878
Vogelsberger, M., Genel, S., Genel, S., et al. 2014, Nature, 509, 177
Wang, X., Jones, T. A., Treu, T., et al. 2017, The Astrophysical Journal, 837, 89
White, S. D. M., & Rees, M. J. 1978, Monthly Notices of the Royal Astronomical Society, 183, 341
Wisnioski, E., Föster Schreiber, N. M., Wuyts, S., et al. 2015, The Astrophysical Journal, 799, 209
Wuyts, E., Wisnioski, E., Fossati, M., et al. 2016, The Astrophysical Journal, 827, 74
Yates, R. M., Kauffmann, G., & Guo, Q. 2012, Monthly Notices of the Royal Astronomical Society, 422, 215
Yuan, T. T., Yuan, T., Kewley, L. J., & Rich, J. A. 2013, The Astrophysical Journal, 767, 106
Zahid, H. J., Dima, G. I., Kewley, L. J., Erb, D. K., & Davé, R. 2012, The Astrophysical Journal, 757, 54
Zahid, H. J., Dima, G. I., Kudritzki, R.-P., et al. 2014, The Astrophysical Journal, 791, 130
Zahid, H. J., Kewley, L. J., & Bresolin, F. 2011, The Astrophysical Journal, 730, 137
Zanella, A., Daddi, E., Le Floch, E., et al. 2015, Nature, 521, 54
Zitrin, A., Fabris, A., Merten, J. C., et al. 2015, The Astrophysical Journal, 801, 44