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Through the Looking GLASS:
Spatially Resolving the Physical Properties
of Star-Forming Galaxies with Slitless Spectroscopy

A dissertation submitted in partial satisfaction

of the requirements for the degree

Doctor of Philosophy in Astronomy and Astrophysics

by

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ABSTRACT OF THE DISSERTATION

Through the Looking GLASS:
Spatially Resolving the Physical Properties
of Star-Forming Galaxies with Slitless Spectroscopy

by

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Doctor of Philosophy in Astronomy and Astrophysics
University of California, Los Angeles, 2019
Professor Tommaso L. Treu, Chair

To explore the chemo-structural properties of galaxies at cosmic noon (i.e. z 2), I developed a highly effective method for sub-kiloparsec scale spatially resolved spectroscopy of strongly lensed galaxies using space-based wide-field slitless grism data. Applying this method to the deep Hubble Space Telescope near-infrared grism data, I obtained precise gas-phase metallicity maps of 81 star-forming galaxies at z 1.2-2.3, over half of which reside in the dwarf mass regime. My work presents the first statistically representative sample of high-z dwarf galaxies with their metallicity spatial distribution measured with sufficient resolution. These metallicity maps reveal a variety of baryonic physics, such as efficient radial mixing from tidal torques, rapid accretion of low-metallicity gas, and various feedback processes which can significantly influence the chemo-structural properties of dwarf galaxies. In particular, we find two galaxies at z 2 displaying strongly inverted metallicity radial gradients, suggesting that powerful galactic winds triggered by central starbursts carry the bulk of stellar nucleosynthesis yields to the outskirts. Furthermore, 10% of the metallicity gradients measured in our sample are inverted, which are hard to explain by currently existing hydrodynamical simulations and analytical chemical evolution models. My method can also be readily applied to data from future space missions employing grism instruments, e.g., JWST, WFIRST.

The dissertation of Xin Wang is approved.

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To my wife Dr. Xiao-Lei Meng

who have nourished and sustained me

with her illuminating love

especially during the darkest hours

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PUBLICATIONS

Wang, X., Huang, Y. F., & Kong, S. W. On the Afterglow from the Receding Jet of Gamma-Ray Bursts. 2009, *Astron. Astrophys.*, 505, 1213 (arXiv:0903.3119)

Wang, X., Huang, Y. F., & Kong, S. W. Constraint on the Counter-jet Emission in GRB Afterglows from GRB 980703. 2010, *Sci. China-Phys. Mech. Astron.*, 53 (Suppl.1), 259

Meng, X.-L., Zhang, T.-J., Zhan, H., & **Wang, X.** Morphology of Galaxy Clusters: A Cosmological Model-Independent Test of the Cosmic Distance-Duality Relation. 2012, *Astrophys. J.*, 745, 98 (arXiv:1104.2833)

Wang, X., Meng, X.-L. et al. Observational Constraints on Cosmic Neutrinos and Dark Energy Revisited. 2012, *J. Cosmol. Astropart. Phys.*, 11, 018 (arXiv:1210.2136)

Wang, X., Meng, X.-L., Huang, Y. F., & Zhang, T.-J. Testing X-ray Measurements of Galaxy Cluster Gas Mass Fraction Using the Cosmic Distance-Duality Relation and Type Ia Supernovae. 2013, RAA, 13, 1013 (arXiv:1305.2077)

Schmidt, K. B., Treu, T., Brammer, G. B., Bradac, M., **Wang, X.** et al. Through the Looking GLASS: HST Spectroscopy of Faint Galaxies Lensed by the Frontier Fields Cluster MACSJ0717.5+3745. 2014, *Astrophys. J. Letters*, 782L, 36 (arXiv:1401.0532)

Jones, T., **Wang, X.** et al. The Grism Lens-Amplified Survey from Space (GLASS) II. Gas-Phase Metallicity and Radial Gradients in an Interacting System At z~2. 2015, *Astron. J.*, 149, 107 (arXiv:1410.0967)

Wang, X. et al. The Grism Lens-Amplified Survey from Space (GLASS) IV. Mass reconstruction of the lensing cluster Abell 2744 from frontier field imaging and GLASS spectroscopy. 2015, *Astrophys. J.*, 811, 29 (arXiv:1504.02405)

Rodney, S., ..., **Wang, X.**, et al. Illuminating a Dark Lens : A Type Ia Supernova Magnified by the Frontier Fields Galaxy Cluster Abell 2744. 2015, *Astrophys. J.*, 811, 70 (arXiv:1505.06211)

Treu, T., Schmidt, K. B., Brammer, G. B., Vulcani, B., **Wang, X.** et al. The Grism Lens-Amplified Survey from Space (GLASS). I. Survey Overview and First Data Release. 2015, *Astrophys. J.*, 812, 114 (arXiv:1509.00475)

Schmidt, K. B., ..., **Wang, X.** The Grism Lens-Amplified Survey from Space (GLASS). III. A census of Lyα Emission at $z \gtrsim 7$ from HST Spectroscopy. 2016, *Astrophys. J.*, 818, 38 (arXiv:1511.04205)

Hoag, A., ..., **Wang, X.** et al. The Grism Lens-Amplified Survey from Space (GLASS). VI. Comparing the Mass and Light in MACSJ0416.1-2403 using Frontier Field imaging and GLASS spectroscopy. 2016, *Astrophys. J.*, 831, 182 (arXiv:1603.00505)

Huang, K., ..., **Wang, X.** Detection of Lyman-Alpha Emission From a Triple Imaged z=6.85 Galaxy Behind MACS J2129.4-0741. 2016, *Astrophys. J. Letters*, 823L, 14 (arXiv:1605.05771)

Morishita, T., ..., **Wang, X.**, et al. The Grism Lens-Amplified Survey from Space (GLASS). IX. The dual origin of low-mass cluster galaxies as revealed by new structural analyses. 2017, *Astrophys. J.*, 835, 254 (arXiv:1607.00384)

Vulcani, B., ..., **Wang, X.** The Grism lens-amplified survey from space (GLASS). VIII. The influence of the cluster properties on Halpha emitter galaxies at $0.3 < z < 0.7$. 2017, *Astrophys. J.*, 837, 126 (arXiv:1610.04615)

Wang, X. et al. The Grism Lens-Amplified Survey from Space (GLASS) X. Sub-kiloparsec resolution gas-phase metallicity maps at cosmic noon behind the Hubble Frontier Fields cluster MACS1149.6+2223. 2017, *Astrophys. J.*, 837, 89 (arXiv:1610.07558)

Morishita, T., Abramson, L. E., Treu, T., Schmidt, K. B., Vulcani, B., **Wang, X.** Characterizing Intracluster Light in the Hubble Frontier Fields. 2017, *Astrophys. J.*, 846, 139 (arXiv:1610.08503)

Schmidt, K. B., ..., **Wang, X.** The Grism Lens-Amplified Survey from Space (GLASS). XI. Detection of CIV in Multiple Images of $z = 6.11$ Lyα Emitter Behind RXCJ2248.7-4431. 2017, *Astrophys. J.*, 839, 17 (arXiv:1702.04731)

Williams, P. R., ..., **Wang, X.** Discovery of three strongly lensed quasars in the Sloan Digital Sky Survey. 2018, *MNRAS*, 477L, 70 (arXiv:1706.01506)

Kelly, P. L., ..., **Wang, X.** et al. An individual star at redshift 1.5 galaxy-cluster lens. 2018, *Nature Astronomy*, 2, 334 (arXiv:1706.10279)

Abramson, L. E., ..., **Wang, X.** et al. The Grism Lens-Amplified Survey from Space (GLASS). XII. Spatially Resolved Galaxy Star Formation Histories and True Evolutionary Paths at z>1. 2018, *Astron. J.*, 156, 29 (arXiv:1710.00843)

Morishita, T., Abramson, L. E., Treu, T., **Wang, X.** et al. Metal Deficiency in Two Massive Dead Galaxies at z~2. 2018, *Astrophys. J. Letters*, 856L, 4 (arXiv:1803.01852)

Strait, V., ..., **Wang, X.** et al. Mass and Light of Abell 370: A Strong and Weak Lensing Analysis. 2018, *Astrophys. J.* accepted (arXiv:1805.08789)

Quinn, E., ..., **Wang, X.** et al. Mass Modeling of Frontier Fields Cluster MACS J1149.5+2223 Using Strong and Weak Lensing. 2018, *Astrophys. J.*, 859, 1 (arXiv:1806.00698)

Wang, X. et al. Discovery of Strongly inverted metallicity gradients in Dwarf Galaxies at $z\sim2$. 2018, *Astrophys. J.* in press (arXiv:1808.08800)

Hirtenstein, J., Jones, T., **Wang, X.** et al. The OSIRIS Lens-Amplified Survey (OLAS) I: Dynamical Effects of Stellar Feedback in Low Mass Galaxies at z~2. 2018, *Astrophys. J.* in press, (arXiv:1811.11768)

CHAPTER 1

Introduction

say something about GLASS, slitless spectroscopy, metallicity, etc.

CHAPTER 2

Discovery of Strongly Inverted Metallicity Gradients in Dwarf Galaxies at $z\sim2$

2.1 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[1]) 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; Henry et al., 2013; Jones et al., 2013; Sanchez 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; Mollá & 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

[1]Throughout the paper, we refer to gas-phase metallicity as metallicity for simplicity.

(Cresci et al., 2010; Queyrel et al., 2012; Stott et al., 2014; Troncoso et al., 2014; Sanchez 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_*) $\gtrsim 10^{10} M_\odot$ (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 ($\sim 10^6$K for a $M_h \sim 10^{12} M_\odot$ halo) and then radiate away the thermal energy to condense and form stars (vis-á-vis "hot-mode" accretion), gas streams can remain relatively cold (¡10^5K) 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 virialized 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).

2.1.1 Conclusion

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.

[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).

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, if any, 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 **??**. We describe our analysis methods alongside main results in Section **??**, and conclude in Section **??**. Throughout this paper, a flat ΛCDM cosmology is assumed.

Bibliography

Belfiore, F., Maiolino, R., Tremonti, C. A., Sanchez, S. F., Bundy, K., Bershady, M. A., Westfall, K. B., Lin, L., Drory, N., Boquien, M., Thomas, D., & Brinkmann, J. 2017, Monthly Notices of the Royal Astronomical Society, 469, 151

Birnboim, Y., & Dekel, A. 2003, Monthly Notices of the Royal Astronomical Society, 345, 349

Bouche, N., Dekel, A., Genzel, R., Genel, S., Cresci, G., Förster Schreiber, N. M., Shapiro, K. L., Davies, R. I., & Tacconi, L. J. 2010, The Astrophysical Journal, 718, 1001

Bresolin, F., Gieren, W., Kudritzki, R.-P., Pietrzynski, G., Urbaneja, M. A., & Carraro, G. 2009, The Astrophysical Journal, 700, 309

Bresolin, F., & Kennicutt, R. C. J. 2015, Monthly Notices of the Royal Astronomical Society, 454, 3664

Carton, D., Brinchmann, J., Contini, T., Epinat, B., Finley, H., Richard, J., Patrício, V., Schaye, J., Nanayakkara, T., Weilbacher, P. M., & Wisotzki, L. 2018, Monthly Notices of the Royal Astronomical Society, 1805.08131

Cresci, G., Mannucci, F., Maiolino, R., Marconi, A., Gnerucci, A., & Magrini, L. 2010, Nature, 467, 811

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

Dekel, A., & Birnboim, Y. 2006, Monthly Notices of the Royal Astronomical Society, 368, 2

Dekel, A., & Mandelker, N. 2014, Monthly Notices of the Royal Astronomical Society, 444, 2071

Dekel, A., Sari, R., & Ceverino, D. 2009a, The Astrophysical Journal, 703, 785

Dekel, A., Zolotov, A., Tweed, D., Cacciato, M., Ceverino, D., & Primack, J. R. 2013, Monthly Notices of the Royal Astronomical Society, 435, 999

Dekel, A., Birnboim, Y., Engel, G., Freundlich, J., Goerdt, T., Mumcuoglu, M., Neistein, E., Pichon, C., Teyssier, R., & Zinger, E. 2009b, Nature, 457, 451

Erb, D. K., Shapley, A. E., Pettini, M., Steidel, C. C., Reddy, N. A., & Adelberger, K. L. 2006, The Astrophysical Journal, 644, 813

Few, C. G., Gibson, B. K., Courty, S., Michel-Dansac, L., Brook, C. B., & Stinson, G. S. 2012, Astronomy and Astrophysics, 547, A63

Finlator, K., & Davé, R. 2008, Monthly Notices of the Royal Astronomical Society, 385, 2181

Gibson, B. K., Pilkington, K., Brook, C. B., Stinson, G. S., & Bailin, J. 2013, Astronomy and Astrophysics, 554, A47

Henry, A. L., Martin, C. L., Finlator, K., & Dressler, A. 2013, The Astrophysical Journal, 769, 148

Ho, I. T., Kudritzki, R.-P., Kewley, L. J., Zahid, H. J., Dopita, M. A., Bresolin, F., & Rupke, D. S. N. 2015, Monthly Notices of the Royal Astronomical Society, 448, 2030

Hopkins, P. F., Kereš, D., Onorbe, J., Faucher-Giguère, C.-A., Quataert, E., Murray, N., & Bullock, J. S. 2014, Monthly Notices of the Royal Astronomical Society, 445, 581

Hou, J. L., Prantzos, N., & Boissier, S. 2000, Astronomy and Astrophysics, 362, 921

Jones, T. A., Ellis, R. S., Richard, J., & Jullo, E. 2013, The Astrophysical Journal, 765, 48

Kereš, D., Katz, N. S., Fardal, M., Davé, R., & Weinberg, D. H. 2009, Monthly Notices of the Royal Astronomical Society, 395, 160

Kereš, D., Katz, N. S., Weinberg, D. H., & Davé, R. 2005, Monthly Notices of the Royal Astronomical Society, 363, 2

Kewley, L. J., Geller, M. J., & Barton, E. J. 2006, The Astronomical Journal, 131, 2004

Kewley, L. J., Rupke, D. S. N., Zahid, H. J., Geller, M. J., & Barton, E. J. 2010, The Astrophysical Journal, 721, L48

Kobayashi, C., & Nakasato, N. 2011, The Astrophysical Journal, 729, 16

Lilly, S. J., Carollo, C. M., Pipino, A., Renzini, A., & Peng, Y.-j. 2013, The Astrophysical Journal, 772, 119

Ma, X., Hopkins, P. F., Feldmann, R., Torrey, P., Faucher-Giguère, C.-A., & Kereš, D. 2017, Monthly Notices of the Royal Astronomical Society, 466, 4780

Maiolino, R., Nagao, T., Grazian, A., Cocchia, F., Marconi, A., Mannucci, F., Cimatti, A., Pipino, A., Ballero, S. K., Calura, F., Chiappini, C., Fontana, A., Granato, G. L., Matteucci, F., Pastorini, G., Pentericci, L., Risaliti, G., Salvati, M., & Silva, L. 2008, Astronomy and Astrophysics, 488, 463

Mannucci, F., Cresci, G., Maiolino, R., Marconi, A., & Gnerucci, A. 2010, Monthly Notices of the Royal Astronomical Society, 408, 2115

Mannucci, F., Salvaterra, R., & Campisi, M. A. 2011, Monthly Notices of the Royal Astronomical Society, 414, 1263

Mollá, M., & Díaz, A. I. 2005, Monthly Notices of the Royal Astronomical Society, 358, 521

Mott, A., Spitoni, E., & Matteucci, F. 2013, Monthly Notices of the Royal Astronomical Society, 435, 2918

Peng, Y.-j., & Maiolino, R. 2014, Monthly Notices of the Royal Astronomical Society, 443, 3643

Pérez-Montero, E., García-Benito, R., Vílchez, J. M., Sanchez, S. F., Kehrig, C., Husemann, B., Puertas, S. D., Iglesias-Páramo, J., Galbany, L., Mollá, M., Walcher, C. J., Ascasíbar, Y., Delgado, R. M. G., Marino, R. A., Masegosa, J., Pérez, E., Rosales-Ortega, F., Sánchez-Blázquez, P., Bland-Hawthorn, J., Bomans, D. J., López-Sánchez, Á.-R., Ziegler, B., & collaboration, t. C. 2016, Astronomy and Astrophysics, 1608.04677

Pilkington, K., Few, C. G., Gibson, B. K., Calura, F., Michel-Dansac, L., Thacker, R. J., Mollá, M., Matteucci, F., Rahimi, A., Kawata, D., Kobayashi, C., Brook, C. B., Stinson, G. S., Couchman, H. M. P., Bailin, J., & Wadsley, J. W. 2012, Astronomy and Astrophysics, 540, A56

Pipino, A., Lilly, S. J., & Carollo, C. M. 2014, Monthly Notices of the Royal Astronomical Society, 441, 1444

Prantzos, N., & Boissier, S. 2000, Monthly Notices of the Royal Astronomical Society, 313, 338

Queyrel, J., Contini, T., Kissler-Patig, M., Epinat, B., Amram, P., Garilli, B., Le Fèvre, O., Moultaka, J., Paioro, L., Tasca, L. A. M., Tresse, L., Vergani, D., López-Sanjuan, C., & Pérez-Montero, E. 2012, Astronomy and Astrophysics, 539, A93

Recchi, S., Spitoni, E., Matteucci, F., & Lanfranchi, G. A. 2008, Astronomy and Astrophysics, 489, 555

Rich, J. A., Torrey, P., Kewley, L. J., Dopita, M. A., & Rupke, D. S. N. 2012, The Astrophysical Journal, 753, 5

Rupke, D. S. N., Kewley, L. J., & Chien, L. H. 2010, The Astrophysical Journal, 723, 1255

Sanchez, S. F., Rosales-Ortega, F., Iglesias-Páramo, J., Mollá, M., Barrera-Ballesteros, J. K., Marino, R. A., Pérez, E., Sánchez-Blázquez, P., González Delgado, R. M., Cid Fernandes, R., de Lorenzo-Cáceres, A., Mendez-Abreu, J., Galbany, L., Falcón-Barroso, J., Miralles-Caballero, D., Husemann, B., García-Benito, R., Mast, D., Walcher, C. J., Gil de Paz, A., García-Lorenzo, B., Jungwiert, B., Vílchez, J. M., Jílková, L., Lyubenova, M., Cortijo-Ferrero, C., Díaz, A. I., Wisotzki, L., Márquez, I., Bland-Hawthorn, J., Ellis, S. C., van de Ven, G., Jahnke, K., Papaderos, P., Gomes, J. M., Mendoza, M. A., & López-Sánchez, Á.-R. 2014, Astronomy and Astrophysics, 563, A49

Sanders, R. L., Shapley, A. E., Kriek, M. T., Reddy, N. A., Freeman, W. R., Coil, A. L., Siana, B. D., Mobasher, B., Shivaei, I., Price, S. H., & de Groot, L. 2015, The Astrophysical Journal, 799, 138

Stott, J. P., Sobral, D., Swinbank, A. M., Smail, I. R., Bower, R. G., Best, P. N., Sharples, R. M., Geach, J. E., & Matthee, J. 2014, Monthly Notices of the Royal Astronomical Society, 443, 2695

Strom, A. L., Steidel, C. C., Rudie, G. C., Trainor, R. F., Pettini, M., & Reddy, N. A. 2016, eprint arXiv:1608.02587, 1608.02587

Torrey, P., Cox, T. J., Kewley, L. J., & Hernquist, L. 2012, The Astrophysical Journal, 746, 108

Tremonti, C. A., Heckman, T. M., Kauffmann, G., Brinchmann, J., Charlot, S., White, S. D. M., Seibert, M., Peng, E. W., Schlegel, D. J., Uomoto, A., Fukugita, M., & Brinkmann, J. 2004, The Astrophysical Journal, 613, 898

Troncoso, P., Maiolino, R., Sommariva, V., Cresci, G., Mannucci, F., Marconi, A., Meneghetti, M., Grazian, A., Cimatti, A., Fontana, A., Nagao, T., & Pentericci, L. 2014, Astronomy and Astrophysics, 563, A58

Vogelsberger, M., Genel, S., Springel, V., Torrey, P., Sijacki, D., Xu, D., Snyder, G. F., Bird, S., Nelson, D., & Hernquist, L. 2014, Nature, 509, 177

Wuyts, E., Wisnioski, E., Fossati, M., Förster Schreiber, N. M., Genzel, R., Davies, R., Mendel, J. T., Naab, T., Röttgers, B., Wilman, D. J., Wuyts, S., Bandara, K., Beifiori, A., Belli, S., Bender, R., Brammer, G. B., Burkert, A., Chan, J., Galametz, A., Kulkarni, S. K., Lang, P., Lutz, D., Momcheva, I. G., Nelson, E. J., Rosario, D., Saglia, R. P., Seitz, S., Tacconi, L. J., Tadaki, K.-i., Übler, H., & van Dokkum, P. G. 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., 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., Kewley, L. J., Geller, M. J., Hwang, H. S., Silverman, J. D., & Kashino, D. 2014, The Astrophysical Journal, 791, 130

Zahid, H. J., Kewley, L. J., & Bresolin, F. 2011, The Astrophysical Journal, 730, 137