Galaxies in 3D across the Universe
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Galaxy Growth at Early Times from 3D Studies

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Abstract. Spatially- and spectrally-resolved studies have proven very powerful in exploring the processes driving baryonic mass assembly and star formation at redshifts $z \sim 1-3$, the heyday of massive galaxy formation. This contribution presents selected key results from near-infrared integral field spectroscopic studies of $z \sim 1-3$ galaxies, including from the SINS/zC-SINF and KMOS^{3D} surveys with SINFONI and KMOS at the ESO Very Large Telescope, highlights synergies with observations at other wavelengths, and discusses some of the implications for early galaxy evolution from mass assembly to feedback processes.

1. The new picture of galaxy evolution and the role of near-IR IFU surveys

In the emerging *"equilibrium growth model,"* early galaxies are fed by smooth accretion from their halos and minor mergers, replenishing their gas reservoirs and fueling their star formation (e.g., Dekel *et al.* 2009; Lilly *et al.* 2013). The balance between accretion and star formation maintains galaxies on a tight "main sequence" (MS) in stellar mass ($M_\star$) vs star formation rate (SFR), with ~ 0.3 dex scatter, whose evolution reflects the decrease in cosmic SFR density from its peak around $z \sim 2$ to the winding down epochs at $z \leqslant 1$ (e.g., Elbaz *et al.* 2007; Rodighiero *et al.* 2011; Whitaker *et al.* 2012). This scenario is further empirically motivated by the evolution of molecular gas mass fractions and the dominance of disk-like systems among MS star-forming galaxies (SFGs) out to $z \sim 2.5$ (e.g., Förster Schreiber *et al.* 2009; Wuyts *et al.* 2011; Tacconi *et al.* 2013; Wisnioski *et al.* 2014). The growth of galaxies thus appears to be tightly regulated, until they reach $M_\star \sim 10^{11}\,\mathrm{M}_\odot$ where their star formation is rapidly quenched (e.g., Peng *et al.* 2010).

Spatially-resolved kinematics, star formation, and ISM conditions of $z \sim 1-3$ galaxies from observations of rest-optical line emission with sensitive near-IR integral field units (IFUs) at $8-10$m-class telescopes have provided some of the key empirical evidence in support of the above picture — highlighting the importance of internal dynamical processes such as violent gravitational instabilities in gas-rich disks, and of stellar and AGN feedback. The richness of information provided by such "3D studies" allows one to map the gas motions, the sites of on-going star formation, and spatial variations in gas-phase metallicity and nebular excitation across galaxies. Detailed line profile analysis can further reveal multiple emission line components and, in particular, the broad emission signature of outflowing gas. With IFUs, not only the kinematics but also the location, size, and geometry of outflows can be determined, all essential parameters to derive mass ejection rates and mass loading that are unconstrained from traditional rest-UV studies.

Obtaining such detailed but crucial information of faint distant galaxies requires a substantial investment of on-source integration per target. Near-IR IFUs at large ground-based telescopes such as SINFONI at the Very Large Telescope (VLT), OSIRIS on Keck II, and NIFS on Gemini-North, are all single-object IFUs. In the decade up to

2013, published studies using these instruments assembled data of ~ 300 galaxies at $z \approx 1-4$ in ~ 300 nights. "SINS/zC-SINF," carried out with SINFONI, provided the largest such survey with 110 SFGs at $z \sim 1.5-3$ observed in natural seeing ($4-5$ kpc resolution) and 35 of them followed up at higher resolution ($1-2$ kpc) with adaptive optics (AO; Förster Schreiber *et al.* 2006, 2009; Genzel *et al.* 2006, 2008, 2011; Mancini *et al.* 2011; Newman *et al.* 2013). SINS/zC-SINF probes the bulk of the $z \sim 2$ SFG population over two orders of magnitude in stellar mass and SFR ($M_\star \sim 3 \times 10^9 - 3 \times 10^{11}$ $M_\odot$, SFR $\sim 10-800$ $M_\odot yr^{-1}$). Other near-IR IFU surveys in the range $1 < z < 3.5$ have targeted galaxies with various selection criteria, probing somewhat different mass/luminosity ranges and/or focussing on different redshift intervals, and include among others "MASSIV" (e.g., Épinat *et al.* 2009, 2012; Contini *et al.* 2012), "AMAZE" and "LSD" (e.g., Gnerucci *et al.* 2011a,b), "WiggleZ" (Wisnioski *et al.* 2011, 2012), "sHiZELs" (Swinbank *et al.* 2012a,b), the "BX/BM" OSIRIS samples (Law *et al.* 2009, 2012; Wright *et al.* 2009). A small but important set of strongly lensed $z > 1$ galaxies was also observed with near-IR IFUs, reaching an effective resolution on sub-kpc scales in the source plane and even as small as $100-200$ pc in a few cases (Stark *et al.* 2008; Jones *et al.* 2010a,b, 2013; Yuan *et al.* 2011, 2012; Wuyts *et al.* 2014a).

With the new near-IR KMOS instrument at the VLT, featuring 24 IFUs deployable over a $7'$-diameter field (Sharples *et al.* 2013), survey efficiency is now considerably boosted. Samples of a few 1000's of distant galaxies may now be collected in the same amount of ~ 300 nights. Moreover, the effective cost of accessing fainter galaxies in so far poorly explored regimes of galaxy parameters is much reduced — useful data of even a handful of such objects with single-IFUs implies prohibitively large time allocations. KMOS thus opens up new opportunities for progress through more complete and homogeneous censuses. Aside from improved statistics, advances in our physical understanding of the processes driving galaxy evolution will continue to require *sensitivity*, *high resolution*, and *synergies with multi-wavelength observations*. High S/N is needed to measure reliably weaker emission lines and details of line profiles. AO-assisted observations are necessary to resolve objects down to the 1kpc-scales of galaxy components (bulges, star-forming clumps). Information about the distribution of the bulk of stellar populations (tracing past evolution) and of the cold molecular gas (the fuel of on-going/future star formation) is essential for a full and coherent picture, and to constrain timescales and scaling relations.

The next sections summarize selected key results from near-IR IFU studies, with an emphasis on the SINS/zC-SINF survey and highlights from the 1^{st}-year data of the KMOS^{3D} survey. A comprehensive review covering near-IR single-object IFU studies is given by Glazebrook (2013).

2. Kinematics and structure of SFGs, and properties of disks at $z \sim 1-3$

The SINS/zC-SINF and other near-IR IFU surveys of kinematics revealed that $> 50\%$ of $z \sim 1-3$ SFGs are fairly regular rotation-dominated disks, whereas a minority consists of disturbed (major) merging systems or more compact, velocity dispersion-dominated objects (e.g., Shapiro *et al.* 2008; Förster Schreiber *et al.* 2009; Law *et al.* 2009; Jones *et al.* 2010b; Gnerucci *et al.* 2011a; Épinat *et al.* 2012; Newman *et al.* 2013). The rotation velocity $v_{\rm rot}$ scales roughly linearly with galaxy size, consistent with centrifugally-supported baryonic disks of constant angular momentum parameter within virialized dark matter halos. The rest-optical light and stellar mass maps from high-resolution HST near-IR imaging of the SINS/zC-SINF AO sample also show a majority of disk-like profiles and reveal a significant bulge-like component in the most massive galaxies (Förster Schreiber

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et al. 2011a; Tacchella *et al.* 2014). Concurring evidence for the prevalence of high-z disks has come from HST-based studies of rest-UV/optical morphologies and stellar mass distributions of large mass-selected samples out to $z \sim 2.5$, which showed that MS SFGs typically have a disk-like stellar structure with a systematic increase of bulge-to-disk ratio towards high masses (e.g. Wuyts *et al.* 2011; Lang *et al.* 2014). These results from kinematics and stellar structure provided some of the compelling evidence that smoother mass accretion modes onto galaxies and internal dynamical processes within galaxies play an important — if not dominant — role in growing galaxies.

High-z disks were found to be characterized by remarkably high intrinsic gas velocity dispersions of $\sigma_0 \sim 30-100$ km s^{-1}, large gas-to-baryonic mass fractions of $\sim 30\%-50\%$, and luminous kpc-sized star-forming clumps (e.g., Genzel *et al.* 2006, 2008; Förster Schreiber *et al.* 2006, 2009, 2011b; Law *et al.* 2009; Cresci *et al.* 2009; Jones *et al.* 2010b; Wisnioski *et al.* 2011; Swinbank *et al.* 2012a; Newman *et al.* 2013). At $z \sim 2$, the velocity dispersions are $5-10$ times higher than in present-day disks, implying that high-z disks are dynamically hotter and geometrically thicker, plausibly as a consequence of enhanced accretion, gas fractions, and SFRs. Elevated velocity dispersions were also measured from high-resolution IRAM/Plateau de Bure interferometric observations of CO emission in $z \sim 1-2$ star-forming disks, confirming that it is a property of the entire ISM and not just of the ionized gas layer (Tacconi *et al.* 2013, e.g.,). These properties, along with trends of increasing central dynamical mass fraction and bulge-to-disk ratio with galaxy mass and evolutionary stage, and possibly older clump ages at smaller galactocentric distances (e.g., Genzel *et al.* 2008, 2011; Förster Schreiber *et al.* 2011b; Wuyts *et al.* 2012; Tacchella *et al.* 2014), are consistent with theoretical arguments and numerical simulations of turbulent gas-rich disks in which giant star-forming clumps result from violent gravitational instabilities and bulges form via efficient secular processes on timescales < 1 Gyr (e.g., Bournaud *et al.* 2007, 2014; Ceverino *et al.* 2012; Dekel & Burkert 2014). Bulge growth in high-z disks can lead to "morphological quenching" as the central stellar spheroidal component stabilizes the gas-rich disk against fragmentation (e.g., Martig *et al.* 2009). Dynamical analysis of the SINS/zC-SINF AO sample revealed increasingly centrally peaked Toomre Q values well above unity in the inner $2-3$ kpc of the most massive galaxies, where star formation is suppressed and a massive stellar bulge is present — tantalizing evidence for inside-out gravitationally-driven quenching acting at $z \sim 2$ (Genzel *et al.* 2014a).

3. Vigorous feedback from star formation and AGN

Major breakthoughs emerged from the high quality, S/N, and resolution SINFONI+AO data from the SINS/zC-SINF survey. Strong, spatially-extended ionized gas outflows were discovered via a broad FWHM ~ 450 km s^{-1} Hα+[NII] component underneath the narrower emission tracing star formation, often associated with individual bright clumps in the disks (Genzel *et al.* 2011; Newman *et al.* 2012a,b). This discovery pinned down the roots of the ubiquitous galactic-scale winds at high-z so far only observed on > 10 kpc scales (e.g., Shapley *et al.* 2003; Weiner *et al.* 2009). Shock excitation plausibly due to these *star formation-driven outflows* is detected around bright clumps in the best-case, highest S/N disk (Newman *et al.* 2012a). The winds appear to set at a SFR surface density ~ 1 M$_\odot$yr^{-1}kpc^{-2}, ten times higher than the break-out threshold in nearby starbursts and attributed to enhanced gas pressure in $z \sim 2$ disks. Outflow rates from clumps and from the galaxies reach up to several times their SFRs — the first empirical constraint at $z > 1$ on mass loading, a key parameter in theoretical models of star formation-driven feedback. Such vigorous feedback may disrupt intensely star-forming

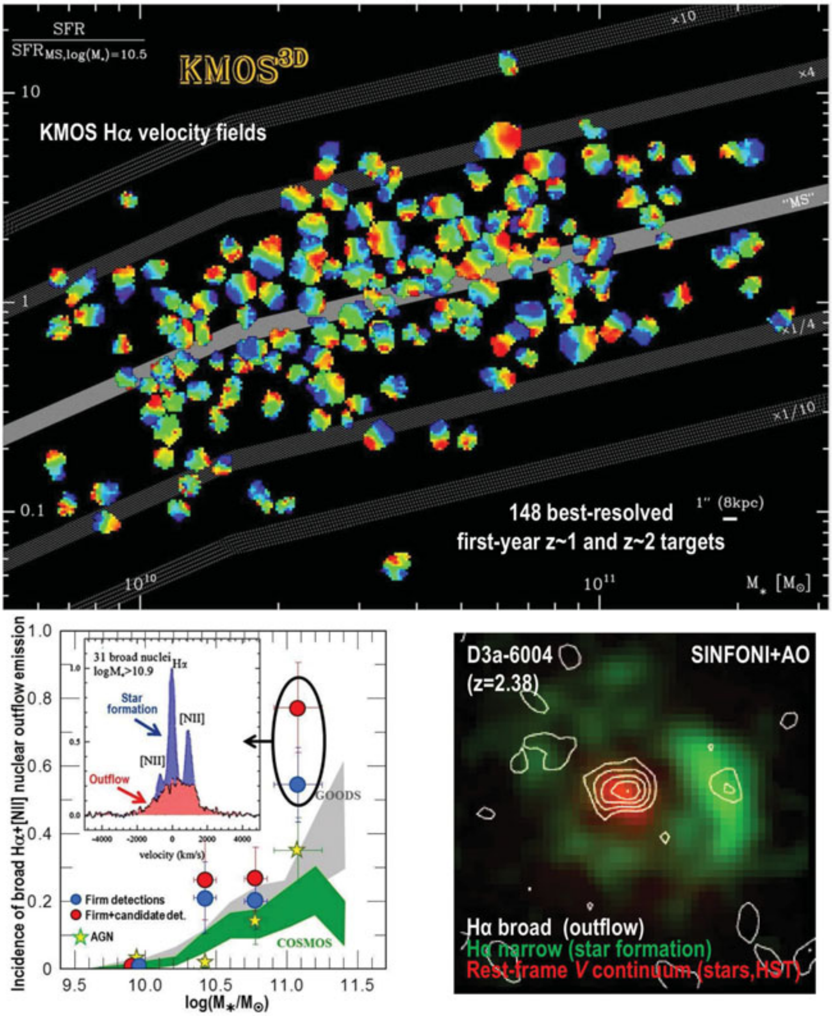

Figure 1. *Top:* Hα velocity fields for the 148 best-resolved $z \sim 1$ and $z \sim 2$ targets among the 246 galaxies observed in the first year of the KMOS^{3D} survey with the multi-IFU VLT/KMOS instrument (adapted from Wisnioski *et al.* 2014). All galaxies are shown on the same angular scale and are plotted within 0.2 dex of their location in the stellar mass versus SFR plane (with SFRs normalized to the SFR of the "main sequence" (MS) at the median $z \approx 0.9$ and ≈ 2.3 of the respective samples). Blue to red colors correspond to blue- to redshifted velocities relative to the systemic velocity of each galaxy. At least 70% of all the galaxies observed exhibit rotation–dominated disk kinematics, robustly confirming previous results from smaller samples observed with single-object IFUs. *Bottom left:* Incidence as a function of galaxy stellar mass of nuclear AGN-driven outflows, as revealed by the presence of a broad FWHM $\sim 1000 - 2000$ kms^{-1}, high-excitation component detected in Hα, [NII], and [SII] emission originating from the central few kpc of $z \sim 1 - 2.5$ of galaxies (adapted from Genzel *et al.* 2014b). There is a sharp onset of this incidence around $\log(M_\star/M_\odot) \sim 10.9$ (large blue/red circles) among the sample of > 100 galaxies analyzed (mostly from the KMOS^{3D} and SINS/zC-SINF surveys), reaching $\sim 2/3$ above this mass and at least as high as the fraction of luminous AGN from independent classical AGN indicators (star symbols and shaded areas). *Bottom right:* Deep SINFONI+AO observations have resolved the broad emission associated with nuclear AGN-driven outflows in the most massive $z \sim 2$ SINS/zC-SINF targets, and imply typical intrinsic sizes of $2 - 3$ kpc. One example is shown here, with the galaxy D3a-6004 (from Förster Schreiber *et al.* 2014). The white contours, green colors, and red colors correspond to the distribution of the broad emission tracing the nuclear outflow, the narrow Hα emission tracing star formation, and the rest-optical light from the bulk of stars. This galaxy has a significant stellar bulge and a prominent star-forming ring, and dynamical stability analysis is suggest it may also be undergoing morphological quenching (Genzel *et al.* 2014a).

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gas-rich clumps before they migrate as bound entities to the galaxy centers (e.g., Genel *et al.* 2012; Wuyts *et al.* 2012).

The SINFONI+AO data further revealed evidence of *nuclear AGN-driven outflows* in all of the most massive SINS/zC-SINF galaxies ($\log(M_\star/\mathrm{M}_\odot) > 10.9$), all of which are near-MS disks hosting a significant bulge (Förster Schreiber *et al.* 2014). Although classical AGN diagnostics indicate half of these galaxies host an AGN, none is bolometrically important. The broad emission in the inner few kpc of these massive SFGs has a larger FWHM $\sim 1000 - 1500$ kms^{-1} and higher [NII]/H$\alpha > 0.5$; inferred mass outflow rates are comparable or larger than the SFRs in the centers of the galaxies. The detection of this broad emission component in Hα *and* in the forbidden [NII] and [SII] lines, together with the intrinsic extent of $2-3$ kpc and the velocity width, are telltale signatures of an outflow driven by a Type 2 AGN. While energetic AGN-driven outflows have been reported at high-z in very luminous but rare QSOs, submillimeter, and radio galaxies (e.g., Nesvadba *et al.* 2011; Harrison *et al.* 2012; Cano-Díaz *et al.* 2012; Brusa *et al.* 2014), the SINS/zC-SINF survey has now detected nuclear AGN-driven winds in *typical* massive SFGs. The frequency of these AGN-driven outflows at the high-mass end suggests they have a large duty cycle and, given the inferred outflow rates, may contribute to shutting down star formation by efficiently expelling gas out of the inner regions of the galaxies.

4. Next steps with KMOS

With KMOS, it is now possible to expand near-IR IFU studies to larger, more homogeneous and complete samples. Our team has undertaken KMOS^{3D}, a comprehensive multi-year survey of Hα+[NII]+[SII] emission of 600+ $z = 0.7-2.7$ mass-selected galaxies (see also contribution by E. Wuyts *et al.*, this volume). KMOS^{3D} capitalizes on the 3D-HST and CANDELS HST Treasury Surveys, providing unique multi-wavelength data and large mass-limited samples with accurate redshifts. The survey will enable us to establish firmly the connection between galaxy kinematics and stellar structure, determine the role of star formation and AGN in governing stellar mass growth, test systematically the imprint of feedback on galaxy formation efficiency, and explore the influence of environment. By observing similarly selected samples and targeting the same spectral diagnostics over the full $0.7 < z < 2.7$ range, KMOS^{3D} will allow us to track consistently the evolution in galaxy properties over 5 Gyrs all across the peak epochs of cosmic star formation activity. First-year results from deep observations of nearly 250 targets, split in about equal-sized samples at median $z \approx 0.9$ and $z \approx 2.3$, show that our strategy emphasizing unbiased selection and sensitivity is successful at providing high quality data of individual galaxies and extending into regimes unexplored so far by near-IR IFU surveys. These results: (1) confirm with greater robustness the prevalence of kinematically-identified disks among SFGs at $\log(M_\star/\mathrm{M}_\odot) > 9.5$ and both $z \sim 1$ and $z \sim 2$, and show a decrease by a factor of ≈ 2 of the intrinsic dispersion σ_0 consistent with expectations from the evolution of cold gas mass fractions in the framework of marginally-stable gas-rich disks (Wisnioski *et al.* 2014, and E. Wuyts *et al.* this volume); (2) strengthen the ubiquity of nuclear AGN-driven outflows in massive high-z SFGs from a larger sample (with a 6-fold increase at the highest masses) that clearly reveals a fairly sharp onset at $\log(M_\star/\mathrm{M}_\odot) \sim 10.9$ of the incidence of this phenomenon, reaching about 2/3 above this mass — a fraction at least as high as that of luminous AGN identified in the X-ray, optical, infrared, and radio (Genzel *et al.* 2014b); (3) set tighter constraints, in combination with data from SINS/zC-SINF and from LUCI multi-object spectroscopy at the Large Binocular Telescope, on the slope and evolution of the mass-metallicity relation in the range $0.7 < z < 2.7$, and the (lack of) dependence on SFR at fixed z (Wuyts *et al.* 2014b, and E. Wuyts *et al.* this volume).

We can look forward to a great many new findings over the next few years from our KMOS^{3D} and other surveys undertaken with KMOS (e.g., Sobral *et al.* 2013; Stott *et al.* 2014) in conjunction with high resolution AO-assisted IFU follow-ups and multi-wavelength information — a new era in near-IR IFU studies has begun!

References

Bournaud, F., Elmegreen, B. G., & Elmegreen, D. M. 2007, *ApJ*, 670, 237
Bournaud, F., Perret, V., Renaud, F., *et al.* 2014, *ApJ*, 780, 57
Brusa, M., Bongiorno, A., Cresci, G., *et al.* 2014, *MNRAS*, in press (arXiv:1409.1615)
Cano-Díaz, M., Maiolino, R., Marconi, A., *et al.* 2012, *A&A*, 537, L8
Ceverino, D., Dekel, A., Mandelker, N., *et al.* 2012, *MNRAS*, 420, 3490
Contini, T., Garilli, B., Le Fèvre, O., *et al.* 2012, *A&A*, 539, A91
Cresci, G., Hicks, E. K. S.., Genzel, R., *et al.* 2009, *ApJ*, 697, 115
Dekel, A., Sari, R., & Ceverino, D. 2009, *ApJ*, 703, 785
Dekel, A. & Burkert, A. 2014, *MNRAS*, 438, 1870
Elbaz, D., Daddi, E., Le Borgne, D., *et al.* 2007, *A&A*, 468, 33
Épinat, B., Contini, T., Le Fèvre, O., *et al.* 2009, *A&A*, 504, 789
Épinat, B., Tasca, L., Amram, P., *et al.* 2012, *A&A*, 539, A92
Förster Schreiber, N. M., Genzel, R., Lehnert, M. D., *et al.* 2006, *ApJ*, 645, 1062
Förster Schreiber, N. M., Genzel, R., Bouché, N., *et al.* 2009, *ApJ*, 706, 1364
Förster Schreiber, N. M., Shapley, A. E., Erb, D. K., *et al.* 2011a, *ApJ*, 731, 65
Förster Schreiber, N. M., Shapley, A. E., Genzel, R., *et al.* 2011b, *ApJ*, 739, 45
Förster Schreiber, N. M., Genzel, R., Newman, S. F., *et al.* 2014, *ApJ*, 787, 38
Genel, S., Naab, T., Genzel, R., *et al.* 2012, *ApJ*, 745, 11
Genzel, R., Tacconi, L. J., Eisenhauer, F., *et al.* 2006, *Nature*, 442, 786
Genzel, R., Burkert, A., Bouché, N., *et al.* 2008, *ApJ*, 687, 59
Genzel, R., Newman, S. F., Jones, T., *et al.* 2011, *ApJ*, 733, 101
Genzel, R., Förster Schreiber, N. M., Lang, P., *et al.* 2014a, *ApJ*, 785, 75
Genzel, R., Förster Schreiber, N. M., Rosario, D., *et al.* 2014b, *ApJ*, in press (arXiv:1406.0183)
Glazebrook, K., 2013, Publ. Astron. Soc. Australia, 30, 56
Gnerucci, A., Marconi, A., Cresci, G., *et al.* 2011a, *A&A*, 528, A88
Gnerucci, A., Marconi, A., Cresci, G., *et al.* 2011b, *A&A*, 533, A124
Harrison, C. M., Alexander, D. M., Swinbank, A. M., *et al.* 2012, *MNRAS*, 426, 1073
Jones, T. A., Ellis, R. S., Jullo, E., & Richard, J. 2010a, *ApJ*, 725, L176
Jones, T. A., Swinbank, A. M., Ellis, R. S., Richard, J., & Stark, D. P. 2010b, *MNRAS*, 404, 1247
Jones, T. A., Ellis, R. S., Richard, J., & Jullo, E. 2013, *ApJ*, 765, 48
Lang, P., Wuyts, S., Somerville, R. S., *et al.* 2014, *ApJ*, 788, 11
Law, D. R., Steidel, C. C., Erb, D. K., *et al.* 2009, *ApJ*, 697, 2057
Law, D. R., Shapley, A. E., Steidel, C. C., *et al.* 2012, *Nature*, 487, 338
Lilly, S. J., Carollo, C. M., Pipino, A., Renzini, A., & Peng, Y. 2013, *ApJ*, 772, 119
Mancini, C., Förster Schreiber, N. M., Renzini, A., *et al.* 2011, *ApJ*, 743, 86
Martig, M., Bournaud, F., Teyssier, R., & Dekel, A. 2009, *ApJ*, 707, 250
Nesvadba, N. P. H.., Polletta, M., Lehnert, M. D., *et al.* 2011, *MNRAS*, 415, 2359
Newman, S. F., Shapiro Griffin, K., Genzel, R., *et al.* 2012a, *ApJ*, 752, 111
Newman, S. F., Genzel, R., Förster Schreiber, N. M., *et al.* 2012b, *ApJ*, 761, 43
Newman, S. F., Genzel, R., Förster Schreiber, N. M., *et al.* 2013, *ApJ*, 767, 104
Peng, Y., Lilly, S. J., Kovac, K., *et al.* 2010, *ApJ*, 721, 193
Rodighiero, G., Daddi, E., Baronchelli, I., *et al.* 2011, *ApJ*, 739, L40
Shapiro, K. L., Genzel, R., Förster Schreiber, N. M., *et al.* 2008, *ApJ*, 682, 231
Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, *ApJ*, 588, 65
Sharples, R., Bender, R., Agudo Berbel, A., *et al.* 2013, The Messenger, 151, 21
Sobral, D., Swinbank, A. M., Stott, J. P., *et al.* 2013, *ApJ*, 779, 139

Stark, D. P., Swinbank, A. M., Ellis, R. S., *et al.* 2008, *Nature*, 455, 775
Stott, J. P., Sobral, D., Swinbank, A. M., *et al.* 2014, *MNRAS*, 443, 2695
Swinbank, A. M., Smail, I., Sobral, D., *et al.* 2012a, *ApJ*, 760, 130
Swinbank, A. M., Sobral, D., Smail, I., *et al.* 2012b, *MNRAS*, 426, 935
Tacchella, S., Lang, P., Carollo, C. M., *et al.* 2014, *ApJ*, submitted
Tacconi, L. J., Neri, R., Genzel, R., *et al.* 2013, *ApJ*, 768, 74
Weiner, B. J., Coil, A. L., Prochaska, J. X., *et al.* 2009, *ApJ*, 692, 187
Whitaker, K. E., van Dokkum, P. G., Brammer, G., & Franx, M. 2012, *ApJ*, 754, L29
Wisnioski, E., Förster Schreiber, N. M., Wuyts, S., *et al.* 2014, *ApJ*, submitted (arXiv:1409.6791)
Wisnioski, E., Glazebrook, K., Blake, C., *et al.* 2011, *MNRAS*, 417, 2601
Wisnioski, E., Glazebrook, K., Blake, C., *et al.* 2012, *MNRAS*, 422, 3339
Wright, S. A., Larkin, J. E., Law, D. R., *et al.* 2009, *ApJ*, 699, 421
Wuyts, S., Förster Schreiber, N. M., van der Wel, A., *et al.* 2011, *ApJ*, 742, 96
Wuyts, S., Förster Schreiber, N. M., Genzel, R., *et al.* 2012, *ApJ*, 753, 114
Wuyts, S., Förster Schreiber, N. M., Nelson, E. J., *et al.* 2013, *ApJ*, 779, 135
Wuyts, E., Rigby, J. R., Gladders, M. D., & Sharon, K. 2014a, *ApJ*, 781, 61
Wuyts, E., Kurk, J., Förster Schreiber, N. M., *et al.* 2014b, *ApJ*, 789, L40
Yuan, T.-T., Kewley, L. J., Swinbank, A. M., Richard, J., & Livermore, R. C. 2011, *ApJ*, 732, L14
Yuan, T.-T., Kewley, L. J., Swinbank, A. M., & Richard, J. 2012, *ApJ*, 759, 66

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