Molecular Gas Conditions in AGN Host Galaxies and Submillimeter Galaxies at z~2

Chelsea E. Sharon[1], Dominik Riechers[1], Jacqueline Hodge[2], Chris Carilli[2], Fabian Walter[3], Ran Wang[4], Axel Weiß[5], Frank Bertoldi[6], Jeff Wagg[7], and Kirsten Knudsen[8]

[1]Cornell University, [2]NRAO, [3]MPIA, [4]KIAA Beijing, [5]MPIfR, [6]Universität Bonn, [7]SKA Organization, [8]Chalmers University of Technology

Background

- Observations of CO rotational line ratios probe the physical conditions (density, temperature, etc.) of the molecular gas reservoirs that fuel star formation.
- Initial observations of z~2–3 submillimeter galaxies (SMGs) and AGN-host galaxies showed a systematic difference in the CO(3-2)/CO(1-0) line ratio between the two populations (e.g., Swinbank et al. 2010; Harris et al. 2010; Ivison et al. 2011; Riechers et al. 2011) where SMGs have a multi-phase molecular ISM that includes a large cold gas reservoir and AGN-host galaxies have only a warmer single-phase molecular ISM.
- This observed dichotomy potentially supports an evolutionary connection between the two populations where an AGN phase ends rapid star formation in SMGs (via outflows or suppressed accretion) or the molecular gas has been funneled by gravitational torques via mergers to a small high-excitation region near the central supermassive black hole.
- However, this dichotomy was based on a small sample (13) of well-studied galaxies.

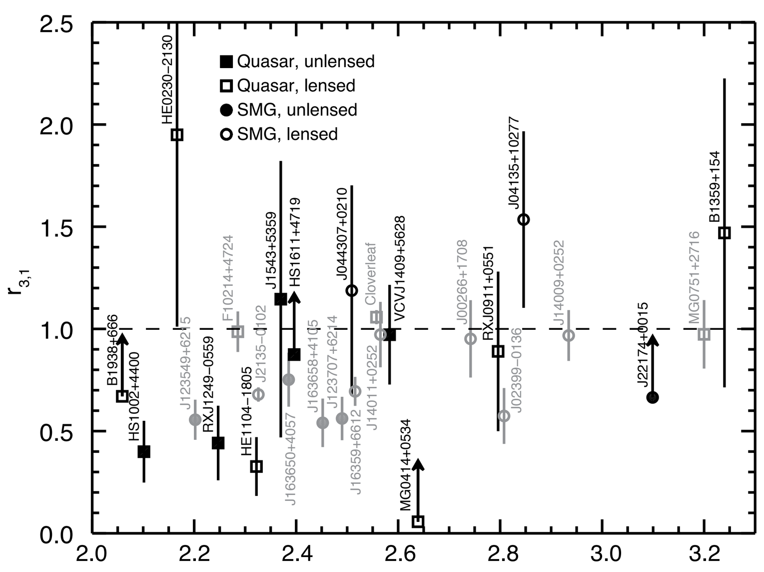
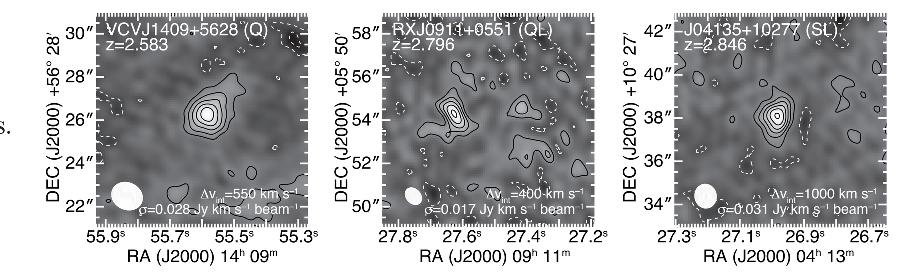


Figure 1. The CO(3–2)/CO(1–0) line ratio as a function of redshift for the complete sample of galaxies. Black symbols are our new detections and gray symbols are sources from the literature.

Observations

- We observed CO(1–0) with the Karl G. Jansky Very Large Array for most z~2–3 SMGs and AGN-host galaxies with existing CO(3–2) measurements.
- We successfully detected 10 galaxies and obtained upper limits for four more; Figure 1 shows the CO(3–2)/CO(1–0) ratio for the entire sample and three of our strongest detections are in Figure 2.
- We also use these observations to robustly determine gas masses and gas-to-dust ratios, and to clean the Schmidt-Kennicutt relation of potential excitation biases.

Figure 2. CO(1–0) integrated line maps for three of our strongest detections. Contours are multiples of ±1.5σ.



Do SMGs and AGN Host Galaxies have different CO(3–2)/CO(1–0) Line Ratios?

Original Distribution

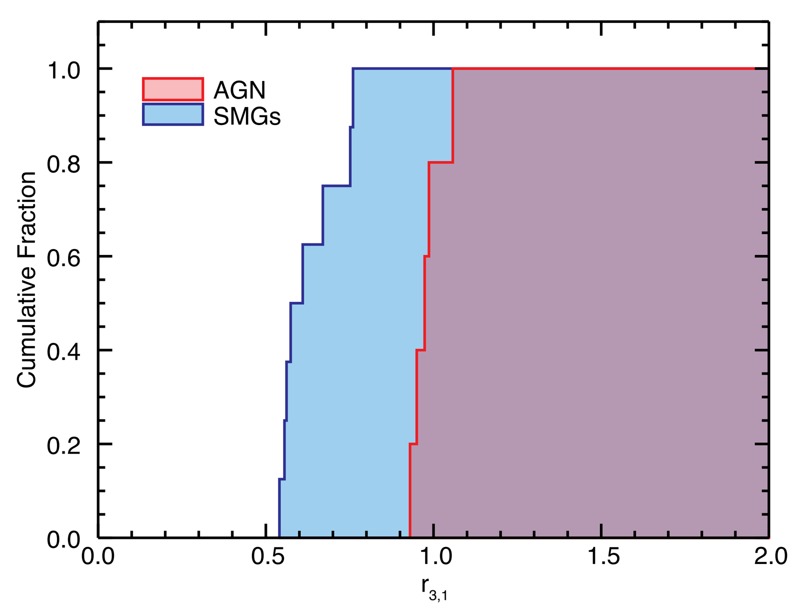


Figure 3. Cumulative distribution of CO(3–2)/CO(1–0) line ratio measurements for AGN-host galaxies (blue) and SMGs (red) from Swinbank et al. (2010), Harris et al. (2010), Ivison et al. (2011), and Riechers et al. (2011).

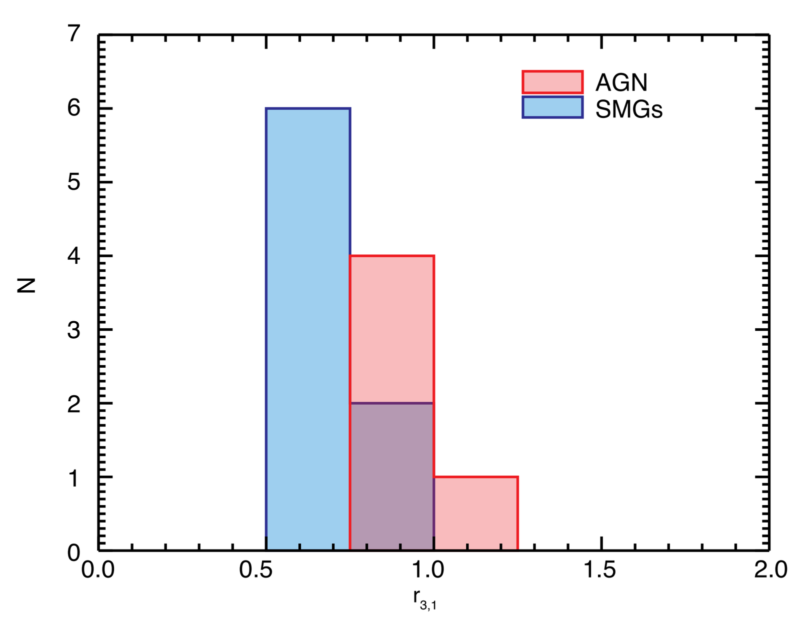


Figure 4. Histogram showing the distribution of CO(3–2)/CO(1–0) line ratio measurements for AGN-host galaxies (blue) and SMGs (red) from Swinbank et al. (2010), Harris et al. (2010), Ivison et al. (2011), and Riechers et al. (2011). Bin widths are $\Delta r_{3,1}$=0.25.

$$r_{3,1} = \frac{\int S_\nu(\mathrm{CO}(3{-}2))dv}{\int S_\nu(\mathrm{CO}(1{-}0))dv}\left(\frac{\nu_{\mathrm{CO}(1-0)}}{\nu_{\mathrm{CO}(3-2)}}\right)^2$$

- In Figures 3 and 4 we show the cumulative distribution and histogram of the 13 original CO(3–2)/CO(1–0) line ratio measurements (in units of brightness temperature, $r_{3,1}$) for z~2–3 SMGs and AGN-host galaxies clearly showing a tight cluster of SMGs near $r_{3,1}$=0.6 and AGN-host galaxies near $r_{3,1}$=1.0.
- For our expanded sample of 23 galaxies, we find that the $r_{3,1}$ distributions for SMGs and AGN-host galaxies (Figures 5 and 6) are consistent with being drawn from the same parent population (p>0.2) and having the same average $r_{3,1}$ (p>0.36) even when forcing ambiguously classified galaxies into categories most in line with previous results or removing weak detections.
- Some galaxies have been re-classified and some line ratio measurements have been updated to reflect the most recent interferometric detections.
- The disappearance of the dichotomy between these galaxy classes may be caused by including sources that are not as well studied (causing incorrect classifications) and that some of the SMGs may have buried AGN (in addition to the updated line measurements mentioned previously).

Our New Distribution

Figure 5. Cumulative distribution of CO(3–2)/CO(1–0) line ratio measurements for AGN-host galaxies (blue) and SMGs (red) for our new larger sample and literature detections. Some line ratios from the literature have been revised based on improved interferometric detections, and some galaxies have improved classifications.

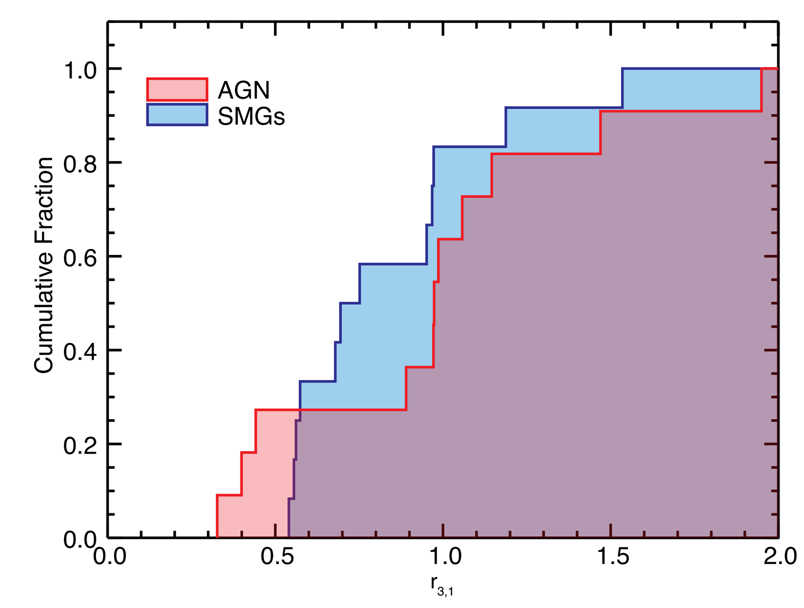
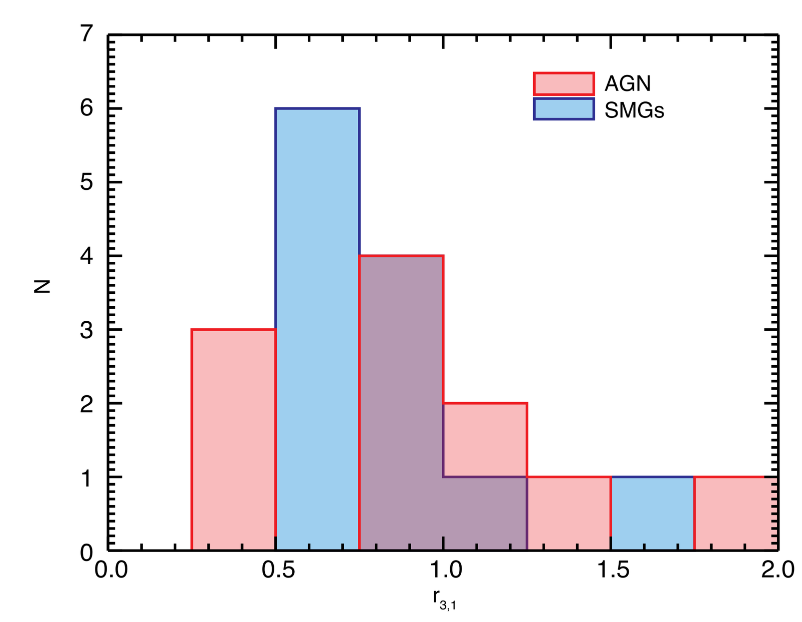


Figure 6. Histogram showing the distribution of CO(3–2)/CO(1–0) line ratio measurements for AGN-host galaxies (blue) and SMGs (red) for our new larger sample and literature detections. Some line ratios from the literature have been revised based on improved interferometric detections, and some galaxies have improved classifications. Bin widths are $\Delta r_{3,1}$=0.25.



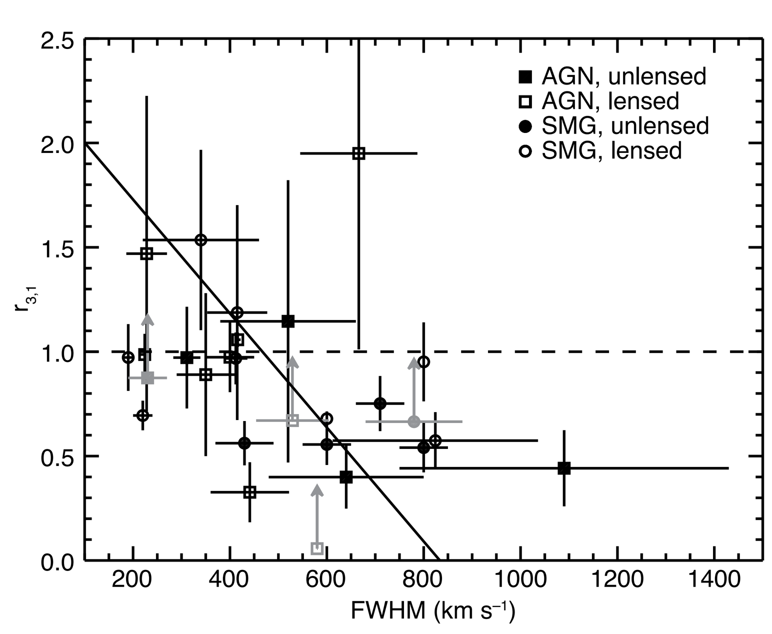


Figure 7. CO(3–2)/CO(1–0) line ratio as a function of the CO(3–2) line FWHM. Lower limits are shown in gray. We see no systematic difference between SMGs and AGN-host galaxies, but we do see a trend of higher CO excitation at lower line widths (slope of (2.73±1.65)×10^{-3} (km s^{-1})$^{-1}$). This is consistent with a spatially extended cold gas phase that is not well-mixed with any higher excitation molecular gas phases. We expect some natural scatter about this trend due to the galaxy orientation relative to our line of sight.

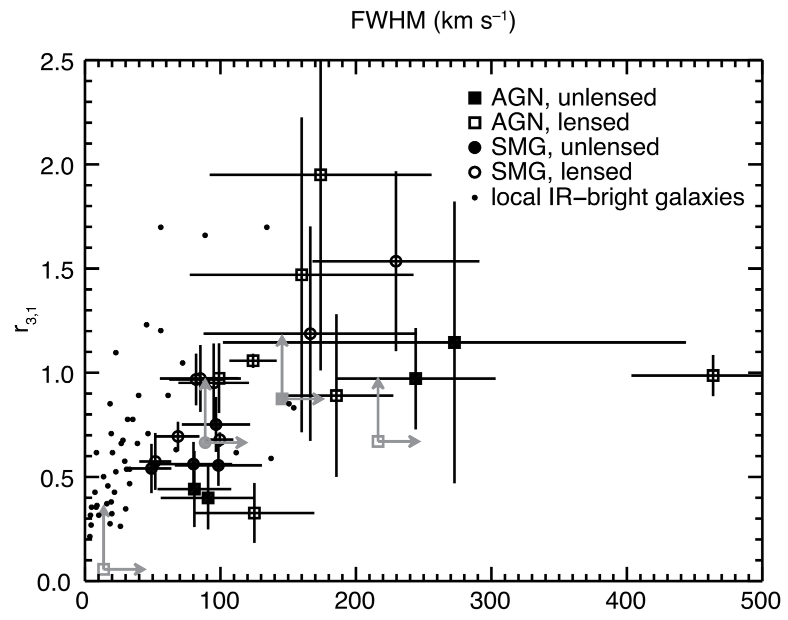


Figure 8. CO(3–2)/CO(1–0) line ratio as a function of the far infrared-to-CO line luminosity (i.e., star formation efficiency). Lower limits are shown in gray. In addition to our z~2 sample, we also show points for a collection of local infrared-bright galaxies from Yao et al. (2003). For both the low and high-redshift galaxies we see a strong trend of increasing gas excitation for higher star formation efficiencies. We also see that the high redshift galaxies have larger star formation efficiencies than the low redshift galaxies.

Further Analysis

- We also compare the CO(3–2)/CO(1–0) line ratio for SMGs and AGN-host galaxies as a function of a third observed parameter.
- In general, we do not find the CO line excitation correlates with other parameters of the galaxy, with the exception of the CO(3–2) FWHM (Figure 7) and the star formation efficiency (Figure 8; see also Yao et al. 2003).
- We use the matched CO(1–0) and CO(3–2) line measurements to clean the Schmidt-Kennicutt relation of potential excitation bias.
- We find no significant change in the offset or slope of the integrated Schmidt-Kennicutt relation between versions which use CO(1–0) and versions which use CO(3–2), whether or not we exclude AGN or apply magnification corrections (Figures 9 and 10).
- If we include low-redshift infrared-bright galaxies (Yao et al. 2003) in the analysis of the Schmidt-Kennicutt relation, the slope increases significantly and the normalization changes; the normalization is the only term which shows a significant difference between the two CO lines.

Figure 9. The integrated Schmidt-Kennicutt relation (the far infrared luminosity vs. CO line luminosity) for our sample. We show CO(1–0) (black; upper limits in gray) and CO(3–2) (red) measurements for each source as well as a small number of other high-redshift systems for comparison (labeled). Luminosities have not been corrected for magnification by gravitational lensing.

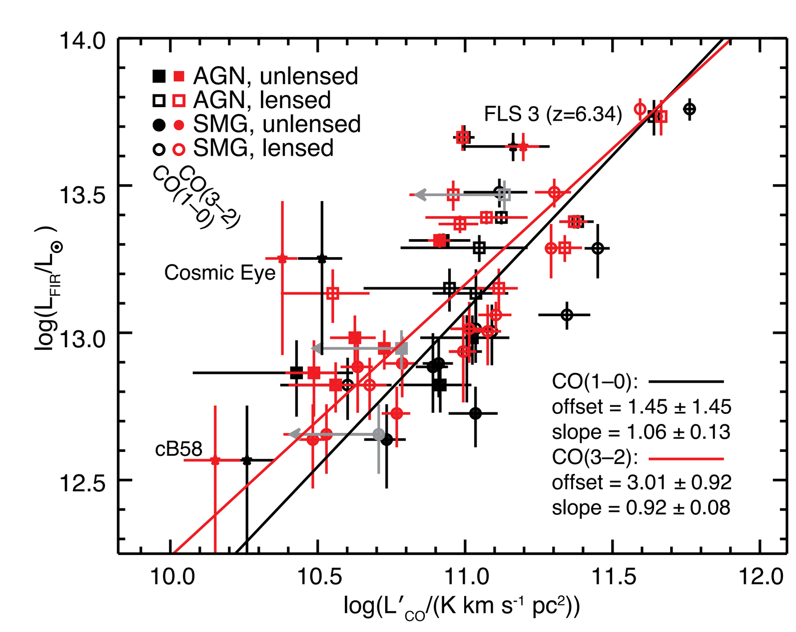
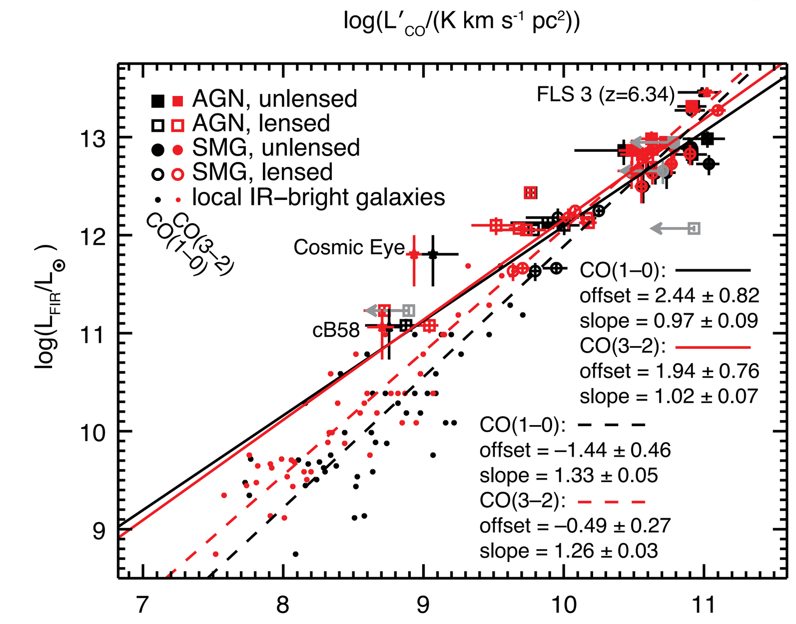


Figure 10. The integrated Schmidt-Kennicutt relation (the far infrared luminosity vs. CO line luminosity) for our sample and infrared-bright galaxies from Yao et al. (2003), corrected for magnification by gravitational lensing. We show CO(1–0) (black; upper limits in gray) and CO(3–2) (red) measurements for each source as well as for a small number of other high-z systems for comparison (labeled). The solid line is the fit to just the high-redshift sample and the dashed line includes low-redshift galaxies.



Summary

- We evaluate an expanded sample of z~2–3 galaxies for differences in CO line excitation, including 10 sources with new CO(1–0) detections and four new CO(1–0) upper limits.
- For our expanded sample, we find that the CO(3–2)/CO(1–0) line ratio distributions for SMGs and AGN-host galaxies are consistent with being drawn from the same parent population (p>0.2).
- We find that the gas excitation as probed by the CO(3–2)/CO(1–0) line ratio correlates with the CO(3–2) line FWHM and star formation efficiency, but no other galaxy properties.
- We find no significant change in either the offset or index of the integrated Schmidt-Kennicutt relation unless we include low-redshift infrared-bright galaxies; the offset for the combined low- and high-redshift sample is the only excitation-dependent parameter that we found.

References: Alloin et al. 2007, A&A, 470, 53; Ao et al. 2008, A&A, 491, 747; Barvainis et al. 1998, ApJL, 492, L13; Barvainis et al. 2002, ApJ, 571, 712; Beelen et al. 2004, A&A, 423, 411; Bothwell et al. 2013, MNRAS, 429, 3047; Carilli & Walter 2013, ARAA, 51, 105; Chapman et al. 2003, ApJ, 599, 92; Coppin et al. 2008, MNRAS, 389, 45; Danielson et al. 2011, MNRAS, 410, 1687; Downes et al. 2003, ApJ, 582, 37; Frayer et al. 2003, AJ, 126, 73; Genzel et al. 2003, ApJ, 584, 633; Greve et al. 2005, MNRAS, 359, 1165; Hainline et al. 2004, ApJ, 609, 61; Harris et al. 2010, ApJ, 723, 1130; Ivison et al. 2010b, A&A, 518, L35; Ivison et al. 2011, MNRAS, 412, 913; Kneib et al. 2005, A&A, 434, 819; Kovács et al. 2006, ApJ, 650, 592; Magnelli et al. 2012, A&A, 539, 155; Omont et al. 2003, A&A, 398, 857; Page et al. 2001, Science, 294, 2516; Riechers et al. 2011, ApJL, 739, L32; Riechers2011b, ApJ, 730, 108; Riechers et al. 2011c, ApJL, 733, L11; Riechers et al. 2013a, ApJ, 765, L31; Sharon et al. 2013, ApJ, 765, 6; Sharon et al. 2015, ApJ, 798, 133; Sheth et al. 2004, ApJL, 614, L5; Smail et al. 2002, MNRAS, 331, 495; Swinbank et al. 2010, Nature, 464, 733; Tacconi et al. 2006, ApJ, 640, 228; Thomson et al. 2012, MNRAS, 425, 2203; Weiß et al. 2003, A&A, 409, L41; Weiß et al. 2009a, ApJL, 705, L45; Yao et al. 2003, ApJL, 588, 711