# Taking Census of Massive, Star-Forming Galaxies formed 1 Gyr After the Big Bang

Casey, C.; Capak, P.; Staguhn, J.; Armus, L.; Blain, A.; Bethermin, M.; ... ; Zavala, J.

**Citation**

Casey, C., Capak, P., Staguhn, J., Armus, L., Blain, A., Bethermin, M., ... Zavala, J. (2019). Taking Census of Massive, Star-Forming Galaxies formed 1 Gyr After the Big Bang. *Bulletin Of The American Astronomical Society*, *51*(3), 212. Retrieved from https://hdl.handle.net/1887/84990

# Astro2020 Science White Paper

# Taking Census of Massive, Star-Forming Galaxies formed <1 Gyr After the Big Bang

**Thematic Areas:** ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

**Principal Author:**
Name: Caitlin M. Casey
Institution: The University of Texas at Austin
Email: cmcasey@utexas.edu
Phone: +1(512) 471-3405

**Co-authors:** Peter Capak (IPAC/Caltech), Johannes Staguhn (NASA Goddard/Johns Hopkins University), Lee Armus (IPAC/Caltech), Andrew Blain (University of Leicester), Matthieu Bethermin (LAM), Jaclyn Champagne (University of Texas at Austin), Asantha Cooray (University of California Irvine), Kristen Coppin (University of Hertfordshire), Patrick Drew (University of Texas at Austin), Eli Dwek (NASA/Goddard), Steven Finkelstein (University of Texas at Austin), Maximilien Franco (University of Hertfordshire), James Geach (University of Hertfordshire), Jacqueline Hodge (Leiden Observatory), Jeyhan Kartaltepe (Rochester Institute of Technology), Maciej Koprowski (University of Hertfordshire), Claudia Lagos (International Centre for Radio Astronomy Research, University of Western Australia), Desika Narayanan (University of Florida), Alexandra Pope (University of Massachusetts Amherst), David Sanders (University of Hawai'i), Irene Shivaei (University of Arizona), Sune Toft (DAWN/University of Copenhagen), Joaquin Vieira (University of Illinois), Fabian Walter (Max Planck Institute for Astronomy), Kate Whitaker (University of Connecticut), Min Yun (University of Massachusetts Amherst), Jorge Zavala (University of Texas at Austin).

**Abstract:** Two decades of effort have been poured into both single-dish and interferometric millimeter-wave surveys of the sky to infer the volume density of dusty star-forming galaxies (DSFGs, with SFR $\gtrsim 100\,M_\odot\,yr^{-1}$) over cosmic time. Though obscured galaxies dominate cosmic star-formation near its peak at $z \sim 2$, the contribution of such heavily obscured galaxies to cosmic star-formation is unknown beyond $z \sim 2.5$ in contrast to the well-studied population of Lyman-break galaxies (LBGs) studied through deep, space- and ground-based pencil beam surveys in the near-infrared. Unlocking the volume density of DSFGs beyond $z > 3$, particularly within the first 1 Gyr after the Big Bang is critical to resolving key open questions about early Universe galaxy formation: **(1)** What is the integrated star-formation rate density of the Universe in the first few Gyr and how is it distributed among low-mass galaxies (e.g. Lyman-break galaxies) and high-mass galaxies (e.g. DSFGs and quasar host galaxies)? **(2)** How and where do the first massive galaxies assemble? **(3)** What can the most extreme DSFGs teach us about the mechanisms of dust production (e.g. supernovae, AGB stars, grain growth in the ISM) <1 Gyr after the Big Bang? We summarize the types of observations needed in the next decade to address these questions.

**Background:** Among all star-forming galaxies, DSFGs are the most massive and extreme: they are characterized by high star formation rates, typically above $100\,\mathrm{M_\odot\,yr^{-1}}$, and typical stellar masses above $10^{10}\,M_\odot$. As a byproduct of their high star-formation rates they are very dusty galaxies, whereby $> 95\%$ of the emission from hot, young stars is obscured by dust and reprocessed from rest-frame UV to rest-frame far-infrared emission (see reviews of Sanders & Mirabel 1996, Blain et. al. 2002, and Casey, Narayanan & Cooray 2014). Today we know that, though rare in the nearby Universe, these DSFGs are $1000\times$ more common at $z \sim 2$, such that they dominate all of cosmic star formation (e.g. Gruppioni et. al. 2013). However, their volume density at $z \gtrsim 2.5$ is still unconstrained (see Figure 1). Completing an accurate census predicates any representative studies of their physical evolution and fundamental role in driving galaxy evolution.

Unfortunately the strategy which has been so successful for studying the rest-frame optical and near-infrared emission from 'normal' high-redshift galaxies (e.g. Lyman-break galaxies, LBGs)—deep pencil beam surveys in extragalactic legacy fields—cannot (and has not) enabled a clear census of dust-obscured galaxies at $z > 3$ (e.g. Dunlop et. al. 2016, Franco et. al. 2018). This is because DSFGs are relatively rare compared to LBGs (at $z \sim 2$ there are roughly 100 LBGs for every DSFG, despite contributing equal amounts to cosmic star-formation); this is a direct result of DSFGs being at the tip of the galaxy mass function. Whitaker et. al. (2017) demonstrate directly that, indeed, it is galaxies with the highest stellar masses ($>10^{10}\,\mathrm{M_\odot}$) that are most obscured by dust ($>$90%), while fainter, low-mass galaxies have lower total obscuration fractions ($\sim$20-80%). This trend with mass results in very different forms of the galaxy luminosity function (LF) in the rest-frame UV vs. the rest-frame FIR: the UVLF is characterized by a steep faint-end slope and an exponential fall-off at the bright end (e.g. Finkelstein 2016), while the IRLF is characterized by a shallow faint-end slope and broken powerlaw with increasing luminosity.

Thus, the vast majority of DSFGs identified to date have been found in wide-area ($>$0.1–100 $\mathrm{deg^2}$) surveys from single-dish FIR and millimeter telescopes like JCMT/SCUBA and SCUBA-2 (starting with Smail et. al. 1997), *Herschel Space Observatory* (e.g. Elbaz et. al. 2011, Casey et. al. 2012b,c), and the AzTEC instrument on JCMT, ASTE and the LMT (e.g. Scott et. al. 2008, Aretxaga et. al. 2011). Meticulous multi-wavelength follow-up of $\sim$100s of these sources over the past decades have revealed that the vast majority of them sit at redshifts $1 \lesssim z \lesssim 3$ (e.g. Chapman et. al. 2005, Cowie et. al. 2018) and are either fueled by major galaxy mergers or represent a class of particularly gas-rich massive disk galaxies undergoing intense star formation (e.g. Ivison et. al. 2012, Hodge et. al. 2013, 2016).

The primary hindrance to the identification and characterization of DSFGs at *earlier* epochs comes from the difficulty in accurately identifying the handful that might sit at higher redshifts. This difficulty is, in part, due to the very negative K-correction at (sub)millimeter wavelengths: though it is a 'blessing' that DSFGs are just as bright at $z \sim 10$ as at $z \sim 1$, it substantially obfuscates our ability to robustly identify their redshifts with long-wavelength emission alone. (Sub)millimeter colors can trace either a DSFGs' dust temperature or (rough) redshift, a degeneracy that hinders the quick characterization of DSFGs. The large beamsizes of typical DSFG selection surveys further obfuscates their accurate identification.

As a thought experiment (one presented in Casey et. al. 2018a and in Figure 1), if we are to distinguish between two extremely different star-formation rate densities (SFRDs) to describe the possible high-$z$ volume density of DSFGs, we would need to accurately identify the redshifts of *all* ($>$98%) DSFGs selected at, e.g., 850$\mu$m. This conclusion is reached by a forward evolution model, asserting an adopted IRLF and analyzing how submm number counts and sample redshift

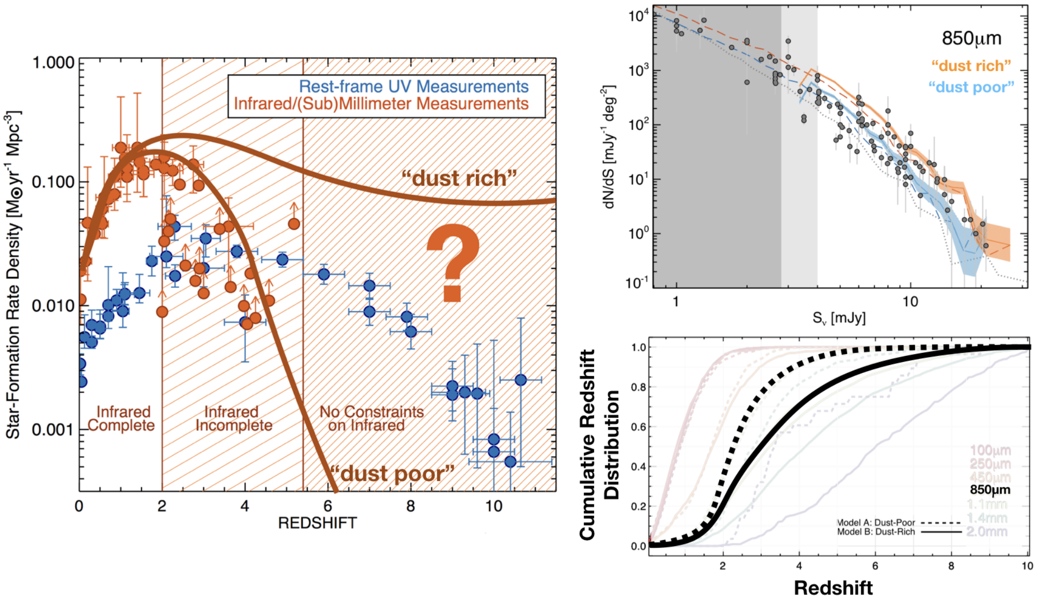

Figure 1: *(Figures modified from Casey et. al. 2018a.)* **Left:** The cosmic star-formation history of the Universe as measured at rest-frame UV wavelengths (blue points) and infrared through millimeter measurements (orange points). No dust correction has been applied to the UV. While rest-frame UV measurements now reach out beyond $z > 10$ thanks to deep *HST* near-infrared imaging campaigns, in contrast surveys of obscured emission in galaxies is incomplete at $z > 3$ and completely unconstrained at $z > 5$. Casey et. al. (2018a) tests two dramatically different possibilities for the obscured fraction of the SFRD, shown by the dark orange lines. They show (shockingly) that we do not yet have data good enough to distinguish between these two models. **Upper right:** The difference between these two extreme 'dust poor' and 'dust rich' models in 850$\mu$m number counts against data (gray points). **Lower Right:** Difference in the expected redshift distribution for 850$\mu$m-selected DSFGs for the two models: no dataset has the precision needed to distinguish even between these two models.

distributions would present. Out of a sample of 100 DSFGs, the extreme 'dust rich' model in Fig. 1 predicts 7 DSFGs to sit above $z > 4$ while the 'dust poor' model predicts only 3 DSFGs to sit above $z > 4$ (also see Casey et. al. 2018b for implications with ALMA deep fields). Unfortunately, the most spectroscopically-complete samples of DSFGs (like the ALESS and SPT samples; Vieira et. al. 2013, Danielson et. al. 2017) are, at most, ∼50-90% complete, thus lacking the precision necessary to draw accurate conclusions as to the number density of early-Universe DSFGs.

This concept paper focuses on strategies for finding and characterizing such early Universe ($z > 3$) DSFGs, with particular focus on pushing toward higher redshifts when DSFG formation scenarios place more stringent constraints on the formation of the earliest massive galaxies, <1 Gyr after the Big Bang.

**Broader Importance to Galaxy Evolution:** Knowing the prevalence of dust-obscured star formation is particularly important at $z \gtrsim 5$, when cosmic time becomes a constraint on the physical processes involved in producing dust, metals and stars seen in galaxies. For example, if DSFGs contribute significantly to cosmic star-formation at this epoch (as suggested by new observational results from Zavala et. al. 2018), then it would imply that dust production mechanisms must be particularly efficient and likely happen via supernovae (Matsuura et. al. 2011, Dwek et. al. 2014), combined with low destruction rates, rather than from coagulation in the upper atmospheric winds of AGB stars, or coagulation or accretion of dust in the ISM (Matsuura et. al. 2006, 2009, Jones et. al. 2013). It might also have a fundamentally different composition (e.g. De Rossi et. al. 2018).

Furthermore, not only do early DSFGs teach us about dust formation, but they also shed light on the formation of the first massive halos. Their halos are just as massive, if not more massive than quasar host galaxies at similar epochs (e.g. Wang et. al. 2011, Bethermin et. al. 2013, Maniyar et. al. 2018), and yet the number density of DSFGs may be as much as 10-100× higher than rare quasars given the prolonged duration of a starburst episode with respect to the short-lived quasar phase. The detection of DSFGs like SPT0311 at $z = 6.9$ (Strandet et. al. 2017, Marrone et. al. 2018) with a measured gas mass $>10^{11}\,\mathrm{M}_{\odot}$ push the limits: at this epoch, the most massive halo detectable in the entire observable universe would only be $\sim$3-5× more massive than what is measured, and the implied baryon collapse efficiency near 100%. Are there more similarly-extreme DSFGs at these epochs, or at higher redshifts, to be found? Without a measurement of the underlying number density of DSFGs around this epoch, we lack a good handle on the relative rarity of massive halos like SPT0311, thus few *observational* constraints on hierarchical formation itself during the first Gyr.

**Current Barriers to Progress:** There are several reasons the aggregate $z > 3$ DSFG population has proved elusive, most of which are directly attributable to a dearth of data or necessary *complete* follow-up on existing targets. Overcoming these barriers to progress requires a careful analysis of their causes (many are discussed at further length in Casey et. al. 2018a,b, and Zavala et. al. 2018). Here we summarize what we see as the primary limitations to analysis in the current era:

**1. DSFGs are rare and the faint-end slope of the IRLF is shallow.** Deep, pencil beam millimeter-wave surveys on the order of a few tens of arcmin$^2$ only result in detection of tens of sources, the vast majority of which sit at $z < 3$. This is what has been found by pioneering ALMA deep fields conducted at 1 mm (Dunlop et. al. 2016, Aravena et. al. 2016, Franco et. al. 2018). The core reason that DSFGs are rare is because dust-obscured star formation preferentially lives in massive galaxies (as found by Whitaker et. al. 2017). Because the sky density of DSFGs is relatively low, large areas of sky need to be mapped (on the order of $\gtrsim$ 1-10 deg$^2$) to find a sufficient number of sources ($\gtrsim$ 100), of which only a handful (at most) will sit at $z > 4$ (see Casey et. al. 2018a,b). Due to the strong negative K-correction at millimeter wavelengths, pushing deep pencil beam surveys deeper will, perhaps counter-intuitively, result in detections of lower redshift ($z \sim 1$), less extreme systems (like LIRGs, with $10 \lesssim \mathrm{SFR} \lesssim 100\,\mathrm{M}_{\odot}$) rather than an increase in the higher-redshift DSFG population (e.g. Bethermin et. al. 2015). These less extreme systems are likely to be well characterized by optical/near-infrared surveys.

**2. DSFGs at $z \gtrsim 4$ are a needle in a haystack relative to those at $1 < z < 3$, thus easy to mis-identify.** The expected number counts (density of sources of certain flux densities) at 850$\mu$m–1 mm *and* the anticipated shape of the redshift distribution is largely <u>insensitive</u> (within uncertainties) to the two dramatically different hypothetical universes presented in Figure 1. This is because the vast majority of all DSFGs sit at $1 < z < 3$ (e.g. Danielson et. al. 2017, Cowie et. al. 2018), where they are known to dominate all of cosmic star formation. Even in the extreme 'dust rich' case, whereby DSFGs are proposed to dominate cosmic star formation at $z > 4$, their number density on the sky would be rather low. This phenomenon is also present in LBG samples, although redshifts are far more straightforward to infer for LBGs, and so confusing a $z \sim 2$ LBG with a $z \sim 6$ LBG is unlikely, whereas it is very possible to confuse DSFGs at these two epochs. This results in a 'needle in the haystack' problem for $z \gtrsim 4$ DSFGs: they are incredibly rare and not at all easy to pick out from the average millimeter flux density selected sample.

Further aggravating the 'needle in the haystack' problem are DSFG mis-identifications. In other words, it is rather easy to mis-identify a DSFG's redshift or optical/near-IR counterpart, particularly when DSFGs are originally selected in poor-spatial-resolution single-dish datasets, with beamsizes 15–30″ across, and only some have interferometric follow-up from ALMA that spatially locates the position of millimeter wave emission. Even in cases of clear positional localization via interferometry, DSFGs can be confused with foreground optically-luminous galaxies within 1–2″, and only identified as background sources through serendipitous means: for example, through detection of millimeter line emission with ALMA or PdBI/NOEMA (GN20, HDF850.1, and AzTEC-2; Daddi et. al. 2009, Walter et. al. 2012, Jiminez-Andrade et. al., in prep). These mis-identifications can easily wash out the census of DSFGs at $z > 4$, where precision and sample completeness is needed at the level of 98–99%.

**3. Selection of DSFGs has been carried out primarily at $\lambda \leq 1$ mm.** (Sub)millimeter extragalactic surveys have largely been carried out at 850$\mu$m (SCUBA & SCUBA-2), 250–500$\mu$m (*Herschel*/SPIRE) or 1 mm (AzTEC/ALMA), with the largest area ($\gg$1 deg$^2$) covered only by *Herschel*. As shown in Figure 2, the shorter wavelengths are less sensitive surveys are to DSFGs at $z > 3$. 1 mm surveys are sensitive to high-$z$ DSFGs, though samples are dominated ($\sim$95%) by the more numerous $z < 3$ DSFGs. Selection at longer wavelengths, in particular 2 mm, would effectively filter-out the low-$z$ DSFGs while pushing the sensitivity of surveys deeper at higher-$z$. Unfortunately, no significant surveys have yet been carried out at 2mm, save small GISMO maps in HDF and COSMOS (Staguhn et. al. 2014, Magnelli et. al. 2019, submitted).

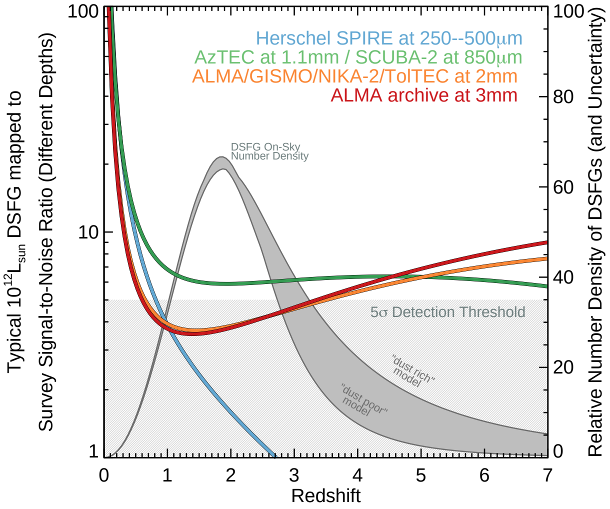

Figure 2: The detection signal-to-noise of DSFGs in (sub)mm datasets as a function of redshift, scaled by typical survey sensitivity for a $10^{12}\,L_\odot$ system. Wavelengths shown are 250–500$\mu$m (*Herschel*/SPIRE; blue), 1.1 mm (AzTEC; green, also representative of SCUBA-2 at 850$\mu$m), 2 mm (ALMA/GISMO/NIKA-2/TolTEC, orange), and 3 mm (ALMA, red, see Zavala et. al. 2018c). Below a signal-to-noise of five, sources are not detectable (light gray region). On the right axis (and gray band) is the relative number density of DSFGs, showing uncertainty projected from the dust rich and dust poor models from Figure 1 (dark gray region). *This figure shows that the vast majority of DSFGs sit at $1 < z < 3$, and the most effective filter for the highest-z DSFGs is selection at 2–3 mm, which greatly mitigates the 'foreground.'* These tracks do account for CMB heating (da Cunha et. al. 2013) and an average $\lambda_{\rm peak} = 100\,\mu$m (rest-frame).

**Strategy to identify the highest-redshift Obscured Galaxies in the 2020s:** As we look toward the next generation of instruments and facilities that could be used to detect highly obscured, massive galaxies like DSFGs in the early Universe, we recognize that the strategy our community must adopt will be quite different than the strategy that was so successful for pioneering *Hubble* deep fields. Drilling deeper in the millimeter is likely to result in a modest increase in source density with a lower average redshift for fainter sources. This is because the obscured galaxy luminosity function is much shallower at the faint end than the UV luminosity function and due to the very strong negative K-correction in the millimeter. Thus, **a census of obscured galaxies at $z > 3$ requires ambitious large surveys ( $\gtrsim$ 1-10 deg$^2$) carried out at 1.4 mm–2 mm with large single-dish millimeter observatories with large fields of view. To-date, no such surveys have**

**been carried out that fulfill this criterion**; this, despite the fact it was a top priority from the 2010 decadal review at the mid-scale (the CCAT project).

The US is one of the few regions that does not have open access to the single-dish (sub)millimeter facilities needed to carry out this work, despite our tremendous investment in millimeter wave astrophysics through ALMA[1]. In order to take an accurate census of the highest-redshift massive galaxies and successfully pursue a number of other science objectives that are unique to such facilities, the US community needs to prioritize either the funding of existing facilities (like JCMT or the LMT) or build a 30–50 m facility (like the originally planned CCAT, or join the new European AtLAST project). In the near-term, the instrumentation that will contribute to this census are:

**GISMO:** The 2 mm GISMO instrument conducted two blank field mapping projects at the IRAM 30 m (Staguhn et. al. 2014, Magnelli et. al. 2019) and has the potential to continue cutting-edge 2 mm mapping in the very near future at a facility like JCMT or LMT. Timing is crucial for *JWST* follow-up on the galaxies' stellar emission. Selection at 2 mm is an efficient method of isolating the highest-redshift DSFGs by filtering out the majority of lower redshift DSFGs, and GISMO has provided the first efficient way to reach <1 mJy depths needed to detect a sufficient number of sources per area on the sky (this is needed because the 2 mm number counts, despite being a useful way to isolate high-$z$ sources, are very steep and shallower maps will detect very few sources).

**NIKA-2 at the IRAM 30 m:** NIKA-2 is going to push both 1 mm and 2 mm surveys at the IRAM 30 m over the next decade. The two bands could work well to isolate the highest redshift DSFGs of interest in blank surveys.

**TolTEC at the LMT:** The TolTEC instrument will be installed on the LMT in the early 2020s and carry out ground-breaking continuum surveys at 1 mm, 1.4 mm, and 2 mm with unparalleled mapping speed using MKID technology. Similar to NIKA-2, the three bands could work to simultaneously and effectively filter DSFGs into intermediate and high-redshift subsamples.

**SPT 3G:** Though a CMB experiment, the SPT 3G survey will be substantially deeper than the original SPT surveys, forging into parameter space where unlensed DSFGs would be detectable. While the telescope is much smaller than other facilities (10 m), which results in a larger beamsize, confusion noise will not dominate as the source density at 2–3 mm is low. SPT 3G will cover more sky than TolTEC and more efficiently detect rarer, brighter DSFGs.

**ALMA:** ALMA is extremely sensitive and versatile, despite being fundamentally limited to very narrow regions of sky, for lack of its wide-area mapping capability. Nevertheless, it can play a crucial role in the census of DSFGs at high-$z$ through programs pushing in new directions. For example, the first 2 mm map (deeper than existing GISMO maps) is in the Cycle 6 ALMA queue from the COSMOS team, requiring 41 hours in band 4 to cover 230 arcmin$^2$ to 0.9 mJy RMS, though it is not yet observed. The depth and angular resolution of such deep mosaics can discern between drastically different models of DSFG number density at $z > 4$. Similarly, existing 3 mm (band 3) programs focused on alternate science goals (e.g. detection of CO at $z \sim 1-2$) can be sufficiently deep to reveal serendipitous continuum sources (as in Zavala et. al. 2018c) over hundreds of arcmin$^2$. While existing 1 mm ALMA deep fields (Dunlop et. al. 2016, Aravena et. al. 2016, Franco et. al. 2018) lack large numbers of sources, they represent only a narrow exploration of ALMA's blind mapping capabilities.

---

[1] There is no US access to the IRAM 30 m, and there is institutionally-restricted access in the US to the JCMT (the University of Hawai'i), the LMT (University of Massachusetts Amherst), and the future, descoped CCAT prime project (Cornell).

**References:**

Aravena et. al. (2016) ApJ 833, 68
Aretxaga et. al. (2011) MNRAS 415, 3831
Bethermin et. al. (2013) A&A 557, 66
Bethermin et. al. (2015) A&A 576, 9
Blain et. al. (2002) Physics Reports 369, 111
Casey et. al. (2012b) ApJ 761, 140
Casey et. al. (2012c) ApJ 761, 139
Casey et. al. (2018a) ApJ 862, 77
Casey et. al. (2018b) ApJ 862, 78
Casey, Narayanan & Cooray (2014) Physics Reports 541, 45
Cowie et. al. (2018) ApJ 865, 106
Daddi et. al. (2009) ApJ 694, 1517
Danielson et. al. (2017) ApJ 840, 78
De Rossi et. al. (2018) ApJ 869, 4
Dunlop et. al. (2016) MNRAS 466, 861
Dwek et. al. (2014) ApJL 788, 30
Elbaz et. al. (2011) A&A 533, 119
Finkelstein (2016) PASA 33, 37
Franco et. al. (2018) A&A 620, 152
Geach et. al. (2017) MNRAS 465, 1789
Hodge et. al. (2013) ApJ 768, 91
Hodge et. al. (2016) ApJ 833, 103
Ivison et. al. (2012) MNRAS 425, 1320
Jiminez-Andrade et. al., in prep
Jones et. al. (2013) A&A 558, 62
Magnelli et. al. (2019) ApJ submitted
Maniyar et. al. (2018) A&A 614, 39
Marrone et. al. (2018) Nature 553, 51
Matsuura et. al. (2006) MNRAS 371, 415
Matsuura et. al. (2009) MNRAS 396, 918
Matsuura et. al. (2011) Science 333, 1258
Sanders & Mirabel (1996) ARA&A 34, 749
Scott et. al. (2008) MNRAS 385, 2225
Smail et. al. (1997) ApJL 490, 5
Staguhn et. al. (2014) ApJ 790, 77
Strandet et. al. (2017) ApJL 842, 15
Vieira et. al. (2013) Nature 495, 344
Walter et. al. (2012) Nature 486, 233
Wang et. al. (2011) AJ 142, 101
Whitaker et. al. (2017) ApJ 850, 208
Zavala et. al. (2018) ApJ 869, 71