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The effect of lensing on the identification of SCUBA galaxies

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ABSTRACT

Spectroscopic surveys of submillimetre(submm)-selected sources have uncovered optically bright galaxies at $z \lesssim 1$ close to the positions of several submm sources. Naive statistical analyses suggest that these galaxies are associated with the submm emission. However, in some cases, it is difficult to understand this association given the relatively modest redshifts and unprepossessing spectral characteristics of the galaxies. These are in stark contrast to those expected from the massive dust-enshrouded starbursts and AGN thought to power the bulk of the bright submm population. We present new observations of optically bright counterparts to two luminous submm sources, along with a compilation of previously proposed optically bright counterparts with $z \lesssim 1$. We suggest that the majority of these associations between bright galaxies and submm sources may be as a result of the action of the foreground galaxies as gravitational lenses on the much fainter and more distant submm sources. We discuss the implications of this conclusion for our understanding of the SCUBA population.

Key words: gravitational lensing – galaxies: formation – galaxies: starburst – infrared: galaxies – submillimetre.

1 INTRODUCTION

The intentional use of gravitational lenses has been a particularly profitable route to probe the nature of the submm galaxy population (Smail, Ivison & Blain 1997; Chapman et al. 2002a; Cowie, Barger & Kneib 2002; Smail et al. 2002). The lens amplification facilitates the identification and characterization of counterparts at other wavelengths (Smail et al. 2002), and has produced some of the best-studied examples of the submm population (e.g. Ivison et al. 1998, 2000; Soucail et al. 1999). Blank field submm surveys have also been undertaken (e.g. Hughes et al. 1998; Barger et al. 1999; Eales et al. 1999, 2000; Borys et al. 2002; Scott et al. 2002; Webb et al. 2002), these cover large contiguous areas and are in principle simpler to analyse than the lens surveys. However, without the boost from a cluster lens, identifying counterparts in the blank-field surveys has proved to be an arduous task. For example, it has taken four years of effort to track down the brightest source in the *Hubble Deep Field* North, HDF850.1 (Dunlop et al. 2002).

The published blank-field SCUBA surveys have reliably identified a small fraction of their submm sources in the optical and near-infrared (Gear et al. 2000; Lutz et al. 2001), with a handful having spectroscopic redshifts, e.g. Westphal-MMD11 (Chapman et al. 2002b); CUDSS 3.8, 3.10, 14.13 and 14.18 (Eales et al. 2000; Webb et al. 2002). Although the spectral properties of some of these proposed counterparts appear reasonable given their redshifts, several of them must have very low dust temperatures compared to similar luminosity galaxies in the local Universe, if they are to produce the observed submm emission at the proposed redshifts, $z \lesssim 1$ (Eales et al. 1999; Dunne & Eales 2001).

There are only three SCUBA galaxies with spectroscopic redshifts which have been confirmed in CO line emission, all these lie at $z \geqslant 1$ (e.g. Frayer et al. 1998, 1999), consistent with the estimates of the median redshift for the whole population of $z \sim 2$–3 from their submm and radio spectral properties (Hughes et al. 1998; Carilli & Yun 2000; Smail et al. 2000; Yun & Carilli 2002), with few galaxies at $z \ll 1$. Current models of the SCUBA galaxy redshift distribution $N(z)$ (Blain et al. 2002; Chapman et al. 2002d; Ivison et al. 2002) suggests the number of sources at $z < 1$ is probably around 2 per cent and is very unlikely to exceed 5 per cent. The existence of a moderate fraction of SCUBA galaxies with redshifts of $z \ll 1$ would therefore indicate a strongly bimodal redshift distribution, and suggest that two physically distinct classes of SCUBA galaxies contribute to the faint submm counts. Alternatively, the apparent low-redshift counterparts could be misidentifications – but why then are they so frequent?

Given the expected high median redshift of the submm population and the steep number counts seen for the brighter submm sources (Blain et al. 1999; Scott et al. 2002), gravitational lensing by foreground galaxies is one possible explanation for the anomolously high rate of association of submm sources with low-redshift, optically bright galaxies. Surveys of distant QSOs have provided

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estimates of the rate of lensing for optical samples of $z > 1$ QSOs, 0.7 per cent (e.g. Surdej et al. 1993; Jaunsen et al. 1995; Kochanek, Falco & Schild 1995, see also Kochanek 1993). A more reliable constraint comes from lens searches in the radio waveband where obscuration in the lens is not a concern: these suggest that a modest fraction of flux-limited radio-loud AGN samples, 0.25–0.57 per cent, are strongly lensed by field galaxies at $z \lesssim 1$ (e.g. King et al. 1999; Myers et al. 1999). This same population of lenses will act on the similarly distant SCUBA population, although differences in the intrinsic count slope of the two populations will lead to a different rate of occurence of strong (and weak) lensing in flux limited submm samples. The issue of the effects of gravitational lensing on field surveys in the submm waveband have been discussed by Blain (1996, 1998), who suggested that ∼2 per cent of SCUBA galaxies with $S_{850}\,\mu\mathrm{m} \simeq 10$ mJy will be amplified by $\geqslant 2\times$ by foreground lenses. The number of published submm sources is now sufficient that we should be able to test this prediction and in doing so investigate the nature of those SCUBA galaxies which apparently lie at $z \ll 1$.

2 OBSERVATIONS AND REDUCTION

We have embarked on a programme to obtain spectroscopic redshifts for a large sample of radio-selected, optically bright submm sources. The goal of this project is to identify the optically brightest SCUBA galaxies (Ivison et al. 1998, 2000, 2001) which are suitable for detailed follow-up on 10-m class telescopes. To achieve this we extended the previous work on submm observations of optically faint radio-selected sources (e.g. Chapman et al. 2001b) to brighter counterparts. Chapman et al. (2002e) demonstrated the success of this approach, recovering ∼60 per cent of the SCUBA population. The expectation is that the remaining 40 per cent include both optically luminous SCUBA galaxies (Ivison et al. 1998, 2000) and very high redshift sources which are too faint in the radio waveband to be detected (e.g. Frayer et al. 2000). The bias against very distant SCUBA galaxies in radio surveys depends on their dust temperature: hotter submm-detected sources can be seen out to higher redshifts, $z \gtrsim 3$, while colder sources are more difficult to detect in the radio waveband (Chapman et al. 2002d).

The initial observations for our survey of optically bright SCUBA sources involved spectroscopy of seven sources with the Echellette Spectrograph and Imager (ESI) on the Keck II telescope in 2001 July. The echellette mode provides complete coverage from 0.32–1 μm at high spectral resolution ∼1Å, allowing very good sky subtraction into the atmospheric OH forest at the red end of the spectra. The spectral integrations were 1800 s for each source. High signal-to-noise flats and wavelength calibrations were taken shortly before the observations of each target, and fluxes were calibrated using spectra of red standard stars. The data were reduced with the MAKEE software using the recipe described in Barlow & Sargent (1997).

These observations generated redshifts for five new candidate counterparts to submm galaxies, to be discussed in a future paper. However, the proposed optically bright counterparts to two of these sources lie at much lower redshifts than expected from their radio and submm properties. Here we discuss these two sources are: SMM J16370+4106 from the SCUBA survey of Scott et al. (2002) and SMM J22173+0014 from Chapman et al. (2001a). We show radio/optical overlays of these two sources in Fig. 1 and summarize their properties in Table 1. The calibrated spectra are shown in Fig. 2 with their spectral features identified: the proposed optically bright counterpart to SMM J16370+4106 lies at $z = 0.845$, while the galaxy identified with SMM J22173+0014 has $z = 0.510$.

Table 1. Properties of the lensed submm sample.

Source	δr^a arcsec	z_{lens}	z_{CY}	T_{d}^b/K	L_{FIR}^c $10^{11}\,\mathrm{L}_\odot$	I-mag^d	$S_{850\,\mu\mathrm{m}}$ mJy	$S_{1.4\,\mathrm{GHz}}$ μJy	
SMM J16370+4106	2.0	0.845	2.2	20.3 ± 1.3	12 ± 3	21.4	11.2 ± 2.0	99 ± 20	N2 850.1, Ivison et al. (2002)
SMM J22173+0014	1.7	0.510	2.4	17.8 ± 0.8	6.1 ± 1.0	19.4	15.0 ± 3.0	145 ± 18	SSA22 850.2, Chapman et al. (2001a)
SMM J00266+1708^e	1.5	0.44	2.9	15.3 ± 0.6	3.6 ± 0.4	22.0	18.6 ± 1.5	100 ± 15	ERO: M12, Frayer et al. (2000)
SMM J04431+0210^d	2.3	0.18	> 2.6	<14.3	<0.29	18.4	7.2 ± 1.5	<57, 3σ	ERO: N4, Smail et al. (1999)
SMM J12369+6212	0.6	∼1.1	4.1	<17.8	<6.3	22.6	7.4 ± 0.5	<24, 3σ	HDF 850.1, Dunlop et al. (2002)

Notes. ^{a}Angular separation between the bright galaxy and the nominal position of the submm, mm or radio centroid. $^bT_{\mathrm{d}}$ is the dust temperature required for the source to have a radio/submm photometric redshift consistent with the spectroscopic measurement of the galaxy. ^{c}The FIR luminosity calculated from the radio-L_{FIR} relation at the spectroscopic redshift. ^{d}The I-band magnitude of the optically bright counterpart. ^{e}Fluxes have not been corrected for cluster lensing.

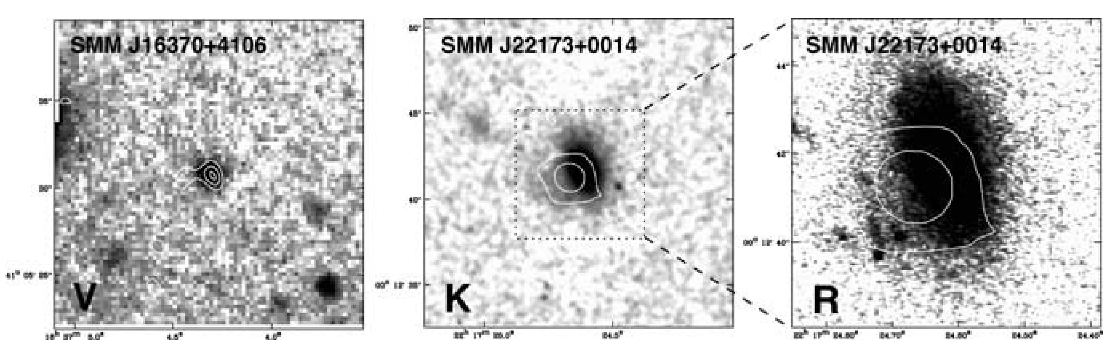

Figure 1. Images (18 × 18 arcsec^2) of the two $z < 1$ candidate submm sources observed using ESI: SMM J16370+4106 (left panel, V-band) and SMM J22173+0014 (centre panel, K-band). The right-hand panel shows a zoomed 7 × 7 arcsec^2 view of SMM J22173+0014 as seen in an *HST* STIS R'_{573} image. Radio contours are overlaid starting at 3σ, and increasing in 1σ intervals.

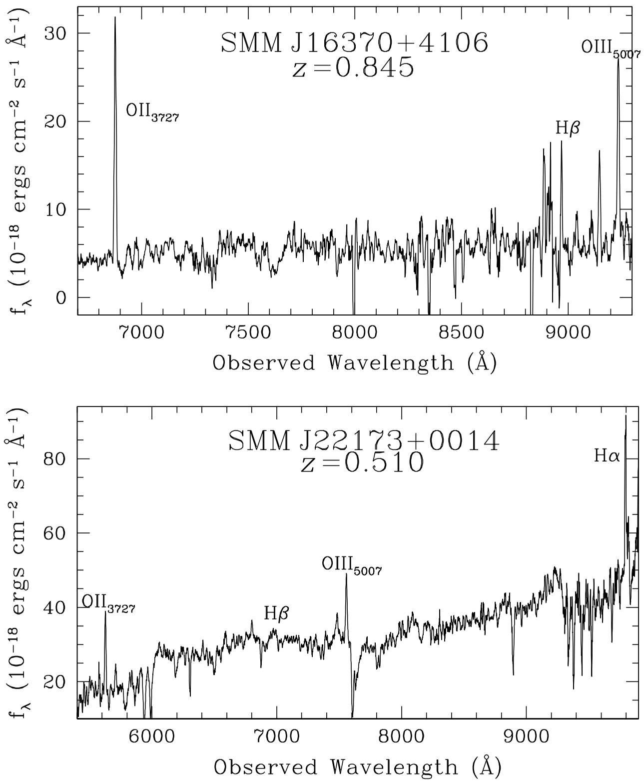

Figure 2. Keck/ESI spectra of SMM J16370+4106 (upper panel) and SMM J22173+0014 (lower panel). We identify redshifted emission lines in the spectra of both galaxies which place them at $z < 1$.

We note that the spectrum of SMM J22173+0014 shows broad lines indicative of a low-luminosity type 1 AGN: such activity is not infrequent in the high-redshift field population Cowie et al. (1996). The spectrum of SMM J16370+4106 looks like a typical H II region, and could conceivably be the unobscured component of a star-forming galaxy.

As we discuss below the properties of both of these systems strongly suggest that the optically bright, spectroscopically identified galaxies are not in fact the source of the submm emission, but instead may be foreground gravitational lenses which are amplifying more distant, optically faint SCUBA galaxies.

3 ANALYSIS AND DISCUSSION

We have cataloged two new > 10 mJy submm sources which are within 1–2 arcsec of $I < 21.5$ galaxies at $z = 0.510$ and 0.845. Relative radio-optical astrometry was realized by first calibrating the *I*-band images to the USNO reference frame for each field using about 70 stars, yielding an rms offset of 0.05 arcsec. The brightest ∼30 1.4-GHz sources were then selected, approximately 1/2 having compact optical counterparts. The final radio-optical rms astrometric error is 0.3 arcsec, and is dominated by the source centroiding, $\mathrm{FWHM}/(2 \times S/N) = 5\,\mathrm{arcsec}/17 = 0.3$ arcsec. In the absence of detections in deep, high resolution radio maps, the coarse spatial resolution of the SCUBA detections would mean that these offsets would not be significant. Combined with the low surface density of $I < 21.5$ galaxies this would lead to a high probability that the submm source is associated with the optically bright galaxy. There are two possible explanations for these associations: (1) either the optically bright galaxies are the source of the submm emission, or

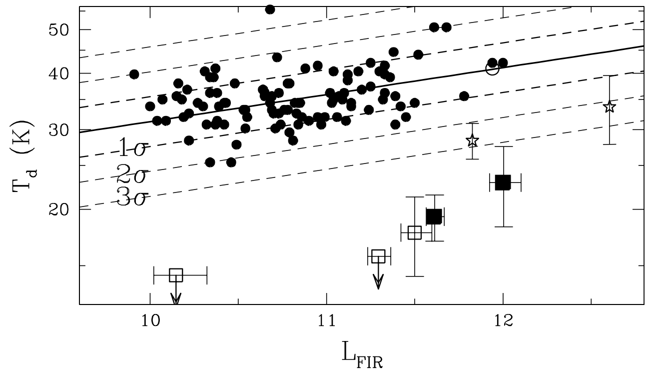

Figure 3. The distribution of $T_{\rm d}$ versus far-infrared luminosity for local luminous, dusty galaxies (circles), the best-fitting relationship is shown as a solid line and the error bounds by dashed lines. We show our two new systems by filled squares, assuming that the submm and radio emission is associated with the bright optical galaxy, as well as the lensed submm sources from the literature (open squares). We also show two distant, luminous *ISO*-FIRBACK galaxies from Chapman et al. (2002d) which have low dust temperatures (stars).

(2) these galaxies are lensing the true submm sources, which are fainter and lie at much higher redshifts.

If the spectroscopically identified galaxies are the source of the submm and radio emission then we can estimate the characteristic dust temperatures, $T_{\rm d}$, which these galaxies must have for the spectroscopic redshift to be consistent with the measured radio/submm spectral index and the associated photometric redshift (e.g. Carilli & Yun 2000) to within the 0.2 dex scatter of the FIR/radio relation (Helou et al. 1985): see Table 1. The values are compared with the distribution of dust temperatures (Dunne et al. 2000) as a function of galaxy luminosity in Fig. 3. The distribution is log normal, consistent with the best fit distribution for the local 1.2-Jy *IRAS* sample (Chapman et al. 2002f).

We list for comparison in Table 1 the properties of three sources from published SCUBA surveys which are all believed to be lensed by foreground galaxies: SMM J00266+1708 (Frayer et al. 2000) and SMM J04431+0210 (Smail et al. 1999), both of which lie within ∼2 arcsec, but are not coincident with, bright foreground galaxies; and also include HDF850.1 (Hughes et al. 1998; Downes et al. 1999) which has recently been confirmed as a likely lensed source by Dunlop et al. (2002).

We now discuss the properties of the two new submm sources to attempt to distinguish between the two possible explanations.

SMM J16370+4106 is associated with a close pair of radio sources. The brighter radio component is consistent with being coincident with the optically bright galaxy, within the optical/radio astrometric uncertainty (∼0.3 arcsec). The fainter radio component lies ∼2 arcsec east of the bright optical galaxy. Both radio components could be associated with the bright galaxy as the chance of a radio/submm source being lensed by a foreground radio source is low, owing to the low radio source density at these flux levels. At the same time, the astrometric uncertainty does not allow us to reject the possibility that this system is a highly amplified double image lensing configuration, straddling the optical lens, which would circumvent the radio source number density/probability argument. The required $T_{\rm d}$ for SMM J16370+4106 at $z = 0.845$ is 20 ± 1 K, placing it ∼4σ below the local relation in Fig. 3 and strengthening the lensing hypothesis.

SMM J22173+0014 lies only 30 arcsec from a known submm source in a $z = 3.1$ galaxy overdensity (Steidel et al. 1998), yet appears to be associated with a luminous early-type spiral at $z = 0.510$. However, the radio centroid is significantly offset from the optical galaxy centre, five times the 0.3-arcsec relative astrometric error in the VLA/optical frames. The radio emission falls close to a faint K-band extension from the galaxy (Fig. 1). The *HST* image obtained subsequent to the spectroscopic observations reveals a morphologically complex systems, reminiscent of a merger, coincident with this extension. In addition, the calculated T_d required to reproduce the radio/submm spectral index at this redshift is only 18 ± 1 K, putting this source $\sim 5\sigma$ below the local mean T_d for its luminosity (Fig. 3). Together, these arguments suggest that SMM J22173+0014 is a distant submm source lensed by a foreground galaxy at $z = 0.510$. The configuration of this system is very similar to that seen in SMM J00266+1708 and SMM J04431+0210, which have bright edge-on spiral galaxies within 2–3 arcsec of the submm source (Frayer et al. 2000; Smail et al. 1999). These configurations are also consistent with the results from Blain et al. (1999), who have shown that nearly edge-on spirals provide a high lensing probability, due to the large projected surface mass density.

While there is strong evidence that the two new submm sources are both lensed systems, we first need to consider selection effects in the radio/submm sample. The local luminous *IRAS* galaxies in Fig. 3 show a broad distribution in T_d, with no examples as cold as the SCUBA galaxies would need to be to be $z < 1$. However, the *IRAS* galaxies represent a restframe 60-μm selected sample, while the SCUBA galaxies are initially identified in terms of their 1.4-GHz and 850-μm emission. This will tend to bias their selection towards galaxies with lower T_d (Eales et al. 1999). This effect has recently been demonstrated for two SCUBA sources from the *ISO*-FIRBACK survey (Chapman et al. 2002d). These 170-μm selected sources have accurate radio positions which identify them with relatively low-redshift $L_{FIR} \sim 10^{12}$ $L_\odot$ galaxies ($z = 0.45$ and 0.91) which both exhibit clear merger morphologies. The best-fitting dust temperatures for these luminous galaxies (calculated for consistancy with the sample in Fig. 3) are 26 ± 1.4 K and 31 ± 2.5 K, indicating that some cold, but luminous galaxies do exist at high redshifts (Fig. 3). There is also some evidence that the dust temperature distribution may be broader at higher redshifts (Chapman et al. 2002f), making these apparently cold sources more common. The 1σ errors on SMM J16370+4106 overlap with those of the cold FIRBACK sources, suggesting that the cold dust explanation is conceivable for this source. However, none of these galaxies have as low T_d as is required for SMM J22173+0014 and we therefore conclude that SMM J22173+0014 most probably represents a lensed SCUBA galaxy.

Assuming that at least one, and perhaps both, of these two submm sources are likely to be lensed, we now estimate the proportion of similarly lensed sources in a typical SCUBA survey. Our survey started with a radio-identified subsample of the total submm population, with the requirement that the radio source was aligned with an $I < 23.5$ optical galaxy to within *2* arcsec. The fraction of all radio identified submm sources with a bright ($I < 23.5$) galaxy nearby (Chapman et al. 2002c) is 16 per cent. About 60 per cent of all bright ($S > 5$ mJy) submm galaxies are identified by radio pre-selection. We found above that one or two of the five sources in our Keck/ESI sample were likely to be lensed. This implies 3–5 per cent of the radio detected submm population could be lensing candidates, with a lower limit of 2–3 per cent for the whole SCUBA population.

We have also discussed three lensed SCUBA galaxies from the literature which are very similar to the two candidate systems presented here. The submm source HDF 850.1 appears to be lensed by a foreground elliptical galaxy, this gives a rate of lensed sources of 1/8, or ~ 13 per cent with a large uncertainty, for the *Hubble Deep Field* sources discussed by Hughes et al. (1998) and Serjeant et al. (2002). The other two lensed sources come from the Smail et al. (2002) cluster sample, these are of course more likely to suffer galaxy–galaxy lensing owing to the higher foreground galaxy concentration in the clusters used in this survey. For that reason we take the rate of galaxy-lensing from this survey as an upper limit, 2/15 sources, or $\leqslant 13$ per cent. Overall this suggests that around 3–5 per cent of submm sources from SCUBA surveys are likely to be gravitationally amplified by foreground galaxies.

The rate of lensing we find is nearly an order of magnitude higher than the incidence of multiple-imaging in similarly distant QSO samples, which combined with the radio morphologies of the galaxies discussed here indicates that these are unlikely to be highly amplified, multiply imaged SCUBA sources. With our current crude knowledge of the lensing configurations in these systems, it is impossible to produce detailed lens models. However, the relative separation of the source and lens, along with the apparent lack of multiple images suggests amplifications $\lesssim 5$.

The probability of lensing in SCUBA surveys depends on the form of the submm counts, with the steep count slope seen for submm sources brighter than 5 mJy (Scott et al. 2002), ~ 2 per cent of the ~ 10 mJy sources could be amplified by $\geqslant 2\times$ (Blain 1998). This figure is roughly in agreement with our findings, especially if SMM J16370+4106 actually represents a cold, luminous galaxy.

We note that amplification bias similar to, but weaker than, that invoked here has been invoked as a possible explanation for the strong cross correlation detected between foreground bright galaxies and submm sources by Almaini et al. (2002). We also note that lensing is expected to manifest at the ~ 1 per cent level given the surface density of sources now reached in the deepest radio maps, at ~ 15 μJy (e.g. Fomalont et al., in preparation; Owen et al., in preparation). However, the effect cannot be much greater, as the μJy radio source count slopes are close to Euclidean, and the $N(z)$ is less extended than for the submm-selected samples ($\langle z \rangle \sim 0.6$, Richards et al. 1999; Chapman et al. 2002c).

4 CONCLUSIONS

We have identified two submm sources with apparent optically bright counterparts, $I < 21.5$, at modest redshifts, $z < 1$. We suggest two possible explanation for these sources, and similar systems in the literature.

First, that the identifications are correct and these galaxies represent a class of very cold, luminous submm source (Chapman et al. 2002d). For SMM J16370+4106 at $z = 0.845$, this interpretation appears possible, but seems less likely for the second, even colder source, SMM J22173+0014. In both cases, the most powerful test to reject this hypothesis would be to confirm the absence of luminous molecular CO emission at the redshift of the optically bright galaxies (infeasible with present CO band receivers).

Secondly, that the optically bright galaxies are foreground gravitational lenses, which amplify more distant SCUBA sources. This explanation is consistent with both the observed source configurations and spectral properties. In this case we estimate that up to 3–5 per cent of the $\gtrsim 10$ mJy submm sources in blank-field SCUBA surveys could be gravitationally amplified by foreground galaxies. The most important result of this amplification is that it leads to the misidentification of the submm sources with the nearby bright, and typically low-redshift, galaxies. These misidentifications would produce a false tail of low-redshift, $z \ll 1$, submm sources in all far-infrared/submm/mm surveys. This is especially a concern for those surveys where deep, high-resolution data are not available to confirm the correspondance between the radio (pin-pointing the longer wavelength emission source) and optical sources with a precision of ≪1 arcsec.

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