# Unveiling Far-Infrared Counterparts of Bright Submillimeter Galaxies Using PACS Imaging

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that's me


## 1. Motivation:

Several hundred dust-enshrouded high-z sources have been selected through submm/mm imaging with bolometer cameras like SCUBA, LABOCA, AzTEC and MAMBO. The large beam size in the (sub)millimeter (e.g., MAMBO: 11"; SCUBA: 15"; LABOCA: 19") makes the identification of these so-called Submillimeter Galaxes (SMGs) based only on bolometer data difficult. The most suitable tool for counterpart identification are interferometric observations at radio wavelengths. The launch of the Herschel observatory promises a different perspective of SMGs than provided by radio observations only. Here we present our search for PACS counterparts at 100 µm and 160 µm, explore the diagnostic potential of Herschel-PACS for the counterpart identification and compare it with the widely used identification approach using VLA observations.

## 2. Far-Infrared Association of Submillimeter Galaxies

PACS SDP observations of the GOODS North region at 100 µm and 160 µm are part of the Guarantee Time extragalactic PACS survey 'PEP: The PACS Evolutionary Probe' (PI: D. Lutz). The final images achive 3σ sensitivities of ~ 3.0 mJy and ~ 5.7 mJy at 100 and 160 µm respectively. Complementary to the Herschel PACS observations, we use for this work data from the VLA at 1.4 GHz (Morrison et al. 2010, ApJS, 188, 178) and Spitzer-MIPS at 24 µm (Dickinson et al., in preparation).

In the past years, several groups surveyed the GOODS North region using the bolometer cameras SCUBA, AzTEC and MAMBO (Hughes et al. 1998, Nature, 394, 241; Borys et al. 2003, MNRAS, 344, 385; Pope et al. 2005, MNRAS, 358, 149; Wang et al. 2004, ApJ, 613, 655; Perera et al. 2008, MNRAS, 391, 1227; Greve et al. 2008, 389, 1489). These observations discovered about 150 SMGs at 850 µm, 1.1 and 1.2 mm. Robustly identified VLA and MIPS 24 µm counterparts are already known in the literature for SCUBA and AzTEC sources (Pope et al. 2006, MNRAS, 370, 1185; Chapin et al. 2009). In addition, Greve et al. (2008) presented VLA counterparts for 11 out of 30 MAMBO sources.

We search for Herschel-PACS counterparts of SMGs that are either detected with an SNR of ≥ 4 or detected by at least two different surveys. 56 SMGs fulfill this criteria which should assure a robust SMG sample to work with. Our sample consists of 36 SCUBA, 12 AzTEC and 8 MAMBO sources and for 15 SMGs spectroscopic redshifts (SMGspec) have been already obtained. We match our SMG sample with the PACS 100 and 160 µm blind catalogue and search for counterparts within a radius of 5.5" for MAMBO sources, 7.5" sources for SCUBA sources and 9" for AzTEC sources. We calculate the corrected Poissonian probability p that an association of SMGs within the search circle is a chance coincidence. This approach corrects the simple Poissonian probability of a detected association for the possibility of associations of different nature but similar probability. We define following quality critieria for assessing the robustness of identified candidate counterparts. We classify association of SMGs with p≤ 0.05 and 0.05 < p ≤ 0.10 as secure respectively possible counterparts.

PACS associations of 56 Submillimeter Galaxies in GOODS-N

| | PACS 100 $\mu m$ | PACS 160 $\mu m$ |
|---|---|---|
| # secure association | 12 | 15 |
| # possible association | 4 | 5 |
| total identification rate | 28.6% | 35.7% |
| (sub)mm-PACS offset | $5.0'' \pm 2.1''$ | $4.9'' \pm 2.0''$ |

| | PACS 100 + 160 $\mu m$ |
|---|---|
| # total association of SMGs | 22 (39.3%) |
| # only detected at PACS 160 $\mu m$ | 6 |
| # only detected at PACS 100 $\mu m$ | 2 |
| new CPTs identified by PACS | 1 |
| # PACS and radio blank fields | 12 (21.4%) |

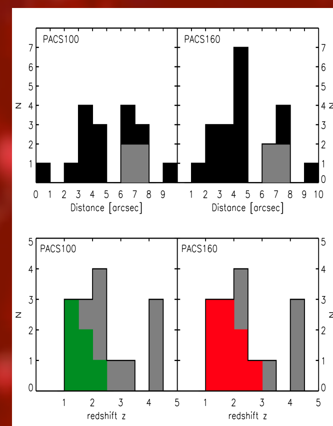


Fig. 1 – *Top panel:* Histogram of distance between the submm/mm position from the bolometric map and PACS positions of associated FIR sources at 100 µm (left) and 160 µm (right). Black and gray indicate secure and possible PACS counterparts. *Bottom panel:* We show the redshift distribution for our SMG sample with spectroscopic redshifts (gray) ansd overplot our PACS detections at 100 µm (green) respectively 160 µm (red).

## 3. Diagnostic Potential of PACS Observations of Submillimeter Galaxies

•We have 43 (28 secure; 15 are possible) radio-identified SMGs in our sample, 50% of them are seen at PACS wavelengths. Vice-versa, only one PACS association (secure) is undetected at 1.4 GHz. VLA observations are more sensitive for sources at redshifts up to z = 4. None of the well-known, spectroscopically identified SMGs at z = 4 have been significantly detected in our PACS imaging, see middle panel of Fig. 2.

•By adding our PACS measurements to existing SCUBA, MIPS 24 µm and VLA 1.4 GHz flux measurements of our SMG sample, we were unable to obtain more accurate photometric redshifts than without PACS data, see left panels in Fig. 3. This finding means that most likely the far-infrared spectral energy distribution of SMGs have significantly different shapes than template libraries of local infrared galaxies, see also right panels in Fig. 3. Further investigations are needed to fully exploit the Herschel-PACS imaging in order to obtain accurate photometric redshifts.

•Searching for correlations between observed properties are essential for constraining the nature, redshift and evolution of SMGs. The PACS color (S160/S100) of SMGs does not vary with redshift and is consistent with the prediction of models from Michalowski et al. (2010, A&A, 514, 67) and Chary & Elbaz (2001, ApJ, 556, 562), see top panel of Fig. 2.
The PACS fluxes are redshift dependent, whereas the (sub)mm flux density at z ≥ 1 is not (due to the negative K-correction), thus one would expect to see a trend between (sub)mm/PACS flux ratio for both PACS bands, see also predictions based on different templates in the middle and lower panel of Fig. 2. Indeed, we find a fairly good trend both for S850/S160 respectively S850/S100 versus spectroscopic redshift for the $SMG_{spec}$ subsample over the whole redshift range spanned by our SMGs from z ~ 1 – 4. We conclude that the (sub)mm/PACS flux ratio seems to be a promising redshift indicator and may help to select/mark SMGs at very high-redshifts.

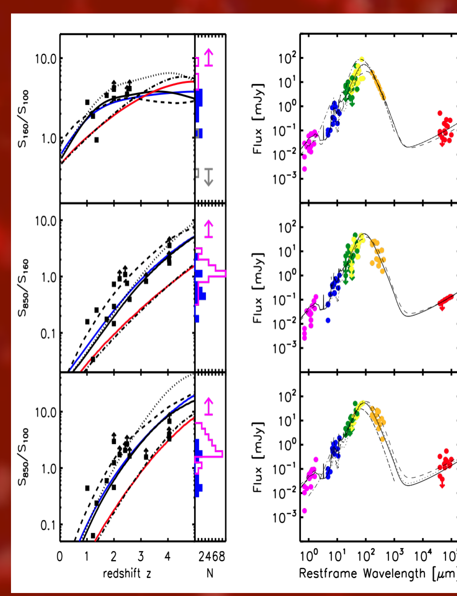


Fig. 2 --- *Left panels*: We show SMGs with spectroscopic redshifts. From top to bottom we plot the flux ratios S160/S100, S850/S160 and S850/S100 versus spectroscopic redshift. Template SEDs of a local LIRG with $L_{IR} \approx 1 \times 10^{11}$ $L_{sun}$ (blue solid line), a local ULIRG with with $L_{IR} \approx 1 \times 10^{12}$ $L_{sun}$ (black sold line) and a HyLIRG with $L_{IR} \approx 1 \times 10^{13}$ $L_{sun}$ (red-solid line), all from Chary & Elbaz (2001) and an average SMG (black-dashed line, Michalowski et al. 2010), are shown for comparison. Average SEDs including Spitzer-IRS spectroscopy of local ULIRGs (black-dashed-dotted line, Armus et al. 2007, ApJ, 656, 148) and SMGs (black-dotted line, Pope et al., 2008, ApJ, 675, 1171) are shown as well. The histograms present the distribution of SMGs without spectroscopic redshifts (blue-filled), lower limits of flux ratios are displayed by the pink-empty histogram. For the S160/S100 flux ratio we show the upper limit as gray-empty histogram. *Right panels:* From to bottom, we plot the composite rest-frame SED – IRAC 3.6 µm (pink), MIPS 24 µm (blue), PACS (100 µm (green), PACS 160 µm (yellow), SCUBA 850 µm (gold), VLA 20 cm (red) – of our spectroscopic sample normalized on SCUBA, VLA and PACS 160 µm fluxes. Template SEDs are shown for comparison. Both data points and templates are normalized on an SMG with a SCUBA flux of 8 mJy at z=2.2

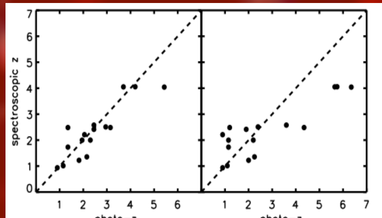


Fig. 3 --- Comparison of spectroscopic and photometric redshifts. In the left panel we show photometric redshifts based on radio, 850 µm and 24 µm flux densities measurements fir SMG counterparts with spectroscopic redshifts in GOODS North (adopted from Daddi, Dannerbauer et al. 2009, ApJ, 694, 1517).

➢ *Dannerbauer H., Daddi E., Morrison G. & the PEP team, 2010, ApJL, 720, 144*