The ALMA Frontier Fields Survey

I. 1.1 mm continuum detections in Abell 2744, MACS J0416.1-2403 and MACS J1149.5+2223 *

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ABSTRACT

Context. Dusty star-forming galaxies are among the most prodigious systems at high redshift (z > 1), characterized by high star-formation rates and huge dust reservoirs. The bright end of this population has been well characterized in recent years, but considerable uncertainties remain for fainter dusty star-forming galaxies, which are responsible for the bulk of star formation at high redshift and thus play a key role in galaxy growth and evolution.

Aims. In this first paper of our series, we describe our methods for finding high redshift faint dusty galaxies using millimeter observations with ALMA.

Methods. We obtained ALMA 1.1 mm mosaic images for three strong-lensing galaxy clusters from the Frontier Fields Survey, which constitute some of the best studied gravitational lenses to date. The ≃2′ × 2′ mosaics overlap with the deep HST WFC3/IR footprints and encompass the high magnification regions of each cluster for maximum intrinsic source sensitivity. The combination of extremely high ALMA sensitivity and the magnification power of these clusters allows us to systematically probe the sub-mJy population of dusty star-forming galaxies over a large surveyed area.

Results. We present a description of the reduction and analysis of the ALMA continuum observations for the galaxy clusters Abell 2744 (z = 0.308), MACS J0416.1-2403 (z = 0.396) and MACS J1149.5+2223 (z = 0.543), for which we reach observed rms sensitivities of 55, 59 and 71 μJy beam−1 respectively. We detect 12 dusty star-forming galaxies at S/N ≥ 5.0 across the three clusters, all of them presenting coincidence with near-infrared detected counterparts in the HST images. None of the sources fall close to the lensing caustics, thus they are not strongly lensed. The observed 1.1 mm flux densities for the total sample of galaxies range from 0.41 to 2.82 mJy, with observed effective radii spanning ≃0′′05 to 0′′37 ± 0′′21. The lensing-corrected sizes of the detected sources appear to be in the same range as those measured in brighter samples, albeit with possibly larger dispersion.

Key words. gravitational lensing: strong – galaxies: high-redshift – submillimeter: galaxies

* Reduced mosaic images are only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/597/A41
** Hubble Fellow.

1. Introduction

Past studies of dusty, star-forming galaxies (DSFGs) at infrared (IR) through radio wavelengths have firmly established their role in the growth and evolution of massive galaxies across cosmic
time (see reviews by Blain et al. 2002; and Casey et al. 2014). At the bright end, DSFGs are observed to have IR luminosities in excess of 10^{13} L_\odot, yet appear extraordinarily compact, with typical resolved half-light radii of R_\text{e} \approx 1–1.5 kpc (e.g., Bussmann et al. 2013; Ikarashi et al. 2014; Simpson et al. 2015; Miettinen et al. 2015; hereafter B13, 114, S15 and M15, respectively). The bulk of their IR emission is thought to be powered by star formation (Alexander et al. 2005), with unobserved star-formation rates (SFRs) of up to several thousands of M_\odot yr\(^{-1}\) and SFR densities of \(\gtrsim 100 M_\odot\) yr\(^{-1}\) kpc\(^{-2}\). As such, DSFGs represent the most intense starbursts in the Universe. While little is known about fainter DSFGs (sub-mJy population), extrapolation of the DSFG population is estimated to account for roughly half of the IR background light in aggregate (e.g., Magnelli et al. 2011; Viero et al. 2013). Obtaining a working knowledge of the underlying physics that drives the distribution of faint lensed DSFGs thus appears to be critical for understanding cosmic galaxy assembly.

Many DSFGs are optically faint (\(I_{AB} \gtrsim 24\) mag, \(K_{AB} \sim 21–22\)), due to a combination of high redshift and strong dust-extinction (e.g., Barger et al. 2000; Smail et al. 2004; Chapman et al. 2005). This has made unbiased estimates of their population statistics and physical properties (i.e., dust, gas and stellar contents and morphologies) challenging and expensive with current technology. It also suggests that finding and characterizing the fainter DSFG population may prove even harder. Nonetheless, the fainter population is particularly interesting because their SFRs are in the same range as those found for ultraviolet (UV) and optically selected samples such as star-forming BzK galaxies, BX/BM galaxies, and Lyman break galaxies (LBGs), which comprise the normal galaxy “main sequence” (e.g., Noeske et al. 2007). Meaningful comparisons between the more abundant faint DSFGs and these unobserved main sequence populations could help to elucidate the factors that determine the dust content in galaxies with comparable properties.

One way to make progress toward the study of faint DSFGs, in the face of instrumental confusion limits at far-IR (FIR) and submillimeter (submm) wavelengths (\(\sim 2–7\) mJy beam\(^{-1}\) between 0.25–1.3 mm as well as traditional difficulties associated with expensive multi-wavelength follow-up, is to leverage with the power of gravitational lensing. Such studies have helped provide detailed characterizations of many dozens of intrinsically faint DSFGs selected either in wide area submm surveys as galaxy–galaxy lenses (e.g., Blain et al. 1996; Negrello et al. 2007, 2010; Wardlow et al. 2013) or behind massive lensing galaxy clusters (e.g., Smail et al. 1997; Cowie et al. 2002; Swinbank et al. 2010). Although immensely insightful, such studies can suffer from additional uncertainties due to the quality of the mass models, microlensing, and potential biases stemming from the cross-section of the DSFG population which is more easily lensed (i.e., compact starbursts). Robustly determined mass models and observations over long timescales can limit the impact of these problems.

Building on past works of lensed DSFGs, here we employ the novel sensitivity of the Atacama Large Millimeter/submillimeter Array (ALMA) to detect DSFGs roughly 1 dex fainter than the aforementioned confusion limits, behind three strong-lensing galaxy clusters: Abell 2744 (\(z = 0.308\)), MACS J0416.1-2403 (\(z = 0.396\)) and MACS J1149.5+2223 (\(z = 0.543\), hereafter A2744, MACS J0416, MACS J1149, respectively)\(^1\).

Importantly, these clusters are part of the Frontier Fields (FFs) Survey\(^2\), a legacy project which combines the power of gravitational lensing by massive clusters (with magnifications of \(\mu > 5–10\) over up to several arcmin\(^2\) regions and 100’s of multiple images) with extremely deep multi-band HST and Spitzer imaging of six lensing clusters and adjacent parallel fields (Coe et al. 2015). While the primary goal of these observations is to potentially detect and characterize \(z \gtrsim 1\) galaxies 10–50 times intrinsically fainter than any seen before (e.g., Atek et al. 2014; Zitrin et al. 2014; Zheng et al. 2014; Laporte et al. 2015; McLeod et al. 2015; Infante et al. 2015), the HST+Spitzer observations and their associated ancillary data enable several ALMA related science cases.

The FFs campaign is comprised of allocations of 840 HST orbits and 1000 Spitzer hrs, respectively, taking advantage of the two Great Observatories unsurpassed spatial resolution and/or depth. The fields have amassed a wealth of multi-wavelength ancillary data. Notably, each cluster already has extensive space+ground-based archival data (e.g., 16-band HST, XMM-Newton, Chandra, Spitzer, Herschel, and VLA imaging) and more than 800 spectroscopically confirmed sources (cluster+background galaxies), including VLT/VIMOS confirmations for most of the major gravitational arcs/images down to \(\sim 26\) ABmag (PI Rosati). To this, the FFs campaign adds deep ACS (\(F_{435W} = F_{606W} = F_{814W} \approx 28.4–29.0\) ABmag), WFC3 (\(F_{105W} = F_{125W} = F_{140W} = F_{160} \approx 29.1–29.4\) ABmag), and IRAC1/IRAC2 (\(\approx 25.0\) ABmag) imaging (e.g., Coe et al. 2015; Lotz et al. 2016). These are complemented by new and growing data from HST, Chandra, JVLA, VLT HAWK-I/VIMOS/MUSE, Keck DEIMOS/LRIS/MOSFIRE, and Magellan FourSTAR/IMACS/MMIRS. The current data already allow the assembly of 10,000’s of accurate \(z_{\text{spec}}\)’s, 400/200/10’s of Lyman Break dropouts at \(z > 6/7/8\), and spectacularly resolved images of \(>600\) = 1–6 gravitational arcs (2–10") and multiple-lenses in a central region of each cluster (e.g., Richard et al. 2014). The FFs clusters represent the best studied gravitational lenses, with the best available estimates of magnifications and uncertainties (ever-improving lens models are available from many teams)\(^3\). Thus they are key regions on the sky to observe normal galaxies at high-z, and warrant strong mm constraints. The search for DSFGs on the FFs using Herschel data has already found nine sources with magnification \(\mu > 4\) at \(z < 1.5\) and other nine sources at \(z > 2\) (Rawle et al. 2016).

Each of the three FFs clusters is being complemented with a \(\approx 2'\times 2'\) 1.1 mm ALMA mosaic, coincident with the deep HST WFC3/IR imaging region, achieving an rms depth of 55–71 \(\mu\)Jy beam\(^{-1}\)\(^3\), depending on the field. The 1.1 mm band benefits from the negative K-correction due to the typical galaxy spectral energy distribution (SED), and thus effectively provides a redshift unbiased census between \(z = 1–10\) (e.g., Blain et al. 2002). The data allow us to pinpoint locations of extreme star formation and probe factors of 2–10x fainter into the \(L_\text{IR}\) and SFR distributions compared to similar blank-field surveys due to typical lensing boosts. The data also allow constraints on the SFRs and line emission for 1000’s of optical and IR objects undetected in our 1.1 mm survey (individually and in aggregate).

This paper is the first in a series, and primarily describes the reduction and analysis of the ALMA 1.1 mm data for A2744, MACS J0416, and MACS J1149 (hereafter, the ALMA-FFs). We focus this paper on the observed sources properties in the lensed

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\(^1\) Approved ALMA Cycle 3 observations of the remaining three FFs clusters, namely MACS J0717.5+3745, Abell 370, and Abell 1063S, are in progress.

\(^2\) http://www.stsci.edu/hst/campaigns/frontier-fields/

\(^3\) http://www.stsci.edu/hst/campaigns/frontier-fields/Lensing-Models
image plane. To fully characterize the detected sources in the source plane, a combination of redshifts estimates and mass models for the galaxy clusters is needed. Separate companion papers will detail the identification, redshift estimation and initial characterization of multi-wavelength counterparts (Laporte et al., in prep.), physical properties based on SED-fitting and morphological studies in the source plane (González-López et al., in prep.), number counts (Muñoz Arancibia et al., in prep.), and stacking analyses of multiply imaged sources and dropout candidates (Carvajal et al., in prep.). This paper is organized as follows: in Sect. 2 we outline the observations and describe the reduction and imaging procedures; in Sect. 3 we discuss our source detection methods and sensitivity estimates; in Sect. 4 we assess the fluxes and angular extents of the detected sources; and in Sect. 5 we summarize our results. Throughout the paper we assume a concordance cosmology and quote errors at 1σ.

### Table 1. ALMA observation log.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Abell 2744</td>
<td>0.308</td>
<td>00:14:21.2</td>
<td>−30:23:50.1</td>
<td>29-Jun.-2014/31-Dec.-2014</td>
<td>15.1</td>
<td>783.5</td>
<td>170.0</td>
<td>115.6</td>
</tr>
<tr>
<td>MACS J0416.1−2403</td>
<td>0.396</td>
<td>04:16:08.9</td>
<td>−24:04:28.7</td>
<td>04-Jan.-2015/02-May-2015</td>
<td>15.1</td>
<td>348.5</td>
<td>114.6</td>
<td>62.8</td>
</tr>
<tr>
<td>MACS J1149.5+2223</td>
<td>0.543</td>
<td>11:49:36.3</td>
<td>+22:23:58.1</td>
<td>14-Jan-2015/22-April-2015</td>
<td>15.1</td>
<td>348.5</td>
<td>110.5</td>
<td>61.0</td>
</tr>
</tbody>
</table>


The final sensitivity depends on various factors such as the precipitable water vapor (PWV) and elevations of the field in the sky. As we will see in Sect. 2.4, these have important repercussions on the uniformity of the mosaics.

#### 2.2. Reduction

The reduction of the datasets was done using the common astronomy software applications package (CASA; McMullin et al. 2007). Our reduction procedure closely followed the reduction scripts delivered by joint ALMA observatory (JAO) together with the datasets.

Out of the three clusters, MACS J0416 is the only one where the observations were reduced using the ALMA pipeline included in CASA version 4.2.2. The manual ("script") reduction of A2744 and MACS J1149, as well as all imaging and analysis of the clusters, were performed using CASA version 4.3.1. The clusters A2744 and MACS J1149 fall under the "non-standard" category (multiple array configurations and unfinished executions), therefore were not reduced using the pipeline.

We adopted most of the manual data flagging implemented by the JAO staff for our final reductions. These flags correspond to bad antennas, bad channels and time dependent bad behaviors. These manual flags were used in the reduction scripts as well as in the ALMA pipeline reduction. However, after our initial reductions, we found that the manual reductions scripts for A2744 and MACS J1149 were overly conservative in flagging the edge channels of the spectral windows, corresponding to a ≈12% loss in the total frequency coverage. After visual inspection of the calibrator spectra for MACS J0416, we found that the ALMA pipeline, on the other hand, correctly left these edge channels unflagged for this cluster. After reinstating the flagged edge channels for A2744 and MACS J1149, the rms values of the new images improved by ≈5% compared to the initial images delivered by ALMA. A final inspection of the calibrator spectra confirmed that such flagging was not needed. Incidentally, the ALMA Cycle 2 Technical handbook states that for the Frequency Division Mode (FDM) spectral windows, the usable bandwidth is equal to the total bandwidth (1875 MHz), consistent with our data.

For A2744, the amplitude calibrators were J2258−279 and Uranus, the bandpass calibrators were J2258−2758 and J2258−279, and the phase calibrators were J0011−2612 and J2359−3133. For MACS J0416, the amplitude calibrators were J0334−401, Ganymede and Uranus, the bandpass calibrators were J0334−4008, J0519−4546, J0334−401, J0423−0120 and J0416−2056, and the phase calibrator was J0416-2056. Finally, for MACS J1149, amplitude calibrators were 3C 273, Titan and

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4 [https://almascience.nrao.edu/aq](https://almascience.nrao.edu/aq)

Table 2. Mosaic properties for the different galaxy clusters.

<table>
<thead>
<tr>
<th>Cluster name</th>
<th>Map</th>
<th>$b_{\text{max}}$ [&quot;]</th>
<th>$b_{\text{min}}$ [&quot;]</th>
<th>$b_{\text{PA}}$ [&quot;]</th>
<th>rms [μJy beam$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abell 2744</td>
<td>Natural</td>
<td>0.63</td>
<td>0.49</td>
<td>86.14</td>
<td>55</td>
</tr>
<tr>
<td>MACS J0416</td>
<td>Natural</td>
<td>1.52</td>
<td>0.85</td>
<td>−85.13</td>
<td>59</td>
</tr>
<tr>
<td>MACS J1149</td>
<td>Natural</td>
<td>1.22</td>
<td>1.08</td>
<td>−43.46</td>
<td>71</td>
</tr>
</tbody>
</table>

Notes. Column 1: cluster name. Column 2: image weighting method used. Column 3: major axis of synthesized beam, $b_{\text{max}}$, in arcseconds. Column 4: minor axis of synthesized beam, $b_{\text{min}}$, in arcseconds. Column 5: position angle of synthesized beam, $b_{\text{PA}}$, in degrees. Column 6: highest sensitivity (lowest rms) achieved in each synthesized image, in μJy beam$^{-1}$.

Callisto, the bandpass calibrator was J1256–0547 and the phase calibrator was J1159+2914. We estimate that the flux calibration for each field is accurate to ~8% based on a comparison of the amplitudes for the different flux calibrators.

2.3. Imaging

Mosaicked images were created using natural weighting, which is generally the most sensitive since it optimally weights all of the baselines (Briggs et al. 1999). Image details are provided in Table 2: the unique synthesized beams and rms sensitivities depended on the specific observations of each cluster. The A2744 dataset has the lowest rms (55 μJy beam$^{-1}$) amongst the observed clusters, as well as the smallest beam due to the more extended array configuration in which it was partially observed; MACS J0416 and MACS J1149 have natural weighted beams which are nearly twice as large as that of A2744.

The data were imaged using the multi-frequency synthesis algorithm in CLEAN, adopting the clark psmfmode, the mosaic imagermode, and a 0’’1 pixel size, which is small enough to sample the synthesized beams listed in Table 2. Dirty images were made using niter = 0, providing the rms values presented in the last column in Table 2. The cleaned images were generated using niter = 1000 and a threshold of four times the rms measured in the dirty images, with no masking applied during cleaning. The cleaned images have the same rms values as the dirty ones.

Figures 1–3 present the natural-weighted clean images for the three observed FFs clusters, respectively. These images have not been corrected for the primary beam (PB) sensitivity response, which is discussed below.

2.4. Mosaic sensitivity

Various factors can affect the mosaic sensitivity across different pointings. These include the intrinsic primary beam response shape, as well as any factor that can decrease the sensitivity in a given pointing (e.g., higher $T_{\text{sys}}$, less data). The PB correction images for each cluster (Fig. 4) should contain all relevant information regarding fluctuations from the nominal sensitivity.

We find that the PB correction for A2744 is roughly constant and high across the mosaic (=1), demonstrating that the final sensitivity is uniform over the entire mosaic. For MACS J0416 and MACS J1149, however, the PB correction images are not smooth, indicating sensitivity variations by as much as ~15–20% across the mosaics in both cases.

For MACS J0416, the sensitivity loss appears to result from the flagging of several baselines owing to shadowing (i.e., when the primary beam of one antenna is partly covered by another) during the most sensitive, lowest PWV execution. It should be noted that all of the executions observed for MACS J0416 start from the top right pointing and end with the bottom left pointing, such that they map the mosaic from top to bottom and west to east. During the most sensitive execution, the first pointing was initiated at an elevation of ~41° while the last concluded at ~27°. The latter results in significant shadowing when using a compact array such as C36-2. This particular elevation difference across the mosaic will lead to sensitivity fluctuations for two reasons. First, the shadowing flagging is higher in the bottom left pointing, resulting in less data (14% of the data in the last pointing were flagged by shadowing). At the same time, lower elevation observations result in higher phase scatter and higher $T_{\text{sys}}$ values for the same pointings, further decreasing the sensitivity. The combination of these factors explains the observed drop in sensitivity toward the bottom left side of the mosaic for MACS J0416.

For MACS J1149, there is a sharp drop in sensitivity in the bottom left pointings, as well as a mild gradient in the upper right pointings. The explanation for the sharp drop lies in the fact that, during one of the most sensitive executions, the last 30 pointings of the mosaic were not observed, resulting in an incomplete mosaic execution. Thus the bottom left portion of the mosaic only contains five of the six executions, yielding lower sensitivity. The weak sensitivity gradient in the upper right pointings can be explained similarly to MACS J0416, whereby one of the most sensitive executions began at a low elevation and was more strongly affected by shadowing and higher $T_{\text{sys}}$ values.

In conclusion, A2744 has uniform sensitivity across the mosaic, while MACS J0416 and MACS J1149 do not. This varying sensitivity must be accounted for when studying the statistical properties of the detected sources.

3. Results

3.1. Source extraction

The search for sources was performed in the PB-uncorrected continuum cleaned images, which allows the detection of sources as a function of signal-to-noise independent of the final (non-uniform) sensitivity reached in different regions of the mosaics. The first step was to find the rms values that best represented each image. We limited the region used for source detection to that where the PB sensitivity is higher than 0.5 of the peak sensitivity (PB ≥ 0.5). After selecting all the pixels with PB ≥ 0.5, we performed a sigma clip at 5σ to remove clear bright 1.1 mm sources and used the remaining pixels to obtain an initial estimate of the rms. With this initial rms, we searched for all pixels with signal-to-noise ($S/N$) ≥ 5 and used the clustering algorithm DBSCAN in Python:scikit-learn (Pedregosa et al. 2011) to group the pixels that corresponded to unique sources. Each initial source was fit with a six-parameter 2d Gaussian function and these corresponding models were removed from the continuum maps to obtain an initial source-free image. The final rms was measured in each source-free image and is presented in Table 2.
Fig. 1. 1.1 mm continuum map for the galaxy cluster A2744 made with natural weighting. The image has an rms of 55 $\mu$Jy beam$^{-1}$ and has not been corrected by the primary beam sensitivity for visualization purposes. The color scale corresponds to $-5\sigma$ to $5\sigma$ from blue to red. The black curve corresponds to the point where the primary beam correction is equal to 0.5, meaning where the sensitivity is $2\sigma$. Squares show the positions of the sources with $S/N \geq 5$. In the small box bottom left corner we show the synthesized beam of $0.63 \times 0.49$ and position angle of $86.16^\circ$. The critical curves (i.e. where magnification is infinite) for a source at $z = 2$ given by the model Zitrin-NFWv3 (Zitrin et al. 2009, 2013) are shown in green.

3.2. High-significance continuum detections

To obtain a final list of detections, we selected all pixels with $S/N > 4$ and performed the same modeling as described above, however at this stage we also fit a 2d-Gaussian function with only three free parameters, fixing the shape to that of the synthesized beam and allowing changes only in flux density and position. This was done to check to what extent the detected sources may be resolved. We adopted a traditional $S/N$ cut of $\geq 5$ to select “secure” detections, which we present in Table 3. The positional error is estimated by fitting the sources in the $uv$-plane (See Sect. 4.2.1). Based on the deep HST $F160W$ imaging, a counterpart search was performed by selecting the sources in the HST catalogs with separations to the ALMA source coordinates smaller than the corresponding ALMA synthesized beams. All but one of these sources have clear near-IR (NIR) counterparts and the majority are exceptionally red (see Fig. 7 for color images); the association with such rare sources strongly confirms the reliability of the mm detections.

The only source where a counterpart match is challenging is A2744-ID02, as the ALMA detection sits in a region where emission is quite faint even in the $F160W$ filter and undetected in the bluer bands, exhibiting a highly dust extincted spectral energy distribution. As seen in Fig. 7, the counterpart of A2744-ID02 appears to be extended in the east-west axis, with 2–3 faint NIR objects (“clumps”) lying on either side of the extended 1.1 mm emission and fainter “bridge” emission extending both in between these clumps as well as toward a bright compact peak of NIR emission $\sim 1\farcs5$ to the west of the ALMA source. All of the emission is red in NIR colors, similar to the other
Fig. 2. 1.1 mm continuum map for the MACS J0416 made with natural weighting. The image has an rms of 59 $\mu$Jy beam$^{-1}$ and has not been corrected by the primary beam sensitivity for visualization purposes. The color scale and black curve are the same as in Fig. 1. Squares show the positions of the sources with $S/N \geq 5$. In the small box bottom left corner we show the synthesized beam of $1.52'' \times 0.85''$ and position angle of $-85.13$. The critical curves (i.e. where magnification is infinite) for a source at $z=2$ given by the model Zitrin-NFWv3 (Zitrin et al. 2009, 2013) are shown in green.

Table 3. High-significance ($\geq 5\sigma$) continuum detections.

<table>
<thead>
<tr>
<th>ID</th>
<th>$\Delta \alpha_{J2000}$ [hh:mm:ss]</th>
<th>$\Delta \delta_{J2000}$ [dd:mm:ss]</th>
<th>$\Delta \alpha, \Delta \delta$ [&quot;]</th>
<th>$S/N$</th>
<th>$S_{1.1\text{mm}, \text{peak}}$ [mJy beam$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2744-ID01</td>
<td>00:14:19.80</td>
<td>-30:23:07.66</td>
<td>0.011, 0.008</td>
<td>25.9</td>
<td>1.433 $\pm$ 0.056</td>
</tr>
<tr>
<td>A2744-ID02</td>
<td>00:14:18.25</td>
<td>-30:24:47.47</td>
<td>0.055, 0.015</td>
<td>14.4</td>
<td>1.292 $\pm$ 0.091</td>
</tr>
<tr>
<td>A2744-ID03</td>
<td>00:14:20.40</td>
<td>-30:22:54.42</td>
<td>0.038, 0.024</td>
<td>13.9</td>
<td>0.798 $\pm$ 0.058</td>
</tr>
<tr>
<td>A2744-ID04</td>
<td>00:14:17.58</td>
<td>-30:23:00.56</td>
<td>0.020, 0.015</td>
<td>13.8</td>
<td>0.932 $\pm$ 0.068</td>
</tr>
<tr>
<td>A2744-ID05</td>
<td>00:14:19.12</td>
<td>-30:22:42.20</td>
<td>0.056, 0.040</td>
<td>7.7</td>
<td>0.655 $\pm$ 0.086</td>
</tr>
<tr>
<td>A2744-ID06</td>
<td>00:14:17.28</td>
<td>-30:22:58.60</td>
<td>0.076, 0.080</td>
<td>6.5</td>
<td>0.574 $\pm$ 0.089</td>
</tr>
<tr>
<td>A2744-ID07</td>
<td>00:14:22.10</td>
<td>-30:22:49.67</td>
<td>0.035, 0.030</td>
<td>6.2</td>
<td>0.455 $\pm$ 0.074</td>
</tr>
<tr>
<td>MACS J0416-ID01</td>
<td>04:16:10.79</td>
<td>-24:04:47.53</td>
<td>0.037, 0.037</td>
<td>15.4</td>
<td>1.010 $\pm$ 0.066</td>
</tr>
<tr>
<td>MACS J0416-ID02</td>
<td>04:16:06.96</td>
<td>-24:03:59.96</td>
<td>0.130, 0.107</td>
<td>6.8</td>
<td>0.406 $\pm$ 0.062</td>
</tr>
<tr>
<td>MACS J0416-ID03</td>
<td>04:16:08.81</td>
<td>-24:05:22.58</td>
<td>0.116, 0.064</td>
<td>5.8</td>
<td>0.389 $\pm$ 0.067</td>
</tr>
<tr>
<td>MACS J0416-ID04</td>
<td>04:16:11.67</td>
<td>-24:04:19.44</td>
<td>0.148, 0.156</td>
<td>5.1</td>
<td>0.333 $\pm$ 0.066</td>
</tr>
<tr>
<td>MACS J1149-ID01</td>
<td>11:49:36.09</td>
<td>+22:24:24.60</td>
<td>0.116, 0.102</td>
<td>5.9</td>
<td>0.442 $\pm$ 0.074</td>
</tr>
</tbody>
</table>


A41, page 6 of 17
Fig. 3. 1.1 mm continuum map for MACS J1149 made with natural weighting. The image has an rms of 71 µJy beam$^{-1}$ and has not been corrected by the primary beam sensitivity for visualization purposes. The color scale and black curve are the same as in Fig. 1. Squares show the positions of the sources with $S/N \geq 5$. In the small box bottom left corner we show the synthesized beam of 1''2 × 1''08 and position angle of $-43^\circ46$. The critical curves (i.e. where magnification is infinite) for a source at $z = 2$ given by the model GLAFICv3 (Kawamata et al. 2016) are shown in green.

ALMA-FFs counterparts. The resolved ALMA emission appears to be elongated roughly coincident with a suppression in the $F160W$ emission, suggesting that the ALMA source may arise from a dusty region that divides the faint $F160W$ clumps, which may represent less-obscured regions from a single extended object with strong and variable extinction. Interestingly, at longer wavelengths ($K_s$ and IRAC 3.6–8.0µm), the flux at the ALMA position increases relative to the clumps, such that by 8µm the peak emission is in fact centered almost exactly on the ALMA position. This scenario is supported by the fact that the clumps have similar photometric redshifts of $z_{\text{ph}} \approx 2.5$. We select the nearest detected clump (~0''7 offset) as the counterpart to the ALMA detection. A full characterization of the NIR counterpart galaxies will be discussed in Laporte et al. (in prep.), where we find that all of the NIR counterpart galaxies have photometric redshifts of $z \geq 1$ (none are members of the lensing galaxy clusters).

Figure 5 shows the histogram of $S/N$ values measured in all pixels with $PB \geq 0.5$ for each cluster. The noise distribution of our images is well-matched to a Gaussian distribution in the low $S/N$ regime, while an excess of positive signal is seen clearly beyond $S/N \gtrsim 4$–5, indicative of real signal from extragalactic sources. Weak hints of deviations from the Gaussian distribution in the measured pixel $S/N$ are observed in the image of A2744 around $-5\sigma$, suggesting there might be some small, additional systematic errors that have not been accounted for; such deviations appear to increase when we include regions with $PB < 0.5$, although in general these are few compared to the...
large positive excess seen in this field. Further investigations into
the cause of these small deviations were unfruitful, and thus we
only caution that there may be unaccounted for systematic errors
at the 5–10% level.

4. Discussion
4.1. Purity
In order to establish the purity levels of our detections, we need
to estimate how many false detections we expect per $S/N$ for
a given observation. We use the task Simobserve in CASA to
simulate observations with similar properties as the ones ob-
tained in our campaign. For the simulations the thermal noise
is added using an atmospheric profile for the ALMA site (Pardo
et al. 2001) and assuming the observations are performed when
the field transits (this assumption is not critical for the pur-
poses here). We adopt the nominal second (MACS J0416 and
MACS J1149) and third (A2744) most compact ALMA antenna
configurations (C36-2 and C36-3) during cycle 2, which are the
closest matches to the ones used in the real observations. The
other parameters such as frequency coverage, PWV and inte-
gration time are set to achieve an rms similar to the ones ob-
tained for each cluster field. After construction of the simula-
tions, we used the noisy measurement set files to create images
in the same manner as used to produce the real observations.
These images were then analyzed with the same algorithm used
to detect sources (Sect. 2.3).

We performed 30 simulations per antenna configuration and
recorded the number of detections with $S/N \geq 5$ recovered by
our code. The number of detections was then renormalized as a
function of $S/N$ for each antenna configuration. For all antenna
configurations, we obtain $N \leq 1$ simulated-noise detections for
$S/N \geq 5$, meaning that our $S/N \geq 5$ sample should all be true
detections assuming that the noise properties of the simulations
are similar to those in the observations.

The deviation from a perfect Gaussian distribution ratio at
$S/N \sim -5.0$ in the data distribution observed in Fig. 5 and
discussed in Sect. 3.2 can be explained by low-number statistics,
as the same behavior is observed in the simulated observations his-
tograms when Gaussian noise is assumed. It is important to note
that because of the stochastic behavior in the extreme tails of the
distribution, extra care needs to be taken when using the negative
pixels as a noise reference, as some fraction of noise distribu-
tions will never be completely symmetrical, even when Gaussian
noise is assumed. This effect can easily lead to misinterpreta-
tions when using the negative pixels as a reference to estimate
the purity of continuum detections. For instance, in MACS J0416
and MACS J1149, we find no negative sources with $S/N \leq -5.0$,
while in A2744 we find two sources with $S/N \leq -5.0$ compared
to seven sources with $S/N \leq +5.0$. The implied purity for A2744
is thus $\sim 0.7$ based on negative count symmetry. However, based
on the NIR counterparts found for all the ALMA sources with
$S/N \geq 5$, we estimate a “true” detection purity closer to $=1$
for the three clusters, consistent with the simulations. Although

Fig. 4. Primary beam (PB) correction images for each cluster, adopting natural weighting. Thus final PB-corrected images would correspond to
Figs. 1–3 divided by the corresponding PB corrections shown here. Likewise, the final sensitivity corresponds to the measured sensitivity divided
by the PB image. For A2744 the sensitivity is uniform across the mosaic, while for MACS J0416 there is a clear sensitivity gradient from top right
to bottom left, and in MACS J1149 the upper and lower regions of the mosaic have sensitivities substantially lower than in the uniform middle
portion (See Sect. 2.4 for details).

Fig. 5. Normalized histogram of the $S/N$ per pixel for the three
cluster images adopting natural weighting. A2744, MACS J0416, and
MACS J1149 are shown in green, orange and blue, respectively. The
black curve shows the $S/N$ distribution expected for a Gaussian noise
distribution, which is well matched to the image $S/N$ histograms, aside
from possible deviations present near $S/N \sim -5.0$ and the clear positive
tail denoting emission from real sources. In the bottom panel we show
the ratio between the data counts and the Gaussian noise distribution for
each bin. The error bars correspond to Poisson errors using the number
of elements per bin. The deviation from unity in the ratio at
$S/N \sim -5.0$ in the three cluster images can be explained by low-number statistics.
Such behavior is also observed in the $S/N$ distribution tails of simu-
lated images created with only Gaussian noise convolved with the same
synthesized beams.
the difference between the purity estimated from negative counts and the "true" purity is not statistically significant (only 1.1σ), it exemplifies the extra care needed when using the negative counts for purity estimates.

4.2. Flux estimates

4.2.1. Image fit

We obtained three flux density measurements for each source. The first two methods fit for the flux density in the image plane assuming a point source (PS) and an extended source (6 parameters Gaussian function, hereafter EXT), respectively, while the third method fits for the flux density in the uv-plane. Fitting the sources in the image plane is substantially more straightforward, but inherits certain dependencies based on the weighting method used to construct the images.

To measure the flux densities from the images, we fit an elliptical Gaussian to each source. For a PS, we fixed the size and angle of the elliptical Gaussian to that of the synthesized beam, and only allow for changes in flux and position. For an EXT, we allow all the six parameters describing the 2d Gaussian to vary. For both fits, a reduced χ² is estimated using all available image pixels that satisfy S/N > 2 (to limit the fit to pixels associated with the source). The degrees of freedom are estimated as d.o.f. = N − P, where N is the number of pixels with S/N > 2 and P is the number of free parameters in the fit (three for a PS and six for an EXT). The measured flux densities and reduced χ² values are presented in Table 4. These values were measured in the natural weighting images.

The 1σ uncertainties in the flux densities measurements are of the order of 0.1 mJy. We should expect a number density of \( \approx 10^{18} \) deg\(^{-2} \) sources with flux densities >0.084 mJy (Fujimoto et al. 2016). Even for the largest beam obtained in MACS J1149 (Table 2) we obtain \( \approx 140 \) beams per source at such flux density levels, therefore expecting a negligible flux boosting from confused sources in our results.

4.2.2. uv-plane fit

To measure the flux in the uv-plane we used uvmccefit\(^6\), which is a Python implementation to fit models to interferometric data

\[ L = \sum_{uv} \left( \frac{[V_{\text{ALMA}} - V_{\text{model}}]^2}{\sigma^2} + \log 2\pi\sigma^2 \right). \]

where \( \sigma \) is the 1σ uncertainty level for each uv complex visibility (hereafter visibility; Fourier transform of the intensity distribution on the sky) given by the associated weights. In practice, each source is typically observed by only a handful of pointings from the full mosaic, and each of these pointings will have an associated weight that we must apply to its visibilities to combine with those from neighboring pointings. Because well-determined weights for the visibilities of each pointing are needed, we performed the following procedure for each source before fitting.

We estimate an initial source position based on the continuum images and select all pointings which lie within 19" (PB \( \geq 0.1 \)) of the initial position. We then shift the phase center of all the selected pointings to the position of the source. We correct the amplitudes of the visibilities by the initial PB correction of each pointing with respect to the position of the source as data\( _i = \text{data}_i / \text{PB}_i \), where i is the index of each pointing. The weights of the visibilities are then corrected by the same PB correction as for the amplitudes as weight\( _i = \text{weight}_i \times \text{PB}_i^2 \).

\( \chi^2 \) and six for an EXT. The measured flux densities and reduced χ²/d.o.f. for EXT model. Column 6: integrated flux density and 1σ statistical error assuming a PS model in mJy.

<table>
<thead>
<tr>
<th>ID</th>
<th>( F_{\text{int,PS}} ) [mJy]</th>
<th>( F_{\text{int,EXT}} ) [mJy]</th>
<th>( \chi^2_{\text{red,PS}} )</th>
<th>( \chi^2_{\text{red,EXT}} )</th>
<th>( F_{\text{uv-fit}} ) [mJy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2744-ID01</td>
<td>1.495 ± 0.081</td>
<td>1.545 ± 0.081</td>
<td>1.7</td>
<td>1.6</td>
<td>1.570 ± 0.073</td>
</tr>
<tr>
<td>A2744-ID02</td>
<td>1.656 ± 0.131</td>
<td>3.262 ± 0.213</td>
<td>10.3</td>
<td>2.2</td>
<td>2.816 ± 0.229</td>
</tr>
<tr>
<td>A2744-ID03</td>
<td>1.074 ± 0.084</td>
<td>1.979 ± 0.137</td>
<td>7.9</td>
<td>2.0</td>
<td>1.589 ± 0.125</td>
</tr>
<tr>
<td>A2744-ID04</td>
<td>1.012 ± 0.099</td>
<td>1.173 ± 0.111</td>
<td>2.0</td>
<td>1.7</td>
<td>1.009 ± 0.074</td>
</tr>
<tr>
<td>A2744-ID05</td>
<td>0.859 ± 0.125</td>
<td>1.422 ± 0.188</td>
<td>3.0</td>
<td>0.7</td>
<td>1.113 ± 0.135</td>
</tr>
<tr>
<td>A2744-ID06</td>
<td>0.822 ± 0.129</td>
<td>2.274 ± 0.274</td>
<td>12.1</td>
<td>11.9</td>
<td>1.283 ± 0.241</td>
</tr>
<tr>
<td>A2744-ID07</td>
<td>0.500 ± 0.108</td>
<td>0.716 ± 0.149</td>
<td>1.5</td>
<td>1.4</td>
<td>0.539 ± 0.082</td>
</tr>
<tr>
<td>MACS J0416-ID01</td>
<td>1.144 ± 0.089</td>
<td>1.356 ± 0.111</td>
<td>3.0</td>
<td>0.6</td>
<td>1.319 ± 0.103</td>
</tr>
<tr>
<td>MACS J0416-ID02</td>
<td>0.455 ± 0.081</td>
<td>0.626 ± 0.111</td>
<td>2.8</td>
<td>2.0</td>
<td>0.574 ± 0.132</td>
</tr>
<tr>
<td>MACS J0416-ID03</td>
<td>0.375 ± 0.091</td>
<td>0.477 ± 0.114</td>
<td>4.7</td>
<td>4.3</td>
<td>0.411 ± 0.072</td>
</tr>
<tr>
<td>MACS J0416-ID04</td>
<td>0.367 ± 0.089</td>
<td>0.456 ± 0.111</td>
<td>3.0</td>
<td>2.9</td>
<td>0.478 ± 0.166</td>
</tr>
<tr>
<td>MACS J1149-ID01</td>
<td>0.500 ± 0.104</td>
<td>0.635 ± 0.125</td>
<td>1.1</td>
<td>0.5</td>
<td>0.579 ± 0.134</td>
</tr>
</tbody>
</table>

**Notes.** Column 1: source ID. Column 2: integrated flux density and 1σ statistical error assuming a PS model, in mJy. Column 3: integrated flux density and 1σ statistical error assuming a 6-parameter extended Gaussian model (EXT), in mJy. Column 4: reduced χ²/d.o.f. for PS model. Column 5: reduced χ²/d.o.f. for EXT model. Column 6: integrated flux density and 1σ statistical error from uv fitting, in mJy.
Fig. 6. Cutout images of the secure continuum detections in the FFs clusters. **Left**: 1.1 mm continuum emission image adopting natural weighting, with colors as in Fig. 1. Solid black curves show the positive S/N contours with natural weighting, starting from ±2σ up to ±5σ in steps of 1σ, and then above ±5σ in steps of 2.5σ. Dashed curves show the negative S/N contours. In the bottom left corner we show the corresponding synthesized beam. For A2744-ID06 we additionally overlay solid purple curves showing the S/N contours from the corresponding Taper weighted image. The best-fit 2d elliptical Gaussian model is shown as a green region whose size denotes where the emission is half of the maximum. The yellow points represent the position of optical/NIR detected galaxies. **Right**: residual of the 1.1 mm continuum emission after the best-fit model is subtracted from the $uv$ visibilities. The color scale is identical to the left-hand side.
concatenate all the pointings into a new dataset, which should now contain a correct set of relative weights for the visibilities, since the appropriate factor was applied to the weights given by the calibration. Finally, we scale the weights such that:

$$\sum \text{weight} \times \text{real}^2 + \text{weight} \times \text{Im}^2 = N_{\text{visibilities}}.$$

\texttt{uvmcmcfit} uses EMCEE (Foreman-Mackey et al. 2013) to sample the posterior probability density function (PDF) of the model parameters. Between 10000–240000 iterations were required, depending on the speed of convergence. We used a “burn-in” phase of 5000 iterations to identify the “best-fit” model parameters. The flux density given by the posterior PDF is presented in the last column of Table 4. The errors presented correspond to the 1σ range of the posterior PDF. The best-fit models are presented in Fig. 6.

To test that we are recovering most of the observed flux density with the $uv$-plane fit, we created a “Taper” image for each observation. This Taper image also adopts natural weighting but includes a uv taper with an outer taper equal to 1′5, which yields a beam size $\geq 1′.5$ but substantially worse rms sensitivity. We apply the same method used to measure the flux density in the natural weighted images on the Taper images. In Fig. 8 we present the flux density measured using the $uv$-plane fit in the natural image and the $F_{\text{Taper,EXT}}$ measured in the Taper images. We see that the two estimates agree within the errors, demonstrating that we apparently recover a substantial amount (if not all) of the extended flux with the $uv$-plane fit method. We recover the total flux density even in the complex case of A2744-ID06 (see Fig. 6), where the Taper image emission is substantially more extended than the natural weighted emission. Given these findings, we adopt the $F_{\text{Taper,EXT}}$ flux estimates for all sources.

4.3. Source sizes

To estimate the sizes of the observed sources (in the natural weighting image plane), we used the “best-fit” models that were fit in the previous subsection. The source size parameters were estimated from the posterior PDF, in the same manner as for the fit in the previous subsection. The source size parameters were estimated in all three clusters. The assumed properties are $r_e = 0′.37, q_e = 0.56$ and $\phi_e = 81′.5$. After fitting the sizes of the ingested sources, the average parameter measurements were $r_e = 0′.36 \pm 0′.04, q_e = 0.55 \pm 0.08$ and $\phi_e = 83.5′ \pm 13.4′$. These all lie within 1σ of the input parameters for the ingested sources, demonstrating that reliable size measurements can be made for extended sources with $S/N$ values similar to even our weakest detections. Unfortunately, a full characterization of the reliability of size measurements for low signal-to-noise sources using \texttt{uvmcmcfit} over all parameter space is well beyond the scope of this paper, and we refer interested readers to Bussmann et al. (2013, 2015) for such details.

In order to analyze the delensed size distribution of the extended sources, we need to estimate the magnification values of each galaxy behind the galaxy cluster, which relies both on the source redshift and the cluster lensing model. MACS J0416-ID01 and MACS J0416-ID02 are the only sources with measured redshifts, $z = 2.086$ and $z = 1.953$ respectively, obtained from the Grism Lens-Amplified Survey from Space (GLASS, Treu et al. 2015). For the rest of the sources, we will assume that they lie at $z = 2$ and use the range $z = 1–3$ as an estimate of the error associated with this assumption. This average redshift and dispersion are consistent with the redshift distribution of published 1.1 mm detected galaxies found by ALMA to date Simpson et al. (2014), Dunlop et al. (2016). Since none of the...
Fig. 7. 6′′ × 6′′ color image cutouts of the NIR counterparts to the ALMA detections, with blue corresponding to bands $F435W + F060W$, green to bands $F810W + F105W$ and red to bands $F125W + F140W + F160W$. The cyan contours denote the ALMA 1.1 mm emission, whereby the levels are displayed on a logarithmic scale at $±3, 4, 5.3, 7.1, 9.5, 12.6, 16.8, 22.5, 30 \times \sigma$, with $\sigma$ being the primary beam corrected noise level at the position of the source. The ALMA synthesized beam corresponding to each observation is shown in the lower left corner of each cutout. A green star represents the position of the associated NIR counterpart, while the magenta ellipse shows the $1\sigma$ range of the center of the ALMA emission based on the $u\nu$-plane fit. In all cases, the positional error associated with the NIR position is small compared to that of the ALMA emission.
sources are close to the critical curves of the clusters, as seen in Figs. 1–3, the redshift uncertainty will not be critical to the magnification estimate.

As stated above, each of these cluster fields has a set of lensing models that were created by several independent teams using different assumptions and techniques (Bradac et al. 2005, 2009; Diego et al. 2015; Jauzac et al. 2015a,b, 2016; Johnson et al. 2008, 2010; the lensed galaxy SDP.81 observed by ALMA Partnership et al. 2015) and with an intrinsic size estimated by Valchánov et al. (2011), Rybak et al. (2015); objects from the UKIDSS ultra deep survey (UDS) part of the SCUBA-2 cosmology legacy survey and the un-lensed objects from the Herschel Multi-tiered Extragalactic Survey (HerMES), both observed with ALMA (Simpson et al. 2015; Bussmann et al. 2015).

We estimate the magnification values as in Coe et al. (2015), by taking the 16th, 50th and 84th percentiles of the magnification values given by the full range of all the models in the FFs archives. We propagate the $\sigma = 1–3$ redshift uncertainty for the sources which lack spectroscopic redshifts into the magnification errors. For MACS 0146 and MACS 0416 we only use the v3 or newer models, as the v3 models correspond to those made using the deep Frontier Fields images for modeling. For MACS J1149, no v3 models are available, so we use the latest available model from each team.

In Table 5 we present the derived magnification values for the sources. Most of the magnification values lie around $\mu \sim 2$, with the highest reaching a value of $\mu = 4.2$. For MACS J0416-ID01 and MACS J0416-ID02, the galaxies with spectroscopic redshifts, the magnification errors are produced solely by the systematic errors among the lens models of different teams. A comparison of the magnification errors between sources should not dominate the adopted redshift uncertainty. It is a dominating factor in the magnification error budget.

With magnification estimates in hand, we proceed to determine the intrinsic parameters of the detected sources. We correct the effective radius as $r_e/\sqrt{\mu}$ and the flux density as $F_{\nu,\text{fit}}/\mu$. The obtained values are presented in Table 5. The errors in the lensing-corrected values are estimated based on the $1\sigma$ range of the resulting distributions of $r_e/\sqrt{\mu}$ and $F_{\nu,\text{fit}}/\mu$ using the parent distributions.

With this information, we now compare our magnified angular sizes and flux densities with those of bright sources recently constrained by ALMA and previous interferometric studies in Fig. 10. The comparison samples correspond to: four bright sources observed with the Submillimeter Array (SMA Ho et al. 2004) presented by Younger et al. (2008, 2010); the lensed galaxy SDP.81 observed by ALMA Partnership et al. (2015) and with an intrinsic size estimated by Valchánov et al. (2011), Rybak et al. (2015); objects from the UKIDSS ultra deep survey (UDS) part of the SCUBA-2 cosmology legacy survey and the un-lensed objects from the Herschel Multi-tiered Extragalactic Survey (Herschel). 

We do not include strongly lensed galaxies identified in wide field surveys, since they can be affected by the size bias. These type of surveys select galaxies by observed flux density, which is the product of the intrinsic flux density and magnification. This typically favors sources with high magnification values, which in turn biases sources to be preferentially smaller. This effect is produced by the small region of high magnification in the source plane, as small sources near the source plane caustics will have a higher flux-weighted magnification than more extended sources (Serjeant 2012; Hezaveh et al. 2012; Wardlow et al. 2013; Spilker et al. 2016). The ALMA-FFs sample is much less affected by the size bias, since none of our detections lie close to the critical curves and therefore do not have high magnification values.

It is immediately clear that the samples studied here probe observed flux densities up to an order of magnitude fainter than those measured in the comparison samples. Roughly 2/3 of the ALMA-FFs sources have effective radii of $r_e/\text{demag} \gtrsim 0''16$, compared to the average of $(r_e) \sim 0''1$ measured in brighter samples.
This high fraction of more extended sources could imply that the sub-mJy population is intrinsically more extended than the brighter compact sources. However, once we factor in the two point-like sources \( r_s \leq 0.05 \) and the three marginally extended sources, there appears to be considerable dispersion among the fainter ALMA-FFs population. To investigate this issue further, we fit a linear regression between flux density and effective radius as \( \log r_e = m \times \log F_v + b \) to the ALMA-FFs and HerMES samples, where the same code was used to determine \( r_e \). For simplicity, we convert the upper limits for the point-like sources in our sample into measured sizes. The best-fit regression values are \( m = -0.08 \pm 0.10 \) and \( b = -0.95 \pm 0.05 \), demonstrating that there is no obvious size evolution. In Fig. 10 we show the fit relation (dashed line) together with its 2 \( \sigma \) range (orange region).

### 4.4. Positional offsets

Because the ALMA-detected sources may be optically faint and/or red, we use the deep HST WFC3 F160W image in the FFs to search for NIR counterparts. In general, we adopt the closest galaxy as the true counterpart (typical separations smaller than \( \sim 0.2'' \)). Once the counterparts are selected, we fit a simple 2d elliptical Gaussian to the NIR emission to more accurately measure the positions of the counterparts centroids in the same manner as the positions of the ALMA sources.

In Fig. 11, we present the measured positional offsets between the 1.1 mm and NIR emission of the detected galaxies. A2744-ID02 was left out of this analysis, as it appears to arise from a very obscured part of an extended counterpart galaxy, as described in Sect. 3.2. This offset appears real and highlights an important case when the FIR/mm and optical/NIR are not co-spatial, similar to physical offsets seen in the local starburst galaxy NGC 4038/9 (Wang et al. 2004; Klaas et al. 2010). The intrinsic offset between the FIR/mm and optical/NIR emission can be enlarged by lensing when observed in the image plane, as in our case. Since one of the goals of this analysis is to check the astrometric agreement between HST and ALMA, we therefore exclude this galaxy from our offset measurement. The measured median offsets between the NIR and mm sources are \( \Delta R.A = 0.02 \pm 0.03 \) and \( \Delta Dec = -0.13 \pm 0.02 \), with a combined offset scatter of \( \approx 0.1'' \). The errors in the offsets include the uncertainties of the NIR and ALMA emissions centers presented in Table 6 and plotted in Fig. 7. These offsets are consistent with the astrometric offsets (\( \approx 0.1'' \)) measured for the Subaru catalogs to which the HST A2744 data was tied.

By comparing the observed positions of the phase calibrators used in the ALMA observations to those in the literature we find offsets of \( \Delta R.A = < 0.01 \) and \( \Delta Dec = < 0.01 \) for A2744 and MACS J1149 and \( \Delta R.A = 0.012 \) and \( \Delta Dec = < 0.016 \) for MACS J0416. Although the measured offset in MACS J0416 is somewhat larger than those measured in the other two clusters, all are minimal compared to the observed offsets in the detected sources, indicating that the measured offsets are not due to astrometric problems in the ALMA observations.

The small scatter measured for the secure sample indicates that the NIR and FIR/mm emission are nearly co-spatial, except for the special case of A2744-ID02 described above. These results also demonstrate that the astrometric consistency between the HST and ALMA reference frames appears robust to \( \approx 0.1'' \). The measured offsets could be due to small astrometric offsets or true spatial offsets between the sources optical/NIR and FIR/mm emission. Under the assumption that we have a perfect astrometric agreement between ALMA and HST, the average offset for all the sources plotted in Fig. 11 is \( 0.17 \pm 0.02 \). To rule out the effects of lensing, we tracked the positions of the centroids in ALMA and HST to the source plane using the lensing models of Zitrin-NFWv3 and Zitrin-LTMv1 and measured intrinsic offsets.

We selected Zitrin-NFW models since they were observed to better follow the median distribution of magnifications given by the combinations of all lens models Priewe et al. (2017). This measurement includes the effect of lensing shear. Individual source plane offsets are given in Table 6, while the average demagnified offset is still \( 0.14 \pm 0.02 \), which is \( \approx 1.2 \) kpc at \( z = 2 \). The source plane offset errors include the positional uncertainties in both the NIR and ALMA emission but we have not propagated the systematic lens models uncertainties. For A2744-ID02, the demagnified offset to the brightest peak, assuming \( \z = 2 \), is \( 0.48 \pm 0.04 \) including only the uncertainties in the position of both NIR and ALMA emissions. This offsets corresponds to \( 4.1 \pm 0.3 \) kpc at \( z = 2 \) similar to the spatial offset of \( \sim 4 \) kpc measured in GN20 at \( z = 4.05 \), one of the best studied SMGs at high redshift (Hodge et al. 2015). It is clear that these ALMA observations can open a window to study and resolve the obscured star-formation activity in galaxies at high redshift.

While A2744-ID02 is the most obvious case, an interesting aspect of the counterpart offsets is that for nine out of 12 ALMA-FFs sources (i.e., A2744-ID01, A2744-ID02, A2744-ID03, A2744-ID04, A2744-ID06, A2744-ID07, M0416-ID02, M0416-ID03, and M0416-ID04), the ALMA centroid position falls on a darker portion of the counterpart galaxy compared to the NIR peak (see Fig. 6). This effect has been noted other ALMA surveys (e.g., Wiklind et al. 2014; Dunlop et al. 2016), and attributed to the fact that the FIR/mm emission region likely suffers from strong dust extinction. This physical effect may be an important term in the remaining measured offsets, although the current error bars make this difficult to constrain for individual sources.

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7 https://archive.stsci.edu/pub/hlsp/frontier/abell2744/catalogs/subaru/astrometry/
Table 6. High-significance ($\geq 5\sigma$) continuum detections NIR counterpart positions and offsets.

<table>
<thead>
<tr>
<th>ID</th>
<th>$\alpha_{2000}$ [hh:mm:ss.ss]</th>
<th>$\delta_{2000}$ [±dd:mm:ss:ss]</th>
<th>$\Delta\alpha$, $\Delta\delta$ ['']</th>
<th>Image plane offset ['']</th>
<th>Source plane offset ['']</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2744-ID01</td>
<td>00:14:19.8058</td>
<td>-30:23:07.6094</td>
<td>0.002, 0.002</td>
<td>0.09 ± 0.01</td>
<td>0.04 ± 0.01</td>
</tr>
<tr>
<td>A2744-ID02</td>
<td>00:14:18.2000</td>
<td>-30:24:47.3000</td>
<td>0.002, 0.001</td>
<td>0.68 ± 0.05</td>
<td>0.48 ± 0.04</td>
</tr>
<tr>
<td>A2744-ID03</td>
<td>00:14:20.4013</td>
<td>-30:22:54.6038</td>
<td>0.007, 0.006</td>
<td>0.18 ± 0.02</td>
<td>0.16 ± 0.02</td>
</tr>
<tr>
<td>A2744-ID04</td>
<td>00:14:17.5816</td>
<td>-30:23:00.7324</td>
<td>0.003, 0.004</td>
<td>0.18 ± 0.02</td>
<td>0.11 ± 0.02</td>
</tr>
<tr>
<td>A2744-ID05</td>
<td>00:14:19.1273</td>
<td>-30:22:42.3394</td>
<td>0.007, 0.003</td>
<td>0.17 ± 0.04</td>
<td>0.15 ± 0.04</td>
</tr>
<tr>
<td>A2744-ID06</td>
<td>00:14:17.2759</td>
<td>-30:22:58.8000</td>
<td>0.003, 0.003</td>
<td>0.22 ± 0.07</td>
<td>0.12 ± 0.05</td>
</tr>
<tr>
<td>A2744-ID07</td>
<td>00:14:22.1091</td>
<td>-30:22:49.7821</td>
<td>0.004, 0.002</td>
<td>0.16 ± 0.03</td>
<td>0.11 ± 0.02</td>
</tr>
<tr>
<td>MACS J0416-ID01</td>
<td>04:16:10.7762</td>
<td>-24:04:47.5002</td>
<td>0.001, 0.001</td>
<td>0.20 ± 0.03</td>
<td>0.18 ± 0.03</td>
</tr>
<tr>
<td>MACS J0416-ID02</td>
<td>04:16:06.9539</td>
<td>-24:03:59.9277</td>
<td>0.002, 0.003</td>
<td>0.14 ± 0.08</td>
<td>0.12 ± 0.06</td>
</tr>
<tr>
<td>MACS J0416-ID03</td>
<td>04:16:08.8169</td>
<td>-24:05:22.3970</td>
<td>0.003, 0.003</td>
<td>0.22 ± 0.06</td>
<td>0.17 ± 0.06</td>
</tr>
<tr>
<td>MACS J0416-ID04</td>
<td>04:16:11.6688</td>
<td>-24:04:19.6271</td>
<td>0.002, 0.002</td>
<td>0.23 ± 0.12</td>
<td>0.18 ± 0.08</td>
</tr>
<tr>
<td>MACS J1149-ID01</td>
<td>11:49:36.0961</td>
<td>+22:24:24.4659</td>
<td>0.002, 0.001</td>
<td>0.20 ± 0.09</td>
<td>0.25 ± 0.14</td>
</tr>
</tbody>
</table>


Fig. 9. Measured effective radii $r_e$ as a function of flux density for the ALMA sources. We plot sources from A2744 (left) and MACS J0416+MACS J1149 (right) separately, since the latter have factors of $\approx 2$ larger beam sizes. The solid black line in each plot corresponds to the average value of $r_e$ measured for simulated point sources ingested into the data. The dashed black lines likewise correspond to limits of $1, 2$ and 3 times the standard deviation ($\sigma$) above the mean for simulated point sources, respectively, as a function of flux density. For visualization purposes, we only plot simulated lines for MACS J0416 in the right panel, noting that the limits for MACS J1149 are roughly identical. Additionally, A2744-ID02 is not shown in the left plot, since its flux density is much higher ($\approx 2.8$ mJy) and it is clearly extended. Based on the criteria in Sect. 4.3, two sources are considered point-like, three sources are marginally extended, and seven are significantly extended.

5. Summary

We have presented an analysis of the ALMA observations for the Frontier Fields galaxy clusters A2744, MACS J0416, and MACS J1149. The deepest 1.1 mm ALMA natural weighted images made for the three clusters achieve rms sensitivities of 55, 59 and 71 $\mu$Jy beam$^{-1}$ with natural weighting, respectively. The beam sizes range from $\approx 0.5\arcsec$ to $\approx 0.8\arcsec$ for the FFs clusters images, with A2744 achieving higher resolution due to observations partially made in a more extended configuration.

The mosaic sensitivity of the observations vary from cluster to cluster. A2744 shows a fairly uniform sensitivity across the mosaic. MACS J0416 and MACS J1149 show lower sensitivities in some areas of the mosaics, produced mainly by an incomplete execution and shadowing during observations at low elevations. These sensitivity differences across the mosaic were accounted for when deriving source properties and purity studies of the detected sources.

A total of 12 sources are detected with $S/N \geq 5$ in the natural-weighted maps created for the three clusters. The range in observed flux densities goes from 0.411 to 2.816 mJy. Using the code $uv$mcfit we fit 2D Gaussian models in the $uv$-plane to the detected sources to estimate total flux densities and angular sizes of the galaxies at 1.1 mm. The range of observed effective radii in the fit Gaussian models goes from $\approx 0.05\arcsec$ to $\approx 0.4\arcsec$. We estimated magnification values using the available lensing models, assuming that the sources lie at $z = 2$ if no spectroscopic redshift is available. The resulting magnification values range between $\mu = 1.5$–4.2, and were used to correct the sizes and flux densities. We find that the demagnified (intrinsic) sizes of the FFs sample are consistent with brighter sources previously measured (Simpson et al. 2015; Bussmann et al. 2015).
However, there is considerable dispersion in the FFs sample and roughly 2/3 of the FFs sources have demagnified sizes that are a factor of $\geq 1.6$ larger than the average of the brighter sources, implying that a substantial portion of the sub-mJy submm sources may be mildly more extended than their brighter counterparts. Larger samples are required to confirm this.

We find that all but one of the ALMA detections has a clear HST $F160W$ counterpart, with an observed scatter of $\sim 0.1''$. The small scatter indicates that in general the mm and optical emission are effectively co-spatial and that the astrometry between the ALMA and HST observations is in reasonably good agreement. We note that there may be a possible offset of $\sim -0.04'$.13 in Declination (likely in the A2744 field). If we assume perfect astrometric agreement between ALMA and HST, the observed offset would represent a real spatial offset between the peak of the optical and FIR emission of $\sim 1$ kpc on average. For A2744-ID02, the offset between peak mm and NIR emission is substantially larger, $\sim 0.5''$ or $\sim 4$ kpc in the source plane. The latter source provides an intriguing case to study spatially resolved highly obscured star-formation activity at high redshift.

The continuum images used in this paper, as well as the sensitivity maps and visibilities are available for download at this web address (http://www.astro.puc.cl/~jgonzal/ALMA-FF.html).

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