Planck intermediate results. XXVII. High-redshift infrared galaxy overdensity candidates and lensed sources discovered by Planck and confirmed by Herschel-SPIRE


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Abstract

We have used the Planck all-sky submillimetre and millimetre maps to search for rare sources distinguished by extreme brightness, a few hundred millijansky, and their potential for being situated at high redshift. These “cold” Planck sources, selected using the High Frequency Instrument (HFI) directly from the maps and from the Planck Catalogue of Compact Sources (PCCS), all satisfy the criterion of having their rest-frame T planck star formation rates of typically 700 M⊙ × yr−1. If the observed overdensities are actual gravitationally-bound structures, the total IR luminosity of all their SPIRE-detected sources peaks at 4 × 10^13 L⊙, leading to total star formation rates of perhaps 7 × 10^10 M⊙ yr−1 over overdensity. Taken together, these sources show the signatures of high-z (z > 2) protoclusters of intensively star-forming galaxies. All these observations confirm the uniqueness of our sample compared to reference samples and demonstrate the ability of the all-sky Planck-HFI cold sources to select populations of cosmological and astrophysical interest for structure formation studies.

Key words. Galaxies: high-redshift, clusters, evolution, star formation – Cosmology: observations, large-scale structure of Universe – Submillimetre: galaxies – Gravitational lensing: strong

1. Introduction

Cosmological structure formation in the linear regime is now fairly well constrained by observations at the largest scales (e.g.,
Tegmark et al. 2004, Cole et al. 2005. In the non-linear regime the situation is less clear because structure formation becomes a complex interplay between dark matter collapse and the hydrodynamics of baryonic cooling. In the particularly dense environments of the most massive dark matter halos, this interplay should lead to vigorous episodes of rapid star formation and galaxy growth, giving rise to copious amounts of FIR (far-infrared) emission (Tegmark et al. 2004, Cole et al. 2005). In the non-linear regime, while lensed sources act as probes of dark matter halos, and both are probes of cosmological parameters such as Ωm (matter density today divided by the critical density of the Universe) and σ8 (the rms fluctuation in total matter – baryons + CDM + massive neutrinos – in 8 h⁻¹Mpc spheres today at z = 0) (Planck Collaboration XVI 2014). Furthermore, clusters of galaxies are crucial objects that bridge astrophysics and cosmology, sometimes with some tensions, particularly regarding the measurement of σ8 (Planck Collaboration XVI 2014, Planck Collaboration XX 2014, Planck Collaboration I 2015, Planck Collaboration XII 2013), all of which has led to a debate between cluster phenomenology and cosmological physics.

The extragalactic sky in the submillimetre (submm) and millimetre (mm) regime has been of considerable scientific interest for over two decades, with the distinct advantage that the steep rise in the redshifted Rayleigh-Jeans tail of the modified blackbody emitted by the warm dust in infrared galaxies largely compensates for cosmological dimming, the “negative k-correction” (Franceschini et al. 1993, Blain & Longair 1993, Guiderdoni et al. 1997). As a consequence, the flux density of galaxies depends only weakly on redshift, opening up a particularly interesting window into the high-redshift Universe (typically 2 < z < 6). Constant improvements in bolometer technology have led to impressive samples of high-z galaxies being identified with ground-based, balloon and space-borne telescopes (e.g., Hughes et al. 1998, Barger et al. 1998, Chapman et al. 2005, Lagache et al. 2005, Patanchon et al. 2009, Devlin et al. 2009, Chapin et al. 2009, Negrello et al. 2011, Vieira et al. 2010, Oliver et al. 2011, Eales et al. 2011).

Nevertheless, only with the recent advent of wide-field surveys with astrophysical and cosmological scope have the systematic searches become efficient enough to identify the brightest of these objects with flux densities above about 100 mJy at 350 μm, e.g., with Herschel (Pilbratt et al. 2010, Eales et al. 2011, Oliver et al. 2010), the South Pole Telescope (Vieira et al. 2010), WISE (Wright et al. 2010, Stanford et al. 2014), and Spitzer (Pappovich 2008, Stanford et al. 2012). Such sources are very rare. For example, the surface density of red sources brighter than 300 mJy at 500 μm is 10⁻² deg⁻² for strongly lensed galaxies, 3 × 10⁻² deg⁻² for AGN (active galactic nuclei, here radio-loud, mostly blazars), and 10⁻¹ deg⁻² for late-type galaxies at moderate redshifts (e.g., Negrello et al. 2007, 2010). Other models predict similar trends (Paciga et al. 2009, Lima et al. 2010, Bethermin et al. 2011, Hezaveh et al. 2012). This makes even relatively small submm surveys interesting for searches of high-redshift objects, as long as they cover large parts of the sky. Studies of gravitationally lensed galaxies at high redshifts originating from these surveys (Negrello et al. 2010, Combes et al. 2012, Bussmann et al. 2013, Herranz et al. 2013, Rawle et al. 2014, Wardlow et al. 2013) illustrate the scientific potential of such surveys for identifying particularly interesting targets for a subsequent detailed characterization of high-z star formation through multi-wavelength follow-up observations.

The power of wide-field surveys in detecting the rarest objects on the submm sky is even surpassed with genuine all-sky surveys, which systematically and exhaustively probe the brightest objects in their wavelength domain down to their completeness limits. Here we present a search for the rarest, most extreme high-redshift (z > 2) candidates on the submillimetre sky, which was performed with the Planck all-sky survey (Planck Collaboration I 2014, 2015). The Planck Catalogue of Compact Sources (PCCS, Planck Collaboration XXVIII 2014) has a completeness limit of about 600 mJy at the highest frequencies, which corresponds to L_{FIR} ≈ 5 × 10^{13} L_☉ at z = 2. With a 5′ beam (Planck Collaboration VII 2014) at the four highest frequencies (corresponding to a physical distance of about 2.5 Mpc at z = 2), we expect that sources with bona fide colours of high-z galaxies in the Planck-HFI bands are either strongly gravitationally lensed galaxies, or the combined dust emission of multiple galaxies in a shared vigorously star-forming environment in the high redshift Universe. The latter case is consistent with the result that submm galaxies or ULIRGs (Ultra Luminous Infrared Galaxies) are strongly clustered (Blain et al. 2004, Farrah et al. 2006, Masliochetti et al. 2007, Austermann et al. 2009, Santos et al. 2011, Ivison et al. 2012, Valtchanov et al. 2013, Noble et al. 2013, Clements et al. 2014), and may include massive galaxy clusters during their major growth phase. It is also possible of course that the sources are chance alignments of multiple high-redshift galaxies projected onto the same line of sight (Negrello et al. 2005, 2007, 2010, Chiang et al. 2013), or of multiple, lower-mass galaxy groups or clusters.

Identifying high-redshift cluster candidates directly by the signatures of their total star formation is a very useful complement to the diagnostics used to identify galaxy clusters so far. Most systematic searches today focus on the primary constituents of more evolved, lower-redshift clusters, like their populations of massive, passively evolving galaxies (‘red-sequence galaxies’), the hot intracluster medium (either through X-ray emission or the Sunyaev-Zeldovich effect), or the suspected progenitors of today’s brightest cluster galaxies, in particular high-redshift galaxies (Steidel et al. 2000, Brand et al. 2003, Kodama et al. 2007, Scoville et al. 2007, Venemans et al. 2007, Papovich 2008, Daddi et al. 2009, Brodwin et al. 2010, Galametz et al. 2010, Papovich et al. 2010, Capak et al. 2011, Hatch et al. 2011, Kuiper et al. 2011, Ivison et al. 2013, Muzzin et al. 2013, Wylezalek et al. 2013).

1 Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
2. Sample selection and observations

2.1. Planck observations and selection

Planck observed the whole sky at frequencies between 30 and 857 GHz (Planck Collaboration 2014). We made two different selections to follow-up with Herschel: first, using the maps and looking for cold sources of the CIB; second, using the public catalogue of compact sources (PCCS).

2.1.1. Cold sources of the CIB in the Planck maps

We make use of the Planck-HFI (High Frequency Instrument, Planck Collaboration VII 2014) data as well as the IRAS/IRIS data (Miville-Deschênes & Lagache 2005) at 100 µm. For this purpose we use the cleanest 26% of the sky (in the Planck 857 GHz map), defined by a minimal cirrus contamination, $N_{HI} < 3 \times 10^{20} cm^{-2}$. The detection and selection algorithm, based on Montier et al. (2010) can be summarized in the following seven steps (Planck Collaboration 2015).

(i) CMB cleaning: the 143 GHz Planck-HFI map is extrapolated to the other bands according to a CMB spectrum and removed from the maps at other frequencies.

(ii) Galactic cirrus cleaning: the IRAS/IRIS 100 µm map, considered as a “warm template” of Galactic cirrus, is extrapolated to the Planck-HFI bands, taking into account the local colour, and removed from the maps following the prescription of the CoCoCoDeT algorithm (Montier et al. 2010).

(iii) Construction of excess maps: the 545 GHz excess map is defined as the difference between the cleaned 545 GHz map and a power law interpolated between the cleaned maps at 857 GHz and 353 GHz.

(iv) Point source detection in the excess maps: we apply a Mexican hat type detection algorithm (González-Nuevo et al. 2006) with a size parameter of $R = 5'$ in the 545 GHz excess maps.

(v) Single frequency detection: we also require a detection in each cleaned map at 857 and 353 GHz.

(vi) Colour-colour selection: we apply two criteria on the $S_{857}/S_{545}$ (i.e., 545 GHz to 857 GHz) and $S_{353}/S_{545}$ (i.e., 353 GHz to 545 GHz) flux density ratios to select the reddest sources.

This produces a dozen hundred candidates on the cleanest 26% region of the submm sky. We note that this procedure has been set-up early on in the Planck project. The final catalog of Planck high-z candidates is being generated using a similar (but not exactly identical) method which will be described in a forthcoming paper (Planck Collaboration 2015). In particular, the CMB estimate will not be the 143 GHz HFI map, but instead a forthcoming paper (Planck Collaboration 2015).

2.1.2. Planck PCCS sources

We make use of the PCCS to choose a sample of high-z sources selected by the expected peak in their thermal dust spectrum in the rest-frame far infrared. Our four step procedure here is based on the work of Negrello et al. (2010). First of all, we use the 857 GHz Galactic mask, keeping 52% of the

3 Planck data (maps and catalogues) can be downloaded from the Planck Legacy Archive http://pla.esac.esa.int/pla/aio/planckProducts.html
Planck Collaboration: high-z sources discovered by Planck and confirmed by Herschel

Figure 1. SPIRE maps at 250, 350, and 500 µm of one typical overdensity in our sample (a Planck cold source of the CIB – Cosmic Infrared Background). The thick white contour at 350 µm shows the Planck IN region at 857 GHz, and the same is true for the map at 500 µm at 545 GHz (i.e., the 50% contour of the Planck source maximum). Thin contours correspond to the overdensity of SPIRE sources at each wavelength, marked at 2σ, 3σ, etc. (see Sect. 4.2 for details). SPIRE identifies a few (typically 5 to 10) sources inside the Planck contour. We use these contours to separate the IN and OUT zones. These data come from a 7′ × 7′ SPIRE scan (see Table 1 and Sect. 2.3).

Figure 2. SPIRE maps at 250, 350, and 500 µm for a lensed source. In this case a single very bright SPIRE source is detected. This source is confirmed at the Jy level and has a redshift of z = 3.0, measured from multi-line spectroscopy acquired at IRAM using EMIR (Canameras 2015). The white contour is the Planck IN region, defined in the same way as in Fig. 1. These data come from a 7′ × 7′ SPIRE scan (see Table 1 and Sect. 2.3).

the sky (Planck Collaboration Int. VII 2013). Secondly, we select all the sources with S/N > 4 at 545 GHz and the colours S_857/S_545 < 1.5 (where S_ν is the flux density at frequency ν in GHz) and S_217 < S_353. Thirdly, we inspect each source with respect to the NASA/IPAC Extragalactic Database (NED), IRAS maps (Neugebauer et al. 1984), and optical maps using ALADIN. Any object identified as a local galaxy, a bright radio source or Galactic cirrus is removed (about half of the objects). Finally, we remove any PCCS source already falling in the H-ATLAS or South Pole Telescope (SPT) survey fields.

2.2. The Planck parent sample and three subsamples

Planck and Herschel were launched on 14 May 2009, and started routine scientific observations a few months later (Planck Collaboration 2011; Pilbratt et al. 2010). Our Planck parent sample has evolved with time as a function of the delivery of internal releases of the intensity maps (typically every 6 months). We thus built three samples: one for each main Herschel Open Time call for proposals (OT1 and OT2), and a last one for the Herschel 'must-do' DDT (Director’s Discretionary Time) observations (which we call HPASSS for Herschel and Planck All Sky Legacy Survey Snapshot). We requested only SPIRE data, as it is better optimized than PACS for
Table 1. SPIRE programmes following-up Planck cold sources of the CIB. HPASSS is composed of 124 sources selected from the maps (two were repeated, so 126 fields), together with 28 from the PCCS (four were cirrus dominated, so 24 net fields). A total of 228 sources are useable (Sect. 2.2).

<table>
<thead>
<tr>
<th>Programme</th>
<th>No. of fields</th>
<th>Map size</th>
<th>AOR+ time</th>
</tr>
</thead>
<tbody>
<tr>
<td>OT1</td>
<td>10</td>
<td>15' × 15'</td>
<td>3147 s</td>
</tr>
<tr>
<td>OT2</td>
<td>70</td>
<td>7' × 7'</td>
<td>838 s</td>
</tr>
<tr>
<td>HPASSS</td>
<td>124 (96) + 24 (28)</td>
<td>7' × 7'</td>
<td>838 s</td>
</tr>
<tr>
<td>Total</td>
<td>228 (234)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Astronomical Observation Request.

b Nine HPASSS sources are from archival data.

the targeted redshift range. Our main goal was to identify the counterparts contributing to the Planck-HFI detections, hence the focus on rapid SPIRE follow-up of a maximum number of targets. Obtaining PACS observations would have enhanced the angular resolution and wavelength coverage, but for these short observations would not have resulted in further constraints in most cases.

The samples are summarized in Table[1] together with the map sizes and time per Astronomical Observation Request (AOR). The OT1 sample refers to the Herschel first call for Open Time observations in July 2010 (P.I.: L. Montier). The OT2 sample refers to the Herschel second call for Open Time observations in September 2011 (P.I.: H. Dole). Figs. 1 and 2 show examples of this observation strategy. The Herschel and Planck All-Sky Source Legacy Survey (HPASSS) was set up by the Planck collaboration (P.I.: H. Dole) in the response to 'must-do' DDT programme in June 2012. At that time, the preliminary PCCS was internally released to the collaboration, and we could benefit from the unique and timely Herschel and Planck synergy when the Planck products were approaching their final state and when Herschel surveys already demonstrated the robustness of our detections. Four fields from the PCCS appear as cirrus structures: diffuse, extended submillimetre emission without noticeable point sources. These fields were removed from the sample. This means that four out of 234 fields (1.7%) were contaminated by Galactic cirrus. The success rate of avoiding Galactic cirrus features is thus larger than 98%, thanks to our careful selection on the Planck maps of the cleanest 35% of the sky.

Our final sample thus contains 228 fields (i.e., 234 minus two repeated fields minus four cirrus-dominated fields). They are composed of (See Table[1]): 10 sources from OT1; 70 sources from OT2; 124 objects from HPASSS CIB; and 24 sources from HPASSS PCCS.

Each SPIRE field of a Planck target is then separated into two zones: IN and OUT of the Planck source at 545 GHz (the frequency where our selection brings the best S/N ratio). The IN region boundary is defined as the 50% Planck intensity contour, i.e., the isocountour corresponding to 50% of the peak Planck flux, and encompasses the Planck-HFI beam. The OUT region is defined to be outside this region (see the thick white contours in Figs. 1 and 2).

2.3. SPIRE data processing, total SPIRE sample and definition of IN and OUT Planck regions

The SPIRE data were processed starting with 'Level 0' using HIPE 10.0 [Ott 2010] and the calibration tree 'spirecalal01', using the Destrriper module [https://nhsccsi.ipac.caltech.edu as mapmaker (baselines are removed thanks to an optimum fit between all timelines) for most observations. For 33 AORs, we had also to remove some particularly noisy detectors (PSWB5, PSWF8, and PSWE9 affected for Operational Days 1304 and 1305) from the Level 1 timelines. In that case, we processed the data with the naive scan mapper using a median baseline removal (the destrriper module worked with all bolometers in Level 1). Turnarounds have been taken into account in the processed data. The useable sky surface area is thus extended, and goes beyond the nominal 7' × 7' or 15' × 15' as specified in the AORs (Table[1]).

Table 2. SPIRE 1σ total noise (instrument + confusion) levels measured in various fields, in mJy. Our Planck fields are denoted 'Planck high-z'.

<table>
<thead>
<tr>
<th>Field</th>
<th>1σ noise level</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>250 μm</td>
</tr>
<tr>
<td>Planck high-z</td>
<td>9.9</td>
</tr>
<tr>
<td>HerMES Lockman-SWIRE</td>
<td>10.1</td>
</tr>
<tr>
<td>HLS</td>
<td>14.1</td>
</tr>
</tbody>
</table>

Since we are close to the confusion limit, we included a check to confirm that the non-uniform coverage imposed by including the edges does not change the source detection statistics.

We have a total of 234 SPIRE targets. Of these, two fields were repeated observations, and have been used to check the robustness of our detections. Four fields from the PCCS appear as cirrus structures: diffuse, extended submillimetre emission without noticeable point sources. These fields were removed from the sample. This means that four out of 234 fields (1.7%) were contaminated by Galactic cirrus. The success rate of avoiding Galactic cirrus features is thus larger than 98%, thanks to our careful selection on the Planck maps of the cleanest 35% of the sky.

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2.4. Ancillary SPIRE data sets

For a first characterization of our sample, and to infer whether it is different from other samples of distant galaxies observed with SPIRE, we will compare with the data obtained in other SPIRE programmes. Since we suspect that most of our targets contain overdensities like proto-clusters of galaxies, it will be useful to contrast it with samples of galaxy clusters at lower redshift, as well as against blank fields. Our two comparison samples are as follows.

1. The HerMES [Oliver et al. 2010] and H-ATLAS [Eales et al. 2010] public data as reference fields. In particular, we will be using the 'level 5' Lockman HerMES field, which has a similar depth to our SPIRE observations.
2. The SPIRE snapshot programme of local or massive galaxy clusters [Egami et al. 2010] including: the "Herschel Lensing Survey" (HLS); the "SPIRE Snapshot Survey of Massive Galaxy Clusters" (OT1); and the "SPIRE Snapshot..."
3. SPIRE Photometry

3.1. Photometric analysis

We first measure the noise in each map at each wavelength (channel) by fitting a Gaussian function to the histogram of the maps and deriving the standard deviation, \( \sigma_{\text{channel}} \), a mixture of confusion noise (Dole et al. 2003; Nguyen et al. 2010) and detector noise. The values are reported in Table 1. Data are sky subtracted and at mean 0, as done in HIPE 10. All pixels are used to plot the noise histogram. Histogram have a Gaussian shape, with a bright pixel tail. The bright pixel tail contribution (larger than 3 sigma) to the histogram is nearly 1% in number for each field at 350\( \mu m \). Then we extract the sources using a blind method and by a band-merging procedure described in the following sections.

We employ Monte Carlo simulations to check our photometry at each wavelength: injection of sources in the data, and blind extraction, in order to measure the photometric accuracy (Fig. 3). As expected, the photometric accuracy is of the order of 10% at flux densities larger than a few tens of mJy, and decreases towards smaller flux densities closer to our noise level.

Finally, we use the OT2 data from “The highest redshift strongly lensed dusty star-forming galaxies” (P.I. J. Vieira) programme to carry out technical checks, since those AORs are very similar to ours.

### Figure 3

Photometric accuracy from Monte Carlo source injections in real maps at 250, 350 and 500\( \mu m \). The 3 \( \sigma \) (dotted line) and 4 \( \sigma \) (dashed line) levels are also shown. See Sect. 3.2 for details.

### Figure 4

Completeness levels from Monte Carlo source injections in SPIRE maps of different data sets at 250, 350 and 500\( \mu m \). Plotted are our Planck fields (black), HerMES sources (orange), and Herschel Lensing Survey (HLS) clusters (blue). The 50% (dotted line) and 80% (dashed line) completeness levels are also shown. See Sect. 3.2 for details.

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7 Herschel public data can be downloaded from the Herschel Science Archive: [http://herschel.esac.esa.int/Science_Archive.shtml](http://herschel.esac.esa.int/Science_Archive.shtml)

8 for nominal SPIRE map pixels of 6, 10, and 14\( \prime \prime \), respectively.
4. Statistical Analysis of the Sample

3.3. Band-merged catalogues

We use the 350µm map-based catalogue from StarFinder as the input catalogue. This wavelength has two advantages: first, its angular resolution meets our need to identify the sources; and second, it is consistent with the Planck colour selection, which avoids the many low-z galaxies peaking at 250µm. As will be shown in Sect. 4.1, our sample has an excess in number at 350µm compared to reference samples drawn from the HerMES Lockman SWIRE level 5 field or the low-redshift HLS cluster fields, in agreement with the existence of an overdensity of SPIRE sources in the Planck beam.

Our band-merging procedure has three steps. First of all, we optimize the measurement of the source position using the 250µm channel, where available. Secondly, we measure a preliminary flux density on each source, which will serve as a prior to avoid unrealistic flux measurements while deblending. Thirdly, we perform spatially-simultaneous PSF-fitting and deblending at the best measured positions with the newly determined prior flux densities as inputs for FastPhot (Bethermin et al. 2010b). The details are described in Appendix A. This method provides better matched statistics (more than 90% identifications) than the blind extraction method performed independently at each wavelength (Sect. 3.2, Table A.2 vs. Table A.1). We finally have a total of about 7100 SPIRE sources, of which about 2200 are located in the Planck IN regions (giving an average of about 10 SPIRE sources per Planck IN field).

4. Statistical Analysis of the Sample

4.1. Number counts: significant excess of red sources

We compute the differential Euclidean-normalized number counts $S^2 dN/dS$, with $S$ being the flux density at wavelength $\lambda$, and $N$ the number of sources per steradian. The counts are not corrected here for incompleteness, or for flux boosting (Eddington bias), since we are interested in the relative behaviour between the samples. The detected sources used here are extracted using the blind technique (Sect. 3.2). We cut the samples at 4$\sigma$ for these counts ($\sigma$ values in Table 2). We used five different data sets to estimate the number counts:

- **Planck IN+OUT**, our 228 Planck entire fields, each covering about 20′ × 20′;
- **Planck IN**, our 228 Planck fields, using only the central parts corresponding to the Planck 50% contour level (determined separately for each source), called the IN region;
- **Planck OUT**, our 228 Planck fields, using only the part exterior to the Planck 50% level, called the OUT region;
- **HerMES Lockman**, HerMES level 5 field in Lockman (Oliver et al. 2010), covering 18.2 deg$^2$;
- **HLS**, 535 cluster-fields of Egami et al. (2010), covering 5.6 deg$^2$; five from the Herschel Lens Survey KPOT, 282 from OT1, and 248 from OT2, hereafter referred to as HLS.

The number counts of all these data sets are plotted in Fig. 5 and reported in Appendix B in Tables B.1, B.2, and B.3. We derive from the total number count the following results:

(i) The counts measured in the entire Planck fields (blue circles, meaning IN + OUT), HerMES Lockman, and HLS clusters, are generally compatible with each other at 250µm, except for a few points at large flux density, above...
300 mJy, where the numbers are small. This means that, on average, these fields do not show any strong deviations between them.

(ii) The observed counts (uncorrected for incompleteness) show the characteristic shape of the Eddington bias: a cutoff below about 40 mJy, an excess around 50 mJy, and a behaviour compatible with the models at higher flux densities. It is beyond the scope of this paper to re-derive unbiased number counts (e.g., Glenn et al. 2011; Oliver et al. 2015; Clements et al. 2016), as we only focus on the relative trends.

(iii) The IN counts at large flux densities ($S > 300$ mJy) show a systematic excess at 350 and 500 µm over the counts in the wide blank field (Lockman) as well as cluster fields. At 300 mJy, the overdensity factors are, respectively, 4.1 and 3.7 at 350 µm, and about 20 and 16 at 500 µm. This chromatic excess (i.e., larger excess at longer wavelengths) is consistent with the hypothesis of the presence of a population of high-redshift lensed candidates at $z = 2$–4. We will show in Sect. 5 that this is indeed the case.

(iv) The IN counts at 250 µm are a bit higher (for $S_{250} < 100$ mJy) than in Lockman, and are lower at larger flux densities. This means that the SPIRE counterparts of the Planck sources have, on average, counts that deviate little from blank fields at this wavelength.

(v) The IN counts at 350 µm for $S_{350} > 50$ mJy are a factor between 1.9 and 3.4 higher than in Lockman and in the cluster fields. This means that, on average, the SPIRE counterparts of the Planck sources have a significant excess of 350 µm sources compared to wide blank fields or $z < 1$ HLS cluster fields. This is expected, given our Planck selection criteria.

(vi) The IN counts at 500 µm for $S_{500} > 50$ mJy are a factor of 2.7–8 higher than in the Lockman and cluster fields. As in item (v) above, this means that, on average, the SPIRE images of the Planck source targets show a significant excess of 500 µm sources compared to wide blank field or $z < 1$ HLS cluster fields.

(vii) The OUT counts are compatible with the wide blank extragalactic fields, as well as the cluster fields. Our OUT zones can thus also be used as a proxy for the same statistics in blank fields.

As a conclusion, the SPIRE observations of the Planck fields reveal “red” sources. The SPIRE images exhibit a significant excess of 350 and 500 µm sources in number density compared with wide blank fields (HerMES Lockman SWIRE of the same depth) or fields targeting $z < 1$ galaxy clusters (HLS). This significant excess should be expected given the Planck colour selection, and is now demonstrated with secure SPIRE detections. It is therefore clear that there is no significant contamination by cirrus confusion in our Planck sample, and that where there is a Planck high-z candidate, Herschel detects galaxies.

4.2. Overdensities

We compute the dimensionless overdensity contrast $\delta_1$ of our fields at wavelength $\lambda$ via

$$\delta_1 = \frac{\rho_{\text{IN}} - \rho_{\text{OUT}}}{\rho_{\text{OUT}}} \quad (1)$$

where $\rho_{\text{IN}}$ is the surface density of SPIRE sources in the Planck IN region, and $\rho_{\text{OUT}}$ is the mean surface density of SPIRE sources computed in the Planck OUT region, at SPIRE wavelength $\lambda$. We have already shown (Sect. 4.1 and Fig. 5) that the OUT region has a density equivalent to that of blind surveys, and is thus a good estimate of $\rho$, the mean surface density. To reduce the Poisson noise, we use the counts from all the OUT regions.

The overdensity contrasts $\delta_1$ extend up to 10, 12, and 50 at 250, 350, and 500 µm, respectively, with a median overdensity $\delta_1$ of $\delta_{250} = 0.9$, $\delta_{350} = 2.1$, and $\delta_{500} = 5.0$. This means that our Planck IN regions have an excess of SPIRE sources. Indeed, there are 50 fields with $\delta_{350} > 10$, and 129 with $\delta_{500} > 4$ (with significance levels always higher than 4 $\sigma$, see below). At 350 µm, there are 19 fields with $\delta_{350} > 5$, 37 fields with $\delta_{350} > 4$ and 59 fields with $\delta_{350} > 3$, as shown in Fig. 6 (left panel, in blue). In Appendix D we also use the densities measured with AKDE to estimate the overdensities.

How significant are these overdensity contrasts? To quantify this we compute the mean density field using the AKDE algorithm (adaptive kernel density estimator, see Valchandov et al. 2013 and also Pisani 1996; Ferdosi et al. 2011). The principle is to generate a two-dimensional density field based on the positions of the sources from a catalogue, filtered (smoothed) according to the source surface density. From this smoothed field, we compute the standard deviation and hence we derive the significance $\sigma_\rho$ of the overdensity. We also run 1000 Monte Carlo runs to get a better estimate of the scatter on $\sigma_\rho$ (by creating AKDE density maps using random source positions – but otherwise using the real catalogs of each field – and measuring the RMS over those 228000 realizations). All our fields show overdensities larger than 1.8 $\sigma_\rho$, with a median of 7 $\sigma_\rho$ (Fig. 6 right panel). The typical number of sources in an overdensity is around 10, but with a fairly wide scatter.

We can then choose to select the reddest sources, this being a possible signature of a higher redshift or a colder dust temperature. We define the SPIRE red sources with the following cuts in colour based on the distributions shown in Fig. 7: $S_{350}/S_{250} > 0.7$; and $S_{500}/S_{350} > 0.6$. When selecting only the red sources, the overdensity significance increases: The mean is now 12 $\sigma_\rho$ and the median 9 $\sigma_\rho$. We have 50 % of the sample at 10 $\sigma_\rho$ or more (when selecting the red sources), which is more than a factor of 3 larger than when selecting all SPIRE sources. 23% of the sample is above 15 $\sigma_\rho$ (Fig. 6 right panel), i.e., 51 fields.

These high significance levels can be contrasted with the mean $\delta_{500} = 0.25$ obtained by Rigby et al. (2014) at the locations of 26 known protoclusters around very powerful radio-galaxies, drawn from the list of 178 radiogalaxies at $z > 2$ of Miley & de Breuck (2008). They can also be compared to the few similar examples in Clements et al. (2014), with at most 4.7 $\sigma_\rho$ at 350 µm. We show in Fig. 6 right panel, in orange, the cumulative normalized significance $\sigma_\rho$ of 500 random positions in the Lockman field; Using this test sample illustrates the high significance of the overdensities of our sample.

Examples of some overdensities are shown in Appendix D where we present a gallery of representative SPIRE data.

4.3. Colours of the sources

Using the band-merged catalogue (Sect. 3.3), we can derive the colours of the sources, i.e., the ratios of the observed flux densities $S_{500}/S_{350}$ vs. $S_{250}/S_{350}$. In this colour-colour space, redder sources will have higher $S_{500}/S_{350}$ ratios and lower $S_{250}/S_{350}$ ratios, and will tend to lie in the lower left part of the diagram.

We provide in Fig. 7 the source surface density histograms for the two SPIRE colours: $S_{350}/S_{250}$ and $S_{500}/S_{350}$ (red, Planck
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**Figure 6.** Left: Cumulative histogram of the overdensity contrast \(\delta_{350}\) (blue) of each Planck field (based on 350 \(\mu\)m SPIRE sources). Overdensities are fairly large, with 59 fields having \(\delta_{350} > 3\). Right: Cumulative (normalized) statistical significance in \(\sigma\) derived from the density maps. Blue represents all our SPIRE sources, red represents only redder SPIRE sources, defined by \(S_{350}/S_{250} > 0.7\) and \(S_{500}/S_{350} > 0.6\), and orange 500 random fields in Lockman. Most of our fields have a significance greater than 4 \(\sigma\), and the significance is higher still for the redder sources. See Sect. 4.2 for details.

**Figure 7.** Colour counts: source surface density as a function of the SPIRE colour, \(S_{350}/S_{250}\) (left), and \(S_{500}/S_{350}\) (right). Histograms are: red solid line, Planck IN; black line, Planck OUT; green, Planck IN lensed fields only; blue line, \(z < 1\) HLS clusters; and orange dashes, Lockman SWIRE. The Planck IN sources (total and/or lensed sources) show a much higher surface density than other samples, owing mainly to our all-sky search strategy. See Sect. 4.3 for details.

IN; black, Planck OUT; green, only the lensed fields; blue, HLS; and dashes, HerMES). The IN sources show three times larger surface densities in \(S_{350}/S_{250}\), and four times larger surface densities in \(S_{500}/S_{350}\) than OUT and Lockman sources. The IN source distribution peaks at much higher surface density than any other sample, suggesting that our sample is dominated by red and overdense SPIRE sources.

Following the approach of Amblard et al. (2010), we generate the SED of \(10^6\) modified blackbodies with 10\% Gaussian noise and explore three parameters: the blackbody temperature \((T)\) in the range 10–60 K; the emissivity \((\beta)\) in the range 0–2; and the redshift for \(z = 0–5\). For each set of parameters we convert the fixed, observed SPIRE wavelengths into rest frame wavelength (at redshift \(z\), thus varying with \(z\)) using: \(\lambda_{\text{rest}} = \lambda_{\text{SPIRE}}/(1 + z)\). We then calculate the flux at each wavelength using \(\lambda_{\text{rest}}\) and compute the colours \(S_{250}/S_{350}\) and \(S_{500}/S_{350}\) for each set of parameters. Fig. 8 shows those realizations, colour-coded in redshift (deep purple for \(z = 0\), up to red for \(z = 4\)). Our SPIRE IN sources are shown in black. They predominantly fall in the redshift region corresponding to \(z \sim 1.5 – 3\). We note, however, that the redshift-temperature degeneracy is present in
Figure 8. *Herschel*-SPIRE colour-colour diagram of IN sources (black dots) on top of redshifted blackbodies. *Left*: colour codes redshift. *Right*: colour codes dust temperature in kelvin. Although there is a degeneracy between redshift and temperature, the colours suggest a range of $z \sim 1.5$–3 for the SPIRE sources corresponding to the *Planck* IN regions. The upper right symbol gives the typical (median) error bars of the measured points. See Sect. 4.3 for details.

Figure 9. Classification of 228 *Planck* fields with *Herschel*-SPIRE. The $x$-axis represents the maximum flux of the SPIRE source within the IN region: lensed source candidates are selected if they fall above 400 mJy (i.e., the right column, seven sources). The $y$-axis represents the wavelength at which the brightest SPIRE source peaks in the IN region. Overdensities are thus selected in the lower left four cells. The colour represents the number of fields in each cell (as shown in the colour bar). The numbers in the cells are the number of fields and percentage in each cell. Our sample is thus dominated by overdensities peaking at 350 $\mu$m. See Sect. 4.4 for details.

Figure 10. A high-$z$ cluster candidate observed by *Planck*, *Herschel*, and *Spitzer*-IRAC (image covering 0.5’ × 0.3’). We show the IRAC channel 1 (3.6 $\mu$m) image, with SPIRE 350 $\mu$m white contours overlaid. Colour contours represent statistical significance of the local overdensity, from light blue to red: 3, 4, 5, 6, and 7 $\sigma$. See Sect. 6.1 for details.

4.4. Classification of the sources

We classify the *Herschel* fields in an automated way and for preliminary analysis into two main categories: (1) overdensities, appearing as clustered sources, and (2) lensed candidates, appearing as a bright single source as a counterpart of the *Planck* source. To make this classification, we measure within the IN *Planck* region the flux density and colour of the brightest SPIRE source.

This suggestive result (Amblard et al. 2010; Pope & Chary 2010; Greve et al. 2012), and will be discussed in Sect. 6.3.
We sort the fields using two criteria: (1) the SPIRE channel at which the source has its maximum flux density; and (2) its flux density at 350 µm. We will use this two-parameter space to classify the sources. This classification provides the first set of information about the sources, although a definitive classification will require follow-up data to confirm the nature of the sources.

In this space, the lensed candidates will populate the “red” and “bright” areas (typically 350 or 500 µm peaks, and \(S_\nu > 400 \text{ mJy}\). This does not necessarily mean that all the sources in this area will be strongly gravitationally lensed (although this is confirmed by further follow-up, see following sections).

The overdensity candidates will be located in a different area of this two-parameter space than the lensed candidates. They will tend to populate the fainter end (typically \(S_\nu < 200 \text{ mJy}\)) and will have red colours (typically 350 or 500 µm peaks).

We do not expect many 250 µm peaks because of the Planck colour selection, for which there is a bias towards redder colours and thus potentially higher-redshift sources. Fig. 3 summarizes the classes of SPIRE identifications of the Planck high-\(z\) (meaning \(z > 1.5\)) candidates, based on those criteria. We show that the vast majority of our sample is composed of overdensities of 350 µm peaks. The number of lensed candidates is rather small in comparison, amounting to seven sources based on this criterion. All are confirmed to be strongly gravitationally lensed galaxies (Canameras 2015). We will show later that visual inspection led us to discover a few more lensed sources.

The dashed lines in Fig. 7 show the colour vs. surface density of the lensed candidate population, whose red colours are confirmed.

Finally, we derived number counts (as in Fig. 5) but now by separating the overdensities from the lensed sources that dominate the counts at large flux densities, typically \(S > 250 \text{ mJy}\) (shown in Appendix C in Fig. C.1). This separation suggests that the excess at large flux densities in the number counts of our sample is due to the presence of bright lensed sources, compared to reference samples (HLS, HerMES).

5. Strongly gravitationally lensed source candidates

5.1. Validation of existing lensed sources

Negrello et al. (2007) and Bethermin et al. (2012) predicted that a small, but significant fraction of very bright high-redshift (\(z > 2\)) submillimetre galaxies are strongly gravitationally lensed, dusty starbursts in the early Universe. Negrello et al. (2010) presented observational evidence of these predictions. In addition, Fu et al. (2013) confirmed the nature of the source H-ATLAS J114637.9-001132 as a strongly gravitationally lensed galaxy at \(z = 3.3\); this source was part of the first release of the Planck ERCSC Catalogue (Planck Collaboration VII 2011; Planck Collaboration 2011), and fell fortuitously into the H-ATLAS survey field (see also Herranz et al. 2013). Another independent confirmation that Planck sources can be strongly gravitationally lensed came from the source HLS J091828.6+514223, confirmed as a bright, \(z = 5.2\) gravitationally lensed galaxy behind the massive intermediate-redshift galaxy cluster Abell 773 (Combes et al. 2012), as part of the Herschel Lensing Survey (Egami et al. 2010). This source was independently found in our survey and is part of the Herschel/Planck OT2 selection. It is excluded from our sample to satisfy the condition of non-redundancy.

5.2. Previously unknown gravitationally lensed sources

In the absence of extensive follow-up, it is challenging to distinguish between single or multiple strongly gravitationally lensed galaxies behind the same foreground structure and overdensities of intrinsically bright submillimetre galaxies, for all but the brightest gravitationally lensed sources. Moreover, at flux densities of about \(S_{350} = 250 \text{ mJy}\) and above, isolated SPIRE point sources may turn out to be associations of multiple FIR galaxies when observed at higher spatial resolution (Ivison et al. 2015).

As a first step towards identifying the gravitational lensed candidates in our sample (Sect. 4.3), we therefore focused on those targets where SPIRE shows only a single, very bright source, with the typical FIR colours of high-redshift (\(z > 2\)) galaxies associated within one Planck beam. We thus identified seven isolated SPIRE point sources, as described in Sect. 4.4, plus five others at slightly fainter flux densities. All have peak flux densities at 350 µm, including 11 with \(S_{350} = 300–1120 \text{ mJy}\) (Canameras 2013). Six of these galaxies were taken from the PCCS, the remaining six originate from the sample of Planck Collaboration (2015). Although the initial selection of lensed candidates was carried out by eye upon the reception of the SPIRE imaging, seven of these targets were also identified with our automatic classification (Sect. 4.4). We used the IRAM 30-m telescope to obtain firm spectroscopic redshifts via a blind CO line survey with the wide-band receiver EMIR. We identify 2–6 lines per source, which confirms they are at redshifts \(z = 2.2–3.6\). Interferometry obtained with the IRAM Plateau de Bure interferometer and the Submillimeter Array, as well as several empirical calibrations based on FIR luminosity and dust temperature (following Harris et al. 2012), and CO line luminosity and line width (following Kneiwe et al. 2012), demonstrate that these are indeed strongly gravitationally lensed galaxies, amongst the brightest on the submm sky (Canameras 2015).

6. Candidate high-\(z\) overdensities

Without rejecting the possibility that the observed overdensities of red SPIRE sources could be chance alignments of structures giving coherent colours (e.g., Chiang et al. 2013), we can ponder the nature of those overdensities. Could they be high-redshift star-forming galaxy proto-clusters? Indeed, recent studies, such as Gobat et al. (2011), Santos et al. (2011, 2013, 2014), and Clements et al. (2014) confirm the presence of high redshift (\(z > 1.5\)) galaxy clusters emitting enough energy in the submillimetre to be detected. Those previously detected clusters are, however, in a different state of evolution than our candidates. Many of the confirmed clusters exhibit X-ray emission, suggesting already mature and massive clusters. The following sections investigate different aspects of our sample, which is uniquely selected by strong submm emission over the whole sky, enabling us to unveil a rare population.

6.1. First confirmations

It is beyond the scope of this paper to summarize all the follow-up observations conducted so far, but we give here three highlights, which will be discussed in more detail in subsequent papers.

Our sample contains a source from Herschel OT1 that was followed up early as a pilot programme. Using CFHT and Spitzer imaging data, and VLT and Keck spectroscopy, a structure was identified at \(z \sim 1.7–2.0\) (Flores-Cacho et al., 2014, in prep.). By fitting a modified blackbody and fixing redshifts at respectively
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Figure 11. Left: SPIRE 3-colour image of one Planck high-$z$ overdensity candidate (located in the centre), in an image covering about $20' \times 20'$. We note the bluer source on the left (circled), which corresponds to the galaxy cluster shown on the right. Right: a confirmed $z = 1.58$ galaxy cluster XMMU J0044.0-2033 (Santos et al. [2011]) which lies close to our Planck high-$z$ source. The background image is a two colour composite of Spitzer-IRAC channel 1 (3.6 $\mu$m) and channel 2 (4.5 $\mu$m), covering about $3' \times 2'$. The contours are Herschel-SPIRE 350 $\mu$m. See Sect. 6.1 for details.

Figure 12. Stacks of SPIRE 350 $\mu$m data (8.7' $\times$ 8.7'): (a) 220 Planck Herschel fields; (b) 278 HLS clusters; (c) 500 sources in the HerMES Lockman field, peaking at 350 $\mu$m; and (d) 500 random positions in the HerMES Lockman field. Black contours show the density of red sources (using AKDE). Our Planck fields clearly exhibit a high significance of extended (a few arcminutes) submm emission, due to the presence of many red point sources, not seen in the HLS or HerMES sources. See Sect. 6.2 for details.
1.7 and 2.0, we find an average dust temperature for the sources of, respectively, 27\(\text{K}\) and 35\(\text{K}\).

Another field has been imaged by Spitzer as part of our GO-9 programme – see Fig. 10 for the IRAC 3.6\(\mu\text{m}\) image with the SPIRE 350\(\mu\text{m}\) contour. The colour ratios of IRAC flux densities 3.6\(\mu\text{m}/4.5\mu\text{m}\) of the sources detected in the overdensity exhibit red colours, indicating their probable high-redshift nature (Papovich 2008). The overdensity of IRAC 3.6\(\mu\text{m}\) sources has a statistical significance of 7\(\sigma\)s (Martinache et al., 2014, in prep.). While not yet confirmed as a proto-cluster or cluster through spectroscopy, this structure, seen with Spitzer at near-infrared wavelengths, supports the hypothesis of strongly clustered highly star-forming infrared sources.

Finally, we have also found one SPIRE field with overlapping data from the literature. The observations from Santos et al. (2011) confirm the presence of a \(z = 1.58\) cluster using optical/NIR spectroscopy. This particular high-z cluster has also been detected in X-rays, leading to a total mass estimate of about \(3–5 \times 10^{14}\)\(M_{\odot}\). It is located a few arcminutes from one of our targets (Fig. 11 right), so is not formally an identification of our Planck source, but rather a coincidence. While not connected to our target source here, this cluster can nevertheless bring useful information. The SPIRE colours of this cluster are bluer than our sources. Since our target shows redder SPIRE colours, this suggests it has a higher redshift or a cooler dust temperature.

6.2. Large clustering of our sample revealed with stacking

We can see that the Planck fields show clear and significant extended (a few arcminutes) emission due to the clustering of bright submm sources. This kind of extended emission of clustered submm sources is not observed in the HLS clusters, nor around 350\(\mu\text{m}\) peaking HerMES sources. The random stack validates the absence of a systematic effect in stacking (Dole et al. 2006; Bethermin et al. 2010a; Viero et al. 2013; Planck Collaboration XVIII 2014). This proves that our sources are of a different nature than mature HLS clusters or average HerMES submillimetre sources.

We overplot in Fig. 12 the contours in density (see Sect. 4.2) of the SPIRE red sources (defined in Sect. 4.2). The stacks indicate that the Planck sample exhibits strong overdensities of red SPIRE sources. By contrast, the HLS sample shows a smooth and weak density of red sources (except for the presence of some point sources – the background lensed galaxies). As expected, the HerMES sample shows a stack consistent with the SPIRE PSF, while the random sample is consistent with noise.

6.3. Dust temperatures, photometric redshifts, luminosities, and star formation rates

With the hypothesis that our overdensities are actually gravitationally bound structures, i.e., clusters of star-forming, dusty galaxies, the overdensity colours (Fig. 7) suggest a peak redshift around \(z = 1.5–3\) (Fig. 8). Using a modified blackbody fit (with \(\beta = 1.5\) and fixing the dust temperatures to \(T_d = 25, 30, 35, 40, \) and 45\(\text{K}\)), we obtain the redshift distributions shown in Fig. 13 for the roughly 2200 sources found in the IN regions for these overdensities. For \(T_d = 35\text{K}\), the distribution peaks at \(z = 2\). For higher dust temperatures, the peak of the distribution is shifted towards higher redshifts, since dust temperature and redshift are degenerate for a modified blackbody, where \(d_T/(1+z) = \text{constant}\).

Many studies (e.g., Mardelli et al. 2014; Elbaz et al. 2011; Greve et al. 2012; Mardelli et al. 2012; Symeonidis et al. 2013; Weiss et al. 2013; Magnelli et al. 2014) suggest that dust temperatures of \(z = 2\) sources are typically of the order of 35\(\text{K}\), consistent with the few measurements in hand (see Sect. 6.2). With the conservative assumption that \(T_d = 35\text{K}\) for all sources (e.g., Greve et al. 2012), we can derive the IR luminosity for each SPIRE source (by integrating between 8\(\mu\text{m}\) and 1\(\text{mm}\)), and find that it has a broad distribution peaking at \(4 \times 10^{12}\)\(L_{\odot}\) (Fig. 14). Assuming that the conventionally assumed relationship between IR luminosity and star formation (Kennicutt 1998; Bell 2003) holds, and that AGN do not dominate (as was also found for the objects previously discussed by Santos et al. 2014 and Clements et al. 2014), this would translate into a peak SFR of \(700 M_{\odot}\text{yr}^{-1}\) per SPIRE source (Fig. 15). If we were to use colder dust temperatures, the peak SFR would be at about \(200 M_{\odot}\text{yr}^{-1}\) per SPIRE source (Fig. 15). If we were to use warmer dust temperatures, the SFR would increase because the implied redshift would be higher and still compatible with other observations, e.g., the compilation of submillimetre galaxies in Greve et al. 2012, where \(L_{\text{IR}}\) is measured in the range \(3 \times 10^{12}–10^{14}\)\(L_{\odot}\) and \(T_d\) in the range 30–100\(\text{K}\), for redshifts above 2.

We can also estimate the IR luminosities and SFRs of the overdensities, i.e., potential clusters of dusty galaxies at high-z, rather than the single SPIRE sources that we used above. With typically 10 SPIRE sources in the IN region, we sum up the IR luminosities of SPIRE sources within the IN region (under the same assumption of \(T_d = 35\text{K}\)) to obtain a peak IR luminosity...
of $4 \times 10^{13} L_\odot$. This translates to a peak SFR of $7 \times 10^3 M_\odot$ yr$^{-1}$ per structure, as seen in Fig. 15.

Our estimates of $L_{IR}$ are within the range of FIR luminosities expected for massive, vigorously star-forming high-z structures (e.g., Brodwin et al. 2013), which are perhaps protoclusters in their intense star formation phase, and are consistent with the four bound structures found in Clements et al. (2014). These $z \sim 2$ intensively star forming proto-clusters are also expected in some models, e.g., the proto-spheroids of Cai et al. (2013), or the halos harbouring intense star formation discussed in Bethermin et al. (2013).

Figure 14. Infrared luminosities ($L_{IR}$) of the approximately 2200 SPIRE sources in the IN regions, as a function of the fixed dust temperature: 35 K (purple, right histogram), and also shown for illustration 25 K (blue, left histogram). See Sect. 6.3 for details.

6.4. Massive galaxy clusters in formation?

It is of course tempting to postulate that all (or at least a subset) of our sources include massive galaxy clusters in the process of formation. However, demonstrating this conclusively with the present Herschel photometry alone is not possible. We have therefore undertaken a comprehensive multi-wavelength photometric and spectroscopic follow-up campaign to directly constrain the nature of our sources and in particular, to investigate whether they are good candidates for being the progenitors of today’s massive galaxy clusters seen during their most rapid phase of baryon cooling and star formation.

Even without such an explicit analysis of the astrophysical nature of our candidates, we can already state that: (1) our estimated luminosities are consistent with the expected star formation properties of massive galaxy clusters, as obtained from stellar archaeology in galaxies in nearby clusters and out to redshifts $z \sim 1$; and (2) our total number of overdensities are consistent with the expected numbers of massive high-z galaxy clusters, as obtained from models of dark matter halo structure formation.

For point (1), a broad consensus has now been developed whereby most of the stellar mass in massive cluster galaxies was already in place by $z \approx 1$. The most stringent observational constraint is perhaps the tight red sequence of cluster galaxies in colour-magnitude diagrams of massive galaxy clusters in the optical and near-infrared (e.g., Renzini 2006), which suggests that massive cluster galaxies formed most of their stellar populations within a short timescale of $\lesssim 1$ Gyr, i.e., within one cluster dynamical time, with little star formation thereafter. Rest-frame optical studies of distant clusters suggest that the bright end of the red sequence was already in place by $z \approx 1$ (Rudnick et al. 2009), with a likely onset amongst the most massive galaxies by $\approx 2$, or even before (Kodama et al. 2007).

Figure 15. Star formation rate (SFR) for individual SPIRE sources in the overdensity sample (i.e., in the Planck IN region). For $T_d = 35$ K, a dust temperature favoured by the literature, (purple, right histogram) the distribution peaks at 700 $M_\odot$ yr$^{-1}$. We also show for illustration $T_d = 25$ K (blue left histogram peaking at 200 $M_\odot$ yr$^{-1}$). See Sect. 6.3 for details.

The shortness of the star formation period in nearby clusters allows us to derive an order-of-magnitude estimate of the total star formation rates during this period, as implied by the fossil constraints, and the resulting FIR fluxes. To obtain upper limits on the stellar mass formed during this epoch, we use stellar mass estimates obtained for 93 massive X-ray-selected clusters with $M_{500} = (10^{14} - 2 \times 10^{15}) M_\odot$ at $z = 0 - 0.6$ by Lin et al. (2012) based on WISE 3.4 µm photometry. $M_{500}$ is the total mass within the central cluster regions where the mass surface density exceeds the cosmological value by at least a factor of 500. Lin et al. find that in this mass range, stellar mass scales with $M_{500}$ as ($M_* / 10^{12} M_\odot$) = $(1.8 \pm 0.1) (M_{500} / 10^{14} M_\odot)^{0.7 \pm 0.4}$. For clusters with $M_{500} = 1 \times 10^{14}$ $M_\odot$ (or $2 \times 10^{13}$ $M_\odot$, their highest mass), this corresponds to $M_* = 2 \times 10^{12}$ $M_\odot$ (or $1.5 \times 10^{13}$ $M_\odot$). We do not expect that including the intracluster light would increase these estimates by more than a few tens of percent (e.g., Gonzalez et al. 2007), which is a minor part of the uncertainty in our rough order-of-magnitude estimate.

These mass and timescale estimates suggest total star formation rates in the progenitors of massive galaxy clusters at lower redshifts of a few $\times 10^4$ and up to about $2 \times 10^4$ $M_\odot$ yr$^{-1}$. Using the conversion of Kennicutt (1998) between star formation rate and infrared luminosity (Sect. 6.3), this corresponds to $L_{IR} \approx (10^{13} - 10^{14}) L_\odot$. This is well within the range of the global star formation rates and $L_{IR}$ values in our sample of overdensities.

For point (2), the absence of such objects, we use the Tinker et al. (2008) halo model to compute the expected surface density of dark matter halos. We expect between 8500 and $1 \times 10^5$ dark matter halos at $z \gtrsim 2$ having masses $M_{200} > 10^{14} M_\odot$ and $10^{15} M_\odot$, respectively, over 35% of the sky. With the as-
7. Conclusions

Our Planck sample based on a colour selection of cold sources of the CIB is overwhelmingly dominated in number by significant galaxy overdensities peaking at 350 μm, and a minority of rare, bright z > 1.5 strongly gravitationally lensed sources, among which are the brightest ever detected in the submillimetre. This confirms the efficiency of Planck to select extreme and rare submillimetre sources over the whole sky, as well as the need for higher angular resolution imaging using Herschel (and current/planned ground-based submm/mm observatories) to identify and study them.

From the analysis of Herschel observations of the sample of 228 Planck cold sources of the CIB, we draw several conclusions.

- Less than 2% of the fields are Galactic cirrus structures. When a clean and controlled selection is performed on Planck, there is thus no reason to expect a large cirrus contamination when using a conservative Galactic mask.
- With about 93% of the overdensities peaking at 350 μm, and 3.5% peaking at 500 μm, our sample unambiguously selects sky areas with the largest concentrations of red SPIRE galaxies, consisting of highly significant overdensities.
- Some of the overdensities are confirmed high-z structures, e.g., a source at z ≃ 1.7–2.0 (Flores-Cacho et al. 2014, in prep.).
- The significance in density contrast of the overdensities (e.g., half of the fields above 10σ, when selecting red SPIRE sources) is higher than any other sample targeting protoclusters or high-z clusters in the submillimetre, confirming the relevance of the strategy of using Planck data on the cleanest parts of the sky to uncover high-z candidates.
- The SPIRE sources in the overdensity fields have a peak redshift of z = 2 or 1.3, if we fix the dust temperature at T_d = 35 K or 25 K, respectively.
- With the assumption of T_d = 35 K, each SPIRE source has an average IR luminosity of 4 × 10^{12} L_⊙, leading to star formation rates for each source peaking at 700 M_⊙ yr^{-1}. If confirmed, these exceptional structures harbouring vigorous star formation could be proto-clusters in their starburst phase.
- Assuming the SPIRE sources are located in the same large-scale overdensity, we derive a total IR luminosity of 4 × 10^{13} L_⊙, leading to total star formation rates of 7 × 10^3 M_⊙ yr^{-1}, and with around 10 detected sources per structure.
- About 30% of our sample is composed of intensely gravitationally lensed galaxies. This sample is unique, as it targets the brightest observed such sources, typically above 400 mJy at 350 μm and reaching up to the jansky level. They are all spectroscopically confirmed to lie at redshifts z = 2.2–3.6 (Canameras 2015, Nesvadba 2015).
- The novelty and efficiency of our new sample is that it provides about 50 times more fields for a Planck-Herschel co-analysis than in existing Herschel surveys searching for serendipitous Planck sources (e.g., Clements et al. 2014), for only a fraction of the Herschel observing time.
- Our new sample exhibits high density contrasts with a high significance: for the red sources, 30% of our sample (about 70 fields) shows significance levels higher than 4.5σ, and 15% of our sample (34 fields) are higher than 7σ. The presence of the overdensities (and the hypothesis that these could be actual forming, bound structures) is consistent with other findings (Santos et al. 2014, Clements et al. 2014, Noble et al. 2013, Wylezalek et al. 2013b). Our Planck extraction and confirmation with Herschel provides an efficient selection over the whole sky, biased towards star-forming sources, giving a few hundred candidates (Fig. 15). This selection nicely complements the structures found at z ~ 2 already detected by different means, e.g., with the X-ray signature of hot IGM gas, with stellar mass overdensities, Lyα emission, or in association with radio-galaxies (Pentericci et al. 1997, 2000, Brodwin et al. 2005, Miley et al. 2006, Nesvadba et al. 2006, Venemans et al. 2007, Doherty et al. 2010, Popovich et al. 2010, Brodwin et al. 2010, 2011, Hatch et al. 2011, Gobat et al. 2011, Santos et al. 2011, Stanford et al. 2012, Santos et al. 2013, 2014, Brodwin et al. 2013, Galametz et al. 2013, Rigby et al. 2014, Wylezalek et al. 2013a, Chiang et al. 2014, Cooke et al. 2014, Cucciati et al. 2014). However, it is hard to estimate the

![Figure 16](image-url). Total star formation rate (SFR) per Planck IN region, i.e., for the overdensity sample, assuming each overdensity is an actual high-z cluster of dusty galaxies, located at a redshift given by the SPIRE photometric redshift, and using a modified blackbody fit with a fixed dust temperature of T_d = 35 K (purple, right histogram peaking at 7 × 10^3 M_⊙ yr^{-1}), this temperature being favoured by the literature. We also show the total SFR for T_d = 25 K, giving a peak at 2 × 10^3 M_⊙ yr^{-1}. The structures could be intensively star-forming clusters. See Sects. 6.3 and 6.4 for details.
Planck Collaboration: high-z sources discovered by Planck and confirmed by Herschel

A fraction that may be comprised of random alignments of unrelated clumps (e.g., Chiang et al. 2013), since the fluctuation field due to clustering is highly non-Gaussian. Ancillary data (particularly redshifts) are needed to confirm the associations, and an ambitious follow-up programme is underway.

To further characterize the overdensities discovered by Planck and confirmed by Herschel, we also started to stack them in many ancillary data sets. The first data set is the Planck lensing map (Planck Collaboration XVII 2014). The goal is to detect a signature of the presence of large gravitational potentials, as has been demonstrated already by correlating the CIB fluctuations with the lensing map (Planck Collaboration XVIII 2014). The second data set is to use the nine frequency maps and the diffuse tSZ map obtained by MILCA (Huriel et al. 2013). The goal here is to detect a signature of the thermal Sunyaev-Zeldovich (tSZ) effect (Sunyaev & Zeldovich 1969, 1972) and thus the presence of hot gas. These analyses will be published in a subsequent paper.

The Planck data thus provide unique and powerful samples to uncover rare populations, exploitable for extragalactic studies, as was shown with our successful follow-up with Herschel of 228 Planck high-z candidates. There are hundreds more Planck high-z candidates (the full catalogue is being finalized and will be published in Planck Collaboration 2015) to be studied and characterized.

Acknowledgements. The development of Planck has been supported by: ESA; CNES/INSU-CNRS-INP (France); ASI, CNR, and INAF (Italy); NASA and DoE (USA); STFC and UKSA (UK); CSC, MICINN, JA, and RES (Spain); Teles, Aof, and CSC (Finland); DLR and MPG (Germany); CSA (Canada); DTU Space (Denmark); SER/SO (Switzerland); RCN (Norway); SFI (Ireland); FCT/MCTES (Portugal); and FRACE (EU). A description of the Planck Collaboration and a list of its members (including the technical or scientific activities in which they have been involved, can be found at http://www.sciops.esa.int/index.php/project=planck).

The Herschel spacecraft was designed, built, tested, and launched under a contract to ESA by OHB System AG (Germany) and IGN (Spain) and thus the presence of hot gas. These analyses will be published in a subsequent paper.

References


Note: The references are not fully restructured to maintain the original page format of the document.
Appendix A: SPIRE band-merging procedure

Table A.1. Percentages of SPIRE sources matched at 250 and 500 μm from the 350 μm input SPIRE catalogue, and the frequency of matches (i.e., number of sources found per 350 μm source). Here, IN refers to the Planck source region, and OUT refers to the zone outside the Planck 50% contour (see Sect. 2.3). The rows are: no match (top); one match; two matches; and three matches (bottom). More than 60% of the SPIRE 350 μm sources corresponding to the Planck sources (i.e., the IN regions) have counterparts at 250 and 500 μm.

<table>
<thead>
<tr>
<th>250 μm</th>
<th>500 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN</td>
<td>OUT</td>
</tr>
<tr>
<td>No match</td>
<td>. . . . . .</td>
</tr>
<tr>
<td>1 match</td>
<td>. . . . . .</td>
</tr>
<tr>
<td>2 matches</td>
<td>. . . . . .</td>
</tr>
<tr>
<td>3 matches</td>
<td>. . . . . .</td>
</tr>
</tbody>
</table>

We describe here the details of the band-merging procedure, highlighted in Sect. 3.3

First step: positional optimization of blind catalogues using shorter wavelength data.

- Apply a 4σ cut to the 350 μm blind catalogue obtained with StarFinder (Sect. 2.3). This cut is imposed to obtain a high purity of detections.
- Match by position the 350 μm catalogue with the 250 μm catalogue, within a radius of one 250 μm FWHM.

The following depends on whether there are 0, 1, 2, or more matches:

- if zero sources are found at 250 μm, this is a non-detection at 250 μm:
Table A.2. After the SPIRE band-merging process, the percentage of SPIRE sources that do not have any flux density measurement (i.e., are blended or not detected or have multiple matches in Table A.1). More than about 90% of the Planck IN sources have counterparts at all three SPIRE wavelengths.

<table>
<thead>
<tr>
<th></th>
<th>250 µm</th>
<th>350 µm</th>
<th>500 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IN</td>
<td>OUT</td>
<td>IN</td>
</tr>
<tr>
<td>No detections . . . .</td>
<td>0.2%</td>
<td>0.6%</td>
<td>0.2%</td>
</tr>
<tr>
<td>S/N &lt; 3 . . . .</td>
<td>3.2%</td>
<td>7.6%</td>
<td>0.9%</td>
</tr>
</tbody>
</table>

Appendix B: SPIRE number counts tables

The measured number counts shown in Fig. 5 are provided in tables B.1, B.2, and B.3. We note that those counts are not corrected for incompleteness or for flux boosting, since here we are interested only in the relative distribution of the samples (and the quantification of the excess of one sample to another).

Appendix C: Number counts by type: overdensity or lensed sources

As discussed in Sect. 4.2, Fig. C.1 represents the counts for overdensity fields (left) and lensed fields (right). This shows that the bright part of the number counts is dominated by single bright objects, i.e., the lensed sources. However, these lensed counts cannot be used for statistical studies of the lensed sources because we have only used the surface area of the Planck IN region.

Appendix D: Overdensities using AKDE

We can also use another estimator for the density contrast $\delta_{350}$ by taking the measured source density from AKDE. If we compute the density minus the median density divided by the median density, we obtain the distribution shown in Fig. D.1.

Appendix E: Gallery of selected sources

We provide 3-colour images for a few sources drawn from the 228 of our sample. Each plot shows:

- a 3-colour image of the SPIRE data, with 250 µm in blue, 350 µm in green, and 500 µm in red (using the python APLpy module: show_rgb);
- the Planck contour (IN region, i.e., 50% of the peak) as a bold white line;
- the significance of the SPIRE overdensity contrast (starting at 2 $\sigma$ and then incrementing by 1 $\sigma$) as yellow solid lines.

Figure E summarizes the 228 SPIRE sample.

---

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Table B.1. Differential Euclidean-normalized number counts $S^{2.5} dN/dS$ at 250 $\mu$m, not corrected for incompleteness or flux boosting. They are given here only for relative distributions.

<table>
<thead>
<tr>
<th>$\langle S_{250} \rangle$</th>
<th>$S_{250}$ range</th>
<th>IN Planck [mJy]</th>
<th>OUT Planck [Jy$^{1.5}$ sr$^{-1}$]</th>
<th>Total Planck [Jy$^{1.5}$ sr$^{-1}$]</th>
<th>Lockman [Jy$^{1.5}$ sr$^{-1}$]</th>
<th>HLS [Jy$^{1.5}$ sr$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.</td>
<td>11.- 12.</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>12.</td>
<td>12.- 13.</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>13.</td>
<td>13.- 14.</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>16.</td>
<td>16.- 17.</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>25.</td>
<td>25.- 29.</td>
<td>9276. ± 343.</td>
<td>6075. ± 108.</td>
<td>6493. ± 104.</td>
<td>4828. ± 122.</td>
<td>750. ± 38.</td>
</tr>
<tr>
<td>34.</td>
<td>34.- 40.</td>
<td>40868. ± 838.</td>
<td>21384. ± 238.</td>
<td>24227. ± 351.</td>
<td>29237. ± 351.</td>
<td>3299. ± 94.</td>
</tr>
<tr>
<td>75.</td>
<td>75.- 90.</td>
<td>19583. ± 944.</td>
<td>10611. ± 269.</td>
<td>11781. ± 264.</td>
<td>13593. ± 388.</td>
<td>11697. ± 288.</td>
</tr>
<tr>
<td>116.</td>
<td>116.- 141.</td>
<td>7545. ± 791.</td>
<td>4960. ± 248.</td>
<td>5297. ± 239.</td>
<td>6494. ± 362.</td>
<td>6011. ± 278.</td>
</tr>
<tr>
<td>467.</td>
<td>467.- 576.</td>
<td>626. ± 626.</td>
<td>1785. ± 409.</td>
<td>1634. ± 365.</td>
<td>1524. ± 482.</td>
<td>975. ± 308.</td>
</tr>
<tr>
<td>753.</td>
<td>753.- 931.</td>
<td>5100. ± 2550.</td>
<td>573. ± 331.</td>
<td>1164. ± 440.</td>
<td>310. ± 310.</td>
<td>1190. ± 486.</td>
</tr>
</tbody>
</table>

Table B.2. Differential Euclidean-normalized number counts $S^{2.5} dN/dS$ at 350 $\mu$m, not corrected for incompleteness or flux boosting. They are given here only for relative distributions.

<table>
<thead>
<tr>
<th>$\langle S_{350} \rangle$</th>
<th>$S_{350}$ range</th>
<th>IN Planck [mJy]</th>
<th>OUT Planck [Jy$^{1.5}$ sr$^{-1}$]</th>
<th>Total Planck [Jy$^{1.5}$ sr$^{-1}$]</th>
<th>Lockman [Jy$^{1.5}$ sr$^{-1}$]</th>
<th>HLS [Jy$^{1.5}$ sr$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.</td>
<td>11.- 12.</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>12.</td>
<td>12.- 13.</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>13.</td>
<td>13.- 14.</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>16.</td>
<td>16.- 17.</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>19.</td>
<td>19.- 21.</td>
<td>107. ± 34.</td>
<td>162. ± 16.</td>
<td>155. ± 15.</td>
<td>–</td>
<td>148. ± 16.</td>
</tr>
<tr>
<td>25.</td>
<td>25.- 29.</td>
<td>7931. ± 317.</td>
<td>4114. ± 88.</td>
<td>4611. ± 87.</td>
<td>648. ± 45.</td>
<td>415. ± 29.</td>
</tr>
<tr>
<td>50.</td>
<td>50.- 59.</td>
<td>31093. ± 913.</td>
<td>10831. ± 209.</td>
<td>13473. ± 217.</td>
<td>16222. ± 325.</td>
<td>8986. ± 194.</td>
</tr>
<tr>
<td>75.</td>
<td>75.- 90.</td>
<td>16805. ± 875.</td>
<td>4650. ± 178.</td>
<td>6235. ± 192.</td>
<td>6880. ± 276.</td>
<td>4938. ± 187.</td>
</tr>
<tr>
<td>467.</td>
<td>467.- 576.</td>
<td>1879. ± 1085.</td>
<td>94. ± 94.</td>
<td>327. ± 163.</td>
<td>305. ± 216.</td>
<td>195. ± 138.</td>
</tr>
<tr>
<td>753.</td>
<td>753.- 931.</td>
<td>6374. ± 2851.</td>
<td>382. ± 270.</td>
<td>1164. ± 440.</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Figure C.1. Differential Euclidean-normalized number counts, $S^{2.5} dN/dS$, for various data sets at 350 $\mu$m, to illustrate the difference between the overdensity fields (left) and the lensed fields (right). This is the same as Fig. 6 except that we have split the fields into only overdensity fields and only lensed fields. Lensed sources thus dominate the statistics at large flux densities, while overdensities dominate at smaller flux densities. See Sect. 4.4 for details.
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**Table B.3.** Differential Euclidean-normalized number counts $S_{500}^2 \frac{dN}{dS}$ at 500 $\mu$m, not corrected for incompleteness or flux boosting. They are given here only for relative distributions.

<table>
<thead>
<tr>
<th>($S_{500}$) $S_{500}$ range [mJy]</th>
<th>IN Planck [Jy$^{1.5}$ sr$^{-1}$]</th>
<th>OUT Planck [Jy$^{1.5}$ sr$^{-1}$]</th>
<th>Total Planck [Jy$^{1.5}$ sr$^{-1}$]</th>
<th>Lockman HLS [Jy$^{1.5}$ sr$^{-1}$]</th>
<th>HLS</th>
</tr>
</thead>
<tbody>
<tr>
<td>11. 11.- 12. –</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>12. 12.- 13. –</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>13. 13.- 14. –</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>16. 14.- 17. –</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>3. ± 2.</td>
</tr>
<tr>
<td>19. 17.- 21. –</td>
<td>5. ± 3.</td>
<td>4. ± 2.</td>
<td>–</td>
<td>42. ± 8.</td>
<td></td>
</tr>
<tr>
<td>25. 21.- 29. 685. ± 93. 346. ± 26. 390. ± 25. –</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>138. ± 17.</td>
</tr>
<tr>
<td>34. 29.- 40. 13397. ± 482. 3474. ± 95. 4768. ± 104. 4614. ± 140. 437. ± 34.</td>
<td>–</td>
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<td>–</td>
<td>–</td>
</tr>
<tr>
<td>50. 40.- 59. 15600. ± 647. 2890. ± 108. 4547. ± 126. 5692. ± 193. 1964. ± 90.</td>
<td>–</td>
<td>–</td>
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<td>–</td>
</tr>
<tr>
<td>75. 59.- 90. 5875. ± 517. 751. ± 72. 1419. ± 92. 1473. ± 128. 935. ± 81.</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>116. 90.- 141. 1078. ± 299. 199. ± 50. 314. ± 58. 484. ± 99. 232. ± 55.</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>182. 141.- 223. 791. ± 354. 142. ± 58. 227. ± 68. 77. ± 54. 172. ± 65.</td>
<td>–</td>
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<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>290. 223.- 357. 1559. ± 697. 140. ± 81. 325. ± 115. 76. ± 76. 97. ± 69.</td>
<td>–</td>
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<td>–</td>
<td>–</td>
</tr>
<tr>
<td>467. 357.- 576. 2506. ± 1253. 94. ± 94. 408. ± 183. –</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>753. 576.- 931. 3825. ± 2208. –</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

**Figure E.1.** Representative Planck targets, showing 3-colour SPIRE images: blue, 250 $\mu$m; green, 350 $\mu$m; and red, 500 $\mu$m. The white contours show the Planck IN region, while the yellow contours are the significance of the overdensity of 350 $\mu$m sources, plotted 2 $\sigma$, 3 $\sigma$, 4 $\sigma$, etc.
Planck Collaboration: high-$z$ sources discovered by *Planck* and confirmed by *Herschel*

**Figure E.2.** Representative *Planck* targets. Same as Fig. E.1.

**Figure E.3.** Representative *Planck* targets. Same as Fig. E.1.
Planck Collaboration: high-$z$ sources discovered by Planck and confirmed by Herschel

**Figure E.4.** Representative Planck targets. Same caption as Fig. E.1.

**Figure E.5.** Representative Planck targets. Same caption as Fig. E.1.

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27 Dipartimento di Fisica e Astronomia G. Galilei, Università degli Studi di Padova, via Marzolo 8, 35131 Padova, Italy
28 Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Via Saragat 1, 44122 Ferrara, Italy
29 Dipartimento di Fisica, Università La Sapienza, P.le A. Moro 2, Roma, Italy
30 Dipartimento di Fisica, Università degli Studi di Milano, Via Celoria, 16, Milano, Italy
31 Dipartimento di Fisica, Università degli Studi di Trieste, via A. Valerio 2, Trieste, Italy
32 Dipartimento di Fisica, Università di Roma Tor Vergata, Via della Ricerca Scientifica, 1, Roma, Italy
33 Discovery Center, Niels Bohr Institute, Blegdamsvej 17, Copenhagen, Denmark
34 European Southern Observatory, ESO Vitacura, Alonso de Cordova 3107, Vitacura, Casilla 19001, Santiago, Chile
Planck Collaboration: high-z sources discovered by \textit{Planck} and confirmed by \textit{Herschel}

\textbf{Figure E.6.} Representative \textit{Planck} targets. Same caption as Fig. 1E.1

\textbf{Figure E.7.} Representative \textit{Planck} targets. Same caption as Fig. 1E.1

35 European Space Agency, ESAC, Camino bajo del Castillo, s/n, Urbanización Villafranca del Castillo, Villanueva de la Cañada, Madrid, Spain
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40 HGSFP and University of Heidelberg, Theoretical Physics Department, Philosophenweg 16, 69120, Heidelberg, Germany
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Planck Collaboration: high-\(z\) sources discovered by Planck and confirmed by Herschel

**Figure E.8.** Mosaic showing the 228 SPIRE fields.
Planck Collaboration: high-z sources discovered by Planck and confirmed by Herschel