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Planck 2013 results. XXXII. The updated *Planck* catalogue of Sunyaev-Zeldovich sources★

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ABSTRACT

We update the all-sky *Planck* catalogue of 1227 clusters and cluster candidates (PSZ1) published in March 2013, derived from detections of the Sunyaev–Zeldovich (SZ) effect using the first 15.5 months of *Planck* satellite observations. As an addendum, we deliver an updated version of the PSZ1 catalogue, reporting the further confirmation of 86 *Planck*-discovered clusters. In total, the PSZ1 now contains 947 confirmed clusters, of which 214 were confirmed as newly discovered clusters through follow-up observations undertaken by the Planck Collaboration. The updated PSZ1 contains redshifts for 913 systems, of which 736 (∼80.6%) are spectroscopic, and associated mass estimates derived from the Y_z mass proxy. We also provide a new SZ quality flag for the remaining 280 candidates. This flag was derived from a novel artificial neural-network classification of the SZ signal. Based on this assessment, the purity of the updated PSZ1 catalogue is estimated to be 94%. In this release, we provide the full updated catalogue and an additional readme file with further information on the *Planck* SZ detections.

Key words. errata, addenda – large-scale structure of Universe – galaxies: clusters: general – catalogs

1. Introduction

Cluster samples selected by their Sunyaev–Zeldovich (SZ) signal have only recently reached significant sizes, for instance, the

★ The catalogue is 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/581/A14

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Early SZ (ESZ) catalogue from the *Planck* Satellite[1] (Planck Collaboration VIII 2011; Planck Collaboration XXIX 2014), and catalogues from the South Pole Telescope (SPT; Reichardt et al. 2013; Bleem et al. 2015) and the Atacama Cosmology Telescope (ACT; Marriage et al. 2011; Hasselfield et al. 2013). These are now considered as new reference samples for cluster studies and associated cosmological analyses.

The present note describes updates to the construction and properties of the *Planck* catalogue of SZ sources PSZ1 (hereafter PXXIX2013, Planck Collaboration XXIX 2014), released in March 2013 as part of the first *Planck* data delivery. The PSZ1 catalogue contains 1227 entries, including 683 so-called previously known clusters. This category corresponds to the association of *Planck* SZ source detections with known clusters from the literature. The association is set to the first identifier as defined in the hierarchy adopted by PXXIX2013, namely: (i) identification with MCXC clusters (Piffaretti et al. 2011); (ii) identification with Abell and Zwicky objects; (iii) identification with clusters derived from SDSS-based catalogues (primarily from Wen et al. 2012); (iv) identification with clusters from SZ catalogues (Hasselfield et al. 2013; Reichardt et al. 2013); (v) searches in the NED and SIMBAD databases. Considerable added value, including consolidated redshift values, has been obtained by compiling ancillary information. These redshifts include spectroscopic, photometric, and estimated values. Spectroscopic redshifts were preferentially reported, even when they were obtained from the measurement of a single galaxy. Photometric and estimated redshifts refer to values obtained from photo-z codes or red sequence estimates, respectively. Masses were computed for all clusters with redshift values.

Since its delivery in March 2013, we have continued to update the PSZ1 catalogue by focusing on the confirmation of newly discovered clusters in PSZ1. This process has first involved updating the redshifts of some previously known clusters (Sect. 2). We also made use of recent results from dedicated follow-up observations conducted by the Planck Collaboration with the RTT150 (Planck Collaboration Int. XXVI 2015) and ENO telescopes (Planck Collaboration, in prep.), which together allowed us to observe and measure estimated, photometric, and spectroscopic redshifts for ~150 PSZ1 sources (Sect. 3.1). In addition, we used published results from PanSTARRS (Liu et al. 2015) and from the latest SPT catalogue (Bleem et al. 2015), as described in Sects. 3.3 and 3.4. For all clusters with redshifts, we computed the estimated masses using the Y_z mass proxy (Arnaud et al., in prep. and PXXIX2013; Sect. 4). Finally, we revisited the cluster-candidate classification scheme, which in PXXIX2013 was organised into three classes (*class*-1, 2, 3) in order of decreasing reliability. As described in Sect. 5, we now used the SZ spectral energy distribution (SED) to refine the quality assessment of the cluster candidates by adopting a new quality flag derived from the artificial neural-network analysis developed by Aghanim et al. (2015). In Appendix A, we describe the updated PSZ1 catalogue including the new fields, specifying the redshift type and associated reference.

2. Redshift updates for previously known clusters

In the external validation process performed in PXXIX2013, a total of 683 PSZ1 sources were associated with clusters published in X-ray, optical, or SZ catalogues or with clusters found in the NED or SIMBAD databases. We refer to these as previously known clusters. Their redshifts, when available, were compiled from the literature and a consolidated value, preferencially spectroscopic, was provided with the PSZ1 catalogue. In the present update, we first re-examine the previously known clusters of the PSZ1 catalogue.

The dedicated follow-up of *Planck* PSZ1 clusters with RTT150 described in Planck Collaboration Int. XXVI (2015) provided updates to the redshifts of 19 previously known clusters. The follow-up of *Planck* PSZ1 clusters with ENO telescopes additionally updated the redshifts of five previously known clusters.

We updated the redshifts of ten PSZ1 sources associated with SPT clusters provided in Bleem et al. (2015). Finally, we queried the NED and SIMBAD databases and searched in the cluster catalogues constructed from the SDSS data (Wen et al. 2012 and Rozo et al. 2014) for additional spectroscopic redshifts. When these were available, we report them in the updated version of the PSZ1 catalogue. The full process led us to change the redshifts of 34 previously known PSZ1 clusters. We also changed the published photometric redshift of one ACT cluster (ACT-CL J0559-5249) to a spectroscopic redshift value.

In summary, 69 sources from the PSZ1 catalogue associated with previously known clusters now have updated redshifts. Most of these consist of updates from photometric to spectroscopic values; however, eight redshifts were measured for the first time for previously known clusters.

3. *Planck*-discovered clusters

The PSZ1 catalogue contained 366 cluster candidates, classified as *class*-1 to 3 in order of decreasing reliability, and 178 *Planck*-discovered clusters confirmed mostly with dedicated follow-up programmes undertaken by the Planck Collaboration. Since the delivery of the PSZ1 catalogue in March 2013, a number of additional confirmations, including results from the community, were performed and redshifts were updated from photometric to spectroscopic values.

Combining the results from follow-up with the RTT150 (Planck Collaboration Int. XXVI 2015), ENO telescopes (Planck Collaboration, in prep.), Liu et al. (2015), Rozo et al. (2014), and Bleem et al. (2015), a total of 86 PSZ1 sources have been newly confirmed as *Planck*-discovered clusters with measured photometric or spectroscopic redshifts.

3.1. From RTT150 results

As part of the Planck Collaboration optical follow-up programme, candidates were observed with the Russian Turkish Telescope (RTT150[2], Planck Collaboration Int. XXVI 2015) within the Russian quota of observational time, provided by the Kazan Federal University and Space Research Institute (IKI, Moscow). Direct images and spectroscopic redshift measurements were obtained using the TÜBİTAK Faint Object Spectrograph and Camera (TFOSC[3]). For the clusters with

[1] *Planck* (http://www.esa.int/Planck) is a project of the European Space Agency (ESA) with instruments provided by two scientific consortia funded by ESA member states (in particular the lead countries France and Italy), with contributions from NASA (USA) and telescope reflectors provided by a collaboration between ESA and a scientific consortium led and funded by Denmark.

[2] http://hea.iki.rssi.ru/rtt150/en/index.php

[3] http://hea.iki.rssi.ru/rtt150/en/index.php?page=tfosc

the highest redshift, complementary spectroscopic observations were performed with the BTA 6 m telescope of the SAO RAS using the SCORPIO focal reducer and spectrometer (Afanasiev & Moiseev 2005).

These observations have confirmed and provided redshifts for a total of 24 new candidates. Eleven of these have spectroscopic redshifts. We have updated the PSZ1 catalogue by including these newly obtained redshifts.

3.2. From ENO telescopes

As part of the Planck Collaboration optical follow-up programme, candidates were also observed at European Northern Observatory (ENO[4]) telescopes, both in imaging (at IAC80, INT, and WHT) and spectroscopy (at NOT, GTC, INT, and TNG). The observations were obtained as part of proposals for the Spanish CAT time and of an International Time Programme (ITP), accepted by the International Scientific Committee of the Roque de los Muchachos and Teide observatories. We summarise here the main results of these observing programmes. More details will be presented in a companion article (Planck Collaboration, in prep.).

These observations have confirmed and provided new redshifts for a total of 26 candidates, which are reported in the updated PSZ1 catalogue. These include the confirmation of 12 SZ sources as newly discovered clusters: two *class* 1 high-reliability candidates, five *class* 2, and five *class* 3 candidates.

3.3. From PanSTARRS

Based on data from the Panoramic Survey Telescope and Rapid Response System (PanSTARRS, Kaiser et al. 2002), Liu et al. (2015) have searched for optical confirmation of the 237 *Planck* SZ detections that overlap the PanSTARRS footprint.

We only report here the photometric redshifts for unambiguously confirmed clusters. Of these, 15 objects were included in the RTT150 follow-up, for which the redshifts are published in Planck Collaboration Int. XXVI (2015), and three objects were included in the ESO follow-up described above. In these cases, we report the Planck Collaboration follow-up redshift values in the updated PSZ1 catalogue. An additional two *Planck* clusters confirmed by PanSTARRS have a counterpart in the Rozo et al. (2014) catalogue, with spectroscopic redshifts that we update in the PSZ1 catalogue.

A total of 40 Planck-discovered clusters are confirmed, for the first time, by Liu et al. (2015) in the PanSTARRS survey. All of these have photometric redshifts that we have reported in the updated PSZ1 catalogue.

3.4. From SPT

A new catalogue of SZ clusters detected with the South Pole Telescope (SPT) cluster catalogue was published in Bleem et al. (2015). It provides an ensemble of spectroscopic and photometric redshifts. Four candidate *class* 1 and 2 clusters from the PSZ1 catalogue were confirmed and have photometric redshifts in Bleem et al. (2015). These are included in the updated PSZ1 catalogue.

[4] ENO: `http://www.iac.es/eno.php?lang=en`

3.5. From SDSS-RedMapper catalogue

Comparison with the SDSS-based catalogue from Rozo et al. (2014) provided confirmation and new redshift values for five Planck-discovered clusters. This includes confirmation of two *Planck* cluster-candidates (one *class* 2 and one *class* 3 candidate). We use the spectroscopic redshift values available in the Rozo et al. (2014) in the updated PSZ1 catalogue.

4. Mass estimate

The size-flux degeneracy discussed for example in Planck Collaboration VIII (2011) and PXXIX2013 can be broken when z is known, using the M_{500}–$D_A^2 Y_{500}$ relation between θ_{500} and Y_{500} see (Arnaud et al., in prep.). The Y_{500} parameter, denoted Y_z, is derived from the intersection of the M_{500}–$D_A^2 Y_{500}$ relation and the size-flux degeneracy curve. The SZ mass proxy Y_z is equivalent to the X-ray mass proxy Y_X.

For all the *Planck* clusters with redshifts, Y_z was computed assuming a flat universe with $h = 0.7$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$, allowing us to derive an homogeneously defined SZ mass proxy, denoted $M_{500}^{Y_z}$, based on X-ray calibration of the scaling relations (see discussion in PXXIX2013)[5]. We show in Fig. 2 the distribution of masses obtained from the SZ-based mass proxy for all clusters with redshifts. Note that since we used an X-ray calibration of the scaling relations, these masses are uncorrected for any bias due to the assumption of hydrostatic equilibrium in the X-ray mass analysis. The shaded black area shows the distribution of masses for clusters with redshifts higher than 0.5. They represent a total of 78 clusters.

5. Cluster candidates

Since the delivery of the *Planck* catalogue and with the confirmation in this addendum of 86 candidates as new clusters, the updated PSZ1 catalogue now contains 280 cluster candidates. In the original PSZ1, these latter were classified as *class* 1 to 3 in order of decreasing reliability; the reliability being defined empirically from the combination of internal *Planck* quality assessment and ancillary information (e.g., searches in RASS, WISE, SDSS data). The updated PSZ1 catalogue contains 24 high-quality (*class* 1) SZ detections, whereas lower reliability *class* 2 and 3 candidates represent 130 and 126 SZ sources, respectively.

With the updated PSZ1 catalogue, we now provide a new objective quality assessment of the SZ sources derived from an artificial neural-network analysis. The construction, training, and validation of the network is based on the analysis of the SED of the SZ signal in the *Planck* channels. The implementation is discussed in detail by Aghanim et al. (2015). The neural network was trained with an ensemble of three samples: the confirmed clusters in the PSZ1 calatogue with a good or high-quality SZ signal; the *Planck* Catalogue of Compact Sources catalogue, which represents detections in the IR and those induced by radio source; and random positions on the sky as examples of noise-induced, very low-reliability detections.

In practice, we provide for each SZ source of the updated PSZ1 catalogue a neural-network quality flag, Q_N, defined as in Aghanim et al. (2015). This flag separates the high-quality SZ detections from the low-quality sources such that $Q_N < 0.4$

[5] For a few clusters with redshifts that show pathological 2D posteriors, it was not possible to estimate realistic masses.

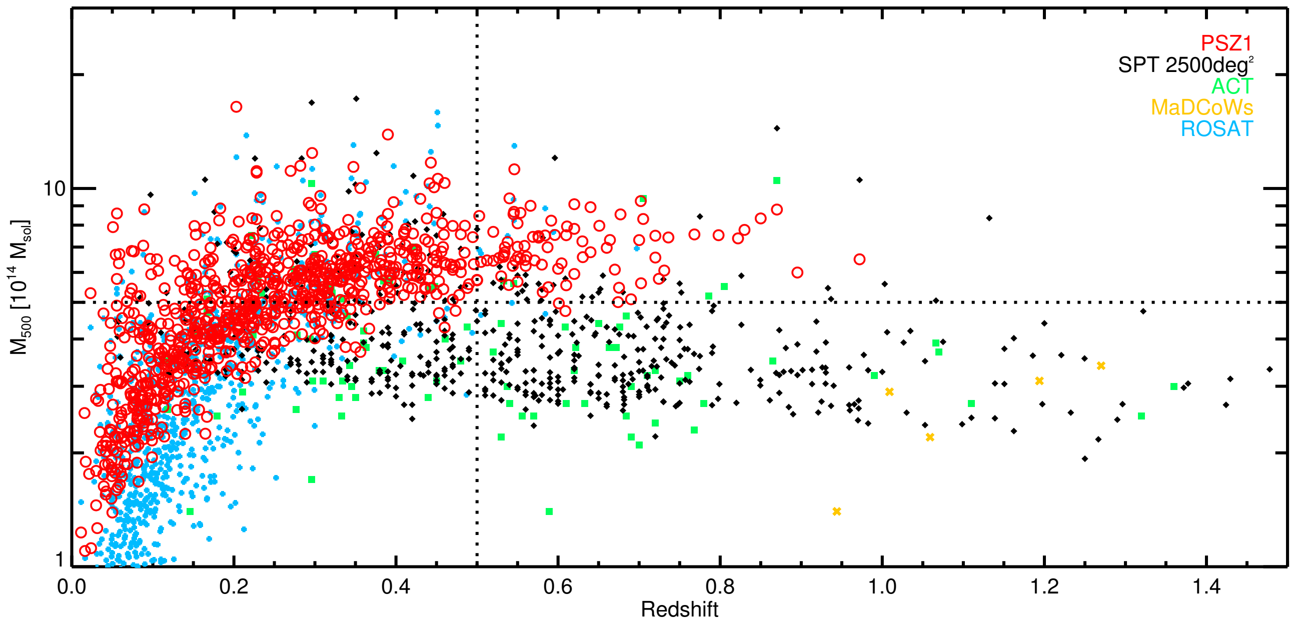

Fig. 1. Distribution in the M–z plane of the *Planck* SZ cluster catalogue (open red circles; Planck Collaboration XXIX 2014) compared with those from SPT (black; Reichardt et al. 2013; Bleem et al. 2015) and ACT (green; Marriage et al. 2011; Hasselfield et al. 2013), MaDCoWS (yellow; Brodwin et al. 2015), and NORAS and REFLEX from the MCXC meta-catalogue (blue; Piffaretti et al. 2011 and references therein). Some clusters may appear several times as distinct points as a result of differences in the mass estimate between surveys. The black dotted lines show the *Planck* mass limit for the medium-deep survey zone at 20% completeness (as defined in Planck Collaboration XXIX 2014) for a redshift limit of $z = 0.5$.

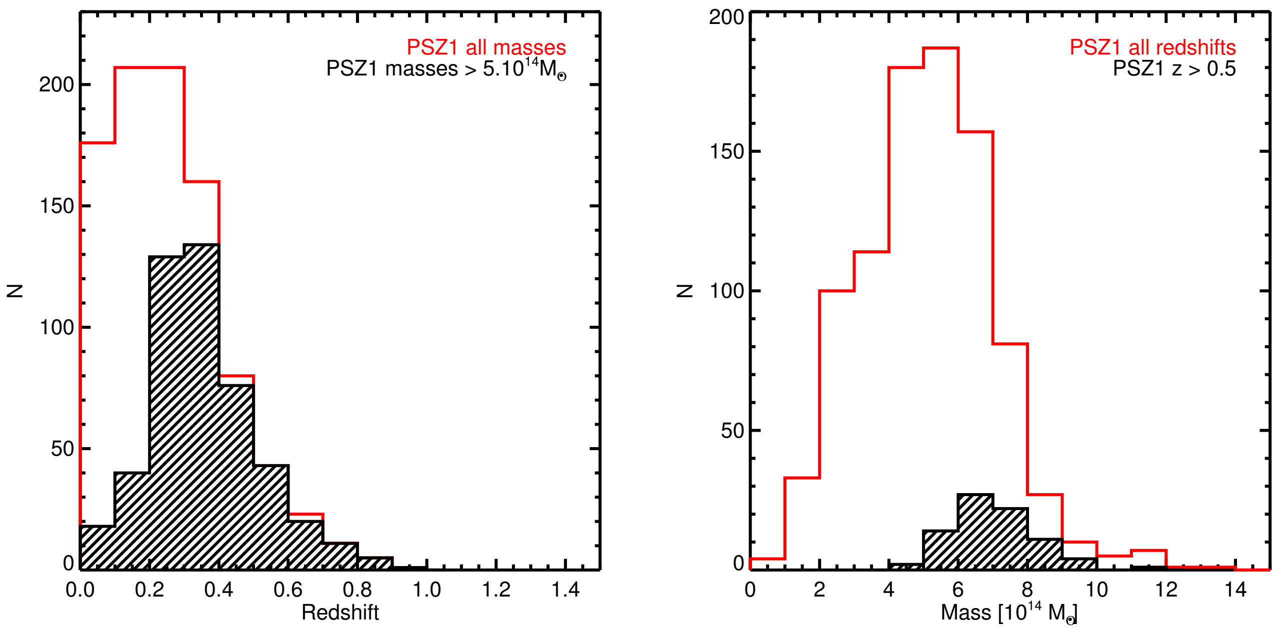

Fig. 2. Distribution of redshifts (*left panel*) and masses (*right panel*) for the *Planck* SZ clusters. The black shaded area represents the population of clusters with redshift higher than 0.5 (*right panel*) and mass higher than 5×10^{14} $M_{\odot}$ (*left panel*).

identifies low-reliability SZ sources with a high degree of success. Figure 4 summarises the number of sources for each class of *Planck* cluster-candidates that are below and above the threshold value of $Q_{\rm N} = 0.4$. The *class* 1 cluster-candidates all have $Q_{\rm N} > 0.4$, except for one source, for which $Q_{\rm N} = 0.39$. The fraction of good $Q_{\rm N} > 0.4$ SZ detections in the *class* 2 category is about 80%, while the fraction of $Q_{\rm N} > 0.4$ candidates drops to about 30% for the *class* 3 cluster-candidates.

6. Summary

We have updated the *Planck* catalogue of SZ-selected sources detected in the first 15.5 months of observations. The catalogue contains 1227 detections and was validated using external X-ray and optical/NIR data, alongside a multi-frequency follow-up programme for confirmation.

The updated PSZ1 catalogue now contains 947 confirmed clusters, including 264 brand-new clusters, of which 214 have

Table 1. Summary of the updates of PSZ1v2 for each cluster or candidate type.

	PSZ1 (2013)				PSZ1v2 (2015)		
	Number	Redshift		Updates	Number	Redshift	
		Type	Number			Type	Number
"Previously known"	**683**			**0**	**683**		
		undef	29	−8		undef	21
		estim	5	−4		estim	1
		phot	97	−43		phot	54
		spec	552	+55		spec	607
"Planck – discovered"	**178**			**+86**	**264**		
		undef	19	−6		undef	13
		phot	72	+50		phot	122
		spec	87	+42		spec	129
Class1	**54**			**−30**	**24**		
		undef	54	−30		undef	24
		phot	–	*+22*		phot	–
		spec	–	*+8*		spec	–
Class2	**170**			**−40**	**130**		
		undef	170	−40		undef	130
		phot	–	*+26*		phot	–
		spec	–	*+14*		spec	–
Class3	**142**			**−16**	**126**		
		undef	142	−16		undef	126
		phot	–	*+10*		phot	–
		spec	–	*+6*		spec	–

been confirmed by the Planck Collaboration follow-up programme. The remaining 280 cluster candidates have been divided into three classes according to their reliability, that is, according to the quality of evidence that they are probably bona fide clusters. To date, high-quality SZ detections in PSZ1 represent 24 sources, all of which are classified as high-quality clusters by our neural-network quality-assessment procedure. Lower reliability *class* 2 and 3 candidates represent 130 and 126 SZ sources, respectively (Table 1). We find that ~80% of the *class* 2 candidates are classified as high-quality clusters by our neural-network quality-assessment procedure, whereas only 35% of the *class* 3 sources are considered high-quality SZ detections. Based on this assessment, the purity of the updated PSZ1 catalogue is ~94%.

A total of 913 *Planck* clusters (i.e., 74.2% of all SZ detections) now have redshifts, of which 736 are spectroscopic values (i.e., 80.6% of all redshifts). The left-hand panel of Fig. 2 shows the redshift distribution of all clusters (red) and the distribution for the clusters with masses higher than $5 \times 10^{14} M_{\odot}$ (shaded black). The median redshift of the PSZ1 catalogue is about 0.23, and about 35% of the *Planck* clusters lie at redshifts higher than $z = 0.3$.

The origins and types of redshifts are shown in Fig. 3 (this information is available in the updated catalogue). Association with MCXC clusters (Piffaretti et al. 2011) provides about 49.8% of the redshifts, all of which are spectroscopic. Follow-up observations undertaken by the Planck Collaboration provide 24.6% of the redshifts, about two thirds of which are spectroscopic. SDSS-based catalogues yield 11.7% of the redshifts, more than half of which are spectroscopic. NED and SIMBAD database searches yield 5.9% of the redshifts, the vast majority of which are spectroscopic. PanSTARRS data provide 4.4% of the redshifts, all of which are photometric. Finally, association with the SPT and ACT SZ catalogues represents ~3.5% of all redshifts, most of which are spectroscopic.

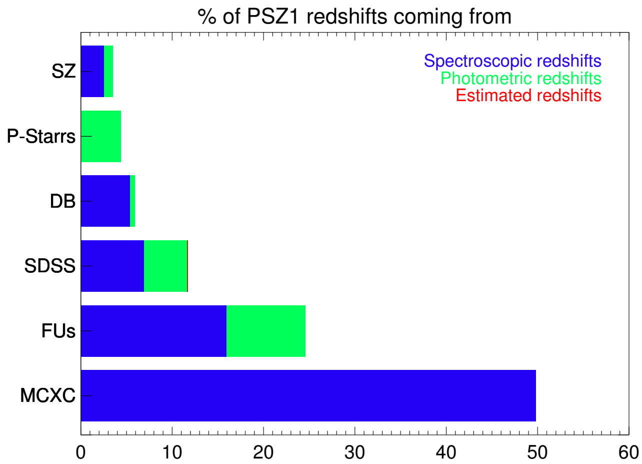

Fig. 3. Percentage of origin and type (photometric, spectroscopic) of the redshifts reported in PSZ1. To date, associations with MCXC clusters provide 49.8% of the redshifts, all spectroscopic. Follow-up observations by the Planck collaboration (FUs) provide 24.6% of the redshifts, of which 64.73% are spectroscopic. Associations with clusters from SDSS-based catalogues result in 11.7% of all redshifts, of which 58.9% are spectroscopic. Redshifts from the NED and SIMBAD databases represent 5.9% of all redshifts, 90.7% of which are spectroscopic. PanSTARRS data confirm 4.4% of the total redshift number, all of them photometric. Finally, the association with SZ catalogues (SPT and ACT) represents 3.5% of all redshifts, of which 71.9% are spectroscopic.

For the *Planck* clusters with redshifts, we have provided a homogeneously defined mass estimated from the Compton Y-parameter. The M–z distribution of the *Planck* clusters is

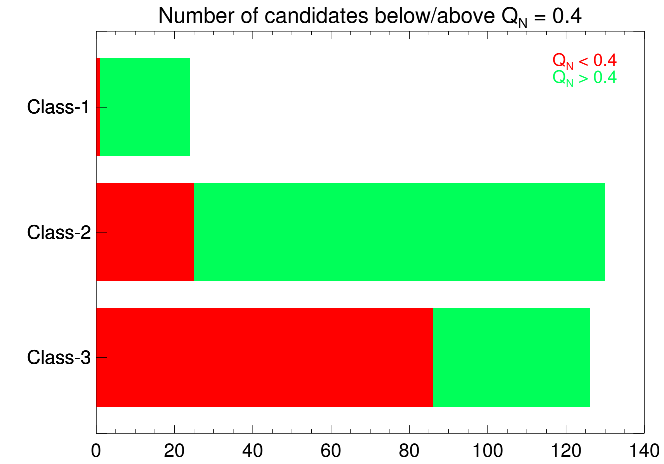

Fig. 4. Number of *Planck* cluster-candidates below and above the neural-network quality-flag threshold $Q_{\rm N} = 0.4$, denoting a high-quality SZ detection, for each reliability class.

shown by open red circles in Fig. 1, where it is compared with other large cluster surveys. Note that the masses are not homogenised and some clusters may appear several times as a result of differences in the mass estimation methods between surveys. The *Planck* cluster distribution probes a unique region in the M–z space occupied by massive, $M \geq 5 \times 10^{14}\,M_\odot$, high-redshift ($z \geq 0.5$) clusters. The *Planck* detections almost double the number of massive clusters with redshift higher than 0.5 with respect to other surveys.

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Appendix A: Description of the updated PSZ1 catalogue

The updated *Planck* catalogue of SZ sources is available at PLA[6] and the SZ cluster database[7].

The updated PSZ1 gathers in a single table all the entries of the delivered catalogue mainly based on the *Planck* data and the entries of the external validation information based on ancillary data (Appendices B and C of Planck Collaboration XXIX 2014, respectively). It also contains additional entries. It is provided in a fits format, together with a readme file.

The updated catalogue contains, when available, cluster external identifications[8] and consolidated redshifts. We added two new entries: the redshift type and the bibliographic reference. The three entries associated with the consolidated redshift reported in the catalogue are thus:

- Type of redshift: a string providing the different cases.
  `undef`: undefined
  `estim`: estimated from red sequence
  `phot`: photometric redshift
  `spec`: spectroscopic redshifts
- Source of redshift: an integer value representing the origin of the redshifts.
  –1: No redshift available
  1: MCXC updated compilation
  2: Databases NED and SIMBAD-CDS
  3: SDSS cluster catalogue from Wen et al. (2012)
  4: SDSS cluster catalogue from Szabo et al. (2011)
  5: SPT
  6: ACT
  7: Search in SDSS galaxy catalogue from Planck Collab., from Fromenteau 2010 and Fromenteau et al. (priv. comm.)
  8: SDSS catalogue from Rozo et al. (2014)
  10: Pan-STARRS1 Survey confirmation
  20: *XMM-Newton* confirmation from Planck Collab.
  50: ENO confirmation from Planck Collab.
  60: WFI-imaging confirmation from Planck Collab.
  65: NTT-spectroscopic confirmation from Planck Collab.
  500: RTT confirmation from Planck Collab.
  600: NOT confirmation from Planck Collab.
  650: GEMINI-spectroscopic confirmation from Planck Collab.
- Bibliographical references for the redshift.

We also added a new entry describing the quality of the SZ detection in more detail. This is the flag $Q_{\rm N}$ derived from the artificial neural-network SED-based quality assesssment described in Aghanim et al. (2015).

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[6] `http://www.sciops.esa.int/index.php?page=Planck_Legacy_Archive&project=planck`
[7] `http://szcluster-db.ias.u-psud.fr`
[8] The external identification corresponds to the first identifier as defined in the external validation hierarchy adopted in Planck Collaboration XXIX (2014).

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