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New extragalactic research paths opened by *Planck*

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The *Planck* mission has clearly demonstrated that, although not specifically designed for the observation of extragalactic sources, the space-borne experiments aimed at investigating the Cosmic Microwave Background (CMB) have the potential to bring breakthrough science also in this field. One example is the detection of high-z galaxies with extreme gravitational amplifications. The combination of flux boosting and of stretching of the images has allowed the investigation of the structure of galaxies at $z \simeq 3$ with the astounding spatial resolution of $\simeq 60\,$pc. Another example is the detection of proto-clusters of dusty galaxies at high z, when they may not yet possess the hot intergalactic medium allowing their detection in X-rays or via the Sunyaev-Zeldovich effect.

Keywords: Galaxies: high-redshift – galaxies: evolution – submillimetre: galaxies – galaxies: clusters: general.

1. Introduction

Extragalactic sources are one of the foregrounds that contaminate the maps produced by experiments aimed at mapping the Cosmic Microwave Background (CMB). On the other hand, space borne CMB experiments, like *Planck*, have properties that allow them to produce unique surveys of extragalactic sources:

- they cover a broad spectral range hardly, if at all, accessible from the ground and only lightly covered by other space missions;

- they offer an all-sky coverage, ideal to look for rare phenomena;
- they have a poor angular resolution that is, in general, a strong limitation for extragalactic surveys but, as we will see, becomes a resource to detect high-z proto-clusters of dusty galaxies.

Two main populations of extragalactic sources show up in *Planck*'s frequency range, extending from 30 to 857 GHz: blazars, that dominate up to about 150–200 GHz, and active star-forming galaxies dominating at higher frequencies (Fig. 1).

Planck has provided unique information on these source populations. In this paper we will confine ourselves to only two examples: strongly gravitationally lensed high-z galaxies (Sect. 2) and proto-clusters of dusty galaxies (Sect. 3). In Sect. 4 we summarize our main conclusions.

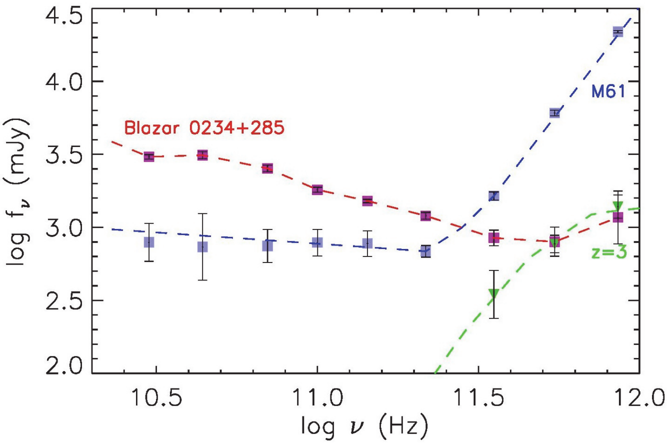

Fig. 1. Examples of spectral energy distributions (SEDs) of the extragalactic sources detected by *Planck*: a blazar, a nearby star-forming galaxy (M61) and a strongly lensed galaxy at $z \simeq 3$. Data points are *Planck* measurements.

2. Strongly lensed galaxies

Herschel surveys have demonstrated that bright sub-mm galaxies, such as those detected by *Planck*, have a strikingly bimodal redshift distribution (Fig. 2). Unlensed galaxies are local (only a few are at $z \geq 0.06$), while the gravitationally lensed ones are at $z > 1$. This implies that the two sub-populations can be easily distinguished[2,3].

Another nice property of sub-mm selected strongly lensed galaxies is that they show up in a waveband different from that of the foreground lens: the former are bright at far-IR/sub-mm wavelengths but very faint in the optical because of dust obscuration; on the contrary, the latter are mostly passively evolving early-type galaxies, essentially invisible at far-IR/sub-mm wavelengths, but bright in the

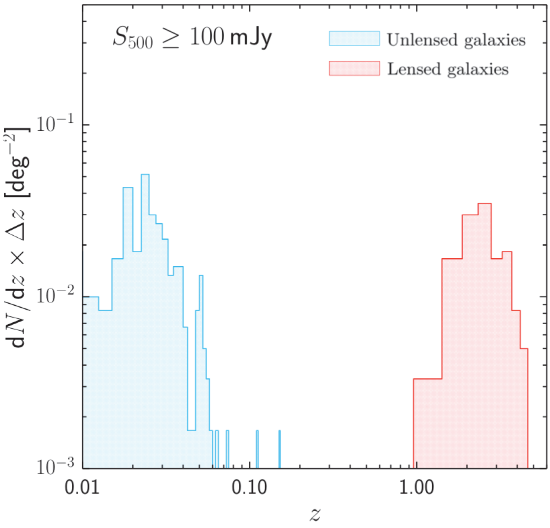

Fig. 2. Redshift distribution of dusty galaxies detected by the *Herschel*–ATLAS survey with $S_{500\mu\mathrm{m}} > 100$ mJy (Ref. 1).

optical and in the near-IR. Hence there is no mutual contamination of the two images.

The 11 strongly lensed galaxies discovered on *Planck* maps[4] have redshifts in the range 2.2–3.6. For comparison, those discovered by optical searches have mostly $z < 1$ (cf. Fig. 7 of Ref. 5). Thus optical/near-IR and (sub-)mm surveys are nicely complementary: the former see evolved galaxies while the latter catch them in the most active star-formation phase.

This brings us to the main reason why the (sub-)mm selection of strongly lensed galaxies is important: high spatial and spectral resolution follow-up of these objects will have a crucial role in providing answers to major, still open issues on galaxy formation and evolution: which are the main physical mechanisms shaping the galaxy properties: in situ processes? interactions? mergers? cold flows from the intergalactic medium? How do feedback processes work? To settle these issues we need direct information on the structure and the dynamics of high-z galaxies. But these are compact, with typical sizes of 1–2 kpc (e.g., Ref. 6), corresponding to angular sizes of 0.1–0.2 arcsec at $z \simeq 2$–3. Thus they are hardly resolved even by ALMA and by the HST. If they are resolved, high enough S/N ratios per resolution element are achieved only for the brightest galaxies, probably not representative of the general population.

Strong gravitational lensing provides a solution to these problems. The *Planck* dusty GEMS (Gravitationally Enhanced subMillimetre Sources)[4] have estimated magnifications, μ, in the range 10–50, making them the brightest sub-mm sources in the sky. The gravitational stretching of the images has allowed ALMA observations of one of them, PLCK_G244.8+54.9 at $z \simeq 3.0$ with $\mu \simeq 30$, to reach the astounding spatial resolution of $\simeq 60\,\mathrm{pc}$, substantially smaller than the size of Galactic giant molecular clouds[7].

Cañameras et al.[7] have also obtained CO spectroscopy, measuring the kinematics of the molecular gas with an uncertainty of 40–50 km/s. This spectral resolution makes possible a direct investigation of massive outflows driven by AGN feedback at high z. In this way Spilker et al.[8] were able to detect a fast (800 km/s) molecular outflow due to feedback in a strongly lensed galaxy at $z = 5.3$. The outflow carries mass at a rate close to the SFR and can thus remove a large fraction of the gas available for star-formation.

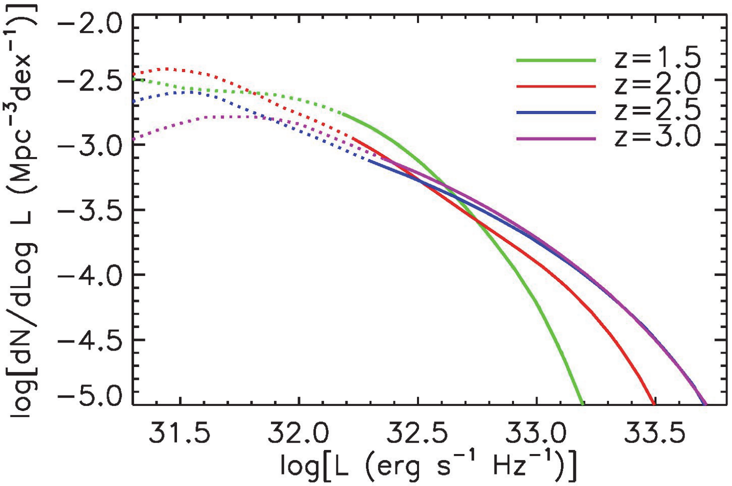

Fig. 3. Portions of the 500 μm galaxy luminosity function at various z covered by *Herschel* surveys to a flux limit of 50ṁJy. The corresponding fraction of resolved luminosity density ranges from 29% to 66%.

3. Protoclusters

Classical techniques for detecting galaxy clusters (optical/near-IR “red sequence”, X-ray emission, Sunyaev-Zeldovich (SZ) effect) preferentially or exclusively select evolved objects, with mature galaxy populations and a hot intra-cluster medium. As a result, most known clusters are at $z < 1.5$, i.e. below the peak of global star-formation activity.

This reflects the anti-correlation between density and specific star-formation rate (sSFR), well established in the low-z universe. However the sSFR in clusters increases with increasing redshift faster than in the field matching field values at $z \gtrsim 1.2$[11]. Correspondingly the “red sequence” disappears and the hot intergalactic gas, making clusters visible in X-rays or via the SZ effect, is no longer necessarily in place.

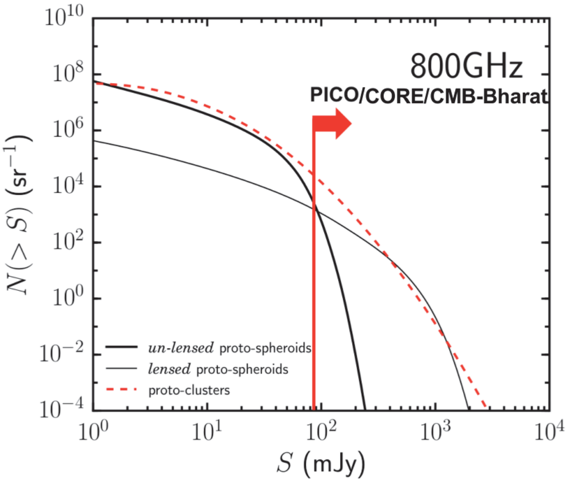

Fig. 4. Integral number ounts at 800 GHz of lensed and unlensed dusty galaxies predicted by the model by Ref. 9 and of proto-clusters[10]. The vertical red line shows the estimated detection limit of planned next generation CMB experiments.

On the other hand, member galaxies become increasingly bright at far-IR/sub-mm wavelengths. As mentioned above, individual high-z galaxies are not detectable by space-borne CMB experiments unless their flux densities are boosted by gravitational lensing. However, the summed emission of galaxies within a strong overdensity (proto-cluster) shows up as an intensity peak in the maps.

As illustrated by Fig. 3, proto-clusters stand out more clearly in low-resolution sub-mm maps, such as those that have been provided by *Planck* or will hopefully be provided by planned next-generation experiments like PICO, CORE and CMB Bharat, than in much higher resolution point source surveys at the same wavelengths because the available point source surveys miss a substantial fraction of the cluster. This is in keeping with the findings[12,13] that the sub-mm flux densities of proto-cluster candidates measured by *Planck* are about 2 to 3 times larger than the summed luminosities of member galaxies detected with *Herschel* within the *Planck* beam, although part of the difference is to be attributed to the ‘flux boosting’ affecting the low signal-to-noise *Planck* measurements.

Although *Planck* has demonstrated the power of low-resolution surveys for the study of large-scale structure, its resolution was too poor to detect individual proto-clusters[10]. Studies of the high-z 2-point correlation function and *Herschel* images of the few sub-mm bright protoclusters detected so far, at z of up to 4, indicate sizes of $\simeq 1'$ for the cluster cores, nicely matching the FWHM of the highest frequency channels of planned next generation experiments.

As illustrated by Fig. 4, such experiments will detect many tens of thousands of these objects as peaks in sub-mm maps, in addition to the evolved ones, detected by the SZ effect. This will constitute a real breakthrough in the observational validation of the formation history of the most massive dark matter halos, traced by clusters, a crucial test of models for structure formation. Follow-up observations will characterize the properties of member galaxies, probing the galaxy evolution in dense environments and shedding light on the complex physical processes driving it.

4. Conclusions

Planck has demonstrated the unique capability of all-sky CMB experiments to explore astrophysical phenomena otherwise unaccessible to the present day instrumentation.

Those presented are only examples. Other examples are blazar astrophysics and high frequency polarization of extragalactic sources, including dusty galaxies.

Proposed next generation CMB experiments, like PICO, CORE and CMB Bharat, have the capability to make a giant leap forward in these fields by detecting several thousands high-z strongly lensed galaxies at least up to $z \simeq 5$ and proto-clusters at least up to $z \simeq 4$.

Acknowledgments

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References

1. M. Negrello, S. Amber, A. Amvrosiadis, et al., *MNRAS* **465**, 3558 (2017).
2. M. Negrello, F. Perrotta, J. González-Nuevo, et al., *MNRAS* **377**, 1557 (2007).
3. M. Negrello, R. Hopwood, G. De Zotti, et al., *Science* **330**, 800 (2010).
4. R. Cañameras, N. P. H. Nesvadba, D. Guery, et al., *A&A* **581**, A105 (2015).
5. T. Treu, *Ann. Rev. Astr. Ap.* **48**, 87 (2010).
6. S. Fujimoto, M. Ouchi, K. Kohno, et al., *ApJ* **861**, 7 (2018).
7. R. Cañameras, N. Nesvadba, R. Kneissl, et al., *A&A* **604**, A117 (2017).
8. J. S. Spilker, M. Aravena, M. Béthermin, et al., *Science* **361**, 1016 (2018).
9. Z.-Y. Cai, A. Lapi, J.-Q. Xia, et al., *ApJ* **768**, 21 (2013).
10. M. Negrello, J. Gonzalez-Nuevo, G. De Zotti, et al., *MNRAS* **470**, 2253 (2017).
11. C. R. Wagner, S. Courteau, M. Brodwin, et al., *ApJ* **834**, 53 (2017).
12. D. L. Clements, F. G. Braglia, A. K. Hyde, et al., *MNRAS* **439**, 1193 (2014).
13. Planck Collaboration Int. XXXIX, *A&A* **596**, A100 (2016).