Searching for protoclusters in the far-infrared with Herschel/SPIRE

E. E. Rigby[1], H. Röttgering[1], N. Hatch[2], B. Sibthorpe[3], Y. K. Chiang[4], R. Overzier[4,5], R. Herbonnet[1], S. Borgani[6], D. L. Clements[7], H. Dannerbauer[8], C. De Breuck[9], G. De Lucia[6], J. Kurk[10], F. Maschietto[1], G. Miley[1], A. Saro[11], N. Seymour[12], B. Venemans[13]

[1]Leiden University, [2]Nottingham University, [3]SRON Netherlands Institute for Space Research,[4]University of Texas, [5]Observatório Nacional, Brazil, [6]INAF, [7]Imperial College London, [8]Universität Wien, [9]ESO, [10]Max-Planck-Institut für Extraterrestrische Physik, [11]Ludwig-Maximilians-Universität, [12]CSIRO, [13]Max-Planck Institute for Astronomy

Universiteit Leiden

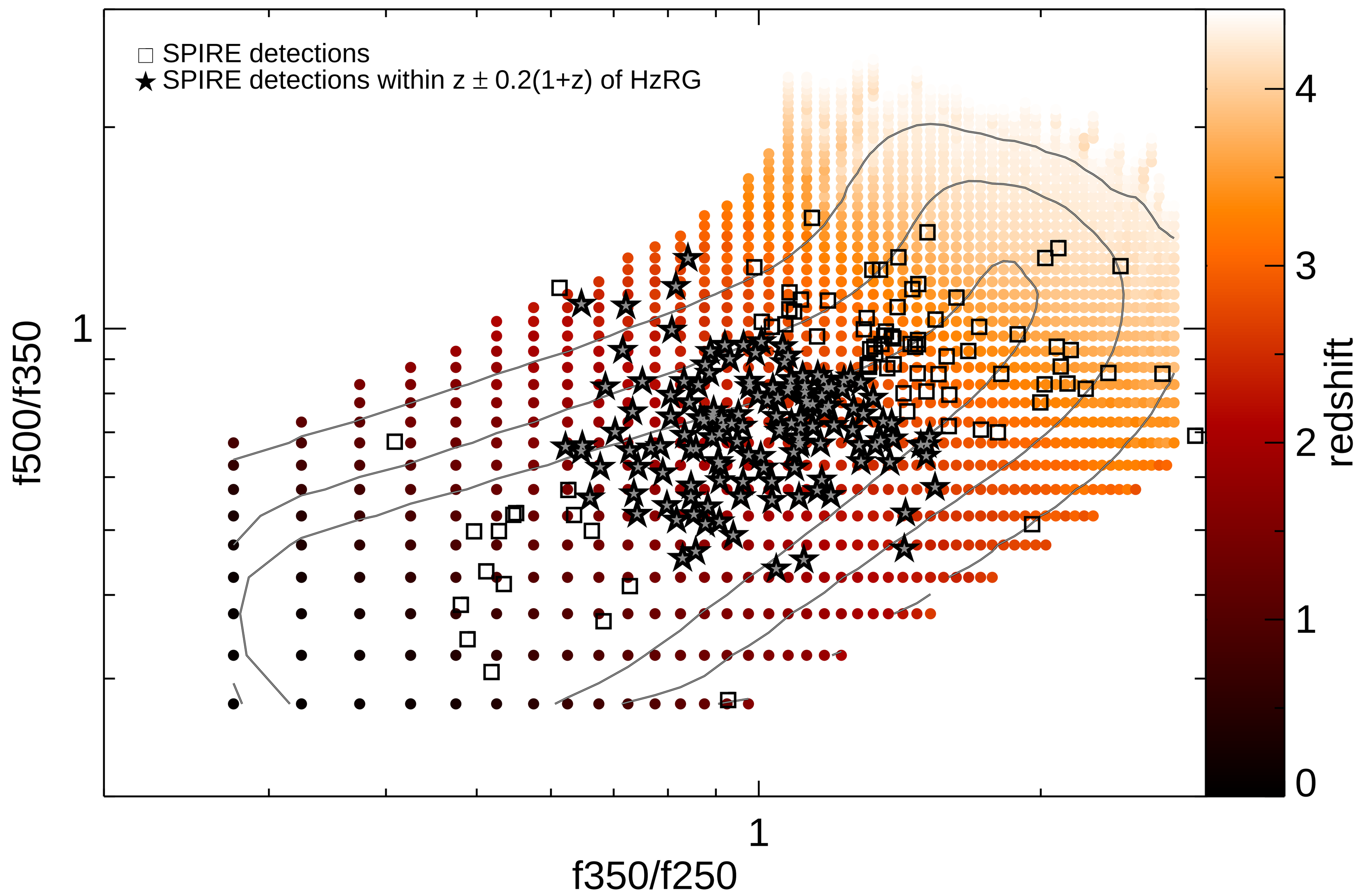
Why study protoclusters?

- Protoclusters are the high–redshift seeds of local rich clusters. Studying them is an important tool for understanding galaxy and cluster formation during a crucial epoch of their evolution. Historically these overdense structures have been located by targeting luminous high–redshift radio galaxies (HzRGs) as these massive objects are the likely progenitors of Brightest Cluster Galaxies; see Miley & De Breuck (2008) for a review.
- Far–infrared observations are a key tool in finding and characterising star–forming protocluster members. They allow the amount of dust–obscured star formation at $2 < z < 4$, when these galaxies build up most of their stellar mass, to be measured by breaking the degeneracy between age and dust content in spectral energy distribution modelling.
- The normal field of view of most infra–red or optical instruments is comparable, or even smaller than the angular size of protoclusters (~10′), which severely hampers their study. The *Herschel* Space Observatory, with its combination of sensitivity and fast mapping speed, has improved this situation and far–infrared protocluster candidates are beginning to be discovered within the surveys carried out with *Herschel* (e.g. Clements et al. in prep, Ivison et al. 2013, Valtchanov et al. 2013).
- We have carried out the first targeted survey of HzRG fields using the SPIRE instrument. We map an area sufficient to encompass the full extent of a protocluster, together with its surrounding environment.

The *Herschel* protocluster survey

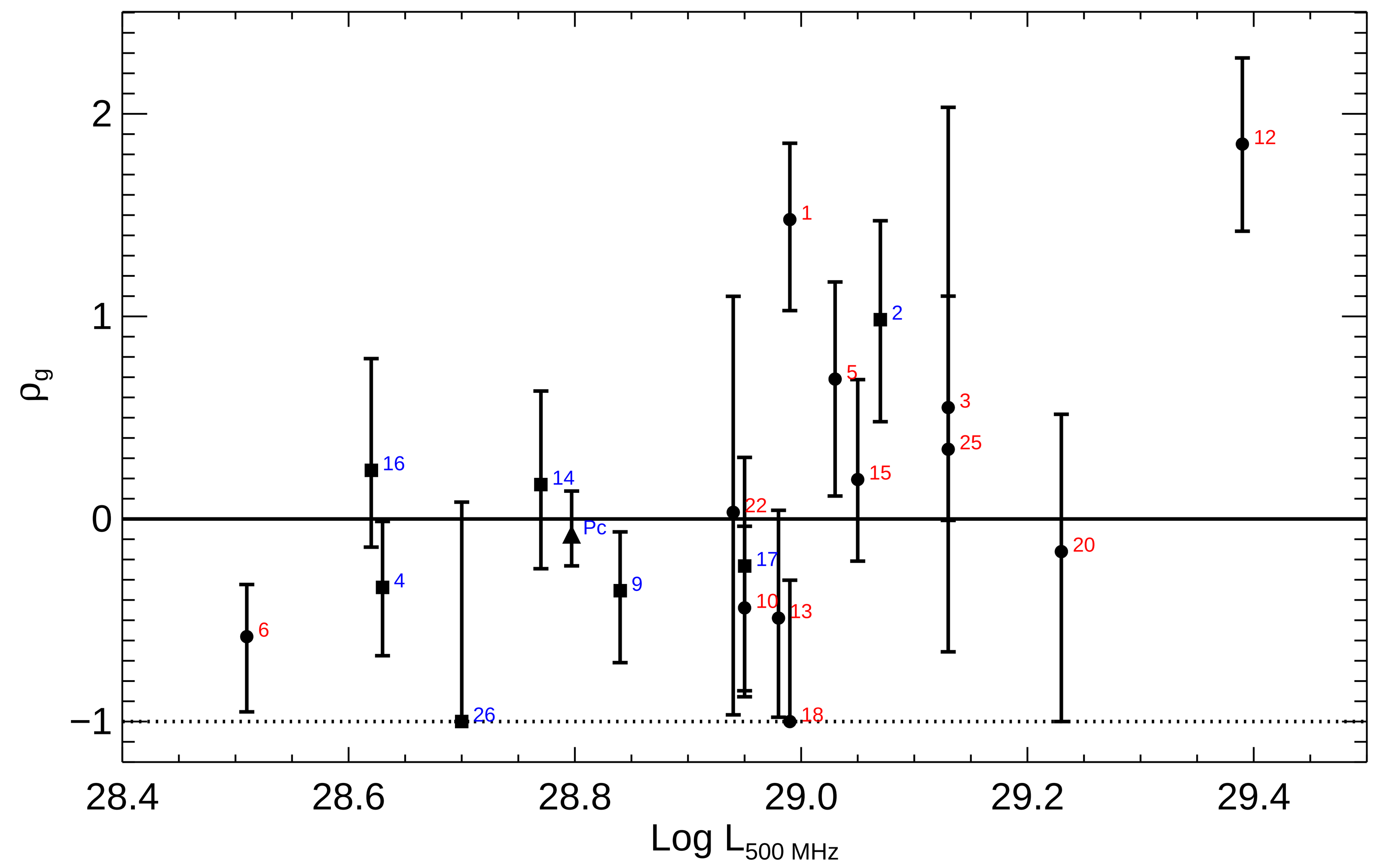
- The 26 HzRGs we target have $L_{500\mathrm{MHz}} > 10^{28.5}$ W Hz^{-1} and are evenly spread across $2 < z < 4$. Eight are known protoclusters, identified via previous Lyα or Hα observations. They were observed at 250, 350 and 500 μm with SPIRE; the resulting maps cover ~500 arcmin^2.
- The SPIRE data were reduced using the standard *Herschel* pipeline and individual catalogues for each of the 3 bands were created using the STARFINDER algorithm (Diolaiti et al. 2000). These were then combined, using the 500 μm catalogue as a prior, to create a matched catalogue for each field. Of the 26 original fields, 7 were excluded from the subsequent analysis as they were contaminated by galactic cirrus.

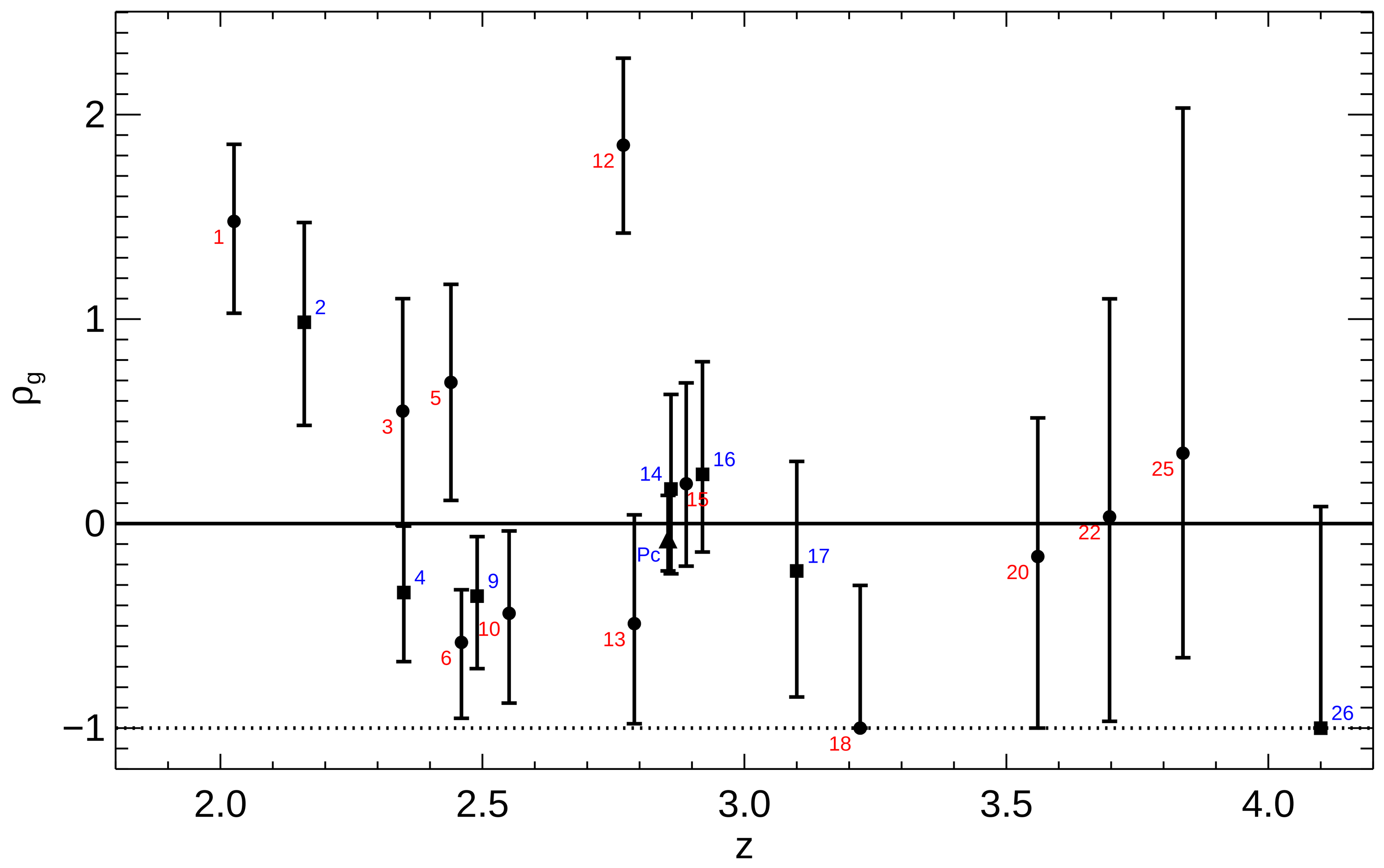
Custom redshift selection



- We restrict our protocluster search to sources which lie within $\pm 0.2(1+z)$ of the redshift of the HzRG in each field. We do this by comparing their SPIRE colours with those of an artificially redshifted galaxy template (constructed following Roseboom et al. 2012), as illustrated here for one of our fields at $z = 2.2$. Stars and squares indicate sources selected and rejected as potential protocluster members respectively; solid points show the colour track of the template galaxy, broadened by a Gaussian uncertainty of 10%, as it evolves in redshift. Lines show the 1, 2 and 3σ contours in the template distribution.

Surface density analysis

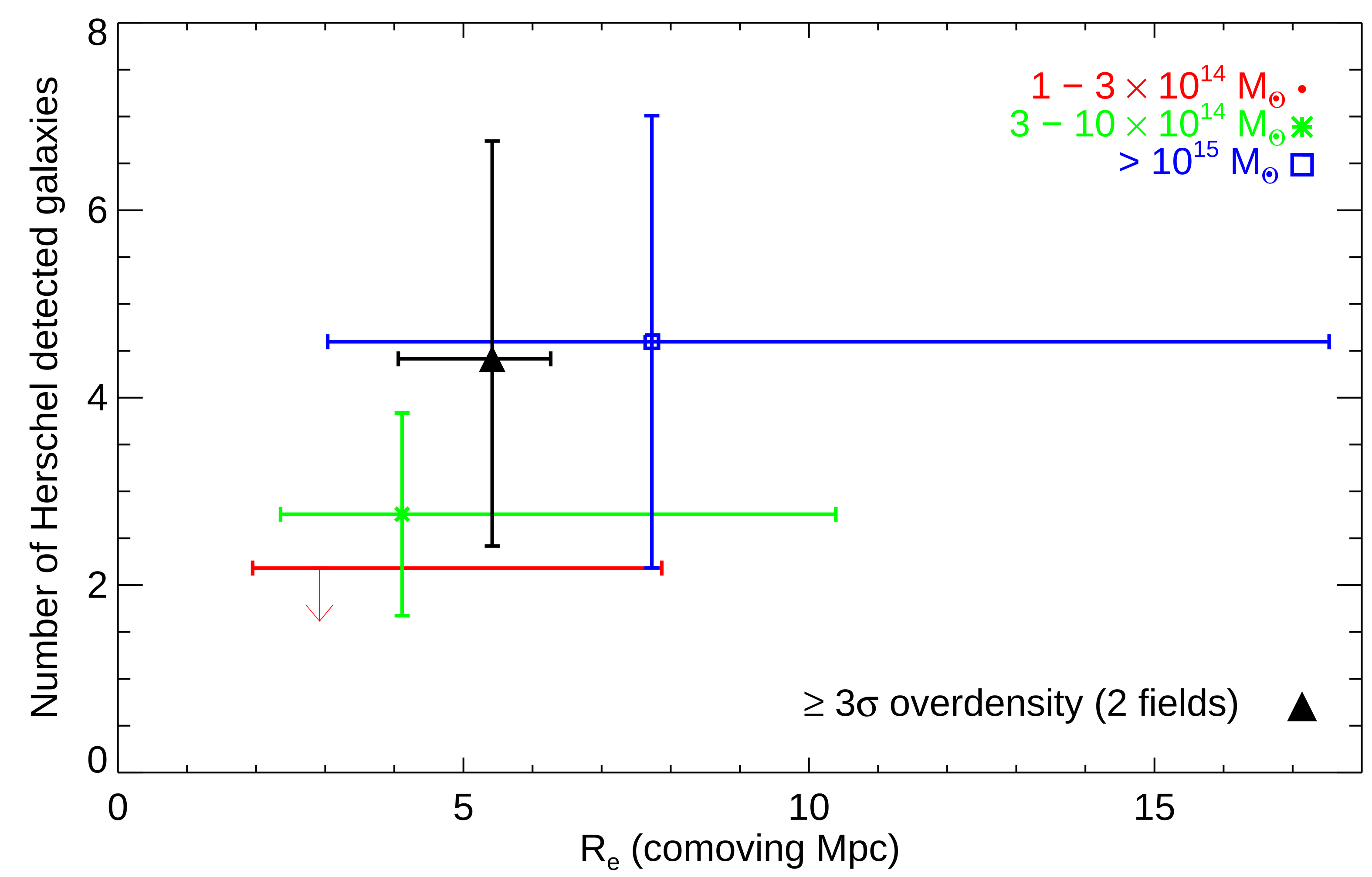




- **Top:** The surface density of galaxies, ρ_g, in each field as a function of radio power of the central HzRG (defined as $\rho_g = (\rho_{\mathrm{obs}} - \rho_{\mathrm{bkg}})/\rho_{\mathrm{bkg}}$ where ρ_{obs} and ρ_{bkg} are the observed surface density around the HzRG and mean background surface density respectively). **Bottom:** As Top but plotted as a function of redshift of the central HzRG. In both cases galaxies are colour–selected from the matched catalogue and counted within a radius of 6 comoving Mpc and $\pm 0.2(1+z)$ of the position and redshift of the HzRG. Numbers correspond to the field labels. Blue colours and square symbols highlight the 7 known protoclusters, and the average overdensity of these fields is labelled 'Pc'. A value of $\rho_g = -1$ (indicated by the horizontal dotted line) corresponds to a field containing no galaxies which satisfied the position and redshift criteria.
- Of the 19 low–cirrus fields considered, 2 are $> 3\sigma$ overdense and both are not previously known protoclusters (only 1 of the known protoclusters shows signs of an overdensity, but only at the 2σ level). Larger overdensities tend to lie at $L_{500\mathrm{MHz}} \gtrsim 10^{29}$ and $z < 3$, but there are no definite trends with either parameter. However, this apparent preference for brighter HzRGs is consistent with previous work (Galametz et al. 2012 & references therein).
- The 2 fields with the strongest overdensities are detected at the 3.9 and 4.3σ level respectively. The probability of finding $2 \geq 3\sigma$ overdensities such as these by chance, given that 19 fields were observed is 5×10^{-4}. These results, therefore, are inconsistent with being due to random background fluctuations.

Are the overdensities consistent with protoclusters?

- A simple characterisation of the galaxy overdensities seen here can be found by comparing them to protocluster predictions from cosmological simulations. Chiang et al. (in prep) follow the evolution with redshift of ~ 3000 clusters in the Millennium Simulation (Springel et al. 2005, Guo et al. 2011), and can therefore match the properties of a local massive cluster to the high–redshift protocluster it grew from. This is compared to the *Herschel* results by applying a redshift–dependent cut in star–formation rate ($SFR \geq c10^{0.2z}$ M$_\odot$/yr), assuming that the detected galaxies mirror the highest rank of SFR in the simulated galaxy population at a given redshift. The normalisation constant, c, is adjusted such that the mean surface density of simulated sources matches that observed in the reference field.



- The above Figure shows the number of galaxies contained within simulated protoclusters as a function of their radial extent, for 3 different bins in descendent (i.e. $z = 0$) mass (coloured points). The black triangle shows the average size and number of galaxies of the $\geq 3\sigma$ overdensities in the *Herschel* sample. The uncertainties on the simulated points represent the spread in the simulated distribution; the uncertainties on the real data point come from the spread in the radial extent calculation.
- The position of the average $\geq 3\sigma$ galaxy overdensities seen in the *Herschel* data implies an enclosed mass for these structures of $> 10^{14}$ M$_\odot$, which is consistent with that determined previously for HzRG–selected protoclusters (e.g. Venemans et al. 2007, Hatch et al. 2011). However, it should be noted that the large redshift range searched means that contamination of the overdensity from foreground and background galaxies is likely. Firm confirmation of the galaxy excesses seen here can only be done by reducing the redshift uncertainty.

Summary & Conclusions

- Investigating the far–infrared environments surrounding 19 HzRGs has revealed significant galaxy overdensities in 2 fields. These are unlikely to be due to random background fluctuations and are consistent with simulated protoclusters of mass $> 10^{14}$ M$_\odot$.
- The surface density of these fields at these wavelengths is generally low, which must in part be due to the large SPIRE beam making overdensities hard to identify here. Overall these results demonstrate that *Herschel* has the potential to identify protocluster candidates, but that this is a less successful technique here than at other wavelengths. It is likely that SPIRE is probing different structures than those identified using classical narrow–band or mid–infrared imaging. Future work will combine these SPIRE data with radio imaging to improve the selection of protocluster member galaxies, and understand the different far–infrared populations.

References

•Diolaiti et al. 2000, Proc. SPIE, 4007, 879 •Galametz et al. 2012, ApJ, 749, 169 •Guo et al. 2011, MNRAS, 413, 101 •Hatch et al. 2011, MNRAS, 410, 1537 •Ivison et al. 2013, arXiv:1302.4436 •Miley & De Breuck 2008, A&A Rev., 15, 67 •Roseboom et al. 2012, 419, 2758 •Springel et al. 2005, Nature, 435, 629 •Valtchanov et al. 2013, arXiv:1309.4223 •Venemans et al. 2007, A&A, 461, 823

emmaerigby@gmail.com

Rigby et al., 2013, MNRAS in press