

# Herschel-ATLAS: SDSS cross-correlation induced by weak lensing

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on behalf of the Herschel-ATLAS collaboration



## Abstract

We report a highly significant spatial correlation between galaxies with  $S_{350\mu\text{m}} \geq 30$  mJy detected in the equatorial fields of the Herschel Astrophysical Terahertz Large Area Survey (H-ATLAS) with estimated redshift  $>1.5$  and SDSS galaxies at  $0.2 \leq z \leq 0.6$ . The significance of the cross-correlation is much higher than those reported so far for samples with non-overlapping redshift distributions selected in other wavebands. Extensive, realistic simulations confirmed that the cross-correlation is explained by weak gravitational lensing. We also find that lensing can induce an apparent clustering of randomly distributed background galaxies, but the amplitude of the corresponding angular correlation function is at least a factor of 10 lower than observed for our sample of H-ATLAS galaxies. Finally simulations show that, although halos of group/cluster size are the dominant contributors to the cross-correlation between H-ATLAS and SDSS galaxies, the gravitational magnification effects on counts of sub-mm sources are nevertheless dominated by galaxy-galaxy strong lensing.

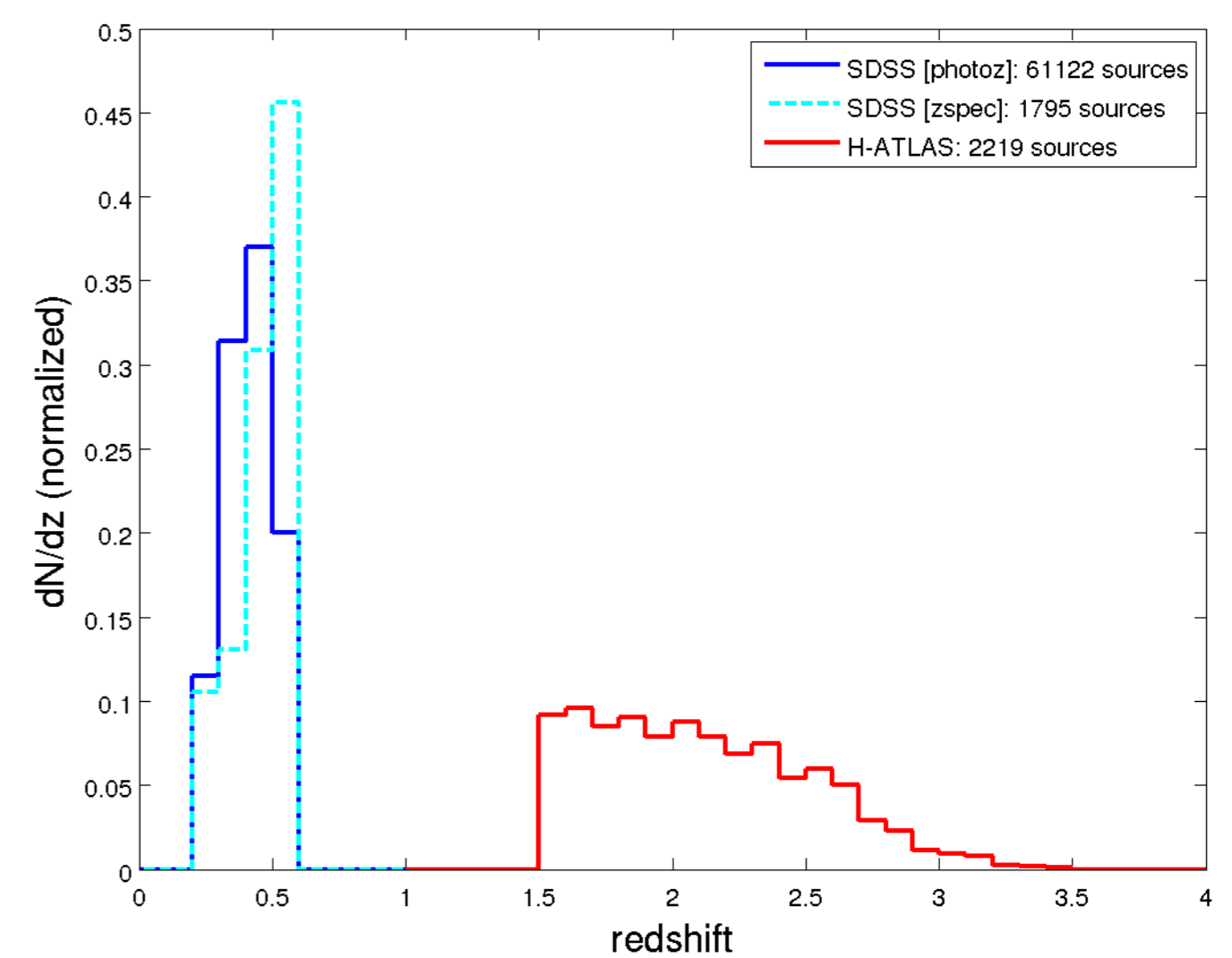
## Sample Selection

We have selected our background sample from the catalog of sources detected in the three equatorial fields of the Herschel Astrophysical Terahertz Large Area Survey (H-ATLAS; Eales et al. 2010), covering, altogether, 161 deg<sup>2</sup>.

To extract candidate high-redshift ( $z \geq 1.5$ ) galaxies we have adopted, following Lapi et al. (2011), the following criteria: i)  $250 \mu\text{m}$  flux density  $S_{250} \geq 35$  mJy; ii) no Sloan Digital Sky Survey (SDSS) counterpart with reliability  $R > 0.8$ , as determined by Smith et al. (2011); and iii)  $\geq 3\sigma$  detection at  $350 \mu\text{m}$ . We added the further constraint  $S_{350} \geq 30$  mJy to facilitate the comparison with the simulations. Finally, our background sample comprises all sources with photometric redshift  $z \geq 1.5$  (estimated as in Gonzalez-Nuevo et al. (2012)), 26,630 sources in total.

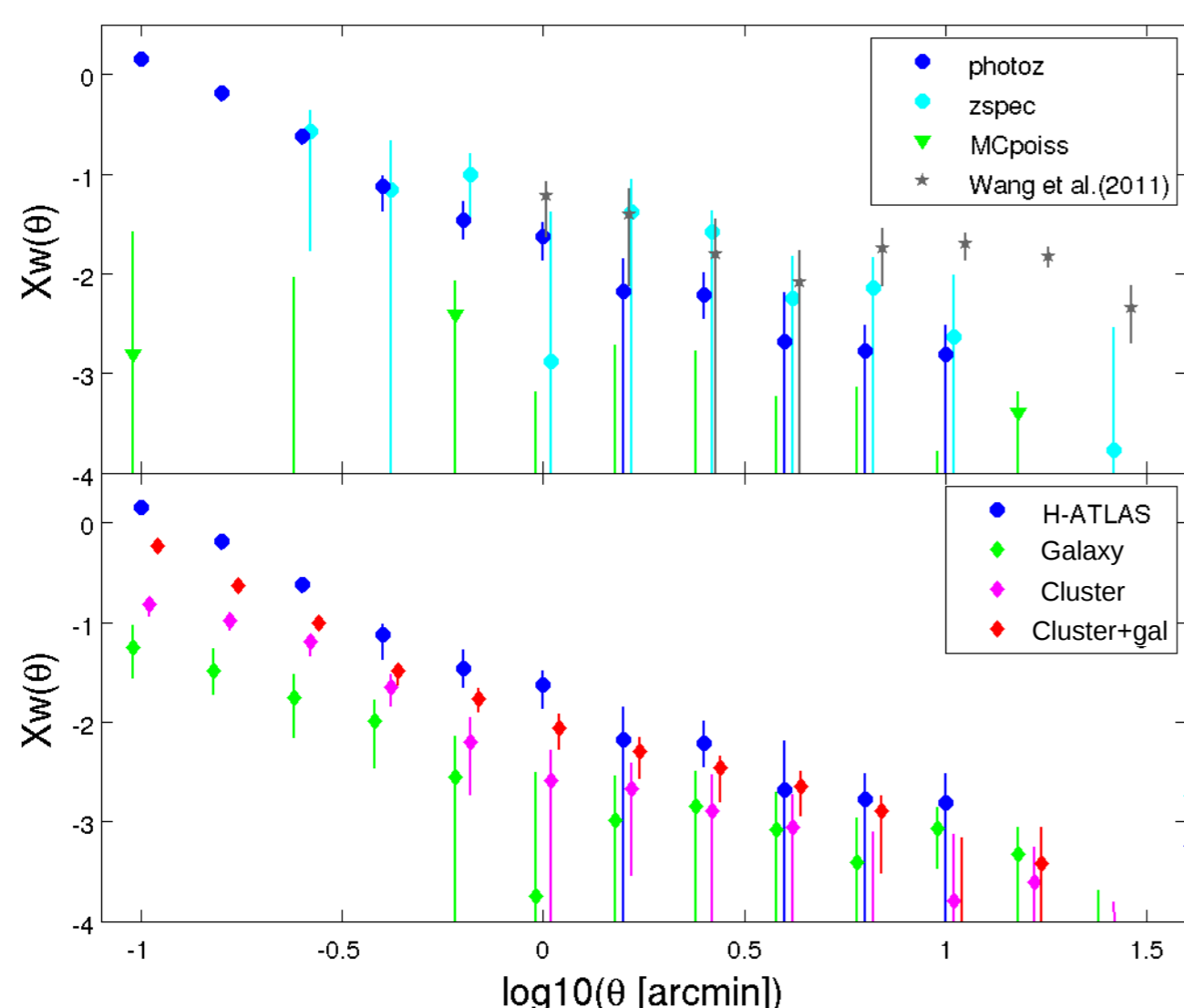
Our main foreground sample is extracted from the Ninth Data Release (DR9) of the SDSS (Ahn et al. 2012) and comprises all galaxies in the H-ATLAS fields with  $r < 22$  and photometric redshift in the range  $0.2 \leq z \leq 0.6$  (hereafter: *photoz* sample). Taking into account that low stellar masses,  $10^{10} M_{\odot}$ , will produce negligible amplifications for the angular scales considered in our analysis, we have arbitrarily set up a lower limit of  $M_{\text{H}} > 10^{10.4} M_{\odot}$ . In addition, we have also introduced an upper limit in r-band luminosity,  $L_r < 10^{11.6} L_{\odot}$ , in order to remove sources with anomalously high r-band magnitudes (0.3% of the total). The sample comprises 686,333 galaxies in total.

We have also defined a spectroscopic sample (hereafter: *zspec* sample), comprising SDSS DR9 galaxies with spectroscopic redshifts in the range  $0.2 \leq z \leq 0.6$ . This sample is far smaller than the *photoz* one. It comprises 19,360 galaxies in total.



Redshift distributions of the background H-ATLAS sample (red histogram) and of the SDSS samples (photometric in blue and spectroscopic in cyan) for one of the regions.

## Cross-correlation functions



Top panel: Cross-correlation between the H-ATLAS sample and the photometric and the spectroscopic foreground samples (blue and cyan circles, respectively). Measurements from Wang et al. (2011) are also plotted for comparison (gray stars). The green upper limits are the result of  $\sim 2000$  realistic Monte-Carlo simulations not accounting for the effect of lensing. Bottom panel: Observed cross-correlation between the H-ATLAS sample and the *photoz* samples (blue circles) compared with the one inferred from simulations of lensing by galactic halos (green diamonds), by group/cluster halos with an NFW density profiles (magenta diamonds) and a combination of both (red diamonds).

The cross-correlation function of 2 source populations is the fractional excess probability, relative to a random distribution, of finding a source of population 1 and a source of population 2 respectively within infinitesimal solid angles separated by an angle  $\theta$  (Peebles 1980). We have computed the cross-correlation between our background and foreground samples using a modified version of the Landy & Szalay (1993) estimator:  $xw(\theta) = (D1D2 - D1R2 - D2R1 + R1R2) / R1R2$

Our results are in broad agreement with those previously obtained by Wang et al. (2011), but reaching smaller angular scales with a very high significance when considering the *photoz* sample. This is in fact the best detection of lensing-induced cross-correlation reported so far. On the other hand, the limited number of foreground galaxies penalizes the significance of the signal derived from the *zspec* sample. However, the similarity between the signal from both foreground samples makes us confident that potential systematics uncertainties in the photometric redshift estimation are negligible from the point of view of our current results.

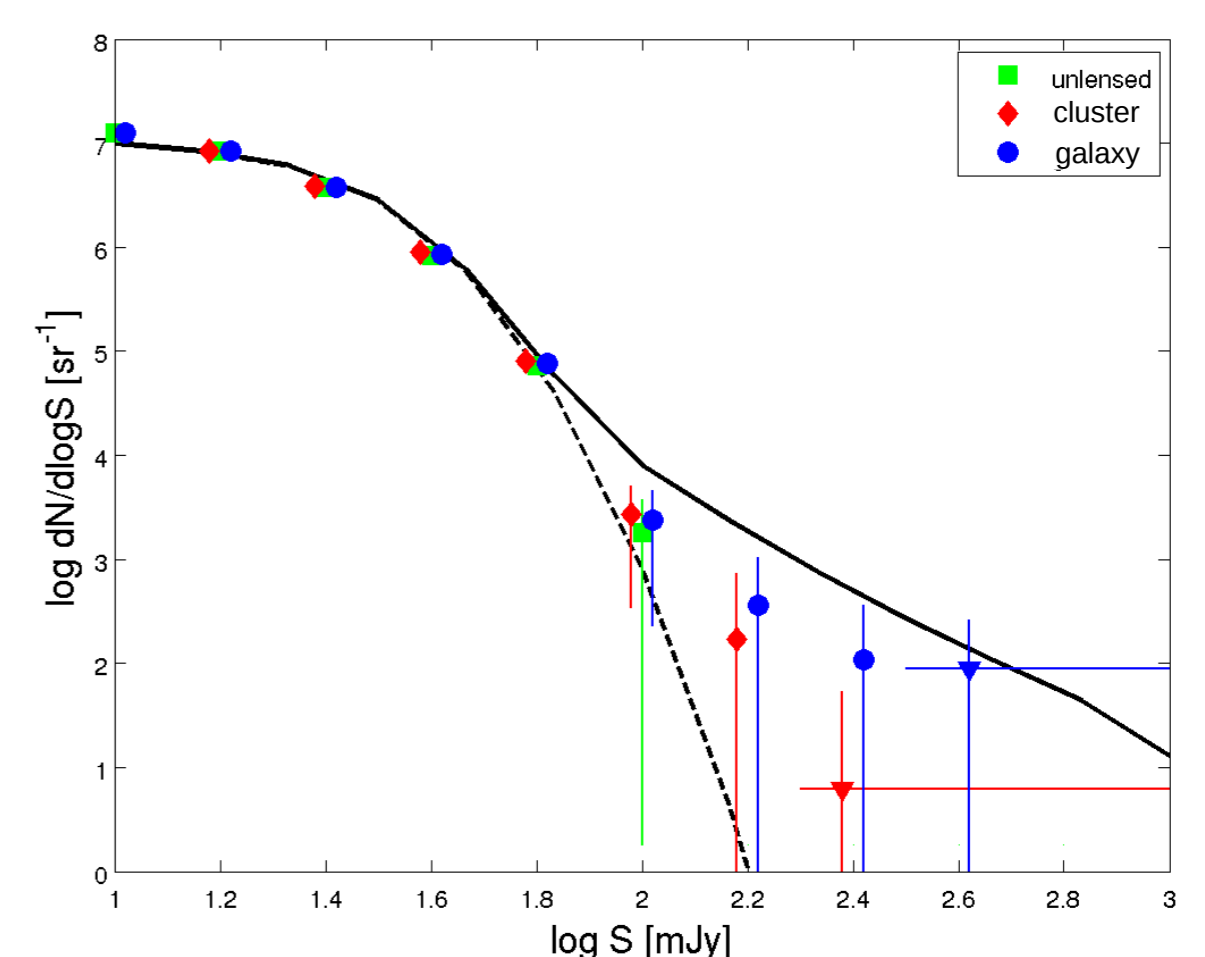
We have performed simulated 3-dimensional distributions of background sources (for the foreground samples we have used their real positions, redshifts and r-band magnitudes) down to  $S_{350\mu\text{m}} = 10$  mJy drawing them from the redshift-dependent luminosity functions of un-lensed galaxies yielded by the Cai et al. (2013) model. The clustering properties of the sources were rendered using the software by Gonzalez-Nuevo et al. (2005) with the spatial correlation functions  $\xi(r, z)$  given by the Xia et al. (2012) model. Next, we have estimated the magnification of each background source by the foreground source closest to its line of sight using the formalism by Lapi et al. (2012).

The simulations confirm that a statistically significant cross-correlation appeared at the relevant scales, demonstrating that the observed signal is indeed due to gravitational lensing. Moreover, the simulations results agree with the classical cross-correlation halo model interpretation, making clear the importance of the 1-halo term and satellites contribution to understand the measured signal. A proper halo model analysis and the required simulations to study in detail the smallest scales of the cross-correlation signal are beyond the purpose of the current paper (Gonzalez-Nuevo et al. 2013) and they will be performed in a future work.

## Conclusions

We have reported a highly significant correlation between the spatial distribution of H-ATLAS galaxies with estimated redshift  $>1.5$  and that of SDSS galaxies at  $0.2 \leq z \leq 0.6$ . Extensive, realistic simulations have shown that the cross-correlation is explained by weak gravitational lensing and its much higher significance compared to those reported so far for spatially disjoint samples selected in other wavebands from the extreme steepness of the sub-mm source counts. A future work will try to extract astrophysical quantitative information about the DM halos by comparing the measured cross-correlation signal with dedicated realistic simulations considering the distribution of sub-halos and their densities, as well as observational constraints like angular resolution or sensitivity.

We have also investigated the effect of clustering of foreground galaxies on the observed angular correlation function of H-ATLAS galaxies. We find that lensing can indeed induce an apparent clustering of randomly distributed background galaxies, but the amplitude of the corresponding angular correlation function is at least a factor of 10 lower than observed. Finally we find that, although halos of group/cluster size are the dominant contributors to the cross-correlation between H-ATLAS and SDSS galaxies, the gravitational magnification effects on counts of sub-mm sources are nevertheless dominated by galaxy-galaxy strong lensing.



Gravitational lensing effect on the recovered source number counts at  $350 \mu\text{m}$  from the Monte-Carlo simulations. The black lines show the number counts from the Lapi et al. (2011) model with (solid) and without (dashed) including the effect of gravitational lensing. The corresponding simulated counts are represented by the blue circles and by the green squares: the latter stand for the unlensed counts, the former include the effect of galaxy-galaxy lensing. The red diamonds show the effect on the counts of weak lensing by group/cluster halos. The triangle symbols in the brightest flux density bin indicate that those results are just upper limits.

## References

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