A systematic search for galaxy proto-cluster cores at $z \sim 2$

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Abstract. A proto-cluster core is the most massive dark matter halo (DMH) in a given proto-cluster. To reveal the galaxy formation in core regions, we search for proto-cluster cores at $z \sim 2$ in $\sim 1.5\,\mathrm{deg}^2$ of the COSMOS field. Using pairs of massive galaxies $(\log(M_*/M_\odot) \geqslant 11)$ as tracers of cores, we find 75 candidate cores. A clustering analysis and the extended Press-Schechter model show that their descendant mass at $z = 0$ is consistent with Fornax-like or Virgo-like clusters. Moreover, using the IllustrisTNG simulation, we confirm that pairs of massive galaxies are good tracers of DMHs massive enough to be regarded as proto-cluster cores. We then derive the stellar mass function and the quiescent fraction for member galaxies of the 75 candidate cores. We find that stellar mass assembly and quenching are accelerated as early as $z \sim 2$ in proto-cluster cores.

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1. Proto-cluster cores

The most massive and largest dark matter haloes (DMHs) in today's universe are called galaxy clusters. The mass of galaxy clusters is typically $\gtrsim 10^{14}\,M_\odot$ and a mature cluster hosts hundreds to thousands of galaxies with large fraction of quiescent galaxies and/or elliptical galaxies. To reveal the galaxy formation of cluster galaxies, progenitors of local clusters at $z \gtrsim 2$, proto-clusters, should be investigated. They are defined as a whole structure that will collapse into a cluster by $z = 0$. A proto-cluster typically extends to more than 20 comoving Mpc at $z \sim 2$, being split into a number of DMHs and unbound regions. Among those substructures, we define the "core" of the proto-cluster as the most massive DMH. A theoretical study has studied galaxy evolution in proto-clusters (Muldrew *et al.* 2018). They have found that galaxies in core regions have different properties from those in fields and the rest of the proto-cluster regions: a more top-heavy stellar mass function, a higher fraction of quiescent galaxies.

In this study, we propose a new method to find proto-cluster cores at $z \sim 2$, the epoch when massive cores appear (Chiang *et al.* 2017). The extended Press-Schechter model predicts that a DMH whose mass is $\gtrsim 2$–$3 \times 10^{13}\,M_\odot$ at $z \sim 2$ typically evolves into the cluster mass regime, $\gtrsim 10^{14}\,M_\odot$, by $z = 0$. We regard DMHs with $\gtrsim 2$–$3 \times 10^{13}\,M_\odot$ at $z \sim 2$ as proto-cluster cores and search for such massive systems. We use a "pair" of massive galaxies $(M_* \geqslant 10^{11}\,M_\odot)$ as a tracer of cores.

2. Proto-cluster core candidates

We use data from the COSMOS2015 galaxy catalogue (Laigle *et al.* 2016). We only use galaxies with $\mathrm{mag}(K_s) \leqslant 24.0$ and $1.5 \leqslant z \leqslant 3.0$. First, we explore pairs of massive

galaxies ($M_* \geqslant 10^{11} \, M_\odot$) whose angular and redshift separations are less than $30''$ and 0.12, respectively. We find 75 pairs as core candidates, among which 54% are estimated to be real. Then, we estimate their halo mass by clustering analysis. Using cross-correlation technique, we derive $2.6^{+0.9}_{-0.8} \times 10^{13} \, M_\odot$, or $4.0^{+1.8}_{-1.5} \times 10^{13} M_\odot$ after contamination correction. Therefore, pairs of massive galaxies are good tracers of massive haloes at least at $z \sim 2$. We also calculate the descendant halo mass of the pairs. Using the extended Press-Schechter model, we show they grow into haloes with mass of $\gtrsim 10^{14} \, M_\odot$ at $z = 0$. Therefore, we regard the pairs of massive galaxies as proto-cluster cores.

3. Implications from simulation

We further investigate the effectiveness of pairs of massive galaxies as tracers of proto-cluster cores. For this purpose, we employ a mock galaxy catalogue of the IllustrisTNG project (Nelson *et al.* 2019). We extract mock galaxies with $M_* \geqslant 10^{11} \, M_\odot$ at $z = 2$, and search for massive galaxy pairs whose separations are less than $0.3 \, \mathrm{pMpc}$. What we find is the following:

- M_* of central galaxy versus host halo mass: we check the relationship between stellar mass of the central galaxy and host halo mass. At fixed stellar mass, DMHs which host pairs are more massive than those which do not by ~ 0.2 dex, suggesting that pairs are good tracers of massive haloes.
- Pair-host fraction: we derive the fraction of DMHs which host pairs of massive galaxies as a function of halo mass. We find that more than 50% of massive haloes with $\gtrsim 3 \times 10^{13} \, M_\odot$ host pairs of massive galaxies.
- Mass growth of pair-host haloes: we find that 62% of pair-host haloes grow into clusters ($M_{\mathrm{DMH}} \geqslant 10^{14} \, M_\odot$) at $z = 0$.

4. Properties of member galaxies of core regions

We examine the stellar mass function (SMF) for galaxies in the detected cores. To calculate the SMF, we assume that DMHs hosting a pair are spheres with a radius of $0.3 \, \mathrm{pMpc}$. It is found that the SMFs of total and star-forming galaxies in the cores have a flat shape below $\log(M_*/M_\odot) < 11$. We also calculate the ratio between the SMFs of core member galaxies and those of field galaxies. We normalise this ratio by total mass. We find that galaxies in the cores have a more top-heavy SMF than the field. This suggests that the formation of high- (low-) mass galaxies can be enhanced (suppressed) in the core regions given the fact that the ratio of the SMFs is above (marginally below) unity for higher- (lower-) mass galaxies than $\log(M_*/M_\odot) = 10$.

In addition to the SMF, we also examine the fraction of quiescent galaxies. We find clear excess at $\log(M_*/M_\odot) \lesssim 10.6$ compared to field galaxies although no excess at $\log(M_*/M_\odot) \gtrsim 10.6$. This suggest that core environment quenches low-mass galaxies more efficiently than high-mass ones. Considering the mass range $9 \leqslant \log(M_*/M_\odot) \leqslant 11$, the fraction of quiescent galaxies in the cores is three times higher than that of the field. We conclude that mass assembly and quenching are accelerated in a proto-cluster core.

References

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