Clustering properties and halo occupation of Lyman-break galaxies at z~4

Jaehong Park\textsuperscript{1}, Hansik Kim\textsuperscript{1}, Stuart B. Wyithe\textsuperscript{1}, Cedric G. Lacey\textsuperscript{2}, Carlton M. Baugh\textsuperscript{2} and R. L. Barone-Nogent\textsuperscript{1}

\textsuperscript{1} School of Physics, The University of Melbourne
\textsuperscript{2} Institute for computational cosmology, University of Durham

Advanced Workshop on Cosmological Structures from Reionization to Galaxies, ICTP, Trieste, Italy, 2015
Contents

1. Introduction
   1.1 Galaxy Clustering
   1.2 Lyman-break galaxies (LBGs)

2. Galaxy formation model
   2.1 Selecting LBGs

3. Result
   3.1 Angular correlation function (ACF)
   3.2 Halo occupation distribution (HOD)

4. Summary
1.1 Clustering

Spingel et al. (2005)
1.1 Clustering

- The formation of dark matter haloes can be successfully described by analytical models and by N-body simulations.

- However, the galaxy formation process itself remains poorly understood.

- One way to investigate the astrophysical connection between dark matter haloes and galaxies is by comparing the clustering in models with the clustering estimated from galaxy observations.

Spingel et al. (2005)
1.2 Lyman-break galaxies (LBGs)

- To investigate high-redshift (z > 3) galaxies Lyman-break technique is broadly used.

- LBGs are star-forming galaxies, detected by the spectral feature formed because rest-frame far UV emission is absorbed (below 912 Å) by neutral hydrogen.

- Since the original work of Steidel et al. (1996) at z ~ 3, researchers have extended this technique to select galaxies up to z ~ 10.
1.2 Lyman-break galaxies (LBGs)

- Recently the number of high-redshift galaxies observed has increased dramatically.

- Bouwens et al. (2014) identified LBGs up to $z \sim 10$ in combined survey fields consisting of the Hubble eXtreme Deep Field (XDF) and CANDELS fields, which are the deepest existing surveys.

- Barone-Nugent et al. (2014) studied clustering properties using Bouwens’ samples by measuring the angular correlation function (ACF).
2. Galaxy formation model

Semi-analytical model (GALFORM)

Lagos et al. (2012)

Dark Matter Simulation:
MILLENIUM-II
$100^3 \, h^{-3}\text{Mpc}^3$ box size

Galaxy formation physics:
- the growth of galactic discs
- star formation in galactic discs
- feedback processes
- chemical evolution of stars
- ...

Image credits: Jaehong Park
2. Galaxy formation model

Semi-analytical model (GALFORM)
Lagos et al. (2012)

Dark Matter Simulation:
MILLENNIUM-II
$100^3 \, h^{-3} \text{Mpc}^3$ box size

Galaxy formation physics:
- the growth of galactic discs
- star formation in galactic discs
- feedback processes
- chemical evolution of stars
- ...
2.1 Selecting LBGs

- We select LBGs using the colour selection criteria described in Bouwens et al. (2014)

\[(B_{435} - V_{606} > 1) \land (i_{775} - J_{125} < 1) \land (B_{435} - V_{606} > 1.6(i_{775} - J_{125}) + 1)\]

- We also consider observational flux limits for model galaxies.

<table>
<thead>
<tr>
<th>Field</th>
<th>Area (arcmin²)</th>
<th>CFHT+ Subaru</th>
<th>(B_{435})</th>
<th>(V_{606})</th>
<th>(i_{775})</th>
<th>(I_{814})</th>
<th>(z_{850})</th>
<th>(Y_{098}/Y_{105})</th>
<th>(J_{125})</th>
<th>(JH_{140})</th>
<th>(H_{160})</th>
</tr>
</thead>
<tbody>
<tr>
<td>XDF(^b)</td>
<td>4.7</td>
<td>—</td>
<td>29.8(^c)</td>
<td>30.3(^c)</td>
<td>29.1</td>
<td>29.4(^c)</td>
<td>30.3</td>
<td>29.8</td>
<td>29.8</td>
<td>29.8</td>
<td>29.8</td>
</tr>
<tr>
<td>HUDF09-1</td>
<td>4.7</td>
<td>—</td>
<td>29.0</td>
<td>29.0</td>
<td>29.0</td>
<td>29.0</td>
<td>29.3</td>
<td>26.7(^d)</td>
<td>29.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HUDF09-2</td>
<td>4.7</td>
<td>—</td>
<td>28.8</td>
<td>29.9</td>
<td>29.3</td>
<td>29.8</td>
<td>29.2</td>
<td>29.5</td>
<td>26.7(^d)</td>
<td>29.3</td>
<td></td>
</tr>
<tr>
<td>CANDELS-S/Deep</td>
<td>64.5</td>
<td>—</td>
<td>28.2</td>
<td>28.5</td>
<td>28.0</td>
<td>28.8</td>
<td>28.0</td>
<td>28.6</td>
<td>26.7(^d)</td>
<td>28.4</td>
<td></td>
</tr>
<tr>
<td>CANDELS-S/Wide</td>
<td>34.2</td>
<td>—</td>
<td>28.2</td>
<td>28.5</td>
<td>28.0</td>
<td>28.1</td>
<td>28.0</td>
<td>28.0</td>
<td>26.7(^d)</td>
<td>27.7</td>
<td></td>
</tr>
<tr>
<td>ERS</td>
<td>40.5</td>
<td>—</td>
<td>28.2</td>
<td>28.5</td>
<td>28.0</td>
<td>28.0</td>
<td>27.9</td>
<td>28.4</td>
<td>26.7(^d)</td>
<td>28.1</td>
<td></td>
</tr>
<tr>
<td>CANDELS-N/Deep</td>
<td>62.9</td>
<td>—</td>
<td>28.2</td>
<td>28.5</td>
<td>28.0</td>
<td>28.8</td>
<td>28.0</td>
<td>28.6</td>
<td>26.7(^d)</td>
<td>28.4</td>
<td></td>
</tr>
<tr>
<td>CANDELS-N/Wide</td>
<td>60.9</td>
<td>—</td>
<td>28.2</td>
<td>28.5</td>
<td>28.0</td>
<td>28.0</td>
<td>28.0</td>
<td>27.6</td>
<td>26.7(^d)</td>
<td>27.6</td>
<td></td>
</tr>
<tr>
<td>CANDELS-UDS</td>
<td>151.2</td>
<td>28.9(^e)</td>
<td>—</td>
<td>28.0</td>
<td>—</td>
<td>28.0</td>
<td>—</td>
<td>27.3</td>
<td>26.7(^d)</td>
<td>27.5</td>
<td></td>
</tr>
<tr>
<td>CANDELS-COSMOS</td>
<td>151.9</td>
<td>29.2(^e)</td>
<td>—</td>
<td>27.8</td>
<td>—</td>
<td>27.9</td>
<td>—</td>
<td>27.3</td>
<td>26.7(^d)</td>
<td>27.5</td>
<td></td>
</tr>
<tr>
<td>CANDELS-EGS</td>
<td>150.7</td>
<td>28.7(^e)</td>
<td>—</td>
<td>28.5</td>
<td>—</td>
<td>28.5</td>
<td>—</td>
<td>27.5</td>
<td>26.7(^d)</td>
<td>27.7</td>
<td></td>
</tr>
<tr>
<td>BORG/HIPPIES(^f)</td>
<td>218.3</td>
<td>—</td>
<td>27.0-28.7</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>26.5-28.2</td>
<td>26.5-28.4</td>
<td>—</td>
<td>26.3-28.1</td>
</tr>
</tbody>
</table>

Bouwens et al. (2014)

- We apply the colour selection criteria to galaxy catalogues in sequential snapshots from \(z=2.83\) to 5.29.
The predicted redshift distributions from the model are comparable with observations.
3.1 Angular Correlation Function (ACF)

- Angular correlation function (ACF) provides information of clustering by measuring excess probabilities of galaxy pairs compared with a random distribution as a function of angular separations.

The Limber's equation (Limber 1954) relates the real space correlation function, $\xi(r)$:

$$w(\theta) = \frac{2 \int_0^\infty [N(z)]^2 / R_H(z) (\int_0^{2r} du \xi(r_{12}, z)) dz}{[\int_0^\infty N(z) dz]^2}$$

where $N(z)$ is the redshift distribution of selected galaxies and $R_H(z)$ is the hubble radius. For comoving distances $r_1$ and $r_2$ of a pair of galaxies, we denote $u = r_1 - r_2$, $r_{12} = \sqrt{u^2 + r^2 \theta^2}$ and $r = \frac{r_1 + r_2}{2}$. 

Acknowledgments

I calculated the ACF with bright galaxies. I selected bright galaxies following Barone-Nugent et al. (2014), with a random distribution as a function of angular separations. To calculate the Limber's equation, we use the real space correlation function (hereafter ACF) by inverting $\theta$ with the observed ACF. In small angular separation from the simulation, the real space correlation function can be written by equation (2) simply becomes

$$\xi(r) = \frac{d}{dr} \frac{d}{dz} [\int_0^\infty N(z) dz]^2$$

In figure (3), we show the predicted ACF (solid red line) compared with the observational result. The predicted ACF is in a good agreement with the simulation. The predicted ACF is in a good agreement with the simulation. In this study, because we only use one simulation output with the maximum redshift distribution of bright galaxies, $z_{max}$.
Overall, the predicted ACFs are in good agreement with both the measured ACFs and the combined ACF.
- Clustering depends on luminosity.  

- Clustering strength is known to depend on luminosity.  

- Barone-Nugent et al. (2014) split sample into bright and faint subsamples at $M_{AB}(1500) - 5 \log(h) \sim -18.5$.  

Park et al. (in preparation)
3.1 ACF

- Clustering depend on luminosity.

- Clustering strength is known to depend on luminosity

- Barone-Nugent et al. (2014) split sample into bright and faint subsamples at $M_{AB}(1500) - 5\log(h) \sim -18.5$.

- We divide the model LBGs into six magnitude bins considering the flux limits for XDF.

Generally, brighter model LBGs have a higher clustering amplitude than fainter ones.
### 3.1 ACF

- Enhanced clustering amplitude on small scales

- On large scales the observed ACFs can be approximated by a power-law parameterisation.

\[ w(\theta) = A_w \theta^{-\beta} \]

The angular correlation amplitude

The correlation slope

- However, the measured ACFs have shown an enhanced clustering amplitude on small scales.

Lee et al. (2006)
3.1 ACF

The fraction of satellite LBGs is important for determining the amplitude of ACF at small scales.

- The measured ACF also shows an enhanced clustering amplitude on small scales.

- The predicted ACFs for deep fields show more enhanced clustering amplitude on small scale.

The fraction of satellite LBGs is important for determining the amplitude of ACF at small scales.
3.2 Halo occupation distribution (HOD)

- Halo occupation distribution describes the average numbers of galaxies as a function of a host halo mass.

- A simple parametric form for the average number of galaxies is

$$\langle N \rangle_M = \begin{cases} 
(M/M_1)^\alpha & \text{for } M > M_{\text{min}}, \\
0 & \text{otherwise},
\end{cases}$$

- $M_1$: the typical halo mass at which there is one galaxy on average.
- $M_{\text{min}}$: the minimum mass of haloes that host galaxies
- $\alpha$: the power-law slope which is related to the abundance of satellite galaxies.

- HOD is a useful way to understand the connection between dark matter halo and galaxy by comparing a correlation function between observation and the HOD modelling.
This sudden drop could be caused by AGN feedback since AGN feedback suppresses star formation in high-mass haloes. Central galaxies in massive halo are not always LBGs. This is in contrast to the HODs interpreted from observations.
4. Summary

* We predict the angular correlation function (ACF) of Lyman-break galaxies and compare with the measured ACF from observations.
  - The predicted ACFs are in good agreement with the measured ACFs and also increase with galaxy luminosity as observed.
  - We show that the fraction of satellite LBGs is important for determining the amplitude of ACF at small scales.

* We show the halo occupation distribution (HOD) of model LBGs.
  - We find that the average number of central LBGs in the model drops sharply in massive haloes.
  - We interpret this sudden drop could be caused by AGN feedback, which is in contrast with observational HOD models for high-redshift.
Thank you.