The Relationship Between Galaxies and Their Dark Matter Haloes Over Cosmic Time

Peter Hatfield, Hintze Fellow, University of Oxford
Laboratório Interinstitucional de e-Astronomia
26th November 2020
Collaborators:

University of Oxford: 
Matt Jarvis 
Aprejita Verma 
Nathan Adams 
Rebecca Bowler 
Catherine Hale 
Clotilde Laigle 
David Alonso 

ESO: 
Boris Haeuussler 

Saudi Information Technology Company: 
Ibrahim Almosallam 

Key papers:
The galaxy-halo connection in the VIDEO Survey at 0.5< z< 1.7
Hatfield+2016 MNRAS, 459, 3, 2618-2631

Environmental quenching and galactic conformity in the galaxy cross-correlation signal

The environment and host haloes of the brightest z~6 Lyman-break galaxies
Hatfield+2018 MNRAS, 477, 3, 3760-3774

Comparing Galaxy Clustering in the Horizon-AGN Simulation and VIDEO Observations
1. Background
2. Galaxy Surveys
3. The HOD Model
4. Clustering in VIDEO
   a) HOD and stellar mass to halo mass ratios
   b) Cross correlations
   c) Comparison to simulations
   d) LBGs
5. Looking ahead
Key Science Results:

- Understanding the **non-linear** clustering of galaxies gives important information about galaxy environment and how galaxies and baryons trace dark matter – beyond just galaxy bias.

- An powerful approach to modelling galaxy clustering is the **Halo Occupation Distribution (HOD)** phenomenology.

- Analysis of clustering in VIDEO supports mass quenching beginning about $z \sim 6-7$, and environmental quenching beginning about $z \sim 1.5$. 
1. Background

- Large-Scale Structure; physics on the scales between galaxies and cosmology
- We now have a large number of probes of cosmology

1888 versus 2019 (Sambit Giri and Hannah Ross, Stockholm)
Our Universe
Cosmology

- Dark Energy: 73%
- Dark Matter: 23%
- Free Hydrogen and Helium: <4%
- Neutrinos: 0.3%
- Stars: 0.5%
- Heavy Elements: 0.03%
Cosmology

Pie Chart of the Universe

- Normal Matter (5%)
- Dark Matter (25%)
- Dark Energy (70%)

(Courtesy of Pat Hall’s blog)
Cosmology

Planck Satellite image of the CMB, ESA
Many different probes of cosmology today
The Universe starts nearly homogeneous; dark matter structure grows under gravity
Dark matter forms non-linear clumps called “haloes”
2. Galaxy Surveys

• Deep wide-field galaxy surveys let us probe cosmology and galaxy physics over cosmic time

• Two-point clustering statistics can tell us a lot about both galaxy environment and the large-scale structure of the Universe
Galaxy Surveys

Miyazaki et al., 2013
Stellar Mass Function
Mutch et al., 2013
Galaxy Physics from Surveys

Cosmic SSFR
Madau and Dickinson., 2014
Mass quenching versus environmental quenching?

Peng+2010
Cosmology from Clustering

Baryonic Acoustic Oscillations

Basset et al., 2010
Cosmology from Clustering

Matter Power Spectrum

Tegmark et al., 2004
Weak Lensing Shear

- Weak-lensing matter power spectrum (matter-matter coupling)
- Galaxy-galaxy lensing (matter-galaxy coupling)
- Galaxy clustering (galaxy-galaxy coupling)
- [Also magnification, CMB lensing potential and much more...]
Radio source counts begin to invalidate Steady State theory in ~1961 (CMB is 1964)
Galaxy clustering in the early 1990’s – an early hint of dark energy? (SNe evidence comes out in 1998/1999, Efstathiou+1990 find suggestion of $\Omega_\Lambda \approx 0.8...$)
Cosmology from Clustering

2019 Nobel Prize in Physics goes to Jim Peebles for work on the large scale structure of the Universe! (and exoplanets)

Davis and Peebles 1982
(2400 galaxies!)
2. Halo Occupation Distribution (HOD) Modelling

- Model the linear and non-linear clustering collectively
- Get more physical properties than bias
Measuring Clustering

Try and form “random” data set of points that have identical properties apart from angular location to data set
Measuring Clustering

\[ \omega(\theta) = \frac{DD}{RR} - 1 \]

(Actually use Landy-Szalay 1993)
Galaxy Bias

Galaxies have a different spatial distribution to matter

Kaiser et al., 1984
Halo Properties Over Cosmic Time

(Plots created using Halomod, Steven Murray+)
Halo Occupation Modelling

-> Measure correlation function (and other variables)
-> Generate model correlation functions from galaxy-halo relation model
-> Fit parameters

HOD Ingredients:
- (Cosmology)
- Halo mass function
- Halo bias prescription
- Dark matter power spectrum
- Halo profiles
- Occupation number
- Poisson assumption
- Central/satellite distinction
- 1-halo and 2-halo terms

\[ \chi^2 = \frac{[n_{\text{gal}} - n_{\text{model}}]^2}{\sigma_n^2} + \sum_i \frac{[\omega_{\text{obs}}(\theta_i) - \omega_{\text{model}}(\theta_i)]^2}{\sigma_{\omega_i}^2}, \]

Wake et al., 2011
Halo Occupation Modelling

(Plots created using *Halomod*, Steven Murray+)
3. Clustering in VIDEO

- Deep NIR and optical data to comparable depth to Euclid over 12deg$^2$
- Work measuring and modelling clustering as a function of stellar mass and star formation rate
The VIDEO Survey
The VISTA Deep Extragalactic Observations Survey

- Infrared (Z, Y, J, H, K_s band) with optical from CHFTLS
- >200 nights over 5 years
- Galaxy and structure evolution up to z=4
- AGN and most massive galaxies up to reionisation
- 3 fields; selected for multi-band data
- Fits between UltraVISTA and VIKING for depth and width
- 1sq degree here, soon 12 sq deg
- Right combination of width and depth for HOD
- VEILS will extend VIDEO fields

<table>
<thead>
<tr>
<th>Filter</th>
<th>Time (h) (per source) (no overheads)</th>
<th>Time (h) (per tile) (+overheads)</th>
<th>Time (h) (full survey) (+overheads)</th>
<th>5σ AB</th>
<th>2&quot; ap.mag. Vega</th>
<th>UKIDSS Vega</th>
<th>Seeing</th>
<th>Moon</th>
<th>Transparency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>17.5</td>
<td>60.8</td>
<td>570</td>
<td>25.7</td>
<td>25.2</td>
<td></td>
<td>0.8</td>
<td>D</td>
<td>THN,CLR</td>
</tr>
<tr>
<td>Y</td>
<td>6.7</td>
<td>23.2</td>
<td>218</td>
<td>24.6</td>
<td>24.0</td>
<td></td>
<td>0.8</td>
<td>G</td>
<td>THN,CLR</td>
</tr>
<tr>
<td>J</td>
<td>8.0</td>
<td>27.9</td>
<td>261</td>
<td>24.5</td>
<td>23.7</td>
<td>22.3</td>
<td>0.8</td>
<td>G</td>
<td>THN,CLR</td>
</tr>
<tr>
<td>H</td>
<td>8.0</td>
<td>29.4</td>
<td>276</td>
<td>24.0</td>
<td>22.7</td>
<td>22†</td>
<td>0.8</td>
<td>B</td>
<td>THN,CLR</td>
</tr>
<tr>
<td>K_s</td>
<td>6.7</td>
<td>23.8</td>
<td>224</td>
<td>23.5</td>
<td>21.7</td>
<td>20.8</td>
<td>0.6</td>
<td>B</td>
<td>THN,CLR</td>
</tr>
</tbody>
</table>

The VIDEO Survey

Lookback Time (Gyr)

Stellar Mass - $M_*/M_\odot$

Redshift - $z$

$M_{lim}(K_s)$

(Colour-cut to remove stars etc.)
Calculating Redshifts

Galaxy Redshifts

- Spec-z
- Photo-z
- Cluster-z

Machine Learning

- Gaussian Processes
- Neural Networks
- ...
Calculating Redshifts
Calculating Redshifts

Calculating Redshifts

Modelling the Clustering

ACFs and HOD fits in VIDEO

Redshift

Stellar Mass
Modelling the Clustering

\[ M_{\text{halo}} / M_\odot \]

\[ M_1 \]

\[ M_{\text{min}} \]

\[ M_\star / M_\odot \]
Modelling the Clustering

\[ \frac{M_\star}{M_{\text{halo}}} = \frac{\Omega_b}{\Omega_{\text{DM}}} \]

\[ \frac{M_\star}{M_{\text{halo}}} = \frac{\Omega_\star}{\Omega_{\text{DM}}} \]

Centrals

Satellites

\[
\begin{align*}
1.50 < z < 1.70 \\
1.25 < z < 1.50 \\
1.00 < z < 1.25 \\
0.75 < z < 1.00
\end{align*}
\]
Modelling the Clustering

Lookback Time (Gyr)

$10^{13}$

$M_h$

$10^{12}$

$0.5$ $1.0$ $1.5$ $2.0$ $2.5$

- Coupon et al. 2015 (clustering and lensing)
- McCracken et al. 2015 (clustering)
- McCracken et al. 2015 (abundance matching)
- Hudson et al. 2015 (lensing)
- Martinez-Manso et al. 2015 (Clustering)
- This work (clustering)
• Most massive galaxies in highest mass halos, most highly biased
• More highly biased at high redshift
• Very small fraction of massive galaxies are satellites
• (Can do joint constraint with cosmology and marginalise out galaxy physics – make use of more of the correlation function)
Comparison with Simulations

- Mock catalogue from Horizon-AGN hydrodynamical cosmological simulation
- C.f. EAGLE, ILLUSTRIS...
- Also run with AGN feedback switched off
Comparison with Simulations

- Compare observations and simulations in a consistent way
- Compare `actual' simulation and `observed' simulation

Laigle et al., 2019
• Doing full HOD model can test if differences in clustering between observations and simulation are a result of systematic differences in estimates of stellar mass, or differences in galaxy-halo relation etc.
Comparison with Simulations

- HOD modelling probably correctly captures SMHR
- Use of photo-z’s seems to lead to increase in estimate of scatter
Comparison with Simulations

![Graph showing comparison between simulated and observed galaxy properties](chart.png)
Conventional HOD assumes galaxies trace $NFW$ profile

If galaxies are preferentially quenched or star forming in certain environments, this makes them follow slightly different profiles, which manifests itself in the 1-halo term

Cross correlations also give information on covariance on occupation numbers

Cross-correlation function can be used to study the ‘interaction’ of two galaxy samples

See Simon+2009

\[
1 + \xi_{1h}(r) \propto \int_{\mathbb{R}^3} Q(r) \rho(r) \rho(r-s) ds
\]

\[
1 + \xi_{1h}(r) \propto Q(r) \int_{\mathbb{R}^3} \rho(r) \rho(r-s) ds
\]
Modelling the Cross-Correlation Function
Modelling the Cross-Correlation Function

(log sSFR<-11, log sSFR>-11)
Lyman-Break Galaxies

Lyman Break Galaxies are one of our best probes into the z=5-9 Universe

Bowler et al., 2014
Lyman-Break Galaxies

• Above z~4 - Lyman Break Galaxies
• High luminosity LBGs are less rare than expected, but still highly clustered (b~8-10) – onset of quenching? (“Most biased objects in the Universe”)
• Relevant for reionisation

Bowler et al., 2014
Hatfield et al., 2018
4. Looking Ahead

- Many exciting upcoming surveys
- Much more things that can be done with small scale clustering
Expanding to higher redshifts, a wider range of stellar masses, and larger angular scales
Into the 2020s...

Euclid+Rubin+SKA
Conclusions

- Measured and modelled clustering in VIDEO
- Information about the role of environment at the peak of star formation, how galaxies trace matter, links to LSS cosmology
- Quenching mechanisms can be added to HOD
- Have measured the clustering of the brightest $z \sim 6$ LBGs

In Future:

- The non-linear galaxy power spectrum in future surveys will give unprecedented precise probes of environment
- More data will justify more sophisticated models
- Redshift-space distortions will add dynamics to the story
- Multi-wavelength data important (Euclid+LSST+SKA)
Galaxy Bias

Springel et al., 2006 (Millennium simulation)

Bias is linear on large scales; complex on halo scales