Clustering and weak lensing of SDSS-III galaxies:
from astrophysics to cosmology

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Miyatake, SM et al., arXiv:1311.1480
SM et al. 2014, (in preparation)
Observations of galaxies can be used to simultaneously constrain galaxy dark matter connection and cosmological parameters!
Cosmological paradigm

Homogeneous Universe

Dark energy

Atoms

Dark matter

(Planck collaboration, 2013)
Galaxy-dark matter connection

\[ \delta_{\text{gal}} = b \delta_m \]

\[ P_{gg}(k) = b^2 P_{dm}(k) \]

- How do galaxies occupy dark matter haloes?

Millenium simulation, Springel et al. 2005

Galaxies

Dark Matter
Approaches to the Galaxy-Dark matter connection

- **Direct observations**
  - Gas kinematics, Strong lensing, weak lensing, satellite kinematics

- **Physical modelling**
  - Semi-analytical models, numerical simulations

- **Statistical modelling**
  - Halo occupation distribution modeling of the clustering and lensing of galaxies
SDSS III BOSS

- Spectroscopic survey
  - ~900000 massive galaxies at z>0.4
- Area on sky: ~10000 sq. deg.
  - (8500 sq. deg. data from DR11 used in this study)

Primary goal: Baryon acoustic feature as a standard ruler
CMASS galaxy sample

- Spectroscopic targets selected weighting continuity slightly to cuts. $M_{*} > 10^{11.1} h_{70}^{-2} M_{\odot}$ to get an approximately volume limited sample

1. $17.5 < i_{\text{mod}} < 19.9$, 
2. $r_{\text{mod}} < 24$, 
3. $d_{\perp} > 0.55$, 
4. $i_{\text{mod}} < 21.5$, 
5. $c_{\text{mod}} = 0.46 + 1.6(d_{\perp} - 0.8)$, where the auxiliary colour $d_{\perp}$ is defined as (Cannon et al. 2006) 
6. $d_{\perp} = r_{\text{mod}} - i_{\text{mod}} - (g_{\text{mod}} - r_{\text{mod}}) / 8.0$. 

Miyatake, SM, et al. (2013, in prep.)
Galaxy clustering signal

- Projected galaxy clustering signal
- Extremely well measured S/N ratio ~67 using ~300000 galaxies in the DR11 subsample.
Galaxy-galaxy lensing signal

- Hatched region
- CFHTLS fields
- Dots
- CMASS galaxies

- Deeper imaging data from CFHT Legacy Survey available in ~100 sq. deg. area overlapping with BOSS.

Figure 2. Distribution of the CMASS galaxy sample, used in this paper, in each of the four CFHTLenS fields as labeled at the top of each panel. The number of CMASS galaxies in each CFHTLenS field is given in the upper right of each panel. The hatched regions denote CFHTLenS fields. The CMASS galaxy sample in this paper is selected based on their redshift and stellar mass estimates so that the sample constitutes approximately volume-limited sample and physically-similar population of galaxies (see text and Fig. 1 for details).

Figure 3. ANAlysis

3.1. Galaxy-galaxy Lensing

Galaxy-galaxy weak lensing measures a coherent distortion of source galaxy shapes due to all matter around lens galaxies, including dark matter (see Mandelbaum et al. 2013, and references therein). The lensing signal is only statistically measurable and can be estimated by stacking tangential component of source galaxy ellipticities with respect to the position of lens galaxy, for all the pairs of lens and source galaxies in each circular annulus. The lensing distortion profile probed in this way is expressed in terms of the projected surface mass density profile of the average mass distribution around the lens galaxies:

\[ t(R) = \bar{\sigma}(<R) \sigma(R) \sigma_{cr}, \]  

where \( R \) is the projected separation between the source and lens galaxies at the redshift of each lens galaxy, \( \bar{\sigma}(<R) \) is the average mass density within a circle of radius \( R \), and \( \sigma_{cr} \) is the critical surface mass density. A spectroscopic redshift for each CMASS galaxy, \( z_l \), enables an estimation of the projected radius from the observed angle separation via

\[ R = d_A(z_l) \theta, \]

where \( d_A(z_l) \) is the comoving angular diameter distance to the lens galaxy. The critical density \( \sigma_{cr} \) for lens and source galaxies at redshifts \( z_l \) and \( z_s \), respectively, is defined as

\[ \sigma_{cr}(z_l, z_s) = \frac{4 \pi G^2 (d_A(z_l) d_A(z_l, z_s) (1 + z_l)^2 d_A(z_s))}{(1 + z_s)^2 d_A(z_s)}. \]  

Here \( d_A(z_s) \), \( d_A(z_l) \), and \( d_A(z_l, z_s) \) are the comoving angular diameter distances for the source-lens system. The factor of \((1 + z_l)^2\) arises from our choice of comoving coordinates. Another component of shear, \( \sigma \), which is a 45° rotated component from the tangential shear, should be statistically consistent with zero for weak gravitational lensing (but potentially nonzero for shape distortions due to systematic errors). Hence we can use the measured \( \sigma \) as a monitor of a possible residual systematics in the lensing measurement.

For each pair of lens and source galaxies, we compute the tangential ellipticity component using

\[ e_t = e_1 \cos 2\theta + e_2 \sin 2\theta, \]  

where \( \theta \) is defined as the angle measured from right ascension direction to a line connecting the lens and source galaxies at source galaxy position. Using spherical trigonometry, the angle to source galaxy position from lens galaxy position can be calculated as

\[ \theta = \arctan \left( \frac{y_2 - y_1}{x_2 - x_1} \right), \]

where \( x_1, y_1 \) and \( x_2, y_2 \) are the coordinates of the lens and source galaxies, respectively.
Galaxy–galaxy lensing signal

- S/N ratio: ~28
- Lensing–signal corrected for shape measurement systematics
Halo model

- Structure in dark matter distribution
- Theorist's simplification :)
The simple picture

- Expected degeneracy
  - Increasing $\Omega_m$ compensated by decreasing $\sigma_8$

Halo occupation distribution

- Parameterization
  - Centrals
    - \( M_{\text{min}}, \sigma^2 \)
  - Satellites
    - \( M_{\text{sat}}, M_{\text{cut}}, \alpha \)

- Average number of galaxies per halo
Inside a dark matter halo

- Dark matter
- Density profile, NFW
- Concentration mass relation
- Central galaxy
- Allow for possible mis-centering
- Satellite galaxies
- Follow the dark matter
Fixed cosmological parameters: WMAP-7 compatible

- Fit HOD parameters, halo shape parameter, and stellar mass of galaxies
- $\chi^2$: 39.55 for 40 degrees of freedom
- Significant covariance on large scales in the clustering signal.
Astrophysical constraints

Figure 8. The constraints on the parameters of our model obtained via a joint analysis of the abundance and clustering of CMASS galaxies and their lensing signal. The histograms on the diagonal of the matrix show the posterior distribution of the parameters given the data, where the blue solid lines show the prior if any, and the green solid line shows the peak of the posterior distribution. The green dashed lines demarcate the 68% confidence interval (only one side is presented in case of one-sided prior). The degeneracies between different parameters can be seen in the non-diagonal panels. Note that the $M_{\text{min}}$ and $M_{\text{sat}}$ is in units of $h^{-1}M_{\odot}$, and $M_{\text{\textdagger}}$ is in units of $h^{-2}M_{\odot}$.

Increasing $M_{\text{\textdagger}}$ increases the amplitude of the galaxy-galaxy lensing signal in the inner regions, and this can be compensated for by a decrease in halo concentration. The scale dependence of the effect on the lensing signal is fairly different and hence the degeneracy is not perfect. As $M_{\text{\textdagger}} \rightarrow 0$, the amplitude of the concentration-mass relation tends to unity, consistent with the central value of the prior distribution, that is the collisionless N-body expectation.

Measuring the galaxy-galaxy lensing signal on scales even smaller than we study in this paper will break this degeneracy.

Fig. 9 shows the 68% and 95% confidence regions in the halo occupation distribution of the CMASS galaxies in our sample. The halos with mass above $\sim 4 \times 10^{13} h^{-1}M_{\odot}$ host at least one galaxy from our sample. The high mass slope of the satellite halo occupation at the high mass end is constrained to be $\kappa = 1.06 \pm 0.11$. Using the best-fit HOD, we find $hM_{\text{\textdagger}} = (2.33 \pm 0.12) \times 10^{13} h^{-1}M_{\odot}$ for the average mass of halos that host CMASS galaxies, while $hM_{\text{\textdagger}} = (3.13 \pm 0.06) \times 10^{13} h^{-1}M_{\odot}$ for the average halo mass for all the CMASS galaxies, where massive halos hosting satellite CMASS galaxies are weighted or counted multiple times in the calculation. In the figure, we also show a comparison between our results and those obtained by White et al. (2011) using an early release of the BOSS galaxy sample. Their analysis did not include the stellar mass and redshift cuts we impose on our sample. Since we are excluding the low stellar mass galaxies from our sample, the parameter $M_{\text{\textdagger}}$, which governs the mass scale above which $hN_{\text{\textdagger}} = 1$, is slightly larger. We also compare our results to the HOD constraints on the LRGs obtained by using a counts-in-cylinder method by Reid & Spergel (2009). The CMASS galaxies have a higher number density and consequently reside in lower mass halos than the LRGs. In order to account for the different redshifts of the CMASS and LRG HOD PARAMETERS

HOD PARAMETERS

STELLAR MASS

CONCENTRATION

Miyatake, SM et al. 2013, arxiv:1311.1480

Subaru seminar, April 30 2014
Astrophysical constraints

HOD PARAMETERS

STELLAR MASS

CONCENTRATION

Miyatake, SM et al. 2013, arxiv:1311.1480

Satellite fraction: 11±1%
Astrophysical constraints

HOD PARAMETERS

STELLAR MASS

CONCENTRATION

Miyatake, SM et al. 2013, arxiv:1311.1480
Subaru seminar, April 30 2014

NO OFF-CENTERING MODEL

Degeneracy between halo shape parameter, and stellar mass
Contraints on stellar population synthesis models

Table 1

<table>
<thead>
<tr>
<th>Model</th>
<th>$\langle M_\star \rangle \left(10^{11} h^{-2} M_\odot \right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portsmouth Passive Kroupa</td>
<td>1.16</td>
</tr>
<tr>
<td>Portsmouth Passive Salpeter</td>
<td>1.98</td>
</tr>
<tr>
<td>Portsmouth Starforming Kroupa</td>
<td>0.96</td>
</tr>
<tr>
<td>Portsmouth Starforming Salpeter</td>
<td>1.49</td>
</tr>
<tr>
<td>Granada Early-forming dust</td>
<td>3.07</td>
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<tr>
<td>Granada Early-forming no-dust</td>
<td>2.59</td>
</tr>
<tr>
<td>Granada Wide-forming no-dust</td>
<td>2.16</td>
</tr>
<tr>
<td>Granada Wide-forming dust</td>
<td>2.57</td>
</tr>
<tr>
<td>PCA Wisconsin M11</td>
<td>1.84</td>
</tr>
<tr>
<td>PCA Wisconsin BC03</td>
<td>1.77</td>
</tr>
<tr>
<td>Fiducial model</td>
<td>$&lt; 1.83 \left(68%\right)$</td>
</tr>
</tbody>
</table>

Miyatake, SM et al. 2013, arxiv:1311.1480

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Cosmological constraints

- The most general model
  - includes off-centering parameters and nuisance parameters for incompleteness of CMASS sample
  - Matter density parameter $\Omega_m$ and amplitude of fluctuations, $\sigma_8$ left free
  - WMAP9+SPT+ACT priors on $\Omega_b$, $n_s$ and $h$

SM et al. 2014, in prep.
Cosmological constraints from joint analysis of clustering and lensing

Varying cosmological parameters allows a much better fit to the large scale clustering signal. Possible to explain both the clustering and lensing signal.

SM et al. 2014, in prep.
Comparison with other probes

SM et al. 2014, in prep.
Comparison with other probes

- Baryon acoustic oscillations results also lie in between the WMAPe and PLANCK results
SuMIRe: Subaru Measurements of Images and Redshift Survey

- Hyper Suprime-Cam
- Subaru
- Subaru Survey
- Subaru telescope
- Subaru camera

<table>
<thead>
<tr>
<th>Layer</th>
<th>Area [deg$^2$]</th>
<th># of pointings</th>
<th>Filters &amp; Depth</th>
<th>Volume [$h^{-3}$Gpc$^3$]</th>
<th>Key Science</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>1,400</td>
<td>916</td>
<td>grizy ($r \approx 26$)</td>
<td>$\sim 4.4$ ($z &lt; 2$)</td>
<td>WL cosmology, $z \sim 1$ galaxies, clusters of galaxies</td>
</tr>
<tr>
<td>Deep</td>
<td>27</td>
<td>15</td>
<td>grizy+3NBs ($r \approx 27$)</td>
<td>$\sim 0.5$ ($1 &lt; z &lt; 5$)</td>
<td>$z \lesssim 2$ galaxies, SNeIa, WL calib.</td>
</tr>
<tr>
<td>Ultradeep</td>
<td>3.5</td>
<td>2</td>
<td>grizy+3NBs ($r \approx 28$)</td>
<td>$\sim 0.07$ ($2 &lt; z &lt; 7$)</td>
<td>high-$z$ gals (LAEs, LBGs), SNeIa</td>
</tr>
</tbody>
</table>

- 23 ongoing completed
- VST-ATLAS
- SkyMapper
- SDSS

- Real time fiber positioning adjustments

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The curious case of SN PS1-10afx

- Discovered in 2010 by Pan-StarrsI
- Peculiar due to its very high luminosity, red colour, rapid rise time
  - About 20-30 times more luminous than typical SN Type Ia/c

- Alternative hypothesis: gravitational lensing caused the 30 fold magnification of a normal Type Ia Sn (Quimby et al. 2012).

- But where is the lensing object?
The curious case of SN PS1-10afx

- First case of strongly lensed Type Ia Supernova
- Time delays can help pin down the Hubble parameter
Summary

- Clustering and weak lensing signal of SDSS-III CMASS galaxy sample
  - Weak lensing only in 120 sq deg area
  - Hyper Suprime-cam survey will image 1400 sq deg, with twice the source number density as CFHTLS

- Astrophysical constraints:
  - Average halo mass of CMASS galaxies: $2.3 \times 10^{13}$ $h^{-1}$ Msun
  - Satellite fraction 11 percent
  - Constraints on halo shape and stellar population synthesis models

- Cosmological constraints
  - Tight constraints on $\Omega_m$ and $\sigma_8$
  - Consistent and complementary with CMB experiments with interesting mild tensions
Thank you!!!