Galaxy cluster cosmology in the LSST Era

abundance

Tom McClintock
Research Associate
Galaxy clusters

LSST:
Will find ~100k massive clusters
Up to ~1M galaxy groups
Complete up to z~1.2 (ish)
All clusters are identified by their photometric properties

Images courtesy DES & E. Rozo
Structure probes cosmology!

Lots of matter + little dark energy = more structure

Lots of dark energy + little matter = less structure

Images courtesy of E. Rozo

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More clusters = more structure
1. Find galaxy clusters

2. Measure cluster masses

3. Model cluster abundance
Galaxy cluster cosmology in 3 easy steps

1. Find galaxy clusters
   (see Ricardo’s talk)

2. Measure cluster masses

3. Model cluster abundance
Finding clusters photometrically - redMaPPer

Clusters identified via the red sequence

Images from Rykoff+ (2014) - arxiv:1303.3562
redMaPPer redshifts

Obtain unbiased, precise redshifts.

Don’t require a vast spectroscopic catalog!

Rykoff+ (2014, 2016)

See also
Bellagamba+ (2017), Oguri+ (2017)
Example cluster catalog

DES: 5000 sq. deg.
(LSST: 18k sq. deg.)

redMaPPer cluster finder

7066 clusters
(76k at the group scale, with >=5 galaxies)

DES Year 1 catalog complete up to z=0.65
Halo mass function

From spherical collapse (you learned this in grad school, remember?)

Models e.g.: Sheth & Tormen (2001), Tinker+ (2008), McClintock+ (2018)

HMF has one or more power law and an exponential
Halo mass function

The graph shows the number of halos per Gpc$^3$ as a function of mass $[h^{-1} M_\odot]$ for different redshifts ($z = 0, 1, 2$). The number of halos decreases with increasing mass, especially at higher redshifts.
Cluster cosmology 101

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$\frac{dn}{dV}$ [Mpc$^{-3}$ M$_\odot^{-1}$] vs. mass [$h^{-1}$ M$_\odot$]

$z = 0$
$z = 1$
$z = 2$
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```
richness
200
100
50
20

redshift
0.2
0.4
0.6

\frac{dn}{dV}[\text{Mpc}^{-3}\text{M}_{\odot}^{-1}]
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}

mass [h^{-1}\text{M}_{\odot}]
10^{12}
10^{13}
10^{14}
10^{15}

z = 0
z = 1
z = 2
```
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Cluster cosmology 101

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We will never have this plot :(}

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Cluster catalog vs. mass-richness relation
Cluster catalog vs. mass-richness relation
Galaxy cluster cosmology in 3 easy steps

1. Find galaxy clusters

2. Measure cluster masses
   (see Mariana’s talk)

3. Model cluster abundance
Cluster masses from gravitational lensing

Images courtesy of NASA/ESA & DES
Weak gravitational lensing

Can detect only statistically detect shear. Mean tangential ellipticity of background galaxies is sensitive to cluster mass.
Abell 2218 - gravitational lensing
Lensing signal is **noise dominated** for individual clusters.

With its large area, DES is great for a **stacked lensing analysis**.

Define groups of galaxy clusters grouped by **richness** and **redshift**, and stack their images.
Cluster weak lensing profiles

Cluster sample split by redshift (top to bottom) richness (left to right)

Black points:
- (differential) surface mass density profile
- Proportional to tangential shear

Red line:
- best fit model

See: 1805.00039
Lensing model + systematics

Lensing model:
- centered (black -)
- miscentered (blue -)
- boost factor, shear+pz (red)
- triaxiality+proj. (not shown)

Boost factor model (not shown):
- NFW 2-parameter model
- *De-boosted* the model lensing profile (See: 1812.05116)

\[ z \in [0.2; 0.35] \]
\[ \lambda \in [20; 30] \]
\[ \chi^2 = 13.7/11 \]
Mass--richness relation

$\langle M | \lambda, z \rangle = M_0 \left( \frac{\lambda}{\lambda_0} \right)^\alpha \left( \frac{1 + z}{1 + z_0} \right)^\beta$

Stacked masses measured at the 8% level.

Normalization constrained at the 5% level.
Mass--richness relation

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<th>Source of systematic</th>
<th>SV Amplitude uncertainty</th>
<th>Y1 Amplitude Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear measurement</td>
<td>4%</td>
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<tr>
<td>Photometric redshifts</td>
<td>3%</td>
<td>2.6%</td>
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<tr>
<td>Modeling systematics</td>
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<td>0.73%</td>
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<td><strong>Total Systematics</strong></td>
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Galaxy cluster cosmology in 3 easy steps

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Cluster abundance

1) Projection effects cause scatter in cluster richneses

2) S-T or Tinker mass functions are accurate at the 5% level or worse!
Cluster abundance - Problems!

1) Projection effects cause scatter in cluster richesses

2) S-T or Tinker mass functions are accurate at the 5% level or worse!
Projection effects

Real cluster

Projection artifact
Projection effects

Need to know how many of these galaxies

Bleed into these clusters

\[ \lambda_{\text{total}} = \lambda_1 + f \lambda_2 \]

- Successfully reproduced in mocks
- Calibrated using the data, meaning this effect introduces no extra free parameters

Costanzi et al.: 1807.07072
Cluster abundance

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1) Projection effects cause scatter in cluster richesses

2) S-T or Tinker mass functions are accurate at the 5% level or worse!

This would dominate the error budget in LSST!
Mass function model needed for LSST!

Cluster cosmology would be **systematics limited**
Solution - interpolate between simulations

Suite of simulations (40 training, 35 testing)

Spread out in a 7 dimensional cosmological parameter space
- 2 dimensions shown here

Measure cluster abundance in sims

Use machine learning techniques to interpolate between simulations.
Predicting abundance at arbitrary cosmology is crucial!

**Training simulations** were less accurate than the **testing simulations**.

Achieved ~1% accuracy for interesting mass scales.

See: 1804.05866
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- Redshift vs. richness
- Mass vs. richness
- Differential mass function vs. mass
Enabling galaxy cluster cosmology in DES

Image courtesy of M. Costanzi

PRELIMINARY
Thank you!

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