CLUSTER COSMOLOGY IN THE DARK ENERGY SURVEY

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https://zoom.us/j/596761139

Modeling of the Selection Function: Costanzi+ 18a (arXiv:1807.07072)
Methodology paper - SDSS Cluster Cosmology: Costanzi+ 18b (arXiv:1810.09456)
DES Y1 Cluster Cosmology: DES Collaboration 19, in prep.
GALAXY CLUSTERS

- Most massive bound objects in the Universe: $M \approx 10^{13} - 10^{15} M_\odot$ and $R = 1 - 5$ Mpc

- Multi-component systems: galaxies and stars ($\approx 5\%$), ICM ($\approx 15\%$), DM ($\approx 80\%$)
THE DARK ENERGY SURVEY

- DES Survey:
  - ~5000 deg\(^2\) of southern sky
  - \(g,r,i,z,(Y)\) bands
  - 10 visits per pointing to reach \(i\sim 24\)

- DES Year 1:
  - ~1500 deg\(^2\) with 10\(\sigma\) depth \(i\sim 22.9\)
  - \(N_{\text{eff}}\sim 6.3\) arcmin\(^{-2}\) (34M source glxs)

From Zuntz+ 17 - DES Year 5 - DES Year 1
- **red-sequence** Matched-filter Probabilistic Percolation cluster finding algorithm *(Rykoff+14)*:

Detect overdensities of red-sequence galaxies and assign a membership probability, $p_{\text{mem}}$, to each cluster member candidate.

\[
\lambda_{\text{ob}} = \sum_{R < R_\lambda} p_{\text{mem}}
\]

\[
z_{\text{ob}}
\]

<table>
<thead>
<tr>
<th>Area [deg$^2$]</th>
<th>Redshift range</th>
<th># of clusters ($\lambda &gt; 20$)</th>
<th>$\sigma_z/(1+z)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1470</td>
<td>0.2$&lt;z&lt;0.65$</td>
<td>~6540</td>
<td>0.006</td>
</tr>
</tbody>
</table>

From McClintock+18
The abundance of galaxy clusters is sensitive to the growth rate of cosmic structures and expansion history of the Universe.

\[ S_8 = \sigma_8 (\Omega_m / 0.3)^{0.5} \]

\( \sigma_8 \): Amplitude of the matter power spectrum

\( \Omega_m \): Present-day total matter density

Dark energy equation of state parameter

Total neutrino mass

Deviation from GR

….

See e.g. Allen+2011 or Kravtsov+2012 for a review.
Massive neutrinos:
- Delay the epoch of matter-radiation equality
- Suppress the growth of density fluctuation on scale smaller than the free-streaming length

Effects on the number density of halos as a function of mass

From Viel+14
Modified gravity models, e.g. $f(R)$:

- Give rise to accelerated expansion and enhance gravity
- Introduce screening mechanism that restores GR in high density environments

Relative effect on the Halo Mass Function compared to $\Lambda$CDM

From Hagstotz+18
From theory to observation

For optically-selected clusters:

$\lambda =$ richness~ # member galaxies
• From theory to observation

From theory

$N(M)$

$M$

$\Omega_m \sigma_8$

E.g. $\Omega_m \sigma_8$?

From observation

$N(\lambda^{ob})$

$\lambda^{ob}$

$\Omega_m \sigma_8$???
Combine cluster abundance and cluster mass estimates to simultaneously constrain cosmology and the richness-mass relation.

From theory:

- $N(M)$
- $\Omega_m$, $\sigma_8$
- E.g. $\Omega_m$, $\sigma_8$

From observation:

- $L(|\theta|D)$
- $N(\lambda^{ob})$
- $M(\lambda^{ob})$
- $\lambda^{ob}$
- E.g. $\lambda^{ob}$
- $\lambda^{ob}$
- $\lambda^{ob}$

Richness-mass relation:

- $\lambda^{ob}$
- E.g. $\lambda^{ob}$
- $\lambda^{ob}$
- $\lambda^{ob}$
- $\lambda^{ob}$
- $\lambda^{ob}$
- $\lambda^{ob}$
- $\lambda^{ob}$

LineA webinar - Oct 2019 | Matteo Costanzi
Gravitational lensing:

Tangential shear: the tangential alignment of background galaxies around foreground clusters due to gravitational lensing

Tangential shear $\propto$ Surface mass density of the cluster
Mass estimates in DES Y1:

- Stack clusters in bin of richness and redshift
- Measure the mean tangential shear of background galaxies in radial bin around the cluster center
- Compute the (excess) surface mass density profile $\Delta \Sigma$
- Fit for the mean mass of the $\lambda/z$ bin

Surface mass density profile from stacked lensing analysis
WL MASS ESTIMATES MODELING AND SYSTEMATICS

<table>
<thead>
<tr>
<th>Source of systematic</th>
<th>Y1 Amplitude Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear measurement</td>
<td>1.7%</td>
</tr>
<tr>
<td>Photometric redshifts</td>
<td>2.6%</td>
</tr>
<tr>
<td>Modeling systematics</td>
<td>0.73%</td>
</tr>
<tr>
<td>Membership dilution + miscentering</td>
<td>0.78% (Varga+19, Zhang+19)</td>
</tr>
</tbody>
</table>

From McClintock+18 (WL mass calibration of redMaPPer DESY1)

Effect of different systematics on the model prediction

Modeling of the cosmological dependence of the WL mass estimates (<1% uncertainty)
The cluster finder might select preferentially clusters with some properties which correlate with WL signal (e.g. elongated along the l.o.s.)

Calibrate selection effects with simulations:

- Run redMaPPer on simulations
- Select clusters in $\lambda/z$ bins
- Select clusters with the same mass/z distribution as the $\lambda/z$ selected sample
- Compare the stacked $\Sigma(R)$ profiles of the two samples
Selection effect bias:

- Mostly explained by projection and triaxility effects
- Lowers mass estimates by ~20%-30% in all richness and redshift bins
- Increases the error on WL mass estimates by a factor of 2 (main source of uncertainty for Y1!)

Mean % error budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma^{\text{tot}} / M$</td>
<td>18%</td>
</tr>
<tr>
<td>$\sigma^{\text{stat}} / M$</td>
<td>10%</td>
</tr>
<tr>
<td>$\sigma^{\text{syst}} / M$</td>
<td>15%</td>
</tr>
</tbody>
</table>
CLUSTER NUMBER COUNTS ANALYSIS

- Bayesian approach

Likelihood model:

$$
L(d|\theta) \propto \exp \left[ -\frac{1}{2} \left( d - m(\theta) \right)^T C^{-1} \left( d - m(\theta) \right) \right]
\sqrt{(2\pi)^M \det(C)}
$$

- $d$: data \{NC($\lambda^{ob},z^{ob}$),$M_{WL}(\lambda^{ob},z^{ob})$\}
- $m(\vartheta)$: expectation values for NC($\lambda^{ob},z^{ob}$),$M_{WL}(\lambda^{ob},z^{ob})$ as a function of the parameters $\vartheta$
- $C$: covariance matrix ($C_{NC}$, $C_{WL}$)
• Expectation value NC (Forward modeling):

\[
\langle N(\Delta \lambda_i^{ob}, \Delta z_j^{ob}) \rangle = \int_{0}^{\infty} d\Delta \Omega_{\text{mask}}(\Delta z^{\text{true}}) \int_{\Delta z_j^{ob}} d\Delta z_i^{ob} \int_{\Delta \lambda_j^{ob}} dV \frac{dV}{d\Delta z^{\text{true}} d\Omega} \langle n(\Delta \lambda_i^{ob}, z^{\text{true}}) \rangle
\]

\[
\langle n(\Delta \lambda_i^{ob}, z^{\text{true}}) \rangle = \int_{0}^{\infty} dM n(M, z^{\text{true}}) \int_{\Delta \lambda_i^{ob}} d\lambda_i^{ob} P(\lambda_i^{ob} | M, z^{\text{true}})
\]

**Effective Survey Area**

**Photo-z error**

**HMF**

**Observed Richness-mass relation**

(a.k.a selection function)
EFFECTIVE SURVEY AREA and HMF / PHOTO-Z UNCERTAINTY

\[
P(z^\text{obs} | z^{\text{true}}) = \mathcal{N}(z^{\text{true}}, \sigma_z(z^{\text{true}}))
\]

Effective Survey Area: <1\% uncertainty

Photo-z error: <1\% uncertainty

Uncertainty HMF

\[
n(M, z) = n(M, z)^{\text{Tinker}} (s \log(M/M^*) + q)
\]

Priors on s & q calibrated with 40 N-body simulations spanning a range of cosmologies.
Observed richness-mass relation:

\[ \lambda^{\text{ob}} = \lambda^{\text{true}}(M,z) + \Delta\lambda(\lambda^{\text{true}},z) \]

\[ P(\lambda^{\text{ob}}|M,z) = \text{Probability to observe a cluster of mass } "M" \text{ and redshift } "z" \text{ with richness } "\lambda^{\text{ob}}" \]

\[ P(\lambda^{\text{ob}}|M,z) = \int_{0}^{\infty} d\lambda^{\text{true}} P(\lambda^{\text{ob}}|\lambda^{\text{true}}) P(\lambda^{\text{true}}|M,z) \]

Richness estimate error introduced by the cluster finder

“Intrinsic” Richness-mass relation
\( \lambda^{\text{true}} \): cluster richness in absence of errors introduced by the cluster finder (e.g., error in the background subtraction, projection effects)

**HOD-like Model:**

\[
\lambda^{\text{true}}(M) = \Theta(M-M_{\min}) \left[ 1 + \lambda^{\text{sat}}(M) \right]
\]

\[
\lambda^{\text{sat}}(M) = \left[ \frac{(M-M_{\min})}{(M_1-M_{\min})} \right]^\alpha
\]

- \( M_{\min} \): Minimum mass to form a CG
- \( M_1 \): Characteristic mass to acquire 1 Sat. Glx.
- \( \alpha \): Slope

\[
\lambda^{\text{sat}}(M) = \Delta^{\text{Pois}} + \Delta^{\text{Gauss}}
\]

\[
\text{PDF}(\Delta^{\text{Pois}}) = \text{Poisson(mean=}\lambda^{\text{sat}}(M))
\]

\[
\text{PDF}(\Delta^{\text{Gauss}}) = \text{Normal(mean=}0,\text{std=}\sigma_{\text{intr}}=\lambda^{\text{sat}}(M))
\]

\[
P(\lambda^{\text{true}}|M,z) = \text{Poisson*Normal} = \text{Skew-Normal distribution}
\]
Main sources of scatter in richness estimates:
- Uncertainties in the background subtraction
- Projection effects
- Percolation (loss of member galaxies due to projection effects)

\[ \lambda_{\text{ob}} = \lambda_{\text{true}}(M) + \Delta \lambda_{\text{obs-noise}} \]
MODELING OBSERVATIONAL NOISE

\[ \lambda^{\text{ob}} = \lambda^{\text{true}}(M) + \Delta \lambda^{\text{obs-noise}} \]

Richness-mass relation with and without obs. noise
MODELING OBSERVATIONAL NOISE

- From **DATA**, we can determine:
  - How background sources/photo-z noise contaminate $\lambda^{\text{true}}$
  - The magnitude of projection effects for two clusters aligned along the same line of sight

- From **SIMULATIONS**, we can determine:
  - How correlated structures (i.e. clusters in projection) contaminate $\lambda^{\text{true}}$

From Background contamination $\rightarrow$ Gaussian kernel
From projection effects $\rightarrow$ high richness tail
From percolation/masking effects $\rightarrow$ low richness tail
Miscentered clusters tend to have low (observed) richness:

We correct the NC data for miscentering effect:

\[ NC^{\text{w/o Misc}} = NC^{\text{Obs}} \gamma^{\text{cen}} \approx 1.03 \pm 0.01 \]

\( \gamma^{\text{cen}} \) derived by modeling (Zhang+19):

Radial offset distribution
(comparing X-ray vs redMaPPer center)

Richness perturbation as a function of the offset distribution
\[ \mathbf{C}_{\text{NC}} = \mathbf{C}_{\text{Poisson}} + \mathbf{C}_{\text{SampVar}} + \mathbf{C}_{\text{Misc}} \]

- \( \mathbf{C}_{\text{Poisson}} \): Contribution due to the Poisson fluctuations in the number of halos at given mass in the survey volume
- \( \mathbf{C}_{\text{SampVar}} \): Sample variance contribution due to the fluctuation of the density field in the survey volume
- \( \mathbf{C}_{\text{Misc}} \): Contribution due to uncertainty in the miscentering corrections

Covariance matrix validated using mock catalog.
LIKELIHOOD MODELING: $\langle M \rangle$

- Expectation value for the mean mass:

$$\log \langle \bar{M}(\Delta \lambda_i^{ob}, \Delta z_j^{ob}) \rangle = \log \frac{\langle M^{tot}(\Delta \lambda_i^{ob}, \Delta z_j^{ob}) \rangle}{\langle N(\Delta \lambda_i^{ob}, \Delta z_j^{ob})w_{src}(z^{ob}) \rangle}$$

$$\langle M^{tot}(\Delta \lambda_i^{ob}, \Delta z_j^{ob}) \rangle = \int_0^\infty d\bar{z}^{true} \Omega_{mask} \frac{dV}{dz^{true}d\Omega}(z^{true})$$

$$\langle nM(\Delta \lambda_i^{ob}, z^{true}) \rangle \int_{\Delta z_j^{ob}} d\bar{z}^{ob} P(z^{ob}|z^{true})w_{src}(z^{ob})$$

$$\langle nM(\Delta \lambda_i^{ob}, z^{true}) \rangle = \int_0^\infty d\bar{M} M_n(M, z^{true}) \int_{\Delta \lambda_i^{ob}} d\lambda^{ob} P(\lambda^{ob}|M, z^{true})$$
COVARIANCE MATRIX FOR $M_{WL}$

Selection Effect Uncertainty
TESTING THE PIPELINE WITH redMaPPer SDSS

\[ \Delta \sigma_8^{SDSS} = 3 \Delta \sigma_8^{DES3x2/Planck} \]
\[ \Delta \Omega_m^{DESY1} = 2 \]
\[ \Delta \Omega_8^{DES3x2/Planck} \]

<table>
<thead>
<tr>
<th>Catalog</th>
<th>Redshift range</th>
<th>Area [deg²]</th>
<th># of clusters ((\mu_{ob}&gt;20))</th>
<th>WL analysis</th>
<th>(\sigma_{Mass})</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS DR8</td>
<td>0.1&lt;z&lt;0.30</td>
<td>10.000</td>
<td>~6964</td>
<td>Simet+17</td>
<td>13%</td>
</tr>
</tbody>
</table>
GOODNESS OF FIT & ROBUSTNESS OF THE ANALYSIS

Goodness of fit

Robustness to model assumptions and systematics

- Gray band: Reference Model
- RND-PNT-INJ: No contribution from correlated structures
- $\sigma_{\text{intr}}(M)$: Mass dependent scatter between $\lambda^{\text{true}}-M$
- $P(\lambda^{\text{true}}|\lambda)$=Lognorm. & $<\lambda^{\text{true}}|M>$= Pow. Law
- $P(\lambda^{\text{ob}}|M)$=Lognorm. & $<\lambda^{\text{ob}}|M>$= Pow. Law & $\sigma_{\text{intr}}(M)$
Mass distribution inside the $\lambda$ bins
COSMOLOGICAL CONSTRAINTS DESY1 $\Lambda$CDM+$\nu$ model

$\Lambda$CDM+$\nu$

<table>
<thead>
<tr>
<th>$\Delta S_8^{DESY1}$</th>
<th>$\Delta S_8^{SDSS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>$\Delta S_8^{SPT-SZ}$</td>
<td>1.7</td>
</tr>
<tr>
<td>$\Delta S_8^{DES3x2}$</td>
<td>1.8</td>
</tr>
<tr>
<td>$\Delta S_8^{Planck18}$</td>
<td>1.8</td>
</tr>
</tbody>
</table>

$\Rightarrow$ Selection effect uncertainty accounts for 16% of the total error budget on $S_8$

DES Collaboration 19, in prep.
Assume DESY1 3x2pt cosmology fit for the $\lambda$-$M$ relation using only NC or $M_{WL}$ data. Internal tension between Y1 NC and $M_{WL}$ data (@ DES 3x2pt cosmology) implies that either:

- The cosmological model is wrong ($\Lambda\text{CDM}+\nu$)
- There are unmodeled systematics, either in the NC or $M_{WL}$ data (or both)

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Internal tension between Y1 NC and $M_{WL}$ data (@ DES 3x2pt cosmology) implies that either:

- The cosmological model is wrong ($\Lambda$CDM+$\nu$)
- There are unmodeled systematics, either in the NC or $M_{WL}$ data (or both)

- If $M_{WL}$ estimates are correct: redMaPPer should be incomplete at ~50% at low $\lambda$ and ~25% at high $\lambda$
- If NC data are correct: $M_{WL}$ should be biased low by ~30% at low $\lambda$ and ~10% at high $\lambda$

DES Collaboration 19, in prep.
• Shear and photo-z systematics would affect the 3x2pt results even more strongly
• Miscentering model validated with 2 x-ray samples
• Cross-match with SZ (Planck, SPT) and X-ray (XCS) samples exclude large incompleteness at $\lambda \gtrsim 40$
• Cross-match with Swift X-ray sample exclude large contamination at $\lambda \approx 30$
• NC modeling/systematics does not have large impact on the posteriors
• Baryonic effects cannot account for 50% mass depletion in $\sim 10^{14}$ $M_\odot$ halos (e.g. Cui+14, Velliscig+14, Henson+17, Springel+17,)
• Too aggressive percolation scheme: decreasing the redMaPPer percolation radius by 20% change the NC by less than 1%

Effect on $\sigma_8$ and $\Omega_m$ of different model assumptions
- Selection effects bias might be overestimated at $\lambda \gtrsim 30$, but cannot explain correction needed at lowest $\lambda$-bin.

- Unmodeled systematic at $\lambda < 30$ (contamination?)
POSSIBLE SOLUTIONS . . .

- Dropping the lowest $\lambda$-bins remove the tension with DES3x2pt but the error on $S_8$ increase by 18%.

- Unmodeled systematic at $\lambda<30$ (contamination?)
Cluster abundance can be a powerful cosmological probe, provided we are able to precisely characterise the relation between observable and underlying halo mass.

DES Y1 cluster catalog can provide cosmological constraints which are independent and competitive with those obtained from other probes but . . .

Numerical simulations suggest that selection effects severely impact the $M_{WL}$ of redMaPPer clusters.

- Mass lowered by ~20% compared to previous estimates
- Currently represent the main source of systematic uncertainty (~50% of the $M_{WL}$ error budget)

Internal tension between NC and $M_{WL}$ pointed out unmodeled systematics (likely) in $M_{WL}$ data, which:

- has to be richness dependent
- has to dilute the WL signal for $\lambda<30$

Removing $\lambda<30$ data greatly reduce the tension, but at the expense of looser constraints.
● redMaPPer DES Y3: 4600 deg² up to z=0.7 → ~3 times more clusters than redMaPPer DES Y1!

● End-to-end simulations needed to calibrate selection effects and validate the modeling. Main limitations: galaxy color and clustering model, resolution limit for shear measurements. Hydro sims to calibrate bias in WL estimates

● Validation of selection effects with external data (especially at low $\lambda$):
  ○ Complete samples of spectroscopic data to validate projection effects
  ○ X-ray follow-up of complete samples to model miscentering and contamination and constrain the $\lambda$-M relation scatter
  ○ Cross-match with SZ and X-ray data to assess completeness (@ medium/high $\lambda$; SPT-3G and eROSITA might help also at low $\lambda$), test selection effects on WL signal (e.g. comparing WL signal of SZ and X-ray selected samples to redMaPPer)

● “Full” forward modeling of NC and WL signal (rather than passing through the mass calibration) to ensure consistency between the likelihoods and correctly account for cross correlations