Cluster Triaxiality on Stacked Weak Lensing Analysis

New Perspectives 2021


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Cluster Cosmology with optical surveys

- Combine cluster abundance and Weak lensing cluster mass estimates to simultaneously constrain cosmology and the richness-mass relation

Credit: Matteo Costanzi
Systematic Biases with Cluster Observables

- Uncertainty shear measurements
- Photo-z uncertainty
- **Triaxiality**
- Miscentering
- Line-of-sight projection
- Membership dilution
- Modeling systematics
- Cosmology dependence

In Y1:
Total systematic uncertainty: 4.3%
Statistical: 2.4%
T. McClintock+18

Statistical uncertainty dominated by shape noise:
- $n_s = \sim 5$ galaxies/arcmin$^2$
- $n_s = \sim 30$ galaxies/arcmin$^2$ for next-gen optical survey, e.g. Rubin (LSST)

Systematics on par with statistical errors, soon to dominate for near future surveys
Triaxiality Bias

Preferential selection of halos with major axes along the LOS

Boosting of lensing signal for high $\cos(i)$ clusters

$\cos(i) = 1$
higher lensing signal

$\cos(i) = 0$
lower lensing signal

Heidi Wu

Dietrich et al., 2014

Osato et al., 2018
A forward model for correcting for triaxiality in DES observable

$$\mu = \cos(i)$$

$$\langle \Delta \Sigma(R, M, \mu) \rangle \text{ for } \lambda \in [\lambda_1, \lambda_2)$$

$$= \int dM \Delta \Sigma(R, M, \mu) \tilde{P}(M)$$

$$= \int d\mu \int dM \int_{\lambda_1}^{\lambda_2} d\lambda \Delta \Sigma(R, M, \mu) P(\lambda|M, \mu) P(\mu|M) P(M)$$

$$\propto \int d\mu \int dM \int_{\lambda_1}^{\lambda_2} d\lambda \Delta \Sigma(R, M, \mu) P(\lambda|M, \mu) P(M)$$

Stacked lensing profile w/o redMaPPer selection

Boosting of observed richness w/ redMaPPer selection
## Simulation Dataset -- Buzzard

<table>
<thead>
<tr>
<th>Halos</th>
<th>RedMaPPer</th>
<th>Halo-cluster matching</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z \in [0.00, 0.34)$, $2.7 \times 10^{10} , h^{-1} M_\odot$</td>
<td>Volume limited sample for $\lambda &gt; 20$. 24,243 clusters in simulated Y1 footprint</td>
<td>Finds matching candidate inside 2D $2 , h^{-1} Mpc$ within $\Delta z &lt; 0.05$</td>
</tr>
<tr>
<td>$z \in [0.34, 0.90)$, $1.3 \times 10^{11} , h^{-1} M_\odot$</td>
<td>~10000 particles for $10^{15} , h^{-1} M_\odot$ halo</td>
<td>Two way uniqueness matching rank-ordered by mass and richness. Matched rate of 97% (23658/24243).</td>
</tr>
<tr>
<td>$\sim 10000$ particles for $10^{15} , h^{-1} M_\odot$ halo</td>
<td>Shape of halos measured by reduced quadrupole moment of particles inside elliptical $R_{vir}$</td>
<td></td>
</tr>
</tbody>
</table>
Bias in shape or orientation?

Marginal shift in prolateness compared to RND and no shift across cos(i) bins

Noticeable boosting of \( P(\cos(i)) \) from uniform, highest at high richness
Effect of triaxiality on richness-mass $P(\lambda|M, \mu)$

\[
\mu(\ln \lambda) = \log(A) + B \times (\ln M - 14 \ln(10))
\]

\[
\sigma^2(\ln \lambda) = \sigma_0^2 + \frac{\exp(\mu(\ln \lambda)) - 1}{\exp(2\mu(\ln \lambda))}
\]
Stacked lensing profiles $\Delta \Sigma (R, M, \mu)$

Assumes a “bottleneck” shape for lensing profiles, in agreement with Osato+18, and quantified in $(M, z)$ bins in this paper:

$$F(R, \mu) = \log \frac{\Delta \Sigma (R, \mu)}{\Delta \Sigma (R)}.$$

$$F(R, \mu) = A(\mu) f(R)$$

$$A(\mu) = A_0 + A_1 \mu + A_2 \mu^2 + A_3 \mu^3$$

$$f(x \equiv \ln(R)) = 1 - \frac{1}{(x - x_0)^2 + \gamma}.$$
Mass estimation using Fisher forecast:

- Marginalizing over $M$, $c$ using Mandelbaum+08 $M$-$c$ relation
- Summed across all $M$, $z$ bins
- Integrating over 100 Mpc using Cov. from Wu+19 for DES-like survey dominated by diagonal shape noise
- Boosting in lensing profile provided by this model

Results:

- 1-5% mass bias for stacked clusters selected by redMaPPer
- Slight richness dependence, highest at medium richness bin.
Triaxiality and projection effects corrects the weak lensing mass at \lambda > 30.

They fail to resolve the “lensing-is-low” tension at \lambda < 30. Hints at other potential systematic.

To further study the bias and richness dependence of triaxiality, we can test this effect through:
- simulations with different halo-galaxy connection models e.g. cosmoDC2
- v.2.0.0 Buzzard
  - Updated cluster clustering properties and red-sequence matching

DES Collaboration 2020
Testing correlations with other systematics

Miscentering

Comparison of ACT SZ center with Brightest Central Galaxy (BCG) for SDSS.
N. Battaglia et al. 2016

Projection Effects

Heidi Wu
Correlation with leading systematics -- miscentering

Left panel:
Buzzard reproduces the richness bias caused by miscentering as observed using SDSS/DES and Chandra from Y. Zhang+19

Right panel:
No correlation found between miscentering and triaxiality

Takeaways:
- Lack of correlation not surprising given the difference in physical origin of these effects
- All miscentered BCGs in Buzzard were identified as a member of the same redMaPPer cluster -- projection effects not prominent cause of miscentering
Correlation with leading systematics -- projection

Top:
No correlation with $\sigma_z$ proxy, quantity observable by real data.

$$w(\Delta z|z_{cl}) = \begin{cases} 1 - \frac{(\Delta z)^2}{\sigma_z(z_{cl})^2}, & |\Delta z| < \sigma_z(z_{cl}) \\ 0, & \text{otherwise} \end{cases} \quad \text{(Costanzi+18)}$$

Bottom:
No correlation with $\lambda_{obs}$ using full projection model

$$\lambda^{obs} = \lambda^{true} + \Delta^{bkg} + \Delta^{prj}_{non\text{-}cor} + \Delta^{prj}_{LSS} + \Delta^{prc}$$

Takeaways:
- Lack of correlation may be puzzling given a shared physical origin.
  - LCDM facilitates cluster formation at nodes of filaments
  - Halo’s semi-major axis is preferentially aligned with filaments’ (e.g. Hahn et al. (2007), Forero-Romero et al. (2014))
- Explained by “One bad apple spoils the whole barrel” effect
  - Minority of clusters in clusters have strong projection (Sunayama+20)
  - All halos, whether in filaments or not, subject to the same level of triaxiality bias
Conclusion

1. We find marginal change in the prolateness of halo distribution for redMaPPer selected clusters.

2. Quantify the change in richness--mass amplitude as a function of orientation.

3. Confirm the bottleneck shape in the transition between one and two halo regimes for halo lensing profiles, in agreement with Osato+18.

4. We find a null correlation between triaxiality and two other leading systematics in DES Y1 cluster cosmology--miscentering and projections, and offer explanations or follow-up studies for this result.

5. We quantify through items (2) and (3) the DES observable of richness-stacked redMaPPer cluster lensing profiles to predict an upward mass bias of 1-5% after correcting for triaxiality.

6. We find that the mean $P(\cos(i))$ and the mass bias are both richness dependent, largest and mid-to-high richness ranges, in accordance with the DES Y1 result that triaxiality does not fully resolve the tension in weak lensing mass at low richnesses.
Extra Slides