Towards observing the imprint of dynamical dark matter interactions within galaxy clusters

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DES working group
Daniel Gruen, Niall McCrann, Tom McClintock, Eduardo Rozo, Erin Sheldon, +++
ΛCDM
Λ: Dark energy properties and other parameters we can constrain from large scale cosmological analyses

CDM: The cold dark matter paradigm can be tested from small scale observations, the non-linear evolution of the density field
ΛCDM

Λ: Cluster cosmology, through the halo mass function, requires cluster finder number counts, and weak lensing mass calibration

CDM: Cluster Substructure: tidal stripping, subhalo lensing

Cold, warm, hot dark matter?

Fuzzy dark matter?

Self interaction?

...
Cartoon version of what we are targeting

- Cluster halo
- Galaxy halo
- Central galaxy
- Cluster member
- Field galaxy
- Stars in Galaxy halo
In simulations the picture is a little bit more complicated ...
Recap on Weak Gravitational lensing

- The light from background “sources” is deflected by the gravitational potential of objects along the line of sight.
- Gravitational shear ~ anisotropic shape distortion of background galaxies.
- The mass properties of the “lens” can be reconstructed by tracking these image distortions.

\[
\Delta \Sigma \equiv \bar{\Sigma}(<R) - \bar{\Sigma}(R) = \Sigma_{\text{crit}} \gamma^T(R),
\]

Tangential shear
Observational scenario in the Dark Energy Survey

From similar images we extract:

- Galaxy catalog
- Galaxy Shapes
- Photometric Redshifts
- Galaxy Clusters

Two example clusters from DES Y3

DES collaboration et al. in prep
Varga et al. in prep
Traditional WL science driver: Cluster cosmology

1) Find clusters in nature by mass proxy

2) calibrate masses from WL

3) recover halo mass function

We can constrain cosmology through the halo mass function...

DES collaboration et al in prep
Costanzi et al 2019
McClintock & Varga et al 2019
Varga et al 2019
Zhang et al 2019
Focus of most studies is mass calibration for cosmology.

These clusters nevertheless host the subhalos we are focusing on.

Drive great number of ancillary studies:

- Redshift bias and calibration (Varga et al 2019)
- Photometric projection effects (Costanzi et al 2019, Gruen et al in prep)
- Photometric centersing (Zhang et al 2019)

### Table: Systematic Uncertainties

<table>
<thead>
<tr>
<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>
<td>1.7%</td>
</tr>
<tr>
<td>Photometric redshifts</td>
<td>3%</td>
<td>2.6%</td>
</tr>
<tr>
<td>Modeling systematics</td>
<td>2%</td>
<td>0.73%</td>
</tr>
<tr>
<td>Cluster triaxiality</td>
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<td>2.0%</td>
</tr>
<tr>
<td>Line-of-sight projections</td>
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<td>2.0%</td>
</tr>
<tr>
<td>Membership dilution + miscentering</td>
<td>≤1%</td>
<td>0.78%</td>
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<tr>
<td><strong>Total Systematics</strong></td>
<td>6.1%</td>
<td>4.3%</td>
</tr>
<tr>
<td><strong>Total Statistical</strong></td>
<td>9.4%</td>
<td>2.4%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>11.2%</td>
<td>5.0%</td>
</tr>
</tbody>
</table>

McClintock & Varga et al. 2018
Subhalo lensing outline

- Measure the lensing signal around cluster galaxies in DES data

- Physical interpretation

Varga et al in prep
See also Niemiec et al 2017, Sifon et al 2016, Li et al 2014
Estimators for gravitational shear

Use a model fit to estimate ellipticity

The intrinsic bias of the estimator is self calibrated on the data, but we still want to know the estimator bias

\[ g_i = (1 + m_i)g_i^{\text{tr}} + \alpha \frac{PSF}{PSF} e_i + c_i, \]

Estimator response formalism:

\[ \langle \gamma \rangle \approx \langle R \rangle^{-1} \langle R \cdot \gamma_{\text{true}} \rangle \approx \langle R \rangle^{-1} \langle e \rangle \]

\[ \langle R \rangle \approx \frac{\langle e_i^+ \rangle^S - \langle e_i^- \rangle^S}{\Delta \gamma_j} + \frac{\langle e_i \rangle^{S+} - \langle e_i \rangle^{S-}}{\Delta \gamma_j} \equiv \langle R_{\gamma} \rangle + \langle R_S \rangle, \]

GREAT08 et al. 2008

Metacalibration, Huff & Mandelbaum 2017, Sheldon & Huff 2017, (DES Y1)
Galaxy Clusters are different from the median line of sight

This present unique systematics:

- Increased chance overlaps (blending) between the light of different galaxies, leading to increased shear bias
- Presence of intra-cluster light, leading to photo-z and shear bias
- Non-weak shear near cluster centers
Construct plausible cluster mock simulations

We have to simulate full line of sight, not just galaxy cluster

- Galaxy distribution (CLF, radial population profile)
- Galaxy Morphology
- Intra Cluster Light

Render the mock clusters into multi-band observations and process them with a DES-like pipeline
Represent the 8D conditional feature space via Kernel Density Estimates

NOTE: For cluster at $z \sim 0.3 - 0.4$ use only $g-r$, and $r-i$ band in color extrapolation, this is motivated by location of 4000Å break, and improves sampling performance

+ Extrapolate properties of undetected galaxies
Simulation Processing pipeline

- Create catalog of clusters as random draw from $P_D(\bar{s}, m, \bar{c}, R \mid \lambda, z)$

- Process with main DES simulation pipeline developed by Niall McCrann et al.

  Galsim $\rightarrow$ SWARP $\rightarrow$ SExtractor $\rightarrow$ MEDS $\rightarrow$ Metacalibration

Mock source galaxy selection in simulations

PRELIMINARY

$M_{\text{clust}} \sim 1 \times 10^{14} \text{ Msun}, z \sim 0.38$

$Y_t$ vs. Theta [deg]

PRELIMINARY
The mock galaxies should look plausible...

DES collaboration et al in prep
Varga et al. in prep
The mock galaxies should look plausible...

Can you tell which one is real and which one is simulated?

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Galaxy cluster from DES Y3

MOCK galaxy cluster rendered via emulator pipeline

*DES collaboration et al in prep*
*Varga et al. in prep*
The path to subhalo weak lensing mass constraints

- Reliable shear estimates (Varga et al in prep, this work)
- Reliable redshift estimates and contamination (Varga et. al 2019)
- Target selection function and projection effects (Gruen et al in prep, Costanzi et al 2019)

What is missing is theoretical predictions on what we expect to see assuming various DM models.

Subhalo truncation?  Stratification?  Disruption?
Summary & Conclusions

- Weak Lensing mass constraints can inform us about the nature and outcome of tidal interactions in the highly non-linear regime of structure evolution.

- The uncertainty budget of lensing measurements is now increasingly dominated by systematics, most of which we can calibrate out.

- At the present level we are relying on empirical relations scaling relations to interpret results.

- What is missing is connecting physical theory of DM to measured behavior.