Probing large scale structure with galaxy and CMB surveys

Eric Baxter, University of Pennsylvania

with Yuuki Omori, Chihway Chang, Bhuvnesh Jain, Judit Prat, Lucas Secco, Shivam Pandey, Tae-Hyeon Shin, Scott Dodelson, Tom Crawford, and many others in the Dark Energy Survey, South Pole Telescope and Atacama Cosmology Telescope collaborations
The standard cosmological model

Credit: WMAP
The large scale structure (LSS) of the Universe

credit: Millennium simulation, Springel et al. 2005
The large scale structure (LSS) of the Universe

LSS provides a tool to answer many fundamental cosmological questions:

What is driving the accelerated expansion of the Universe?
Did inflation occur?
What is the particle nature of dark matter?
What is the sum of the neutrino masses?
Is there evidence for departures from general relativity?

credit: Millennium simulation, Springel et al. 2005
Probing large scale structure with a galaxy survey

Galaxy positions trace large scale structure

Galaxy lensing measures mass directly
Probing large scale structure with a galaxy survey

Light from galaxies

Galaxy positions trace large scale structure

Galaxy lensing measures mass directly
Probing large scale structure with a Cosmic Microwave Background survey

Microwaves sourced from $z \sim 1100$  
($t \sim 380,000$ yrs)

South Pole Telescope
We can use CMB surveys to probe large scale structure at late times!
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Probing large scale structure with a Cosmic Microwave Background survey

Primary anisotropies

Large scale structure induces **secondary** anisotropies

Sunyaev-Zel’dovich effect

We can use CMB surveys to probe large scale structure at late times!
Probing large scale structure with both galaxy and CMB surveys

Part I: large scales
Improving cosmological constraints by correlating galaxy surveys and CMB lensing

Part II: small scales
What is the boundary of a dark matter halo?
Part I: Large scales
Improving cosmological constraints by correlating galaxy surveys and CMB lensing
Two-point correlations between galaxy lensing and galaxy positions

Galaxy surveys measure lensing and galaxy density

Popular statistic is two-point correlation function:
\[ \langle f_1(\hat{n}) f_2(\hat{n} + \theta) \rangle \]

For isotropic Gaussian random field, 2pt functions contain all the information*  

*But...structure is not Gaussian, so 2pt functions don’t contain all the information  
(see work by Haiman, Hui, and others)
Cosmology with lensing correlations

The Limber approximation relates cross-spectrum between fields to an integral along the line of sight of the matter power spectrum:

\[ C_{XY}(\ell) \approx \int d\chi \frac{q_X(\chi)q_Y(\chi)}{\chi^2} P\left( k = \frac{\ell + 1/2}{\chi}, z(\chi) \right) \]

- \( \ell \) = multipole
- \( z \) = redshift
- \( k \) = wavenumber
- \( \chi \) = comoving distance
- \( P(k,z) \) = matter power spectrum
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**Cross-spectrum of fields** \( X \) and \( Y \)

**Geometry**

**Growth and geometry**

- \( \ell \) = multipole
- \( z \) = redshift
- \( k \) = wavenumber
- \( \chi \) = comoving distance
- \( P(k,z) = \) matter power spectrum

**Weight function**, \( q(z) \)

- \( q_{\text{galaxy density}}(z) \)
- \( q_{\text{galaxy lensing}}(z) \)

_Baxter et al. 2016_
The Dark Energy Survey Year 1 2pt analysis

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

\[ \sigma_8 = \text{amplitude of matter fluctuations} \]

\[ \Omega_m = \text{matter density} \]

< galaxies x galaxies >
< galaxies x lensing >
< lensing x lensing >
All three = "3x2pt"

DES Y1, Abbot et al. 2017
Consistent low redshift structure measurements

$S'_{8} \equiv \sigma_{8} (\Omega_{m}/0.3)^{0.5}$

$\sigma_{8} =$ amplitude of matter fluctuations  \hspace{1cm} $\Omega_{m} =$ matter density
Consistent low redshift structure measurements

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- \( \sigma_8 \) = amplitude of matter fluctuations
- \( \Omega_m \) = matter density

Low redshift structure \( z < 1.5 \)

- HSC Y1 (Hikage et al. 2018)
- DES Y1 (Troxel et al. 2018)
- KiDS–450 (Hildebrandt et al. 2017)
- KiDS–450 (Kohlinger et al. 2017)
- CFHTLenS re-analysis (Joudaki et al. 2017)

DES Y1 3x2pt (DES collaboration 2018)
Tension with primary CMB?

Low redshift vs. high redshift?

\[ S_8 \equiv \sigma_8 \left( \frac{\Omega_m}{0.3} \right)^{0.5} \]

\( \sigma_8 \) = amplitude of matter fluctuations  \( \Omega_m \) = matter density

Low redshift structure \( z < 1.5 \)

Primary CMB \( z \sim 1100 \)
Or are there systematic errors?

\[ S_8 \equiv \sigma_8 \left( \Omega_m / 0.3 \right)^{0.5} \]

\( \sigma_8 = \) amplitude of matter fluctuations
\( \Omega_m = \) matter density

Low redshift structure \( z < 1.5 \)
Primary CMB \( z \sim 1100 \)
Challenges of galaxy lensing

Potential sources of systematic error:

- Point spread function
- Overlapping galaxy images
- Intrinsic alignments
- Photometric redshift estimation is hard

As **statistical uncertainties** get smaller, **systematic errors** become increasingly important
Challenges of galaxy lensing

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- Point spread function
- Overlapping galaxy images
- Intrinsic alignments
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CMB lensing to the rescue

The cosmic microwave background (CMB) is also gravitationally lensed by large scale structure.

CMB lensing has several advantages:
- No photometric redshifts
- No overlapping galaxies
- No intrinsic alignments
- High redshift sensitivity (and there are lots of modes at high redshift)
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Baxter et al. 2016

![Graph showing weight functions of galaxy density and CMB lensing]
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CMB lensing provides a powerful probe of large scale structure that is independent of galaxy lensing systematics!
Joint analyses of galaxy and CMB lensing improve robustness of these measurements to biases.

Since galaxy lensing and CMB lensing are sensitive to different systematics, joint analyses self-calibrate potential biases.

Example: **multiplicative bias** (galaxy lensing systematic)

Data: DES Science Verification

![Galaxy bias vs Multiplicative bias graph]

**Baxter** et al. 2016
See also Schaan et al. 2016
The Dark Energy Survey Year 1
Galaxy survey x CMB lensing analysis

Joint measurement of six two-point functions:

\[
\langle \text{galaxy lensing} \times \text{galaxy lensing} \rangle
\]
\[
\langle \text{galaxies} \times \text{galaxies} \rangle
\]
\[
\langle \text{galaxies} \times \text{galaxy lensing} \rangle
\]
\[
\langle \text{galaxies} \times \text{CMB lensing} \rangle
\]
\[
\langle \text{galaxy lensing} \times \text{CMB lensing} \rangle
\]
\[
\langle \text{CMB lensing} \times \text{CMB lensing} \rangle
\]

CMB lensing measurements from the South Pole Telescope and Planck

The “6x2pt” papers:

Methodology + pipeline: Baxter et al. 2018

Omori et al. 2018

Omori, Baxter, 2018

Cosmological results: DES+ SPT, 2018
Bias from the Sunyaev-Zel’dovich effect

Thermal Sunyaev-Zel’dovich caused by inverse Compton scattering of CMB photons with hot electrons

Can potentially bias CMB lensing cross-correlations!

Note: thermal SZ is also a powerful probe of baryonic physics (see Hill, Baxter et al. 2017 Pandey, Baxter et al. in prep)
Beyond $z > 0.7$, signal-to-noise of galaxies x CMB lensing is about the same as galaxies x galaxy lensing.

6x2pt results:
high-redshift sensitivity of CMB lensing

Constraints on galaxy bias, $b$
Beyond $z > 0.7$, signal-to-noise of galaxies $\times$ CMB lensing is about the same as galaxies $\times$ galaxy lensing. 6x2pt results: high-redshift sensitivity of CMB lensing.
**6x2pt results:**

**high-redshift sensitivity of CMB lensing**

Beyond $z > 0.7$, signal-to-noise of galaxies x CMB lensing is about the same as galaxies x galaxy lensing.

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**Diagram:**

Constraints on galaxy bias, $b$ as a function of redshift ($z$). The high redshift regime of future surveys, like LSST and WFIRST.

Omor, ..., **Baxter**, et al. 2018
6x2pt results: robustness to systematics

Galaxy lensing sensitive to multiplicative bias

Galaxy surveys place priors on multiplicative bias, and these priors are derived from image simulations

CMB lensing cross-correlations help data to self-calibrate multiplicative bias

DES+SPT et al. 2018
6x2pt results:
Cosmological constraints

\[ S_8 \equiv \sigma_8 \left( \Omega_m / 0.3 \right)^{0.5} \]
6x2pt results:
Cosmological constraints

Joint galaxy lensing + CMB lensing analysis yields tighter constraints that are more robust to systematic errors!

$S_8 \equiv \sigma_8 (\Omega_m/0.3)^{0.5}$

DES+SPT et al. 2018
Future prospects with large scale structure x CMB lensing

CMB data: larger area, lower noise

Galaxy survey data: wider area, higher redshift

Methodology: eliminating SZ bias

Should know soon whether $S_8$ tension is real or due to systematic errors
Other ways to extract information from two-point functions of LSS

Modeling 2pt functions is challenging:
- Nonlinear power spectrum
- Galaxy bias
- Baryonic effects

Appropriately defined ratios of 2pt functions depend only on distances:

\[
\frac{\langle \delta_g(z_L) \kappa_{S,1} \rangle}{\langle \delta_g(z_L) \kappa_{S,2} \rangle} = \left( \frac{d_A(\chi_{S,1}, \chi_L) d_A(\chi_{S,2})}{d_A(\chi_{S,1}) d_A(\chi_{S,2}, \chi_L)} \right)
\]

and are therefore easy to model at all scales

Have now measured these ratios using DES and SPT (Prat, Baxter et al. 2018)
Galaxy cluster abundance probes information beyond the power spectrum

As most massive bound objects in the Universe, galaxy clusters form in rare, non-Gaussian peaks

Abundance of clusters is exponentially sensitive to growth of structure
Tension between clusters and CMB?

Douspis et al.
Accurate cluster masses are essential to cluster abundance cosmology.
CMB lensing to the rescue...again!

CMB lensing is complementary to galaxy lensing for measuring cluster masses.

Different systematics
- No photometric redshift errors! (dominant systematic for current cluster mass constraints from galaxy lensing)

High redshift sensitivity
- Important for future SZ-selected cluster samples

Red = space-based galaxy lensing
Blue = CMB S4–like experiment

Lewis & King 2006
CMB cluster lensing is a rapidly evolving field...

First detection of CMB cluster lensing in 2016 with South Pole Telescope-selected clusters (Baxter et al. 2016)

3.1σ detection with 513 SZ-selected clusters!
CMB cluster lensing is a rapidly evolving field...

First detection of CMB cluster lensing in 2016 with South Pole Telescope-selected clusters (Baxter et al. 2016)

Recent measurements using optically selected clusters (Geach & Peacock 2017, Baxter et al. 2018)

Now provides useful constraints on cluster mass-observable relations
The Future for CMB cluster lensing

**More clusters:**
Future galaxy and CMB surveys will detect many clusters, and at high redshifts

**Better CMB data:**
larger area, lower noise, polarization

**Methodology:**
less SZ contamination

<table>
<thead>
<tr>
<th>Experiment</th>
<th># of clusters</th>
<th>$\sigma(M)$</th>
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<tbody>
<tr>
<td>CMB - S4</td>
<td>100,000</td>
<td>0.87%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.95%</td>
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<td>1.20%</td>
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<tr>
<td>SPT-3G</td>
<td>10,000</td>
<td>3.28%</td>
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<td>AdvACT</td>
<td></td>
<td>4.35%</td>
</tr>
<tr>
<td>Simons Array - Deep</td>
<td></td>
<td>4.41%</td>
</tr>
<tr>
<td>Simons Array - Wide</td>
<td></td>
<td>5.86%</td>
</tr>
</tbody>
</table>

Raghunathan, Patil, Baxter et al. 2017
Part II: Small Scales
What is the boundary of a dark matter halo?
Lots of interesting physics at “small” scales

Small scales probe
• Dark matter particle properties
• Galaxy formation
• Baryonic feedback
• ...

And there is lots of signal-to-noise!
What defines the boundary of a dark matter halo?

Simulated dark matter halo (Diemer et al. 2013)
What defines the boundary of a dark matter halo?

$R_{200} = \text{Radius at which mean enclosed density is 200x the background density}$
The formation of a dark matter halo

Second turnaround
= first apocenter
= “Splashback”

Fillmore & Goldreich (1984)
Bertschinger (1985)
Diemer & Kravstov (2014)
Adhikari et al. (2014)
Tully (2015)
More et al. (2016)
Splashback

Density profile averaged over many simulated halos

Density

Logarithmic derivative of density

$\Gamma = 0.8$

Splashback radius

$\rho (r) = \rho_s (r/R_s)^{-\nu}$

$\nu > 3.5$

$\nu = 3.5$

$\nu = 1$

$\nu = 0.5$

$\nu = 0$

Splashback as the boundary of a dark matter halo

Can we detect this feature in the data?
Can we detect this feature in the data?

And if so, what can we do with it?
Detecting splashback in the density profiles of real clusters

Use galaxies as proxy for halo mass profile to detect splashback

Cluster and galaxy samples from the **Sloan Digital Sky Survey (SDSS)**

**Diagram:**
- **Left Panel:**
  - Galaxy density profile:
    - SDSS measurements
    - Model fit
    - Infalling matter

- **Right Panel:**
  - $\frac{d \ln \rho_g(r)}{d \ln r}$
  - $r \ [h^{-1}\text{Mpc}]$
  - Total profile
  - Infall-subtracted profile

**Figure 2.**

**Posteriors on the galaxy profile parameters recovered from the MCMC analysis of the galaxy profile measurements.**

**Baxter et al. 2017**

See also Tully 2015, More et al. 2016
Detecting splashback in the mass profile

Galaxies don’t perfectly trace the mass!

First significant evidence for splashback feature using lensing

Directly probing the mass!

Note: this means weak lensing is now reaching sensitivity where models need to include splashback feature for correct mass calibration

Chang, Baxter et al. 2017
Detecting splashback with other clusters samples

Some evidence that splashback measurements are impacted by optical cluster finders
(Chang, **Baxter** et al. 2017
See also More et al. 2016, Busch & White 2017)

Have now confirmed evidence for splashback around SZ-selected cluster samples

**Data:**
South Pole Telescope (clusters)
Atacama Cosmology Telescope (clusters)
Dark Energy survey (galaxies and clusters)
Splashback as a tool for probing cluster physics

Splashback feature defines a measurable scale in clusters that can in principle be determined to high accuracy

\[ \frac{d \ln \rho_g(r)}{d \ln r} \]

---

**Halo accretion rate**

Faster accretion means smaller splashback radius

(Diemer & Kravtsov 2014)
Splashback as a tool for probing cluster physics

Splashback feature defines a measurable scale in clusters that can in principle be determined to high accuracy.

**Gravitational Physics:**

**Dynamical Friction**
Larger galaxies will have smaller splashback radii (Adhikari, Dalal, Clampitt 2016)

**Non-standard gravitational physics**
Modified gravity can impact splashback radius (Adhikari et al. 2018, Contigiani et al. 2018)
Splashback as a tool for probing cluster physics

Splashback feature defines a measurable scale in clusters that can in principle be determined to high accuracy.

**Splashback and quenching**
Simplified picture: galaxies inside splashback radius have encountered dense cluster environment, and their star formation has been quenched, making them red.

Splashback as a tool for probing cluster physics

Splashback feature defines a measurable scale in clusters that can in principle be determined to high accuracy

**Splashback and quenching**
Simplified picture: galaxies inside splashback radius have encountered dense cluster environment, and their star formation has been quenched, making them red

(Baxter et al. 2017,
The future of splashback studies

Splashback measurements transitioning from “detection only” to tool for probing cluster physics (e.g. Baxter et al. 2017)

**Significant improvements in signal-to-noise expected soon:**
- More clusters
- Better weak lensing measurements (DES Year 5, LSST, WFIRST, …)
Summary

Galaxy and CMB surveys provide remarkably complementary views of the large scale structure

**Large scales:**
Cross-correlations of galaxy surveys with CMB lensing yield tight cosmological constraints that are more robust to systematic errors

**Small scales:**
Splashback provides a powerful tool for studying the physics in the outskirts of dark matter halos