Constraining Cosmology with Galaxy Clusters Discovered by the South Pole Telescope

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We live in a flat universe whose density is dominated by dark energy.
Matter Dominated, No dark Energy

Source: Borgani and Guzzo 2001
Matter Dominated, No dark Energy

70% Dark Energy, 30% Matter

Source Borgani and Guzzo 2001
Dark Energy and Cluster Cosmology

Cluster Abundance: $dN/dz$

$$\frac{dN}{d\Omega \, dz} = n(z) \frac{dV}{d\Omega \, dz}$$

Depends on:
- Matter Power Spectrum, $\sigma_8$
- Growth Rate of Structure, $D(z)$

Depends on:
- Rate of Expansion, $H(z)$

Figure: J Mohr
Cluster Abundance: $\frac{dN}{d\Omega dz}$

\[
\frac{dN}{d\Omega dz} = n(z) \frac{dV}{d\Omega dz}
\]

Depends on:
- Matter Power Spectrum, $\sigma_8$
- Growth Rate of Structure, $D(z)$

Depends on:
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For Cosmology with Clusters We Need To Find Them. “Weigh” Them.
3 Approaches: Optical, X-ray, SZ

Recent/Ongoing/Near Future Surveys
3 Approaches: Optical, X-ray, SZ

Recent/Ongoing/Near Future Surveys

Weinberg et al. PhR 520, 87W (2013)
The Sunyaev Zel’dovich (SZ) Effect

Towards a massive cluster, ~1% of CMB photons scatter off of intra-cluster gas
The SZ-observable is tightly correlated with mass.

\[
\int y \, d\Omega \propto \frac{k_B T_e}{m_e c^2} \sigma_T \frac{N_e}{D_a^2}
\]

Integrated Signal proportional to total thermal energy, should faithfully track cluster mass.
We require high-resolution, wide-area surveys to discover significant numbers of clusters.
The South Pole Telescope (SPT)

10-meter sub-mm quality wavelength telescope

**90, 150, 220 GHz and 1.6, 1.2, 1.0 arcmin resolution**

**2007: SPT-SZ**
960 detectors
90,150,220 GHz

**2012: SPTpol**
1600 detectors
90,150 GHz
+**Polarization**

**2017: SPT-3G**
~15,200 detectors
90,150,220 GHz
+**Polarization**

**Funded By:**

U.S. Department of Energy
National Science Foundation
The 2500 deg$^2$ SPT-SZ Survey (2007-2011):

Final survey depths of:

90 GHz: 40 uK$_{CMB}$-arcmin
150 GHz: 17 uK$_{CMB}$-arcmin
220 GHz: 80 uK$_{CMB}$-arcmin
Planck
143 GHz
50 deg²
2x finer angular resolution WMAP
7x deeper
SPT
150 GHz
50 deg$^2$
6.5x finer angular resolution Planck
2.4x deeper
SPT
150 GHz
50 deg²

CMB Anisotropy
Primordial and secondary anisotropy in the CMB

Point Sources
Active galactic nuclei, and the most distant, star-forming galaxies

Clusters of Galaxies
“Shadows” in the microwave background from clusters of galaxies
Finding Clusters in the SPT Survey

- Matched-filter multi-frequency cluster finder (Melin et al. 2006)
> 677 candidates S/N >4.5
in SPT-SZ sample
Multiple-facility Imaging Campaign for Cluster Confirmation

516 Confirmed Clusters
The 2500d SPT-SZ Cluster Sample

- Median $M_{500c} \sim 3 \times 10^{14} M_{\odot}$
- $z_{\text{median}} = 0.55$

The $2500\text{d}$ SPT-SZ Cluster Sample

Lookback Time (Gyr)

Redshift

- Median $M_{500c} \sim 3 \times 10^{14} M_{\odot}$
- $z_{\text{median}} = 0.55$

Multi-wavelength Observations: Mass Calibration

- Multi-wavelength mass calibration campaign, including:

  1. **X-ray** with Chandra

  2. **Weak lensing** from Magellan ($0.3 < z < 0.6$) and HST ($z > 0.6$)

  3. **Dynamical masses** from NOAO 3-year survey on Gemini ($0.3 < z < 0.8$), VLT, Magellan at ($z > 0.8$)

Cosmological Analysis:
Combine X-ray Observables with SPT Cluster Survey

Use Markov-Chain Monte Carlo (MCMC) method to vary cosmology and cluster observable-mass relation simultaneously, while accounting for SZ selection in a self-consistent way.

9 Scaling Relation Parameters
• X-ray ($Y_x-M$) and SZ ($\zeta-M$) relations (4 and 5 parameters):
  A) normalization,
  B) slope,
  C) redshift evolution,
  D) scatter,
  F) correlated scatter

6 Cosmology Parameters (plus extension parameters)
• $\Lambda$CDM Cosmology
  - $\Omega_m h^2$, $\Omega_b h^2$, $A_s$, $n_s$, $\theta_s$
• Extension Cosmology
  - $\omega$, $\Sigma m_\nu$, $f_{NL}$, $N_{eff}$

From Benson+13 to de Haan+16, area in $\sigma_8-\Omega_m$ likelihood space reduced by $\sim 4x$

- Biggest improvement is in direction of parameter space helped by cluster counts

• Updated weak lensing calibration increases mass calibration by 10% (relative to Vikhlinin+09)

• Mass calibration assumes a 10% uncertainty in mass at z=0
  • Limited by small sample (10 clusters) in Vikhlinin+09, Hoekstra+15 comparison
  • Next step is to increase sample and extend to higher redshift

The Next Steps: [lensing, lensing, & more lensing!]

DES
Megacam
HST

- SPT-SZ 2500 deg$^2$
- ROSAT-All sky
- Planck-2015
- ACT

$M_{500c}$ [$10^{14} M_\odot h^{-1}$]

Redshift

$M_{500c}$ [$10^{14} M_\odot h^{-1}$]

Redshift
The Next Steps: [lensing, lensing, & more lensing!]

CMB

\[ M_{500c} \left[ 10^{14} \, M_{\odot} h^{-1} \right] \]

Redshift

SPT-SZ 2500 deg^2
ROSAT-All sky
Planck-2015
ACT
First “Internal” WL Cosmology Results from SPT

Consistent with previous SPT cluster cosmology results as well as other surveys; can constrain scaling relations without priors
Interesting internal pulls as we test consistency of the dataset

SPTcl $\Sigma m_\nu = 0.06 \text{eV}$
Planck $\Sigma m_\nu = 0.06 \text{eV}$

SPTcl
Planck

$z < 0.6$ clusters
$\tau$ prior
fiducial

$\sigma_8$

$\Omega_m$

$P$

$\Sigma m_\nu [\text{eV}]$
The SPT Surveys

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5000 deg² surveyed in total by SPT-SZ and SPTpol
- 150 GHz depths between 4-30 uK-arcmin (from ~Planck depth, to ~7 times deeper)
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5000 deg^2 surveyed in total by SPT-SZ and SPTpol

- 150 GHz depths between 4-30 uK-arcmin (from ~Planck depth, to ~7 times deeper)
**SPTpol-100d: Deep Survey**

- SPTpol 100d “deep field” is 3-4x deeper than SPT-SZ survey
- 81 clusters (~1 per deg\(^2\))
  - 15 clusters at \(z > 1\) (~19% of sample)
- SPTpol-deep 100d field overlaps with multi-wave surveys:
  - **Herschel** SPIRE (250, 350, 500 um) (Viero et al., 1810.10643)
  - **Spitzer** SSDF (3.6, 4.5 um) (Ashby et al., 1308.0201)
  - **ATCA** (1.8 GHz) (Tothill et al., 2013atnf.prop.5598T)
  - **XMM-XXL** (25 deg\(^2\)) (Pierre et al.)
  - **Targeted Chandra** (LP PI: McDonald) on 18 clusters at 0.8 < \(z\) < 1.4; hi-z pre-cursors to the Perseus cluster

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*Huang, Bleem, Stalder et al. 1907.09621*
The SPT Surveys

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5000 deg² surveyed in total by SPT-SZ and SPTpol

- 150 GHz depths between 4-30 uK-arcmin (from ~Planck depth, to ~7 times deeper)
500d Catalog Construction well underway!

- Incorporating all SPTpol 500d data; Final 150 GHz map depth ~5 uK-arcmin
- Ongoing DES-SPT projection for cluster confirmation
- 2 Spitzer programs complete
- NIR imaging on Magellan/FourStar
The SPT Surveys

5000 deg² surveyed in total by SPT-SZ and SPTpol

- 150 GHz depths between 4-30 uK-arcmin (from ~Planck depth, to ~7 times deeper)
The SPTpol Extended Cluster Survey

~2700 sq-degree survey, approximately Planck depths at arcmin resolution
New SZ-Selected catalog from 2700d of SPTpol Data!

- 447 SZ-selected clusters, with SPTpol 100d and SPT-SZ brings total number of clusters selected by SPT to >1,000

- Median redshift $z=0.49$, median mass $M_{500c} \sim 4.4 \times 10^{14} \, M_{\odot}/h_{70}$

- DES redMaPPeR confirmation for clusters to $z \sim 1$

- PanStarrs, WISE, & targeted imaging of clusters (Magellan/PISCO) outside of DES survey & of the highest redshift systems (FourStar, Spitzer)

Bleem+ (in prep)
At the high mass end, we can leverage SPT cluster data to characterize optically-selected clusters from DES.
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\[
\frac{\lambda}{E(z)^C_{\lambda}} \sqrt{\gamma^2 - 3/(\gamma E(z)^{C_{SZ}})}
\]

Mass-Richness Relation

\[M_{200m} [10^{14} M_\odot h^{-1}]\]

\[\text{Redshift} \quad \text{z=0.6} \]

This Work
CMB WL (Raghunathan +19)
Optical WL (Mantz +16)
Optical WL (McClintock +19)

Bleem+ (in prep)
What's next? Evolution of CMB Focal Planes

2001: ACBAR
16 detectors

2007: SPT
960 detectors

Stage-2
2012: SPTpol
~1600 detectors

Stage-3
2017: SPT-3G
~15,200 detectors

Stage-4
2027+: CMB-S4
100,000+ detectors

Detector sensitivity has been limited by photon “shot” noise for last ~15 years; further improvements are made only by making more detectors!
Whats next? Evolution of Focal Planes

More detectors!
(and bigger telescopes)
• SPT-3G data gets to ~Planck depth on 1500d field with a ~week of data.
• Observe 1500d field every ~2 days for 6 years
Preliminary SPT-3G EE Power Spectra:

Knox error bars shown
**Preliminary** SPT-3G EE Power Spectra:

Knox error bars shown
CMB-S4: Next Generation CMB Experiment

Enhance Future Surveys science by overlapping coverage

Figure from Jeff McMahon
High S/N (25-30σ) detection of CMB cluster lensing!

Cluster Forecasts

SPT-3G

Stage 4

Stage 4: Madhavacheril, Battaglia, Miyatake 2017

arXiv:1907.04473
Summary

• SPT has found hundreds of massive galaxy clusters spanning a redshift range $0.05 < z < 1.72$.

• Clean, mass-limited selection leads to a fantastic sample for cosmological and astrophysical studies.

• Cosmological analysis consistent with other cluster studies & CMB Cosmology

• Better mass calibration required to tighten constraints (and work is ongoing!).

• SPT-3G is deployed and observing.

• CMB-S4 will survey $\sim 70\%$ of the sky, detecting $>70,000$ SZ clusters.