Galaxy Cluster Cosmology with the South Pole Telescope and the Dark Energy Survey

with Sebastian Grandis, Matthias Klein, Maria Paulus, Joe Mohr (LMU Munich) and further members of the South Pole Telescope and Dark Energy Survey collaborations

Sebastian Bocquet — CMB-S4 Summer 2021 Meeting
Introduction to cluster abundance cosmology

- Halo abundance prediction from the halo mass function
- Compare observed with predicted number (see figure from Vikhlinin+09)
- Main limitation: how to convert from “mass” to the actual observable(s)? → mass calibration
I. Find cluster candidates
II. Get multi-wavelength follow-up data (including redshifts)

SPT-SZ cluster sample as of 2019, more recent work in a few slides

Precursor analyses based on X-ray mass calibration: Benson+13, Reichardt+13, Bocquet+15, de Haan+16

SPT-SZ cluster sample: 343 SZ-selected clusters above detection SNR 5 and $z > 0.25$

X-ray follow-up data: McDonald+13,17

Weak-lensing follow-up data:
HST-13 (Schrabback+18)
Megacam-19 (Dietrich,Bocquet+19)
III. Weak-lensing mass calibration

Megacam & Hubble data for SPT clusters (Schrabback et al. 2018; Dietrich, Bocquet et al. 2019)

We compare our best fit relation, where the slope was set by a prior we put on the slope. This is particularly obvious for the relations of Mahdavi et al. (2013). We used the degeneracy between the slope and marginal discrepancies at the extreme ends of the mass range under investigation here. For the mass–scaling relation this holds over mass and debiased SPT detection significance.

In Fig. 13 we show the scaling relation between cluster mass and debiased SPT detection significance for these clusters. We used this relation in a cosmological framework, as in de Haan et al. (2016) and Mantz et al. (2016). We pay particular attention to controlling systematic uncertainties in the weak lensing analysis and provide stringent upper limits for a large number of systematic uncertainties.

Finally, we compare our mass estimate for the stack of all 10 clusters from the Megacam sample without X-ray data used in the scaling relation this work to calibrate SZ—mass relation to the 32 clusters with weak lensing data. Points marked in black for the 32 clusters with weak lensing data. Points marked in black for the 32 clusters with weak lensing data.
IV. SPTcl Cosmological constraints

LCDM constraints (w/ massive neutrinos) Bocquet+19

- Wide flat priors on SZ scaling relation parameters fully encompass posterior

- Cluster constraint statistically limited by mass calibration: need more (weak lensing) data! (currently 32 clusters)

- 1.5σ agreement with Planck15 TT+lowTEB

![Figure 4. Distribution of clusters as a function of redshift (left panels) and detections significance (right panels). The top panels show the SPT-SZ data and the recovered model predictions for $\tilde{\nu}_m$. The bottom panels show the residuals of the data with respect to the model prediction. The different lines and shadings correspond to the mean recovered model and the 1 and 2 allowed ranges. The dotted lines show the Poisson error on the mean model prediction. There are no clear outliers and we conclude that the model provides an adequate fit to the data.]

![Figure 5. Constraints on $\Omega_m$ and $\sigma_8$ from this analysis and from a previous analysis that used the same cluster sample (dH16). The consistency ($\chi^2<1$) indicates that our internal mass calibration using WL data agrees with the external X-ray mass calibration priors adopted in dH16. There is good agreement among all probes as the 68% contours all overlap. In particular, the cluster-based constraints yield very similar $\Omega_m$, but WtG favor a somewhat higher $\sigma_8$. Interestingly, the degeneracy axis of WtG is slightly tilted with respect to SPTcl, which we attribute to the different redshift and mass ranges spanned by the two samples. We pay particular attention to a comparison with Planck (TT+lowTEB). Our constraint on $\sigma_8$ ($\Omega_m/0.3$) is lower than the one from Planck ($\Omega_m/0.3 = 0.766 \pm 0.025$) at 0.28 (1.1). In the two-dimensional $\Omega_m$-$\sigma_8$ space, the agreement is $p=0.13$ (1.5). We note that the latest analysis of the cluster sample selected by the Planck satellite is qualitatively in agreement with our constraint, as shown in Fig. 32 in Planck Collaboration et al. (2018a). Notably, the 95% contour of their result, calibrated using CMB lensing, encompasses the Planck primary CMB result in the $\Omega_m$-$\sigma_8$ plane.

4.1.4. Impact of X-ray Follow-up Data

We compare our baseline results from SPTcl (SPT-SZ+WL+X) with the ones obtained from the SPT-SZ+WL data combination, in which no X-ray follow-up data are included. In this case, we apply an informa-
How to improve?

— Larger cluster sample
— More weak-lensing data with small systematic uncertainties
Recent progress

New cluster catalogs:
- Deep 100 square-degree SPTpol-100d survey (Huang+20)
- Wide 2700 square-degree SPTpol-ECS survey (Bleem,Bocquet+20)

~1000 clusters above detection SNR 4.5
Redshifts/optical confirmation mainly from Dark Energy Survey

High-redshift cluster weak-lensing using Hubble Space Telescope
High-z dataset now comprises 30 HST clusters
(Schrabback,Bocquet+21)
Analysis of 9 additional z>1.1 cluster ongoing (Zohren+ in prep.)
• CTIO Blanco Telescope
• 5000 square degrees in grizy
• Survey is complete — analysis of Y3 data ongoing
• Strategically overlaps the SPT survey
SPT and DES surveys

Dark Energy Survey Year 3: griz, 4143 deg2, > 300e6 objects

SPT-SZ + SPTpol-ECS + SPTpol-500d: 5200 deg2
(deeper pol-100d and pol-500d are within SPT-SZ)

Figure 1. Footprint of the SPTpol Extended Cluster Survey (dark blue) as compared to the SPT-SZ (orange) and SPTpol 500d survey (light blue). Optical-near infrared imaging from the Dark Energy Survey (green-dashed region) covers $\approx 58\%$ of the survey footprint and is used to confirm a significant number of survey clusters presented in this work. The survey outlines are overlaid on the IRAS 100 $\mu$m map (Schlegel et al. 1998) with the orthographic projection chosen such that the South Celestial Pole is at the top of the globe. Beyond DES, SPT-ECS also has significant overlap with the southern field of the Kilo-Degree Survey, the Herschel–ATLAS survey, and the 2dFLenS spectroscopic survey.

The survey is composed of ten separate $\approx 250 \times 270$ deg$^2$ “fields”, each imaged to noise levels of $\approx 30 \times 40$ $\mu$K-arcmin at 150 GHz; see Table 1. The fields were observed by scanning the telescope at fixed elevation back and forth in azimuth at $\approx 0.55$ degrees/sec, stepping 10 arcmin in elevation, and then scanning in azimuth again. This process is repeated until the full field is covered in a complete “observation”. Each field was observed $>80$ times and twenty different dithered elevation starting points were used to provide uniform coverage in the final coadded maps.

2.2. Data Processing

The data processing and map-making procedures in this work follow closely those in previous SPT-SZ and SPTpol publications (see e.g., Schaer et al. 2011; Bleem et al. 2015b; Crites et al. 2015; Henning et al. 2018).

First, for each observation, the time-ordered bolometer data (TOD) is corrected for electrical cross talk between detectors and a small amount of bandwidth ($\approx 1.4$ Hz and harmonics) is notch filtered to remove spurious signals from the pulse tube coolers that cool the optics and receiver cryostats. Next, using the cut criteria detailed in Crites et al. (2015), detectors with poor noise performance, poor responsivity to optical sources, and/or anomalous jumps in TOD, are removed. As this work is focused on temperature-based science we relax the requirement that both bolometers in a pixel polarization pair be active for an observation. Relative gains across the array are then normalized using a combination of regular observations of both an internal calibrator source and the galactic HII region RCW38. For the first field observed in the survey—ra23hdec 35 1—internal calibrator was inadvertently disabled during summer maintenance for $\approx 50\%$ of the observations and so these data were relatively calibrated only with RCW38 observations.

The TOD is then processed on a per-azimuth scan basis by fitting and subtracting a seventh-order Legendre polynomial, applying an isotropic common mode filter that removes the mean of all detectors in a given frequency, high-passing the data at angular multipole $l = 300$ and low-passing the data at $l = 20,000$.

Sources detected in preliminary map making runs at 5 ($\approx 9$–15 mJy depending on field depth) at 150 GHz as well as bright radio sources detected in the Australia Telescope 20-GHz Survey (AT20G; Murphy 1 SPT fields are named for their central coordinates.

Bleem+20
SPT-SZ + SPTpol + DES Year 3 weak-lensing
Bocquet et al. in prep.

- O(1000) SPT selected clusters
  - Optical confirmation (Lindsey Bleem, Matthias Klein)
- DES weak-lensing mass calibration up to z~0.85
- Code validation using mocks
- Blind analysis
Cluster member contamination
a.k.a. boost factors (cluster members in lensing source sample)

- P(z) decomposition (e.g., Gruen+14, Varga+19) applied to non-stacked weak-lensing data
- Application to DES Year 1 data (see Figure; Paulus+ to be submitted)
- Following same approach for DES Year 3
Miscentering
Offset between true halo center and observational center

- Joint SZ & optical miscentering model
  - Fits the data
  - Reproduces SZ miscentering in Magneticum hydrodynamical simulation

- See also Saro+15, Gupta+16, Zhang+19
DES Y3 Weak-lensing shear and photo-z

Systematic uncertainty in inv(Sigma_crit)

Significant improvement over DES Year 1

Shout-out to the DES weak-lensing folks!

SPT SNR > 4.5 clusters

0.5 Mpc/h < r < 3.2 / (1+z) Mpc/h

Shear SNR ~ 80
Full weak-lensing model
Following Grandis, Bocquet+21

• Mass modeling (halo profiles, miscentering, uncorrelated LSS)

• Shear modeling (shear and photo-z calibration, cluster member contamination)

• Impact of baryonic effects on halo profiles by comparing Magneticum and Illustris TNG hydrodynamical simulations: 2% difference in mass

‣ Total systematic weak-lensing uncertainty: 3 — 6 % as function of cluster z
Outlook

• Not yet saturating systematic floor

• Weak-lensing mass calibration beyond \( z \sim 0.9 \) remains poorly constrained (but HST lensing up to \( z \sim 1.7 \))

• Looking forward to high-SNR CMB lensing!