The South Pole Telescope Sunyaev-Zel'dovich Cluster Survey
(Contribution to the XXL Extragalactic Survey Workshop)

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The 10-meter South Pole Telescope (SPT) is currently operating at the NSF South Pole research station. The telescope is designed for conducting large-area millimeter- and sub-millimeter-wave surveys of faint, low contrast emission, as required to map primary and secondary anisotropies in the cosmic microwave background. The first-generation receiver on the SPT is a 960-element micro-lithographed planar bolometric array with superconducting transition-edge sensors operating near the background limit to their sensitivity. The first key project, currently underway, is a survey of ≥ 1000 square degrees for galaxy clusters using the Sunyaev-Zel'dovich Effect (SZE). This survey should find many thousands of clusters with a mass selection criterion that is remarkably uniform with redshift. Armed with redshifts obtained from optical follow-up observations, the survey has sufficient statistical weight to place significant constraints on the equation of state of the dark energy. The most important potential source of systematic error in this measurement — the relationship between cluster mass and the integrated SZE — can be significantly reduced using complementary mass estimates from X-ray or lensing data for even a small fraction of clusters detected in the SZE survey.

I. INTRODUCTION

The scientific case for a large-area galaxy cluster survey using the Sunyaev-Zel'dovich Effect (SZE) has been well established over the past ten years[e.g., 1–3]. Most recently, the Dark Energy Task Force (DETF) report[4] recognized the potential of a 4,000 square-degree cluster survey to a mass limit of $\sim 2 \times 10^{14} h^{-1} M_\odot$ — their fiducial "Stage III" cluster experiment — to significantly further our current understanding of dark energy. These survey specifications are similar to those of the ongoing South Pole Telescope Sunyaev-Zel'dovich (SPT-SZ) cluster survey, which will be described in detail in section II.

However, the DETF also stressed the importance of minimizing systematic errors in all of the dark-energy science techniques they studied. For cluster surveys, they identified uncertainties in the relationship between cluster mass and the astronomically observable quantity (in our case, the integrated SZE) as the single most important source of potential systematic error. To mitigate this potential systematic, the DETF recommends: "Combined lensing, Sunyaev-Zeldovich, and x-ray observations of large numbers of galaxy clusters to constrain the relationship between galaxy cluster mass and observables."

We expect to obtain weak lensing data for our entire survey volume from the same dataset that provides cluster redshifts for the SPT-SZ survey, namely the Dark Energy Survey[5]. There is, however, no currently planned large-scale X-ray survey that would provide accurate X-ray mass estimates for even a fraction of the SPT-SZ clusters. This is a major scientific void which the XMM-XXL survey is poised to fill.

II. THE SPT-SZ SURVEY

The SPT-SZ survey is an ongoing survey of ≥ 1000 square degrees of the sky, using a three-color millimeter-wave (mm-wave) camera on the 10-meter South Pole Telescope (SPT, shown observing in figure 1). The combination of an ideal site for mm-wave observations, a carefully designed low-noise telescope, and nearly background-limited detectors should result in a survey depth (when the information from the three bands is combined) of roughly $10\mu\mathrm{K_{CMB}}$ per 1-arcminute pixel. This survey depth and the $\sim$1-arcminute resolution of the instrument results in a typical cluster mass for 5σ detection of roughly $2 \times 10^{14} h^{-1} M_\odot$, depending on assumptions about foregrounds, the cluster mass-SZE relation, and the spatial profile of the cluster SZE.

A. Survey Location

The location of the telescope — within 1km of the geographical South Pole, -89.992° latitude — and the mm-wave emission from the galactic plane make the choice of observing region for the survey quite simple. Restricting ourselves to regions of low thermal dust and synchrotron emission and to observing above 30° elevation (to keep the atmospheric column density through which we observe below a factor of two times the zenith value) clearly defines a region bounded roughly by $20h \leq \mathrm{RA} \leq 7h$, $-65^\circ \leq \delta \leq -30^\circ$. This region is outlined in figure 2, which shows an orthographic projection of the 100μm IRAS dust map [6], rotated such that the South Celestial Pole is up.

FIG. 1: The SPT observing while the sun rises at the South Pole. (Photo credit: Steve Padin)

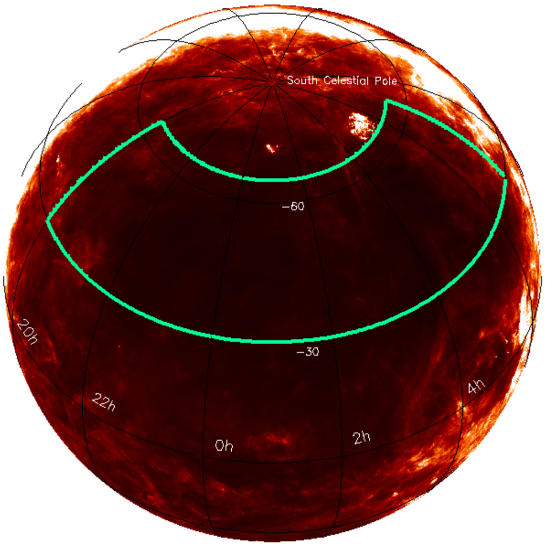

FIG. 2: One possible version of the SPT-SZ observing region, shown as borders on an orthographic projection of the IRAS 100μm dust emission. The area of the enclosed region is roughly 3840 square degrees.

ν_0 (GHz)	$\Delta\nu$ (GHz)	θ_{fwhm} (arcmin)	NET$_{\rm RJ}$ (μK$\sqrt{\rm s}$)	NET$_{\rm CMB}$ (μK$\sqrt{\rm s}$)	NEFD (mJy $\sqrt{\rm s}$)	1-yr depth (μK-arcmin)	2-yr depth (μK-arcmin)
95	30	1.58	248	304	16.0	24.6	17.4
150	38	1.00	172	297	11.4	24.0	17.0
219	40	0.69	184	606	13.4	49.1	34.7

TABLE I: Detector specifications and expected performance in each of the 2008 observation bands. ν_0 is the center of the frequency band and $\Delta\nu$ is the bandwidth. θ_{fwhm} is the full width at half-maximum of the diffraction limited telescope beam. NET$_{\rm RJ}$ and NET$_{\rm CMB}$ are the noise equivalent temperatures in Rayleigh-Jeans and CMB temperature units. NEFD is the noise equivalent flux density. 1-year and 2-year depths are calculated assuming a 4000 square-degree survey, a conservatively estimated 25% observing duty cycle, and a detector yield of 85%.

B. Survey Sensitivity

1. *Raw Focal Plane Sensitivity*

The focal plane for the SPT-SZ receiver consists of a 960-element, 3-band, micro-lithographed planar bolometric array with superconducting transition-edge sensors, fabricated in the microlab at UC Berkeley[7]. The detector parameters are tuned such that the devices operate near the background limit to their sensitivity, even at the very low optical loading conditions at the South Pole. Table I shows the projected sensitivities and beam sizes for the focal plane currently operating in the SPT-SZ receiver. These sensitivities are based on laboratory measurements of detector properties and projections of on-sky coupling efficiency. The 1-year and 2-year depths for each band are calculated assuming a 4000 square-degree survey, a conservative estimate of 25% of the total elapsed time spent observing, and a detector yield of 85%.

The effective depth and resolution of the final SZE maps from which cluster counts will be estimated depend on the relative contribution from the three bands in the final map, which in turn depends on one's assumptions about nature of the foregrounds (and backgrounds) that one is attempting to remove by combining the bands. As rough guesses for depth and resolution in the final SZE map, the combined statistical weight of the 95 GHz and 150 GHz bands and the mean of their beam sizes should not be very far off.

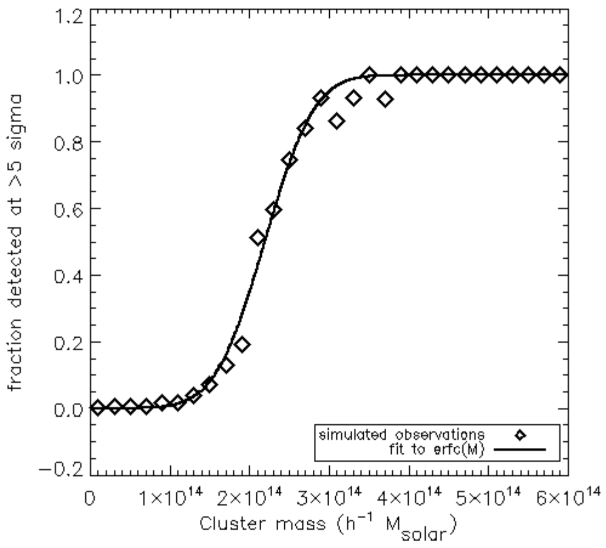

FIG. 3: Fraction of clusters detected at $\geq 5\sigma$ in simulated 2-season SPT-SZ observations as a function of cluster mass.

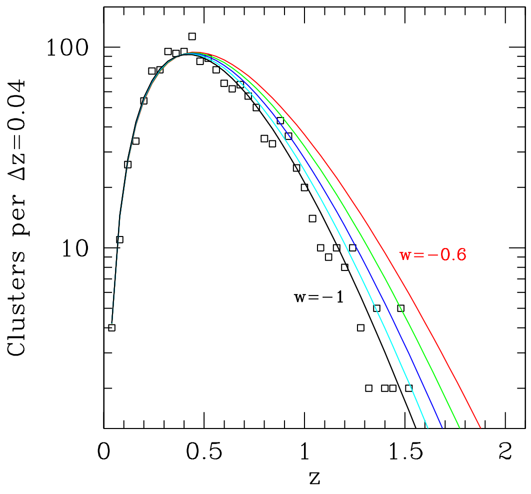

FIG. 4: Projected $dN(>M)/dz$ for $M = 2.5\times10^{14}h^{-1}M_\odot$ and a 4000 square degree survey, assuming a WMAP3 cosmology. The data points are Poisson-scattered around the mean number of clusters above the limiting mass in redshift bins of width $\Delta z = 0.04$. The black line shows the fiducial cosmology (WMAP3 with cosmological constant), and the colored lines show theoretical $dN(>M)/dz$ for different values of the dark energy equation-of-state parameter w. All theory curves are normalized to agree at $z = 0$. (Figure courtesy of Gil Holder)

2. *Simulated Observations*

Using the specifications in table I (specifically the beam sizes and 2-year depth predictions), we have performed simulated cluster observations to determine the SPT-SZ cluster sensitivity. The simulations include thermal SZE from an N-body simulation with semi-analytic gas physics[8], primary CMB, white instrument noise, and two populations of point sources: dusty protogalaxies based on a model of the SCUBA counts[9] and synchrotron-emitting AGNs with a modified Toffolatti population[10]. The amplitude of the AGN contribution is boosted within 1 arcminute of massive ($> 10^{14}h^{-1}M_\odot$) cluster centers in accordance with recent cm-wave measurements[11]. Simulated maps are created in each of our observing bands, then the bands are combined to maximize sensitivity to cluster SZE using a spatial-spectral optimal filter, calculated using the algorithm of [12].

The results of the simulated observation are summarized in figure 3, which shows the fraction of clusters detected at $\geq 5\sigma$ as a function of mass, regardless of cluster redshift (the mock SZE skies used in the simulation contain clusters above our nominal detection threshold from $z = 0$ to $z = 2$). According to a fit of the detection fraction vs. mass relationship to a complementary error function, the typical mass for 5σ detection is $2.2\times10^{14}h^{-1}M_\odot$, and the threshold for 90% completeness is $2.8\times10^{14}h^{-1}M_\odot$. The highest-mass bin in which any clusters are not detected at 5σ is $3.7\times10^{14}h^{-1}M_\odot$.

3. dN/dz

Figure 4 shows how the dN/dZ relation might look for a 4000 square-degree survey with a cluster selection function similar to the one shown in figure 3 and a low-σ_8 WMAP3 cosmology. The exact number of clusters in each redshift bin — and, hence, the size of the fractional Poisson error in each bin — is a very strong function of σ_8 and the mass limit, so we emphasize that figure 4 is not a robust prediction of the SPT-SZ cluster yield; it is just one possible outcome.

III. MASS ESTIMATES FROM SZE DATA: CALIBRATING THE MASS / SZE RELATION

The dN/dz plot in figure 4 assumes two properties of the cluster survey which will not be met by any real survey, including SPT-SZ: 1) The survey is entirely mass-limited, with an infinitely sharp cutoff at some value of cluster mass; 2) Every cluster detected will have a perfect mass measurement associated with it. The nature of the SZE makes cluster surveys such as SPT-SZ closer to mass-limited than any other type of cluster survey, and figure 3 shows that the mass threshold is reasonably sharp. However, the ability of SZE cluster surveys to independently measure the mass of every detected cluster is very much a subject of debate. [13], [14], and others have demonstrated that the cluster mass-integrated SZE relation for individual simulated clusters is quite tight ($\sim 10\%$ scatter), even when realistic gas physics and galaxy formation are included in the simulations (though these effects do change the normalization of the relation significantly).

Achieving this level of correlation between cluster mass and integrated SZE in a real survey, however, may be difficult. [8], [15], and others have pointed out that, in real surveys, confusion due to SZE from other clusters or large-scale structure along the line of sight will put a lower limit on the scatter in the mass-SZE relation. [15] point out further that variations in the gas fraction and spatial profile of the cluster SZE signal due to detailed cluster energetics can result in yet larger scatter.

Even if the scatter in the cluster mass-SZE relation proves to be closer to the 10% seen in individually simulated clusters, there are still the issues of normalization and potential redshift evolution of the relation. As the Dark Energy Task Force recognized, the best way to tackle all of these issues is to obtain as much complementary data as possible on the clusters detected in a survey such as SPT-SZ. X-ray mass estimates for a subset of SPT-SZ clusters from a survey such as XMM-XXL could provide a vital calibration anchor for the mass / SZE relation. For example, [16] showed that constraints on the dark energy equation-of-state parameter w could be degraded by a factor of two in an SPT-SZ-like survey by redshift evolution in the mass / SZE relation, but that the original constraints could be almost fully recovered with independent mass estimates for just 1% of the clusters. This could be accomplished in an X-ray survey of a few tens of square degrees.

As [17], [18], and others have pointed out, there is a wealth of information beyond simple cluster counts in surveys such as SPT-SZ. One can use this complementary information — such as the cluster angular power spectrum and the shape of the measured mass function — to “self-calibrate” the mass-SZE relation. However, [17] show that even in surveys powerful enough to allow such self-calibration, external mass measurements of a small subset of the cluster sample — as few as 100 clusters — provide an anchor to the self-calibration that significantly improves cosmological constraints.

IV. SUMMARY

The South Pole Telescope Sunyaev-Zel’dovich cluster survey is currently underway. The survey will map ≥ 1000 square degrees of the southern sky (between $20h \leq \mathrm{RA} \leq 7h$, $-65^\circ \leq \delta \leq -30^\circ$) with a projected survey size and cluster mass limit that is well matched to the Stage III survey specifications of the Dark Energy Task Force. The single most important potential source of systematic error in the survey is uncertainty in the relation between cluster mass and the integrated Sunyaev-Zel’dovich Effect. This potential systematic can be greatly mitigated using independent mass measurements of a subset of detected clusters, such as would be provided by the XMM-XXL Extragalactic Survey.

ACKNOWLEDGMENTS

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