# The South Pole Telescope

*A white paper for the Dark Energy Task Force*

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## 1 Overview

The primary goal of the South Pole Telescope (SPT) project is to set constraints on the nature of dark energy by measuring its impact on the growth of structure, specifically the evolution of the number density of massive galaxy clusters. The SPT will conduct a deep, large solid angle (4000 deg$^2$) galaxy cluster survey by exploiting the redshift-independence of the Sunyaev-Zel'dovich Effect (SZE). The SPT is a 10-meter submillimeter-wave telescope designed to conduct large surveys with high sensitivity to low surface brightness emission such as SZE measurements and CMB temperature and polarization anisotropy. To this goal the telescope uses an off-axis optical design, has a large field of view, employs three levels of shielding including an enormous ground shield, and is sited under the exceptionally clear and stable atmosphere at the South Pole. The SZE survey will be conducted with a 1000 element bolometric focal plane array configured with channels at 90 GHz, 150 GHz, 220 GHz and 270 GHz. The project is funded by NSF Office of Polar Programs (OPP), and the telescope and receiver are scheduled for deployment starting in 2006 November with the survey starting 2007 March. The survey goal is to cover 4000 deg$^2$ with 10 $\mu$K sensitivity per 1$'$ pixel to the SZE at an effective frequency of 150 GHz. The survey is expected to yield greater than $2 \times 10^4$ clusters with masses greater than $2 \times 10^{14} M_{\circ}$. Armed with cluster redshifts, the statistical power of the survey yields are sufficient to measure the dark energy equation of state parameter with 5% accuracy. Systematics are our primary concern. In this white paper, we will outline methods for addressing the systematics and projections for the resulting dark energy constraints. We will also review related observational and theoretical work to be done to ensure the best dark energy constraints are derived from the SPT SZE survey results.

To test theories of dark energy it is important to measure its affect on geometry, e.g., from Type Ia SN measurements, as well as its affect on the growth of structure, e.g., from cluster number density evolution. By combining both measurements it may be possible to differentiate between a flaw in our theory of gravity and the presence of a dark energy component in our universe.

In addition to the SZE survey, the SPT will conduct deep arcminute resolution CMB temperature

anisotropy measurements with the SZE receiver. A future, second generation receiver is planned to conduct CMB polarization measurements. The temperature and polarization measurements are also useful for constraining the nature of dark energy through its impact on the growth of structure and will provide independent tests. These measurements are not as sensitive as those expected from the SZE survey yields, however, and are therefore not discussed further in this white paper.

# 2 Precursor Observations and Developments

The SPT survey is the most ambitious SZE survey planned. Armed with optically determined cluster redshifts (see the discussion in §6 for plans to obtain redshifts), the SPT-SZE survey provides the statistical power to constrain the dark energy equation of state to 5%. Methods to address the systematics from consistency tests of the survey yields are discussed in the forecast section, §4. Here we review the precursor and follow-up observations as well as theoretical developments that will allow the best dark energy constraints to be derived from the SPT SZE survey yields.

To date all SZE measurements have been restricted to known galaxy clusters; SZE blind surveys have not had the sensitivity on the angular scales required to find clusters. The largest data set of SZE measurements has been made by the OVRO/BIMA cm-wave imaging experiment, in which 60 clusters have measured. The SuZIE experiment has also made multiband observations of 12 of the same clusters. Most of these were first detected in X-ray surveys and therefore have a different selection function than that expected for an SZE survey. The X-ray emission decreases rapidly with redshift and is concentrated in the core of the cluster.

Since the cluster SZE flux is a measure of the total thermal energy, the integrated pressure, it is essentially insensitive to the cluster core and should provide a better understood survey selection function. Furthermore, the SZE brightness is redshift independent, resulting in a SZE survey limit that is a mass limit with little redshift dependence.

Observationally this has been supported by the existing SZE detections and comparison of them with X-ray data (Benson *et al.* 2004; LaRoque 2005). The next step for "precursor" SZE studies is to conduct small SZE surveys so that the resulting cluster yields can be studied in depth by high resolution and multi-band SZE measurements, X-ray imaging and spectroscopic measurements and optical weak and strong lensing measurements. Analysis of these measurements will test the main assumptions of SZE surveys and provide detailed constraints on modeling the structure and evolution of galaxy clusters.

Research in cluster simulations should be conducted in parallel with the follow-up high resolution, multi-band SZE, optical and X-ray imaging and spectroscopy. Through the comparison of all these probes of SZE selected clusters, we will best be able to guide the interpretation of the large SPT SZE survey yields.

## 2.1 Cluster Observations

The first SZE surveys will be done by the Sunyaev-Zel'dovich Array (SZA), the Arcminute Imager (AMI) and APEX-SZ. The SZA is an 8 element interferometric array operating at 30 GHz and 90 GHz that builds upon the earlier OVRO/BIMA SZE work. It is roughly 100 times faster and also better matched to the angular scales of clusters. It is now working, and the SZA team expects to finish a deep 12 deg$^2$ SZE survey in a year. APEX-SZ is a  300 element bolometric array to be deployed on the 12-m ALMA prototype telescope APEX. It should conduct SZE surveys covering of order 100 deg$^2$ at 1 arcminute resolution over the next few years. Its detector technology prototypes the SPT's. The 6-meter Arcminute Cosmology Telescope (ACT) is similar to the SPT, but with lower angular resolution. It is planning to conduct a smaller but deeper survey targeted at CMB anisotropy. The ACT and SPT have similar timelines to deployment.

The unique strength of the SZA is in its imaging capability and ability to simultaneously image radio point sources at high resolution. The yields of the SZA mini-survey will be followed up at higher resolution by the SZA with CARMA which will provide sufficient sensitivity and angular dynamic range to image the SZE at better than 10 arcsecond resolution. The high resolution will allow detailed comparisons with X-ray and other cluster probes.

In the longer term, high resolution SZE imaging should be possible with the 100-meter Green Bank Telescope (GBT) outfitted with the 64-element Penn Bolometer array, the 50-meter Large Millimeter Telescope (LMT) outfitted with Bolocam II and Cluster Imaging Experiment (CIX), and in the more distant

future the 25-m Caltech-Cornell Atacama Telescope. Instruments such as the CIX with several bands in the millimeter and submillimeter and high angular resolution will allow constraints to be placed on the electron temperature and peculiar velocity of individual clusters. These experiments are not suited for conducting large surveys, but they will allow high resolution imaging and spectroscopy for follow-up SZE observations.

## 2.2  Point Source Observations

The foreground, which is the largest challenge for the SPT high resolution SZE observations, are points sources: radio non-thermal emission from AGN and thermal dust emission from galaxies. The number counts and spectra of the thermal emission from dusty galaxies is fairly well understood. The multiband SPT SZE survey should be able to remove their contamination from the resulting SZE maps with a residual noise level well below the survey goal of 10 $\mu$K per pixel.

The contamination from non-thermal radio sources is more difficult to predict. While it is largely assumed that the radio source contamination will not be a problem at frequencies as high as 150 GHz, it has not yet been demonstrated. The cluster radio galaxy population is quite a concern, although there is little direct information about this population at the frequencies and fluxes relevant to the SPT survey. We have recently carried out an analysis of the radio galaxy population at 1.4 GHz in $\sim 600$ clusters. In that study we used the luminosity function and 1.4 GHz–4.85 GHz spectral index distribution to predict the cluster radio galaxy populations at SPT frequencies. We are planning to conduct VLA and SZA surveys to refine our models to accurate predict the radio source contribution to SZE surveys in general and to the SPT survey in particular, so that the effects of the residual point source flux and the effects on survey completeness can be included in the survey analysis.

# 3  Discussion of Expected Error Budget

The statistical power of the SPT cluster survey is enormous, and so our concerns focus on the possible systematic effects that can creep into our analyses. The primary systematics concerns in a cluster survey fall into two categories: (1) cluster mass uncertainties and (2) cluster sample completeness and contamination. In fact, analyses of current cluster samples of a few hundred systems are already systematics limited in their constraints on $\Omega_M$ and $\sigma_8$ because of uncertainties in galaxy cluster masses (e.g. Pierpaoli *et al.* 2001). However, a large solid angle survey that delivers a clean sample of $2 \times 10^4$ clusters would enable us to largely overcome the cluster mass uncertainties through a process of self-calibration. In this process the relationship between the cluster SZE flux or luminosity at a particular redshift and the critically important halo mass can be pulled directly from the survey data by using redundant information in the cluster luminosity function and the clustering of the clusters. Moreover, the optical followup required to determine cluster redshifts provides measurements of the weak lensing signatures for large numbers of clusters. Although these signatures are noisy on a single cluster basis (Dodelson 2004), precise mass constraints can be derived by stacking large numbers of clusters with similar SZE luminosities at a given redshift. These two processes– self-calibration and mass calibration through weak lensing– work best for contiguous, large solid angle surveys that deliver large numbers of clusters. Below we discuss each systematic in turn.

*Cluster masses:* Cluster masses are uncertain because the cluster population is dynamically young, and cluster density profiles merge into the surrounding large scale structure. However, clusters exhibit significant regularity through correlations between simple bulk observables like the X-ray luminosity and the underlying halo mass (Reiprich and Böhringer 2002); similar correlations for the SZE are seen in hydrodynamical structure formation simulations, and there is also evidence of these scaling relations in observations (Benson *et al.* 2004; LaRoque 2005). Thus, although the overall mass scale of clusters with a particular SZE signature is uncertain, we can use the correlation between observables and mass to essentially rank clusters by mass; this is done routinely in the X-ray regime, where the data quality has been adequate for some time now (i.e. Mohr *et al.* 1999; Finoguenov *et al.* 2001; Reiprich and Böhringer 2002). An important point is that these SZE mass-observable correlations will exhibit intrinsic and observational scatter, and this scatter must be included in any cosmological analyses (e.g. Levine *et al.* 2002; Lima and Hu 2005).

In a large cluster survey there are several reservoirs of information about cosmology and cluster structure (including mass). These include the redshift distribution of clusters, the clustering of the clusters and the shape of the SZE luminosity function as a function of redshift. In a recent breakthrough, it has been shown

that there is enough information within a cluster survey to solve for the unknown mass scale and scatter about the mass-observable relation and simultaneously solve for the nature of dark energy (Majumdar and Mohr 2003, 2004; Hu *et al.* 2003; Lima and Hu 2004, 2005). The bottom line is that for a large, clean cluster sample over large, contiguous regions of the sky, one can self-calibrate and overcome the cluster mass uncertainties.

In addition, each cluster survey must have a multiband optical component to determine the photometric redshifts of the clusters. These optical data will be acquired for SPT in a staged followup program described in §6 below. For the Dark Energy Survey followup, the optical datasets will provide shear maps around each known cluster. These shear maps provide an excellent avenue for directly calibrating the mass–observable relation in the survey through stacking of large numbers of shear maps for clusters with similar SZE flux.

*Cluster selection:* The other main challenge is in understanding the cluster selection with sufficiently high accuracy to be able to use a 20,000 cluster sample. Cluster survey completeness and contamination is well understood in the X-ray regime, but because of the novelty of high sensitivity, high angular resolution mm-wave observations, it is still somewhat of a mystery in the SZE. The challenges to SZE cluster detection include primary CMB anisotropy, radio galaxies, dusty galaxies, and projections of background clusters. The multifrequency capability of the SPT helps in overcoming the primary CMB and perhaps also the radio galaxies and dusty galaxies. The arcminute angular resolution will also be extremely helpful in separating cluster signatures from the primary CMB, because the characteristic scale of our typical cluster is a few arcminutes, compared the degree scale peak in the primary anisotropy. For clusters at intermediate redshift, chance projects are not really a concern. This is clear from the surface density ( 6 clusters/deg$^2$) together with a typical cluster size of a few arcminute radius (say $\sim 10$ arcmin$^2$), giving an expectation of about 60 projected clusters over the entire survey (a 0.25% effect).

To use the statistical power of $10^4$ clusters distributed over a range in redshift, we need to limit the effects of uncertainty in our survey completeness and contamination to the few percent level. One advantage SPT will have is the expected low contamination in an SZE survey. Essentially, there are very few non-SZE sources that can masquerade as a negative source at one frequency and a positive source at another. On the other hand, completeness may be a concern because of emission from cluster radio galaxies. As discussed in §2 above, in a recent study of $\sim$600 clusters, Lin & Mohr (in preparation) measured the 1.4 GHz cluster radio galaxy luminosity function and distribution of spectral indices between 1.4 GHz and 4.85 GHz. Using this information they extrapolated to the frequencies of interest, assuming that the cluster radio galaxy population becomes five times stronger by a redshift z=1. Their calculations indicate that as many as 10% of the clusters will contain enough radio galaxy flux to equal or exceed the SZE flux at 150 GHz. Of course, this estimate involves an uncertain extrapolation of a factor of 100 in frequency, and our approach is likely to overestimate the scale of the effect, because the spectral indices tend to flatten and turn over at higher frequency. We have embarked on a program to explore this cluster radio galaxy population, and our goal is to understand its effect on the survey completeness over the redshift range of interest.

Starting from such a low contamination and a completeness approaching 90%, we expect to be able to keep uncertainties in these functions subdominant compared to the Poisson noise. Extensive mock observations of large scale structure simulations informed by the information coming in from SZE precursor experiments like the SZA and APEX-SZ provide a powerful tool for precisely characterizing the level of contamination and completeness in the SPT-SZE survey.

*Additional Uncertainties:* A remaining concern is the level of accuracy in theoretical predictions of the mass function of collapsed objects (e.g. Sheth and Tormen 1999; Jenkins *et al.* 2001). It seems quite likely that the current theoretical uncertainties at the $\sim$10% level are large enough to compromise the dark energy information in a large sample of clusters. However, an extensive simulation effort to improve these predictions is underway; this effort is closely connected to the theoretical push to understand the shear power spectrum so that future large scale optical survey teams can take full advantage their cosmic shear measurements. Theoretical development like this cannot be guaranteed, but the confluence of strong motivation, improved simulation algorithms and faster computing hardware makes it likely that the required improvements will be achieved.

Photometric redshifts for clusters have been shown to be accurate at the level of $\sim 0.02 - 0.05$ out to $z \sim 1$ (Bahcall *et al.* 2003; Gladders and Yee 2005). This accuracy is sufficient for the study of the redshift distribution, which has no sharp features. The photometric redshift accuracy does suggest a different analysis

technique for the study of the clustering of the clusters. One can measure the cluster angular power spectrum within rather thin ($\delta z \sim 0.10$) redshift shells rather than the full 3D power spectrum (Cooray *et al.* 2001). There has been a discussion of residual biases in photometric redshifts and its effect on cluster surveys (Huterer *et al.* 2004); however, with large spectroscopic training sets it is possible to control these biases at the level of $\delta z \sim 0.001$ (see Dark Energy Survey white paper submitted to this same panel), which is small enough so that it makes no meaningful contribution to the error budget.

## 4 Forecasts for Dark Energy Constraints

We include here a forecast for the SPT with full optical followup for cluster redshifts (i.e. SPT+DES). The combined SPT+DES cluster survey should provide a strong handle on the nature of the dark energy. Figure 1 contains forecasts for the joint constraints in $w$-$\Omega_M$ space from the cluster redshift distribution, the cluster power spectrum, and 100 mass measurements (each with 30% $1\sigma$ accuracy) distributed in mass and extending to $z = 1.2$ (Majumdar and Mohr 2004). These forecasts include self–calibration discussed in §3, which accounts for uncertainties in the mass–observable relation and its evolution. Cluster finding and masses should arise primarily from the SZE data, and the DES optical data will provide photometric redshifts (with an accuracy of $\delta z \sim 0.02$ out to $z \sim 1.3$). The fully marginalized 68% constraint on constant $w$ models, is $\delta w = 0.05$ (geometry fixed) and $\delta w = 0.07$ (geometry freely varying). In addition, the joint constraints in $\Omega_M - \Omega_E$ space are shown. For comparison, the constraints expected from SNAP (Perlmutter and Schmidt 2003) and two CMB anisotropy experiments (Eisenstein *et al.* 1999; Spergel *et al.* 2003) are also presented. It is clear that the self-calibrated galaxy cluster survey constraint is similar in precision to those from other forefront techniques; in addition, each technique constrains a different combination of cosmological parameters and is subject to different systematic uncertainties, making these experiments highly complementary.
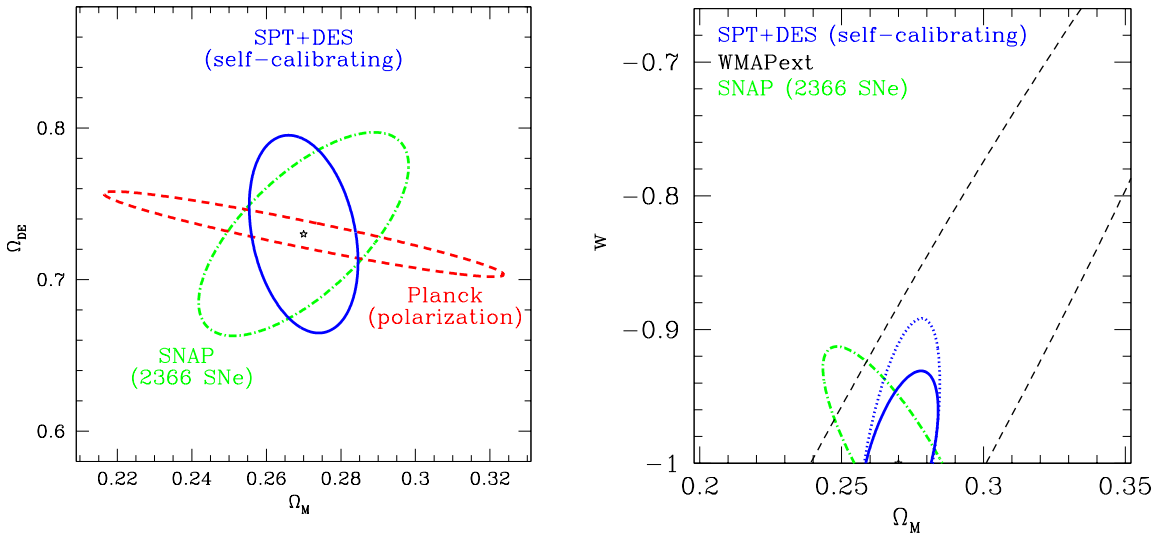


Figure 1: Forecasts for the geometry constraints (left) from the SPT+DES galaxy cluster survey, the SNAP SNe Ia mission, and the *Planck* CMB anisotropy mission together with forecasts for the joint $\Omega_M$-$w$ constraints from the WMAP CMB anisotropy mission, SNAP and SPT+DES. These experiments are highly complementary because each experiment constrains a different combination of cosmological parameters and is subject to different systematics.

*Self-calibration, Priors, Shear constraints and $\frac{dw}{da}$:* The method of self calibrating shown here allows for an arbitrary local normalization and slope of the mass–observable relation together with an arbitrary, power law evolution beyond the expected self–similar evolution. The only information from the survey is the redshift distribution and the cluster power spectrum. Thus, one can solve for cosmology and the cluster mass–observable relation and then carry out a powerful consistency check by examining the agreement between the predicted and observed mass function as a function of redshift in the survey. If the self–calibration

scheme adopted here does not allow for enough freedom to describe the observed clusters, it will show up in this important cross-check. A more dramatic self-calibration within each redshift shell can be carried out by using the shape of the observed mass function (SZE luminosity function; Hu *et al.* 2003); this self-calibration is more costly and will lead to weaker constraints on the dark energy. We do not currently know enough about cluster SZE properties to be able to make definite statements about what level of freedom is required in the self–calibration; thus, forecasts are necessarily uncertain. However, the important point is that we have a range of different methods for overcoming the cluster mass uncertainties down to directly solving for the cluster mass–observable relation in each redshift shell. This breakthrough essentially allows large solid angle, high yield cluster surveys like SPT to overcome the cluster mass uncertainties that have plagued the smaller surveys carried out to date.

For these forecasts only weak priors are used (see Majumdar and Mohr 2004), but folding in strong priors such as forecasts for constraints from Planck temperature and polarization anisotropy can dramatically improve these constraints (see DES white paper). In addition, these forecasts use 100 crude mass estimates(30% statistical accuracy and <10% bias), whereas followup with DES should allow a far larger number of crude mass estimates; this additional mass information will lead to dramatically improved constraints on dark energy. We are exploring this shear constraint in greater detail, but initial estimates are quite encouraging (again, see DES white paper).

Finally, we note that the SPT cluster survey will also provide constraints on changes in the equation of state parameter with redshift $\frac{dw}{da}$. Allowing this additional parameter weakens the constraints on the local value of the dark energy equation of state (Weller *et al.* 2002; Wang *et al.* 2004).

# 5   Risk Areas, Technology R&D, Relationship to LST and JDEM

The risks associated with the SPT SZE survey are associated with physical access and data transmission to the South Pole Site. Physical access is limited to only 3.5 months a year during which all materials for the winter season are shipped to the stations, all work on the station and projects is performed. Exceptionally poor weather or mis-estimated work loads can easily lead to delays of a year. Another risk area is data transmission bandwidth. The SPT survey does not require bandwidths exceeding NSF's projections, but they do exceed current capabilities.

At worse these risks would lead to a one year delay in the start of the SPT SZE survey, to 2008.

No new hardware technology advances are required (anymore!) for the SPT SZE survey.

There are no direct connections between SPT, LST and JDEM. However, the dark energy constraints delivered by SPT would be complementary to those from SNAP, because the parameter degeneracies differ. The SPT partnership with the Dark Energy Survey is certainly driving science and data management development that will be very helpful to LSST.

# 6   Access to Facilities and Other Instrumentation

The optical followup of the SPT survey region is an absolutely critical component of the cluster survey cosmology. It is needed to determine cluster redshifts, and the optical data can also benefit SPT cluster science in several other ways. For example, optical cluster selection is subject to different completeness and contamination problems than SZE cluster selection. It is our hope that a combined optical and SZE selection will deliver a cleaner, better understood sample, and we are working to develop algorithms for this purpose. In addition, the optical data provide weak lensing shear information around each SPT cluster. Although this information is very noisy for a single cluster, it can provide an unbiased mass estimator that can be used by stacking large numbers of clusters to calibrate the cluster mass-SZE observable relation. Although the weak lensing shear is a powerful mass constraint on known clusters, it will be challenging to carry out precision cosmology with shear selected cluster samples, because of the low completeness (<50%) and high contamination (at least one false cluster for every real cluster; see Hamana *et al.* 2004; Hennawi and Spergel 2005).

The staged optical followup program begins immediately with a MOSAIC mini- survey of 100 deg$^2$, continues with cluster by cluster followup with the Simultaneous Multiband Imager (SMI; under construction

by Chris Stubbs) and then ends with the Dark Energy Survey (DES). These programs are briefly summarized below.

- MOSAIC "mini-survey": This is a deep $griz$ survey being carried out with the current MOSAIC camera on the Blanco 4m telescope at CTIO. The survey will cover two 50 deg$^2$ patches in the southern sky that are accessible to SPT as well as three other mm-wave CMB mapping experiments: the Atacama Cosmology Telescope (ACT), the Atacama Pathfinder Experiment (APEX), and the Arcminute Cosmology Bolometer Array Receiver (ACBAR). The target depths ($10\sigma$ in 2.3 arcsec aperture) are $griz_{lim}$=24.0, 23.9, 23.6, 22.3, which will allow us to probe cluster galaxy populations to $L_*$ at z=1 and to $0.5L_*$ at lower redshift. The program requires 45 nights over three seasons, and has been accepted as an NOAO Survey program with the first 15 night run this Fall 2005. Because this optical survey will provide uniform coverage over two large regions, it will enable a joint optical+SZE cluster finding exercise that will help in determining the SZE–only cluster finding completeness, which is needed for the second stage involving SMI.

- SMI: This is a camera designed by Chris Stubbs (Harvard) that will acquire $griz$ band images simultaneously using three dichroics (see SMI white paper). It will be mounted on one of the Magellan 6.5m telescopes, and will have about a 5 arcminute field of view. The camera is currently under construction, and it will be deployed in 2006 or 2007. The camera field is too small to enable a uniform optical survey, and so this instrument will be used to target clusters that have been discovered by the SPT. Using the completeness information from the MOSIAC mini-survey, this SMI+SPT cluster survey will be a powerful cosmology tool beginning in 2007. We estimate that with a 30 night run on Magellan it will be possible to determine photometric redshifts for approximately 2,500 SPT clusters.

- DES: Complete, uniform, $griz$ band optical followup of the SPT survey region will be carried out by the DES beginning in 2009 (see DES white paper). It is a 500 night survey over five seasons on the Blanco 4m that will employ a new, 3 degree$^2$ field of view CCD camera at prime focus. Thick, fully depleted CCDs will deliver high quantum efficiency out to 1 micron. This survey will provide much deeper data in $i$ and $z$ than the MOSAIC survey, pushing to $0.5L_*$ for cluster galaxies out to z=1. Simulations by H. Lin (Fermilab) indicate that cluster redshift estimates from this dataset should have an accuracy of $\delta z\sim 0.02$ out to z=1.3. The uniform coverage means that optical+SZE cluster finding can be carried out over the whole SPT survey region. In addition, the deep $i$ band data will be suitable for producing cluster shear-based mass estimates for a large fraction of the SPT cluster sample. This direct calibration of the cluster masses will enable a dramatic tightening of the dark energy constraints.

# 7 Project Timeline

The SPT telescope and 1000 element bolometer array are scheduled to deploy to the South Pole in 2006 November. The SPT-SZE survey should start in 2007 Spring. It is expected to take at least two seasons to complete the multiband 4000 deg$^2$ SZE survey. The telescope is available for as long as the survey takes.

The optical follow-up program described in §6 above begins in Fall '05 with the first of three observing runs at the Blanco with the MOSAIC camera. Additional runs will take place in '06 and '07. The SMI observing will begin in Fall '07 when the SPT cluster lists are available (although the camera itself will be deployed as much as a year earlier). We expect to propose for a 30 night program on Magellan in Fall '07, '08, and '09 to return followup for up to 15% of the sample. The DES will begin in Fall '09 and carry out full imaging in all four bands over the entire SPT region during its first season. Each following season of DES observing delivers a deeper dataset. After the first year of observing we will have a dataset that is already significantly deeper than the SDSS dataset, and we expect to be able to use those data to determine redshifts for the more than half of our sample that lies at $z < 0.7$. The DES will reach its full depth in Fall '13.

# References

Bahcall, N. A., T. A. McKay, J. Annis, R. S. J. Kim, F. Dong, S. Hansen, T. Goto, J. E. Gunn, C. Miller, R. C. Nichol, M. Postman, D. Schneider, J. Schroeder, W. Voges, J. Brinkmann, and M. Fukugita 2003. A Merged Catalog of Clusters of Galaxies from Early Sloan Digital Sky Survey Data. *ApJS* **148**, 243–274.

Benson, B. A., P. A. R. Ade, J. J. Bock, K. M. Ganga, C. N. Henson, K. L. Thompson, and S. E. Church 2004. Measurements of Sunyaev-Zel'dovich Effect Scaling Relations for Clusters of Galaxies. *ArXiv Astrophysics e-prints*.

Cooray, A., W. Hu, D. Huterer, and M. Joffre 2001. Measuring Angular Diameter Distances through Halo Clustering. *ApJ* **557**, L7–L10.

Dodelson, S. 2004. Cluster masses: Accounting for structure along the line of sight. *Phys. Rev. D* **70**(2), 023008–+.

Eisenstein, D. J., W. Hu, and M. Tegmark 1999. Cosmic Complementarity: Joint Parameter Estimation from Cosmic Microwave Background Experiments and Redshift Surveys. *ApJ* **518**, 2–23.

Finoguenov, A., T. H. Reiprich, and H. Böhringer 2001. Details of the mass-temperature relation for clusters of galaxies. *A&Ap* **368**, 749–759.

Gladders, M. D., and H. K. C. Yee 2005. The Red-Sequence Cluster Survey. I. The Survey and Cluster Catalogs for Patches RCS 0926+37 and RCS 1327+29. *ApJS* **157**, 1–29.

Hamana, T., M. Takada, and N. Yoshida 2004. Searching for massive clusters in weak lensing surveys. *MNRAS* **350**, 893–913.

Hennawi, J. F., and D. N. Spergel 2005. Shear-selected Cluster Cosmology: Tomography and Optimal Filtering. *ApJ* **624**, 59–79.

Hu, W., M. M. Hedman, and M. Zaldarriaga 2003. Benchmark parameters for CMB polarization experiments. *Phys. Rev. D* **67**, 043004–+. astro-ph/0210096.

Huterer, D., A. Kim, L. M. Krauss, and T. Broderick 2004. Redshift Accuracy Requirements for Future Supernova and Number Count Surveys. *ApJ* **615**, 595–602.

Jenkins, A., C. S. Frenk, S. D. M. White, J. M. Colberg, S. Cole, A. E. Evrard, H. M. P. Couchman, and N. Yoshida 2001. The mass function of dark matter haloes. *MNRAS* **321**, 372–384.

LaRoque, S. J. 2005. *Constraints on Cluster Structure and Cosmology from a Comparison of X-ray and Sunyaev-Zel'dovich Effect Properties in Galaxy Clusters*. Ph. D. thesis, University of Chicago.

Levine, E. S., A. E. Schulz, and M. White 2002. Future Galaxy Cluster Surveys: The Effect of Theory Uncertainty on Constraining Cosmological Parameters. *ApJ* **577**, 569–578.

Lima, M., and W. Hu 2004. Self-calibration of cluster dark energy studies: Counts in cells. *Phys. Rev. D* **70**(4), 043504–+.

Lima, M., and W. Hu 2005. Self-Calibration of Cluster Dark Energy Studies: Observable-Mass Distribution. *ArXiv Astrophysics e-prints*.

Majumdar, S., and J. J. Mohr 2003. Importance of Cluster Structural Evolution in Using X-Ray and Sunyaev-Zeldovich Effect Galaxy Cluster Surveys to Study Dark Energy. *ApJ* **585**, 603–610.

Majumdar, S., and J. J. Mohr 2004. Self Calibration in Cluster Studies of Dark Energy: Combining the Cluster Redshift Distribution, the Power Spectrum and Mass Measurements. *ApJ*, in press (astroph/0305341).

Mohr, J., B. Mathiesen, and A. Evrard 1999. Properties of the Intracluster Medium in an Ensemble of Nearby Galaxy Clusters. *ApJ* **517**, 627.

Perlmutter, S., and B. P. Schmidt 2003. Measuring Cosmology with Supernovae. *ArXiv Astrophysics e-prints*, (astroph/0303428).

Pierpaoli, E., D. Scott, and M. White 2001. Power-spectrum normalization from the local abundance of rich clusters of galaxies. *MNRAS* **325**, 77.

Reiprich, T. H., and H. Böhringer 2002. The Mass Function of an X-Ray Flux-limited Sample of Galaxy Clusters. *ApJ* **567**, 716–740.

Sheth, R. K., and G. Tormen 1999. Large-scale bias and the peak background split. *MNRAS* **308**, 119–126.

Spergel, D. N., L. Verde, H. V. Peiris, E. Komatsu, M. R. Nolta, C. L. Bennett, M. Halpern, G. Hinshaw, N. Jarosik, A. Kogut, M. Limon, S. S. Meyer, L. Page, G. S. Tucker, J. L. Weiland, E. Wollack, and E. L. Wright 2003. First Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Determination of Cosmological Parameters. *ApJ submitted*. astro-ph/0302209.

Wang, S., J. Khoury, Z. Haiman, and M. May 2004. Constraining the evolution of dark energy with a combination of galaxy cluster observables. *Phys. Rev. D* *70*(12), 123008–+.

Weller, J., R. A. Battye, and R. Kneissl 2002. Constraining Dark Energy with Sunyaev-Zel'dovich Cluster Surveys. *Physical Review Letters* **88**, 231301–+.