SZ Surveys: Source Detection & Catalog Construction, and Mass Estimates

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There are several instruments currently taking data that are capable of detecting large numbers of clusters using the Sunyaev-Zeldovich effect, including South Pole Telescope (SPT) and Atacama Cosmology Telescope (ACT), as well as Planck on the near horizon. Simple calculations suggest that these instruments should detect thousands of new galaxy clusters, with a selection function that is very simple. This has many people excited at the possibility of using galaxy clusters as precise cosmological probes, with statistical power comparable to next generation supernova cosmology projects and weak lensing surveys.

In using galaxy clusters as cosmological probes, two criteria must be satisfied: 1) the sample should be clean (observables should be well-defined and homogeneous across the sample) and complete (all clusters matching given observables are in the sample) and 2) it must be possible to predict the cluster abundance as a function of cosmological parameters for the observables that are being used.

In terms of the quality of the sample, important concerns are the tightness of the mass-observable relation and source confusion due to projection effects.

On the issue of connecting with theory, most effort to this point has focused on calibrating the mass-observable relation and then using the mass function from N-body simulations. Ultimately, one should simply be producing predictions for whatever observables are desired as cosmological parameters are varied. This remains unfeasible at this point (or at least relatively unexplored). Instead, two possible approaches are to 1) marginalize over the mass-observable relation, allowing the data to determine the parameters of a simple model for relation, or 2) measure masses for a subset of the sample to characterize the masses of the clusters.

Cluster Detection:

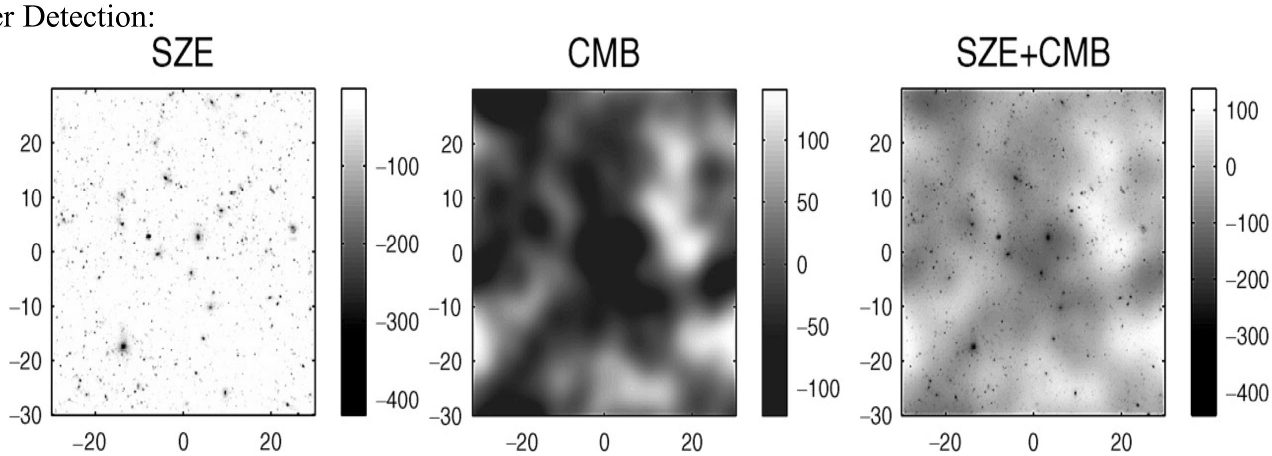

Fig 1: The basic detection problem: the CMB provides a largely diffuse background against which the clusters must be detected. Furthermore, the SZ signal has a different spectrum, allowing both spatial and spectral separation. However, the source density is high enough that the SZ effect can be confusion-limited. Fig from Carlstrom, Holder & Reese 2002.

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There are several upcoming and ongoing experiments that should acquire large SZ-selected catalogs; to name a few: the South Pole Telescope aims to survey 4000 sq. deg to a sensitivity of about 10 uK with arcminute resolution, the Atacama Cosmology Telescope aims to do a smaller patch at even higher sensitivity, while Planck will complement these with an all-sky survey that will gather a large catalog of clusters in the local universe. All of these experiments will be multi-frequency to some extent and have complementary strategies, designs, and instrumentation.

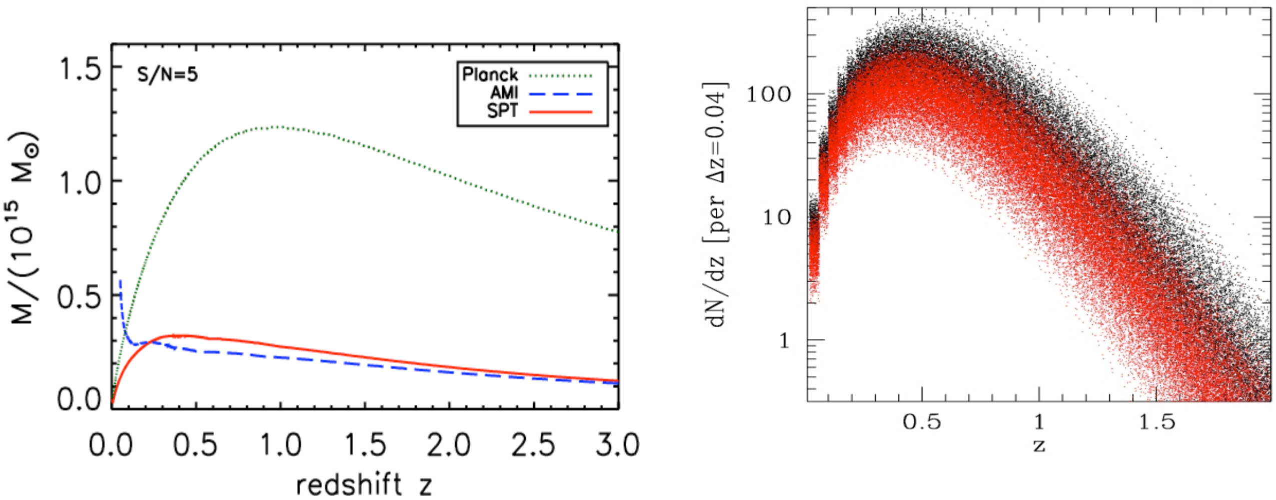

Fig 2: Mass limits for detectability for upcoming and ongoing surveys (left; from Melin et al 2006), and dispersion in predicted counts for SPT (right) for cosmological models consistent with almost all current cosmological observations (CMB+SNe+SDSS). Black points assume "middle of the road" cluster physics while red assumes that masses are lower by 25% for a given observed SZ flux. At current levels, the cosmological cluster abundance is uncertain by a factor of several, a much bigger dispersion than our understanding of cluster physics.

A unique feature of the SZ effect is that the surface brightness is independent of redshift. This is great for detecting high redshift objects, but has the downside of a higher probability of distant sources overlapping each other and causing some confusion.

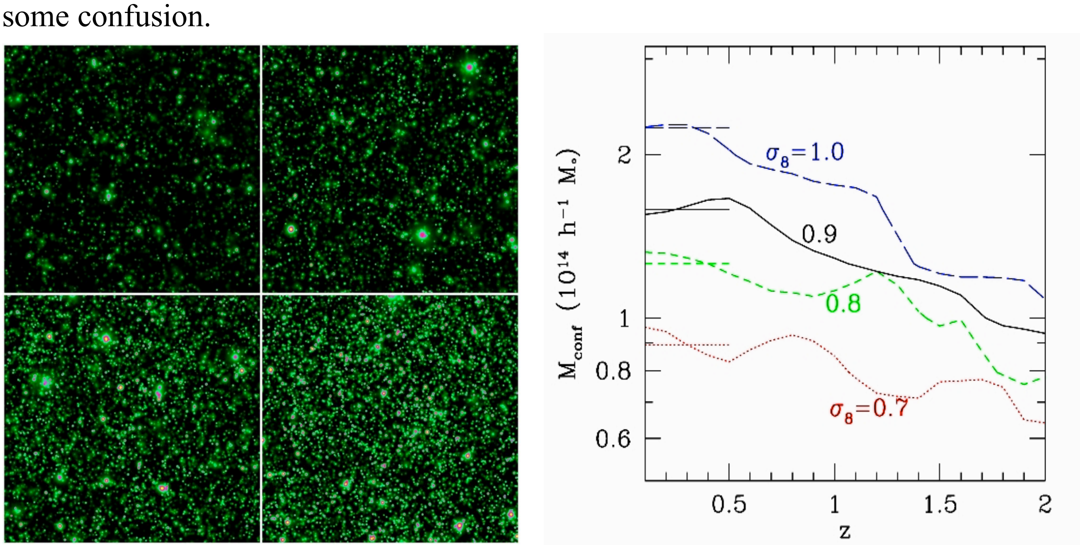

Fig 3: SZ source confusion is a strong function of σ_8, with four maps 2 deg on a side shown for σ_8 varying from 0.6-0.9 (left panel). On the right is shown the mass at which measured fluxes exceed 20% errors entirely due to projection effects. A good rule of thumb is that the SZ effect starts to become confused at a sky density of roughly 10 sources per square degree. Figs from Holder, McCarthy & Babul 2008

In the end, the ability to use SZ surveys as a precise tool will be limited by the understanding of the relation between the observable (SZ flux) and something that can be well-predicted by theory (like mass). A strong advantage of the SZ effect is that there is expected to be a simple and tight relation between the integrated SZ flux and the cluster mass:

$$S_{sz} = AM^{5/3}[\Delta(z)E^2(z)]^{1/3} d_A^{-2}(z)$$

The amplitude depends on the gas fraction, and there are small deviations in both the mass and redshift scaling that depend weakly on cluster physics. In simulations, whether with or without feedback from star formation or AGN, it is found that this tight relation is robust, with roughly the same (perhaps a bit more) scatter as found in the X-ray mass-temperature relation.

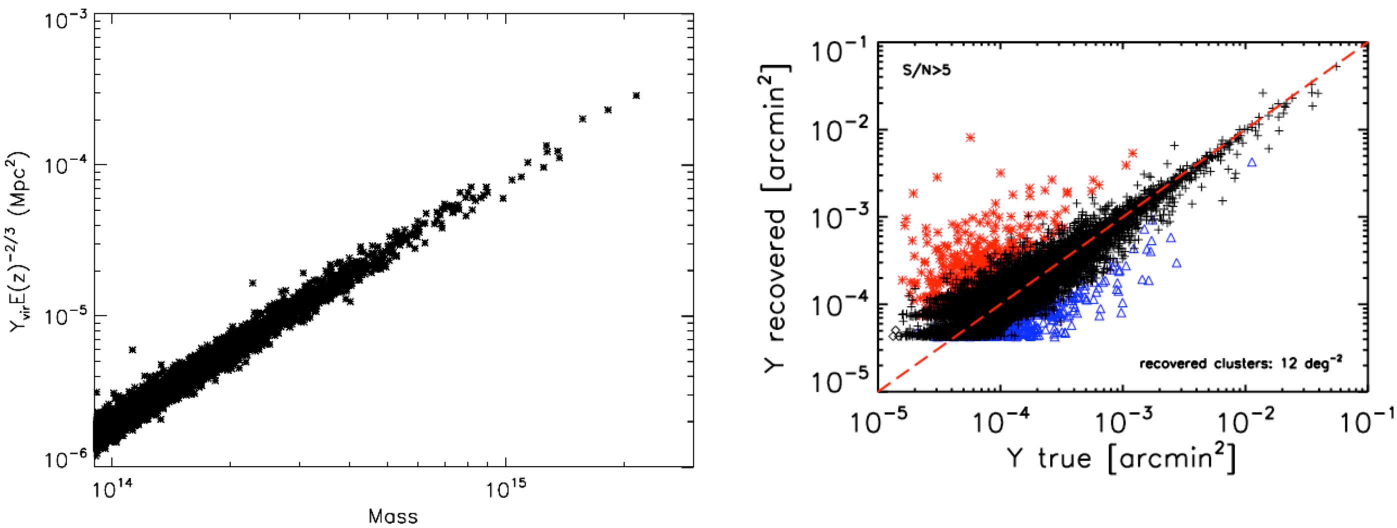

Fig 4: Flux-mass relation obtained from simulations using only the particles in the cluster (left; Hallman et al 2007), or from maps including foreground contamination and instrument noise (right; Melin et al 2006). The intrinsic relation is quite tight, but the realities of source detection and extraction can lead to large scatter.

The scaling the SZ flux-mass relation is not expected to be exactly the simple one shown above, and deviations could arise from poorly understood physical processes related to AGN and supernova feedback. A simple prescription is to allow some (but not much) further freedom in this relation:

$$S_{obs} = S_{theory} A M^{\alpha} (1+z)^{\beta}$$

where the amplitude and evolution parameters are simply further parameters to be determined. This generally goes by the name of "self-calibration" (Majumdar & Mohr 2004), especially when clustering information is added, but is simply the idea of letting the data determine the cluster parameters through the mass function and redshift evolution as a function of SZ flux. In addition, there will be scatter in the flux-mass relation, and it is important to know this scatter if one is to do cosmology. In fact, one can parameterize the flux-mass relation as a probability distribution with some set of moments, introduce the moments as extra parameters and then marginalize over them (Holder et al in prep). Note that the relevant parameter is how well you know the variance, not the rms. This strongly favors cluster surveys methods that have small intrinsic dispersion. See Lima & Hu 2005 for a detailed discussion.

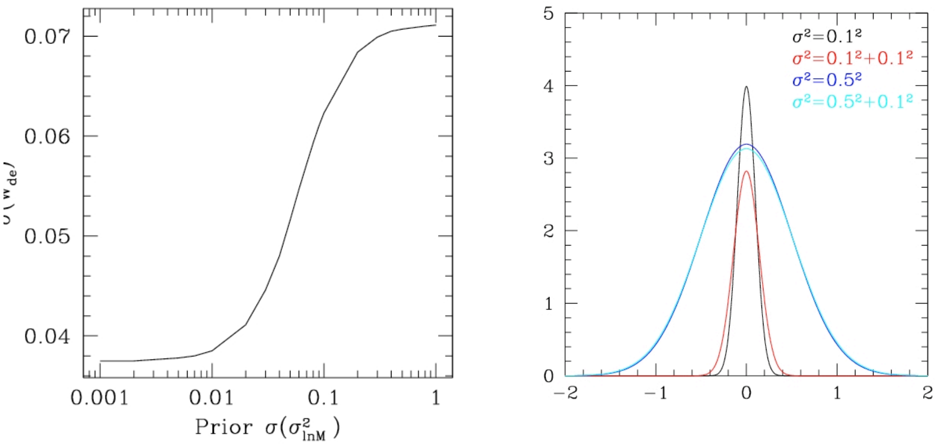

Fig 5: Importance of scatter in the flux-mass relation. Constraints on the dark energy equation of state parameter w as a function of how well the variance of the flux-mass relation is known (left). In the right panel, for orientation, Gaussians with variance increased by 0.01 are shown for initial variance 0.01 and 0.25. If the initial scatter is large, it is nearly impossible to differentiate between pdfs with variances that are within 0.01. (Modeled on Lima & Hu 2005)

A good question is how well the masses need to be known to do precise and accurate cosmology. There is no single number that captures, but a good rule of thumb is that the masses need to be known at percent level accuracy.

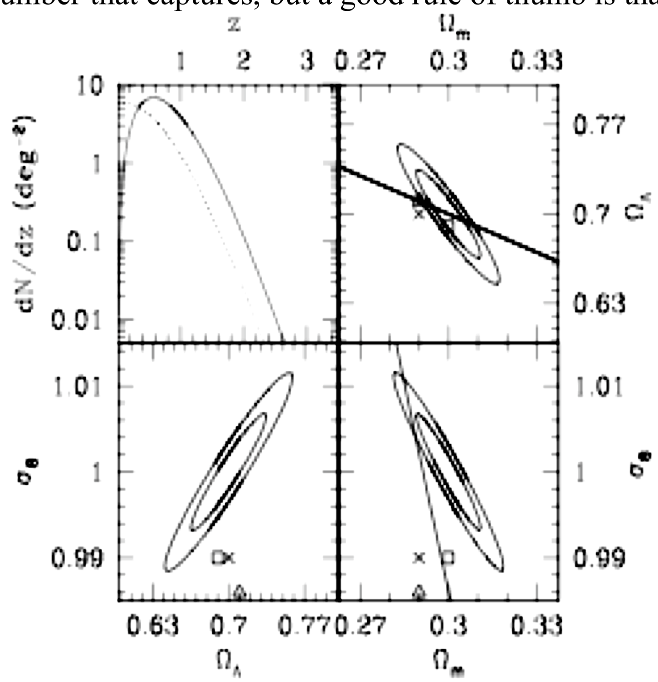

Fig 6: Predicted constraints on LCDM models from SPT-like cluster survey. Top left shows differential (solid) and cumulative (dashed) number counts, other panels are Fisher matrix estimates of constraints assuming a perfectly known mass selection. The triangle and square show the impact of mass function uncertainties, while the X shows the impact of a 5% systematic bias in the limiting mass. For the mass errors to not dominate the error budget, the masses must be measured at the level of a few percent. Fig from Holder, Haiman, Mohr 2001.

One method for estimating masses is to use the clustering amplitude. Clusters are highly biased, and thus are noticeably clustered. This definitely helps, but it adds some complexity to the survey design. It is now essential that the completeness as a function of angle be extremely well-characterized. This may relate directly to issues of scan strategy, with experiments with strongly inhomogeneous noise at perhaps a disadvantage (i.e., ACT may have an easier time doing this than SPT, due to the polar location of the SPT).

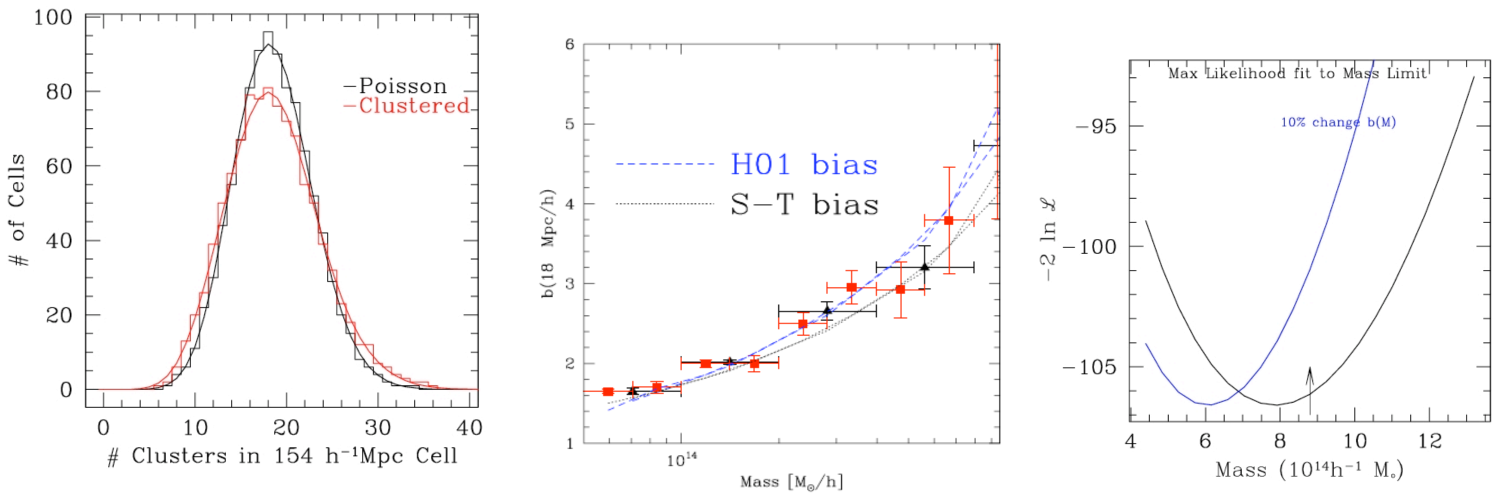

Fig 7: Clustering masses of galaxy clusters. The clustering of clusters in the Hubble volume simulations is easily seen in the left panel from just a simple counts-in-cells plot. The clustering amplitude is set by the halo bias (middle panel) which can be seen to be a strong function of mass, although the theory uncertainty is substantial. In the right panel is the result of a simulated cluster catalog where the clustering was used to try to estimate the mass threshold of the catalog. The true value is shown by the arrow, and it can be seen that the right value is obtained (black curve). Unfortunately, the blue curve assumes a value of the bias that is well within the theoretical uncertainty, and would strongly rule out the input model. Credits: left: Holder 2006, middle: Wetzel et al 2006

External or theoretical calibration?

The requirements (few %) are fairly stringent. This is a requirement on the systematic bias in the mass determination. This means that weak lensing shear calibration must be good at the few percent level: for typical shears of 10%, this means that one must be able to measure the lensing signal at the 0.1% level (averaged over many clusters) in a cluster field in an unbiased way. Similarly, X-ray determinations or N-body+hydro simulations may have a tough time reaching few % accuracy. There is no known floor such that it is impossible to achieve such mass measurements, and it is possible that a combination of self-calibration, independent observations, and theoretical advances may allow % level mass measurements. For dark energy studies, mass measurement errors (systematic biases, not necessarily statistical errors per cluster) must be below 5% to make interesting contributions.

Conclusions:

SZ surveys are ongoing, but significant work remains to better understand selection functions, especially in the face of unknown cluster physics. A key advantage of the SZ effect is the small scatter in the mapping between flux and mass, but even then it will be difficult for the data to simultaneously solve for both the cluster physics parameters and the cosmological ones. Adding clustering information helps, as would external mass measurements. However, both the clustering information and independent mass measurements introduce their own set of theoretical and observational systematic errors.