# The Cluster imaging eXperiment (CIX) and the Importance of Large Single Dish Sub-MM Measurements

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## Goals and Techniques

The goal of the Cluster Imaging eXperiment (CIX) is to improve the understanding of clusters of galaxies, their masses and their peculiar velocity over the redshift range $0.1 < z$ using high spatial (12 arcsecond) resolution Sunyaev-Zel'dovch (SZ) images of selected clusters in four spectral bands spanning the emission null at 217 GHz. The principle advantage of these images is the ability to study clusters, their shape, their internal structure and motions and the contaminating point sources in detail over the complete span of redshift. This capability will improve the understanding of systematic errors in SZ surveys such as the SPT and ACT each of which has a resolution larger than an arcminute. Extracting cosmological information from the surveys is dependent on detailed knowledge of how the SZ signal is related to cluster physical properties. The CIX study will be highly complementary with SZ cluster studies such as SZA and eventually CARMA which will have similar angular resolution at low frequencies.

The initial instrument is a 64 pixel, four spectral band radiometer with 12 arcsecond resolution operating on the Large Millimeter Telescope (LMT). The camera will observe all 4 bands simultaneously in each pixel using a Frequency Selective Bolometer (FSB) focal plane. The initial camera field is 1.6 arcminutes but larger pixel number is possible.

The existence of large-aperture, single-dish radio/sub-mm telescopes is essential to carry out such observations over the a frequency range sufficient to measure internal velocity with the kinetic SZ effect along with sufficient spatial resolution to resolve cluster substructure and separate point sources over a large range of redshift.

## Baseline Proposal

CIX is one of three continuum cameras to be installed on the LMT. The camera will be able to provide a 9 square arcminute field with 256 pixels, each with 5 $\mu$K RMS/pixel for each band, in 8 hours of integration using the sensitivity given in Table 1. Integration needed to observe a cluster is nearly redshift independent for $z > 0.1$. A larger second generation camera can do this in 2 hours. The CIX focal plane will consist of a 64 pixel Frequency Selective Bolometer array with bands centered at 148, 216, 260, and 350 GHz. All bands have the same spatial resolution and observe simultaneously.

## b. Precursor Observations, Developments and Fundamental Calibrations

Observations related to CIX are SZA and CARMA on the one hand and SPT and ACT on the other. CIX is complementary to SZA and CARMA because they will have similar angular resolution and very different frequency coverage. The broad frequency range enables the measure of the kinetic SZ to study internal motion and a strong spectral discriminant against point sources, both radio and dusty galaxies.

The fast mapping surveys such as SPT and ACT will have the statistical power to put constraints on $w$ directly but have potential systematic errors due to variable cluster properties and incompletely subtracted point sources. The high resolution experiments will permit the study of clusters in detail. Along with numerical and theoretical work, this will characterize the systematic errors.

Two members of the CIX group are also PI's of instruments that will provide precursor observations - AzTEC (144 element bolometer array led by Wilson) and SPEED (4 pixel, 4 frequency prototype FSB camera led by Silverberg). Both instruments will be used at existing telescopes over the next several years to make targeted studies of known clusters and both instruments will serve as first generation continuum instruments at the LMT. AzTEC, operating at either 2.1 or 1.1 mm, is capable of imaging clusters in a single bandpass. SPEED will be used to follow-up these images to interrogate point sources.

## c. Expected Error Budget

CIX will probe of systematic errors for SZ cluster surveys. The strength of SZ surveys for probing Dark Energy stems from their potential to provide a nearly redshift independent, mass limited survey. However, mass errors are an important problem for SZ surveys. Mass errors stem from several sources including internal cluster structure or radial profiles different from that of an assumed model. Radio sources either fore- or background or associated with the cluster also can cause systematic mass errors (Carlstrom et al., 2002). Single or low frequency experiments can also be contaminated by primordial CMB fluctuations (Melin et al., 2005).

Observational limitations of using SZ cluster observations for cosmology arise from combinations of the following: 1) The kSZE has the same spectrum as the underlying primary CMB anisotropy and thus cannot be recovered spectrally. 2) Multiple clusters along the line of sight can confuse the interpretation since their SZE signatures will be redshift independent. 3) Internal structure and motions in clusters complicates the relationship between the SZE signal and the cluster properties. 4) Background and foreground radio sources and radio sources in the cluster bias the measured cluster parameters if not removed or accounted for. 5) The presence of luminous dusty galaxies, in particular those lensed by the cluster potential, again adds flux that must be removed both spatially and spectrally. In the best of all worlds these effects add noise to the observable - cluster mass relation. Likely the effects bias the cluster mass determinations and possibly in a redshift dependent way.

With the exception of multiple clusters in the line of sight, all of these systematics are minimized for an experiment with high spatial resolution (many beams per cluster) and broad

**Cluster Parameters**

| | |
|---|---|
| $y$ | $1.02 \times 10^{-4}$ |
| $T_e$ (keV) | 4.74 |
| $v_p$ (km/s) | -170 |
| $z$ | 0.5 |
| $r_{\rm core}$ ($''$) | 23.4 |
| $\beta$ | 1.0 |

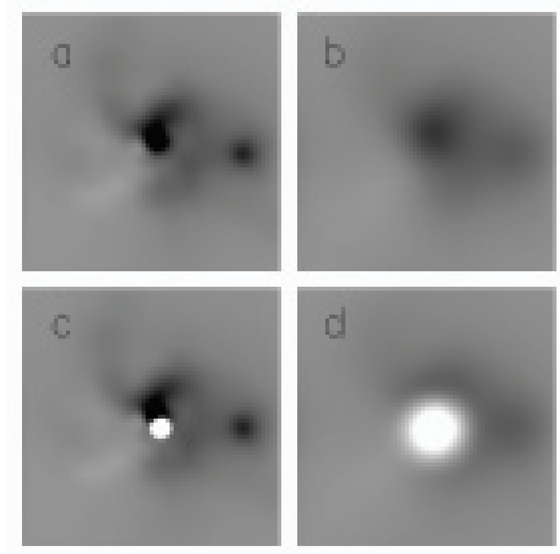


Figure 1: Effect of beam size on observations of kinetic SZ in a z=0.5 cluster. Each panel is a noiseless simulated 150 GHz observation of the kSZE only with a $6'$ side. Panels a) and b) show the total kSZE, bulk flow and internal motion in Cluster 11 from the Springel, White & Hernquist B134 SPH catalog (Springel et al. (2001)), smoothed by a $12''$ beam (panel a) and a $60''$ beam (panel b). Panels c) and d) show the same cluster with an 1.0 mJy radio point source near the cluster center. All panels have a stretch of $\pm 10\mu$K. The cluster parameters are the fits to Cluster 11 of the B134A SPH clusters. The redshift is picked arbitrarily.

frequency coverage that spans the SZE null. Neither property alone is sufficient to avoid these contaminates. For example, the individual contaminating effects on cluster peculiar velocities for a CIX-like experiment with $\sim 1$ arcmin beams are likely to be as large as $\sim 100$ Km/s from the effects of internal flows (Nagai et al. (2003)), $\sim 100$ Km/s from residual CMB fluctuations (Holder (2004)), and perhaps as high as $\sim 200$ km/s from contamination from dusty luminous galaxies (Blain (1998); Knox et al. (2004)). The determination of cluster parameters are degraded by these effects.

| Chan | Frequency [GHz] | $N_{\rm pix}$ | Beamsize [arcsec] | NEP [aW/$\sqrt{\rm Hz}$] | NET [$\mu$K/$\sqrt{\rm Hz}$] | NEFD [mJy/$\sqrt{\rm Hz}$] |
|---|---|---|---|---|---|---|
| C1 | 148 | 64 | 12 | 139 | 593 | 1.14 |
| C2 | 216 | 64 | 12 | 194 | 449 | 1.85 |
| C3 | 260 | 64 | 12 | 266 | 382 | 2.26 |
| C4 | 350 | 64 | 12 | 324 | 505 | 4.02 |

Table 1: Instrument parameters and per-detector sensitivity for the CIX camera on the LMT. Sensitivity calculations assume an atmosphere with 2 mm ppt$H_2O$, a 300K telescope and coupling optics with total effective emissivity of 0.18, and telescope coupling efficiency of 50%. All channels have the same throughput (determined by upstream optics) of 4.5 mm$^2$sr. NET is the noise equivalent temperature to a Rayleigh-Jeans emitter, NEFD is noise equivalent flux density.

The high spatial resolution and the multi-spectral capability of CIX is ideally suited to measure and separate many of these effects. To demonstrate this and determine our sensitivity to cluster parameters in the presence of contaminating sources, we have simulated a CIX/LMT observation of a numerically simulated cluster at $z = 0.5$. Figure 1 shows the noiseless input map of the kinetic SZE smoothed the CIX beam size (Panel a). The structure in the figure is due to both bulk flows inside the cluster and the cluster's own peculiar velocity. To test the ability to recover cluster parameters in the presence of the lensed luminous galaxy background, the simulation was repeated with a lensing boost of 2. Table 2 gives the formal parameter uncertainties resulting from these fits assuming CIX with its nominal $12''$ beam and a CIX-like experiment with a $1'$ beam.

| Instrument | $t_{\rm int}$ (hr) | lensing boost | $\sigma_y \times 10^4$ | $\sigma_{v_p}$ (km/s) | IRPS ($\mu$K − arcmin) |
|---|---|---|---|---|---|
| CIX | 1 | none | 0.077 | 241 | 11 |
| CIX-1' | 1 | none | 0.14 | 477 | 42 |
| CIX | 1 | x2 | 0.13 | 472 | 21 |
| CIX-1' | 1 | x2 | 0.19 | 694 | 61 |
| CIX | 4 | none | 0.052 | 184 | 8.3 |
| CIX-1' | 4 | none | 0.093 | 338 | 20 |
| CIX | 4 | x2 | 0.084 | 312 | 9.3 |
| CIX-1' | 4 | x2 | 0.11 | 412 | 26 |

Table 2: A comparison of the modeled sensitivity to cluster parameters as a function of integration time and cluster lensing of IR sources. Two reference experiments are considered, CIX on the LMT with a 12" beam and a CIX-like experiment with the same $\mathrm{NET_{CMB}}$ but with a 1' beam. All results assume previously measured electron temperature with 1-sigma error of 1 keV. Also tabulated is residual IR point-source contamination in the final kSZ map.

The problem of dusty galaxies lensed by the cluster potential is well served by the combination of multi-frequency observation and high spatial resolution. The 350 GHz channel by itself will serve to detect point sources and also as a spatial template to separate the background galaxy shot noise. In addition, the magnification factor due to lensing of the background dusty galaxies is position dependent and smaller beams allows the relative weighting of different regions to be dependant on the contributions due to magnified galaxies which vary by more than a factor of 2 (Knox et al. (2004)). The high resolution also allows CIX to use an optimization where spatial information on the electron column density derived from the SZE optimizes the measurement of the kSZE (Forni and Aghanim (2004)).

Ultimately, the combination of high angular resolution and multi-spectral coverage will make the CIX instrument particularly effective for SZE cluster studies because it avoids many of the biggest problems with cluster observations. Resolving point sources and observing their spectrum will permit their separation. These simulations show that true internal cluster structure can be observed. Because they result from reprocessing of the CMB, both the SZE and kSZE are redshift independent. The SZE and kSZE are thus valuable observables for clusters spanning all redshifts.

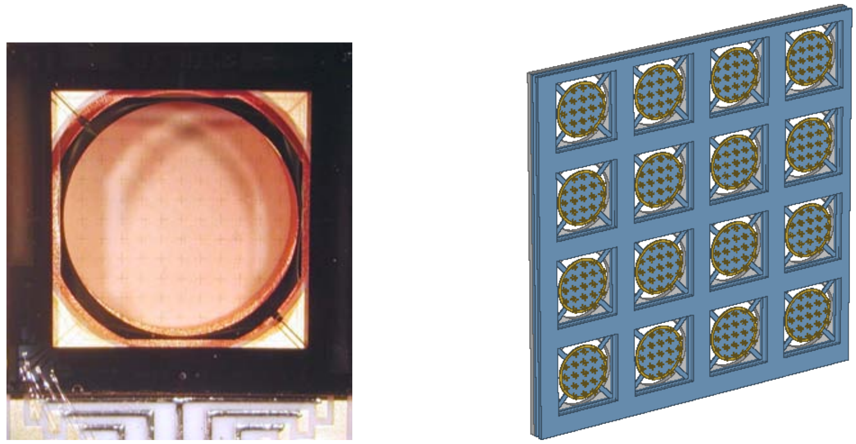

Figure 2: Left, a prototype FSB, on which the CIX design is based. Right, a $4 \times 4$ CIX array element, showing the disk, legs, absorbing grid, $C$ tuning ring, and supporting frame.

## d. Relationship to Dark Energy

Observations with sufficient resolution to observe the internal structure can correct and check the nature of the errors produced by incorrect radial profile and internal structure. These errors can be checked over the entire redshift range from 0.1 to 2 with images having 5 $\mu$K RMS per pixel. Increasing the understanding of the relationship between the SZ observables in low resolution SZ surveys and cluster mass and particularly the redshift dependence of the relationship is critical for reducing the systematic errors in the determination of Dark Energy properties using SZ surveys.

CIX is a tool for studying cluster structure and evolution. However, instrument mapping speed is insufficient to observe enough clusters to make strong statistical statements about the growth of structure either from the spatial distribution of clusters or the evolution of cluster mass — both of which are probes of Dark Energy due to its effect on cluster growth in the interval since $z = 1$. Such statistically strong studies are best carried out with fast mapping SZ surveys such as SPT and ACT, which are currently under construction. The role of CIX is to quantify the relationship between the SZ observables with resolution greater than 1 arcminute and physical cluster properties as a function of redshift. This is an important part of determining systematic effects inherent SZ surveys.

## e. Project Risk and Strengths

The strength of high resolution, multi-band high-frequency SZ measurements is the ability to evaluate the systematics errors present in SZ surveys made with lower resolution. There is some risk in the schedule for the completion of the LMT and the construction of the CIX camera.

## f. Technology Research and Development

The CIX camera uses Frequency Selective Bolometers (FSB) which are currently under development at NASA/Goddard Space Flight Center in collaboration with the University

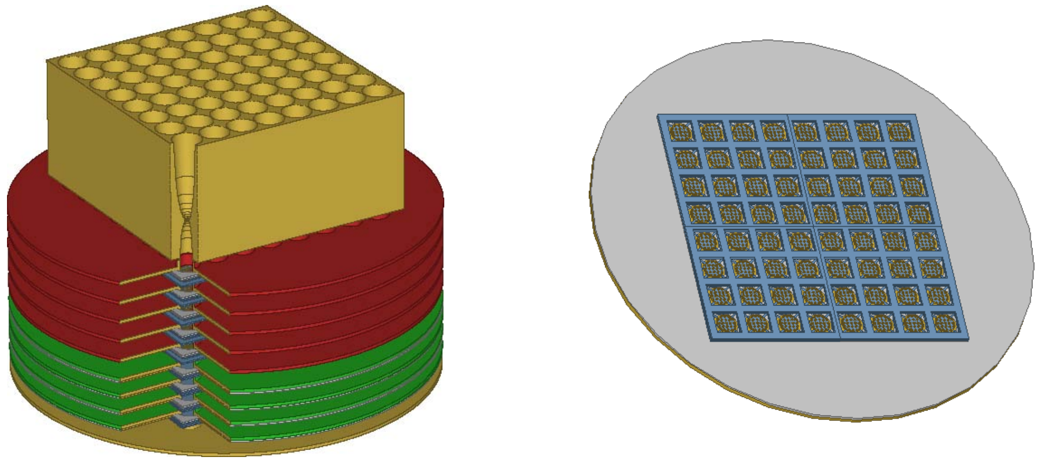

Figure 3: Left, the CIX focal plane assembly. Shown are the 4 detector planes, 5 filter planes, and the array of back-to-back Winston cones. Right, a detector plane, showing the $8 \times 8$ array of FSBs, made in four $4 \times 4$ units. The patterned backshort is mounted at a quarter wave spacing from the bolometer. The array is surrounded by a circuit board that carries the multiplexers and bias resistors (not shown).

of Chicago, the University of Massachusetts, and Case Western Reserve University. Two layer devices with the frequencies needed by CIX have been tested in the lab optically for response and total efficiency. These devices are now at the point where arrays of FSB have been designed but production awaits new funding.

The CIX detector system is a $8 \times 8$ pixel array of FSBs. The FSB is a technology in which detectors responding to different frequencies are stacked on top of each other in a light pipe to obtain a multi-chromatic focal plane (Kowitt et al. (1996)). The key element of the detectors is a resonant absorbing surface on the bolometer, which when paired with a resonant backshort, serves to selectively deposit power on the bolometer. Radiation not absorbed at a particular layer is transmitted on to the detectors below which are tuned to different frequencies.

Each pixel observes simultaneously in 4 frequency bands. The CIX detector assembly is constructed in 4 detector planes — each plane has a FSB array that detects one frequency. The 64 pixel FSB array for each plane consists of a bolometer array and a back short array. They are stacked and bonded with shims to hold them at the correct quarter-wave spacing. A $4 \times 4$ bolometer sub-array is shown in Figure 2, which shows the Si frame, the SiN disk suspended by SiN legs, and the absorber grid. Not shown are the transition edge sensors (TESs), leads and bonding pads. On the left is a photograph of a single prototype FSB, on which the CIX design is based. The temperature of the absorber is sensed with TES sensors, placed at the edge of the disk, outside the optical path.

In addition to the four layers of FSBs, four notch filters and one low-pass filter completes the focal plane design. The filters are two layer resonant mesh filters designed to reduce sensitivity to atmospheric lines near (or in one case, in) the observing band. In front of the stack is an array of back-to-back Winston cones. The cones serve two purposes: first, they define the throughput of the system, and second, they adapt a filled focal place, at $f/3.3$, to a necessarily sparse set of lightpipes, at $f/1.8$. A diagram of the complete assembly, including cone array, the 5 filter planes, and the 4 detector planes, is shown in Fig. 3.

Enabling the CIX instrument is the detector development program at NASA/Goddard Space Flight Center and the development of SQUID readout multiplexors manufactured at NIST.

## h. Access to Facilities

The CIX camera will be the third continuum camera currently slated for use on the LMT. CIX will be one of the observatory cameras and will be available for all users of the LMT.

## i. Timeline

CIX is currently a pending proposal in the NSF ATI program. The proposed camera requires three years for construction from the start of funding. The LMT construction awaits the manufacture of the surface segments which is to begin this year and be completed in 2006. The LMT project goal is to complete the telescope in 2006.

## References

A. W. Blain. Gravitational lensing and the Sunyaev-Zel'dovich effect in the millimetre/submillimetre waveband. *MNRAS*, 297:502–510, 1998.

J. E. Carlstrom, G. P. Holder, and E. D. Reese. Cosmology with the Sunyaev-Zel'dovich Effect. *ARA&A*, 40:643–680, 2002.

O. Forni and N. Aghanim. Separating the kinetic Sunyaev-Zel'dovich effect from primary cosmic microwave background fluctuations. *A&A*, 420:49–60, 2004.

G. P. Holder. Measuring Cluster Peculiar Velocities and Temperatures at Centimeter and Millimeter Wavelengths. *ApJ*, 602:18–25, 2004.

L. Knox, G. P. Holder, and S. E. Church. Effects of Submillimeter and Radio Point Sources on the Recovery of Sunyaev-Zel'dovich Galaxy Cluster Parameters. *ApJ*, 612:96–107, 2004.

M. S. Kowitt, D. J. Fixsen, A. Goldin, and S. S. Meyer. Frequency selective bolometers. *Appl. Opt.*, 35:5630, 1996.

J.-B. Melin, J. G. Bartlett, and J. Delabrouille. The selection function of SZ cluster surveys. *A&A*, 429:417–426, Jan. 2005.

D. Nagai, A. V. Kravtsov, and A. Kosowsky. Effect of Internal Flows on Sunyaev-Zeldovich Measurements of Cluster Peculiar Velocities. *ApJ*, 587:524–532, 2003.

V. Springel, M. White, and L. Hernquist. Hydrodynamic Simulations of the Sunyaev-Zeldovich Effect(s). *ApJ*, 549:681–687, Mar. 2001.