THE CORNELL CALTECH ATACAMA TELESCOPE

Sunyaev-Zeldovich Effect Science with the Cornell-Caltech Atacama Telescope

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See also **(101.03) Strawman Design of a Long-Wavelength Camera for the Cornell-Caltech Atacama Telescope**

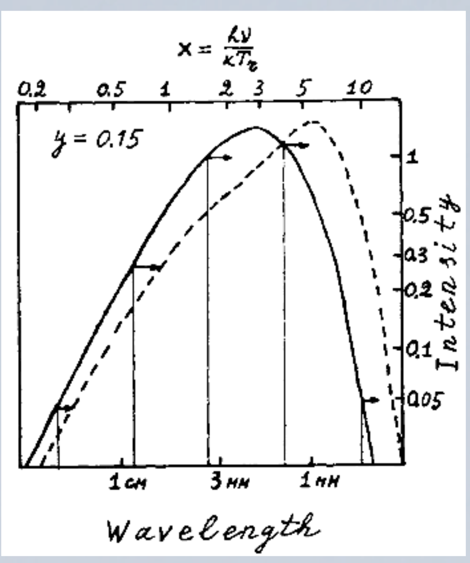
Abstract

The Sunyaev-Zeldovich (SZ) effect will become, over the next decade, an important probe of cosmology and cluster formation astrophysics via wide-area blind surveys for galaxy clusters using the SZ effect (Planck, APEX-SZ, ACT, SPT). The Cornell-Caltech Atacama Telescope (CCAT), with its finer angular resolution and wider frequency coverage relative to the survey telescopes, can play a significant complementary role by pursuing the following types of SZ observations:

- Detailed thermal SZ (tSZ) effect mapping of clusters. CCAT will provide high-resolution SZ profiles to study cluster astrophysics and to aid in calibrating and interpreting these surveys.
- Measurement of the tSZ anisotropy power spectrum at very high angular multipole number, ~ 2000-20000.

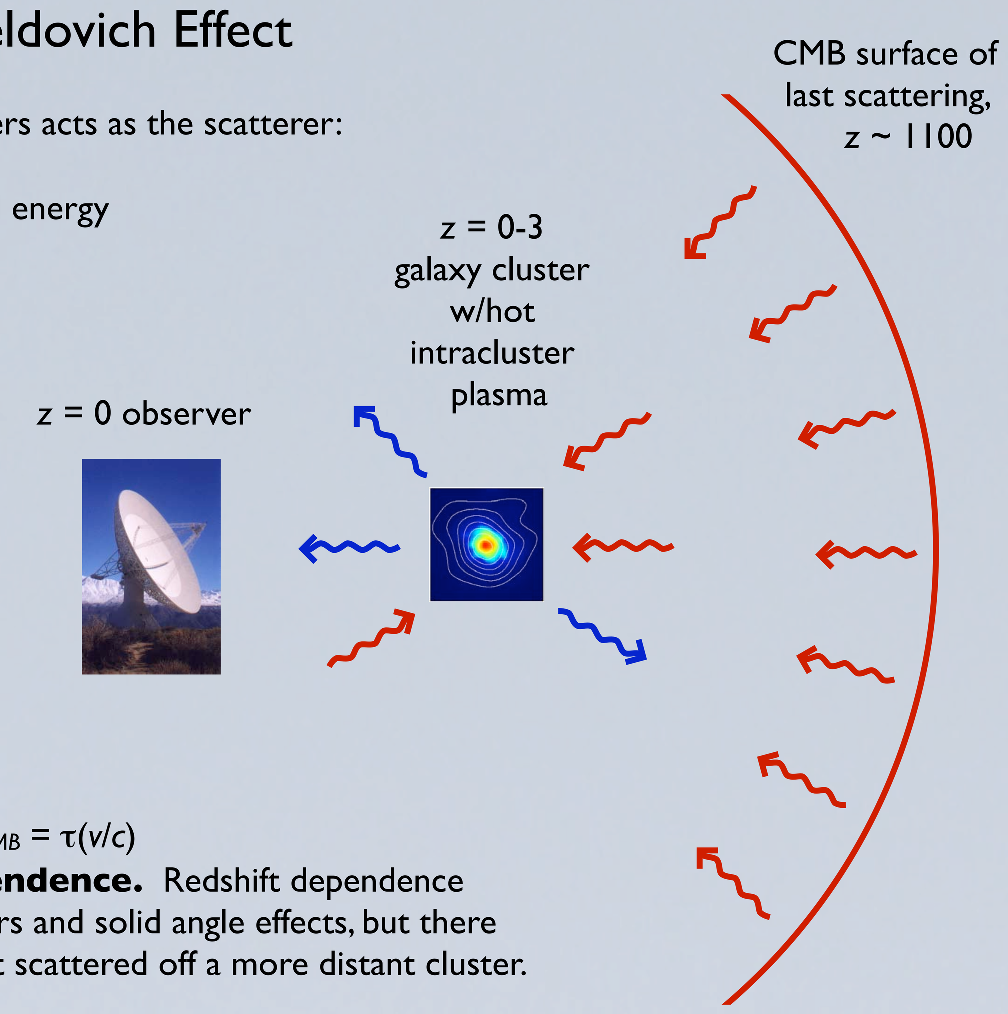
We present expected sensitivities for observing programs of these types.

The Sunyaev-Zeldovich Effect



Spectrum of the CMB (solid) and the thermal SZ effect (dashed). The size of the tSZ effect is greatly exaggerated. (Sunyaev and Zeldovich, 1980)

- **SZ effect** = Compton scattering by free electrons
- Ionized baryonic intracluster medium of galaxy clusters acts as the scatterer: optical depth $\tau \sim 0.01$ for 3×10^{15} M_{Sun} cluster
- **Thermal SZ effect (tSZ)** = exchange of thermal energy between hot electrons ($T_e \sim 10^8$ K ~ 5 keV) and cold CMB ($T_{CMB} \sim 3$K ~ 200 μeV)
  - proportional to ICM pressure, $n_e T_e$
  - new probe of cluster ICM: a new observable in addition to X-ray emission and galaxy counts, extends out to larger radius because $\propto n_e$ vs. n_e^2 for X-ray
  - causes non-thermal change in CMB spectrum; spectrum becomes "colder" at low frequency, "hotter" at high frequency
- **Kinetic** or **kinematic SZ effect (kSZ)** = Doppler shift of CMB due to scattering off of moving cluster
  - proportional to cluster peculiar velocity
  - causes *thermal* change in CMB brightness $\Delta T_{CMB}/T_{CMB} = \tau(v/c)$
- **Both effects have no explicit redshift dependence.** Redshift dependence arises through redshift evolution of cluster parameters and solid angle effects, but there is no $1/r^2$ effect because the CMB was hotter when it scattered off a more distant cluster.

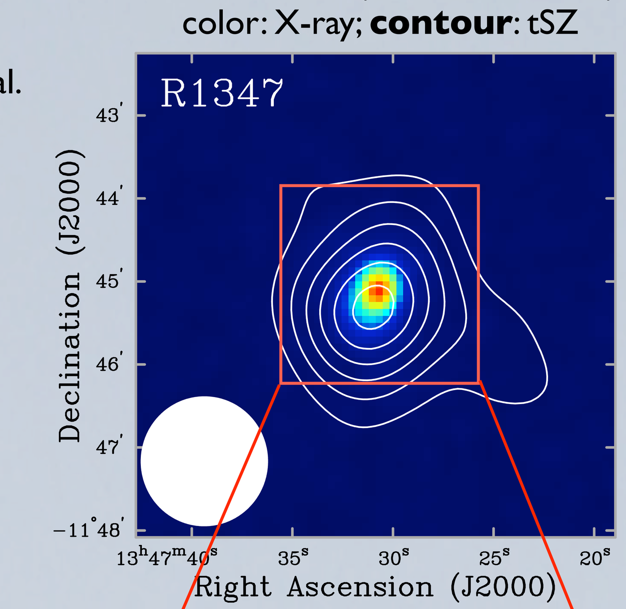


SZ Observational Status and Motivation for CCAT SZ

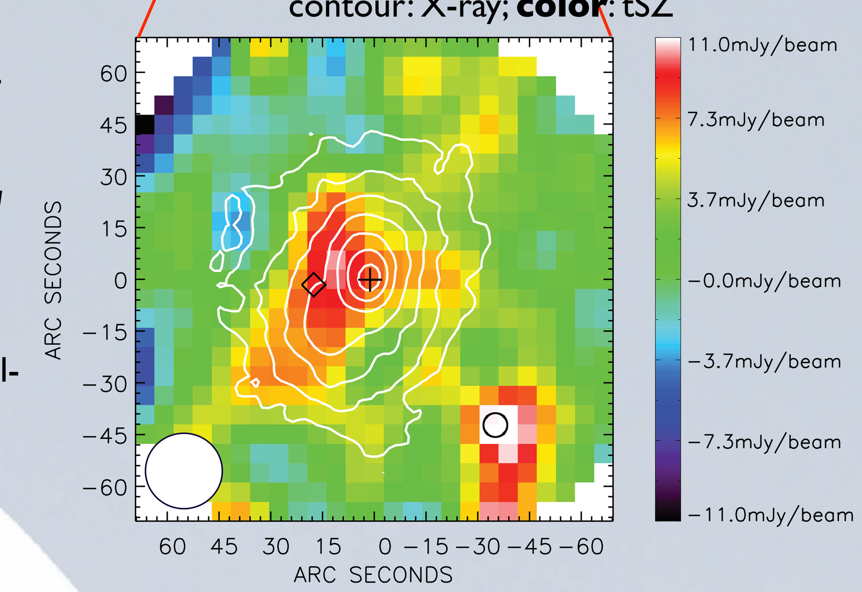
- ~60 massive clusters have been observed in the thermal SZ effect
  - using the OVRO/BIMA interferometers at 30 GHz (Grego et al. 2001, Reese et al. 2002, Bonamente et al. 2006, LaRoque et al. 2006)
  - 11 clusters with SuZIE bolometer array at 150-350 GHz (Benson et al,. 2003, 2004)
  - A handful mapped in their cores with SCUBA at 350 GHz (Komatsu et al. 1999, Kitayama et al. 2004, Zemcov et al. 2003)
- No cluster yet detected blindly by tSZ
- No detection of kSZ yet
- Very little cluster astrophysics done with SZ effect to date
  - LaRoque et al. 2006 measured cluster baryon fraction
  - No real feedback from tSZ pressure data to cluster modeling
- A number of tSZ surveys are taking science data now (APEX-SZ, ACT, SPT)
  - tSZ flux limit gives approximately mass-limited sample (Holder et al. 2001)
  - 6- to 10-m telescopes w/bolometer arrays at 90-275 GHz, giving ~1-1.5' resolution in most sensitive bands (90 and 150 GHz)
  - will detect all clusters > 1×10^{14} M_{Sun} over many 1000s of □°
  - Using follow-up optical redshifts, will constrain cosmological parameters via redshift dependence of cluster abundance
- ***CCAT's angular resolution and wide FoV will provide a new opportunity to study clusters in tSZ with high angular resolution (15-30") and large spatial dynamic range (10' max spatial scale) simultaneously.***

Science impacts:
- Tests of cluster formation simulations from core to beyond virial radius
- Modeling of ICM in unrelaxed clusters (*e.g.*, RXJ1347, bullet cluster): joint estimation of T_e with X-ray at high T_e
- Isolation of interesting regions for finer-res. followup
- Checks of tSZ survey models for tSZ-mass relationship
- Tests for contamination by confusing submm galaxies

30 GHz BIMA (Reese et al 2002)
color: X-ray; **contour**: tSZ



350 GHz SCUBA (Kitayama et al 2004)
contour: X-ray; **color**: tSZ



CCAT Capabilities

CCAT is discussed in Oral Session 121 and Poster Session 101, *Present and Future Submillimeter Surveys.* The expected capabilities of the prospective facility long-wavelength camera, which is most relevant for SZ observations and is discussed in Poster 101.03, are summarized here.

Band Center		*Beam FWHM [arcsec]*	*Field-of-View [arcmin]*	*Single-Pixel Sensitivity*	
Wavelength [μm]	*Frequency [GHz]*			*mJy √sec*	*μK_{CMB} √sec*
740	405	8	10	7	–
865	350	9.5	10	4	–
1100	275	14	20	2.5	1000
1400	215	18	20	2.2	530
2000	150	26	20	2.3	310
3000	100	40	20	2.7	270

Confusion by Submm Galaxies

CCAT beam = 2.5x smaller than for 10-m survey telescopes, both resolve clusters
⇒ confusion by submm galaxies *more* challenging *at native beam size*:
tSZ flux/beam smaller for 25-m, confusing source flux unchanged
But, can obtain confident detection of submm galaxies to lower flux than 10-m.
Also, can degrade tSZ map resolution while removing confusion to full resolution.

Confusion estimate: Calculate expected depth to which one can remove confusing sources (using higher-frequency data because of steeply rising spectra (ν^3 to ν^4))
- Assume confident detection of submm sources in 350 and 405 GHz bands at one per 30 or one per 10 beams
- Extrapolate to tSZ bands (150 to 275 GHz) with range of spectra
- Also list native confusion levels in the 150-275 GHz bands (no 350/405 GHz removal).
- More sophisticated techniques require study in the future; these limits are conservative.
- 100 GHz should also incorporate radio source confusion estimate.

See also the table *Candidate Key Programs in SZ Science for CCAT.*

Band Center Frequency [GHz]	*Submm Galaxy Confusion Limit*			*Confusion Removal Limit using High-Frequency Data [μJy]*							
				1/30 beams in high-frequency band				*1/10 beams in high-frequency band*			
				350 GHz		*405 GHz*		*350 GHz*		*405 GHz*	
	1/30 beams [μJy]	*1/10 beams [μJy]*	*1/beam [μJy]*	ν^3	ν^4	ν^3	ν^4	ν^3	ν^4	ν^3	ν^4
405	1100	530									
350	920	460									
275	850	470	90	450	350	340	230	220	180	170	110
215	560	320	71	210	130	160	87	110	65	79	42
150	240	140	37	72	31	56	21	36	16	27	10
100	100	60	21	21	6	17	4	11	3	8	2

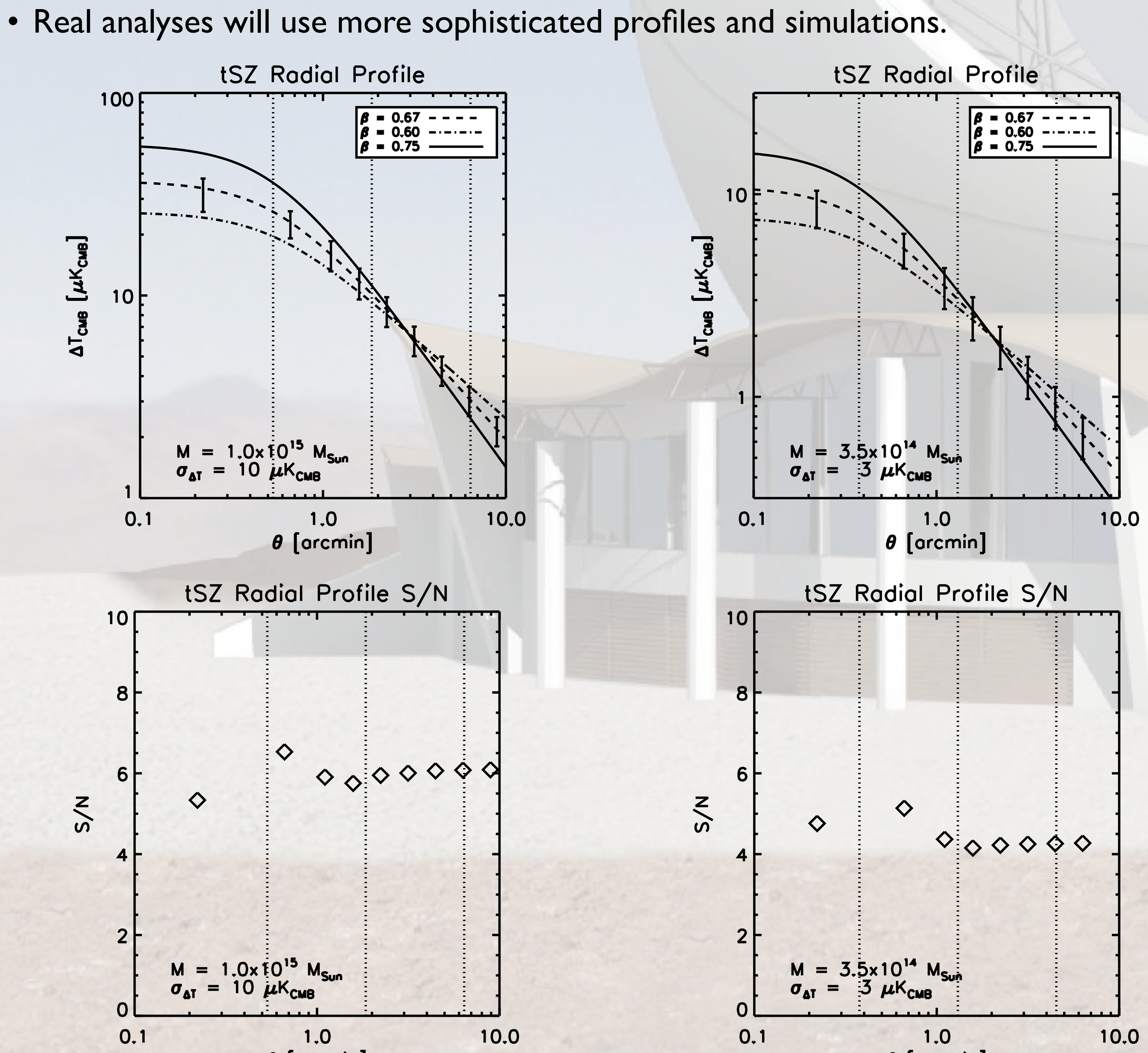
Galaxy Cluster Abundances

- Listed below are approximate abundances of galaxy clusters at various mass limits, for $\sigma_8 = 1$, to provide context for programs listed in the table *Candidate Key Programs in SZ Science for CCAT.*
- The current best value for σ_8 is closer to 0.8, which reduces these numbers substantially (x2 or more); at lower σ_8, CCAT will study a *larger* fraction of all clusters.

Mass Limit	Abundance	# over Full Sky
1×10^{14} M_{Sun}	40 / □°	10^6
3.5×10^{14} M_{Sun}	6 / □°	10^5
1×10^{15} M_{Sun}	0.25 / □°	few x 10^3
3.5×10^{15} M_{Sun}	0.01 / □°	10^2

Example Radial Profiles

- Radial tSZ profiles after azimuthal averaging
- Assume simplistic β-model input profiles; overlay nearby β-model profiles to indicate precision of model constraints; figures do not fully illustrate how CCAT's large spatial dynamic range breaks degeneracy between β and θ_c.
- Real analyses will use more sophisticated profiles and simulations.



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Grego et al, 2001, *Ap. J.*, **552**: 2.
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Kitayama et al., 2004, *PASJ*, **56**: 17.
Komatsu et al., 1999, *Ap. J.*, **516**: L1.
LaRoque et al., 2006, , *Ap. J.*, **652**: 917.
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Zemcov et al., 2003, *MNRAS*, **346**: 1179.

Candidate Key Programs in SZ Science for CCAT

Want key programs in SZ science for CCAT that
- make optimal use of CCAT's technical strengths
- maximize complementarity with wide-area tSZ surveys, ALMA, GBT, LMT, and other facilities.

We focus on two primary programs:
- **tSZ follow-up**: Finer angular resolution follow-up of subset of clusters from wide-area surveys.
- **High-ell tSZ anisotropy:** Complementary measurement of power spectrum of anisotropy due to the tSZ effect in unresolved clusters and large-scale structure.

Prospective depths and S/N per beam of such programs listed below. Notes:
- Radial profile measurements assume azimuthal averaging.
- Last column lists confusing source density at 405 GHz to be removed to reach desired depth.
- "tSZ confusion" not included.
  - tSZ confusion = random fluctuations in tSZ background of ensemble of clusters,
  - tSZ bgnd ~ y ~ 4×10^{-6} (at 150 GHz, 60 μJy/beam or 10 μK_{CMB}), fluctuations of comparable size ⇒ fundamental mass limit ~ 1×10^{14} M_{Sun}
  - Interesting to do anisotropy survey deep into this noise to measure its anisotropy power spectrum.
  - Not treated as fundamental noise limit yet, pending simulation of removal above a flux cut, masking, etc.

Comment on kSZ observations:
- Confusion noise more challenging for kSZ because need good sensitivity at 220 and 275 GHz to confirm spectrum, but submm confusion worse in these bands; feasible by degrading angular resolution in SZ bands
- More efficient to do SZ band measurements with 10-m surveys and submm source detection with CCAT?
- Scientific usefulness of kSZ unclear:
  - Cluster peculiar velocity field: statistical power of kSZ in tens of clusters vs. massive LSS surveys?
  - kSZ anisotropy: are Ostriker-Vishniac and patchy reionization power spectra sufficiently interesting?

Complementarity w/ALMA, GBT, LMT:
- ALMA: resolution *too good* for the application: integration time needed to cover appreciable part of cluster too large. Excellent for detailed studies of core, unusual regions found in CCAT + X-ray
- GBT: 90 GHz camera FoV v. small (0.5 arcmin); larger in future? No access to submm for confusion removal.
- LMT: Small FoV as designed (4 arcmin), insufficient access to submm for confusion removal.

Science Target	*Per-beam sensitivity at 150 GHz*			*# of objects per year*	*# of hours per year*	*# of objects in 5 years*	*# of hours in 5 years*	*Sources/ beam at 405 GHz (ν^3 - ν^4)*
	μK_{CMB}	*μJy*	*S/N*					
tSZ profiles								
High-mass (> 3.5×10^{15} M_{Sun})								
mapping	2	15	5	10	130	50	650	1/10 - 1/30
Medium-mass (1×10^{15} M_{Sun} to 3.5×10^{15} M_{Sun})								
mapping	1	7.5	3	3	160	15	800	1/3 - 1/10
radial profile	10	75	0.3	200	100	1000	600	< 1/30
Low-mass (3.5×10^{14} M_{Sun} to 1×10^{15} M_{Sun})								
radial profile	3	23	0.3	20	120	100	600	1/10 - 1/30
Lowest-mass (1×10^{14} M_{Sun} to 3.5×10^{14} M_{Sun}): These clusters are small enough in size and flux that they are not appreciably resolved by CCAT and are at the submm and tSZ confusion limits. Better done by ALMA.								
tSZ anisotropy survey, S/N = 5 per beam on 0.5 deg^2 fields								
	1.4	10	5	1	120	5	600	1/3 - 1/10