RADIO POINT SOURCES AND THE THERMAL SUNYAEV-ZELDOVICH POWER SPECTRUM

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ABSTRACT

Radio point sources are strongly correlated with clusters of galaxies, so a significant fraction of the thermal Sunyaev-Zeldovich (SZ) effect signal could be affected by point-source contamination. Based on empirical estimates of the radio galaxy population, it is shown that the rms temperature fluctuations of the thermal SZ effect could be underestimated by as much as 30% at an observing frequency of 30 GHz at \( f \gtrsim 1000 \). The effect is larger at higher multipoles. If the recent report of excess power at small angular scales is to be explained by the thermal SZ effect, then radio point sources at an observing frequency of 30 GHz must be a surprisingly weak contaminant of the SZ effect for low-mass clusters.

Subject headings: cosmic microwave background — cosmological parameters — galaxies: clusters: general — radio continuum: galaxies

1. INTRODUCTION

Recent and upcoming measurements of anisotropies in the cosmic microwave background (CMB) may be sensitive enough (a few \( \mu \)K) and at high enough angular resolution (a few arcminutes) to detect fluctuations in the microwave background due to unresolved distant and faint clusters of galaxies, due to the thermal Sunyaev-Zeldovich (SZ) effect. As the largest expected signal of "secondary" anisotropies (anisotropy arising from processes at low redshift), such a detection will mark an important milestone, as well as provide important constraints on cosmological parameters and the thermal history of intracluster gas.

Significant work has gone into the problem of extracting the signal of the "primary" anisotropies (those imprinted at \( z \sim 1100 \)) from the expected foreground sources of contamination, such as dust, star-forming galaxies, and radio point sources. A major aid in this extraction is the lack of correlation between the signal and the contaminant. In searching for the signal of secondary anisotropies, this is no longer the case. While this does not provide any deep or profound problems, it does provide reason for caution in interpretation of detected signals in the presence of foregrounds.

It is well known that clusters of galaxies observed at frequencies near 30 GHz (wavelength 1 cm) are likely to contain radio point sources (Birkinshaw 1999). Therefore, the signal of the thermal SZ effect can be significantly diluted, depending on how these point sources are handled. There are two possible modes of dilution: removal of point sources can lead to removal of SZ signal, and point sources that are not removed can fill in an SZ decrement. In this work we estimate the expected dilution of the thermal SZ effect signal at an observing frequency of 30 GHz, appropriate for an experiment such as CBI (Padin et al. 2001).

While the focus in this paper will be contamination of the thermal SZ effect by radio point sources, at higher frequencies dusty starbursting galaxies could be important contaminants of the SZ signal (Blain 1998), because of gravitational lensing effects. These same contaminants will be troublesome for signals of lensing in the CMB. Multifrequency observations alleviate these concerns somewhat, but the uncertain and heterogeneous spectral behavior of both radio and submillimeter point sources present a challenge for precise measurements of secondary anisotropies.

The thermal SZ effect and its angular power spectrum is reviewed in § 2. In § 3 we outline the relevant statistics of radio point sources in galaxy clusters and apply them to the thermal SZ power spectrum in § 4. The implications of these results are discussed in § 5.

2. THERMAL SZ FROM GALAXY CLUSTERS

The thermal SZ effect (Sunyaev & Zeldovich 1972; Birkinshaw 1999; Carlstrom et al. 2000) arises from Compton scattering of cool CMB photons with hot electrons in the deep potential wells of galaxy clusters. A striking feature of the SZ effect is its unique spectrum. Relative to the CMB, the SZ effect manifests itself as a deficit of photons at frequencies below about 218 GHz and as an excess at higher frequencies. The decrement at low frequencies is particularly useful, since there are very few astronomical signals that show up as “holes” in the sky.

The temperature decrement (or increment), ignoring relativistic corrections (Rephaeli 1995), is given by

\[
\frac{\Delta T_{\text{SZ}}}{T_{\text{CMB}}} = f(x) y = f(x) \int n_c \frac{k_B T_e}{m_e c^2} \sigma_T dl, \tag{1}
\]

where \( y \) is the Compton \( y \) parameter, \( n_c \) is the electron number density, \( T_e \) is the electron temperature, and \( x = h \nu / (k_B T_{\text{CMB}}) \) is the observing frequency in natural units. The frequency-dependent factor is given by

\[
f(x) = \left[ x(e^{x+1} - e^{x-1} - 4) \right].
\]

When integrated over the entire angular extent of the cluster, the SZ flux has a scaling of \( S_{\text{SZ}} \sim d_A^2 f_g h M T_e \), where \( d_A \) is the angular diameter distance in units of \( h^{-1} \) Mpc, \( f_g \) is the gas mass fraction, \( h \) is the Hubble constant in units of 100 km s\(^{-1}\) Mpc\(^{-1}\), and \( M \) is the cluster mass in units of \( h^{-1} M_\odot \). Assuming the virial relation \( T \propto M^{2/3} \) gives the SZ flux scaling with mass as \( M^{5/3} \).

The primary anisotropies in the CMB are thought to be Gaussian in nature and can therefore be characterized entirely through the angular power spectrum. This is not true for either foregrounds or secondary anisotropies. The
angular power spectrum is therefore not nearly as useful, but it does present a common language with which to work, and we will adopt it here.

Adopting the flat-sky approximation, the usual multipole expansion becomes a two-dimensional Fourier transform, with \( l = 2\pi R_{\text{arc}} \), where \( R_{\text{arc}} \equiv (\mu^2 + \nu^2)^{1/2} \) is the radial distance in the Fourier plane and \( \mu \) and \( \nu \) are the Fourier conjugate variables to \( \theta_x \) (e.g., R.A.) and \( \theta_y \) (e.g., decl.) on the sky. The variance of the Fourier amplitudes at radius \( R_{\text{arc}} \) is equal to \( c_l \). Denoting the Fourier transform of the cluster SZ temperature decrement profile as \( T \), the angular power spectrum of a galaxy cluster at the center of a field is simply \( c_l = T^2 \), assuming azimuthal symmetry for the cluster.

Spatial correlations between galaxy clusters are negligible for \( l \gtrsim 100 \) (Komatsu & Kitayama 1999), and in this work we are interested in \( l \gtrsim 1000 \), so the correlations can be safely neglected. The angular power spectrum can therefore be thought of as Poisson shot noise, where each “shot” has an angular profile. For a Poisson process, at each position in the Fourier plane a randomly placed source will have an amplitude \( T \) but will have a random phase. The collection of sources will thus constitute a random walk of the Fourier spectrum, while shifting the normalization of the mass-temperature relation introduces a direct scaling of the amplitude of the angular power spectrum. For example, using the observed normalization of the mass-temperature relation (Finoguenov, Reiprich, & Böhringer 2001) leads to an rms temperature fluctuation that is approximately 50% higher. Given the uncertain relation between the observed X-ray temperatures and the (most relevant for our purposes) mean electron temperature, we choose to use the normalization from simulations.

Putting the pieces together, the integrand of equation (2) is shown as a function of mass and redshift in Figure 1. Self-similar evolution of the intracluster medium was assumed, but the gas evolution history has very little effect on such a plot. At \( l = 1000 \), most of the signal is coming from some massive, relatively nearby clusters, while the dominant contribution to higher \( l \) is coming from distant low-mass clusters, with a significant tail extending to \( z = 2 \).

It is easy to see why radio point sources could be a problem. At \( l = 1000 \), the signal is coming from nearby clusters, where each point source should be relatively bright, and from fairly massive clusters, which have more cluster members and therefore could be expected to have more point sources. These clusters also have stronger SZ emission and are more extended on the sky, which will somewhat mitigate the point-source contamination. At higher \( l \), the clusters have fewer point sources, and the ones that do have are diluted by the luminosity distance. However, the cluster signal is weaker, making point sources relatively more

\[ c_l(l) = \int_0^\infty dz \frac{d_A(z)^2(1+z)^2}{H(z)} \left( \int_0^{l_{\text{max}}} d\ln M T(M, z, l)^2 \right) \left( \frac{dn}{d\ln M} \right), \]

where \( d_A(z) \) is the angular diameter distance, \( H(z) \) is the Hubble constant, and \( \frac{dn}{d\ln M} \) is the differential comoving number density per log interval in mass. A very fast method to obtain \( T \) for somewhat realistic cluster profiles with azimuthal symmetry is to take advantage of fast Hankel transform routines that exist (Anderson 1982). Note that here, and everywhere below, we work in units where \( c_l \) has units of \( \mu K^2 \).

The power spectrum calculation follows exactly the procedure of Holder & Carlstrom (2001). We choose cosmological parameters \( \Omega_m = 0.3 \), \( \Omega_\Lambda = 0.7 \), \( \sigma_8 = 1 \), \( h = 0.7 \), \( \Omega_b h^2 = 0.02 \), \( n = 1 \), and zero neutrino mass. The differential comoving number density is adopted from recent fits to large numerical simulations of structure formation (Jenkins et al. 2001) and is a function of the variance on mass scale \( M \). This variance was calculated using the power spectrum for our adopted cosmological model derived from the fitting functions of Eisenstein & Hu (1999).

As a cluster model, we adopt the simple toy model of Holder & Carlstrom (2001), with a density profile of the form \( n_c \propto 1/(r_c^2 + R_c^2) \), with \( r_c \) a core radius and \( R_c \), the virial radius, derived from the spherical collapse model (Lahav et al. 1991). The relation between core radius and virial radius is taken to be a constant value (10), roughly as would be expected for the case of self-similar evolution of the cluster population. The gas temperature as a function of mass was taken from hydrodynamical simulations (Bryan & Norman 1998), and the gas was assumed to be isothermal.

For this work, we are interested in the relative effects of radio point sources on the SZ angular power spectrum, so the details of the power spectrum are not crucial. We have verified that the results below are robust to the choice of model for generating the SZ power spectrum. The angular power spectrum resulting from our recipe is in broad agreement with results from large cosmological hydrodynamical simulations (Springel, White, & Hernquist 2001). Temperature gradients will affect the details of the shape of the peak of the power spectrum, while shifting the normalization of the mass-temperature relation introduces a direct scaling of the amplitude of the angular power spectrum. For example, using the observed normalization of the mass-temperature relation (Finoguenov, Reiprich, & Böhringer 2001) leads to an rms temperature fluctuation that is approximately 50% higher. Given the uncertain relation between the observed X-ray temperatures and the (most relevant for our purposes) mean electron temperature, we choose to use the normalization from simulations.

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![](image)

**Fig. 1.—** Relative differential contribution to the angular power spectrum, \( dc_l/d\ln M_{\text{cl}} \), normalized to peak contribution. Solid contours show contributions to \( l = 1000 \), with contour levels of 10% of the peak contribution. Dotted contours show contributions to \( l = 4000 \), also with contour levels of 10% of peak.
important. Thus, over the whole range of the peak of the SZ angular spectrum, it is expected that radio point source contamination might be important for experiments at low frequencies.

3. RADIO POINT SOURCES IN GALAXY CLUSTERS

Radio point sources are well measured and cataloged in terms of their flux distribution and source density at an observing frequency of 1.4 GHz, thanks to the NRAO VLA Sky Survey (NVSS) (Condon et al. 1998) and Faint Images of the Radio Sky at Twenty cm (White et al. 1997) surveys. Unfortunately, radio point sources often have nontrivial spectra (Herbig & Readhead 1992), so it is not easy to simply extrapolate from one frequency to another. The mean spectral index from 21 to 1 cm is approximately $\alpha = -0.7$, where $S(\nu) \propto \nu^\alpha$ (Cooray et al. 1998), but there is significant dispersion in the observed spectral indices (Cooray et al. 1998; Taylor et al. 2001).

At 1 cm, there are no large-scale deep surveys for point sources that can be used to accurately characterize the point-source population, but there are a large number of pointed observations toward clusters for SZ effect observations (Carlstrom et al. 2000) at this wavelength. The majority of observed clusters has at least one point source with a flux at 1 cm greater than 1 mJy. When compared with the point-source abundance in fields not containing clusters, it is clear that most point sources in fields with galaxy clusters must be physically associated with the galaxy clusters (Cooray et al. 1998), most likely the galaxy cluster members.

Radio emission from galaxy cluster members has been studied in detail (Ledlow & Owen 1996) at 21 cm ($\nu = 1.4$ GHz), with the fraction of galaxies at a given radio luminosity (per log interval) nearly flat at radio powers (at 21 cm) below $10^{24.8}$ W Hz$^{-1}$ and falling quickly above this power. To the optical and radio flux limits of their survey, roughly 10% of cluster members showed some amount of point-source emission. Assuming a typical spectral index $\alpha = -0.7$ and our fiducial cosmology, the break power at 21 cm corresponds to an observed flux at 1 cm of 7 mJy for a source at $z = 0.2$ and 1 mJy for a source at $z = 0.5$. This flux level is in rough agreement with the typical point-source fluxes observed by the Owens Valley Radio Observatory/Berkley-Illinois-Maryland Association (OVRO/BIMA) SZ imaging experiment (Carlstrom et al. 2000; Reese et al. 2002). If no point-source subtraction of any kind were done, these point sources would be a nonnegligible fraction of the thermal SZ signal from massive clusters ($\sim 10^{15} h^{-1} M_{\odot}$).

The nearly flat probability distribution (in log flux) with point-source flux leads to the typical galaxy cluster having the brightest point source dominating the total radio flux. From an observational standpoint this is desirable, since an SZ experiment only needs to remove a bright point source or two to be confident that the measurement is not contaminated by radio emission from galaxy cluster members.

The expected integrated thermal SZ signal for a $10^{15} h^{-1} M_{\odot}$ at $z \sim 0.5$ is on the order of 10–20 mJy (at 30 GHz) (Holder & Carlstrom 2001) and should scale as $M^{2/3}$. This is in agreement with current observations (Carlstrom et al. 2000), but current data do not extend over a large range in mass. The radio point source flux should scale approximately with the number of galaxies, which scales as the mass (Carlberg et al. 1996). A typical point-source flux for massive galaxy clusters at this redshift is on the order of 1 mJy at 30 GHz and is therefore roughly 5% of the total thermal SZ flux. The relative importance of point sources should therefore scale with mass as $M^{-2/3}$, while the redshift evolution of the relative importance will scale as $(1 + z)^{-1}$ for a flat spectral index. None of these numbers are particularly well constrained observationally, but these estimates constitute our baseline model.

4. EFFECTS OF POINT SOURCES ON THE SZ POWER SPECTRUM

At some level, all clusters have radio point sources. Ideally, one would be able to identify and remove all point sources in the field of view with a beam size that is matched to the size of the point source and much smaller than the extent of the SZ signal. In such a case, the amount of SZ flux removed would be negligible. Not surprisingly, this is exactly the attempted strategy of choice for interferometric SZ experiments, such as the Ryle Telescope (Jones et al. 1993) and OVRO/BIMA (Carlstrom, Joy, & Grego 1996), where high angular resolution measurements are performed simultaneously for point-source removal. It is not feasible to detect all point sources in a field, but such methods can easily remove point sources to a flux level below 10% of the peak SZ flux, with an effective resolution of roughly 10$''$ or better. With such a strategy, the residual effect of point sources on the SZ power spectrum would be negligible.

Such a strategy is not currently feasible for CMB experiments such as CBI. As primarily a CMB experiment, CBI is not concerned with point sources that do not contribute more than about 10 $\mu$K to the rms temperature fluctuations. This translates into a flux threshold of a few mJy at 30 GHz. Clusters with masses near $10^{14} h^{-1} M_{\odot}$ have a total SZ flux of a mJy or less (Holder & Carlstrom 2001), so a 1 mJy point source could be problematic. If all clusters had point sources near 1 mJy, effectively no clusters below $\sim 2 \times 10^{14} h^{-1} M_{\odot}$ in Figure 1 would contribute to the anisotropy, with a somewhat reduced contribution from slightly larger clusters. At $l = 1000$ the difference would be noticeable, but at $l = 4000$ it might be expected that as much as half of the power could be missing.

There are two leading strategies for dealing with point sources. One strategy is to identify possible point sources in catalogs at 21 cm and follow up with pointed observations at high angular resolution. Another strategy is to combine the data in a way that it is insensitive to any amount of flux coming from positions of known point sources, known as a constraint matrix approach (Bond, Jaffe, & Knox 1998). Both methods are susceptible to point sources with “inverted” spectra, where the flux is higher at higher frequencies, and therefore could be missed in the 21 cm catalogs. Such inverted sources are rare and are not expected to be a dominant source of error. For extraction of primary CMB anisotropies both methods work quite well (Padin et al. 2001; Halverson et al. 2002), but for the SZ effect, point-source subtraction will remove all SZ flux within the point-source subtraction beam area from the map at the position of the point source.

Using the constraint matrix method, the data are combined such that any constant amplitude signal in the Fourier plane (with the phase center at the position of the point source) does not contribute to the measured CMB aniso-
tropy. This will remove from the measured power the signal from a coincident cluster, averaged over the data. Because the CMB measurements are sensitive primarily to scales of several arcminutes and higher, this will effectively remove much of the cluster signal. Approximately, the constraint matrix should project out of the data the mean cluster signal in the Fourier plane.

As a toy model, we look at the effects of removing a point source from the center of all clusters. In Figure 2 we show the effects of point-source subtraction for the case of a central point source that has either been removed with a 1′ (FWHM) beam or had power from the center of each cluster projected out of the data by a constraint matrix approach. In the first case, we multiplied the SZ profiles by the appropriate beam and subtracted the result from the initial profile. This is correct only for an experiment with a reference beam that is outside the cluster, which is rarely strictly true, but sufficient for our purposes. For the second case, we calculate the mean amplitude of the cluster profile (in the Fourier domain) weighted by a uniform window function. We assume l coverage between l = 500–4000 and assume uniform coverage of the Fourier plane between these values.

The constraint matrix approach severely underestimates the SZ power, since it is effectively doing point-source removal with the beam size set by the approximate angular resolution of the CMB measurements. Because this is larger than 1′, it is to be expected that such an approach will remove significantly more power than direct subtraction with a 1′ beam. The anisotropy power from galaxy clusters coincident with point sources is effectively “nulled out” because of the relatively large synthesized beam of CBI.

Direct subtraction can lead to underestimate of the power of roughly 50% on scales of l = 3000. Therefore, a detection of a signal of amplitude 100 \( \mu K^2 \) would correspond to a true SZ angular power spectrum of 200 \( \mu K^2 \). Improving the angular resolution of the source subtraction helps considerably, as would using a reference beam within the cluster, as some of the SZ signal would be in both the source beam and the reference beam and would not be subtracted. For this reason, near-future interferometers such as the SZ-Array (SZA) and Arcminute Microkelvin Imager (AMI), with large spacings for point-source removal, should not have severe problems with point-source contamination.

The worst-case scenario is that every point source that CBI projected out of the data was at the center of a galaxy cluster and that every galaxy cluster had a point source at the center. With nearly 100 NVSS sources per square degree and only about 20 clusters above 10^{13} \( h^{-1} M_\odot \) per square degree (Holder & Carlstrom 2001), this only requires one in five sources to be located in clusters. A cursory check of NVSS images of known Abell clusters rules out this hypothesis being correct, but it is not impossible that a significant fraction of galaxy clusters were excluded in this way. If half of the SZ signal is coming from clusters coincident with known point sources, CBI would be missing about half of the fluctuation power from the thermal SZ effect.

In practice, point-source subtraction will only be performed to a limiting flux level, meaning that many clusters will not have source subtraction done. In this case, the remaining point sources will partly fill in the SZ decrement. The extreme case is where none of the point sources are subtracted, leaving all point sources sitting in galaxy clusters, filling in the SZ decrement and reducing the fluctuation power. In fact, for the clusters contributing the bulk of the SZ signal (see Fig. 1), this is most likely a good approximation to CBI.

As a simple model, we assume the scalings with mass from \S 3, with some additional constraints. We assume that all relevant nearby point sources are removed efficiently, and only include point-source contamination for clusters with \( z > 0.2 \). This will slightly underestimate the effect of radio point sources for two reasons. There will invariably be some nearby clusters with relatively faint point sources that have escaped detection, and at the same time, any point-source subtraction, as shown above, can remove a significant amount of SZ flux. We also assume that only clusters with \( M > 10^{13} \ h^{-1} M_\odot \) contain radio sources. We assume a canonical typical point-source flux of 5% of the total SZ flux for a 10^{13} \ h^{-1} M_\odot cluster at \( z = 0.5 \).

In the Fourier domain, point-source amplitudes are completely correlated at each point, and for a central point source the signal will be entirely real. At any point in Fourier space, the combined signal from the cluster and unresolved point sources will be \( S_{\text{net}} = (T - S_{\text{pt}}) \). This will contribute to \( c_l \), on average, \( S_{\text{net}}^2 = c_{l,\text{no}} + (S_{\text{pt}}^2) - 2T \langle S_{\text{pt}} \rangle \), where \( c_{l,\text{no}} \) is the contribution in the absence of residual unsubtracted point sources. If the point sources are not concentrated at the galaxy cluster center (where they would be if the emission is mainly from the bright galaxies) but instead trace the gas, we would expect \( \langle S_{\text{pt}} \rangle \) in the Fourier plane to have the same shape as \( T \), rather than being constant. For simplicity, we assume point sources are strongly centrally concentrated and place them at the cluster centers.

In Figure 3 we show the SZ power spectrum that would be inferred. The power spectrum due to the point sources alone has been subtracted. Unsubtracted point sources cause a significant underestimate of the SZ angular power.
5. DISCUSSION

Point-source contamination makes interpretation of detection of fluctuations in the CMB from the thermal SZ effect very difficult. To compare these fluctuations to predictions from either semianalytic modeling or numerical simulations, some treatment of the effects of point-source subtraction (or nonsubtraction) is required. This would require a recipe for the cluster galaxy populations. Current predictions of the thermal SZ power spectrum are almost certainly overestimating the thermal SZ power that CBI could observe.

The measured power at 30 GHz at high multipoles could be less than 30% of the true SZ power, but more likely is measuring roughly 50%–75%. Specifically, the recent tentative report of temperature fluctuations at high multipoles of close to 500 $\mu$K$^2$ (Mason et al. 2002), if due to the thermal SZ effect would indicate a true signal on the sky of roughly 1000 $\mu$K$^2$. A temperature rms of 25 $\mu$K represents a bit of a challenge for theoretical models (Bond et al. 2002; Komatsu & Seljak 2002), so a true signal greater than 30 $\mu$K would require a major rethinking of the physics of galaxy clusters and/or some fine-tuning of cosmological parameters. The simplest way to increase the expected SZ power is to increase $\sigma_8$. A true SZ signal of more than 30 $\mu$K would suggest $\sigma_8 \gtrsim 1.1$ (Komatsu & Seljak 2002), a value that is not preferred by current CMB data (Bond et al. 2002) but is not ruled out. From Figure 3 of Bond et al. (2002) such a high value could most easily be accommodated if the Hubble constant were significantly lower than the value suggested by HST measurements (Freedman et al. 2001).

Alternatively, if the measured power at high $l$ really is a measurement of the thermal SZ effect, this would be evidence that low-mass clusters at $z \sim 0.5$ are remarkably devoid of bright radio sources. This suggests that upcoming SZ surveys at 30 GHz (SZA) or 15 GHz (AMI) should have surprisingly clear extragalactic skies.

The statistics of point sources at high radio frequencies are very poorly constrained, making detailed predictions of point-source contamination difficult. We have adopted an approach to modeling point-source contamination of SZ signal that is empirically motivated, with only the relative importance of point sources to SZ signal at a single mass scale as a free parameter. Upcoming SZ/CMB experiments with high angular resolution, specifically for the purpose of point-source detection, such as AMI and SZA, will provide a wealth of information on radio point sources at these frequencies, while at the same time providing valuable information on the SZ effect from galaxy clusters.

Single-frequency measurements of the fluctuations due to the thermal SZ effect at frequencies below $\sim 90$ GHz that do not subtract point sources with a small beam to a fairly low flux level will be contaminated at a largely unknown but almost certainly significant level. Higher frequency measurements could have similar problems from dusty starburst galaxies, but most of these sources are expected to not be associated with the galaxy cluster members. While lensing effects lead to an enhancement of the confusion noise (Blain 1998), it does not lead, on average, to an increased average flux.

Experiments with multiple frequencies will be required for a robust determination of the amplitude of the thermal SZ signal, and the strong correlations between radio point sources and galaxy clusters and submillimeter point sources and galaxy clusters (primarily due to gravitational lensing) will require careful attention.

The general problem of correlation between secondary anisotropies and foregrounds will be increasingly important. The thermal SZ effect may be the most significant example, but correlations between the lensing of the CMB, for example, and radio and submillimeter point sources will reduce the expected signal and/or modify the noise properties of any attempted reconstructions. Clearly, a better understanding of the covariance between various foregrounds and backgrounds and secondary anisotropies of interest will be required if such signals are to be used as useful tests of our understanding of cosmology and structure formation.

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