Science with the Low Frequency Bands on ALMA: CMBR, SZE and cosmological applications

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Abstract

The ALMA receiver suite includes provisions for covering the Ka and Q bands from 30 – 45.5 GHz. This contribution summarizes some of the scientific drivers for this capability, in particular observations of the Cosmic Microwave Background Radiation anisotropy and scattering of the CMBR from hot gas in massive clusters of galaxies, the Sunyaev-Zeldovich effect. In addition to its unique capabilities at millimeter and submillimeter wavelengths, ALMA will also be a superb instrument at the smallest centimeter wavelengths. ALMA will complement the VLA with its greater effective collecting area at high frequency and a full view of the Southern Sky. We use examples from current CMB, SZE, gravitational lensing, and other extragalactic observations along with theoretical models of large scale structure evolution and galaxy formation to extrapolate the capabilities of ALMA for these programs.

The Cosmic Microwave Background

The Cosmic Microwave Background Radiation (CMBR) is the relic of the time when the universe was ionized and opaque to photons and thus thermalized at temperatures $T \sim 3000$ K. When the Universe expanded sufficiently (at a redshift of $z \sim 1100$) and the hydrogen was able to recombine, these optical photons were then free to stream to us unimpeded, eventually redshifting into the microwave spectrum at an observed temperature of ~ 2.73 K. Imprinted upon the isotropic 3K background and the large-scale dipole (due to our local peculiar motion with respect to the CMB frame) is a much smaller pattern of ripples — the CMBR anisotropy. These fluctuations were produced by matter clustering at the time of recombination, and thus are one of our most important cosmological fossils.

There are a number of upcoming and proposed CMBR anisotropy experiments, which cover the parameter space of frequency and angular scale. However, the focus is largely on the angular scales above 0.25 degrees, where the primary cosmological signatures appear in the fluctuation power spectrum. As shown in Figure 1, there are few that are able to target the fine scale anisotropies beyond $\ell > 1000$. ALMA will do this.

The current state-of-the-art ground-based experiments are using fast-switching single-beam telescopes to scan over several degrees on the sky at good sites. The Mobile Anisotropy Telescope (MAT), with its 1-meter primary mirror, was built by Mark Devlin (UPenn) and Lyman Page (Princeton) and run at Cerro-Toco on the Atacama site in Chile. MAT has measured the so-called Doppler Peak at the 1 degree angular scale in the CMBR anisotropy power spectrum (Miller et al. 1999) as shown in Figure 2. Similar experiments are also being run at the South Pole.

In addition to single dish scanning experiments such as MAT, small special-purpose interferometers such as the Cosmic Background Imager (CBI: Readhead et al.) and the Degree Angular Scale Interferometer (DASI: Carlstrom et al.) are soon to be operating at the Atacama and South Pole sites respectively. DASI will probe the degree scales similarly to MAT, and the CBI will image the CMBR on scales down to 4 arcminutes.

A significant problem affecting intermediate and small-scale CMBR anisotropy observations is the identification and removal of galactic and extragalactic foreground emission (see Figure 3). For example, the OVRO 5-meter telescope has measured the CMBR anisotropy on angular scales of $10'$ (Leitch et al. 1999) but confusing foreground emission attributed to an anomalous component of the galactic ISM was found and subtracted (Leitch et al. 1996). ALMA, along with the northern CARMA (the combined OVRO and BIMA) are two instruments with the sensitivity, frequency coverage, and angular resolution required to perform accurate foreground assessment. Of course, the nature of these anomalous foregrounds is of astrophysical interest in their own right!

The location and amplitude of the first "Doppler" peaks are controlled by the overall matter and energy density, baryon density and curvature of the Universe. On the other hand, the structure in the CMBR anisotropy power spectrum for multipoles beyond $\ell > 1000$ and angular scales less than $20'$ are sensitive to the "microphysics" that controls the formation of large-scale structures in the Universe we see today. Roughly, 1 arc-minute corresponds to 1 comoving megaparsec. By measuring the anisotropies on these small scales, we can get a snapshot of galaxy cluster-sized density perturbations when their amplitudes were less than 10^{-5} of the mean!

With its precision 12-meter diameter primary and its fast and accurate switching capabilities, ALMA will be a powerful instrument with which to image the CMBR anisotropy on small angular scales. In particular, when "On-The-Fly" (OTF) total power observations are combined with compact array interferometric data, ALMA will be able to produce maps of the CMBR from sub-arcmintue scales up to one degree, at unprecedented sensitivity levels. As seen in Figure 4, mapping 4 square degrees will not only capture the primary CMB fluctuations, but pick out against this background the signatures of massive clusters when they do form.

The Sunyaev-Zeldovich Effect

The space density of the most massive clusters of galaxies is extremely sensitive to cosmological parameters such as the matter density Ω_0, cosmological constant Λ_0, baryon density Ω_B, and "shape parameter" Γ or the Large-Scale Structure related σ_8, the current rms density fluctuation amplitude in spheres of radius $8\,\mathrm{h}^{-1}$Mpc (eg. Bond & Myers 1992b, Bond & Myers 1996, Mohr et al. 1999, Holder & Carlstrom 1999). For example, "wedges" of the universe for four different cosmologies look very different, as shown in Figure 5.

Because clusters can be detected at any redshift using the SZE, without the cosmological dimming that attenuates the X-ray and optical emission, the SZE "sky" looks very different for differing cosmologies, as depicted in Figure 6.

The SZE in nearby clusters (Myers et al. 1997) and intermediate redshift clusters (Carlstrom et al. 1996) has been clearly measured by single dishes and imaged by interferometers respectively. In the near future, the CBI will provide SZE images of nearby clusters with $4'$ resolution at 32 GHz. ALMA, and CARMA in the north, will provide high-sensitivity images of the SZE in the most distant clusters as well as survey regions of the sky for the "ambient" SZE to test cosmological models.

Figure 7 grapically demonstrates the utility of intermerometer measurements of the SZE for intermediate redshift clusters observed by Carlstrom et al. using the existing California millimeter arrays outfitted with 30 GHz receivers. ALMA will be able to extend this to higher redshifts, while the addition of the total-power scans to the interferometer data will improve the image fidelity, especially for probing the low level SZE profile in the outskirts of the clusters.

While the primary anisotropies allow us to peer directly at the linear matter density fluctuations at $z \sim 1100$, the Sunyaev Zeldovich effect shows us these same fluctuations in the nonlinear stage as they evolve and collapse to form massive clusters of galaxies.

Other Applications

ALMA as a centimeter-wave telescope will be an important addition to the world radio astrophysical arsenal, especially considering that the SKA and ATCA will not operate with significant efficiency at these short wavelengths. There are a number of scientific programs that suffer from the lack of a sensitive high-frequency array in the Southern hemisphere. ALMA with 64 12-meter antennas will have an effective collecting area greater than the VLA at 30 GHz and 43 GHz above. For example, at 43 GHz, the VLA has an effective area of 4640 m^2 (for 27 $\times$ 25-m at $\epsilon_a = 0.35$), while ALMA has 5720 m^2 (assuming 64 $\times$ 12-m at $\epsilon_a = 0.79$). Cosmological applications such as the survey for and monitoring of gravitational lenses (eg. Myers 1999) will greatly benefit from ALMA. Studies of the central engines of radio-loud AGN require high-frequency observations to probe deep within the jet. In particular, ALMA will be an important addition to global (and space) VLBI at 7mm. Finally, although the redshifted FIR thermal dust emission from forming galaxies can be detected in the sub-mm and mm (eg. Bond & Myers 1992a), reshifted molecular line emission will be observable at centimeter wavelengths, as well as nonthermal continuum emission from H II regions and the cosmic ray electrons.

Summary

- Anisotropy in the Cosmic Microwave Background on scales below $20'$ probes the linear density field and gravitational potential on cluster and supercluster scales at the time of last scattering ($z \sim 1100$).

- ALMA can efficiently make images of CMB anisotropy temperature and polarization fluctuations at 10mm, 7mm and 3mm.

- On angular scales less than $4'$ ALMA will be able to separate out anisoropies due to the primary CMBR fluctuations and those due to the Sunyaev-Zeldovich effect.

- The total power stability and fast switching capability are critical for the meshing of the ALMA interferometric and single-dish data for imaging of extended astronomical targets such as the CMBR, SZE as well as galactic molecular cloud studies.

- A significant problem facing large-scale CMBR and SZE surveys is the identification and removal of galactic and extragalactic foreground emission. Observations at the wavelength of interest (15mm - 3mm) but at higher angular resolution are required. The VLA and GBT will perform this service in the North, but ALMA will be critical for all-sky surveys such as those done by MAP and Planck.

- Probing the very high-redshift Universe beyond a redshift of 6 out to recombination will be the "final frontier". The capability for observing highly redshifted molecular lines will be critical for shedding light on these "Dark Ages" of cosmology.

- There are a number of other important contributions to extragalactic and galactic astronomy that ALMA at 10mm and 7mm will be critical to, such as VLBI (in conjunction with the VLBA and the Southern Hemisphere VLBI telescopes), surveys for and monitoring of gravitational lenses, disentangling star formation and AGN contributions to the radio spectrum of distant galaxies, and the mapping of the small-scale diffuse anomalous galactic emission seen in CMBR observations.

- Conclusion: *The 10mm and 7mm receiver suite proposed for ALMA will add significant new astronomical capabilities to the array, and moreover these capabilites will be unique in the Southern Hemisphere.*

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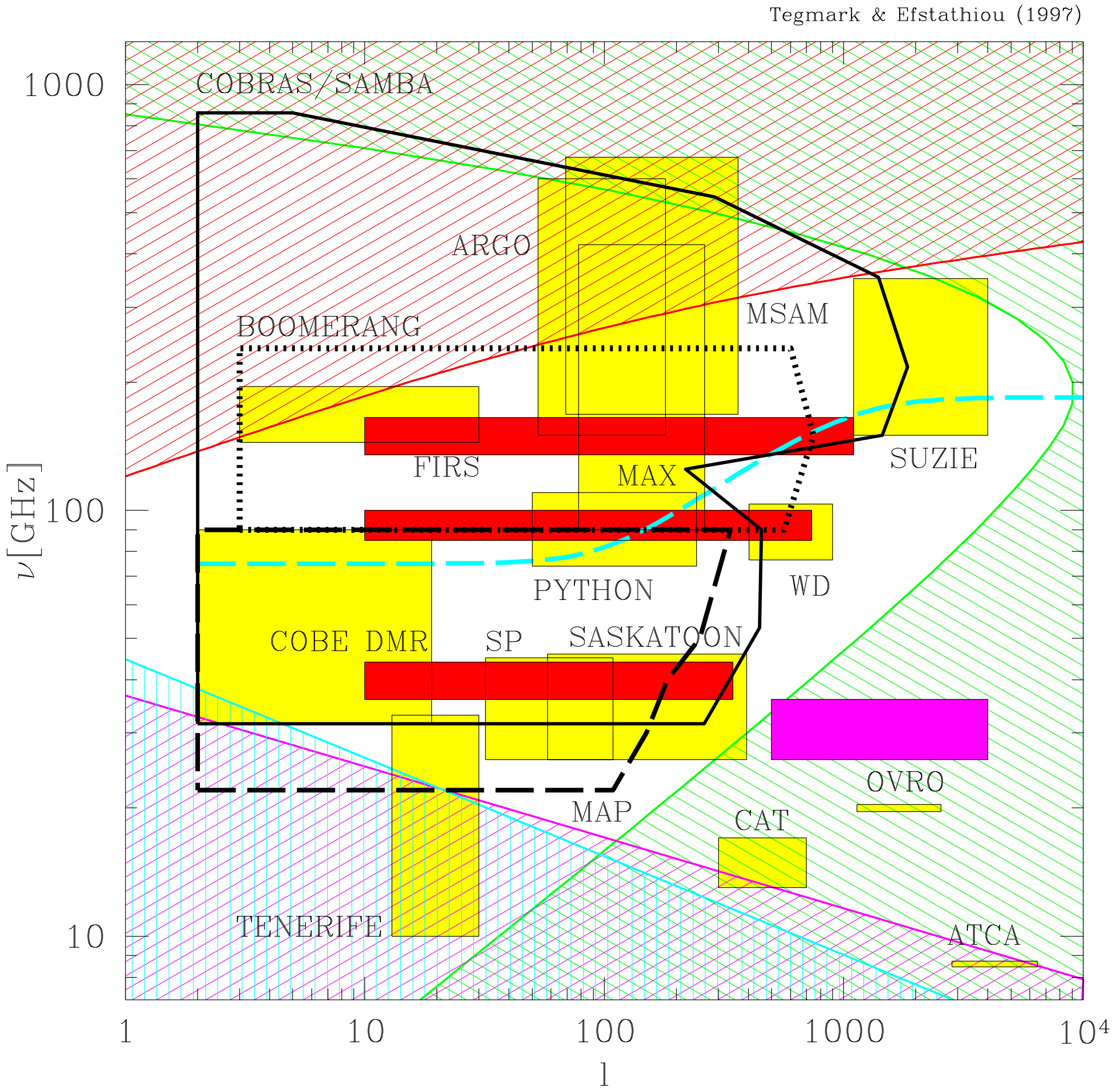


Figure 1: The current status of CMB anisotropy experiments in the plane of frequency versus multipole ℓ, where the angular scale is approximately $180°/\ell$. The filled red boxes show the coverage provided by the MAT experiment, and the filled violet box is that of the CBI. Courtesy Max Tegmark and Mark Devlin.

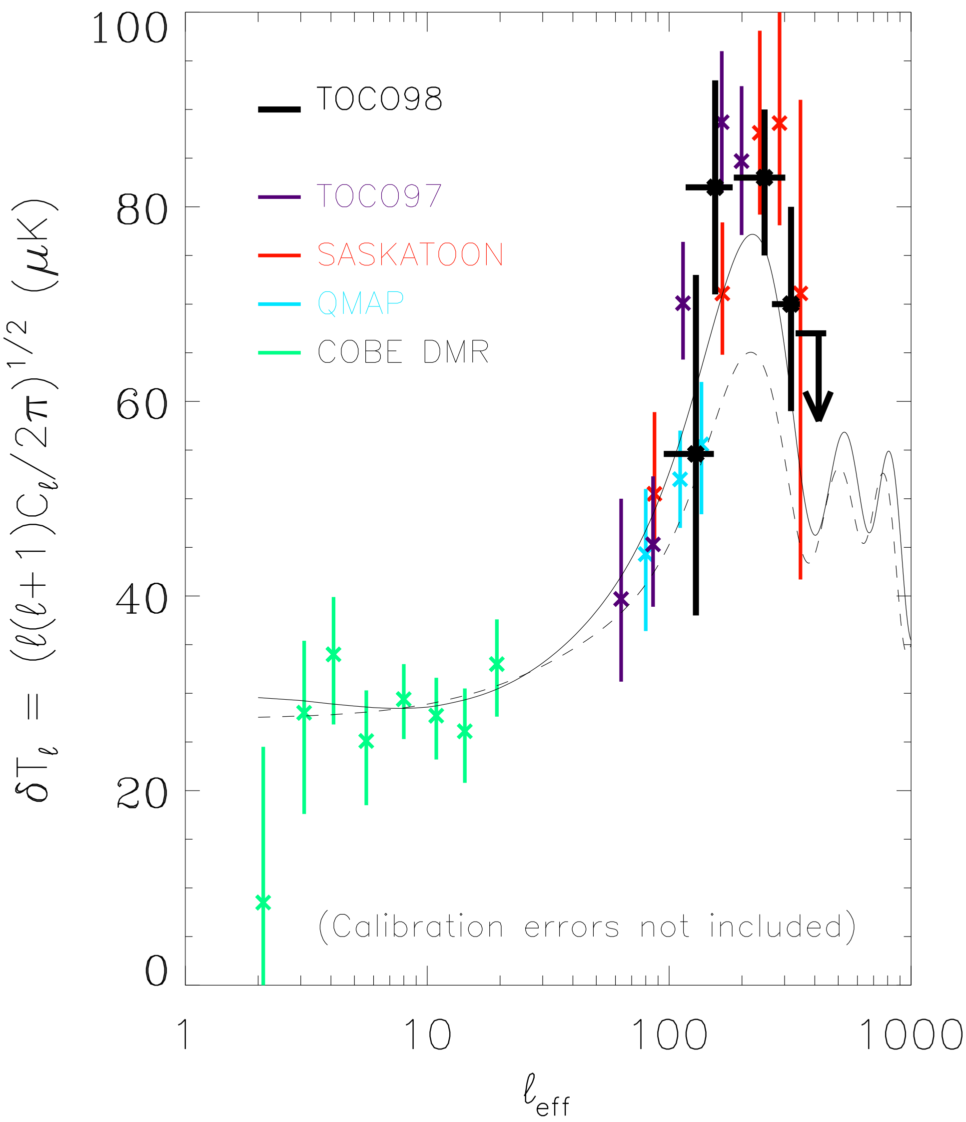


Figure 2: The results from the MAT experiment, showing the angular power spectrum of the CMBR anisotropy. The results from the TOCO97 and TOCO98 runs of map clearly delineate the "First Doppler Peak" at $\ell \sim 200$, as predicted by inflationary cosmological models (solid and dashed curves) with a flat space-time geometry. Courtesy Mark Devlin and Lyman Page.

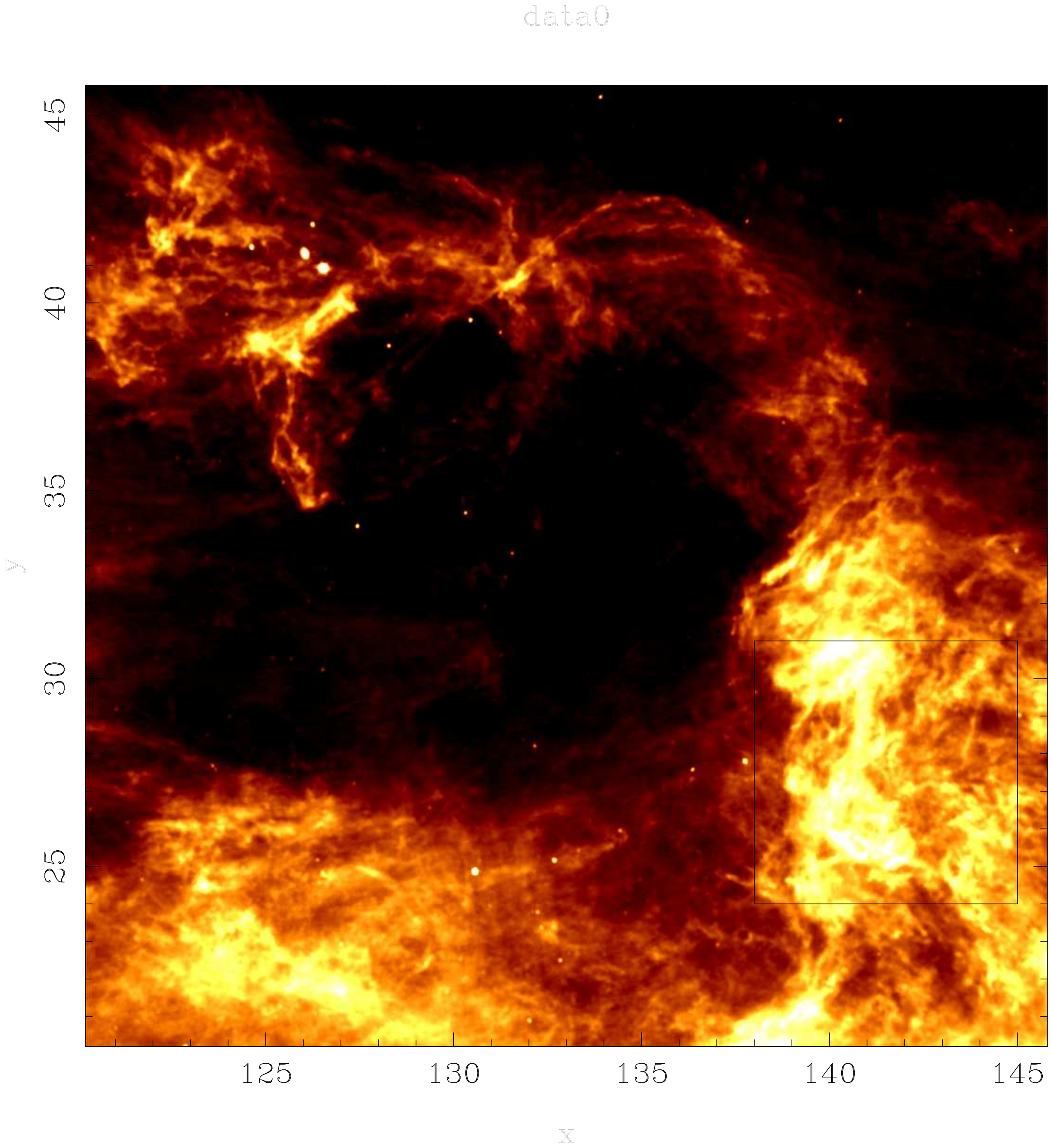


Figure 3: The North Celestial Pole (NCP) loop, from Leitch et al. (1996). The NCP is located at the center of the box at lower right. There is significant contaminating signal ($200\,\mu$K in a $7'$ beam) at 30 GHz from emission associated with this structure.

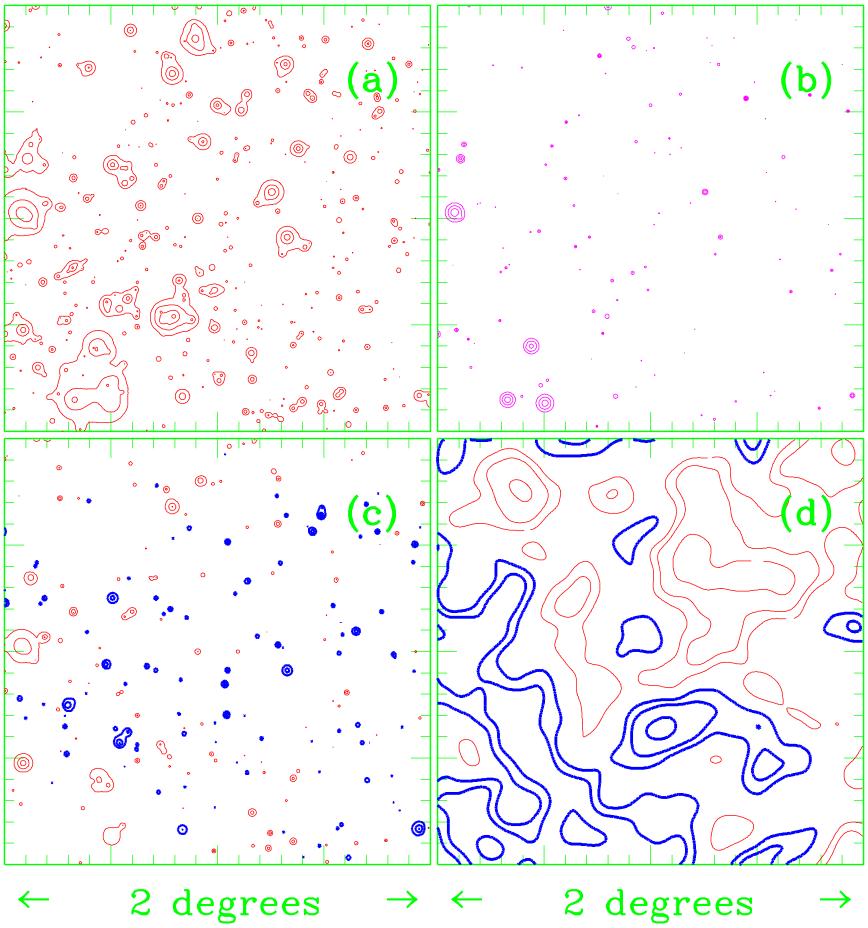


Figure 4: Results of peak-patch simulations of a 2-degree field for a "standard" CDM cosmology with $\Omega_B = 0.05$, scale-invariant spectrum and $\sigma_8 = 0.7$: (a) the SZ effect for 30 GHz, with contours -5×10^{-6}; (b) the associated ROSAT map $(0.1 - 2.4$ keV), with contours 10^{-14} erg cm^{-2} s^{-1}; (c) the Thomson scattering anisotropy induced by the bulk motion of the clusters, with contours now $\pm 1.25 \times 10^{-6}$; (d) primary anisotropies, with contour levels at $\pm 10 \times 10^{-6}$. These would be increased by a factor 1.7 if it were COBE-normalized. Positive contours are heavy, negative contours are light. From Bond & Myers (1996c).

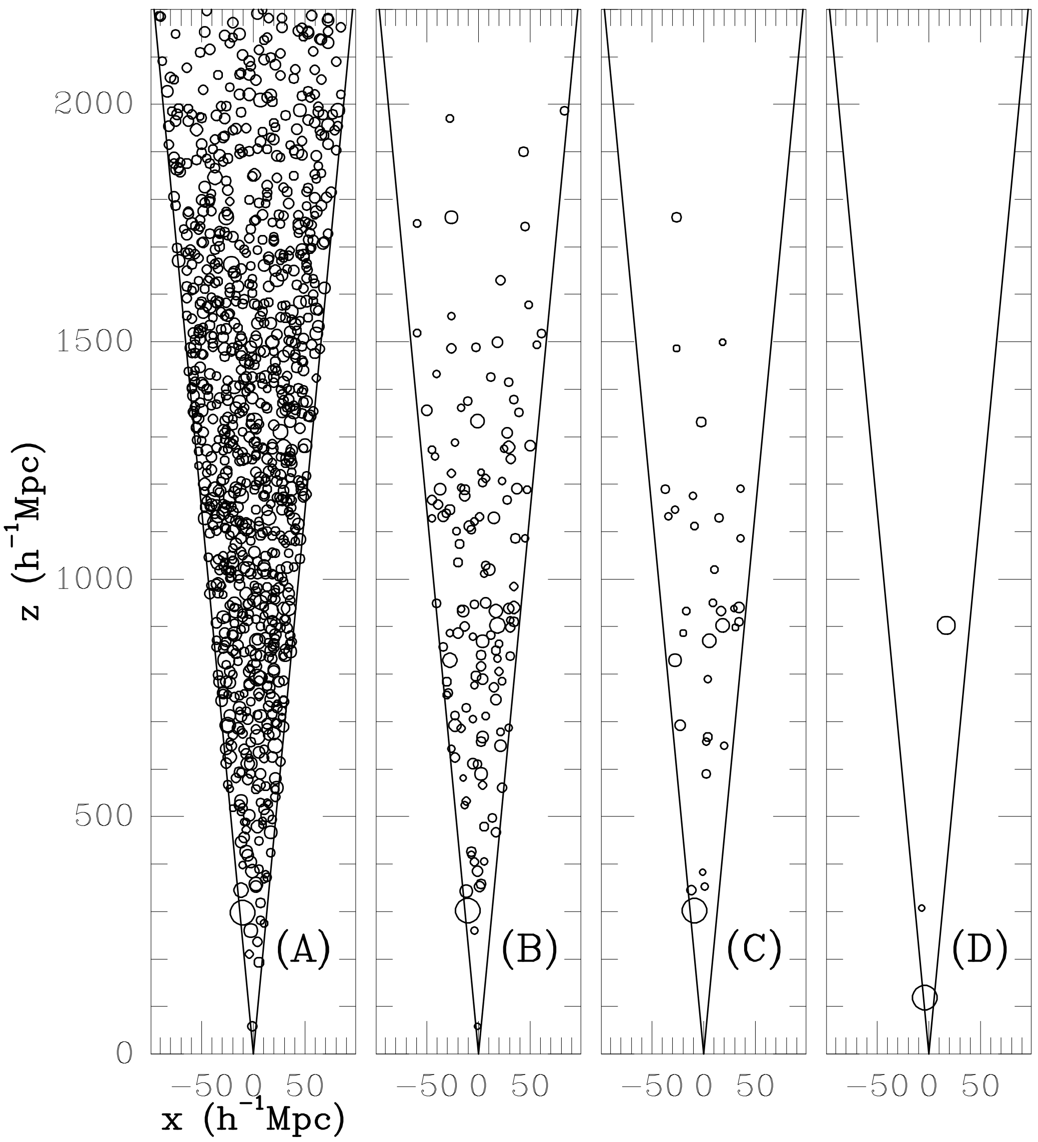


Figure 5: "Wedge" diagrams give the comoving (x, z) positions of clusters with virialized 3D velocity dispersions $\sigma_v > 850\,\mathrm{km\ s^{-1}}$, for $5^\circ \times 5^\circ$ areas of sky out to $z = 1.5$. Redshifts $0.3, 0.5, 0.7, 1$ are at comoving distances $740, 1100, 1400, 1760\,\mathrm{h^{-1}Mpc}$. The circle drawn about the cluster has radius $\propto M^{1/3}$. Four models using the same initial random seeds are shown: (A) $\sigma_8 = 1$ standard CDM, with $n_s = 1$; (B) $\sigma_8 = 0.71$ tilted CDM model, with $n_s = 0.8$; (C) $\sigma_8 = 0.71$ HDM-CDM hybrid, with $\Omega_\nu = 0.3$; (D) $\sigma_8 = 0.45$ CDM with $\Gamma = 0.2$ (such as an open CDM or flat ΛCDM model). The LSS amplitudes σ_8's are normalized to fit the COBE anisotropies. Models (C) and (D) fit the galaxy clustering data. From Bond & Myers (1996).

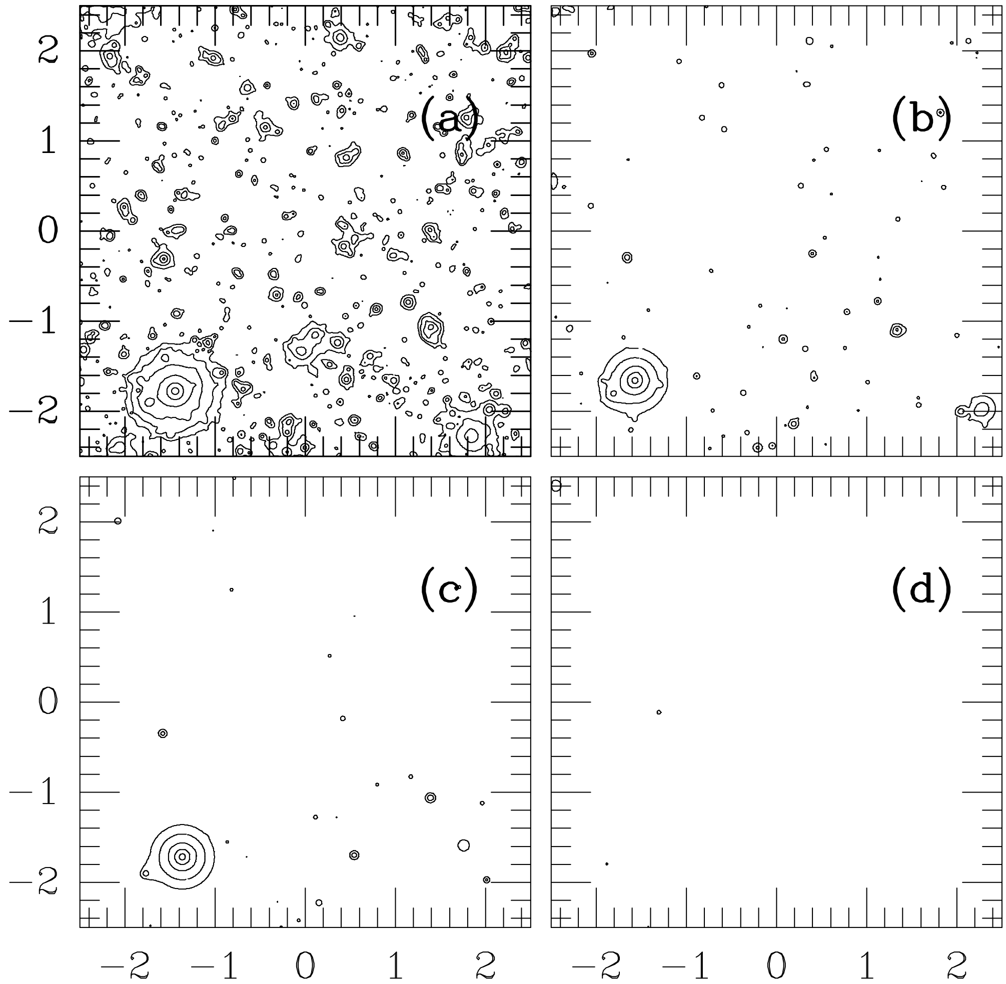
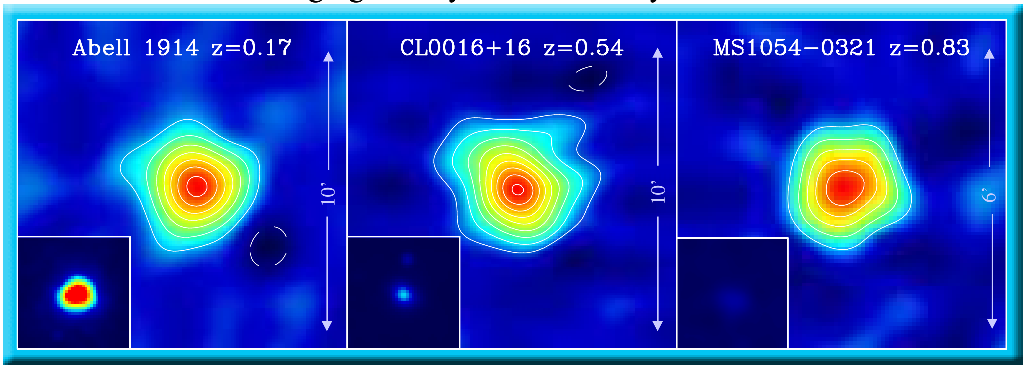


Figure 6: Sunyaev-Zeldovich maps for $5^\circ \times 5^\circ$ simulated patches of the sky, constructed from the four hierarchical peaks catalogues shown in the "wedge" diagrams, (A) to (D). The contours shown are negative, dropping by factors of two from the starting value of $-5 \times 10^{-6}(\Omega_{Beff}/0.1)$, where Ω_{Beff} is the effective baryon abundance. The SZ maps are for observations at 20 GHz smoothed with a $1\rlap{.}'8$ FWHM Gaussian beam, the parameters of the OVRO experiment. From Bond & Myers (1996c).

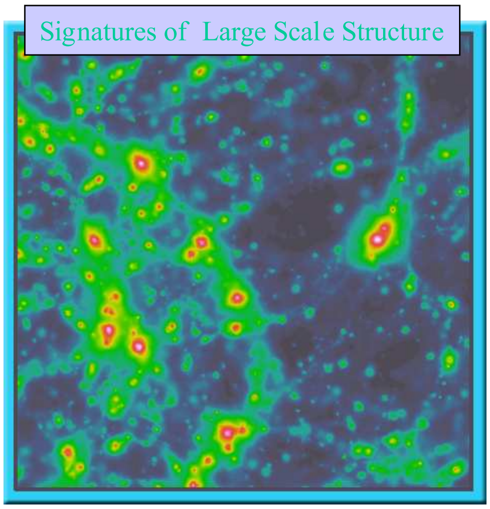
Exploring the Distant Universe with the Sunyaev-Zel'dovich Effect

Hot gas within massive objects interacts with passing cosmic microwave background (CMB) photons, introducing small distortions in the CMB spectrum. The amplitude of this so-called Sunyaev-Zel'dovich effect (SZE) is independent of the distance to the object; thus, SZE observations are powerful probes of the distant universe, which should vastly improve our understanding of the evolution of cosmic structures.

Imaging Galaxy Clusters at any Distance

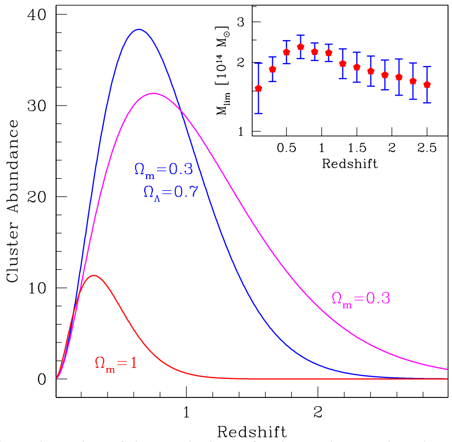


The panel *above* contains SZE images of three galaxy clusters at redshifts z=0.17, z=0.54 and z=0.83 (at z=0.83 the universe is approximately 1/3 its present age). Insets show X-ray images of the same region of each cluster. The SZE signature is comparable at all three distances, whereas the detected X-ray emission (in fact, any emission) decreases rapidly with distance. SZE observations allow one to observe clusters throughout the observable universe!



Above is an image of the SZE effect toward a simulated cluster of galaxy clusters (red/yellow). Very sensitive SZE observations would enable one to image the intercluster material (green/blue), a diffuse cosmic web which is likely to be the largest reservoir of baryons or normal matter in the universe.

Cosmology and Cluster Abundances



Above is a plot of the evolution of galaxy cluster abundance for three different cosmological models. The abundance is the expected number of clusters above mass M_{lim} (see inset) within 1 square degree on the sky, and these models are tuned to produce the observed abundance of nearby clusters (Redshift z=0). As one probes the high redshift universe it becomes easier to discriminate among cosmological models. The inset shows the limiting mass M_{lim} as a function of redshift for a realistic SZE survey instrument.

Figure 7: Observations of the SZE at 30 GHz using the OVRO and BIMA millimeter arrays, and comparisons with models of large-scale structure. The upper panels show three X-ray luminous clusters in SZE and X-ray, where the X-ray images are shown as insets in the SZE images. The contours on the SZE images are identical with spacing of 75 μK and the X-ray images all display the same range of surface brightness. The lower left panel shows the expected SZE given a detailed numerical simulation, and the lower right hand panel shows the expected number counts with redshift as a test of cosmological model. Courtesy J. Mohr.