Cosmology with the Sunyaev-Zel’dovich Effect

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History

- Proposed 1970

- 1990 few reliable detections

- Last decade new detectors, techniques, 50 clusters to $z=1$

- Next decade up 1-2 orders magnitude

- ICM, cosmo parameters, $z=2+$
Uses

- Best combined with other diagnostics, x-ray, lensing, optical velocity dispersion

- SZEx-ray gives distance, independent H measure

- SZEx-ray gives gas mass fraction, OMM

- Large deep SZE surveys will give evolution # of density clusters, determine cosmology, DE eq state
• SZE ideal because mass parameter sets detection limit independent of z

• SZE is CMB distortion by Compton scattering off high-energy electrons

• Direct measure of ICM column density weighted by $T, = \rho T, = P$ integrated along line of sight, $1/DA^2$

• SZE has $dT = \int n \, dl$, x-ray $I = \int n^2 \, dl$ since 2 body process, $T$ from x-ray spec., solve depth

• Assuming sphere gives transverse ang. size, so distance

• Mass limit for given flux sensitivity $\sim 2-3$ for $z>.05$

• 10 sq deg survey will constrain $\Omega M m$
Figure 1  The cosmic microwave background (CMB) spectrum, undistorted (dashed line) and distorted by the Sunyaev-Zel’dovich effect (SZE) (solid line). Following Sunyaev & Zel’dovich (1980a) to illustrate the effect, the SZE distortion shown is for a fictional cluster 1000 times more massive than a typical massive galaxy cluster. The SZE causes a decrease in the CMB intensity at frequencies $\lesssim 218$ GHz and an increase at higher frequencies.
- 1% chance of scattering
- Boosts photon energy $\sim kT/mc^2$
- $\sim 1$ mK distortion
- Decrease $< 218$ GHz, increase $>$
- Cluster gas temp $\sim 10$ keV
- $T \sim M^{2/3}$
\[ \frac{\Delta T_{SZE}}{T_{CMB}} = f(x) \frac{y}{f(x)} = f(x) \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T \, d\ell \]

Compton y parameter

\[ f(x) = \left( x \frac{e^x + 1}{e^x - 1} - 4 \right) \left( 1 + \delta_{SZE}(x, T_e) \right) \]

Peacock p 375
Delta rel correction

\[ \int \Delta T_{SZE} \, d\Omega \propto \frac{N_e \langle T_e \rangle}{D^2_A} \propto \frac{M \langle T_e \rangle}{D^2_A} \]

Integrated signal gives total thermal energy (temp weighted mass)
Figure 2  Spectral distortion of the cosmic microwave background (CMB) radiation due to the Sunyaev-Zel’dovich effect (SZE). The left panel shows the intensity and the right panel shows the Rayleigh Jeans brightness temperature. The thick solid line is the thermal SZE and the dashed line is the kinetic SZE. For reference the 2.7 K thermal spectrum for the CMB intensity scaled by 0.0005 is shown by the dotted line in the left panel. The cluster properties used to calculate the spectra are an electron temperature of 10 keV, a Compton $y$ parameter of $10^{-4}$, and a peculiar velocity of 500 km s$^{-1}$.

Kinetic Sunyaev-Zel’dovich Effect

\[
\frac{\Delta T_{SZE}}{T_{CMB}} = -\tau_e \left( \frac{v_{pec}}{c} \right)
\]
Kinetic Sunyaev-Zel’dovich Effect

\[ \frac{\Delta T_{\text{SZ}}}{T_{\text{CMB}}} = -\tau_e \left( \frac{v_{\text{pec}}}{c} \right) \]

Doppler shift

Relativistic corrections

\[ \left( \frac{k_B T_e}{m_e c^2} \right) \left( \frac{v_{\text{pec}}}{c} \right) \]
\[ \sim 8\% \text{ for } 10 \text{ keV @ 1000 km/s} \]

\[ \left( k_B T_e / m_e c^2 \right)^2 \left( v_{\text{pec}} / c \right) \]
\[ \sim 1\% \]

\[ \left( v_{\text{pec}} / c \right)^2 \]
\[ \sim 0.2\% \]
Polarization of the Sunyaev-Zel’dovich Effect

\[ 0.025 \left( \frac{k_B T_e}{m_e c^2} \right) \tau_e^2 \]

\[ \cdot 0.1 \tau_e \left( \frac{v_{pec}}{c} \right)^2 \]

\[ 0.025 \tau_e^2 \left( \frac{v_{pec}}{c} \right) \]

\[ \tau_e = 0.01 \text{ and a bulk motion of } 500 \text{ km s}^{-1} \]
\[ \gg 10 \text{ nK}, \text{ far beyond the sensitivity of current } \]

\[ 50 \left( \frac{\tau_e}{0.01} \right) \text{nK,} \]
• STATUS OF OBSERVATIONS

• Uncontrolled systematics doomed 1\textsuperscript{st} 20 years

• Sensitivities up 10x now

• Control spatial temporal atmosphere, ground emissions, gain instabilities

• Appropriate angle 1’ for 1 Mpc cluster any z except low z up to 1 deg

• Differential measure, wide separation
Figure 3  Illustration of the characteristic angular scales of primary CMB anisotropy and of the SZE. The images each cover one square degree and the gray scales are in μK. (Left) An image of the SZE from many galaxy clusters at 150 GHz (2 mm) from a state-of-the-art hydrodynamic simulation (Springel et al. 2001). The clusters appear point-like at this angular scale. (Center) A realization of CMB anisotropy for a ΛCDM cosmology. (Right) The combination of the CMB and SZE signals. Note, the SZE can be distinguished readily from primary CMB anisotropy, provided the observations have sufficient angular resolution.
Figure 4  The measured SZE spectrum of Abell 2163. The data point at 30 GHz is from the Berkeley-Illinois-Maryland-Association (BIMA) array (LaRoque et al. 2002), at 140 GHz it is the weighted average of Diabolo and SuZIE measurements (Desert et al. 1998, Holzapfel et al. 1997) (filled square), and at 218 GHz and 270 GHz from SuZIE (Holzapfel et al. 1997) (filled triangles). The best fit thermal and kinetic SZE spectra are shown by the dashed and dotted lines, respectively, with the spectra of the combined effect shown by the solid line. The limits on the Compton $\gamma$-parameter and the peculiar velocity are $y_0 = 3.56^{+0.41+0.27}_{-0.41-0.19} \times 10^{-4}$ and $v_p = 410^{+1030+460}_{-850-440} \text{ km s}^{-1}$, respectively, with statistical followed by systematic uncertainties at 68% confidence (Holzapfel et al. 1997, LaRoque et al. 2002).
• SuZIE, 6-element 140 GHz bolometer array electronically differenced

• BOLOCAM 151-element array @ CSO

• Interferometer measures signal correlation by \( \frac{n(n-1)}{2} \) pairs scopes, only sensitive to ang. scales \( \sim \frac{B}{\lambda} \), cuts noise, cuts pt. sources

• Ryle, Cambridge, 8 13-m, 15 GHz

• OVRO, 6 10.4-m, 30 GHz

• BIMA, 9 6.1-m, 30 GHz
• CBI, 13 .9-m, baselines 1-6 m, 26-36 GHz

• SZI, 8 3.5-m, 26-36 GHz, 85-115 GHz, low noise, combined with OVRO, BIMA

• AMiBA, 19 1.2-m, 90 GHz
SKY SURVEYS WITH THE SUNYAЕV-ZEL’DOVICH EFFECT

Cluster Abundance

(1) the volume per unit solid angle as a function of redshift,
(2) the number density of clusters as a function of mass and redshift, and
(3) an understanding of the expected mass range that should be observable with the particular SZE instrument and survey strategy.

\[ \frac{dV}{d\Omega dz} = D_A^2 \frac{dt}{dz}, \]

\[ \frac{dn(M, z)}{dM} = -\sqrt{\frac{2}{\pi}} \frac{\tilde{\rho}}{M^2} \frac{d \ln \sigma(M, z)}{d \ln M} \frac{\delta_c}{\sigma(M, z)} \exp \left[ \frac{-\delta_c^2}{2\sigma^2(M, z)} \right] \]
Figure 7  Comoving volume element (left) and comoving number density (center) for two cosmologies, $(\Omega_M, \Omega_\Lambda) = (0.3, 0.7) \ (solid)$ and $(0.5, 0.5) \ (dashed)$. (Middle) The normalization of the matter power spectrum was taken to be $\sigma_8 = 0.9$ and the Press-Schechter mass function was assumed. The lower set of lines in the middle panel correspond to clusters with mass greater than $10^{15} \ h^{-1} \ M_\odot$ while the upper lines correspond to clusters with mass greater than $10^{14} \ h^{-1} \ M_\odot$. The right panel corresponds to the cluster redshift distribution per square degree for clusters with masses greater than $10^{14} \ h^{-1} \ M_\odot$, with the normalization of the power spectrum adjusted to produce the same local cluster abundance for both cosmologies ($\sigma_8 = 0.75$ for $\Omega_M = 0.5$). Note that in this case fewer clusters are predicted at high redshift for the higher density cosmology.
Figure 8  (Left) Mass limits as a function of redshift for a typical wide-field type of survey (equivalent to $\sim 15$ mJy at 30 GHz) and a typical deep survey ($\sim 0.5$ mJy). The approximate XMM-Newton serendipitous survey limit is also shown. (Right) Differential (top) and cumulative (bottom) counts as a function of redshift for the two SZE surveys shown at left, assuming a $\Lambda$CDM cosmology (Holder et al. 2000a).
COSMOLOGY FROM SUNYAEV-ZEL’DOVICH EFFECT SURVEY SAMPLES

Distance Determinations, Hubble Constant

\[ D_A \propto \frac{(\Delta T_0)^2 \Lambda_{eH_0}}{S_{x0} T_{e0}^2 \theta_c} \frac{1}{\langle n_e \rangle^{1/2}} \]
- 38 distances to 26 clusters from SZE, X-ray
- 7 \((z < .1)\) OVRO 5-m
- 5 \((.14 < z < .3)\) Ryle
- 18 \((.14 < z < .83)\) OVRO, BIMA
- Fit gives \(H_0 = 60 \ (3) \ \text{km/s/Mpc}\) for \(\text{OM}_{m} = .3, \ \text{OM}_{l} = .7\), systematic \(sd = 30\%\)
- Largest uncertainties nonisothermality, clumping, pt sources
• Chandra, XMM-Newton doing temp profiles clusters

• VLA can remove pt source contamination

• Systematics improved by above & larger SZE surveys

• Beauty is complete independence other techniques, direct distance measure

• Few 100 clusters would trace expansion history, check geometry against Ia SN
Figure 9  SZE-determined distances versus redshift. The theoretical angular diameter distance relation is plotted for three different cosmologies, assuming $H_0 = 60 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ (solid line), $\Omega_M = 0.3$, $\Omega_\Lambda = 0$ (dashed line), and $\Omega_M = 1.0$, $\Omega_\Lambda = 0$ (dot-dashed line). The clusters are beginning to trace out the angular diameter distance relation. References: (1) Reese et al. 2002; (2) Pointecouteau et al. 2001; (3) Mauskopf et al. 2000a; (4) Reese et al. 2000; (5) Patel et al. 2000; (6) Grainge et al. 2000; (7) Saunders et al. 2000; (8) Andreani et al. 1999; (9) Komatsu et al. 1999; (10) Mason et al. 2001, Mason 1999, Myers et al. 1997; (11) Lamarre et al. 1998; (12) Tsuboi et al. 1998; (13) Hughes & Birkinshaw 1998; (14) Holzapfel et al. 1997; (15) Birkinshaw & Hughes 1994; (16) Birkinshaw et al. 1991.
Cluster Gas-Mass Fractions, $\Omega_M$

- ICM order mag more baryons than gals

- Gas mass fraction, $f_g$, should match universal, $f_B \equiv \Omega_B / \Omega_M$, no segregation on 1000 Mpc$^3$

$$\Omega_B h^2 = 0.019 \pm 0.0012$$

Gas mass measured by SZE if know $T$
Total mass from hydro eq, dist gas, $T$
Then $f_g \sim \Delta T_{SZE}/T_e^2$
Cluster Gas-Mass Fractions, $\Omega_M$

- 4 nearby clusters

\[ f_{gh} = 0.16 \pm 0.014 \]

18 Far \(.14 < z < .83\)

Fractions are \( f_{gh} = 0.081^{+0.009}_{-0.011} \) for \( \Omega_M = 0.3, \ \Omega_\Lambda = 0.7 \), \( f_{gh} = 0.074^{+0.008}_{-0.009} \) for \( \Omega_M = 0.3, \ \Omega_\Lambda = 0.0 \) and \( f_{gh} = 0.068^{+0.009}_{-0.008} \) for \( \Omega_M = 1.0, \ \Omega_\Lambda = 0.0 \). The uncer-

Also compare SZE, lensing, both projected mass dist.

Should test dark matter decay
Figure 10  Limits on $\Omega_M$ from SZE-measured cluster gas fractions (Grego et al. 2001). Upper limit on the total matter density, $\Omega_M \leq \Omega_B/(f_B h_{70})$ (solid line) and its associated 68% confidence region (dotted lines) as a function of cosmology with $\Omega_\Lambda \equiv 1 - \Omega_M$. The intercept between the upper dotted line and the dashed line $\Omega_M = \Omega_B/(f_B h_{70})$ gives the upper limit to $\Omega_M$ at 68% confidence. The dot-dashed line shows the total matter density when the baryon fraction includes an estimate of the contribution from baryons in galaxies and those lost during cluster formation. The intercept of the dot-dashed line and the dashed line gives the best estimate of $\Omega_M \sim 0.25$, assuming a flat universe with $h = 0.7$. 
Cluster Peculiar Velocities

Figure 2  Spectral distortion of the cosmic microwave background (CMB) radiation due to the Sunyaev-Zel’dovich effect (SZE). The left panel shows the intensity and the right panel shows the Rayleigh Jeans brightness temperature. The thick solid line is the thermal SZE and the dashed line is the kinetic SZE. For reference the 2.7 K thermal spectrum for the CMB intensity scaled by 0.0005 is shown by the dotted line in the left panel. The cluster properties used to calculate the spectra are an electron temperature of 10 keV, a Compton $\gamma$ parameter of $10^{-4}$, and a peculiar velocity of 500 km s$^{-1}$.

Kinetic Sunyaev-Zel’dovich Effect

$$\frac{\Delta T_{SZE}}{T_{CMB}} = -\tau_e \left( \frac{v_{pec}}{c} \right)$$
• Bracket null @ 218 GHz

• SuZIE, ’99, Abell 2163 (z = .202), Abell 1689 (z = .183), 140 GHz(2.1 mm), 218 GHz(1.4 mm), 270 GHz(1.1 mm)

\[
v_{pec} = +490^{+1370}_{-880} \text{ km s}^{-1}
\]

\[
v_{pec} = +170^{+815}_{-630} \text{ km s}^{-1}
\]

Abell 2163

Abell 1689

Kinetic SZE weak & degenerate with CMB

Hard to measure single cluster peculiar velocity

May be possible to average many clusters
Figure 4  The measured SZE spectrum of Abell 2163. The data point at 30 GHz is from the Berkeley-Illinois-Maryland-Association (BIMA) array (LaRoque et al. 2002), at 140 GHz it is the weighted average of Diabolo and SuZIE measurements (Desert et al. 1998, Holzapfel et al. 1997) (filled square), and at 218 GHz and 270 GHz from SuZIE (Holzapfel et al. 1997) (filled triangles). The best fit thermal and kinetic SZE spectra are shown by the dashed and dotted lines, respectively, with the spectra of the combined effect shown by the solid line. The limits on the Compton y-parameter and the peculiar velocity are $y_0 = 3.56^{+0.41+0.27}_{-0.41-0.19} \times 10^{-4}$ and $v_p = 410^{+1030+460}_{-850-440}$ km s$^{-1}$, respectively, with statistical followed by systematic uncertainties at 68% confidence (Holzapfel et al. 1997, LaRoque et al. 2002).
Energy Densities in the Universe and Growth of Structure

- Evolution of cluster abundance probes OMM & DE eq. of state
- SZE probes high z as easily as local, sensitivity is mass limit
- SZE probes growth of structure, not distance, distinct from CMB measure
- Inflation predicts gaussian fluctuations, SZE can test at high z
- Next serious test of CDM
Energy Densities in the Universe and Growth of Structure

Figure 12  Expected constraints on the matter density $\Omega_M$ and the dark energy equation of state $w$ from the analysis of an SZE survey covering several thousand square degrees in which all clusters above $2.5 \times 10^{14} \, h^{-1} \, M_\odot$ are detected and the redshifts are known. The normalization of the power spectrum has been marginalized over, and contours show 68% and 95% confidence regions for two parameters. Note that no systematic errors have been assumed in deriving the cosmological constraints. As discussed in the text, considerable observational and theoretical work needs to be done before such tight constraints could be extracted from large-scale SZE surveys.
Challenges for Interpreting Sunyaev-Zel’dovich Effect Surveys

• Gas dynamics could affect interpretation

• SZE only sensitive to free electrons, processes that remove e will affect

• Cooling ICM, star formation, SN heating

• Simulations required, should limit OMM error to 10%

• To fully exploit SZE need need limiting mass as f(z) to 5%, uncertainty in mass function to 10%
Figure 13  Effects of gas evolution on cluster survey yields. In the inset the top group of lines correspond to mass limits for an SZE survey similar to the Planck Surveyor satellite survey, with the uppermost line indicating the expected mass limit for a model with significant gas heating while the lower line in the top group shows the expected mass limit of detection for the case of no cluster gas heating. The cosmology chosen is $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 1$. The lower set of lines show the same effects for a deep SZE survey. The main panel shows the expected redshift distributions for the mass limits in the inset. In the main panel the top group of lines correspond to the deep surveys and the lower lines correspond to Planck Surveyor. The solid line within each set shows the expected counts for the case of no heating, and the dashed line shows the effect of gas heating. The dotted curve, i.e., the middle curve in each set, shows a model with no heating but with $\Omega_M = 0.33$ and $\sigma_8$ modified to keep the same number of clusters at $z = 0$ (Holder & Carlstrom 2001). The assumptions of no heating and the very high value of heating for this plot are extreme and should bracket the true gas evolution.
• Next bolometers may detect relativistic corrections, determine T line of sight

• Then know f(g), cooling

• Skip intro, summary