Missing Thermal Energy of the Intracluster Medium

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Seminar

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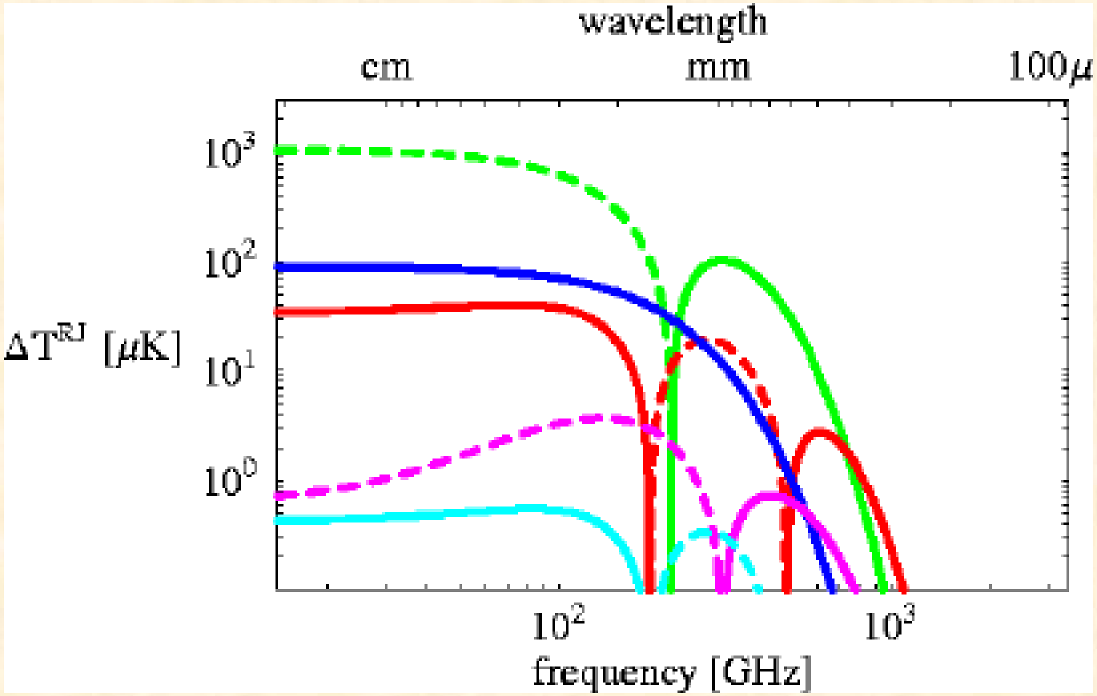
Aim of the Authors

- Study Sunyaev-Zel'dovich signal in a large sample of galaxy clusters by combining signals from known X-ray clusters

Sunyaev-Zel'dovich (SZ) Effect

- Hot (~ 10^7–10^8 K) gas comprising of ~10% of the total mass (80-95% of baryonic mass) of galaxy clusters --- **Intracluster medium (ICM)**
- **SZ effect** → As CMB photons travel from the surface of last scattering to the observer, secondary anisotropies arise due to the interaction of the CMBR with the ICM in a cluster
- **Inverse Compton scattering of CMB photons by high energy electrons in the ICM**
  - Distortion of the CMB spectrum at the mK level
  - Some energy of the electrons is transferred to the low energy CMBR
- Multiple components of the SZ effect (resulting from distinct velocity components of the scattering electrons)
  - **Thermal effect :** CMB photons interact with electrons that have high energies due to their temperature
  - **Kinematic effect :** Electrons have high energies due to their kinetic energy/motion (bulk velocity of the IC gas w.r.t. the rest frame of the CMB)
  - Polarization
- Observed distortions of the CMB spectrum (due to SZ effect) can detect
  - Density perturbations of the universe
  - Dense clusters of galaxies

Spectra of the SZ Components



From top to bottom the components are:

1. Classical thermal SZ effect (τT)
2. Classical kinetic SZ effect (τv)
3. Relativistic corrections to (1) (τT^2)
4. Thermal corrections to (2) ($v \tau T$)
5. Finite optical depth corrections ($\tau^2 T^2$)

- Rayleigh-Jeans temperature vs. frequency of different components of the SZ effect for a simulated typical cluster of galaxies
  - Gas temperature, T = 10 keV
  - Peculiar velocity, v = 1000 km/s toward us
  - Thompson optical depth, $\tau = 0.01$.
- Solid curves indicate increments in the CMB temperature, and the dashed curves decrements.

Back to the Article

X-ray Cluster Catalog

- Assemble catalog from X-ray Galaxy Clusters Database (BAX)
  - Cluster properties : sky position, redshift, X-ray measurements (luminosity / temperature)
- Sample of 260 clusters with measured X-ray temperatures, T_X
- Sub-sample with $T_X > 3$ keV :
  - 193 total
  - Out of 80 with measured central cooling times, 39 have cool core

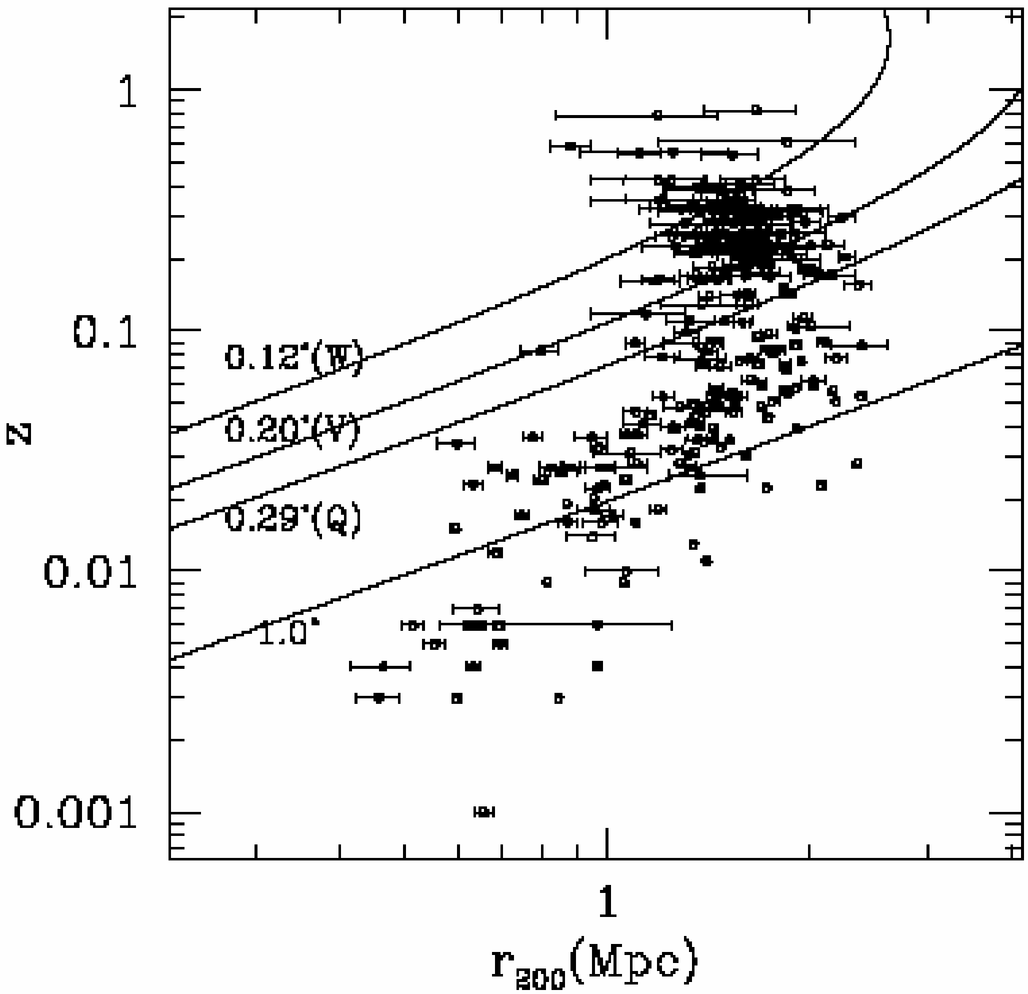


Figure 1. The distribution of cluster redshifts and virial radii (estimated from X-ray temperature; see Sec. 2.2). The three upper lines show the resolution of WMAP bands (associated with the radius of the disk with the same effective area as the detector beams; see Jarosik et al. 2006), while the lower line shows the physical radius of the 1 degree circle at the cluster redshift.

Extracting the SZ Profile

- **Measure mean ICM pressure profile by combining SZ signal from observed X-ray clusters**
- Assume: clusters are self-similar and exhibit universal dark matter & ICM profiles
- Use observed X-ray temperatures of clusters to set the expected extent of the ICM profile
- Use WMAP maps to find mean normalization

- Analytic ICM model

$$r_{200} = (1.16\ \mathrm{Mpc})\left(\frac{H(z)}{100\ \mathrm{km/s/Mpc}}\right)^{-1}\left(\frac{T_X}{5\ \mathrm{keV}}\right)^{1/2}$$

- Spherically symmetric NFW gravitational potential, with concentration c_{200}=5
- Polytropic ICM in hydrostatic equilibrium
- After scaling profiles at r_{200}, SZ signal is searched for out to $4r_{200}$
- Spherically averaged pressure profiles in radial bins (centered at 0.25, 0.5, 1, 2 & $4r_{200}$)
- Pressure interpolation

$$P_{\mathrm{gas}}(r) = A + Br^{-3}$$

$$P_{\mathrm{gas}}(r) \propto r^{-2}\text{, at } r < 0.25 r_{200}$$

Hydrodynamic Simulations

- Cosmological simulation in the flat ΛCDM model
  - Dissipationless dark matter & stars, dissipative gas dynamics
  - Includes radiative cooling, star formation, stellar feedback & metal enrichment
  - Adaptive Refinement Tree (ART) *N*–body + gas dynamics code
  - Eulerian code using adaptive mesh refinement
- 2 different average temperatures of simulated clusters
  - X-ray spectral temperature, T_X : derived from a single-temperature fit to the integrated cluster spectrum
  - Gas mass weighted temperature, $\langle T \rangle$: by weighting the 3D temperature with the gas density measured in simulations
- Simulate 9 massive and hot ($T_X > 3$ keV) galaxy clusters
- Study effects of galaxy formation on SZ effect and the baryon fraction in clusters

Observational Results

Universal Pressure Profile

- Pressure $$P \equiv \rho_{\mathrm{gas}} T$$
- Critical density of Universe at cluster's redshift = ρ_{crit}
- Observed X-ray temperature of cluster = T_X
- Plot clusters with T_X > 3 keV

Mean ICM Pressure Profile

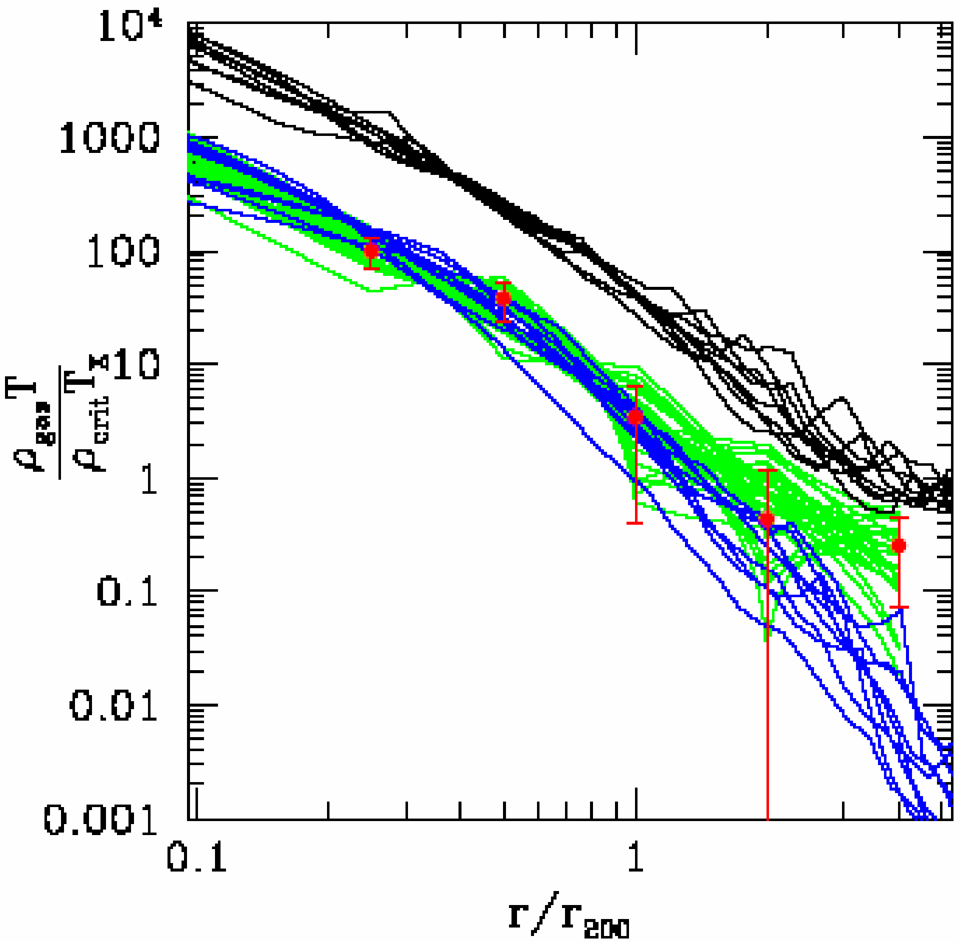


Figure 2. Mean pressure profile of 193 of our most massive clusters with $T_X > 3$ keV (points+errorbars). The green curves are 30 random realizations of the measured points, which reflect the errors, as well as their correlations. The thick curves are predicted pressure profiles from nine simulated clusters with $T_X > 3$ keV, while black curves show dark matter density from the same simulations, divided by the critical density of the Universe.

Integrated Pressure (Thermal Energy) Profile

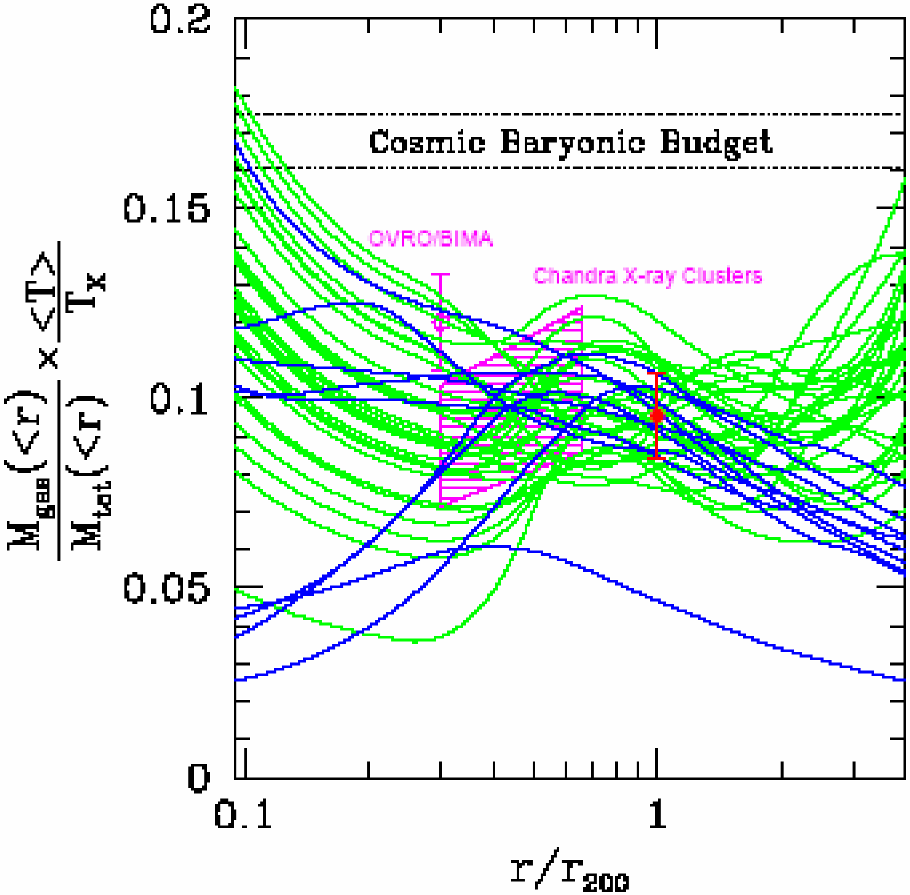


Figure 3. The ratio of total thermal energy to the mass times T_X, for the same clusters as in Fig. 2. The colors are the same as in Fig. 2, and we integrate over the pressure profiles to find total energy, $M_{\rm gas}\langle T\rangle(<r)$, enclosed within radius r, while we estimate the total mass from an NFW profile. The dotted lines show the total cosmic baryonic budget of 0.168 ± 0.007 (Spergel et al. 2006). The dashed region shows the Chandra observational constraints from 8 X-ray clusters (Vikhlinin et al. 2006), while the open point+errorbar is the most recent SZ constraint from OVRO/BIMA interferometers (LaRoque et al. 2006).

Total Thermal Energy of the Cluster

- ICM thermal energy :
- From simulations

$$\frac{\langle T \rangle_{200}}{T_X} = 0.83 \pm 0.06$$

$$\left(\frac{M_{\mathrm{gas},200}}{M_{\mathrm{tot},200}}\right)\left(\frac{\langle T \rangle_{200}}{T_X}\right)_{\mathrm{WMAP}} = 0.095 \pm 0.011$$

- Cluster gas fraction for WMAP data

$$\left(\frac{M_{\mathrm{gas},200}}{M_{\mathrm{tot},200}}\right)_{\mathrm{WMAP}} = 0.114 \pm 0.016$$

- Assuming clusters have universal ratio of dark matter and baryons

$$\frac{M_{\mathrm{baryons}}}{M_{\mathrm{tot}}} \approx \frac{\Omega_{\mathrm{B}}}{\Omega_{\mathrm{M}}} = 0.168 \pm 0.007$$

→ Fraction of cluster baryons missing from the hot ICM

$$\frac{M_{\mathrm{missing}}}{M_{\mathrm{baryons}}} = \frac{M_{\mathrm{baryons}} - M_{\mathrm{gas}}}{M_{\mathrm{baryons}}} = 0.32 \pm 0.10$$

Systematic Trend in the Gas Fraction with X-ray Temperature

- Best-fit power law

$$\left(\frac{M_{\text{gas},200}}{M_{\text{tot},200}}\right)\left(\frac{\langle T\rangle_{200}}{T_X}\right) = (0.098 \pm 0.015)\left(\frac{T_X}{6.4\,\text{keV}}\right)^{0.15\pm0.18}$$

- No significant monotonic trend
- Sub-sample of clusters with resolved cool cores (CC)

$$\left(\frac{M_{\text{gas},200}}{M_{\text{tot},200}}\right)\left(\frac{\langle T\rangle_{200}}{T_X}\right)_{\text{CC}} = 0.142 \pm 0.019$$

- Energy fraction of CC clusters is larger than main sample & **no missing baryons**
- → Cause unknown: systematic problem, or, real anti-correlation between missing baryons & central cooling

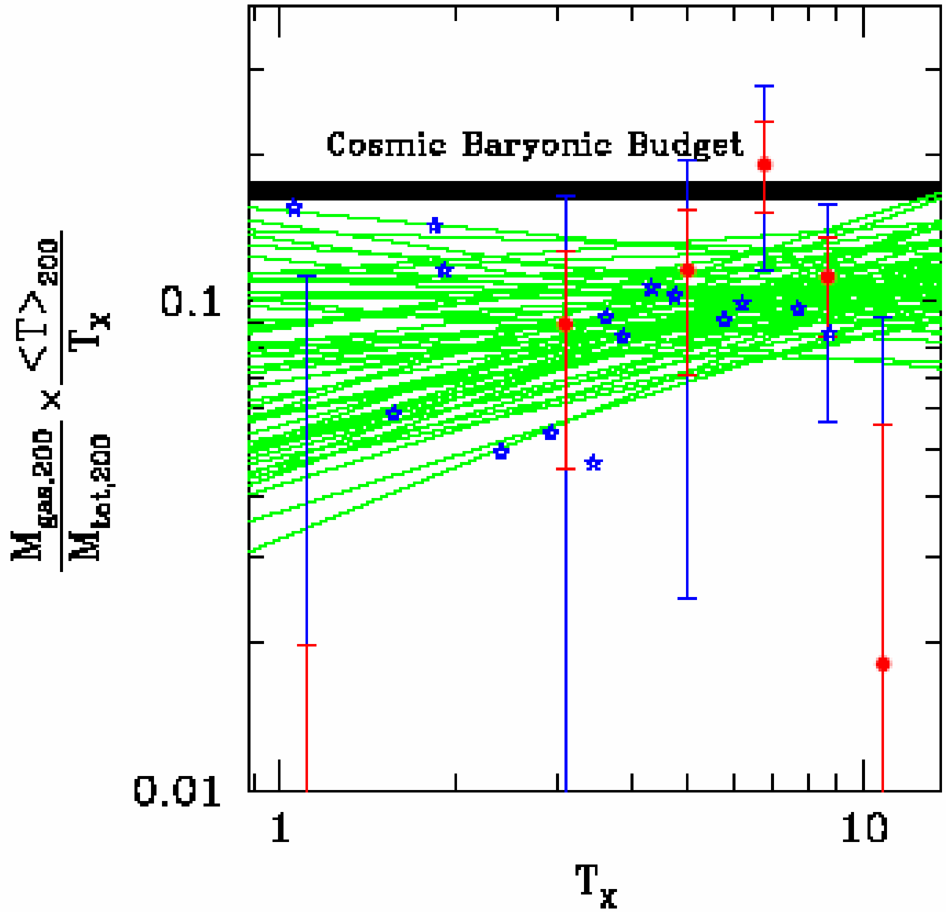


Figure 4. Thermal energy to mass times T_X ratio as a function of T_X. Ssolid points show the total thermal energy to mass ratio within r_{200} for all our clusters, binned within $\Delta T_X = 2$ keV bins. The errorbars show 68% and 95% errors. Open stars show the same ratio for our hydrodynamic simulations, while green (thin) lines show the uncertainty range of best power law fits to our data Eq. 7. The black horizontal bar shows the total cosmic baryonic budget (Spergel et al. 2006).

Discussions

Comparison with a Previous Analysis

- Previous study using 1 yr WMAP :

Afshordi, N., Lin, Y.-T., Sanderson, A.J.R. 2005, ApJ, 629, 1

- Improvements
  - Model-independent method to derive mean ICM profiles
  - 3 yr WMAP data
  - Minimize systematic errors
- Other SZ and X-ray observations give independent verification for missing baryons

Missing Baryons, or, New Astrophysics

- Significant fraction (~ 32%) of baryons missing from ICM
  - Observed stellar mass in cluster galaxies and cold gas (in the relevant T_X range) < 10%

  → 22% baryons is not accounted for
- The baryons might be hidden in a form difficult to observe :
  - Diffuse intracluster light
  - Cold compact dark baryonic clouds formed from local cooling instabilities within ICM
- Thermal diffusion / evaporation of baryons out of cluster virial radius (Loeb, A. 2006, astro-ph/0606572)

Summary

- 9σ detection of SZ signal in CMB maps of WMAP 3 yr data, by studying 193 massive clusters with T_X>3 keV
- Resulting pressure profile agrees well with X-ray & SZ observations, and hydro cluster sim.
- Significant fraction of baryons missing from ICM
  - Missing baryonic component
  - Unknown astrophysical process
- Further investigations (theoretical and observational) of ICM physics is needed to understand galaxy cluster formation

Contamination & Noise for SZ Measurements

- WMAP detector noise
- CMB primary anisotropies
  - Both can be approximated as Gaussian
- Point sources, more at low frequency

Systematic & Theoretical Uncertainties

- The deduced missing baryon fraction can be
  - Overestimated :
  - A lower limit : Observational cluster mass assumes hydrostatic equilibrium, which may underestimate mass by 5–20 %
- Result might be affected by systematic error in assumed r_{200}–T_X relation