Intergalactic Medium
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University of KwaZulu-Natal, Durban, South Africa

CMB photons provide a backlight for structure in the universe.
Cosmic baryon inventory:

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter</th>
<th>Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>Main-sequence stars: spheroids and bulges</td>
<td>0.0015 ± 0.0004</td>
</tr>
<tr>
<td>3.4</td>
<td>Main-sequence stars: disks and irregulars</td>
<td>0.00055 ± 0.00014</td>
</tr>
<tr>
<td>3.5</td>
<td>White dwarfs</td>
<td>0.00036 ± 0.00008</td>
</tr>
<tr>
<td>3.6</td>
<td>Neutron stars</td>
<td>0.00005 ± 0.00002</td>
</tr>
<tr>
<td>3.7</td>
<td>Black holes</td>
<td>0.00007 ± 0.00002</td>
</tr>
<tr>
<td>3.8</td>
<td>Substellar objects</td>
<td>0.00014 ± 0.00007</td>
</tr>
<tr>
<td>3.9</td>
<td>H i + He i</td>
<td>0.00062 ± 0.00010</td>
</tr>
<tr>
<td>3.10</td>
<td>Molecular gas</td>
<td>0.00016 ± 0.00006</td>
</tr>
<tr>
<td>3.11</td>
<td>Planets</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>3.12</td>
<td>Condensed matter</td>
<td>$10^{-5.6} ± 0.3$</td>
</tr>
<tr>
<td>3.13</td>
<td>Sequestered in massive black holes</td>
<td>$10^{-5.4}(1 + \epsilon_n)$</td>
</tr>
</tbody>
</table>

$\Omega_{b,g} = 0.0035 = 8\%$ total baryon density

90% of baryons are in either intergalactic or intercluster medium

Fukugita, & Peebles 2004
X-ray: \(~ n_e(r)^2\)
thermal Sunyaev-Zeldovich effect

and compare with halo model prediction and hydrodynamic simulation

kinetic Sunyaev-Zeldovich effect

Planck intermediate results XXXVII, 2016, A&A
Yi-Chao Li, YZM, Mathieu Remazeilles, Kavilan Moodley, 2018, PRD in press, arXiv: 1710.10876

Thermal SZ maps

The thermal Sunyaev-Zeldovich effect

CMB photons provide a backlight for structure in the universe.
The velocity of clusters of galaxies relative to the microwave background. The possibility of its measurement

R. A. Sunyaev and Ya. B. Zeldovich Academy of Sciences, USSR, Space Research Institute, Profsoyuznaja 88, 117810 Moscow, USSR

Received 1979 May 31
Thermal Sunyaev-Zeldovich effect (tSZ):

\[
\frac{\Delta T}{T} = \left[ \eta \frac{e^{\eta} + 1}{e^{\eta} - 1} - 4 \right] y \equiv g_\nu y
\]

\[
g_\nu \equiv (\eta(e^{\eta} + 1)/(e^{\eta} - 1)) - 4
\]

\[
\eta = \frac{h\nu}{k_B T_{\text{CMB}}} = \frac{h\nu_0}{k_B T_0} = 1.76 \left( \frac{\nu_0}{100 \text{GHz}} \right)
\]

\[
y = \frac{k_B \sigma_T}{m_e c^2} \int_0^l T_e(l)n_e(l) \, dl
\]
WMAP:

Planck:
SZ map from linear combination of Planck frequency bands:
\( \nu_i = 100, 143, 217, 353 \text{ GHz} \).

\[
T_{SZ}/T_0 = y \cdot S_{SZ}(\nu_i) = \sum b_i T(\nu_i)
\]

1. \( \sum b_i S_{SZ}(\nu_i) = 1 \) 

2. \( \sum b_i S_{CMB}(\nu_i) = 0 \)

3. \( \sum b_i S_{dust}(\nu_i) = 0 \)

\[ S_{SZ}(x) = x \coth(x/2) - 4 \quad (x = hv/kT) \]

\[ S_{CMB}(x) = 1 \]

\[ S_{dust}(\nu_i) = \nu^\beta g(x) \]
Planck Full-Sky Maps - 9 Frequencies

- 30 GHz
- 44 GHz
- 70 GHz
- 100 GHz
- 143 GHz
- 217 GHz
- 353 GHz
- 545 GHz
- 857 GHz
Planck SZ y map, version E

Reject $\beta_{\text{dust}} = 2.0, \ r_{2.0}(100 \text{ GHz}) = 0$
Planck SZ no-\(y\) map, version E

\[ y = 0 \quad \text{to} \quad 10^{-4} \]

Reject \(S_{\text{SZ}}(v)\), retain \(\beta_{\text{dust}} = 1.8\)
CFHT mass map:

154 deg^2 in 4 patches

Van Waerbeke et al., 2014, MNRAS
Ma et al. fits a halo model to the observed correlation function. A $\beta$ model fits well, but in this context the data requires a 2-halo term to fit the large angular scale separation.

\[ \chi^2(\alpha, \beta) = \sum_{i,j} \left[ \xi^d(\theta_i) - \alpha \xi^{1h}(\theta_i) - \beta \xi^{2h}(\theta_i) \right] \times C_{ij}^{-1} \left[ \xi^d(\theta_j) - \alpha \xi^{1h}(\theta_j) - \beta \xi^{2h}(\theta_j) \right] \]

<table>
<thead>
<tr>
<th>Data set</th>
<th>2-halo only</th>
<th>1-halo only</th>
<th>No correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>(7.6 \times 10^{-5})</td>
<td>(2.4 \times 10^{-4})</td>
<td>(3.8 \times 10^{-11})</td>
</tr>
<tr>
<td>C</td>
<td>(2.2 \times 10^{-5})</td>
<td>(1.0 \times 10^{-4})</td>
<td>(1.1 \times 10^{-11})</td>
</tr>
<tr>
<td>D</td>
<td>(7.1 \times 10^{-5})</td>
<td>(6.0 \times 10^{-4})</td>
<td>(6.6 \times 10^{-11})</td>
</tr>
<tr>
<td>E</td>
<td>(2.6 \times 10^{-5})</td>
<td>(2.8 \times 10^{-4})</td>
<td>(1.3 \times 10^{-11})</td>
</tr>
<tr>
<td>F</td>
<td>(1.7 \times 10^{-3})</td>
<td>(5.4 \times 10^{-3})</td>
<td>(1.5 \times 10^{-8})</td>
</tr>
<tr>
<td>G</td>
<td>(4.6 \times 10^{-3})</td>
<td>(1.0 \times 10^{-2})</td>
<td>(9.6 \times 10^{-8})</td>
</tr>
<tr>
<td>H</td>
<td>(6.7 \times 10^{-4})</td>
<td>(7.3 \times 10^{-5})</td>
<td>(1.1 \times 10^{-9})</td>
</tr>
</tbody>
</table>

TABLE I: For each y-map B–H, the probability that the fit in Eq. (6) allows: \(\alpha = 0, \beta = 1\) (no 1-halo term, column 2); \(\alpha = 1, \beta = 0\) (no 2-halo term, column 3); and \(\alpha = \beta = 0\) (no cross-correlation, column 4). We assume \(P = \exp(-\Delta \chi^2/2)\).
By applying the virial theorem with $z = 0.37$, for the mass range $10^{12} - 10^{16} \, M_{\odot}$, we get $T_e = 10^5 - 10^8 \, K$. 

Simulation vs data

<table>
<thead>
<tr>
<th>Simulation</th>
<th>UV/X-ray background</th>
<th>Cooling</th>
<th>Star formation</th>
<th>SN feedback</th>
<th>AGN feedback</th>
<th>$\Delta T_{\text{loint}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOCOOL</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>...</td>
</tr>
<tr>
<td>REF</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>...</td>
</tr>
<tr>
<td>AGN 8.0</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$10^{8.0}$ K</td>
</tr>
<tr>
<td>AGN 8.5</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$10^{8.5}$ K</td>
</tr>
<tr>
<td>AGN 8.7</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>$10^{8.7}$ K</td>
</tr>
</tbody>
</table>
The figure shows the angular correlation function $\xi_{xy}(\theta)$ plotted against angular separation $\theta$ in arcminutes. The data is labeled as AGN 8.0, and the curves represent different conditions on radius $R$ and mass $M_{200}$.

The table below summarizes the results for different mass and radius bins:

<table>
<thead>
<tr>
<th>Bin</th>
<th>Simulation</th>
<th>Halo model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low mass, inner radii</td>
<td>7%</td>
<td>26%</td>
</tr>
<tr>
<td>Low mass, outer radii</td>
<td><strong>12%</strong></td>
<td><strong>14%</strong></td>
</tr>
<tr>
<td>High mass, inner radii</td>
<td>56%</td>
<td>28%</td>
</tr>
<tr>
<td>High mass, outer radii</td>
<td>25%</td>
<td>32%</td>
</tr>
</tbody>
</table>

The table includes signal and baryon contributions for each bin. The highlighted values in the table indicate the significant contributions for the low mass, outer radii bin.
In the Fourier-space analysis, we work with the convergence
respectively.

of the halo model for
solid red curves and dashed green curves represent the predictions
w
ecessary weighting,
(details):

multiplicative calibration correction (see Hildebrandt et al.
MNRAS
which increase the cross-correlation area. For RCSLenS, we extend our
Figure 2.

Cross-correlation measurements of
Red Cluster Sequence Lensing Survey (RCSLenS) X Planck thermal SZ effect map
560 deg^2

\[ \xi_{\gamma-y}(\vartheta) \]

\[ \xi_{\gamma-y}(\vartheta) \]

\[ \xi_{\gamma-y}(\vartheta) \]

Evidence of gas outside the virial radius

Planck intermediate results XXXVII, 2016, A&A
Yi-Chao Li, YZM, M Remazeilles, K Moodley, 2018, PRD
The kSZ Effect

\[
\left( \frac{\Delta T}{T_{CMB}} \right)_{kSZ} = -\frac{\sigma_T}{c} \int n_e v_{los} dl
\]
The pressure profile itself, and then calculate the amplification of SZ clusters in a year's time (Planck Collaboration XII 2011). The high-reliability samples of 189 SZ clusters detected over the whole sky from the first ten months of the Planck survey is motivated to provide the community with an all-sky SZ cluster catalogue (Planck Collaboration VIII 2011). Thanks to the Early Release Compact (ERCSC) project, which is delivered alongside the ERCSC (see Planck ERCSC website). Throughout the paper, we adopt a flat fiducial cosmology: observations – cosmic microwave background – large-scale structure of the Universe – Galaxies: clusters: general – Cosmological parameters. In the line of sight, since the electron pressure (Planck Collaboration VIII 2011). Inogamov & Sunyaev (2009) investigated the regularity of cluster pressure profiles with a sample of 33 local clusters observed with XMM-Newton. These sample spans a mass range of $10^{14} - 10^{15} M_{\odot}$. A Universal profile, where the electron pressure parameter denoted as $\tilde{\eta}$, is the Boltzmann constant, and $\nu_{0}$ is the frequency of photons is $70 \text{kHz}$. If the frequency of photons is $70 \text{kHz}$, the frequency dependent $\eta$ is $1.76 \left( \frac{\nu_{0}}{100 \text{GHz}} \right)$. By deriving an average optical depth (kSZ) in Eq. (1) determines the $\Delta T / T = \frac{\eta}{e^{\eta} - 1} - 4 \equiv g_{\nu} y$. The $g_{\nu} \equiv (\eta(e^{\eta} + 1)/(e^{\eta} - 1)) - 4$ for $\nu = \frac{h \nu}{k_{B} T_{CMB}} = \frac{h \nu_{0}}{k_{B} T_{0}} = 1.76 \left( \frac{\nu_{0}}{100 \text{GHz}} \right)$. The $\eta$ is $\frac{k_{B} \sigma_{T}}{m_{e} c^{2}} \int_{0}^{l} T_{e}(l)n_{e}(l) \, dl$. The $\nu / 100 \text{GHz}$ is the frequency dependent $\eta$.

\[ \frac{\delta T}{T_{0}}(\hat{n}) = - \int dl \, \sigma_{T} n_{e} \left( \frac{\nu}{c} \cdot \hat{n} \right) \]

The $\Delta T / T = 5 \times 10^{-4} / l_{e}(T_{CMB})$. The $\Delta T / T = 5 \times 10^{-4} / l_{e}(T_{CMB})$.
SZ map from linear combination of Planck frequency bands: \( \nu_i = 100, 143, 217, 353 \) GHz.

\[
T_{SZ}/T_0 \equiv y \, S_{SZ}(\nu_i) = \sum b_i \, T(\nu_i)
\]

1. \( \sum b_i \, S_{SZ}(\nu_i) = 1 \quad \rightarrow 0 ! \)
   \[S_{SZ}(x) = x \coth(x/2) - 4 \quad (x = h\nu/kT)\]

2. \( \sum b_i \, S_{CMB}(\nu_i) = 0 \quad \rightarrow 1 ! \)
   \[S_{CMB}(x) = 1\]

3. \( \sum b_i \, S''_{dust}(\nu_i) = 0 \quad S''_{dust}(\nu_i) = \nu^\beta \, g(x)\)
\[ w^{T,v}(r) = \langle \delta T_i \nu^{\text{rec}}_{\ell 0}(x_j) \rangle_{i,j}(r) \]
Planck SMICA, SEVEM, NILC maps
and the velocities we are destroying their coherent, large-scale pattern. For all shu-
ished line-of-sight peculiar velocities, i.e. to each CG we approach is displayed in this plot.

CG in the sample (that is, by Fig. 7.

We further study the dependence of the measured vlos.

We again restrict ourselves to the LINEAR approach.

di-

s were computed for positions obtained after ro-

A clear, large-

v.


tSZ amplitude following a mass scaling i

shows that the correlation found between the

correlation function of the kSZ temperature fluctuations (

tary systematic test can be conducted by computing the cross

GALAXY

GALAXY

a more even comparison the HFI 100 GHz and 217 GHz raw


cleaned map, and provide another view of the angular extent of

functions computed from rotated kSZ temperature estimates.

Fig. 8.

One way of quantifying the amplitude of our signal is to

We find a similar situation in the kSZ temperature-

The solid line provides the best fit of the

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Pairwise kSZ signal

\[ \hat{p}_{\text{kSZ}}(r) = -\frac{\sum_{i<j} (\delta T_{\text{kSZ},i} - \delta T_{\text{kSZ},j}) \cdot c_{ij}}{\sum_{i<j} c_{ij}^2} \]

\[ c_{ij} = \frac{(r_i - r_j)(1 + \cos \theta)}{2\sqrt{r_i^2 + r_j^2 - 2r_ir_j \cos \theta}} \]

\[ \bar{\tau} = (0.53 \pm 0.32) \times 10^{-4} \text{ (1.65\sigma)} \quad \text{LowZ North CGC;} \]
\[ \bar{\tau} = (0.30 \pm 0.57) \times 10^{-4} \text{ (0.53\sigma)} \quad \text{LowZ South CGC;} \]
\[ \bar{\tau} = (0.43 \pm 0.28) \times 10^{-4} \text{ (1.53\sigma)} \quad \text{DR13 Group.} \]

Gas within/around filament

Stacking LRG/SDSS pairs (Ms>11.3, 0.15<z<0.43 (N=28247)) on Planck y-map

tangential distance: 6-10 \ h^{-1}\text{Mpc}

radial distance: \pm 6 \ h^{-1}\text{Mpc}
Subtracted

Stacked

LRG SZ

stack

LRG pairs (Ms > 11.3) + y(D)

Uniform
the
sizes

Squeeze

Stretch

Squeeze

Uniform the sizes

Tankinuma et al.

3.3 Null tests and error estimates

The top panel of Figure 2: The best-fit radial profile of the left and right halos shown above.

The second null test is to stack the pairs meeting this criterion as in default LRG pair catalog, so that each pair in the original catalog, we pick one of the two members with less apparent signal between the LRGs. We perform the same repeat this stacking of the full catalog 1000 times to determine the uncertainty of the filament signal quoted above. Taking the same re-
LRG pairs (Ms > 11.3) + y(D) ps mask, 0.15<z<0.47 (N=28247)

Stacked

LRG SZ Subtracted
\[ \Delta y = (1.31 \pm 0.25) \times 10^{-8} \]

5.3\( \sigma \)
\[
y = \int n_e \sigma_T \frac{k_B T_e}{m_e c^2} \, dl
\]

\[
n_e = \bar{n}_{e,i} (1 + \delta)
\]

\[
\bar{n}_{e,i} = \frac{\chi \rho_b(z)}{\mu_e m_p}
\]

\[
\chi = \frac{1 - Y_p(1 - N_{He}/2)}{1 - Y_p/2}
\]

\[
\delta_c \left( \frac{T_e}{10^7 \, \text{K}} \right) \left( \frac{r_c}{0.5h^{-1} \, \text{Mpc}} \right) = 2.7 \pm 0.5
\]
Conclusion:

- Most of the baryons in the Universe is in a warm-hot diffuse status, for which X-ray observation is hard to measure.

- We probe gas by cross-correlating the Sunyaev-Zeldovich map from Planck with CFHTLens lensing mass maps and SDSS LRG pair catalogue to probe gas distributions that are difficult to trace.

- Significant correlation is seen with lensing mass. Data is reasonably well fit by a halo model, but requires gas out to $5 \times$ virial radius. By the virial theorem, the temperature of this gas exactly corresponds to the $10^5—10^7$K, i.e. warm-hot intergalactic medium. This is consistent with the finding from numerical simulation.

- We use the aperture photometry filter to the kSZ map, and find the maximum correlation between kSZ-velocity field is at theta=8 arcmin, corresponding to gas outside virial radius.

- We stack Planck y on the same sample and find the evidence for a “gas bridge” at the level of $y = (1.31 \pm 0.25) \times 10^{-8}$ (68% CL). This corresponds to the temperature of gas bridge to be less than $10^7$ K.

- Our results show that the baryons are no-longer “missing” and they are neither too hot nor too cold, but correlated with underlying mass distribution (lensing and velocity field).