Hunting the baryons in the near universe

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Key questions

• Have we observationally accounted for all the atoms and molecules of the universe?

• Are there significant amounts of thermal and non-thermal particles in a cluster that evaded detection?
Hinshaw et al 2007

ratio of 2\textsuperscript{nd} to 1\textsuperscript{st} acoustic peaks gives baryon to dark matter fraction.
\( \Omega_b^{obs} \) = mass density of observed baryonic (ordinary) matter

For the present-day universe (\( z = 0 \)):
\[
\Omega_b^{obs} = \Omega_\star + \Omega_{HI} + \Omega_{H_2} + \Omega_{\text{clusters}} \approx 0.068
\]

\( \Omega_b \) = total mass density of baryonic matter

This is constrained by the observed abundance of primordial D from spectra of high z quasars:
\[
\Omega_b = 0.039 \pm 0.002 \quad (H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1})
\]

\( \Omega_m \) = total mass density of all matter

\( \Omega_\Lambda \) = energies \( (E = mc^2) \)

shall present ample evidence for \( \Omega_m = 0.35 \pm 0.1 \), \( \Omega_\Lambda = 0.6 \pm 0.15 \)

so that:

- \( \Omega = 1 \), the universe is flat
- \( \Omega_m \approx 10 \Omega_b \Rightarrow \) dark matter
- \( \Omega_\Lambda > 0 \Rightarrow \) cosmological constant
WHERE ARE THE BARYONS?

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ABSTRACT

New high-resolution, large-scale cosmological hydrodynamic galaxy formation simulations of a standard cold dark matter model (with a cosmological constant) are utilized to predict the distribution of baryons at the present and at moderate redshift. It is found that the average temperature of baryons is an increasing function of time, with most of the baryons at the present time having a temperature in the range of $10^5$–$10^7$ K. Thus not only is the universe dominated by dark matter, but more than one-half of the normal matter is yet to be detected. Detection of this warm/hot gas poses an observational challenge, which requires sensitive EUV and X-ray satellites. Signatures include a soft cosmic X-ray background, apparent warm components in hot clusters due to both intrinsic warm intracluster and intercluster gas projected onto clusters along the line of sight, absorption lines in X-ray and UV quasar spectra [e.g., O vi (1032, 1038) A lines, O vii 574 eV line], strong emission lines (e.g., O viii 653 eV line), and low-redshift, broad, low column density Lyx absorption lines. We estimate that approximately one-fourth of the extragalactic soft X-ray background (at 0.7 keV) arises from the warm/hot gas, half of it coming from $z < 0.65$, and three-quarters coming from $z < 1.00$, so the source regions should be identifiable on deep optical images.

Subject headings: cosmology: theory — galaxies: formation — large-scale structure of universe — methods: numerical
From theoretical considerations (Cen & Ostriker 1999) one expects the majority of the baryons at the present epoch of the Universe’s evolution to be ‘hidden’ in the form of a Warm-Hot-Intergalactic-Medium (WHIM) gas. Crudely speaking the argument goes as follows. If $\lambda$ is the characteristic wavelength of the bulk motion of the intergalactic medium at a given epoch, then when these waves collide and break the thermal velocity of the shocked gas will typically be $v \sim H_0 \lambda$ where $H_0$ is the Hubble constant, i.e.

$$v \sim 100(H_0/70)(\lambda/1.5 \text{ Mpc}) \text{ km s}^{-1} \tag{7}$$

where we set $\lambda$ at $\sim$ the present size (virial radius) of galaxy clusters, i.e. $\lambda \sim 1-3$ Mpc. The value of $v$ as given in Eq. (7) corresponds to a gas temperature of $10^5-7$ K.
The WHIM (Warm Hot Intergalactic Medium)

Gas between $10^5 K < T < 10^7 K$ from a cosmological simulation (from R. Cen’s homepage)
Fig. 2.—Evolution of the four components of cosmic baryons (see text for definitions). (a) Volume fractions of the four components in Gyr, and (b) mass fractions in Gyr. Examination of (b) shows that more than half of the baryons at redshift zero are in the temperature range $10^7 \, K > T > 10^3 \, K$. Also shown are the warm/hot components for two other models: an open CDM model with $\Omega_0 = 0.40$ and $\sigma_8 = 0.75$ (dotted lines), and a mixed hot and cold dark matter model with $\Omega_{hot} = 0.30$ and $\sigma_8 = 0.67$ (dashed lines). These two models were computed completely independently by Bryan & Norman (1998).
\[ kT = 8.7 \pm 0.4 \text{keV}, A = 0.3 \] as measured by ASCA
Virial speed of mass in the cluster is given by

\[ 2T + V = 0 \implies mv^2 = \frac{GMm}{R} \implies v = \sqrt{\frac{GM}{R}} \]

Virial theorem

For a rich cluster like Coma,

\[ M \approx 5 \times 10^{14} M_{\text{sun}}, R \approx 2 \text{Mpc} \implies v \approx 1000 \text{km/s} \]

A proton moving in this potential has kinetic energy

\[ \frac{1}{2} m_p v^2 \approx 5 \text{keV} \leftarrow kT \]
The discovery of cluster soft X-rays as *extra* photon emission in the 0.2 – 0.5 keV range above the level expected from the low energy tail of the virialized intracluster gas at X-ray temperatures was made by the EUVE mission in 1995.
Coma Cluster 6’ – 9’ ROSAT and EUVE DS

Solid line is the expected emission spectrum of the hot ICM at $kT = 8.7 \pm 0.4$ keV and $A = 0.3$ solar, as measured by ASCA.
Central soft excess (no background issues) for Coma

Coma 0'–5' arcminute

![Graph showing data for ROSAT and XMM telescopes with energy on the x-axis and normalized counts s^(-1) keV^(-1) on the y-axis.](image)
Is this the gas that ‘hides’ all the missing baryons?
Physical constraints on the model

For intracluster origin of the WHIM

\[ P_{\text{warm}} = P_{\text{hot}} \rightarrow n_w = \left( \frac{n_h}{10^{-3} \text{ cm}^{-3}} \right) \left( \frac{T_h}{T_w} \right) \]

If we take \( T_h = 10T_w, n_w > 10^{-2} \text{ cm}^{-3} \)

Radiative cooling time is important

\[ \tau = 6 \times 10^9 \left( \frac{T}{10^6 \text{ K}} \right)^{0.5} \left( \frac{n_w}{10^{-3} \text{ cm}^{-3}} \right)^{-1} \text{ yrs} \]

For \( T_w \sim 10^6 \text{ K}, n_w > 10^{-2} \text{ cm}^{-3} \):

\( \tau < 6 \times 10^8 \text{ years} \)

WHAT SUSTAINS THE WARM GAS AGAINST SUCH RAPID RADIATIVE COOLING?
Thermal (mekal) model \( kT \approx 10^6 \, K \)
Coma cluster 0.5 – 2 keV with XMM-Newton pointings
Same as previous slide but now all observations have been added. Again, there is no line at the expected redshift of Coma.
Non-thermal interpretation of the cluster soft X-rays

Hwang, C.-Y., 1997, Science, 278, 191

Proposed the origin of the cluster soft excess emission as due to inverse-Compton scattering between intracluster cosmic rays (relativistic electrons with Lorentz factors of a few hundred) and the cosmic microwave background

HOW LARGE A COSMIC-RAY (CR) POPULATION DO WE NEED TO ACCOUNT FOR THE SOFT EXCESS BRIGHTNESS?
Inside a cluster’s core the soft excess of clusters could also be non-thermal in its nature, due to problems with the rapidly cooling thermal baryons, and absence of the OVII line. These non-thermal electrons can also be tested by means of the Sunyaev-Zel’dovich effect.

The soft X-rays outside clusters’ cores might still be of thermal origin.
Giant $\frac{1}{4}$ keV Halo centered at Coma (as detailed by the ROSAT sky survey)
ROSAT/PSPC Radial surface brightness of Coma
In fact, the prediction of Cen & Ostriker 1999 was that the missing baryons should exist as a warm gas in the *outskirts* of clusters.
• What fraction of a cluster’s X-rays is thermal’?
The Observation of Relic Radiation as a Test of the Nature of X-Ray Radiation from the Clusters of Galaxies

Introduction

The x-ray radiation from a number of clusters of galaxies (Coma, Virgo, Perseus) was discovered recently.\(^1\) It is assumed that clusters of galaxies form an important class of powerful x-ray sources, possibly giving the main contribution to the x-ray background radiation of the Universe.\(^2\) What is the nature of these sources? What physical mechanisms give the observed x-ray radiation?

Most likely this is either the bremsstrahlung radiation of hot intergalactic gas or inverse Compton scattering on the relativistic electrons. Again the question arises—what kind of radiation and where is it scattered? The relic
Figure 4. Average $\Delta T$ (from WMAP W-band data) plots for 30 clusters from the ROSAT sample (left) and 39 clusters from the Chandra sample (right). In both figures, the points show our cross-correlation results, whilst the curves show average SZ models (based on the parameters taken from Lieu et al. 2006 and Bonamente et al. 2006) convolved with a Gaussian representing the WMAP beam profile. For the Chandra sample, we plot the full isothermal model (solid line) and the same model limited to $\theta < 2'$ (dashed line).
SZ effect or Not? - Detecting most galaxy clusters’ main foreground effect

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ABSTRACT

Galaxy clusters are the most massive objects in the universe, and they comprise a high temperature intracluster medium of about $10^7$K, believed to offer a main foreground effect for the CMB data with thermal Sunyaev-Zel’dovich (SZ) effect. This assumption has been confirmed with SZ signal detection in hundreds of clusters, but comparing with the huge numbers of clusters within optical selected samples from SDSS data, this only accounts for a few percent. Here we introduce a model-independent new method to confirm the assumption that galaxy clusters offer the thermal SZ signal as their main foreground effect. For the WMAP 7year data, we classified data pixels as "to be" or "not to be" affected by the sample clusters, with a parameter of its nearest neighbor cluster’s angular distance. By comparing the statistical results of these two kinds of pixels, we can see how the sample clusters affect the CMB data directly. We find that Planck-ESZ sample and the Xray samples($\sim 10^2$ clusters) can lead to obvious temperature depression in WMAP 7year data, this confirms the SZ effect prediction. However, each optical selected sample ($\sim 10^4$ clusters), shows an opposite result: the mean temperature rises to about 10 uK. The unexpected qualitative scenario implies that the main foreground effect of most clusters is NOT always the expected SZ effect. This is maybe the reason why the SZ signal detection result is lower than what is expected by the model.
THE NON-THERMAL INTRACLUSTER MEDIUM

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ABSTRACT

\textit{WMAP}'s detection of the Sunyaev–Zel'dovich effect at a much reduced level among several large samples of rich clusters is interpreted in terms of conventional physics. It has been suggested that the central soft X-ray and EUV excess found in some clusters cannot be of thermal origin, due to problems with rapid gas cooling and the persistent non-detection of the O \textsc{vii} line, but may arise from inverse Compton scattering between intracluster relativistic electrons and the cosmic microwave background (CMB). In fact, recent \textit{XMM-Newton} observations of the soft X-rays from Coma and Abell 3112 are equally well fitted by a power law or a thermal virialized gas. Therefore, the missing Sunyaev–Zel’dovich flux could partly be due to an overestimate of the central density of virialized electrons which scatter the CMB. Synchrotron radiation in an intracluster magnetic field of strength of a few \(\mu\)G is responsible for significant additional electron energy loss. Equipartition between relativistic particle and magnetic field energy densities is a realistic possibility. GHz radiation data from a Coma cluster halo yields information on the high-energy steepening of the cluster relativistic electron spectrum. Cluster microwave emission in the \textit{WMAP} passbands by higher energy cosmic-ray electrons and gamma-ray emission from an accompanying cosmic-ray proton flux are also considered. The energetic electrons could originate from active galactic nucleus jet injection, then distributed cluster wide by Alfvén wave sweeping, with accompanying in situ Fermi acceleration.

\textit{Key words:} magnetohydrodynamics (MHD) – radiation mechanisms: non-thermal – X-rays: galaxies: clusters

\textit{Online-only material:} color figure
Can SZ observations shed light on the content in the outskirts of Coma?

A warm gas component can also exert the SZ effect without necessarily requiring a reasonable column density.
Planck SZE map of Coma
Planck SZ profiles of Coma
• Other efforts in search of the missing baryons also look promising.
The Diffuse X-ray Background

~40 AU ~100 pc ~2-5 kpc ~z<1

Local Bubble

Galactic Halo

NH

WHIM

Unresolved point sources
Control Observations

- ~40 AU
- ~100 pc
- ~2-5 kpc
- ~z<1

NH

Galactic Halo

WHIM

Unresolved point sources

Local Bubble

MBM20

Eridanus Hole
Control Observations

**MBM20**
- \( l=211^\circ24'15.7'', b=-36^\circ33'46.7'' \)
- \( N_H=15.9\times10^{20} \text{ cm}^{-2} \)
- Absorption=75% at \( \frac{3}{4} \text{ keV} \)
- \( 112\pm15 \text{ pc} < d < 161\pm21 \text{ pc} \)

**Eridanus Hole**
- \( l=213^\circ25'52.3'', b=-39^\circ5'26.6'' \)
- \( N_H=0.86\times10^{20} \text{ cm}^{-2} \)
- Absorption=8% at \( \frac{3}{4} \text{ keV} \)
Control Observations

Calculated AcF for the two control targets: MBM20 (red) and the Eridanus hole (blue)
Results

Several sigma detection of the WHIM signature in the AcF of XMM-Newton blank fields.

$18 \pm 5\%$
• Is there a more `scientific’ method of measuring the baryonic content of the near universe?
• Within the Galaxy, the column density of ionized baryons to pulsars can accurately be measured using the phenomenon of plasma dispersion.
Dispersive arrival time delay
Line-of-sight ionized baryons

- ~40 AU
- ~100 pc
- ~2-5 kpc
- ~z<1

Local Bubble

NH

Galactic Halo

WHIM

Unresolved point sources
IGM domination of ionized baryonic column density to background quasar

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But the universe has no pulsars!

• Need at least a variable and observable distant source.

• While ionized IGM baryons do cause frequency-dependent delay on the timescale of minutes to hours in the arrival of ~100 MHz emission from distant quasars, quasars with so rapid a variability as to avail themselves for this test are those very ones affected by plasma scintillations in our local interstellar medium (e.g. Dennett-Thorpe & de Bruyn 2002).

• Angular broadening of quasars caused by intergalactic scintillation was assessed by Lazio et al. (2008), who concluded that the only way of securing a useful observational limit is if a quasar nucleus is found to ‘twinkle’ at a position close to that of a local pulsar, as data about the latter may then be used to calibrate out the interstellar effects of the Galaxy.
A NEW WAY OF DETECTING INTERGALACTIC BARYONS

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ABSTRACT

For each photon wave packet of extragalactic light, the dispersion by line-of-sight intergalactic plasma causes an increase in the envelope width and a chirp (drift) in the carrier frequency. It is shown that for continuous emission of many temporally overlapping wave packets with random epoch phases such as quasars in the radio band, this in turn leads to quasi-periodic variations in the intensity of the arriving light on timescales between the coherence time (defined as the reciprocal of the bandwidth of frequency selection, taken here as of order 0.01 GHz for radio observations) and the stretched envelope, with most of the fluctuation power on the latter scale which is typically in the millisecond range for intergalactic dispersion. Thus, by monitoring quasar light curves on such short scales, it should be possible to determine the line-of-sight plasma column along the many directions and distances to the various quasars, affording one a three-dimensional picture of the ionized baryons in the near universe.

Key words: cosmological parameters – galaxies: clusters: general – plasmas – waves
Young's double slit -- ideal
Young’s double slit -- real
Young's double slit -- real

*
Young’s double slit -- real

*
Phase noise of radiation (radio fluctuations)
Intensity variation on various timescales

\[ \left( \frac{\delta I_t}{I} \right)^2 \approx \frac{1}{t\delta \nu} \]
Phase noise limit (high occupation no.)
Two types of photon noise

\[
\left( \frac{\delta I_t}{I} \right)^2 = \left( \frac{\delta N_\gamma}{N_\gamma} \right)^2 = \frac{1}{t\delta\nu}
\]
Two types of photon noise

\[
\left( \frac{\delta I_t}{I} \right)^2 = \left( \frac{\delta N_{\gamma}}{N_{\gamma}} \right)^2 = \frac{1}{t \delta \nu} + \frac{1}{N_{\gamma}}
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Two types of photon noise

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Phase noise

Poisson noise
Two types of photon noise

\[ \left( \frac{\delta I_t}{I} \right)^2 = \left( \frac{\delta N_\gamma}{N_\gamma} \right)^2 = \frac{1}{t \delta \nu} + \frac{1}{N_\gamma} \]

Phase noise

Poisson noise

How do we account for the last term?
Phase noise of radiation (radio fluctuations)
vacuum

\[ \tau \approx 1/\delta \nu \]
Phase noise limit (high occupation no.)

\[
\left( \frac{\delta I_t}{I} \right)^2 = \left( \frac{\delta N_{\gamma}}{N_{\gamma}} \right)^2 = \frac{1}{t \delta \nu}
\]
Poisson limit (low occupation no.)
Poisson limit (low occupation no.)

\[
\left( \frac{\delta I_t}{I} \right)^2 = \left( \frac{\delta N_\gamma}{N_\gamma} \right)^2 = \frac{1}{N_\gamma}
\]
Noise from overlapping and non-overlapping wave packets

\[
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\]

or, equivalently,

\[
(\delta N_{\gamma})^2 = N_{\text{mode}}(\bar{n}_\gamma^2 + \bar{n}_\gamma)
\]

where

\[
N_{\text{mode}} = \frac{t}{\sqrt{2\pi T}}
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Bose-Einstein statistics
Noise from overlapping and non-overlapping wave packets

\[
\left( \frac{\delta I_t}{I} \right)^2 = \left( \frac{\delta N_{\gamma}}{N_{\gamma}} \right)^2 = \frac{1}{t\delta \nu} + \frac{1}{N_{\gamma}}
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Noise from overlapping and non-overlapping wave packets with next order correction due to finite wave packet size

\[
\left( \frac{\delta I_t}{I} \right)^2 = \left( \frac{\delta N_{\gamma}}{N_{\gamma}} \right)^2 = \frac{1}{t\delta\nu} + \frac{1}{N_{\gamma}} \left( 1 - \sqrt{\frac{2T}{\pi t}} \right)
\]

intrinsic size of wave packet in time

without dispersion
Noise from overlapping and non-overlapping wave packets with next order correction due to finite wave packet size

\[
\left( \frac{\delta I_t}{I} \right)^2 = \left( \frac{\delta N_{\gamma}}{N_{\gamma}} \right)^2 = \frac{1}{t\delta\nu} + \frac{1}{N_{\gamma}} \left( 1 - \sqrt{\frac{2T}{\pi t}} \right)
\]

without dispersion, and

\[
\left( \frac{\delta I_t}{\bar{I}} \right)^2 = \frac{1}{t\delta\nu} + \frac{1}{N_{\gamma}} \left( 1 - \sqrt{\frac{2}{\pi} \left( 1 + \xi^2 \right) \frac{T}{t}} \right)
\]

dispersive stretch factor of wave packet with dispersion.
Photons look different after moving through IGM
Typical column densities out of the Galactic plane

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Extragalactic dispersive stretch factor

\[ \xi = 278 \left( \frac{\delta \nu / \nu}{1/6} \right)^2 \left( \frac{\nu}{500 \text{ THz}} \right)^{-1} \left( \frac{n_e}{10^{-7} \text{ cm}^{-3}} \right) \left( \frac{\ell}{1 \text{ Gpc}} \right) \]
Intensity variance reduction: photon anti-bunching

Photon detections as a function of time for (a) anti-bunched, (b) random, and (c) bunched light.
Poisson statistics

total no. of time bins width $t$

$$\bar{n}_1 = \lambda t N_s$$

$$\bar{n}_2 = \frac{1}{2} \lambda^2 t^2 N_s$$
Sub-Poisson statistics

total no. of time bins width $t$

\[ \bar{n}_1 = \lambda t N_s \]

\[ \bar{n}_2 = \frac{1}{2} \lambda^2 t^2 N_s - \sqrt{\frac{1 + \xi^2}{2\pi}} \lambda \mathcal{T} N_s \]

Hence the number of two-photon bins is reduced. The effect is more prominent for bins of small $t$. 
<table>
<thead>
<tr>
<th>mV of source</th>
<th>Obs.</th>
<th>$\lambda$ (in s$^{-1}$)</th>
<th>Column $n_e \ell$ (in cm$^{-3}$ Gpc)</th>
<th>$t$ (in ns)</th>
<th>Statistical significance</th>
<th>$\delta n_2/n_2$</th>
</tr>
</thead>
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<td>10 (star)</td>
<td>Lick 3m</td>
<td>$4 \times 10^6$</td>
<td>$10^{-8}$</td>
<td>1</td>
<td>47.2$\sigma$</td>
<td>$6 \times 10^5/8 \times 10^7$</td>
</tr>
<tr>
<td>13 (3C273)</td>
<td>Lick 3m</td>
<td>$2.5 \times 10^4$</td>
<td>$10^{-7}$</td>
<td>10</td>
<td>13.5$\sigma$</td>
<td>$3,750/38,642$</td>
</tr>
<tr>
<td>15 (quasar)</td>
<td>Keck 10m</td>
<td>$4 \times 10^4$</td>
<td>$10^{-7}$</td>
<td>10</td>
<td>14.0$\sigma$</td>
<td>$6,000/91,592$</td>
</tr>
<tr>
<td>18 (quasar)</td>
<td>Keck 10m</td>
<td>2,560</td>
<td>$3 \times 10^{-7}$</td>
<td>20</td>
<td>7.59$\sigma$</td>
<td>$576/2,873$</td>
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Dead time issues

Several practical issues associated with photon counters should be taken into account, including dead time, afterpulsing and dark counts. The dead time of a photon counter tends to make a perfect Poisson distribution appear to be sub-Poisson. Such an effect could mask the sub-Poisson distribution due to dispersion if proper care is not taken. For example, the counting circuits of a PMT usually introduce a dead time of a few tens of nanoseconds. Such a photon counter would not be able to capture any "double photon" counts if a 1-10 ns counting cycle is used. To address this problem, we propose to use two identical PMT counters separated by a 50:50 beamsplitter. The outputs of the two counters are combined with a sub-ns timing error to form one single stream of photon counts before being gated by a clock. To simplify the data analysis, we can further make the counting cycle same as the counter dead time (by adjusting the PMT electronics and the clock frequency). Such a detection system in principle can capture all the "single photon" counts and half of the ‘double photon’ counts. The latter is because 50 % of the photon pairs arriving within a counting cycle fall onto different PMTs and, therefore, can effectively be tallied with a worsening in the signal-to-noise by the factor of \( \sqrt{2} \).
Afterpulse issues

On the other hand, afterpulsing and dark counts tend to make a perfect Poisson distribution appear to be super-Poisson by adding artificial multi-photon counts. However, with the help of an ideal Poisson source, both effects can be fairly well calibrated and subsequently taken out of the dispersion measurement. Recent development of hybrid photodetectors also offers a detector with almost zero afterpulsing (Suyama (2008)). The counter calibration can be done off-line in the lab. Alternatively, the task can also be done on site by pointing the telescope first to a nearby star and attenuate the incoming photon intensity to a level comparable to the intended quasar.
Conclusion

• The questions about the density and state of the baryons at low z and composition of the IGM are intimately related, and persist after 3 decades since the identification of clusters as X-ray sources.

• Observations are via the emission, absorption, and scattering properties of the baryons.

• Since most of the IGM baryons are ionized, they can also disperse passing radiation.

• Dispersion change the statistical properties of light from a steady background source in a detectable way.