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The missing cosmic baryons found?

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Summary. — The angular power spectrum of the cosmic microwave background radiation (CMB), the relative abundances of primordial hydrogen, deuterium and helium isotopes, and the large-scale structure of the universe all indicate that 4.5% of the current mass density of the universe consists of baryons. However, only a small fraction of these baryons can be accounted for in stars and gas inside galaxies, galaxy groups and galaxy clusters, and in spectral-line absorbing gas in the intergalactic medium (IGM). Too hot to show up in Lyman-absorption, too cool to cause detectable spectral distortions of the cosmic microwave background radiation, and too diffused to emit detectable X-rays, about 90% of the cosmic baryons remain missing in the local universe (redshift $z \sim 0$). Here, we report on prevalent, isotropic, source independent, and fairly uniform soft X-ray absorption along the lines of sight to high-z gamma-ray bursts (GRBs) and quasars. It has the magnitude, redshift and energy dependence that are expected from a hot diffused IGM that contains the missing cosmological baryons and has a mean metallicity similar to that in the intracluster medium (ICM) of galaxy clusters.

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PACS `98.70.Rz` – γ-ray sources; γ-ray bursts.
PACS `98.54.Aj` – Quasars.

1. – Introduction

The intergalactic medium (IGM) is extremely difficult to observe. Its tremendously low density and high temperature are believed to elude most absorption and emission detection. Thus, the observed extragalactic absorption of light from gamma-ray bursts (GRBs) and quasars, the most luminous transient and persistent sources in the universe and the farthest observable objects in it may be the only way to probe the IGM. This absorption is usually assumed to take place mainly in the neutral interstellar medium within their host galaxies (HGs). But, in many cases the equivalent hydrogen column densities that were inferred from their measured UVO and soft X-ray spectra are very different and uncorrelated. Such discrepancies were found both for distant GRBs [1-5] and distant quasars (see, *e.g.*, [6-9] and references therein). In contrast, the metal abundances and column densities of intervening absorbers on the sightlines to galactic and nearby extragalactic sources inferred from soft X-ray and Lyman-α absorption, in general do not yield such discrepant column densities (see, *e.g.*, [3] and references therein).

The extragalactic absorption of soft X-rays from GRBs and quasars at small redshifts is usually dominated by absorption in their host galaxy. However, at large z, the soft X-ray opacity of absorbers is expected to decrease rapidly with z because both the mean metallicity and the photoabsorption cross section at an observed energy decrease rapidly with z. In contrast, the mean opacity of the IGM to soft X-rays is dominated by absorption at small redshifts. It increases rapidly with increasing z to its asymptotic value $\tau(E)$ independent of z beyond $z \sim 2$. Hence, it is not correlated to the UV absorption in the host galaxy and yields a discrepant column density if assumed to take place in/near the host([1]). It was suggested that the discrepant column densities resulted either from misinterpreting flattening of the intrinsic spectral distribution of the soft X-rays at low energy as X-ray absorption, or from the high level of ionization of hydrogen in the absorber in the HG (see, *e.g.*, [6-9] and references therein). Both interpretations, however, required fine tuning in order to reproduce both the E and z dependence of the observed low-energy opacity.

In this paper we propose a different origin for the discrepant column densities inferred from UVO and X-ray observations of high-z GRBs and quasars. While the UVO absorption takes place mainly in the neutral gas in the host galaxies, we suggest that the absorption of their X-rays takes place mainly in the hot intergalactic medium (IGM) that contains all of the missing baryons implied by big bang nucleosynthesis and the observed angular power spectrum of the cosmic microwave background radiation and has the same metallicity as that in the intracluster medium (ICM) of galaxy clusters. We show that the opacity of such an IGM can explain on average the measured soft X-ray absorption of high-z GRBs and quasars. It is isotropic, practically independent of source and saturates at high z, uncorrelated to the UVO absorption in the host and, within observational errors, has the magnitude and energy dependence expected for the hot IGM of standard cosmology.

2. – Intrinsic host column densities from soft X-ray absorption

The extragalactic opacities to soft X-rays emitted by GRBs and quasars that were measured with the X-ray telescope aboard the Swift satellite and with the ROSAT, ASCA, BeppoSAX, Chandra and XMM-Newton satellite, respectively, were assumed to be entirely due to the absorption within the host galaxies at redshift z although the current X-ray spectra contain no redshift information. These opacities were converted to equivalent hydrogen column densities $N_{h,\mathrm{HG}}(z)$ of the GRBs' host galaxies along the GRBs sightline, using

$$\tau(E,z) = \sigma([1+z]E)\, N_{h,\mathrm{HG}}(z)\, (Z/Z_\odot), \tag{1}$$

([1]) At small redshifts the column densities in the host galaxy of GRBs or quasars that are inferred from UVO and soft X-ray absorption can also differ significantly for a different reason: The ionization of electrons in the external atomic shells by the UVO emission of GRBs, and of blazars in particular, extends to much larger galactic distances than the ionization of the inner shells in the metals responsible for the soft X-ray absorption (see, *e.g.*, [6, 2, 3] and references therein).

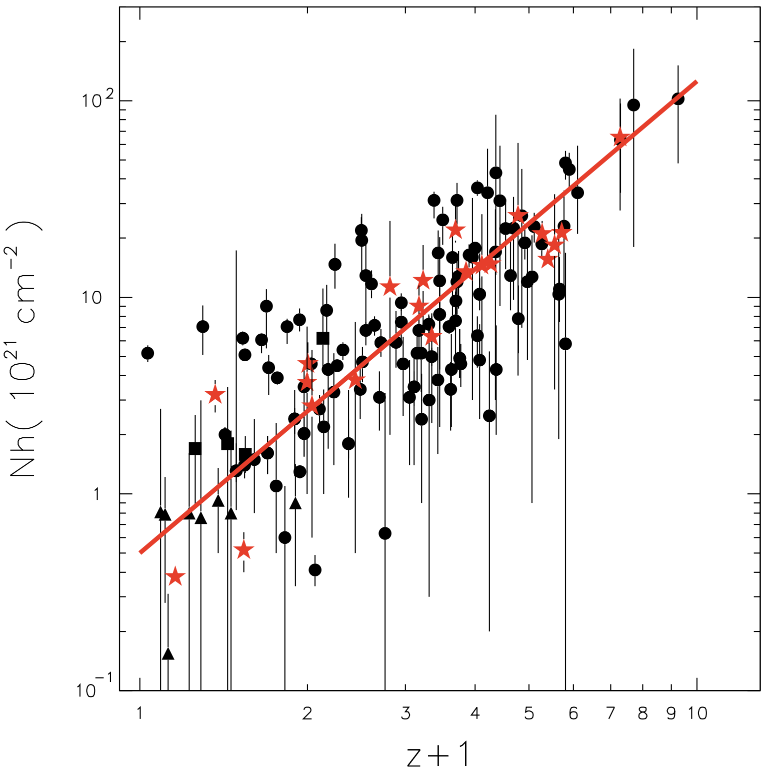

Fig. 1. – Equivalent hydrogen column densities of the HG of GRBs and radio load quasars as a function of redshift that were inferred from their absorbed soft X-ray spectrum, assuming that the extragalactic absorption took place in the neutral, solar composition [11] ISM of their HG at redshift z. The GRB data points are from observations with the Swift XRT [4,10] of long GRBs (circles), off-center SHBs (triangles) and near-center SHBs (squares). The quasar data points (stars) are from observations with ASCA [12], Chandra [13] and XMM-Newton [7,8,14,9,15].

where $\sigma([1+z]E)$ is the absorption cross section of soft X-rays with energy $[1+z]E$ per hydrogen atom in the host galaxy, assuming a neutral absorber with standard solar elemental abundances. Figure 1 shows the effective HI column densities of the host galaxies of GRBs with known redshift as measured with the Swift X-ray telescope [10,4], assuming the standard photospheric solar abundances compiled in [11] and those of radio loud quasars as measured with the X-ray telescopes aboard ASCA [12], Chandra [13] and XMM-Newton [14,9,15] satellites. The observed increase of the mean $N_{h,\mathrm{HG}}$ with z like $(1+z)^{2.4}$ is in stark contrast with its expected decrease with redshift due to the general decline of the mean metallicity with redshift in standard galaxy formation and stellar evolution theories and observed in Lyman-α and damped Lyman-α absorbers (see, *e.g.*, [16,17] and references therein). Moreover, the photoabsorption cross section above the oxygen K edge at $E=0.54\,\mathrm{keV}$ for a neutral absorber with a solar metallicity is well described by $\sigma([1+z]E)\approx\sigma(E)\,(1+z)^{-2.4}$. Hence, the universal increase of $N_{h,\mathrm{HG}}$ with z like $(1+z)^{2.4}$ at large z in both GRB and quasar hosts simply reflects the fact that the observed extragalactic opacity for $z>2$ tends to an asymptotic value independent of z for GRBs and quasars as shown in figs. 2 and 3. In order to produce the observed

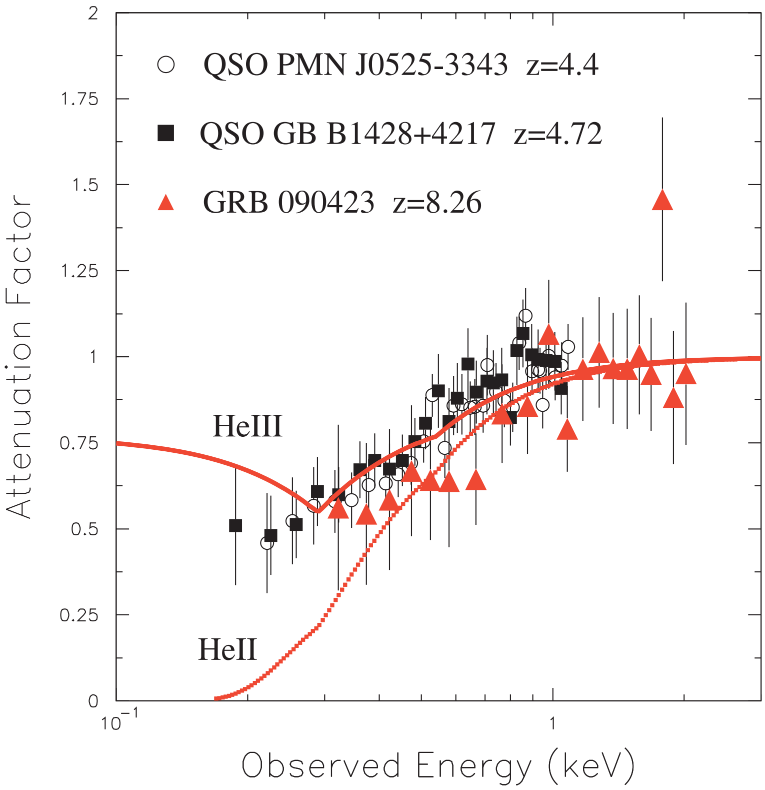

Fig. 2. – Comparison between the extragalactic attenuation of soft X-rays, $\exp[-\tau_{\rm IGM}]$, from the high-redshift blazars PMN J0525-3343 at $z = 4.4$ (circles) and GB B1428+4217 (squares) at $z = 4.72$ [7,8] that was measured with XMM-Newton as a function of X-ray energy, and that measured with Swift XRT in GRB 090423 (triangles) at $z = 8.26$, the largest measured redshift of a GRB [26, 10], and the attenuation in the hot IGM of standard cosmology with the opacity given by eq. (2). At energy below 0.5 keV the IGM opacity depends strongly on the ionization state of helium. The upper line (HeIII) corresponds to a hot IGM where helium is fully ionized, while the lower line (HeII) represents a hot IGM where helium is singly ionized. The data show that the absorber is likely in between these two cases.

z-independent opacity at large z, either the metal column density of HGs of GRBs and quasars by some coincidence satisfies $N_{h,{\rm HG}}(z)\,(Z/Z_\odot) \propto 1/\sigma([1+z]E) \propto (1+z)^{2.4}$, or there is a simpler reason why the extragalactic opacity to soft X-rays along the line of sight to GRBs and quasars becomes independent of z at $z > 2$ and of the X-ray source(2).

3. – The soft X-ray opacity of the IGM

A natural origin of a universal, isotropic, and z-independent X-ray opacity that is observed in high-z GRBs and quasars is the intergalactic medium (IGM) of the

(2) We have not included radio quiet quasars in our analysis because their soft X-ray excess masks their soft X-ray absorption.

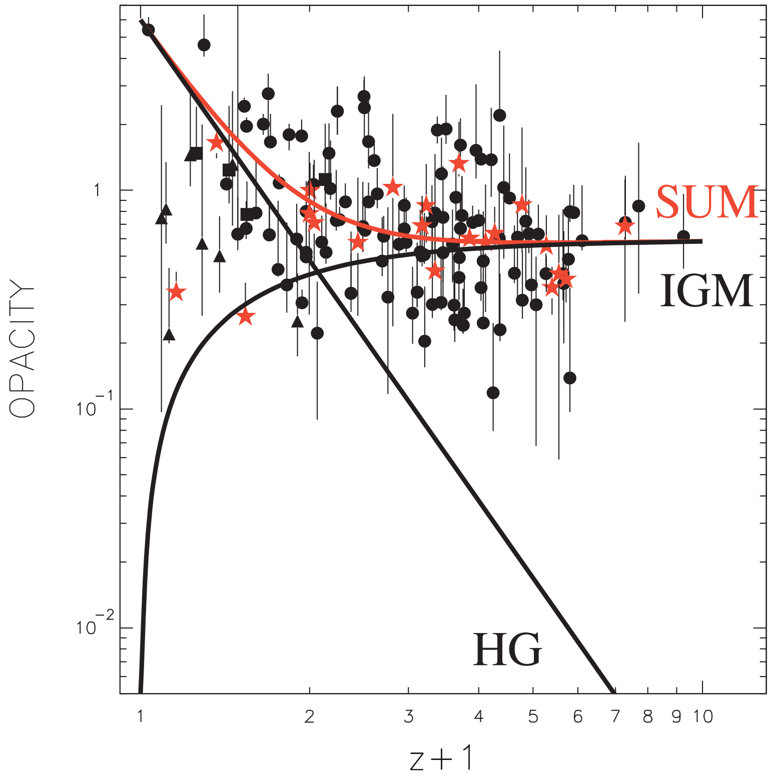

Fig. 3. – Comparison between the extragalactic opacity to soft X-rays at $E \sim 0.5\,\mathrm{keV}$ as a function of redshift measured from GRB and quasar observations and the estimated opacity due to absorption in a hot IGM that contains 90% of the cosmic baryons with completely ionized hydrogen and helium and partially ionized metals. Circles represent long GRBs, squares represent near-center SHBs and triangles represent far-off center SHBs. The GRB data points are from afterglow observations with the Swift XRT [10] and the quasar data points are from observations with ASCA [12], Chandra [13] and XMM-Newton [7, 8, 14, 9, 15]. The contribution to the extragalactic opacity from a host galaxy (HG) with $Nh = 10^{22}\,\mathrm{cm}^{-2}$ at redshift z is also shown.

standard cosmology that contains the bulk of the missing baryons(3). Using standard cosmology with a Hubble constant $H_0 = 71\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and a baryon mass fraction $\Omega_b = 0.045$ [19] of which $\sim 74\%$ are hydrogen nuclei and only a very small fraction of it ($\sim 10\%$) resides in galaxies and galaxy groups and clusters [20], the mean density of hydrogen nuclei in the IGM is $n_h \approx 0.67\,\Omega_b\,(3\,H_0^2/8\,\pi\,G\,m_p)\,(1+z)^3$, and the opacity of such an IGM to soft X-rays emitted at redshift z with locally observed energy E is given by

$$\tau_{\mathrm{IGM}}(E,z) \approx 2.21 \times 10^{21}\,\mathrm{cm}^{-2} \int_0^z \frac{\sigma(E,z')\,(Z/Z_\odot)\,(1+z')^3 \mathrm{d}z'}{(1+z')\,\sqrt{(1+z')^3\,\Omega_M + \Omega_\Lambda}}\,, \tag{2}$$

(3) The baryon mass fraction in the universe that was inferred from Big Bang Nucleosynthesis [18] and from the angular spectrum of cosmic microwave background radiation [19] is $\Omega_b \approx 0.045$. Only 10% of these baryons reside in galaxies and galaxy clusters [20], while the remaining 90% presumably are still in the IGM in the form of a hot gas whose hydrogen and helium are fully ionized.

where $\Omega_M = 0.27$ and $\Omega_\Lambda = 0.73$ [19]. Equation (2) predicts a saturation of τ for $z > 2$ since for $E < 10\,\mathrm{keV}$ the photo-absorption cross section $\sigma(E)$ scales roughly as $E^{-2.4}$, yielding for a redshifted absorber $\sigma(E,z) \sim \sigma(E)(1+z)^{-2.4}$, and $\mathrm{d}\tau/\mathrm{d}z$, which decreases with z more rapidly than $(1+z)^{-1.9}$. This saturation of $\tau(E,z)$ at $z > 2$ is very different from the increase of τ with z, expected and observed in the universe for Compton scattering and line absorption. It is, however, in good agreement with the observed saturation of the soft X-ray opacity inferred from spectral observations of large z GRBs and quasars, as shown in figs. 2 and 3.

Moreover, the mean high-z opacity $\tau(E)$ calculated for the IGM of the standard cosmological model using the best available priors agrees well with that inferred from the measured spectra of high-z GRBs and quasars: The observed metallicity in the intracluster medium (ICM) at low z is roughly $Z/Z_\odot \approx (0.54 \pm 0.10)\,(1+z)^{-1.25\pm0.25}$, *e.g.*, [24] and references therein. This mean metallicity of the ICM seems to describe well also the mean metallicity in damped Lyman-α (DLA) absorbers at $z < 4$ [16, 17], and is consistent [21] with that expected from the mean star formation rate in the universe as a function of z [22], although the spread in metallicity in DLAs [23, 16, 17], galaxies and galaxy clusters [24] at any given z is quite large, probably reflecting different star formation histories in different galaxies and protogalaxies. Assuming a mean IGM metallicity identical to that of the ICM [24] and adopting the photoabsorption cross sections per ISM hydrogen of [25], after removing the contribution from neutral hydrogen and helium, which presumably are fully ionized in the hot IGM, the IGM opacity to X-rays from large z GRBs and quasars at energy above the carbon edge ($E > 0.29\,\mathrm{keV}$) tends to

$$(3)\quad \tau_{\mathrm{IGM}}(E) \approx 0.49\,(0.54\,\mathrm{keV}/E)^{2.4} - 0.\,((0.26\,\mathrm{keV}/E)^{2.4} - 1)\Theta[(0.54\,\mathrm{keV}/E) - 1],$$

where $\Theta(x) = 0$ if $x < 0$ and $\Theta(x) = 1$ if $x > 0$ and $E = 0.54\,\mathrm{keV}$ is the oxygen edge. The approach to this asymptotic behaviour of the opacity at large z is well approximated by $\tau(E,z) = \tau(E)\,(1 - (1+z)^{2.15})$. Below $0.5\,\mathrm{keV}$ the IGM opacity becomes strongly dependent on the ionization state of helium. The above estimates are valid for a uniform IGM. However, for a clumpy IGM, the observed opacity can deviate significantly from its mean asymptotic value.

4. – Comparison between theory and observations

The intrinsic opacity of the hosts of GRBs and quasars as given by eq. (1) with $N_{Z,\mathrm{HG}}(z) = (Z_{\mathrm{HG}}/Z_\odot)\,Nh_{\mathrm{HG}}(0)$ and $\langle Z_{\mathrm{HG}}/Z_\odot\rangle \sim (1+z)^{-1.25}$, decreases with increasing z like $\tau_{\mathrm{HG}}(E,z) = (1+z)^{-3.65}\,\tau_{\mathrm{HG}}(E,0)$. Hence, its mean contribution to the extragalactic opacity becomes negligible at large z. Consequently, the opacity towards high-z GRBs and quasars is dominated by the IGM opacity, which is isotropic, independent of source and redshift and uncorrelated to the UVO absorption in the host. This is demonstrated in fig. 2 where we compare the soft X-ray attenuation of the hot IGM which follows from eq. (2) and the attenuation inferred from observations of the high-redshift blazars PMN J0525-3343 at $z = 4.4$ and GB B1428+4217 at $z = 4.72$ [7, 8] with XMM-Newton and of GRB 090423 [26, 10] at a record redshift $z = 8.26$ with the Swift XRT. These extragalactic opacities were obtained after subtraction of the Galactic absorption using the Galactic HI column densities of [27] and the ISM cross section per HI atom of [25]([4]). The complex low-energy behaviour of the attenuation in the IGM is caused by the dependence of the photoabsorption cross sections on the ionization state of the most abundant elements in the hot IGM. It has a behaviour much different than that of the attenuation in the neutral ISM in our galaxy and the host galaxy. This is demonstrated in fig. 2 where we show the expected opacity of a hot IGM where He is stripped of its two electrons (HeIII) and a warm IGM where He retains one of its two atomic electrons (HeII).

In fig. 3 we compare our estimate of the mean extragalactic opacity to soft X-rays, $\tau(E,z) = \tau_{\rm HG}(E,z) + \tau_{\rm IGM}(E,z)$, as a function of z at $E = 0.5\,{\rm keV}$ as given by eqs. (2) and (1) and the opacity inferred from observations of GRBs and radio loud quasars (RLQs) with a good S/N ratio. The contribution from a host galaxy with an arbitrarily chosen large column density $N_{h,\rm HG} = 10^{22}\,{\rm cm}^{-2}$ as a function of redshift z is also shown in fig. 3. The observations include all Swift/XRT PC observations of GRBs with known redshift when spectral variability is minimal [10,4], observations with ASCA [12] of relatively low-z RLQs (due to relatively low sensitivity and limited soft X-rays bandpass data) and observations of high-z RLQs with Chandra [13] and with XMM-Newton [7, 8, 14, 9, 15] of half a dozen high-z quasars with a relatively good S/N ratio. Only high latitude observations ($N_{h,\rm Gal} < 10^{21}\,{\rm cm}^{-2}$ where the absorptin is not dominated by the Galactic absorption) were included. Figures 2 and 3 clearly show the general trend towards an asymptotic opacity (isotropic, independent of z and the X-ray source) at large z, consistent with that expected for a diffused IGM of standard cosmology.

Figure 3 also shows a large spread in the extragalactic opacity measured in low-redshift GRBs. Such a spread is expected from the variety of host galaxies and of source locations, source environments and sightlines within them. This spread in short hard bursts (SHBs) is also shown in fig. 3. Most of these SHBs have a very small z where the IGM opacity is quite small compared to the intrinsic opacity in the host galaxy. Consequently, one expects the opacities of far-off-center SHBs to be quite small while those of near-center SHBs to be much larger and similar to those of long GRBs whose massive star progenitors are also found mainly near the center of the host galaxy. These trends are clearly seen in fig. 3.

Part of the observed spread at all redshifts results from the approximate nature of the modelling of the intrinsic spectra of GRBs, and from the approximate knowledge of the Galactic HI column density and metallicity along their sightlines. As expected, at large z, where the contribution of the HG becomes negligible, the spread seems to become smaller and the theory seems to describe well the mean value of the observed opacities. A clumpy IGM at low redshifts, whence most of the IGM opacity comes, may also contribute significantly to the spread.

Figure 3 also indicates that the extragalactic opacities to soft X-rays inferred from RLQs have a spread smaller than that of GRBs. It may be due to a much higher photon statistics and lesser temporal variability during their measurements, or to the much smaller not necessarily complete sample.

5. – Conclusion

The extragalactic opacity to soft X-rays from GRBs and quasars at small redshifts is dominated by absorption in their host galaxy. However, the extragalactic opacity to

([4]) The ISM metallicity adopted by [25] agrees well with the updated solar metallicity compiled in [28], which is smaller by a factor ~ 1.62 than that compiled in [11].

soft X-rays from high-z GRBs and quasars probably is dominated by absorption in the IGM at $z \leq 2$. Such an opacity is isotropic, independent of redshift beyond $z \approx 2$ and of source and not related or correlated to the UV absorption in the host galaxy. It yields a discrepant column density of the host, if it is erroneously assumed to be associated with it. The low-energy X-ray attenuation in the hot ionized IGM is different from that of the mostly neutral ISM in our Galaxy and in the host galaxy of the source. In particular, it seems to confirm [29] that the IGM of the local universe contains practically all the currently missing baryons implied by big bang nucleosynthesis [18], the observed angular power spectrum of the cosmic microwave background (CMB) radiation [19] and the Thomson opacity inferred from its polarization [19], but only $\sim 10\%$ are present in the galaxies, galaxy clusters and UVO absorbers in the local universe [20]. Soft X-ray spectra of very luminous high-z blazars with a large S/N ratio can provide more stringent tests of the IGM origin of the extragalactic opacity to soft X-rays from high-z quasars and GRBs. They may also help determine the mean metallicity and the clumpiness of the ionized IGM.

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