The Missing Cosmic Baryons Found ?

Arnon Dar

Gamma Ray Bursts Shed Light On the Missing Cosmic Baryons
E. Behar, S, Dado, A., Dar, S. Kaspi, A. Laor

The angular power spectrum of the CMB (WMAP):

$$\Omega = \Omega_\Lambda + \Omega_M \quad ; \quad \Omega_M = \Omega_{DM} + \Omega_b$$

$$\Omega_\Lambda = 0.734 \pm 0.029$$

$$\Omega_M = 0.266 \pm 0.026$$

$$\Omega_b = 0.045 \pm 0.003$$

Consistent values of Ω_b obtained from BBNS and LSSF

But only a fraction <0.2 of these cosmic baryons reside in visible stars and gas in galaxies and galaxy clusters

Where are the missing (dark) baryons ?

The missing baryons can be present as ionized gas in the IGM and not show up in light absorption !

$$n_b = \Omega_b \frac{3H_0^2}{8\pi G m_p} \approx 2.54 \cdot 10^{-7}\ \mathrm{cm}^{-3}$$

$$n_h \approx 0.75\, n_b \approx 1.91 \cdot 10^{-7}\ \mathrm{cm}^{-3}$$

After recombination, the universe was expected to be neutral, until the first objects in the universe started emitting light which reionized the surrounding IGM. Ionized hydrogen is highly transparent to light. However, as the photo-ionization cross section near the Lyman-alpha limit of neutral hydrogen is very high, even a small fraction of neutral hydrogen in the IGM suppresses the emission observed from distant sources and produces the `Gunn - Peterson (1965) trough'. This trough in the flux of a quasar at z = 6.28 discovered in 2001 , means that the fraction of neutral hydrogen must have been $\geq 10^{-3}$ at z = 6.28 and the universe was already in the final stages of reionization.

IGM:

$$N_b(z) \approx 1.57 \cdot 10^{21}\, \Omega_M^{-1}\, I(z)$$

$$I(z) = [\sqrt{(1+z)^3 \Omega_M + \Omega_\Lambda} - 1] \ \ \text{cm}^{-2}$$

$$N_b(z>1) \to 3.02 \cdot 10^{21} (1+z)^{3/2} \ \text{cm}^{-2}$$

$$\text{tau}(\lambda_{\text{obs}}, z_s) = \int_{z_0}^{z_s} n_h(z)\, \sigma[\lambda_{\text{obs}}/(1+z)]\, dz$$

$$\sigma[\lambda] \sim 7 \cdot 10^{-18} \ [\lambda/\lambda_o]^3 \ \text{cm}^{-2}; \quad \lambda \le \lambda_o = 912 \ \text{Å}$$

$$\sigma[\lambda] \sim 0 \qquad ; \quad \lambda > \lambda_o = 912 \ \text{Å}$$

$$\text{If } n_h \approx n_p \approx 1.91 \cdot 10^{-7} (1+z)^3 \ \text{cm}^{-3} \ \ \text{(non ionized IGM)}$$

$$\text{tau}(\lambda_{\text{obs}}, z_s) \approx 17150 \ \frac{2}{3\ \Omega_M} \sqrt{(1+z)^3 \Omega_M + \Omega_\Lambda} \ \Big|_{z_0}^{z_s}$$

$$z_0 = 0 \ \text{if } \lambda_{\text{obs}} \le \lambda_0; \quad (1+z_0) = \lambda_{\text{obs}}/\lambda_0 \quad \text{if } \lambda_{\text{obs}} \ge \lambda_0$$

Evidence for Reionization at z ~ 6: Detection of a Gunn-Peterson Trough in a z=6.28 Quasar

Robert H. Becker et al.
Astron.J. 122 (2001) 2850

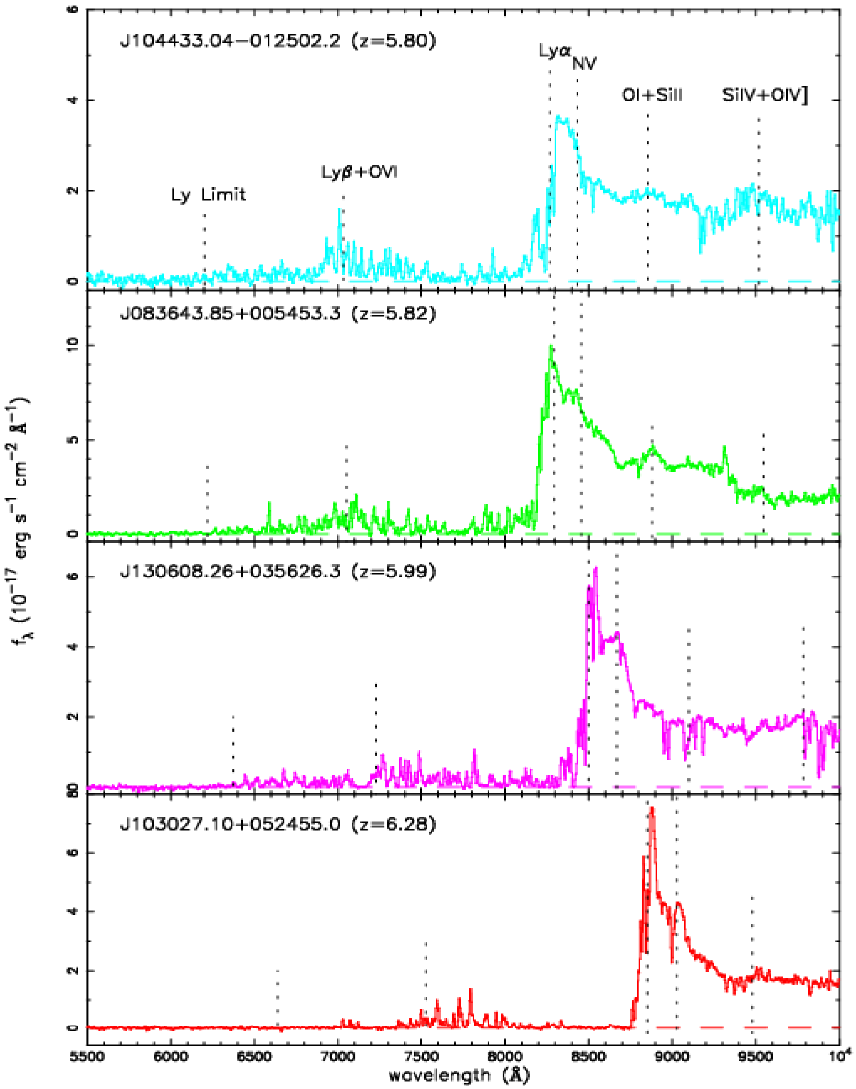


FIG. 1.— Optical spectra of $z \gtrsim 5.8$ quasars observed with Keck/ESI, in the observed frame. The spectra have been smoothed to 4Å pixel^{-1}, and have been normalized to the observed z band flux. The spectrum of SDSS1044–0125 has been taken from Fan et al. (2000). In each spectrum, the expected wavelengths of prominent emission lines, as well as the Lyman limit, are indicated by the dashed lines.

Hot ionized gas emits bremmstrahlung with a power per unit volume:

$$P_{brem} \propto Z_i^3 n_e \, n_i \sqrt{T}$$

The density of the hot ionized gas in the ISM in elliptical galaxies and in the ICM of galaxy clusters, where $10^{-1} < n_p < 10^{-3}\ \mathrm{cm}^{-3}$, is visible in X-rays, but the current cosmic density of the missing baryons is:

$$n_b = \Omega_b \frac{3 H_0^2}{8 \pi G m_p} \approx 2.54 \cdot 10^{-7}\ \mathrm{cm}^{-3}$$

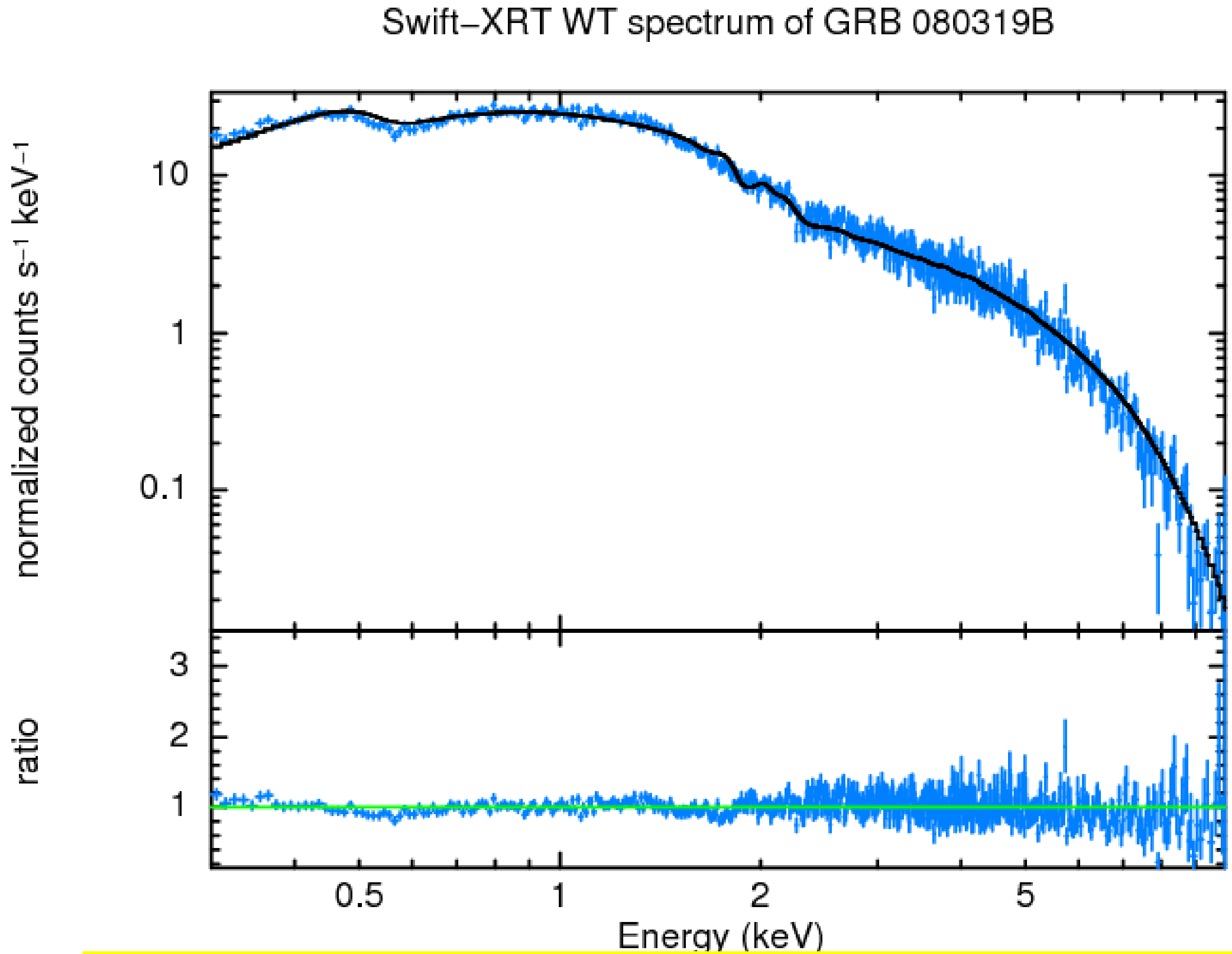
$$(\text{for } H_0 = 71.0 \pm 2.5\ \mathrm{km \cdot s^{-1} \cdot Mpc^{-1}})$$

too low a density to show up in X-rays!

Although hydrogen in the IGM is ionized, the electrons in the inner-most shells in the metals are not ionized!

These metals are soft X-ray absorbers and should be looked for in the absorbed soft X-ray spectrum from very luminous high-z X-ray sources, such as GRBs.

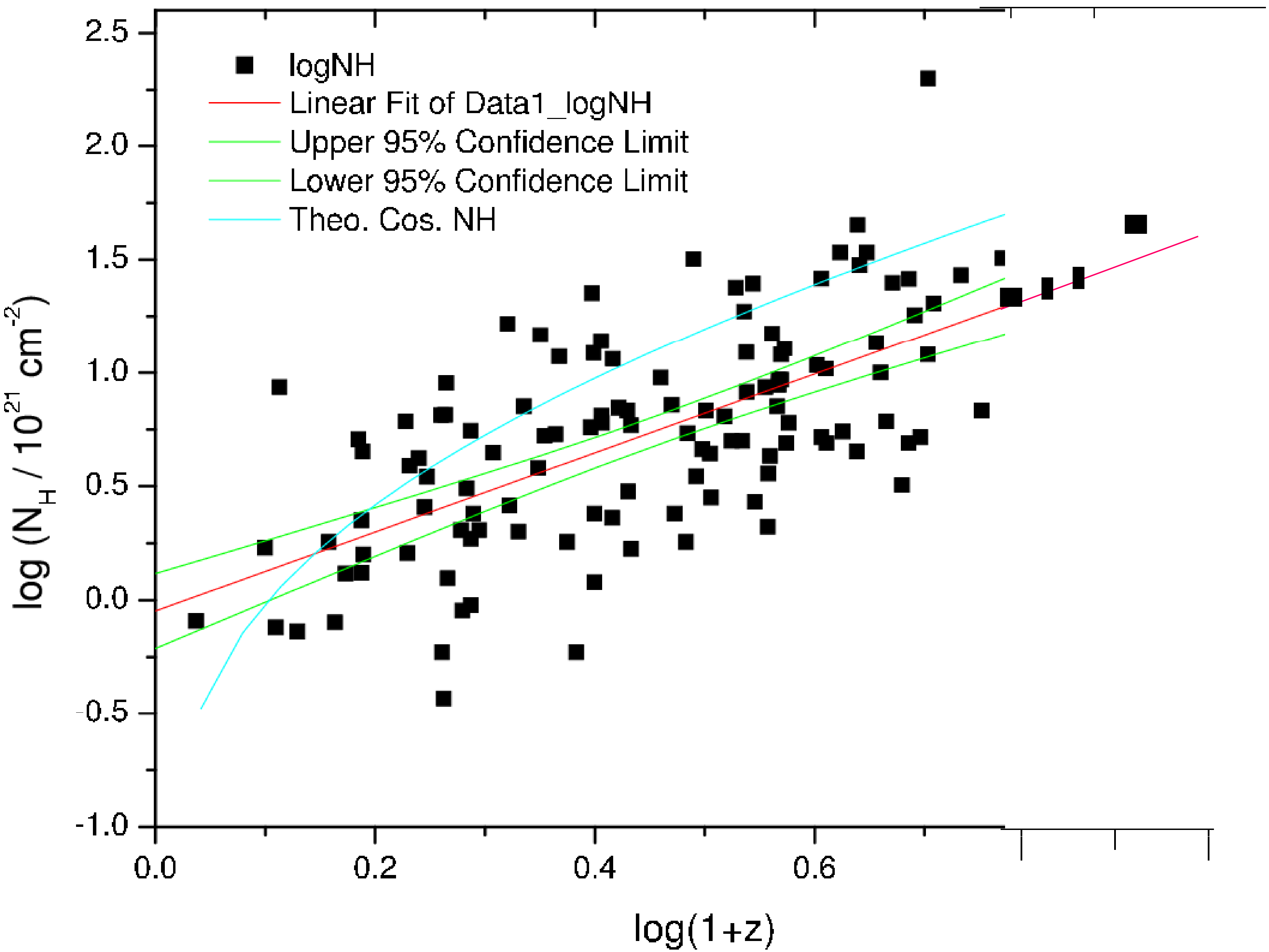
Metal density can be converted to hydrogen density provided the metalicity is known as function of z.



Measured spectrum fitted with an absorb PL:

$$\mathrm{dn_x / dE} \propto e^{\mathrm{-tau(E)}} E^{-\Gamma} \; ; \quad \mathrm{tau(E)} = \mathrm{X_Z} \cdot \mathrm{Nh(z)} \cdot \sigma_Z [(1+z)E]$$

Swift reports Nh(z) assuming solar metalicity and z=z(host)


logNH
Linear Fit of Data1_logNH
Upper 95% Confidence Limit
Lower 95% Confidence Limit
Theo. Cos. NH
log (N_H / 10^21 cm^-2)
log(1+z)
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
0.0
0.2
0.4
0.6

Soft X-ray Opacity :Host Galaxy:

$$\mathrm{tau}(E,z) = X_Z \cdot Nh(z) \cdot \sigma_Z[(1+z)E]$$

Star formation rate: $X_Z \propto (1+z)^{-3/2}$

Structure Formation Theory: $Nh(z) \propto (1+z)^2$;

Quantum Mechanics: $\sigma_Z[(1+z)E] \approx (1+z)^{-2.4} \sigma_{Zsolar}(E)$

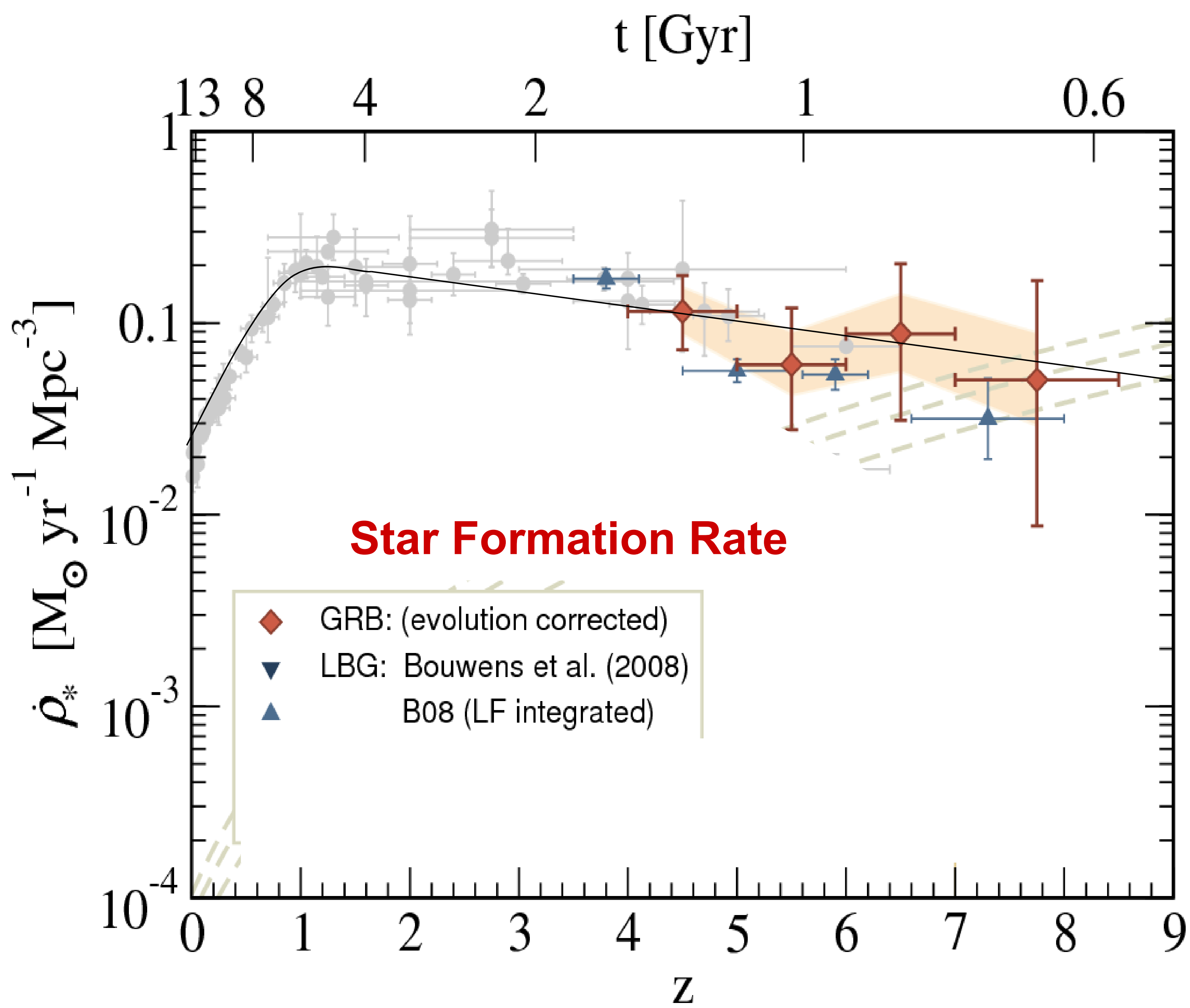
$$\mathrm{tau}(E,z) \approx \mathrm{tau}(E,0) \cdot (1+z)^{-1.9}$$

Soft X-ray Opacity of the IGM :

$$\mathrm{tau}(E,z) = 2.36 \cdot 10^{21}\, \sigma(E) \cdot I(z) \;\rightarrow \mathrm{tau}(E)$$

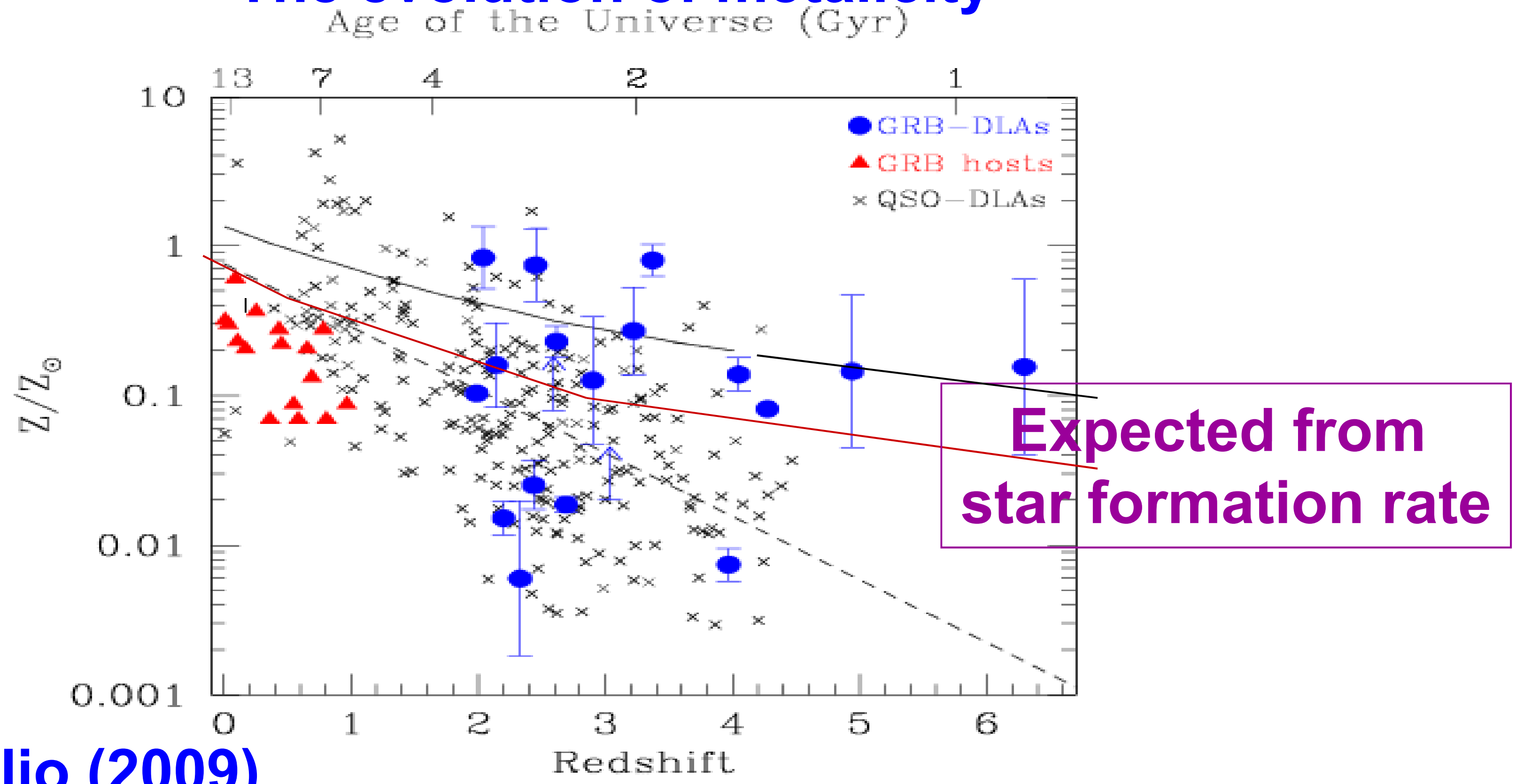
$$I(z) = \int_0^z X_{ICM}(z) dz / \, (1+z)^{0.4} \sqrt{(1+z)^3 \Omega_M + \Omega_\Lambda} \rightarrow \mathrm{const.}$$

$$X_{ICM}(z) \approx (0.3 \pm 0.1) \cdot X_Z(\mathrm{solar})(1+z)^{-3/2}$$



t [Gyr]
13 8 4 2 1 0.6
$\dot{\rho}_*$ [$M_\odot$ yr^{-1} Mpc^{-3}]
1
0.1
10^{-2}
10^{-3}
10^{-4}
0 1 2 3 4 5 6 7 8 9
z
Star Formation Rate
GRB: (evolution corrected)
LBG: Bouwens et al. (2008)
B08 (LF integrated)

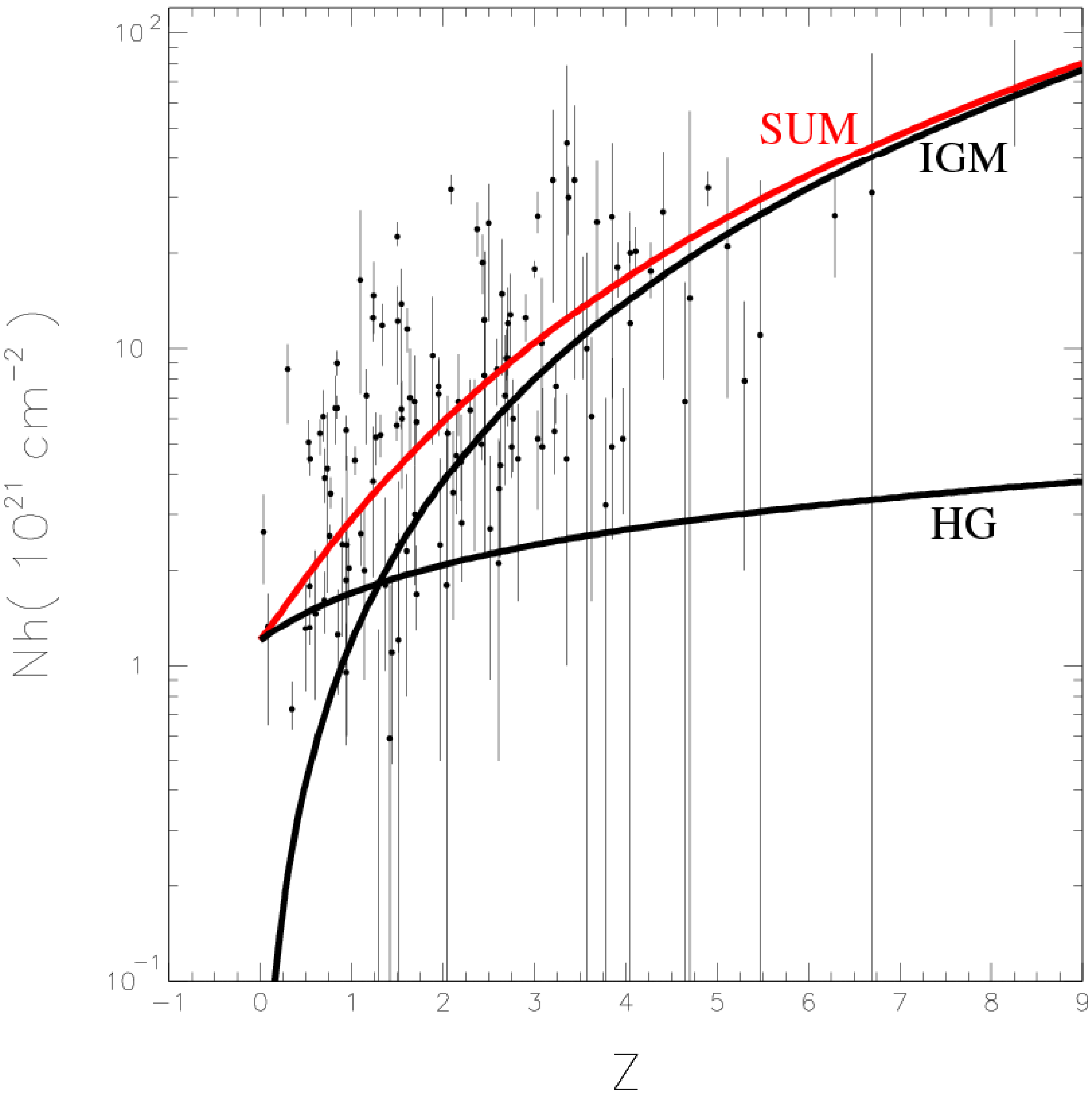
The evolution of metalicity



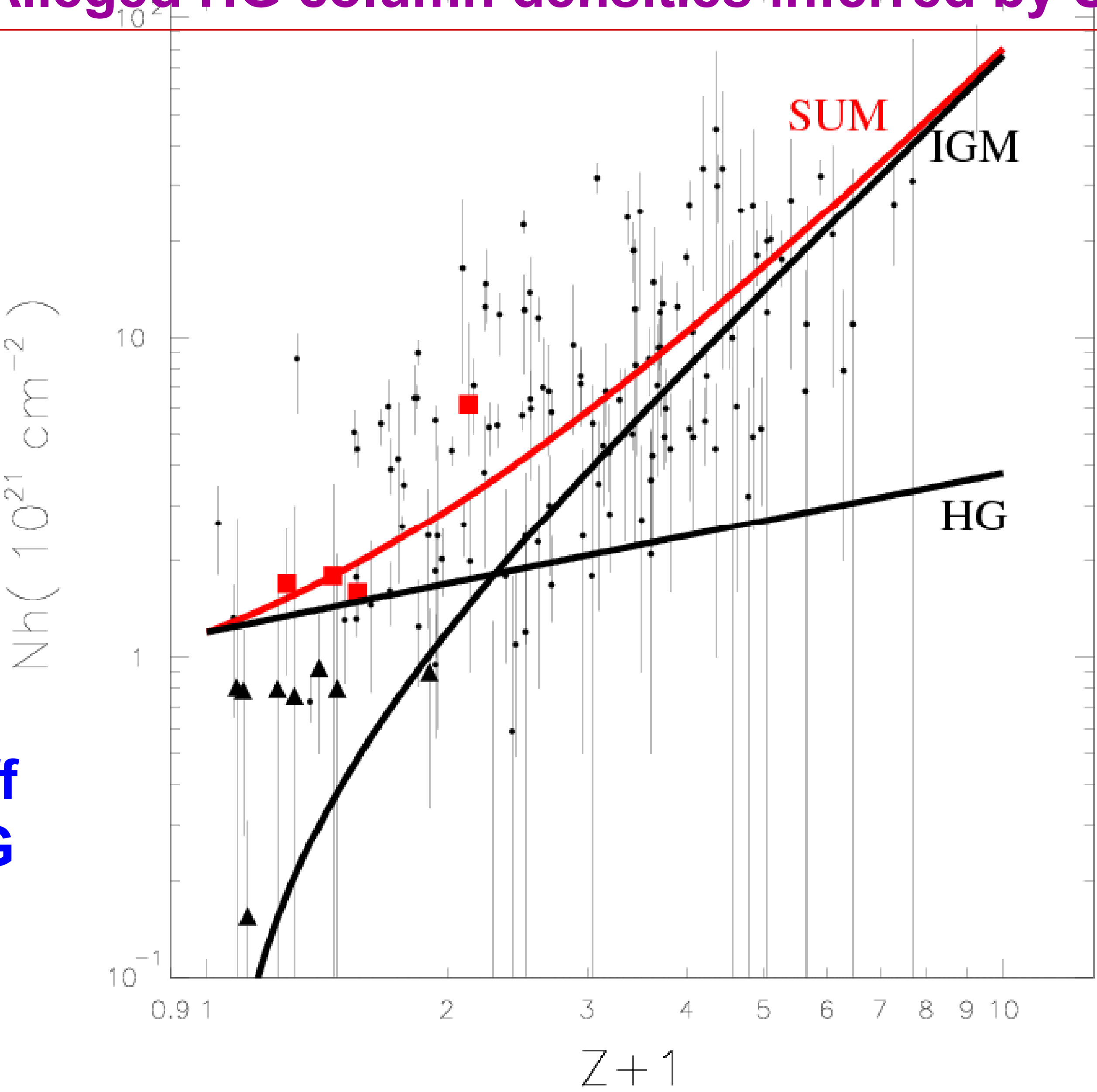
Savaglio (2009)

Figure 2. Redshift evolution of the metallicity relative to solar values, for 17 GRB-DLAs at $z > 2$, 16 GRB hosts at $z < 1$ and $\sim$ 250 QSO-DLAs in the interval $0 < z < 4.4$. Error bars are not available for all GRB-DLAs. Errors for GRB hosts are not estimated. Errors for QSO-DLAs are generally smaller than 0.2 dex. The dashed line is the best-fit linear correlation for QSO-DLAs. The solid line is the mean metallicity predicted by semi-analytic models for galaxy formation (Somerville et al. 2001). The GRB-DLAs metallicity in $2 < z < 4.5$ is on average 2.5 times higher than the average value in QSO-DLAs in the same redshift interval.

Alleged HG column densities inferred by Swift from GRB AGs



Alleged HG column densities inferred by Swift



■ SHB near center of HG

▲ SHB far off center of HG

UV and X-Ray Estimated Column Densities in HG of GRBs
From Watson et al. ApJ, 660, L101 (2007)
and Patel **et al. arXiv:1002.4663**

GRB	z	Log Nh[z] UV	Log Nh[z] Soft X
050319	3.24	20.9	21.8
050401	2.90	22.6	22.3
050505	4.27	22.1	22.1
050904	6.30	21.3	22.6
060210	3.91	21.7	22.3
060522	5.11	20.5	22.2
060607A	3.08	<19.5	21.7
060714	2.71	21.8	22.0
060926	3.21	22.7	22.4
089913	6.73	<20.0	22.5

Why Nh(UV) is much smaller than Nh(X) ?

The beamed radiation from GRBs can ionize most of the hydrogen within its beaming cone in the HG but only a small fraction of the metals:

$$R_Z^2 \approx \frac{\mathrm{Eiso}}{12\,\pi\,(1+z)\,\mathrm{Ep}} \int \frac{\sigma_i(Z)}{E}\,dE$$

$$\sigma_i(Z) \propto 7 \cdot 10^{-18} / Z_{\mathrm{eff}}^2 \ \mathrm{cm}^{-2}$$

For ordinary GRBs, the ionization range is:

$$R_H \sim 100\ \mathrm{pc}; \quad R_O \sim 12\ \mathrm{pc}$$

(There are enough photons unless the GRB takes place in a large molecular cloud)

Nh(UV) << Nh(X) because H is highly ionized (non absorbing UV) both in the HG along the sightline to the GRB and in the IGM while the metals are neither fully ionized by the GRB in the HG nor in the IGM.

Conclusions

The absorption of soft X-rays from GRBs, the brightest sources in the universe, indicates that most of the baryonic matter synthesized in the Big Bang is in the IGM.

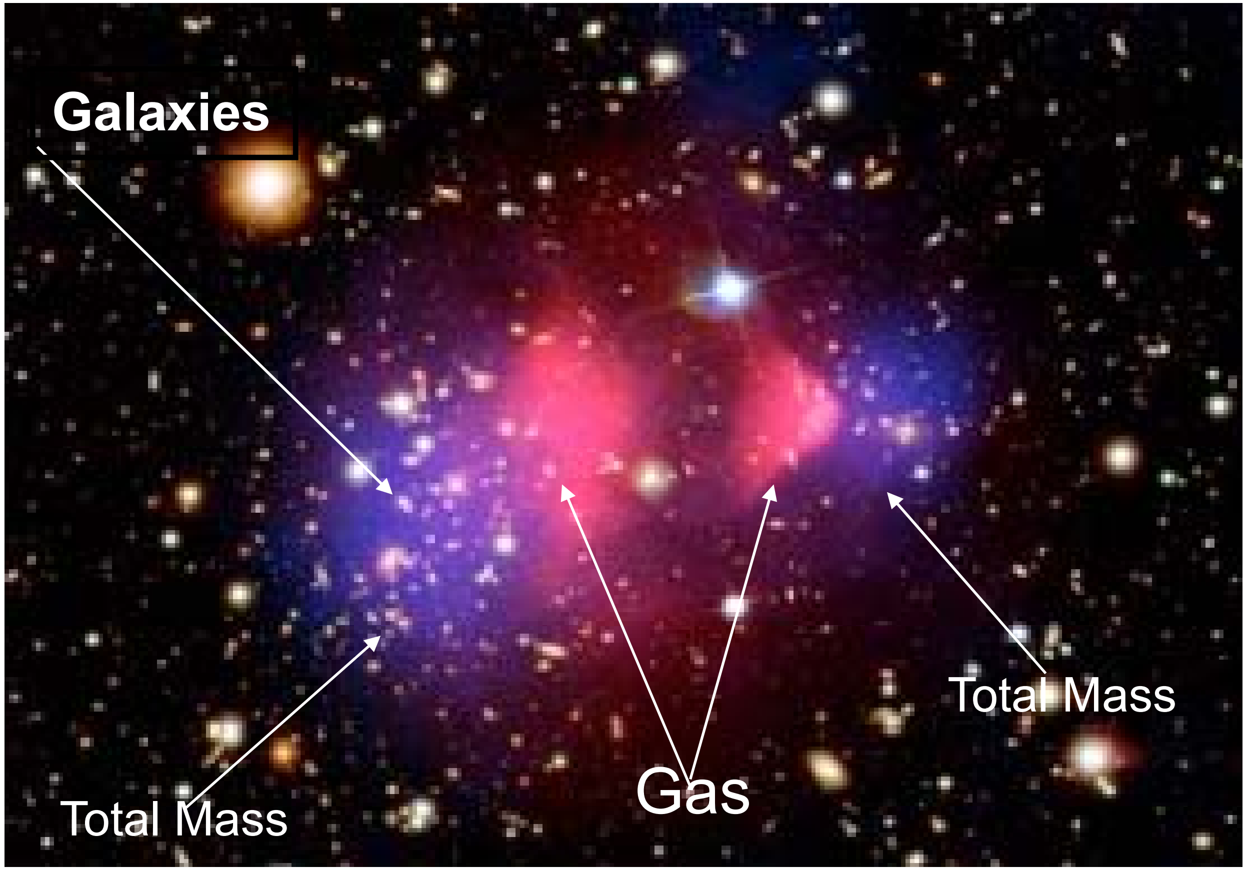
~75% of the baryons in the IGM are ionized hydrogen nuclei and ~25% are in He4 nuclei. Only a small fraction, <0.01%, are in metals not completely stripped-off their atomic electrons and are `visible' in soft X-rays absorption. Most of the absorption takes place relatively nearby (z<1).

The composition of the ICM in hot galaxy clusters where all the ionized gas is visible in X-ray emission, represents well the IGM composition.

It seems that Swift observations of GRBs have found the `missing cosmological baryons'.

Dark Matter or Modified Gravity (e.g. MOND) ?

Evidence for DM from two Cosmic Supercolliders
the "Bullet Cluster" 1E0657-56 and MACSJ0025-1222



$\sigma/m < 0.7\ cm2g{-}1 = 1.3barn/GeV$ (Randall et al.2008)

Galaxies observed Optically
Hot Gas Observed by X-ray Emission
Total Mass Mapped by Weak Gravitational Lensing

Maruša Bradač (UCSB)