Missing Baryons in the IGM

and their Correlation with Structures

Overview

- “Concordance Cosmology” and the number of baryons in the Universe.
- Baryon Budget at z>2: the Lyα Forest
- Baryon Budget at z<2: stars, ICM, cold-gas, residual Lyα-Forest
- The ‘Missing Baryons’ problem in the local Universe, and the WHIM
- The Warm-Phase of the WHIM in the FUV
- The OVI-BLA IGM and its galaxy environment

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The Standard Cosmological Model & the Number of Baryons at z>2

Standard Cosmological Model

FIVE-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE** OBSERVATIONS: COSMOLOGICAL INTERPRETATION

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"By accurately measuring the statistical properties of the microwave background fluctuations, WMAP has helped establish a standard cosmology: a flat Λ cold dark matter (CDM) model composed of atoms, dark matter, and dark energy, with nearly scale-invariant adiabatic Gaussian fluctuations. With our most recent measurements, WMAP has measured the basic parameters of this cosmology to high precision…"

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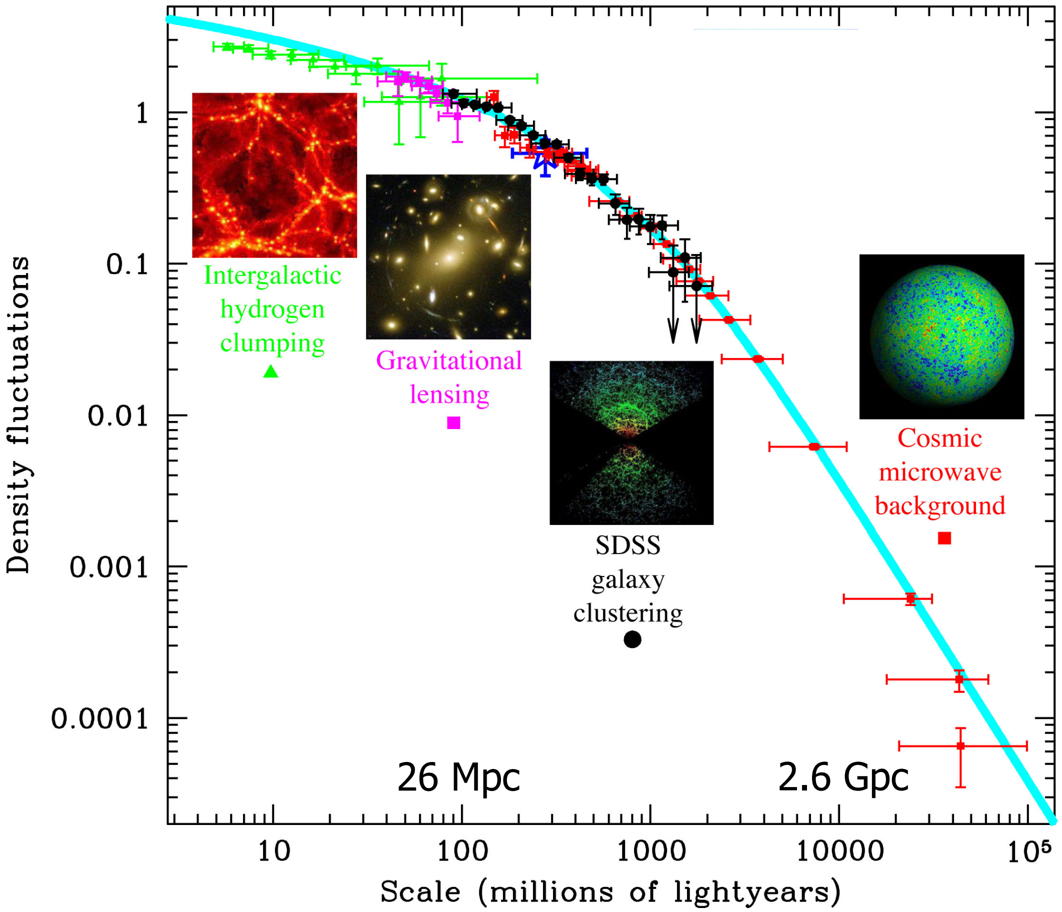
Table 1
Summary of the Cosmological Parameters of ΛCDM Model and the Corresponding 68% Intervals

Class	Parameter	*WMAP* 5 Year ML[a]	*WMAP*+BAO+SN ML	*WMAP* 5 Year Mean[b]	*WMAP*+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.268	2.262	2.273 ± 0.062	$2.267^{+0.058}_{-0.059}$
	$\Omega_c h^2$	0.1081	0.1138	0.1099 ± 0.0062	0.1131 ± 0.0034
	Ω_Λ	0.751	0.723	0.742 ± 0.030	0.726 ± 0.015
	n_s	0.961	0.962	$0.963^{+0.014}_{-0.015}$	0.960 ± 0.013
	τ	0.089	0.088	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0^{c})$	2.41×10^{-9}	2.46×10^{-9}	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.445 \pm 0.096) \times 10^{-9}$
Derived	σ_8	0.787	0.817	0.796 ± 0.036	0.812 ± 0.026
	H_0	$72.4\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	$70.2\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	$71.9^{+2.6}_{-2.7}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$	$70.5 \pm 1.3\ \mathrm{km\ s^{-}\ Mpc^{-}}$
	Ω_b	0.0432	0.0459	0.0441 ± 0.0030	0.0456 ± 0.0015
	Ω_c	0.206	0.231	0.214 ± 0.027	0.228 ± 0.013
	$\Omega_m h^2$	0.1308	0.1364	0.1326 ± 0.0063	$0.1358^{+0.0037}_{-0.0036}$
	z^{d}_{reion}	11.2	11.3	11.0 ± 1.4	10.9 ± 1.4
	t_0^{e}	13.69 Gyr	13.72 Gyr	13.69 ± 0.13 Gyr	13.72 ± 0.12 Gyr

Notes.
[a] Dunkley et al. (2009). "ML" refers to the Maximum Likelihood parameters.
[b] Dunkley et al. (2009). "Mean" refers to the mean of the posterior distribution of each parameter.
[c] $k_0 = 0.002\ \mathrm{Mpc}^{-1}$. $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ (Equation (15)).
[d] "Redshift of reionization," if the universe was reionized instantaneously from the neutral state to the fully ionized state at z_{reion}.
[e] The present-day age of the universe.

Concordance Cosmology

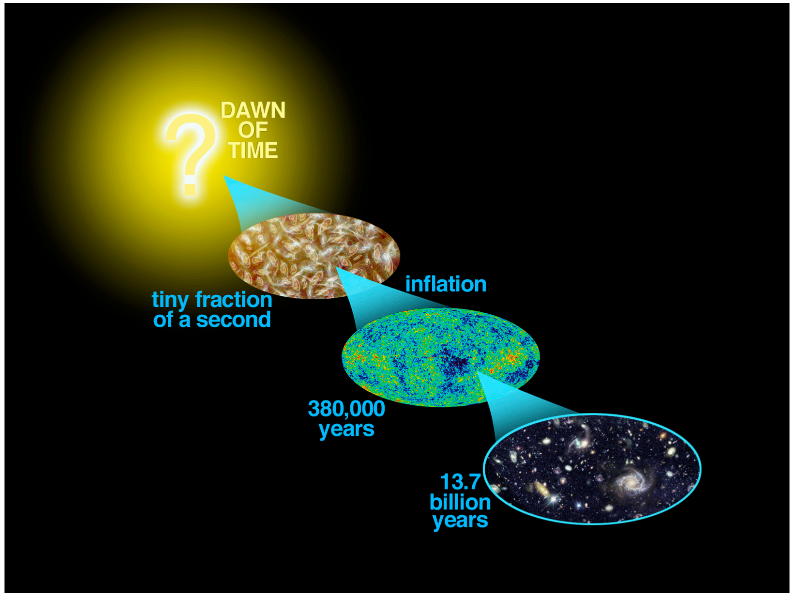


Λ-CDM: Flat Universe

$\Omega_\Lambda = 0.726$

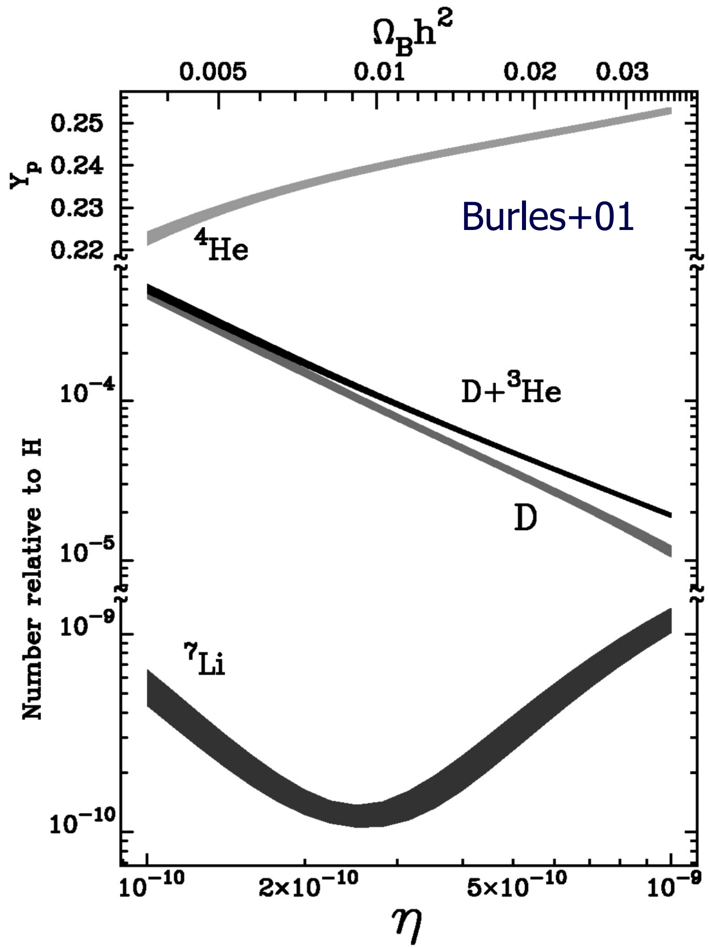
$\Omega_{DM} = 0.2276$

$\Omega_b = 0.0456$



Ω_b from Deuterium and Hydrogen Ratio

"It is well established that the light nuclei hydrogen (H), deuterium (D), 3He, 4He, and 7Li are all made during big bang nucleosynthesis. The relative primordial abundances created in the standard theory of big bang nucleosynthesis (SBBN) for these five nuclei depend on one parameter, the cosmological baryon-to-photon ratio, $\eta = n_b/n_\gamma$ (Kolb & Turner 1990). A measurement of the ratio of any two primordial abundances gives η. The three other primordial abundances are predicted once η is known and measurements of them test the theory." (Kirkman+03)



$$\Omega_b = \rho_b/\rho_c = \rho_b/(3H_0^2/8\pi G)$$

"Because its abundance depends strongly on the baryon density, and its subsequent chemical evolution is so simple (astrophysical processes only destroy D), deuterium can accurately peg the baryon density. Once determined, the baryon density allows the abundances of ^{3}He, ^{4}He, and ^{7}Li to be predicted. These predictions can be used to test the consistency of the big bang framework and to probe astrophysics." (Burles+01)

Ω_b from D/H in QSO Lyα-Forest

THE COSMOLOGICAL BARYON DENSITY FROM THE DEUTERIUM-TO-HYDROGEN RATIO IN QSO ABSORPTION SYSTEMS: D/H TOWARD Q1243+3047

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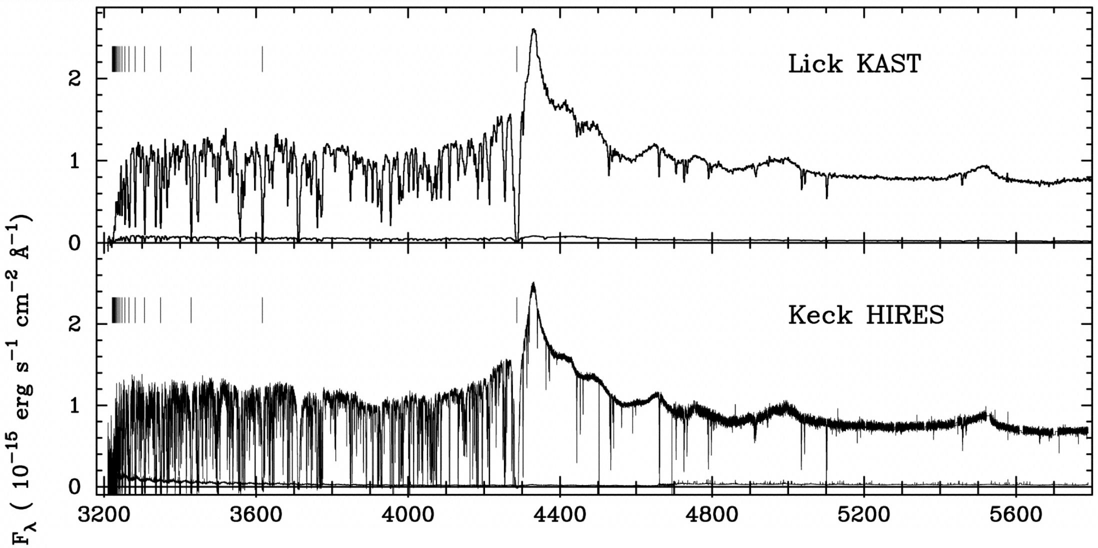


z_{em}=2.56

$z_{D/H}$=2.526

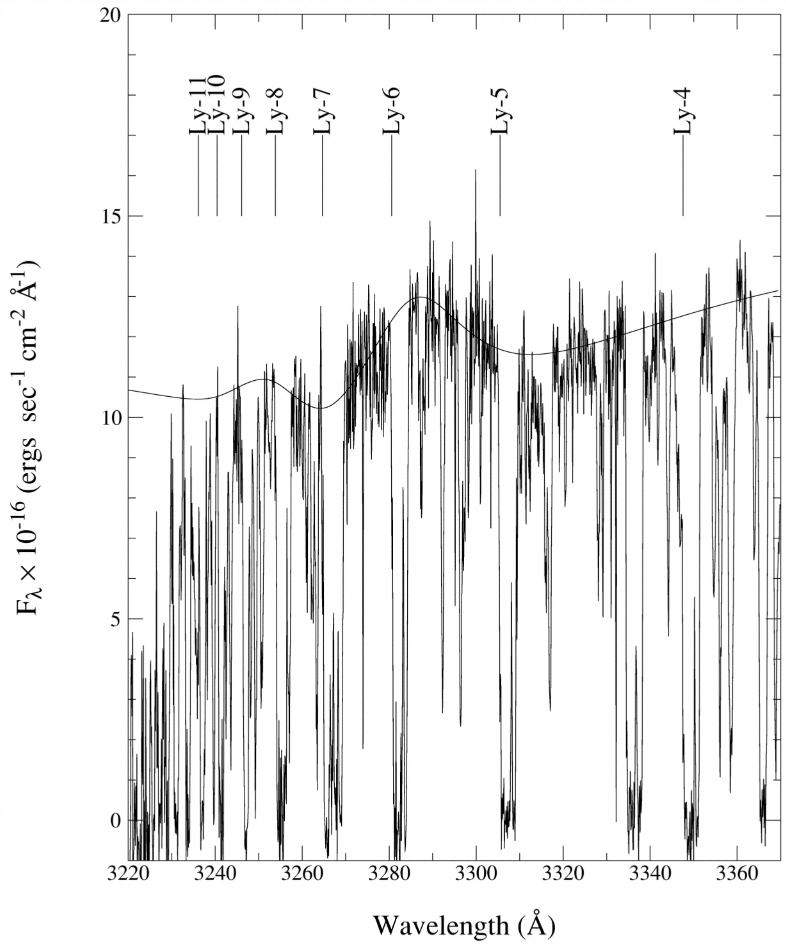
$$I_\nu = I_\nu^0 e^{-\tau\nu}$$

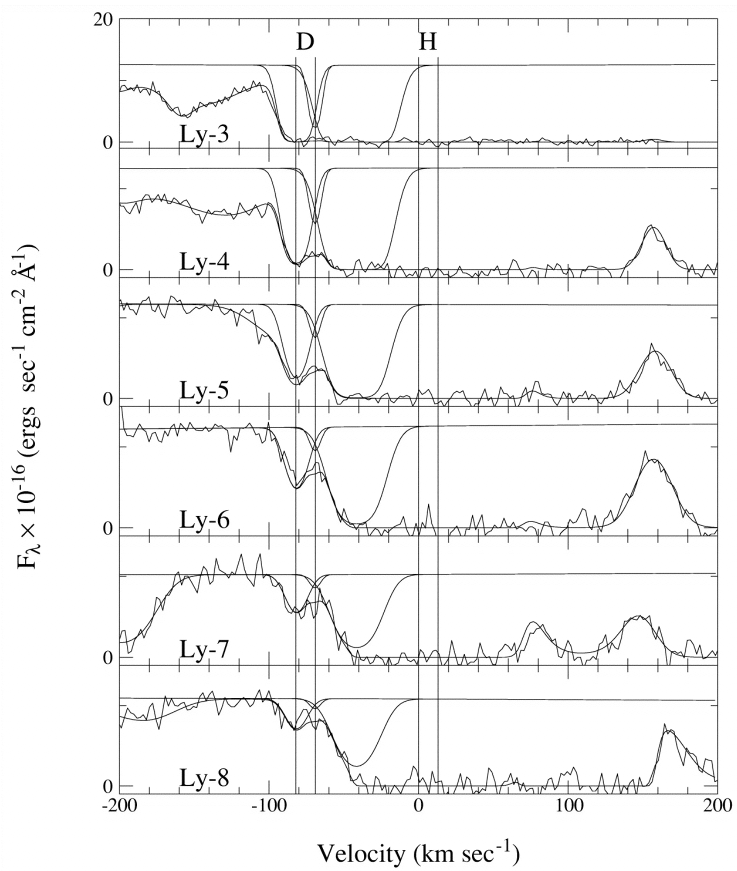
where: $$\tau_\nu = \int_0^L ds\alpha_\nu = n_l L \frac{\pi e^2}{mc} f_{lu}\Phi(\nu)$$

$$\Phi(v) = \frac{1}{\sqrt{\pi}\Delta v_D} H(a, u) , \qquad H(a, u) = \frac{a}{\pi}\int_{-\infty}^{+\infty} \frac{e^{-y^2} dy}{a^2 + (u-y)^2} .$$

And: $a = \Gamma/4\pi\Delta\nu_D$, $u = (\nu-\nu_0)/\Delta\nu_D$

D/H at z = 2.526 (Kirkman+03)





Sources of important systematics:

-the continuum level
-the Ly forest
-the velocity structure of the absorber
-contamination by absorption other than D.

Thermal vs Turbulence (Kirkman+03)

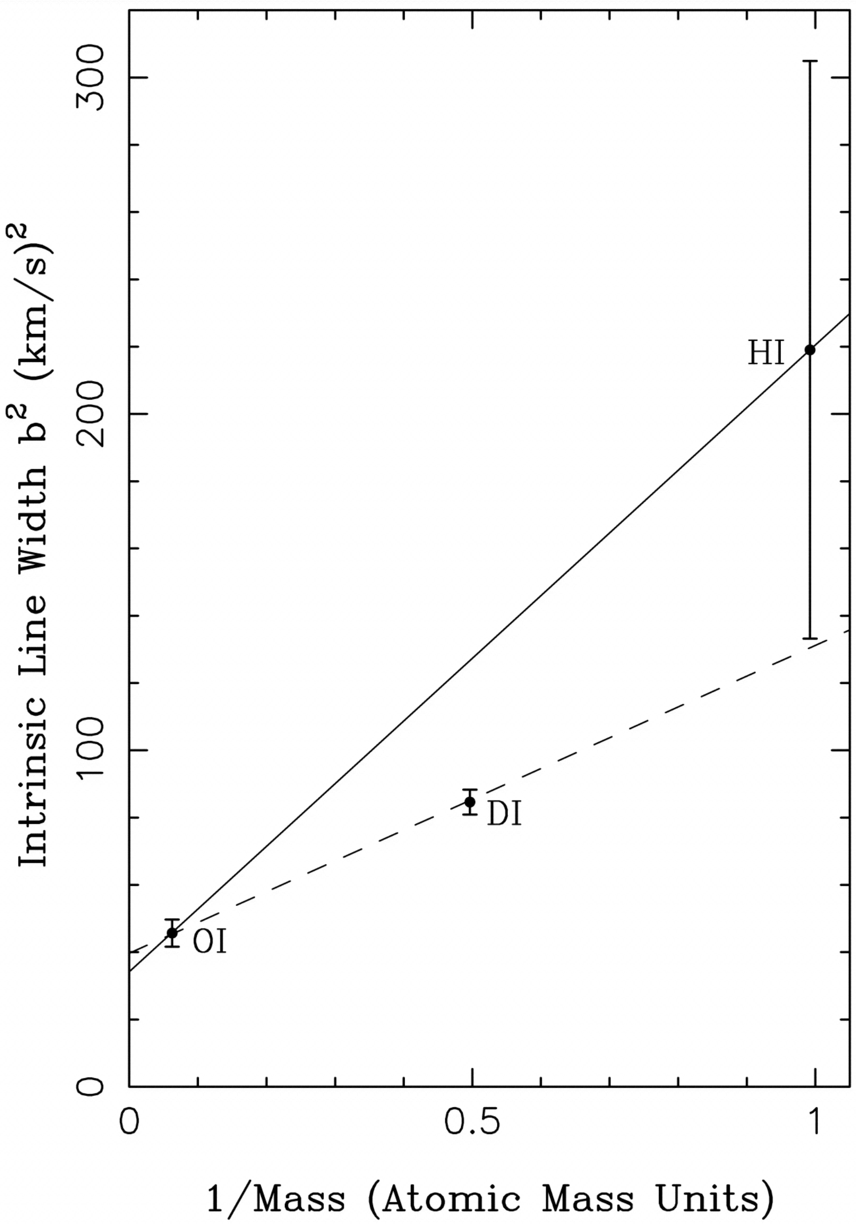
$$b = \sqrt{\frac{2kT}{m} + b_{\rm turb}^2}$$

Knowing b allows one to estimate N_{HI} and N_D

$$W_{X^i} = \int_0^\infty (1 - e^{-\tau_\nu}) d\nu \approx \int_0^\infty \tau_\nu d\nu + \frac{1}{2}\int_0^\infty \tau_\nu^2 + \ldots$$

$$\tau_\nu = N_{X^i} \frac{\pi e^2}{mc} f_{lu} \Phi(\nu)$$

$$\Rightarrow W_{X^i} \approx \frac{\pi e^2}{mc} f_{lu} N_{X^i} + \frac{1}{2}\left(\frac{\pi e^2}{mc} f_{lu} N_{X^i}\right)^2 \int_0^\infty \Phi^2(\nu) d\nu + \ldots$$

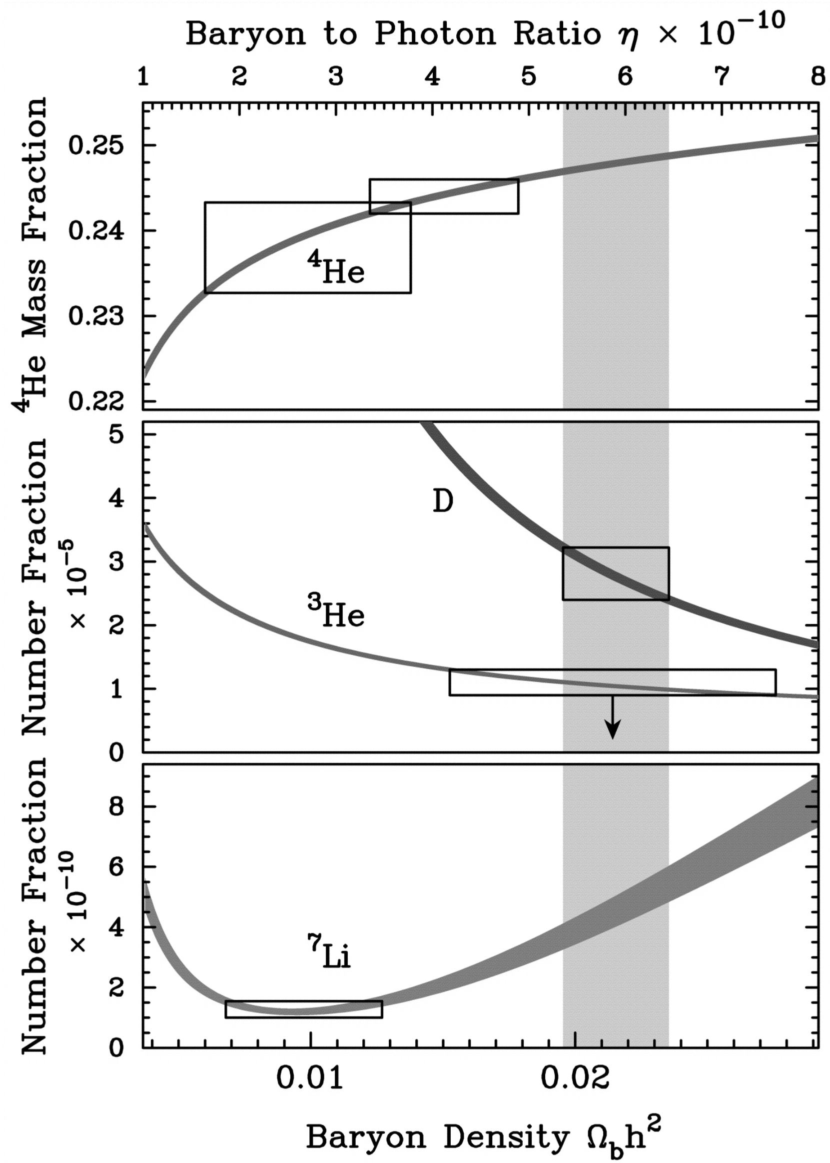


Ω_b from D/H

TABLE 7

RECENT ESTIMATES OF THE BARYON DENSITY

Method	$\Omega_b h^2$	Reference
BBN + D/H	0.0214 ± 0.002	This paper
CMB: *WMAP*....................	0.0224 ± 0.001	Spergel et al. 2003
CMB: BOOMERANG......	$0.021^{+0.003}_{-0.003}$	Netterfield et al. 2002
CMB: DASI......................	$0.022^{+0.004}_{-0.003}$	Pryke et al. 2002
CMB: MAXIMAI	0.033 ± 0.013 (95%)	Stompor et al. 2001
CMB: CBI	$0.022^{+0.15}_{-0.009}$	Sievers et al. 2002
Clusters + SN Ia	$0.019^{+0.007}_{-0.005}$	Steigman 2002



The Number of Baryons in the Lyα-Forest at z>2

The Observables:

Absorption Line Equivalent Widths:

→ Ion Column Densities: N_{ion}

Equivalent Width Ratios:

→ Ionization Balance: Γ, T, n_b

Equivalent Widths and Ion Column Densities

- Same-Ion Line ratios: direct check
- Curve of Growth technique:

$$W_{X^i} = \int_0^\infty (1 - e^{-\tau_\nu}) d\nu \approx \int_0^\infty \tau_\nu d\nu + \frac{1}{2} \int_0^\infty \tau_\nu^2 + \dots$$

$$\tau_\nu = N_{X^i} \frac{\pi e^2}{mc} f_{lu} \Phi(\nu)$$

$$\Rightarrow W_{X^i} \approx \frac{\pi e^2}{mc} f_{lu} N_{X^i} + \frac{1}{2} \left(\frac{\pi e^2}{mc} f_{lu} N_{X^i} \right)^2 \int_0^\infty \Phi^2(\nu) d\nu + \dots$$

Mass and Metal Content of the Forest

$$\Omega_b = \left(\frac{1}{\rho_c}\right)\left(\frac{\mu m_p \sum_i N_H^i}{d_{Tot}}\right)$$

$$N_H = N_{ion} \times A_{element}^{-1} \times \xi_{ion}^{-1}$$

The Lower Bound on the Number of Baryons at z>2
(See Rauch+98 for a Review)

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A LOWER BOUND ON THE COSMIC BARYON DENSITY

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ABSTRACT

We derive lower bounds on the cosmic baryon density from the requirement that the high-redshift intergalactic medium (IGM) contain enough neutral hydrogen to produce the observed Lyα absorption in quasar spectra. These analytic bounds follow from a key theoretical assumption—that absorbing structures are on average no more extended in redshift space than in real space—which is likely to hold in the gravitational instability picture of the Lyα forest, independently of the details of the cosmological model. The other ingredients that enter these bounds are an estimate of (or lower limit to) the intensity of the photoionizing UV background from quasars, a temperature $T \sim 10^4$ K for the "warm" photoionized IGM that produces most of the Lyα absorption, a value of the Hubble constant, and observational estimates of the mean Lyα flux decrement $\bar{D}$ or, for a more restrictive bound, the distribution function $P(\tau)$ of Lyα optical depths. With plausible estimates of the quasar UV background and $\bar{D}$, the mean decrement bound implies a baryon density parameter $\Omega_b \gtrsim 0.0125\ h^{-2}$, where $h \equiv H_0/(100\ \mathrm{km\ s^{-1}\ Mpc^{-1}})$. A recent observational determination of $P(\tau)$ implies that $\Omega_b \gtrsim 0.0125\ h^{-2}$ even for a conservative estimate of the quasar UV background, and $\Omega_b \gtrsim 0.018\ h^{-2}$ for a more reasonable estimate. These bounds are consistent with recent *low* estimates of the primordial deuterium-to-hydrogen ratio $(D/H)_P$, which imply that $\Omega_b \approx 0.025\ h^{-2}$ when combined with standard big bang nucleosynthesis. Since the bounds account only for baryons in the warm IGM, their combination with the nucleosynthesis constraint implies that most of the baryons in the universe at $z \sim 2$–4 were distributed in diffuse intergalactic gas rather than in stars or compact dark objects. The $P(\tau)$ bound on Ω_b is incompatible with some recent high estimates of $(D/H)_P$, unless one drops the assumptions of standard big bang nucleosynthesis or abandons the idea that Lyα forest lines originate in the smooth, large-scale structures of photoionized gas that arise in gravitational instability theories.

Subject headings: cosmology: theory — elementary particles — intergalactic medium —

Ω_b from Flux Decrement & P(τ)

2. A LOWER BOUND FROM THE MEAN FLUX DECREMENT

A uniform IGM with neutral hydrogen density $n_{\mathrm{H\,I}}$ produces a Lyα optical depth

$$\tau_u = \frac{\pi e^2}{m_e c} f_\alpha \lambda_\alpha H^{-1}(z) n_{\mathrm{H\,I}} , \qquad (3)$$

where $f_\alpha = 0.416$ is the Lyα oscillator strength and $\lambda_\alpha = 1216$ Å is the transition wavelength (Gunn & Peterson 1965). The Hubble parameter at redshift z is

$$H(z) = H_0[\Omega_0(1+z)^3 + (1 - \Omega_0 - \lambda_0)(1+z)^2 + \lambda_0]^{1/2} , \qquad (4)$$

where λ_0 is the cosmological constant Λ divided by $3H_0^2$. For realistic assumptions about the UV background, the IGM is highly photoionized, and the neutral hydrogen density is

$$n_{\mathrm{H\,I}} = \frac{n_{\mathrm{H}} n_e \alpha(T)}{\Gamma} = \frac{1.16 n_{\mathrm{H}}^2 \alpha(T)}{\Gamma} , \qquad (5)$$

where $\alpha(T)$ is the recombination coefficient at the gas temperature T, Γ is the photoionization rate, and n_{H} is the total hydrogen density. This condition (eq. [5]) enforces balance between destruction of H I by photoionization and creation by recombination. In gas with $T \gtrsim 10^5$ K, collisional ionization enhances the destruction rate and lowers $n_{\mathrm{H\,I}}$. The mean value of n_{H} is

$$\bar{n}_{\mathrm{H}} = 1.07 \times 10^{-7}(1+z)^3 B \ \mathrm{cm}^{-3} , \qquad (6)$$

with B as defined in equation (1). Equations (5) and (6) assume a hydrogen mass fraction $X = 0.76$ and a helium mass fraction $Y = 0.24$. For gas at temperature $T_4 \equiv T/(10^4$ K) ≈ 1, the recombination coefficient is

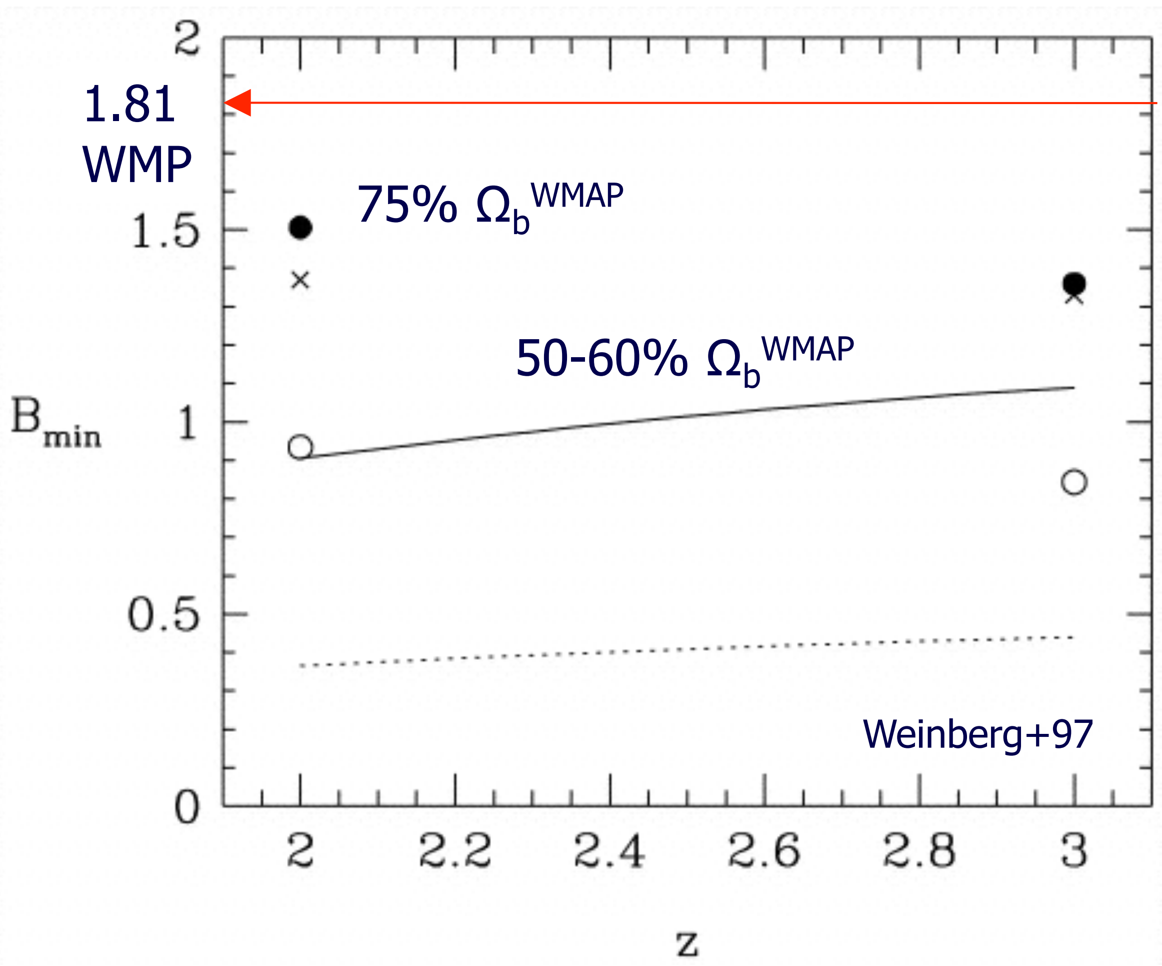
$$\alpha(T) = 4.2 \times 10^{-13} T_4^{-0.7} \ \mathrm{cm}^3 \ \mathrm{s}^{-1} \qquad (7)$$

(Abel et al. 1997). Combining equations (3)–(7) yields

$$\tau_u = 2.31 \times 10^{-4}(1+z)^5(1+\Omega_0 z)^{-1/2} h^{-1} T_4^{-0.7} \Gamma_{-12}^{-1} B^2 , \qquad (8)$$

where $\Gamma_{-12} \equiv \Gamma/(10^{-12}\ \mathrm{s}^{-1})$ and we have assumed $\Lambda = 0$ to compute $H(z)$. Equation (8) agrees with, e.g., equation (36) of HM.

$$B \equiv \frac{\Omega_b h^2}{0.0125} = \frac{\eta}{3.4 \times 10^{-10}} \qquad (1)$$



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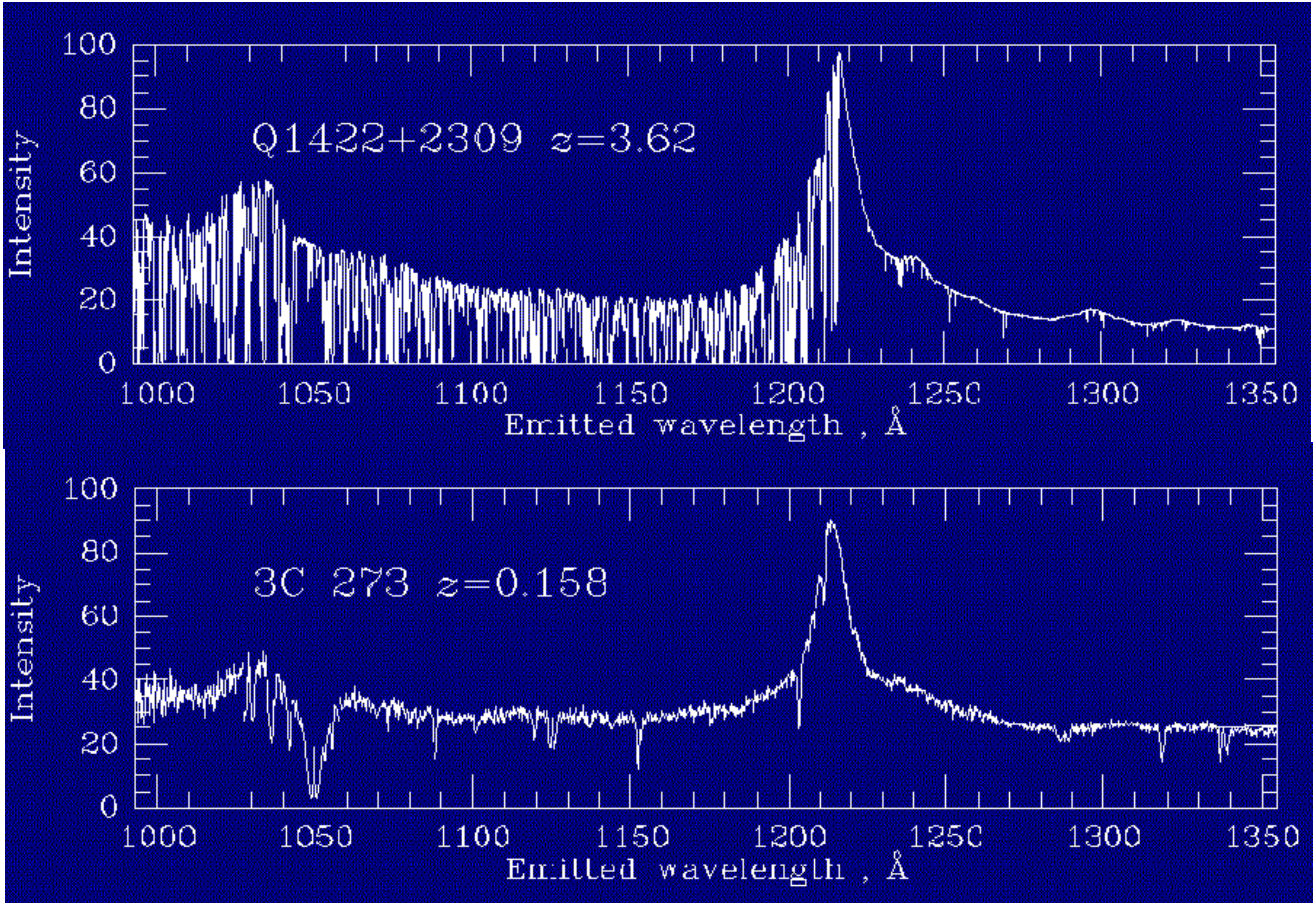
The Number of Baryons at z< 2 & the Missing Baryon Problem

Ly α -Forest in the Local Universe



Where do we see Baryons at z<2?

- Stars in Galaxies

- Neutral and Molecular gas in galaxies (HI + HeI + H2)

- X-Ray gas in Clusters of galaxies

- Residual Ly α -Forest at z<2

- Photoionized and Shock-Heated IGM Metal Absorbers at z<2 (OVI, NeVIII)

- Broad Ly α IGM Absorbers

Baryons in stars

From galaxy Luminosity Function (LF) and Mass to Light ratio (M_s/L):

- The LF derived from the "First Data Release" from the SDSS (2200 deg2, Abazajian03), gives luminosity densities in bands r and z:

  • $L_r = (2.32 \pm 0.25) \times 10^8\, h\, L_\odot\, \mathrm{Mpc}^{-3}$

  • $L_z = (3.9 \pm 0.6) \times 10^8\, h\, L_\odot\, \mathrm{Mpc}^{-3}$

- The (M_s/L_z) ratio is derived by using population synthesis models (PSM) and by surveying large numbers of galaxies in different photometric bands, to estimate the probability distribution of the parameters which PSM depend on. These are: (a) metallicity, (b) age, (c) star formation history and (d) Initial Mass Function (IMF).

Kauffman+03, by using 10^5 SDSS galaxies, estimated $\langle M_s/L_z \rangle \approx 1.5$.

-This gives $\Omega_b(\mathrm{stars}) = 0.0025 \pm 0.0008$ (5.5% Ω_b^{WMAP}) (Fukugita03)

-Uncertainties include 15% from LS, 20% from (M_s/L_z) and 20% from IMF

Baryons in Neutral and Molecular Gas

From HI and HeI (e.g. Rao&Briggs93, Zwaan+03) and CO (Keres+03) Surveys, correcting for He:

-For HI+HeI Fukugita03 gives:

$$-\Omega_b(\mathrm{HI+HeI}) = (6.2 \pm 1.0) \times 10^{-4} \quad (1.36\% \ \Omega_b^{\mathrm{WMAP}})$$

-For H2 Fukugita03 gives:

$$-\Omega_b(\mathrm{H2}) = (1.6 \pm 0.6) \times 10^{-4} \quad (0.35\% \ \Omega_b^{\mathrm{WMAP}})$$

•Therefore:

$$\bullet\Omega_b(\mathrm{HI+HeI+H2}) = (7.8 \pm 1.6) \times 10^{-4} \quad (1.71\% \ \Omega_b^{\mathrm{WMAP}})$$

Baryons in Hot Gas in Clusters

From X-ray luminosity – gravitational mass relationship in Clusters (e.g. Reiprich & Boringher, 2002):

-For a sample of 63 + 106 X-ray clusters of galaxies, ICM density profiles and gas temperatures have been determined. This yielded:

$$-\Omega_{Cluster} = (0.012 \pm 0.004)\text{, for } M > 4.5\ 10^{13}\ M_{\odot}$$

-Fukugita03 assumes the cosmological baryonic to total mass ratio for clusters:

$-\Omega_b/\Omega_m = 0.167$ (Komatsu+09)

-And a Stellar to total mass ratio of:

$-\Omega_b(\mathrm{Star})/\Omega_m = (0.0025 / 0.273) = 0.0092$

-This gives a Gas fraction in Clusters: $f_b = \Omega_b/\Omega_m - \Omega_b(\mathrm{Star})/\Omega_m = 0.158$

•Therefore:

$$\bullet\Omega_b(\mathrm{ICM}) = (1.9 \pm 0.6) \times 10^{-3} \quad (4.2\%\ \Omega_b^{\mathrm{WMAP}})$$

Baryons in Warm + Cold CGM

Fukugita03 derives a large fraction of baryons in a diffuse warm (high-ionization metals) and cold (HI) medium permeating the IGM surrounding galaxies (at ~ the galaxy virial radius)

-By using the average <M/Lr> = (170 ± 21)h ratio derived from lensing observations of an SDSS sample in r band, and for R < 260 kpc (McKay+01)
-And using the Luminosity density in r: $L_r = (2.32 \pm 0.25) \times 10^8\ h\ L_\odot\ \mathrm{Mpc}^{-3}$

-Fukugita+03 derives, for matter within the virial radius of galaxies:

$$-\Omega_m = (0.14 \pm 0.02)$$

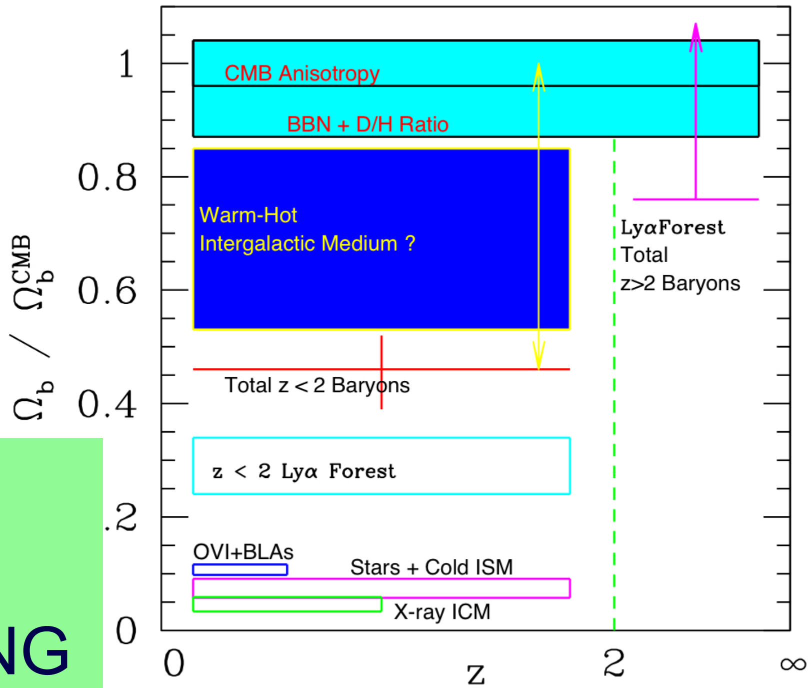
-By adopting the cosmological universal value $\Omega_b/\Omega_m = 0.167$ (Komatsu+09), and subtracting the contribution from stars, HI, HeI and H2:

$$-\Omega_b(\text{W/C-gas}) = 0.022 \pm 0.005 \quad (48.2\%\ \Omega_b^{WMAP})$$

Baryon Budget at z<2

Table 1. Summary of the cosmic baryon budget

component	FHP	new estimate
stars	0.0019–0.0057	0.0025±0.0008
HI+HeI gas	0.00025–0.00041	0.00062±0.00010
H_2 molecular gas	0.00023–0.00037	0.00016±0.00006
hot plasma in clusters	0.0014–0.0044	0.0020±0.0006
warm and cold plasma (by sum)	0.0072–0.030	0.022±0.005



$\Omega_b^{WMAP} - \Omega_b(z<2) = 0.018 \pm 0.003$

i.e. >(40±7)% of baryons are MISSING

The Residual Lyα Forest in the Local Universe

THE LOW-z INTERGALACTIC MEDIUM. III. H I AND METAL ABSORBERS AT $z < 0.4$

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ABSTRACT

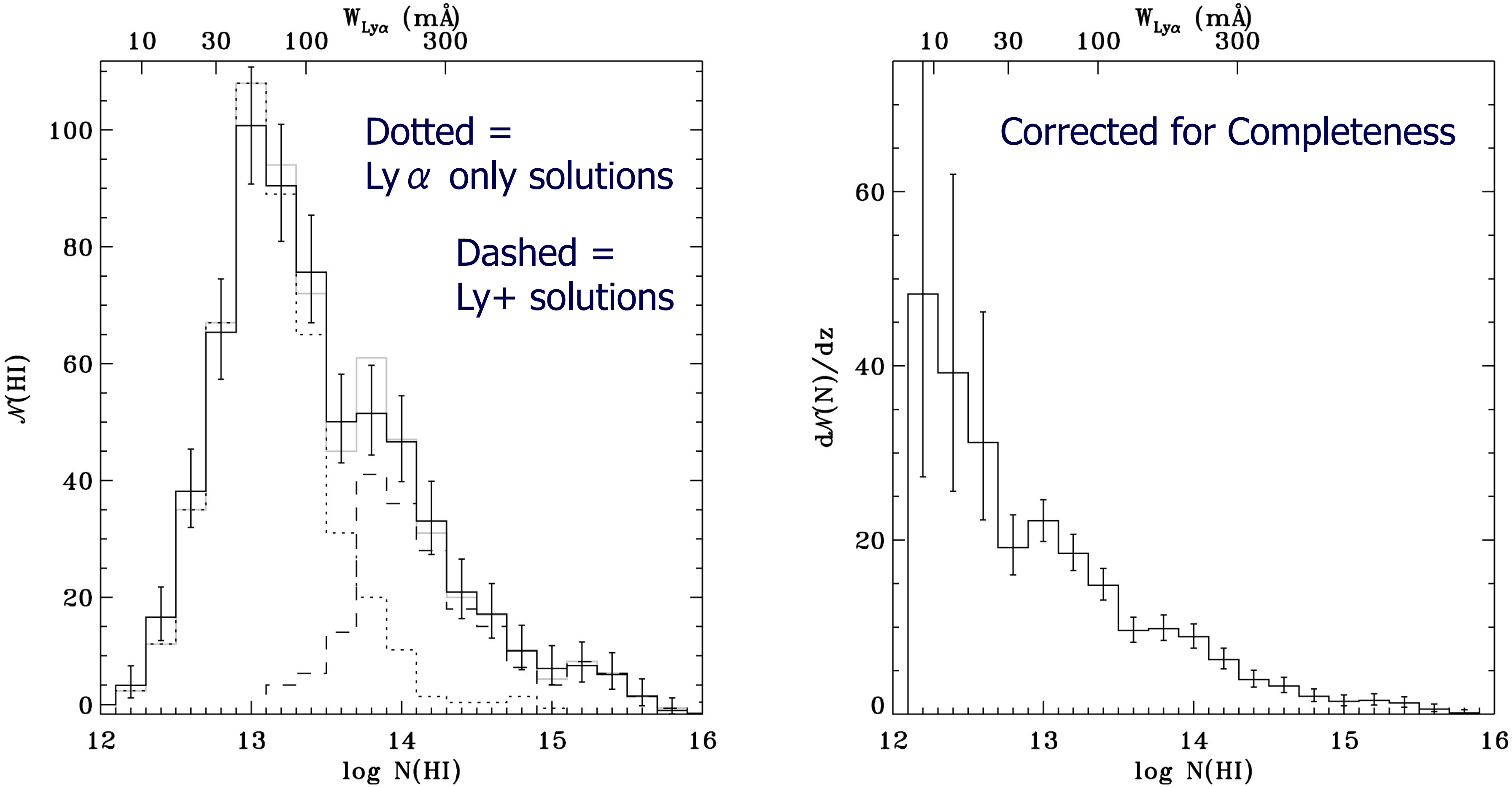
We conduct an ultraviolet (*HST* and *FUSE*) spectroscopic survey of H I (Lyman lines) and seven metal ions (O VI, N V, C IV, C III, Si IV, Si III, Fe III) in the low-redshift IGM at $z < 0.4$. We analyzed 650 Lyα absorbers over redshift path length $\Delta z = 5.27$, detecting numerous absorbers: 83 O VI systems, 39 C III, 53 Si III, 24 C IV, 24 N V, and so on. In the low-z IGM, we have accounted for ~40% of the baryons: 30% in the photoionized Lyα forest and 10% in the ($T = 10^5$–10^6) WHIM traced by O VI. Statistical metallicities are consistent with the canonical value of 10% solar, with considerable scatter. Improved statistics for weak absorbers allows us to estimate $\Omega_{\rm WHIM}/\Omega_b = 0.073 \pm 0.008$ down to $\log N_{\rm O\,VI} = 13.4$ and 0.086 ± 0.008 down to $\log N_{\rm O\,VI} = 13.0$. The O VI absorber line frequency, $d\mathcal{N}/dz = 40^{+14}_{-8}$, down to 10 mÅ equivalent width suggests a 250–300 kpc extent of metals around dwarf galaxies. Many absorbers appear to contain multiphase gas, with both collisional ionization and photoionization determining the ionization state. N V absorption is well correlated with O VI, and both ions show similarly steep power-law indices $d\mathcal{N}/dz \propto N^{-\beta}$ with $\beta_{\rm O\,VI} \approx \beta_{\rm N\,V} \approx 2$ while $\beta_{\rm H\,I} = 1.7$. We conclude that O VI and N V are reliable tracers of the portion of the WHIM at $T \approx 10^5$–10^6 K. C IV may be present in both collisional and photoionized phases; $N_{\rm C\,IV}$ correlates poorly with both $N_{\rm H\,I}$ and $N_{\rm O\,VI}$ and $\beta_{\rm H\,I} < \beta_{\rm C\,IV} < \beta_{\rm O\,VI}$. The ions C III, Si III, and Si IV are well correlated with H I and show patterns typical of photoionization. Adjacent ion stages of the same element (C III/IV and Si III/IV) provide useful constraints on the photoionization parameter, $\log U \approx -1.5 \pm 0.5$.

Subject headings: cosmological parameters — cosmology: observations — intergalactic medium — quasars: absorption lines — ultraviolet: general

Online material: machine-readable tables

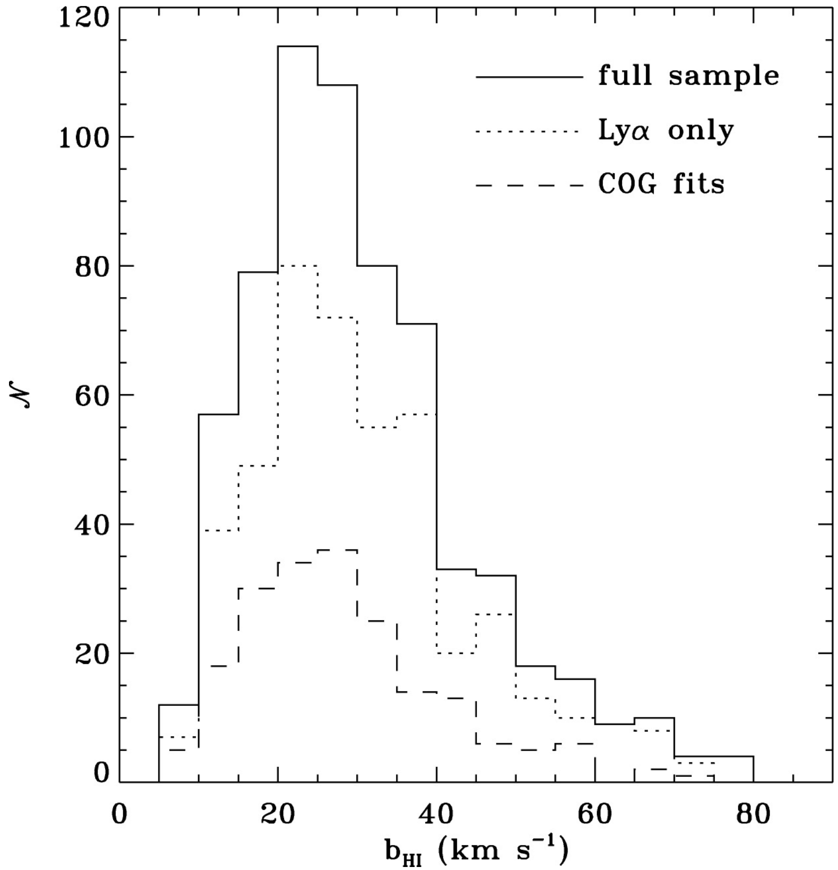
The Residual Lyα Forest in the Local Universe: 2

Number Density of Ly α Absorbers



The Residual Lyα Forest in the Local Universe: 3

Doppler Parameters of Ly α Absorbers



~20% b>40 km/s ➔ BLAs ?

Ω_b(Lyα) in the Local Universe

LOW-z INTERGALACTIC MEDIUM. III.

TABLE 13

BARYON CONTENT OF THE LOCAL LYα FOREST

$\log N_{\rm H\,I}$ Range	$\mathcal{N}$	$\Omega_{\rm Ly\alpha}$ [a]	$\Omega_{\rm Ly\alpha}/\Omega_b$ [a] (%)	$\Omega_{\rm Ly\alpha}$ [b]	$\Omega_{\rm Ly\alpha}/\Omega_b$ [b] (%)
12.5–13.5...................	373	0.0053 ± 0.0015	11.7 ± 3.3	0.0062 ± 0.0019	13.7 ± 4.1
13.5–14.5...................	206	0.0042 ± 0.0004	9.3 ± 0.8	0.0033 ± 0.0003	7.3 ± 0.7
14.5–15.5...................	50	0.0031 ± 0.0006	6.9 ± 1.3	0.0017 ± 0.0003	3.7 ± 0.7
15.5–16.5...................	4	0.0004 ± 0.0002	0.8 ± 0.4	0.0002 ± 0.0001	0.3 ± 0.2
12.5–14.5...................	579	0.0096 ± 0.0016	21.0 ± 3.4	0.0096 ± 0.0019	21.0 ± 4.2
14.5–16.5...................	54	0.0035 ± 0.0006	7.7 ± 1.4	0.0018 ± 0.0003	4.0 ± 0.7
12.5–16.5...................	633	0.0131 ± 0.0017	28.7 ± 3.7	0.0114 ± 0.0019	25.0 ± 4.2

[a] Method of Penton et al. (2000a).
[b] Method of Schaye (2001).

Of the Ω_b = 0.022 that Fukugita03 associates to warm/cold Circum-Galactic Medium, only Ω_b = 0.0131 are actually found in residual Lyα Forest.

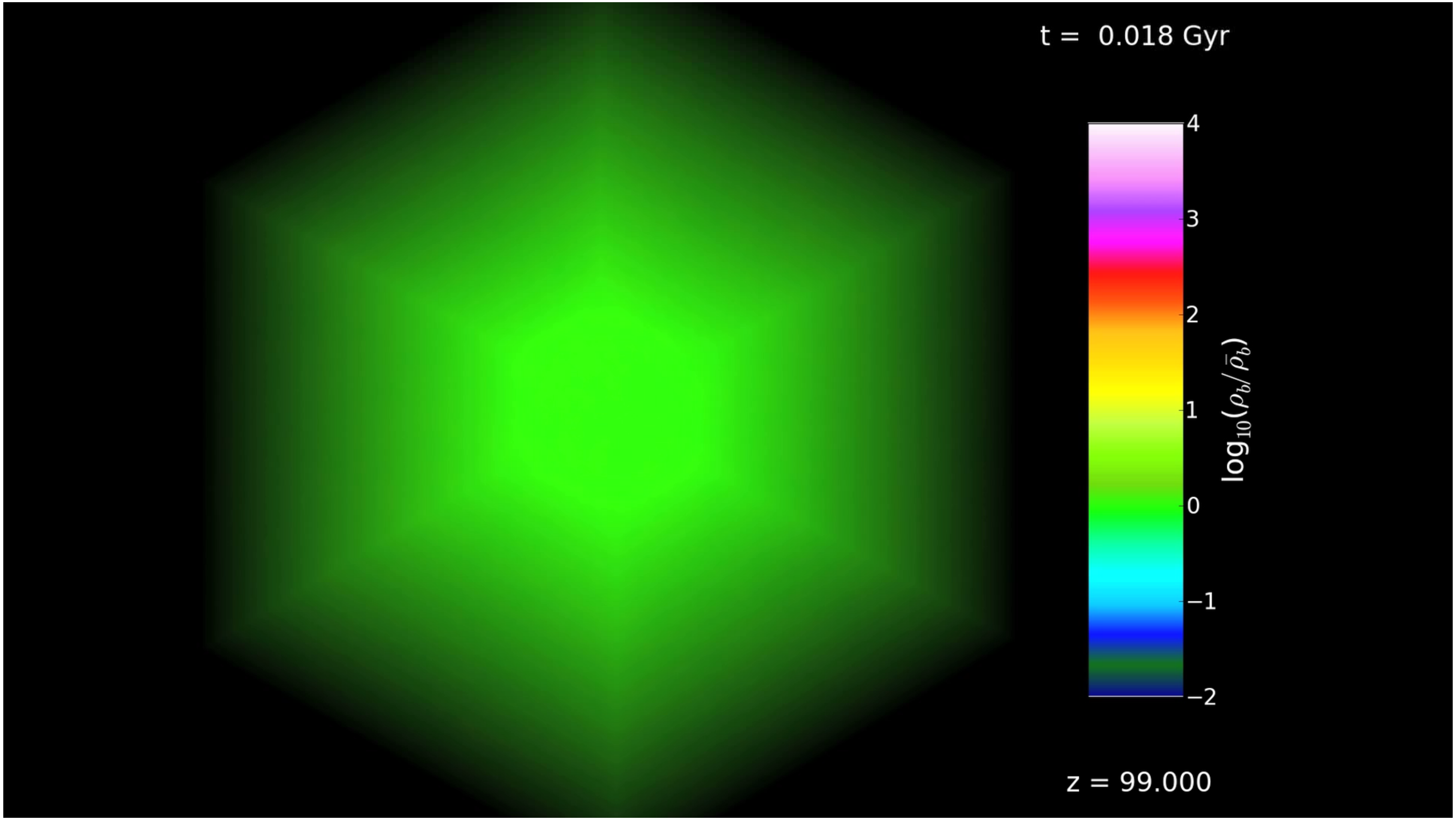
➔ $\Omega_b^{\rm WMAP} - \Omega_b^{\rm Observed} = 0.027 \pm 0.003$

i.e. (59±7)% of baryons are MISSING

3

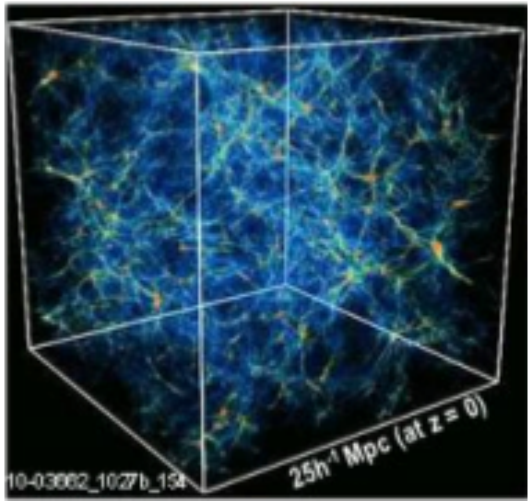
The
the Missing Baryon and the Warm-Hot Intergalactic Medium

The WHIM in Hydro-dynamical simulations

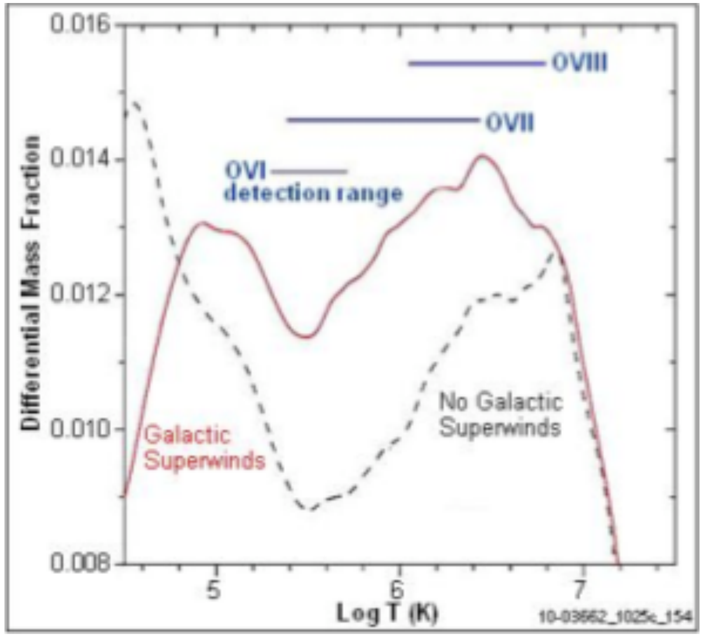


Britton+11, in prep.

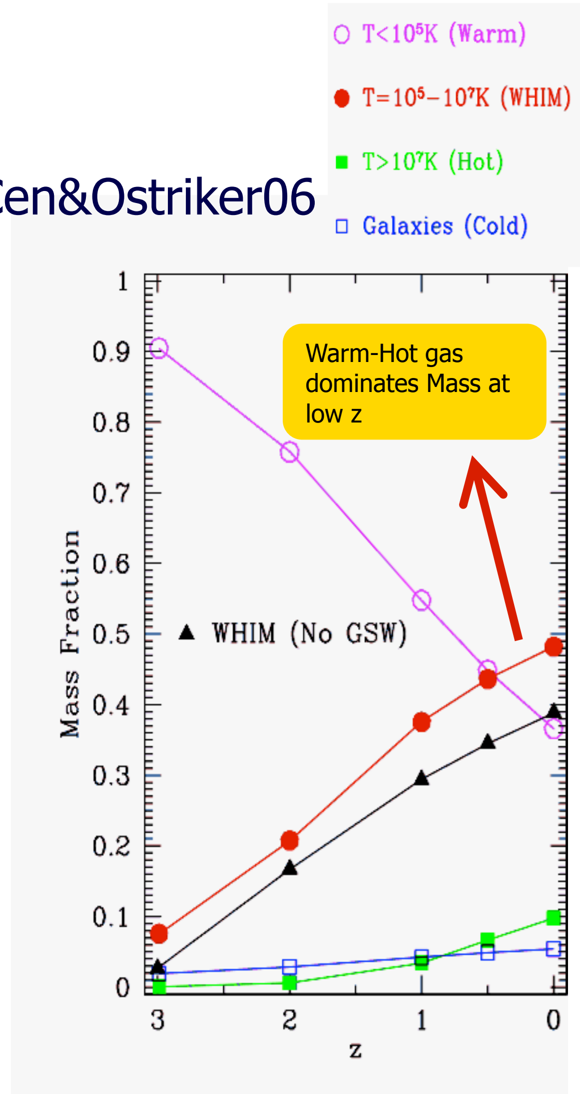
The WHIM in Hydro-dynamical simulations



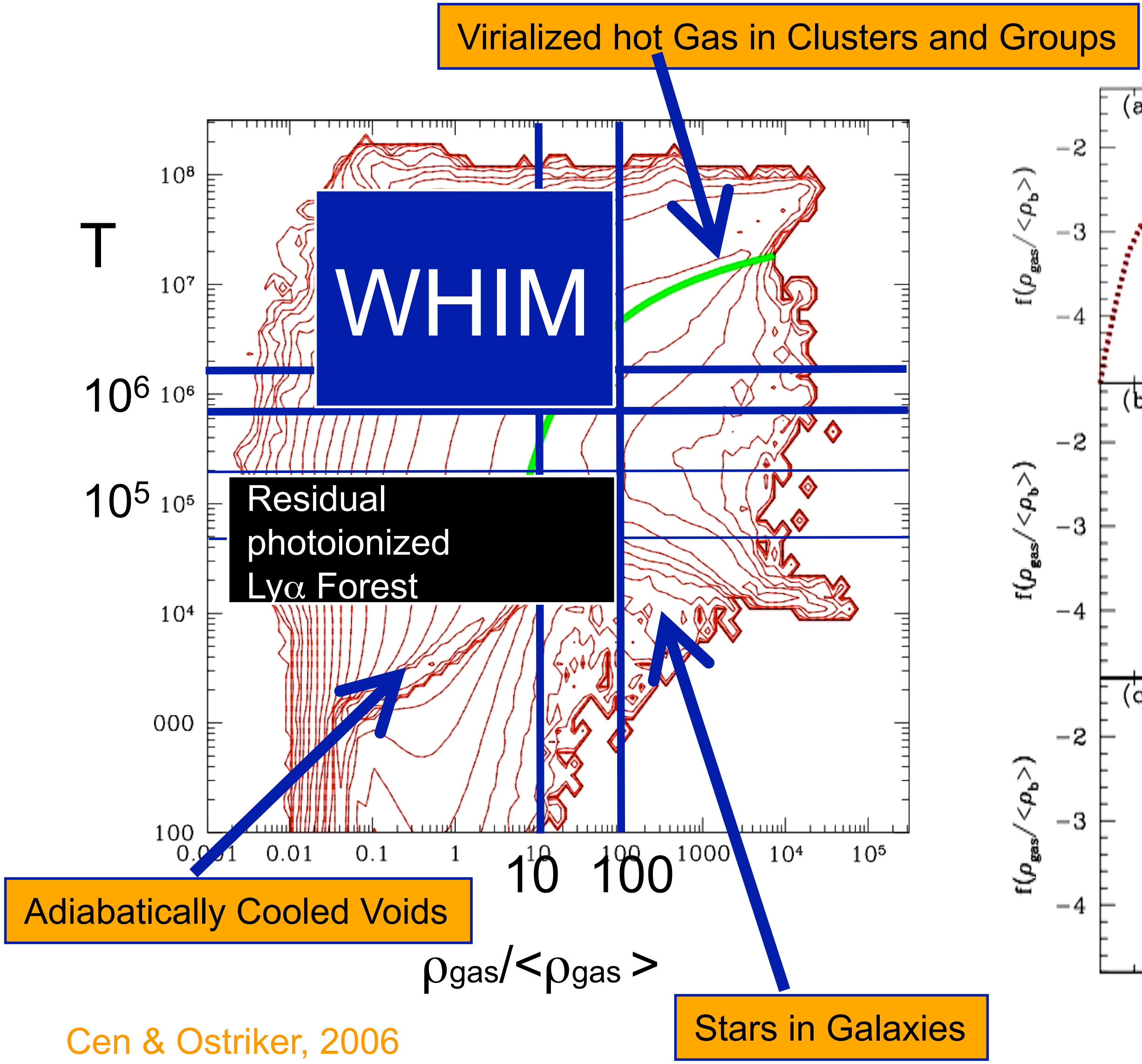
Britton+11

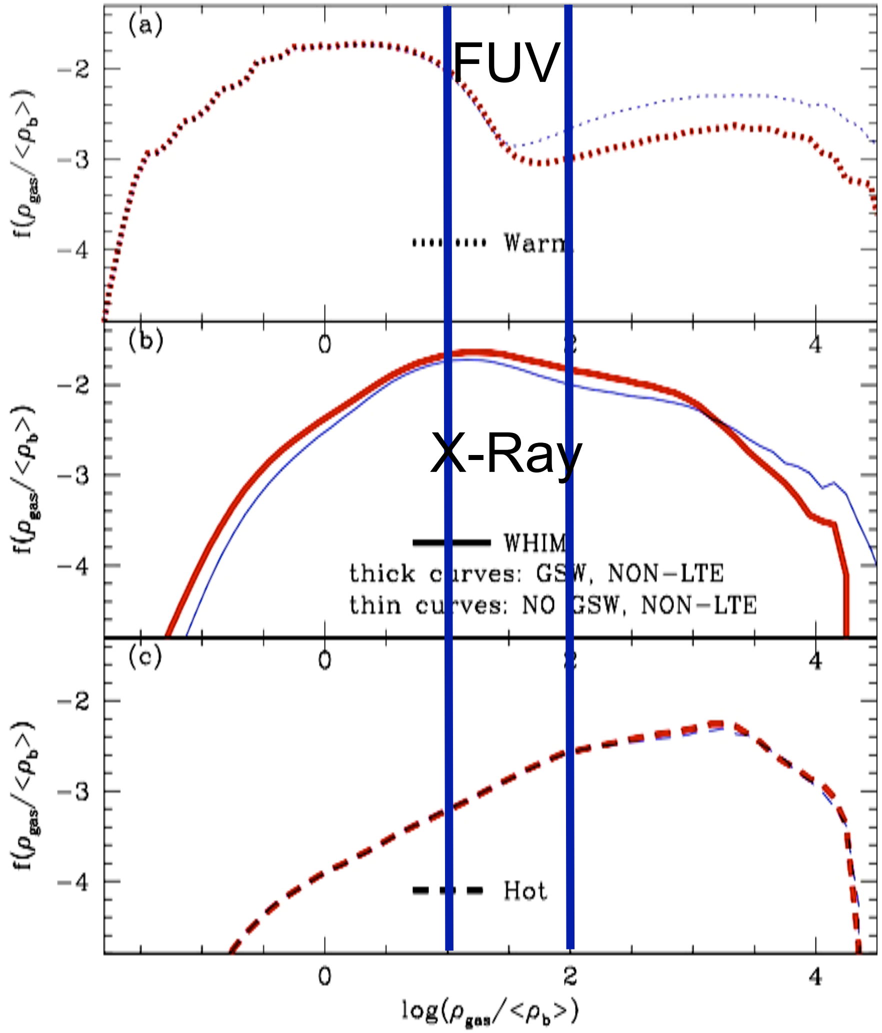


Cen&Ostriker06



Physical State of the Baryons at z=0

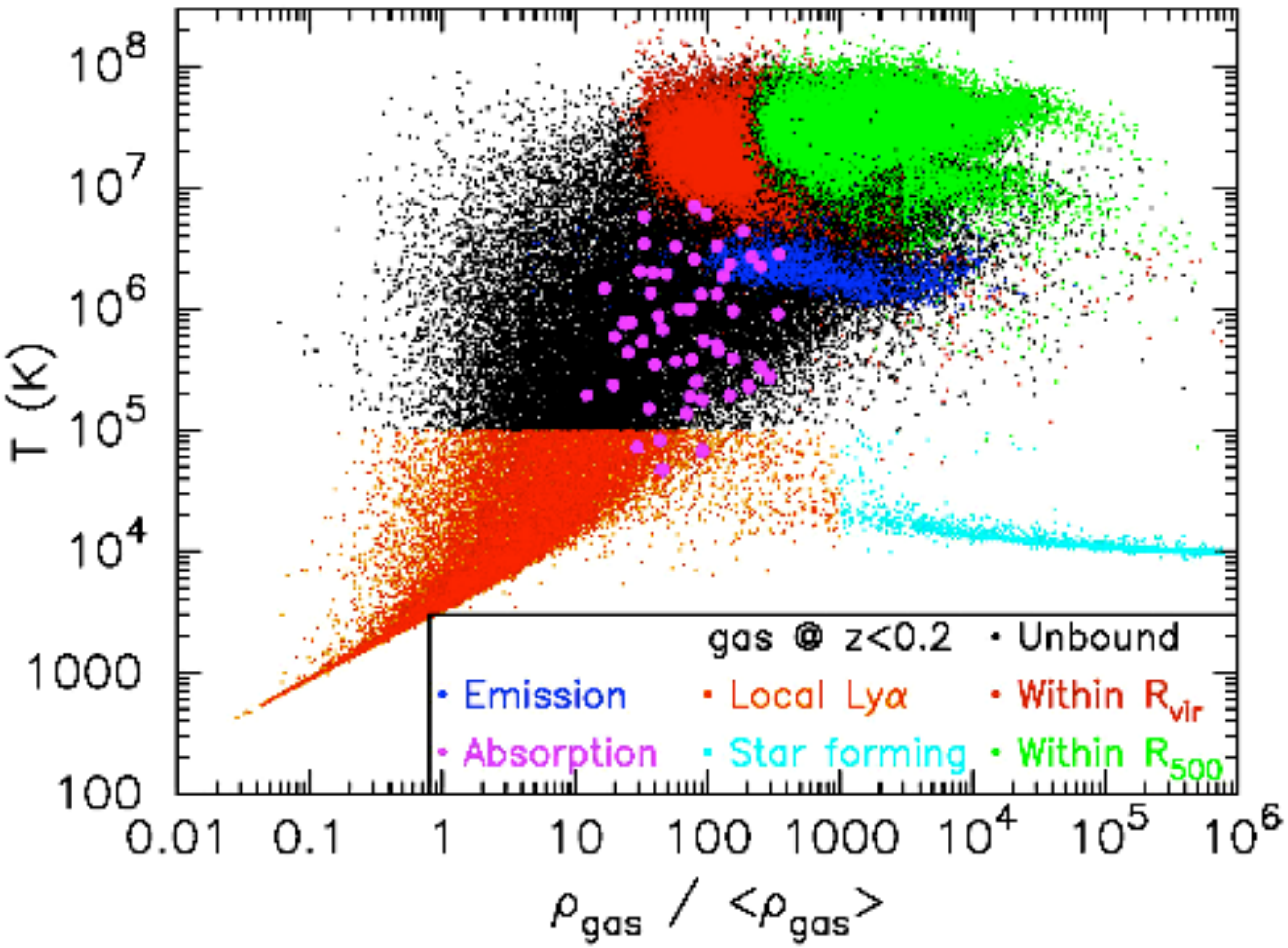




Cen & Ostriker, 2006

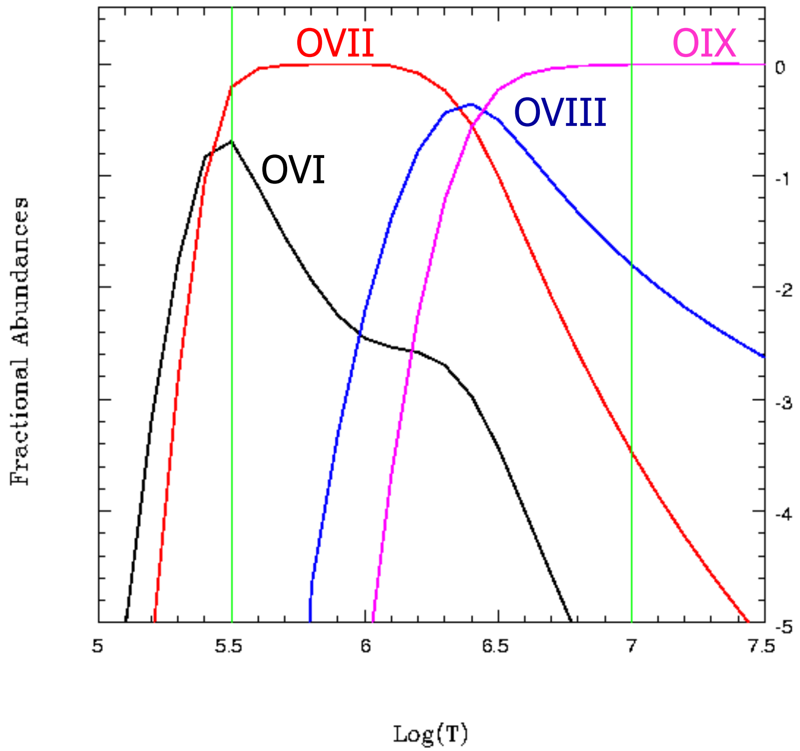
Baryons ρ vs T at z=0

Branchini+10

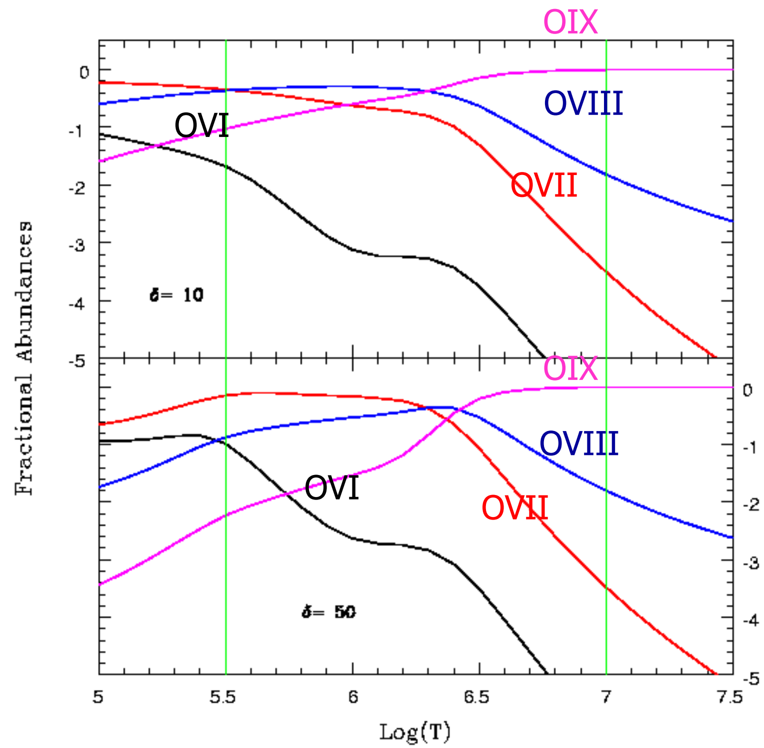


The Meta-Galactic Field Contibution

Collisional Equilibrium

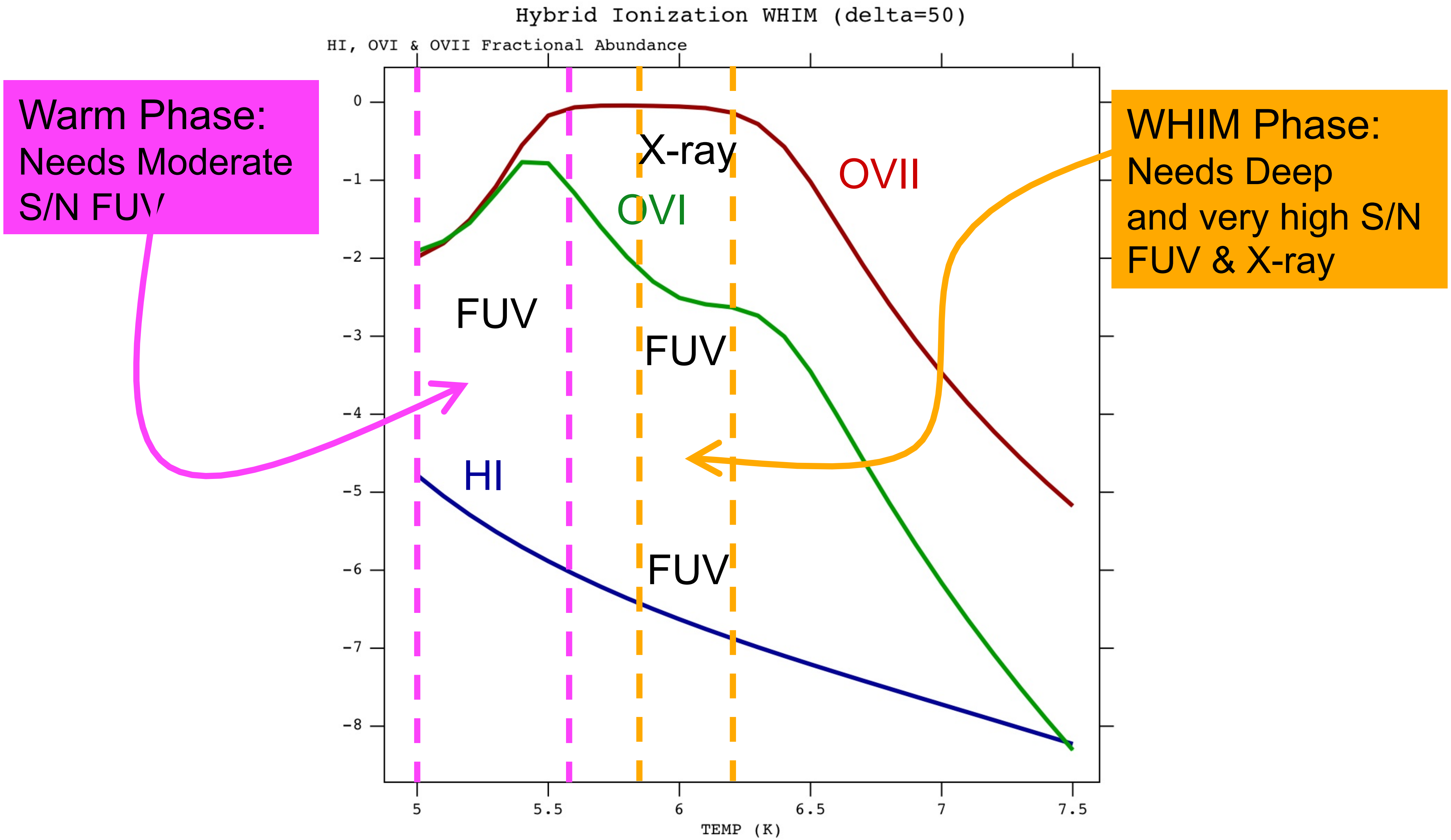


Perturbating with the XRB:
U ~ 0.1 δ^{-1} at any z $\lesssim$ 1



SED from Parmar et al., 1999; Boldt et al., 1987; Fabian & Barcons, 1992)

Ionization Balance in the WHIM



WHIM Observables

Absorption Line Equivalent Widths:

→ Ion Column Densities: N_{ion}

Equivalent Width Ratios:

→ Ionization Balance: T, n_b

Equivalent Widths and Saturation

- Same-Ion Line ratios: direct check
- Curve of Growth technique:

$$W_{X^i} = \int_0^\infty (1 - e^{-\tau_\nu}) d\nu \approx \int_0^\infty \tau_\nu d\nu + \frac{1}{2} \int_0^\infty \tau_\nu^2 + \dots$$

$$\tau_\nu = N_{X^i} \frac{\pi e^2}{mc} f_{lu} \Phi(\nu)$$

$$\Rightarrow W_{X^i} \approx \frac{\pi e^2}{mc} f_{lu} N_{X^i} + \frac{1}{2} \left(\frac{\pi e^2}{mc} f_{lu} N_{X^i} \right)^2 \int_0^\infty \Phi^2(\nu) d\nu + \dots$$

Ionization Balance

- Most metal absorption Lines fall in the linear branch of the Curves of Growth (CoG)

  ➔ EW ∝ Ion Column Density :

$$EW_{X^i} \cong 8.9 \times 10^{-21} (N_H A_X \xi_{X^i}) f_{lu} \lambda^2 \quad \overset{o}{\mathrm{A}}$$

➔ EW ratios ∝ Ionization Balance:

For 2 ions from the same element

$$\frac{\xi_{X^i}}{\xi_{X^{[i+n]}}} = \frac{EW_{X^i}}{EW_{X^{[i+n]}}} \times \frac{f_{lu}(X^{[i+n]})}{f_{lu}(X^i)} \times \left(\frac{\lambda_{X^{[i+n]}}}{\lambda_{X^i}}\right)^2$$

For 2 ions from different elements

$$\frac{\xi_{X^i}}{\xi_{Y^j}} = \frac{EW_{X^i}}{EW_{Y^j}} \times \frac{f_{lu}(Y^j)}{f_{lu}(X^i)} \times \frac{A_Y}{A_X} \times \left(\frac{\lambda_{Y^j}}{\lambda_{X^i}}\right)^2$$

Mass and Metal Content of the WHIM

$$\Omega_b = \left(\frac{1}{\rho_c}\right)\left(\frac{\mu m_p \sum_i N_H^i}{d_{Tot}}\right)$$

$$N_H = N_{ion} \times A_{element}^{-1} \times \xi_{ion}^{-1}$$

FUV | X

FUV & X

X

The HI Problems in a WHIM

- Protons move fast in gas at $T=10^6$ K

  HI Absorption Lines are Broad:

$b(BLA) \geq 130$ km s-1

~ 7 COS-FUV
Res. El. at 1300 A

- HI is only $(10^{-7.2}-10^{-6.2})$ x H in hybrid ionization gas with $\delta=50$ and $T=10^{5.8}-10^{6.5}$ K

  BLAs are shallow:

EW(BLA) ~ 4-40 mA

Assuming:
$A_O = 0.05$xSolar

WHIM Strength & Detectability in the FUV

W_{OVI} ~ 60-600 (1+z) mA (FUV)

W_{HI} ~ 4-40 (1+z) mA (FUV)

Contrast: FUV: 1032/(0.06-0.6) ~ 2000-20000 ~

~ (0.1-1) x $R_{FUSE/HST-STIS/COS}$

FUV: 1215/(0.004-0.04) ~ 30000-300000 ~

~ (1-10) x $R_{FUSE/HST-STIS/COS}$

BLAs Need High-Contrast Spectra

For a Dispersive Spectrometer with FWHM Resolution of $\Delta\lambda^{Spect}$, and an absorption line with FWHM $\Delta\lambda^{Line}$:

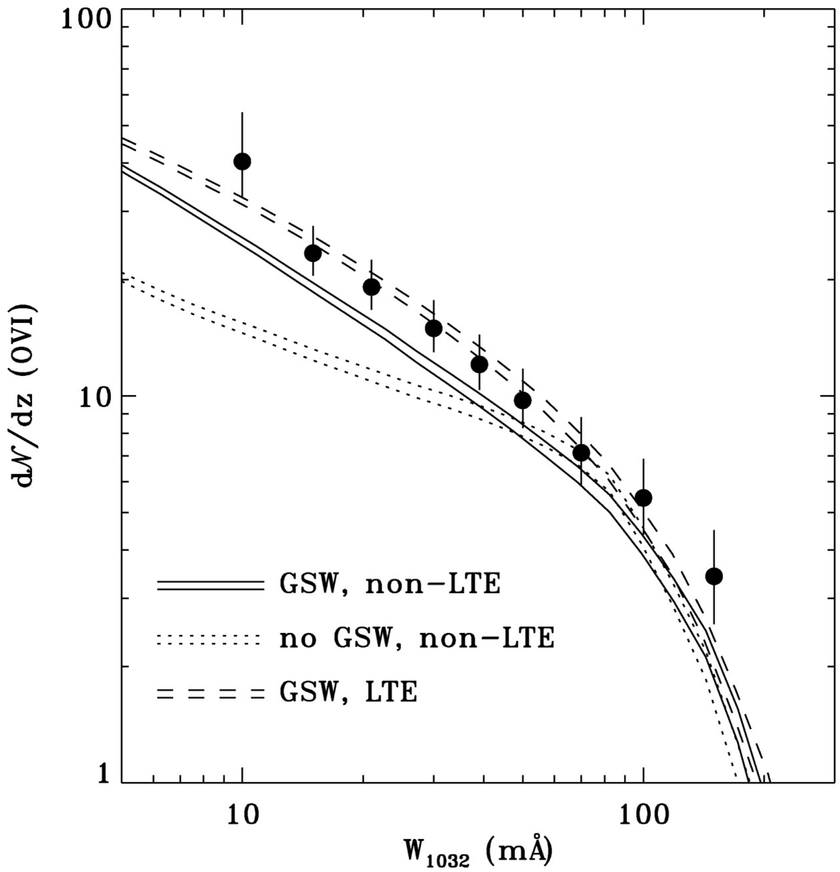
$$\boxed{EW_{Thresh}^{N\sigma} \geq \frac{N\,\Delta\lambda^{Spect}\sqrt{(\Delta\lambda^{Line}/\Delta\lambda^{Spect.})}}{(S/N)_{RE}}}$$

$$\boxed{EW(BLA)_{Thresh}^{5\sigma} \geq \frac{5\sqrt{6.6}(80mA)}{(S/N)_{RE}}}$$

$\Rightarrow$ $(S/N)_{RE(COS)} \geq 50$ => ~ 2500 CPRE

to detect at 5σ BLAs with EW(BLA)=20 mA and b > 130 km s^{-1}

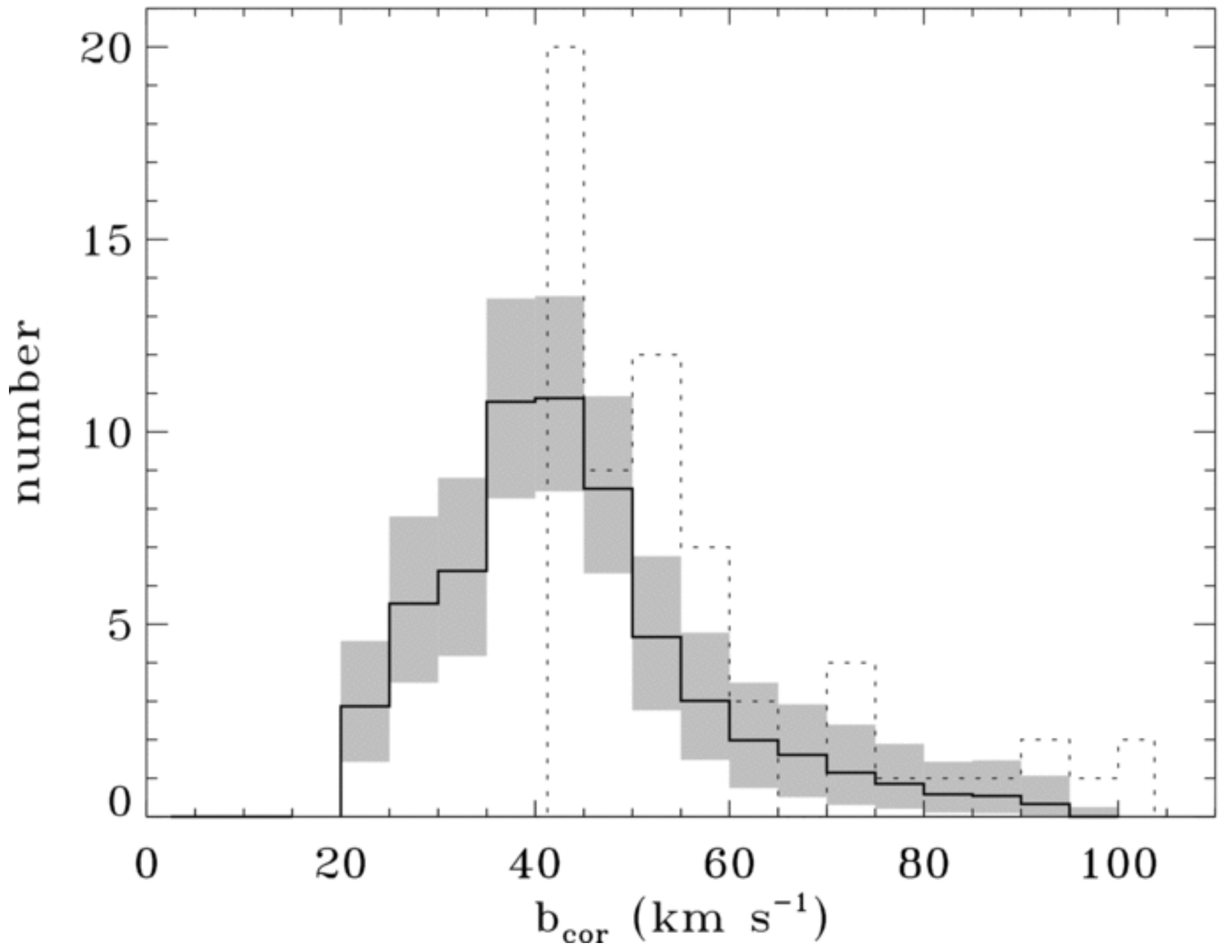
The WHIM (???) in OVI (Danforth&Shull08)



$\Omega_b^{OVI} = 0.0038 \pm 0.0004$ down to $N_{OVI}>10^{13}$ cm^{-2} i.e. (8.6±0.8)% of Ω_b^{WMAP}

New Baryon Budget @z<2: $\Omega_b = 0.0186 + \Omega_b^{OVI} = 0.0224 = 49\% \; \Omega_b^{WMAP}$

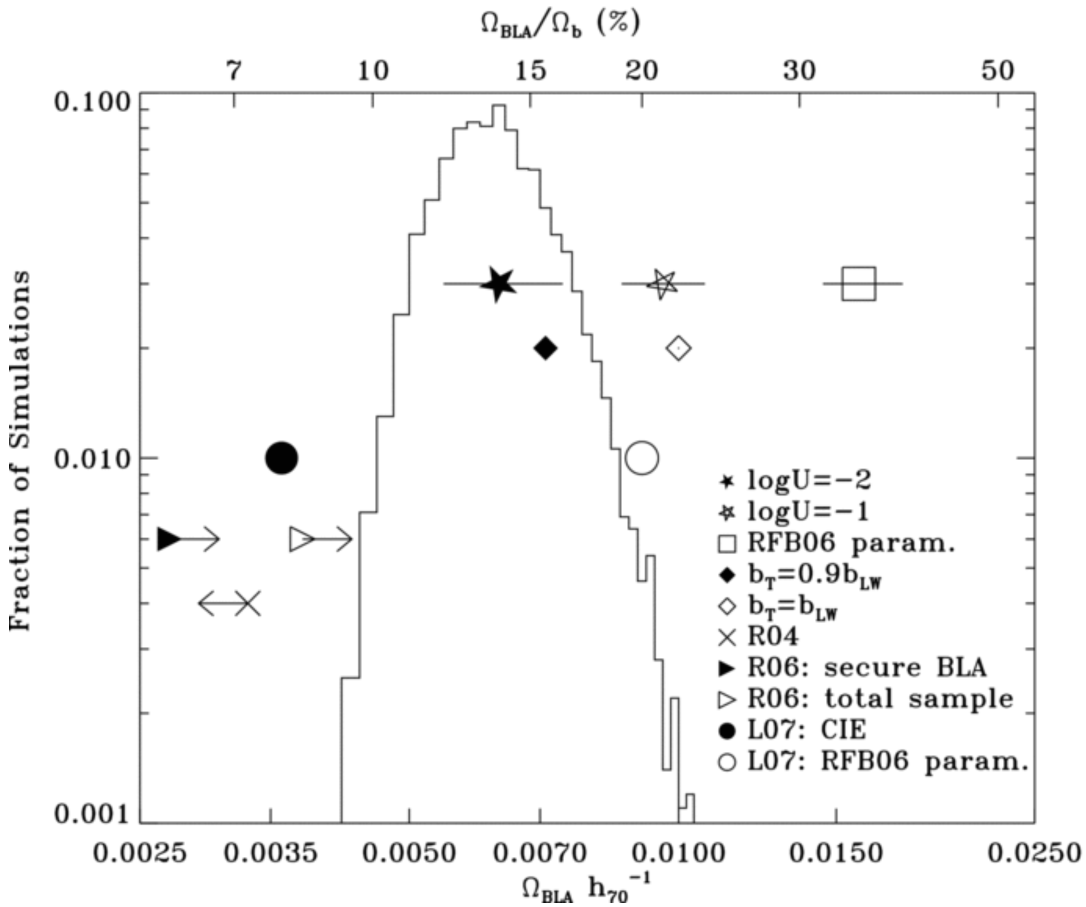
The WHIM (???) in BLAs (Danforth+10)



Doppler Parameter
Corrected for b_{COG}/b_{obs}

Absorber with b_{cor}<40 km/s have not been considered in the Ω_b(BLA) estimate

The WHIM (???) in BLAs (Danforth+10): 2



$\Omega_b^{BLA} = (6.3^{+1.1}_{-0.8})\text{x}10^{-3}$
i.e. ~14% Ω_b^{WMAP}

New Baryon Budget @z<2:
$\Omega_b = 0.0224 + \Omega_b^{BLA} =$
$0.0287 = 64\%\ \Omega_b^{WMAP}$

35% of Baryons Still Missing at z~0

4

The the Galaxy-WHIM Correlation

The Galaxy-OVI Correlation (Stocke+06)

THE GALAXY ENVIRONMENT OF O VI ABSORPTION SYSTEMS

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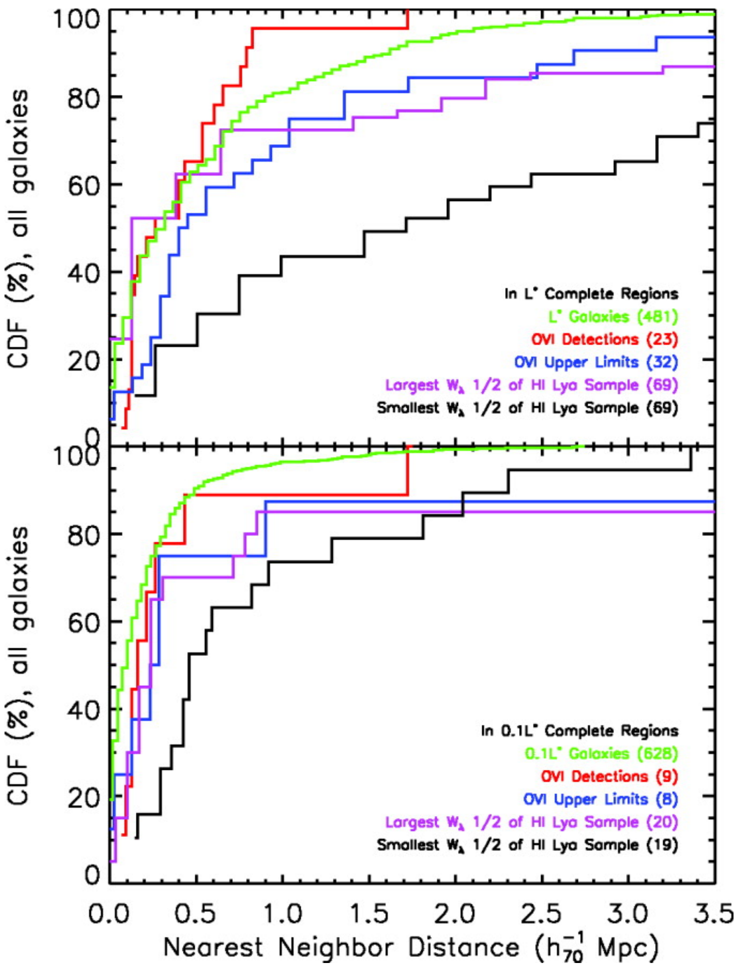
ABSTRACT

We combine a *FUSE* sample of O VI absorbers ($z < 0.15$) with a database of 1.07 million galaxy redshifts to explore the relationship between absorbers and galaxy environments. All 37 absorbers with $N_{\rm O\,VI} \geq 10^{13.2}$ cm^{-2} lie within 800 h_{70}^{-1} kpc of the nearest galaxy, with no compelling evidence for O VI absorbers in voids. The O VI absorbers often appear to be associated with environments of individual galaxies. Gas with 10% $\pm$ 5% solar metallicity (O VI and C III) has a median spread in distance of 350–500 h_{70}^{-1} kpc around L^* galaxies and 200–270 h_{70}^{-1} kpc around 0.1L^* galaxies (ranges reflect uncertain metallicities of gas undetected in Lyα absorption). In order to match the O VI line frequency, $(d\mathcal{N}/dz) \approx 20$ for $N_{\rm O\,VI} \geq 10^{13.2}$ cm^{-2}, galaxies with $L \leq 0.1L^*$ must contribute to the cross section. Lyα absorbers with $N_{\rm H\,I} \geq 10^{13.2}$ cm^{-2} cover $\sim$50% of the surface area of typical galaxy filaments. Two-thirds of these show O VI and/or C III absorption, corresponding to a 33%–50% covering factor at 0.1 $Z_\odot$ and suggesting that metals are spread to a maximum distance of 800 h_{70}^{-1} kpc, within typical galaxy supercluster filaments. Approximately 50%



"All OVI Absorbers with $N_{OVI} > 10^{13.2}$ cm^{-2} lie within 800 h^{-1} kpc from L* galaxies, with no evidence for OVI absorbers in voids".

The Galaxy-BLA Correlation (Danforth+10)

The strong advantage of BLA vs OVI is that they trace baryons independently on metals. So, in principle, BLAs could be found farther from galaxies, where metallicity is lower.

Danforth, Shull & Stocke (2010) find:

A=Probable
B=Possible

Table 3
Galaxy–BLA Relationship in Well-surveyed Fields

AGN	z_{abs}	b_{HI} [a] (km s^{-1})	BLA Classification	log $N_{O\,VI}$ [b] (cm^{-2})	d (Mpc)
PG 1259+593	0.00229	44 COG	A	13.7: [c]	0.06
PKS 0405−123	0.16678	75: LW	B	14.1 ± 0.2	0.11
PKS 0405−123	0.09659	70: LW	B	13.7 ± 0.2	0.27
PKS 0405−123	0.08139	53 LW	A	13.3 ± 0.2	0.49
PG 1116+215	0.06072	54 LW	B	< 13.07	0.75
PG 1116+215	0.09279	100: LW	A	< 13.07	1.3
PG 1116+215	0.01635	51 LW	B	< 13.05	2.0
PG 1116+215	0.08587	53 LW	B	< 13.04	2.9

Notes.
[a] Consensus b-value from Table 2.
[b] O VI column density from DS08.
[c] Detection from Richter et al. (2004) based on nighttime-only *FUSE* data. Formal significance level is low ($< 3\sigma$), however, absorption appears over an exceptionally broad velocity range (-110 km s^{-1} $< v <$ $+220$ km s^{-1}).