The problem of the missing baryons

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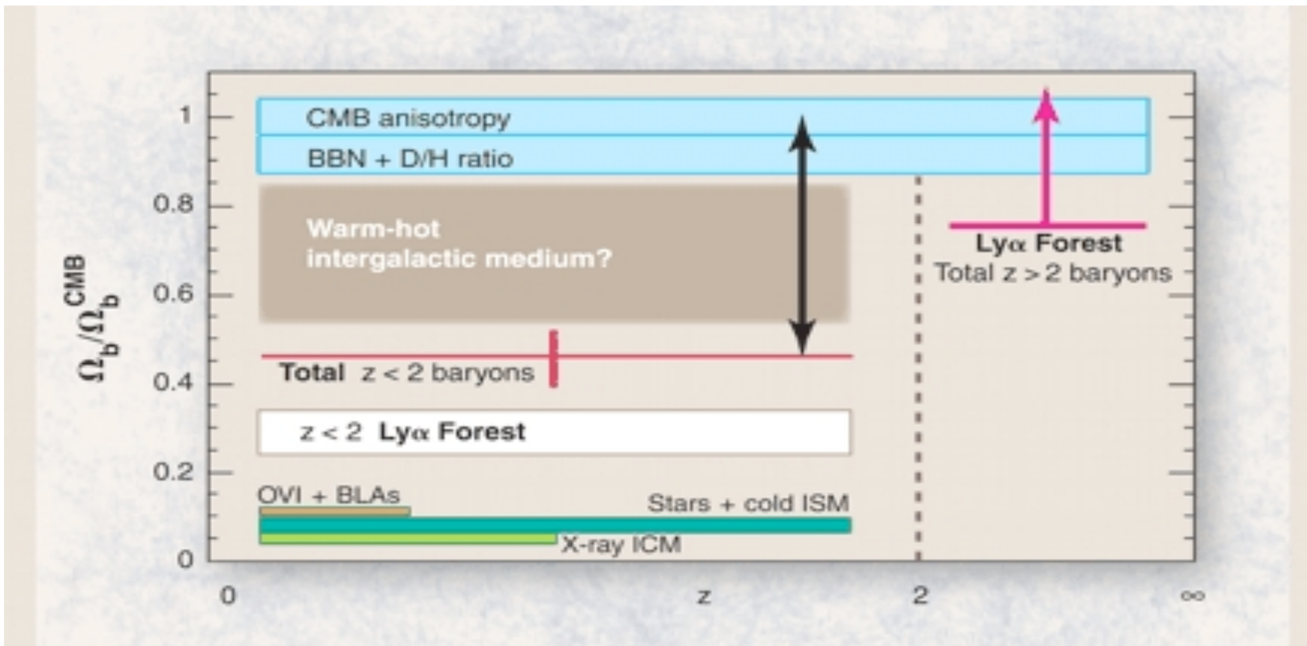
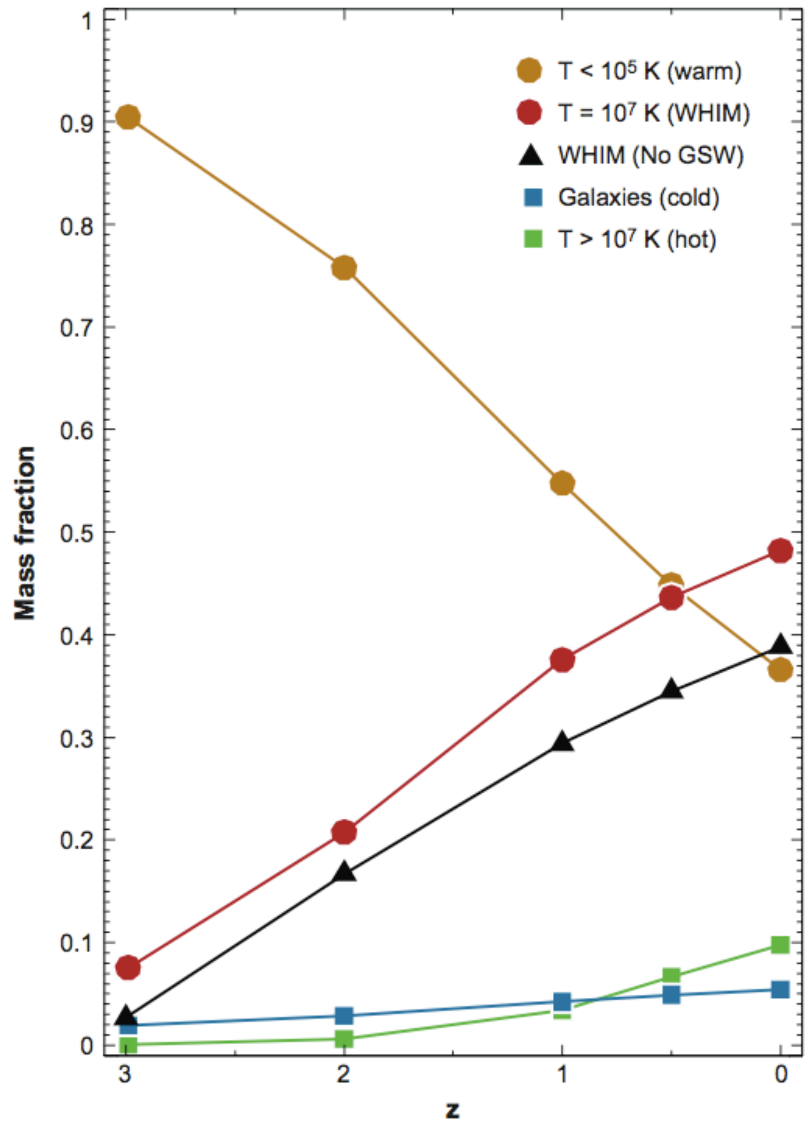
Inferred from	Ω_b (%) for h_{70}=1
BBN + D/H	4.4 ± 0.4
CMB anisotropy	4.6 ± 0.2
Lyα forest at z>2	>3.5
Observations at z<2	
Stars	0.26 ± 0.08
HI + HeI + H_2	0.080 ± 0.016
X-ray gas in clusters	0.21 ± 0.06
Lyα forest	1.34 ± 0.23
Warm + warm-hot OVI	$0.6^{+0.4}_{-0.3}$
Total at z<2	$2.5^{+0.5}_{-0.4}$
Missing baryons at z<2	$2.1^{+0.5}_{-0.4}$

The missing baryons

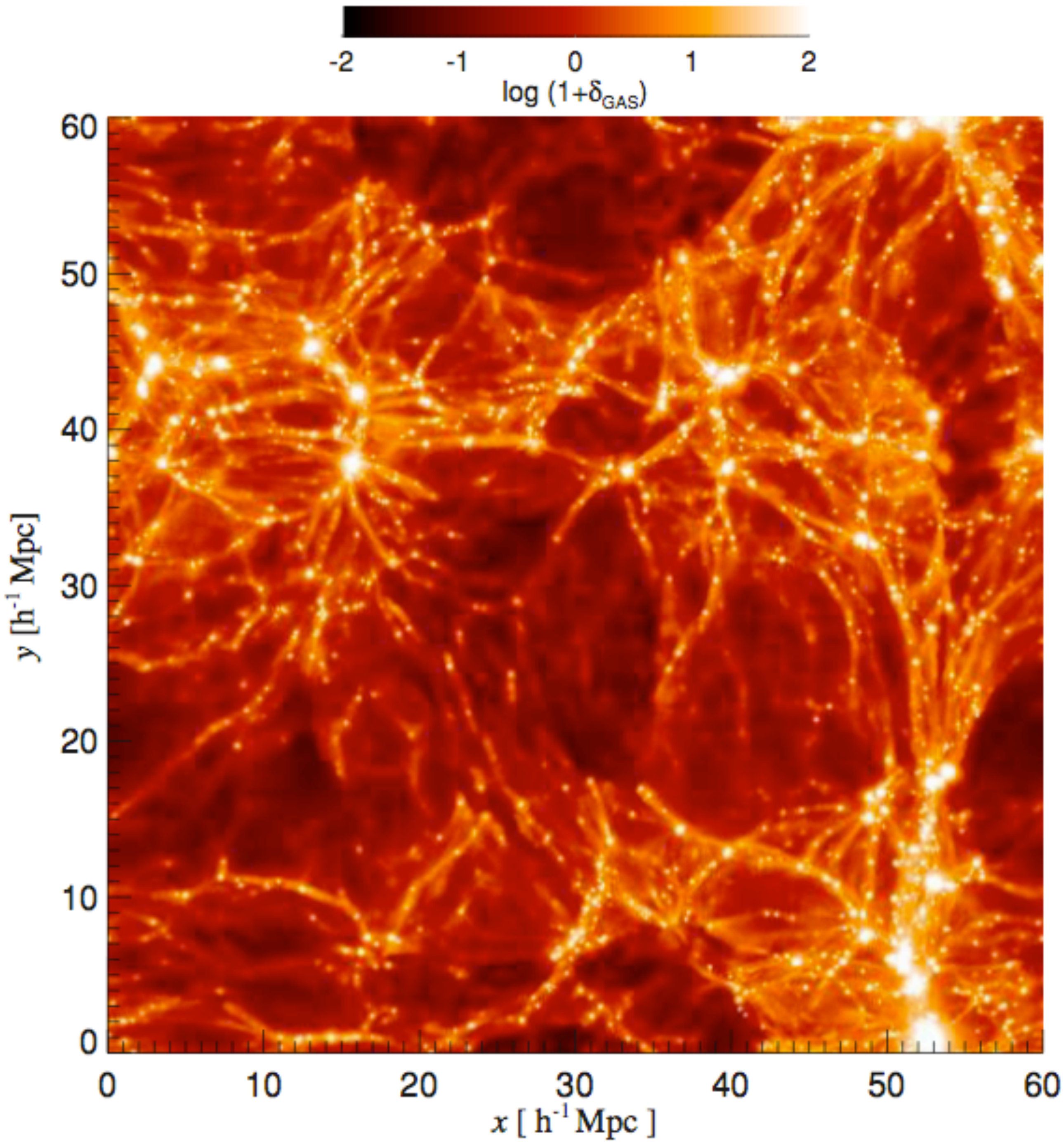


The Warm-Hot IGM

- Hydrodynamical simulations predict that, for $z<1-2$, roughly 30-40% of the baryons lie in a tenuous warm-hot intergalactic medium (WHIM) at overdensities $\delta \approx 5 - 100$
- The WHIM was shock-heated to temperatures of $10^5 - 10^7$ K during the process of structure formation (accretion onto non-linear structures like filaments and clumps)

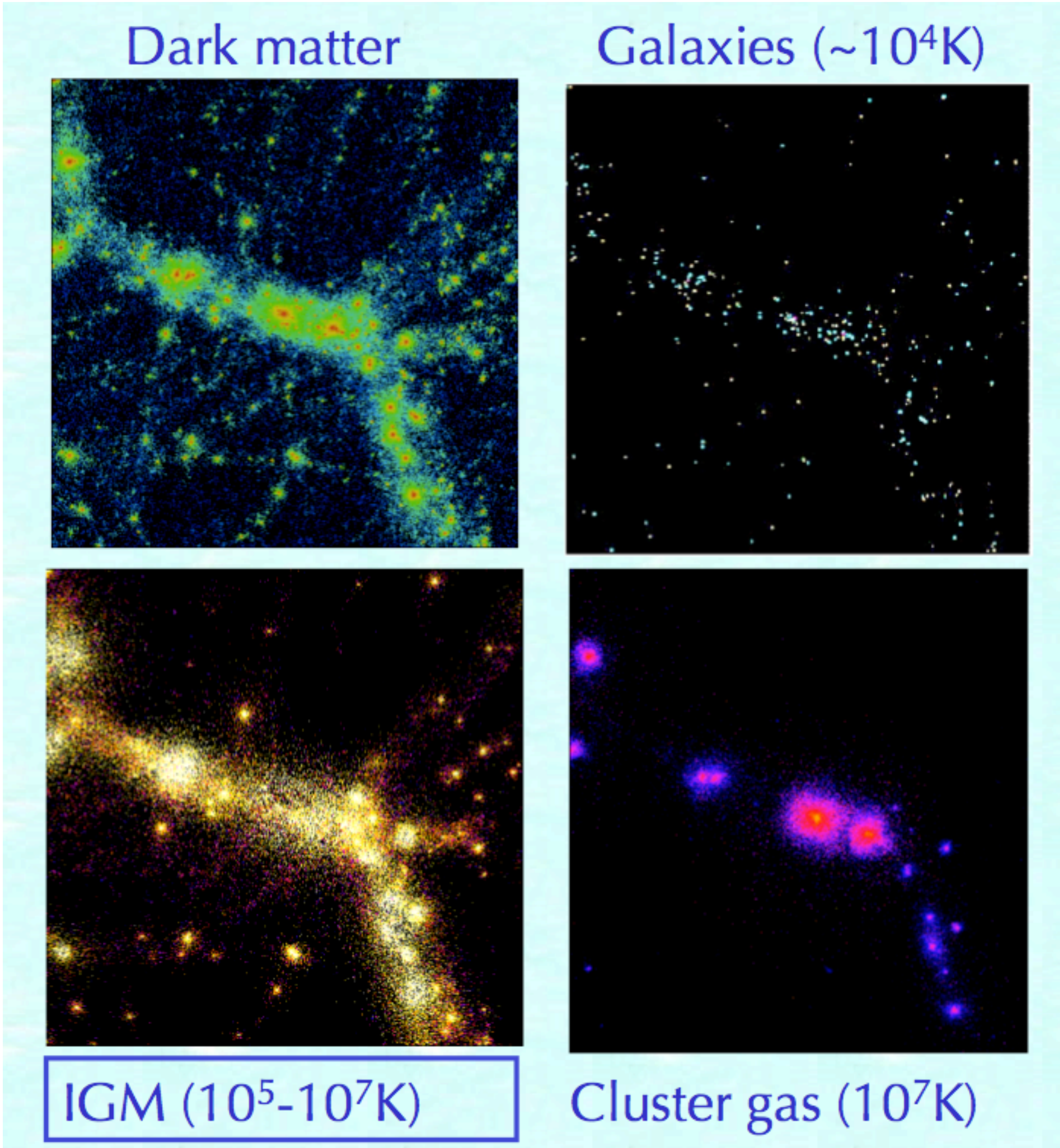


T < 10^5 K (warm)
T = 10^7 K (WHIM)
WHIM (No GSW)
Galaxies (cold)
T > 10^7 K (hot)
Mass fraction
z
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3
2
1
0



-2
-1
0
1
2
log (1+δGAS)
0
10
20
30
40
50
60
y [h-1 Mpc]
x [h-1 Mpc]

30 Mpc/h
5° at z=0.1



The WHIM

- At these temperatures C, N, O and Ne (the most abundant metals in gas with solar-like composition) are highly ionized

- They are mainly found in the ionic states with one or two electrons

- The strongest bound-bound transitions from these ions fall in the soft X-ray band

WHIM lines

Ion	Energy (eV)	f
O VI	11.95+12.01	0.19
O VI 1s–2p	563	0.53
O VII 1s–2p	574	0.70
O VII 1s–3p	666	0.15
O VIII 1s–2p	654	0.42
C V 1s–2p	308	0.65
C VI 1s–2p	367	0.42
Ne IX 1s–2p	922	0.72
Fe XVII 2p–3d	826	3.00
Mg XI 1s–2p	1352	0.74

Notes. Column 1: ion; Column 2: wavelength (eV); Column 3: oscillator strength.

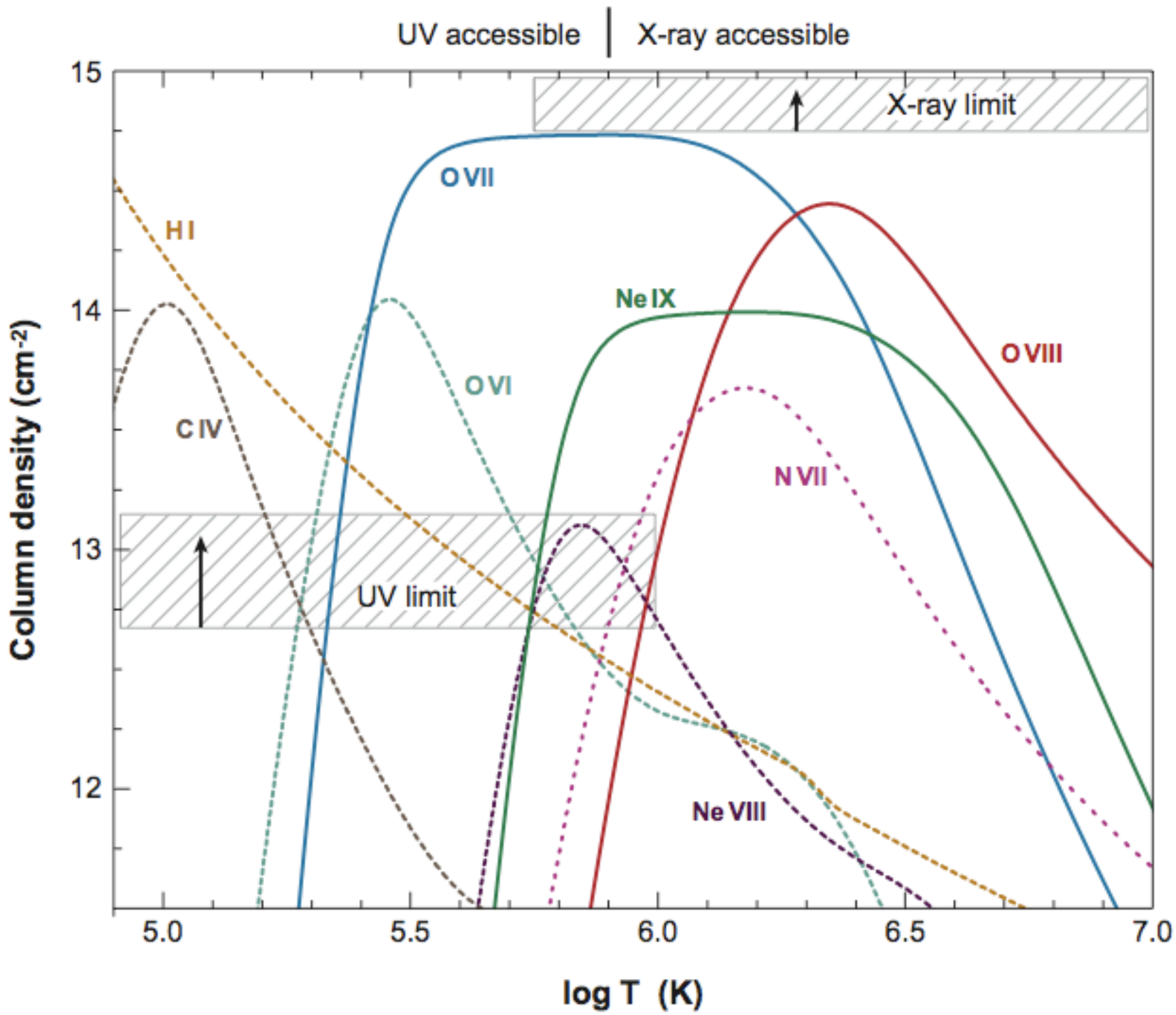


Figure 5

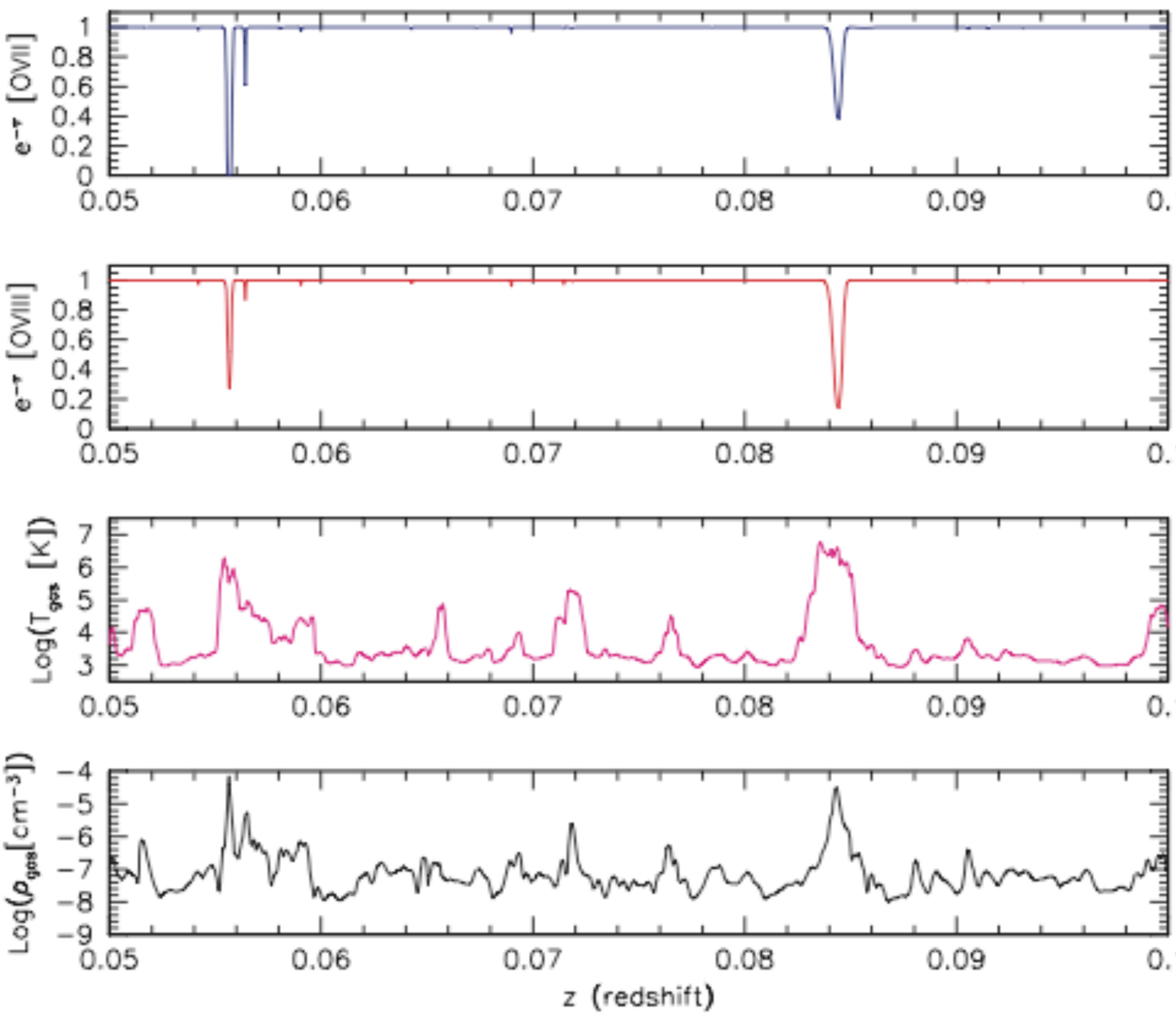
The ion fraction distributions, represented as column densities for a total gas column of 10^{19} cm^{-2} and metallicities of 0.1 $Z_{\odot}$. The UV lines are effective at detecting absorbing gas for $T < 5 \times 10^5$ K and currently have significantly better sensitivity than the X-ray OVII Kα and OVIII Kα lines, which are good diagnostics for gas temperatures ranging from 0.5 to 5×10^6 K. Absorption by OVII, OVIII, and NeIX have been detected at $z = 0$, probably because of the higher metallicity of Galactic Halo gas. The NVII ion (*dotted*), which has a hyperfine line in the radio region, is also shown.

The WHIM in absorption

- A forest of weak absorption lines is expected to be imprinted in the X-ray spectra of all background sources by these WHIM filaments

- This is the direct analog of the Lyman-α forest due to colder neutral hydrogen detected in the optical spectra of quasars

- Typical expected column densities are $N<10^{16}$ cm^{-2} with equivalent widths of W<18-30 mÅ, depending on the particular ion



e^{-τ} [OVII]
e^{-τ} [OVIII]
Log(T_gas [K])
Log(ρ_gas[cm^{-3}])
z (redshift)

WHIM detection

- Metal absorption lines from warm-hot gas at z=0 have been detected in X-rays and in the UV in association with the Milky Way and the Local Group

- To measure the cosmic density of the WHIM requires observation along random, unprivileged, lines of sight

- In the standard cosmology, only a single O_{VII} Kα system with $N>10^{16}$ cm^{-2} is expected along a random line of sight up to z=0.3 with a probability of nearly 60% whereas eight systems with $N>10^{15}$ cm^{-2} are expected

Why is it hard to detect them?

Detectors are smaller in X-ray and spectral resolution is poorer than in other bands:

- COS on HST: 2,000 cm^2 and R=20,000
- LETG on Chandra: 15 cm^2 and R=440
- RGS on XMM: 55 cm^2 and R=360

- The typical equivalent width of the more common WHIM lines (O_{VII}) is 3 mÅ while the spectral resolution of the instruments is roughly 50 mÅ

- Therefore a very large number of photons is needed for a statistically significant detection of a non-saturated line (nearly 2,500 counts for a 3σ detection)

- However, distant soft X-ray sources are faint and this would require prohibitive integration times (the brightest Seyfert galaxies would require 2.5 Ms integration with Chandra even though they only lie at z=0.05)

- One possible solution is to observe variable background sources in unusually bright states

Detection of the WHIM

- On 26-27 October 2002 and 1-2 July 2003, Nicastro et al. observed the blazar Markarian 421 at its historical maxima
- They detected 24 metal absorption lines, 9 of which belonging to 2 intervening absorption systems at z=0.011 (O_{VII}, N_{VII}) and 0.027 (O_{VII}, N_{VII}, N_{VI})
- The remaining lines are identified as belonging to the interstellar medium of our Galaxy or to the Local Group WHIM filament and are not of cosmological relevance

Measuring the density of the WHIM

- Ionization corrections and metallicity estimates can be computed using the $O_{VI} - O_{VII}$, $N_{VI} - N_{VII}$ and HI ratios. Data suggest log(T/K)≈6 and [O/H]>-1.5 (-1.3)

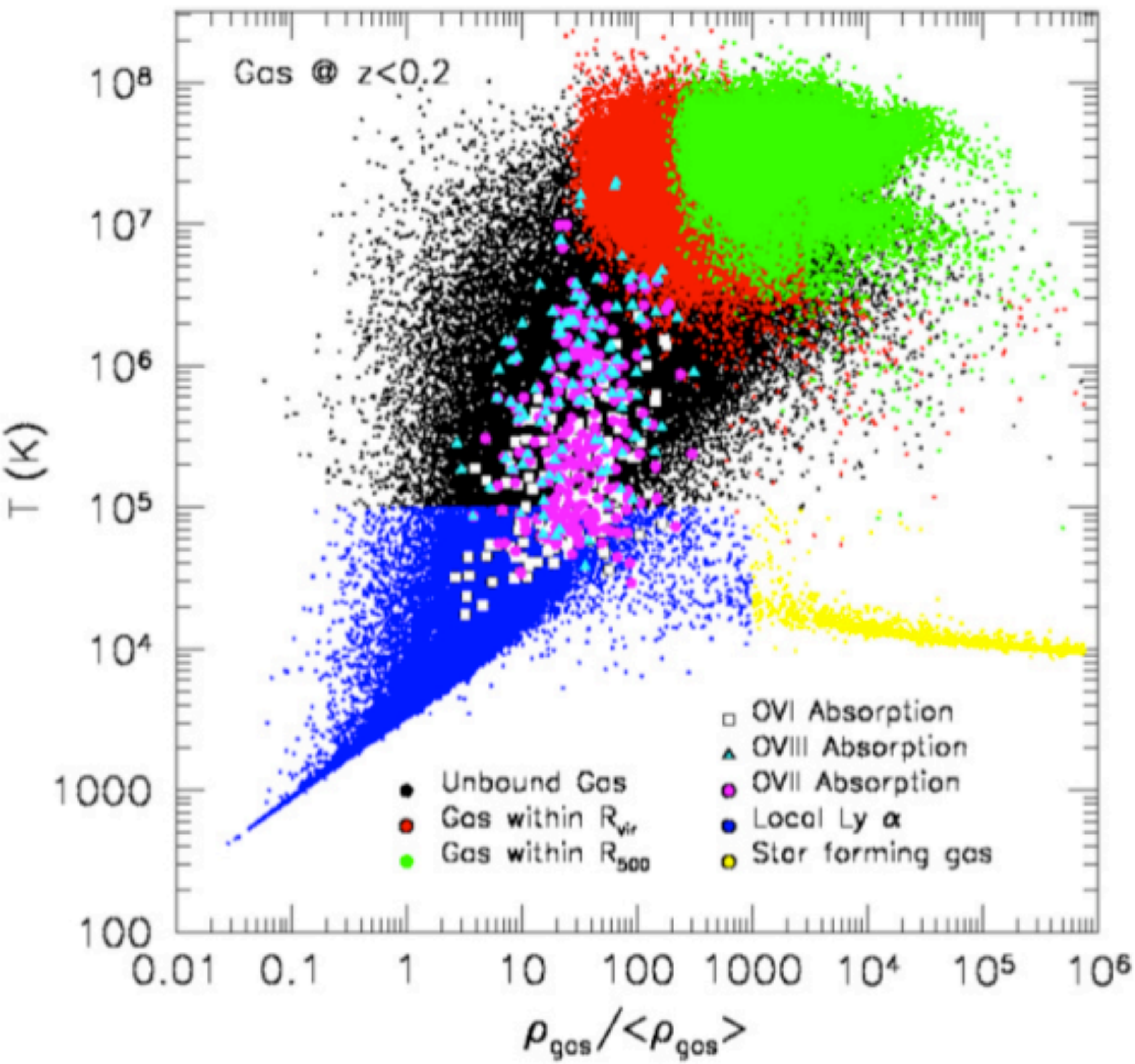
- This allows us to compute the cosmological baryon density in X-ray filaments

$$\Omega_{\rm WHIM} = \frac{\mu m_{\rm H}}{\rho_c} \frac{\sum_{i,j} \left(\frac{A_{\rm H}}{A_O}\right)_{i,j} \left(\frac{N(\rm O\,VII)}{X(\rm O\,VII)}\right)_{i,j}}{\sum_j d_c(z_j)},$$

Missing baryons found?

- Adopting a distance to Markarian 421 of 128 h_{70}^{-1} Mpc and a temperature of the IGM of $10^{6.1}$ K, gives

$$100 \times \Omega_b^{WHIM} = 2.7_{-1.9}^{+3.8} \times 10^{-[O/H]_{-1}}$$



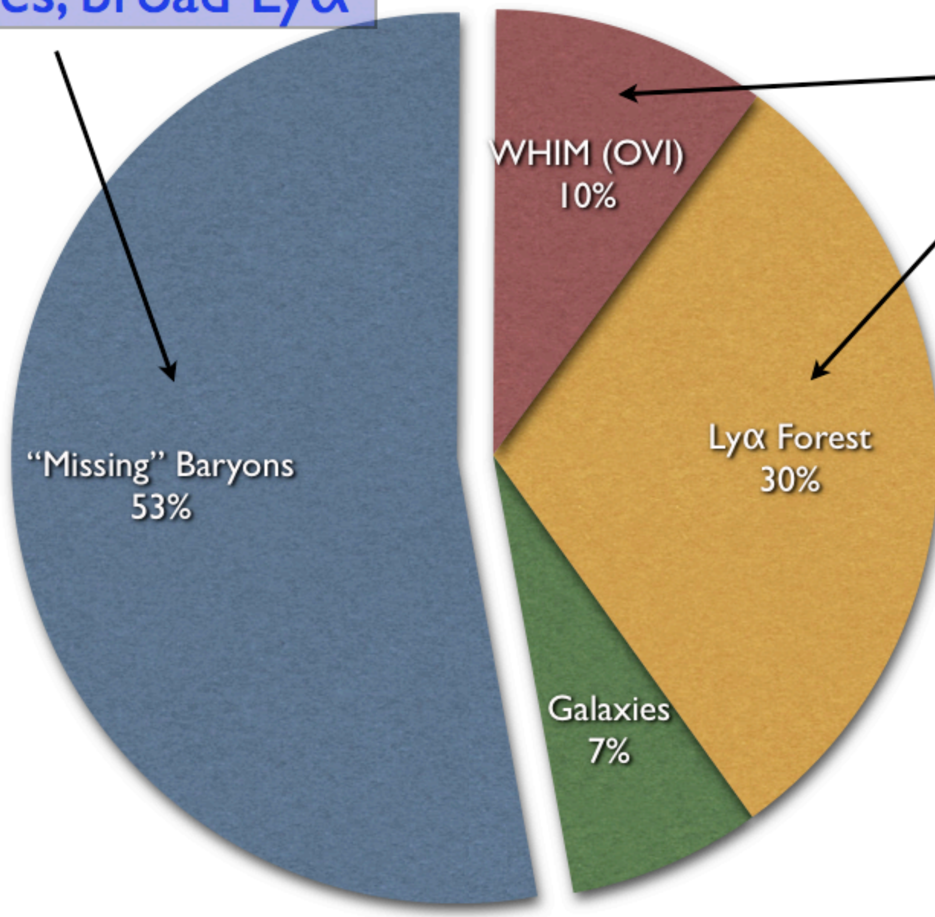
Gas @ z<0.2
T (K)
10^8
10^7
10^6
10^5
10^4
1000
100
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
$\rho_{gas}/<\rho_{gas}>$
OVI Absorption
OVIII Absorption
OVII Absorption
Local Ly α
Star forming gas
Unbound Gas
Gas within R_{vir}
Gas within R_{500}

WHIM perspectives

- This result is controversial as it is based on a single line of sight and ionization corrections are highly uncertain
- Searches of the WHIM with Suzaku were not successful
- The future lies in COS (for the O_{VI}) and the International X-ray Observatory (IXO), with a collecting area of 3,000 cm^2 and a resolving power of R=3,000
- It has been also suggested to use the X-ray afterglow of gamma-ray bursts as background sources

Baryon Census (low-z)

Probed by X-ray lines, broad Lyα



Both of these are uncertain

IGM Systematics:

- EUV radiation field
- Oxygen metallicity
- Ioniz corrections
- Cloud geometry

Summary of Results:

We have accounted for ~50% of the baryons

- 10% in collapsed structures (galaxies, clusters)
- 30% in warm (10^4 K) photoionized gas (Lyα)
- 10% in hot ($10^{5.5}$ K) gas (O VI ultraviolet lines)

Other 50% may be in even hotter (10^6 K) gas

The hot (O VI) gas is close to galaxies, and thus is a reservoir for low-Z gas infall

- Within 200 kpc of 0.1 L^* galaxies (outflows?)
- Cooling ⇒ 0.1 M_{sun}/yr infall to halos?