Evidence for the galaxy missing baryon in a hot X-ray-Halo

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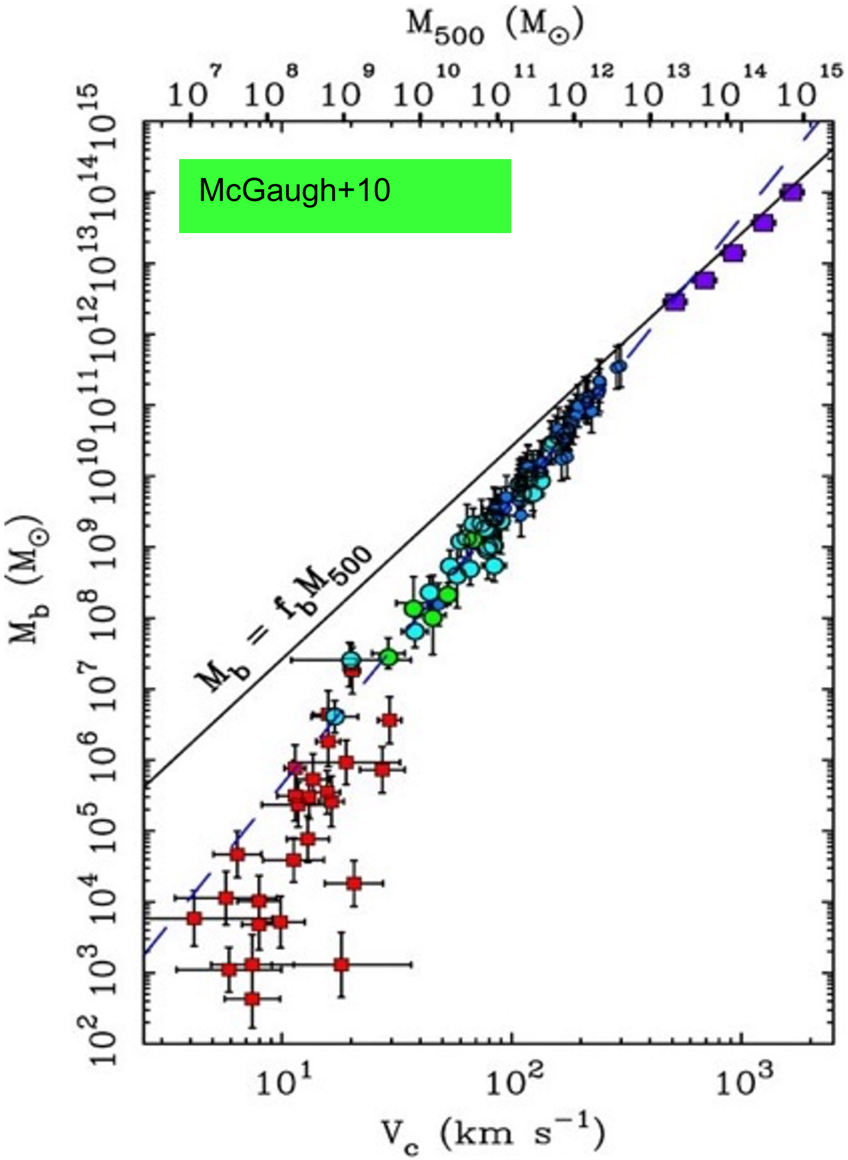
The Galaxy Missing Baryon Problem



$\Omega_b^{Planck18} = 0.0493 \sim 5\%$

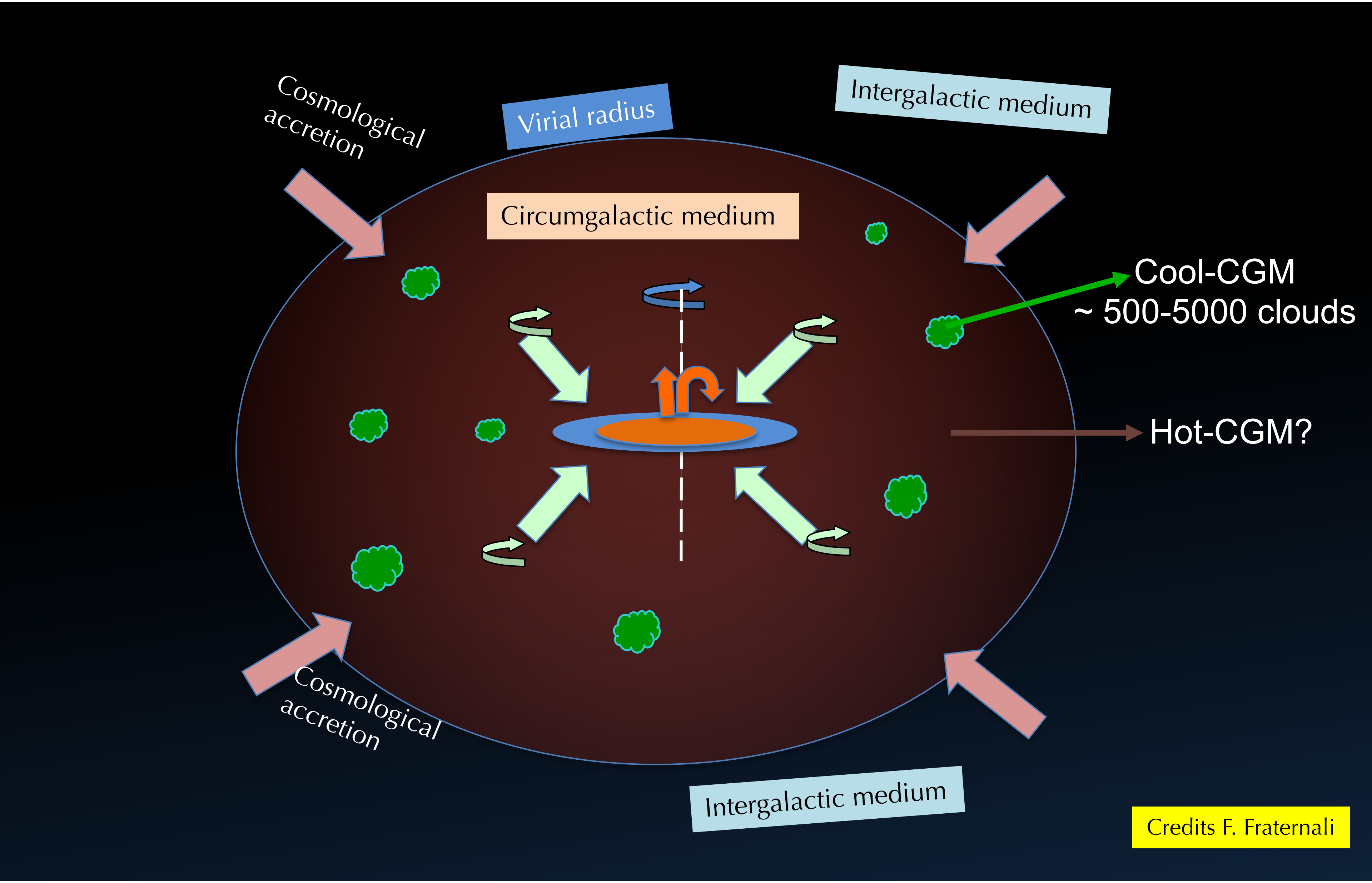
$f_b = \Omega_b / \Omega_m = 0.157$

L* galaxies with $M_h = 10^{12}\ M_\odot$

should have $M_b \sim 1.6\times10^{11}\ M_\odot$

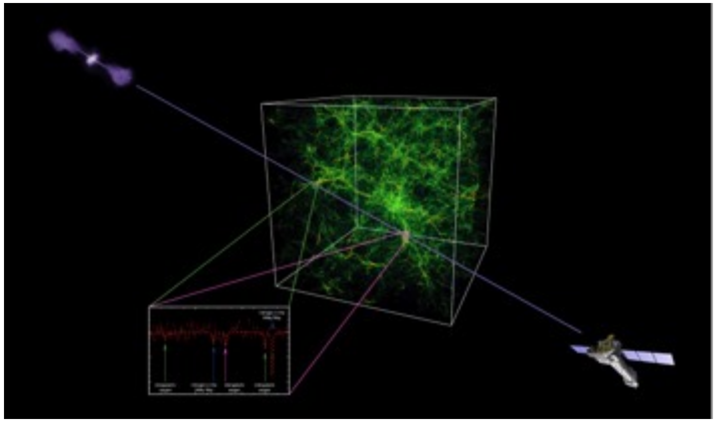
and have $M^* \sim 3\times10^{10}\ M_\odot$

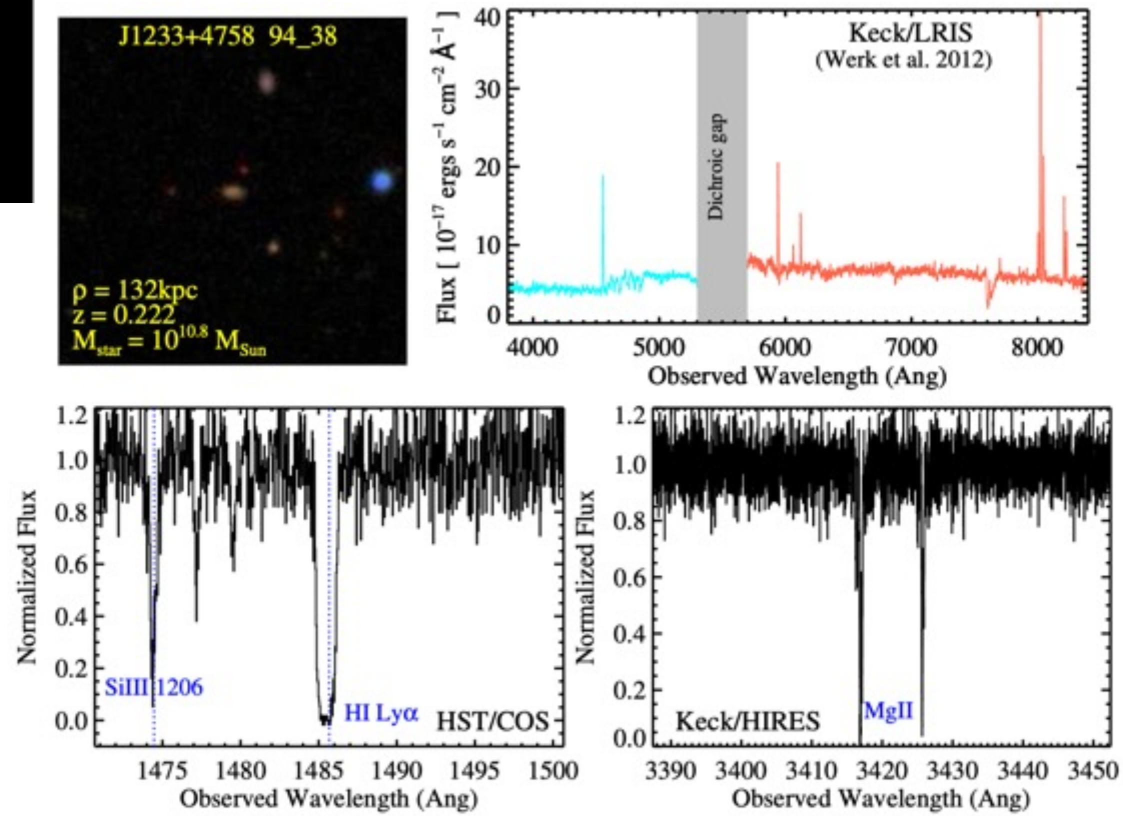
i.e. M_b(missing) ~ $4.3\times M^*$


Cosmological accretion
Virial radius
Intergalactic medium
Circumgalactic medium
Cool-CGM
~ 500-5000 clouds
Hot-CGM?
Cosmological accretion
Intergalactic medium
Credits F. Fraternali

The Cool-CGM: 1

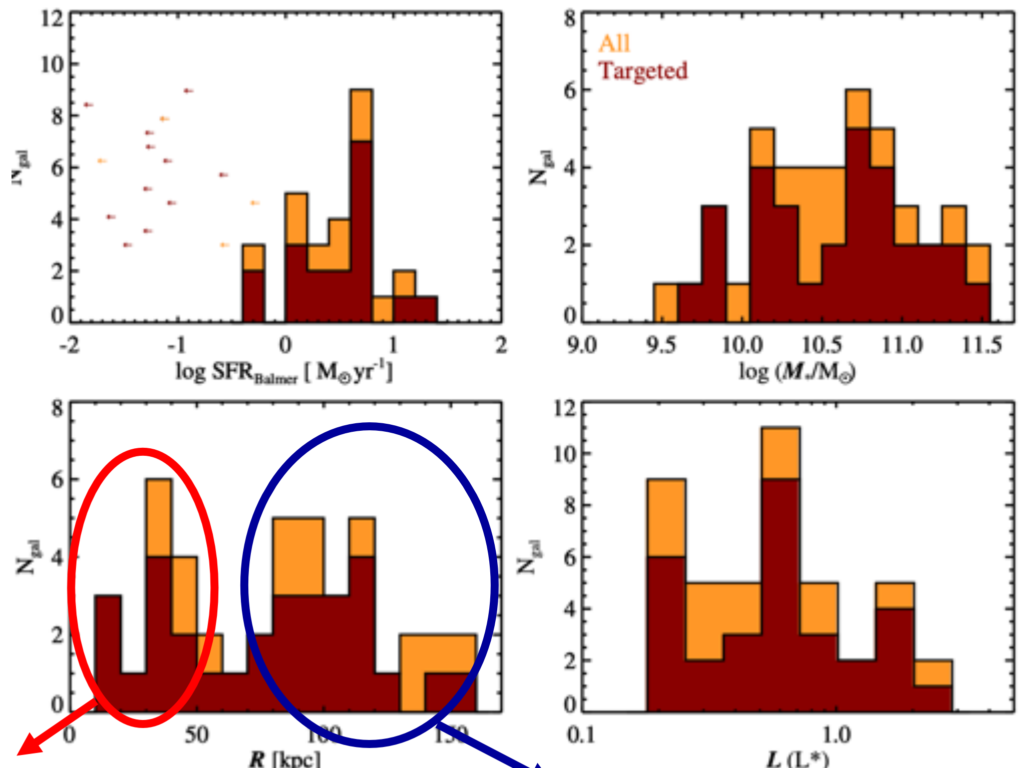
(Berg+19,22, Lenher+13,18,19, Werk+13,14, Wotta+19, Keeney+17, Fox+13, Stocke+13...)

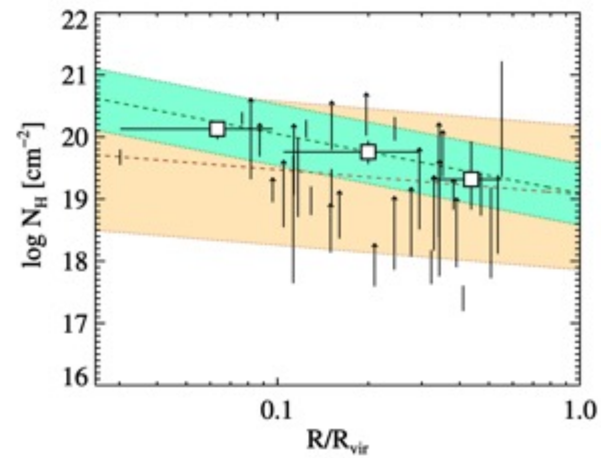




The Cool-CGM: 2

Werk+13,14

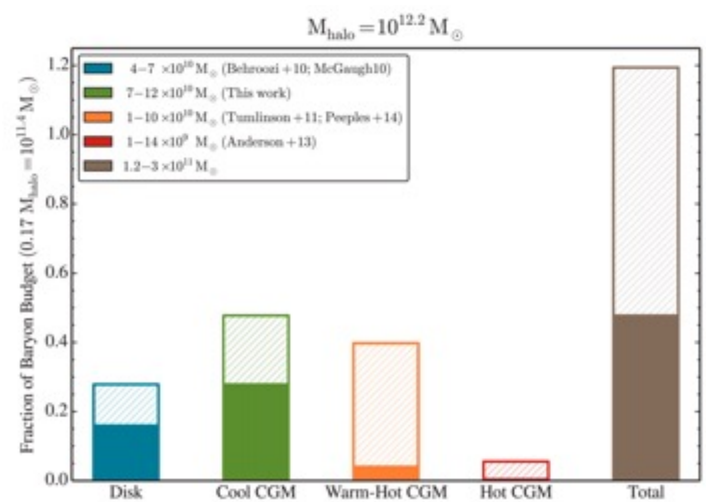




Extended Disk?

Halo

Possibly photoionized by the metagalactic radiation field

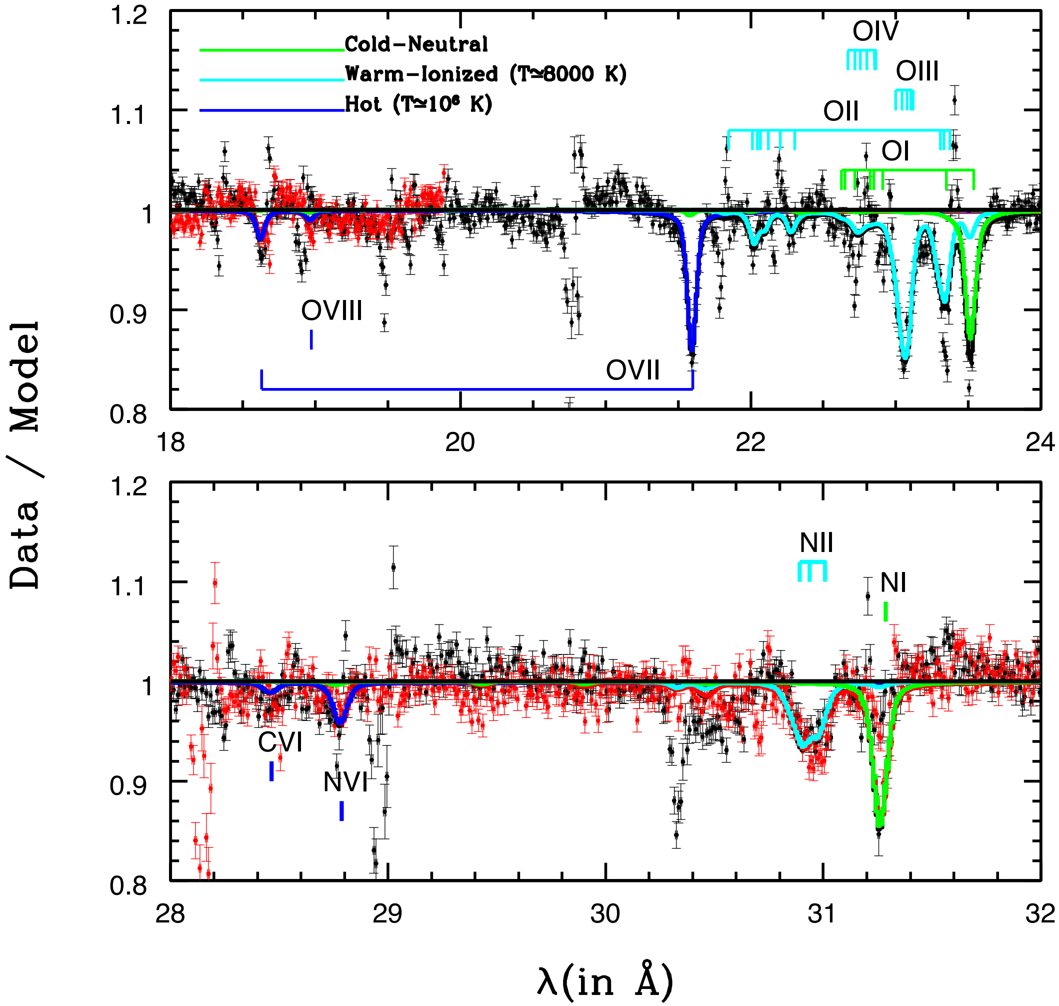


Relevant Questions

- 1) Where are the Galaxy’s baryons?
- 2) Are they in a hot-CGM?
- 3) If so, does it co-exist with the cool-CGM?
- 4) In what physical conditions?
- 5) And is its mass sufficient to close the galaxy baryon census?

All the X-Ray Colors of the Milky Way ISM/CGM Spectrum(Real Data)

XMM-Newton RGS Spectrum of Mkn 421 (z=0.03)



CNMM and LIMM are (mostly) confined in the thin and thick disks.

Where is the HIMM?

The Hot-CGM: Sample Selection

- 30 background quasars with LLSs ($16.2 \leq \log N_{HI} \leq 19$) from Lehner+13
- 11/30 with multiple archival XMM-RGS, and 2/11 also Chandra-LETG, public observations
- 4/11 have SNRE≥4 (allows Poisson) both in RGS and LETG
- 3/4 show hints for OVII Ka absorption and have galaxy association

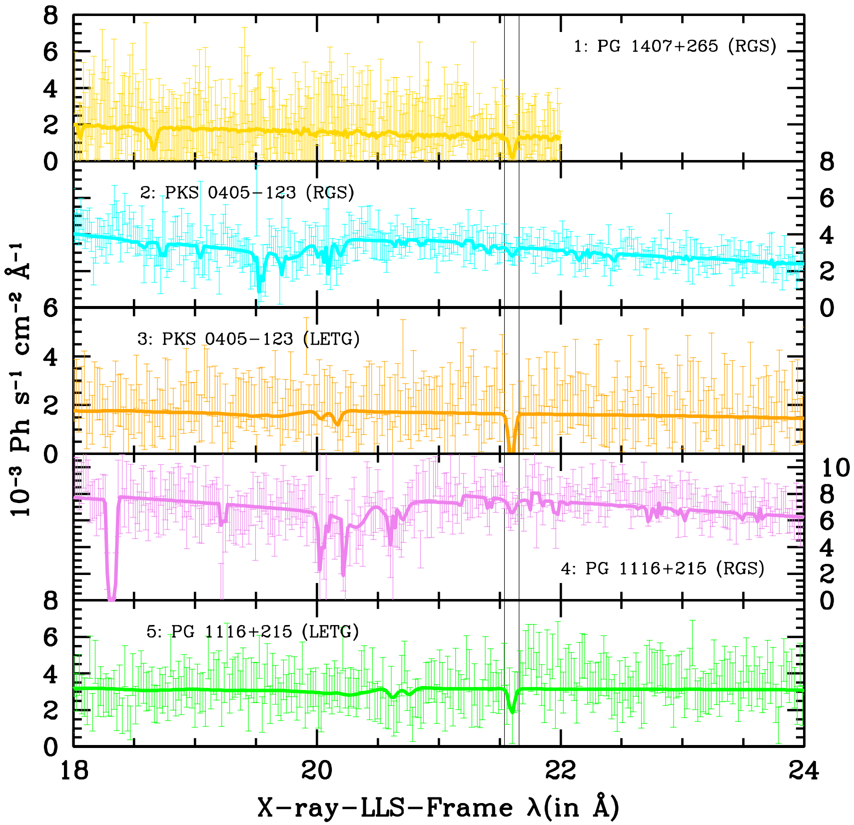
Galaxy-Halo properties

Table 2. *Properties of the LSS and the X-ray Halo*

QSO (LLS #)	z_{LLS}	M_* (in $\log M_\odot$)	M_h (in $\log M_\odot$)	R_{vir} (in kpc)	ρ (in kpc)	[X/H]	$\log N_{OVI}$ (in cm^{-2})	b_{OVI} (in $km\ s^{-1}$)
PG 1407+265 (#1)	0.6828	[a]10.9	12.4	[a]220	[a]91	[b]-1.66	[c]13.99 ± 0.06	[c]28 ± 10
PKS 0405-123 (#2)	0.1672	[d]10.3	[d]11.9	[d]183	[d]117	[b]-0.29	[c]14.59 ± 0.05	[c]78 ± 10
PG 1116+215 (#3)	0.1385	[e]10.3	11.9	[f]192	[g]127	[b]-0.56	[c]13.85 ± 0.05	[c]47 ± 10
X-ray Halo								
Weighted Averages	0.276	10.53	12.1	195	115	-0.514	14.29 ± 0.05	68 ± 10

[a]Burchett et al. (2019). [b]Wotta et al. (2019). [c]Fox et al. (2013). [d]Berg et al. (2023). [e]Assumed to be the same as PKS 0405-123, given the same halo mass. [f]Keeney et al. (2017). [g]Lehner et al. (2013).

Hints of OVII Kα in Single-Source Spectra



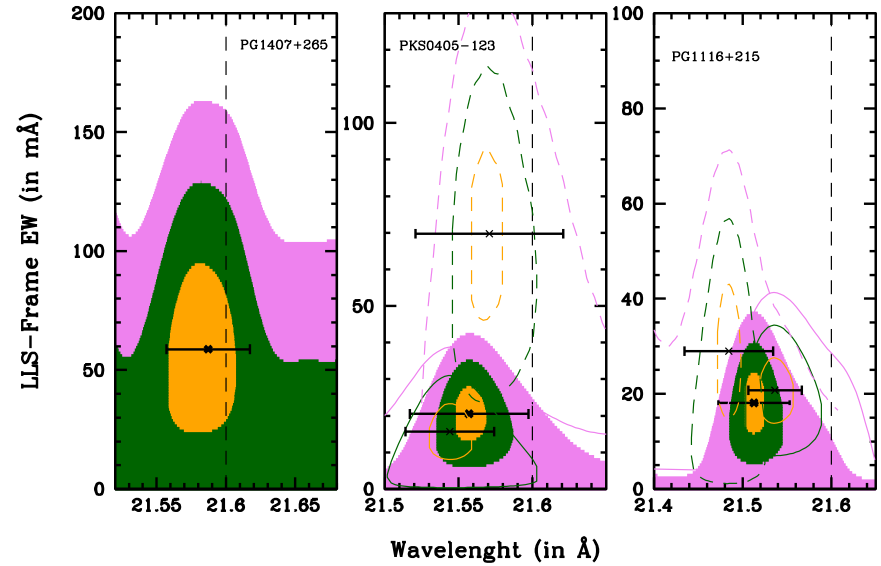


Table 1. *Best-fitting parameters of the X-ray-halo lines in the single spectra of the three targets*

X-Ray Spectrum	$\lambda^{O\,vii\,K\alpha}_{LLS-frame}$ (Å)	$EW^{O\,vii\,K\alpha}_{LLS-frame}$ (mÅ)	Δv (km s^{-1})	Significance
Fits to Individuals Spectra				
1: PG 1407+265 RGS	21.59 ± 0.03	59 ± 35	$-(140 \pm 420)$	1.7σ
2: PKS 0405-123 RGS	21.54 ± 0.03	15.7 ± 7.1	$-(830 \pm 420)$	2.2σ
3: PKS 0405-123 LETG	21.57 ± 0.05	69 ± 25	$-(420 \pm 690)$	2.8σ
4: PG 1116+215 RGS	21.54 ± 0.03	20.8 ± 8.0	$-(830 \pm 420)$	2.6σ
5: PG 1116+215 LETG	21.48 ± 0.05	29.0 ± 14.5	$-(1670 \pm 690)$	2.0σ
Joint-fits to RGS+LETG spectra with EWs linked to the same value				
PKS 0405-123 RGS+LETG	21.56 ± 0.04	20.5 ± 7.3	$-(560 \pm 560)$	2.8σ
PG 1116+215 RGS+LETG	21.51 ± 0.04	18.1 ± 6.5	$-(1250 \pm 560)$	2.8σ
Weighted averages and coadded significance				
X-Ray halo	21.55 ± 0.04	28.5 ± 6.6	$-(690 \pm 560)$	4.3

Simultaneous Fitting

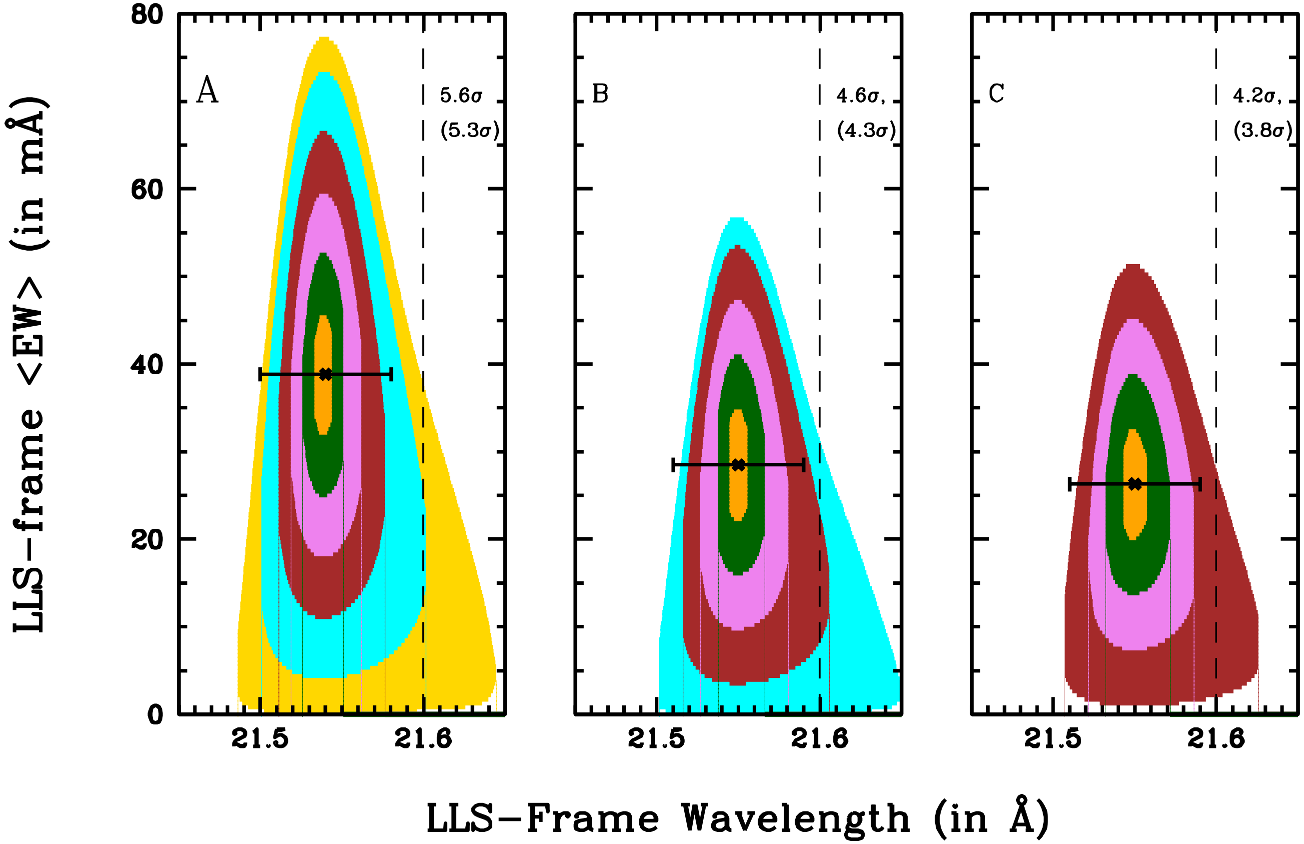
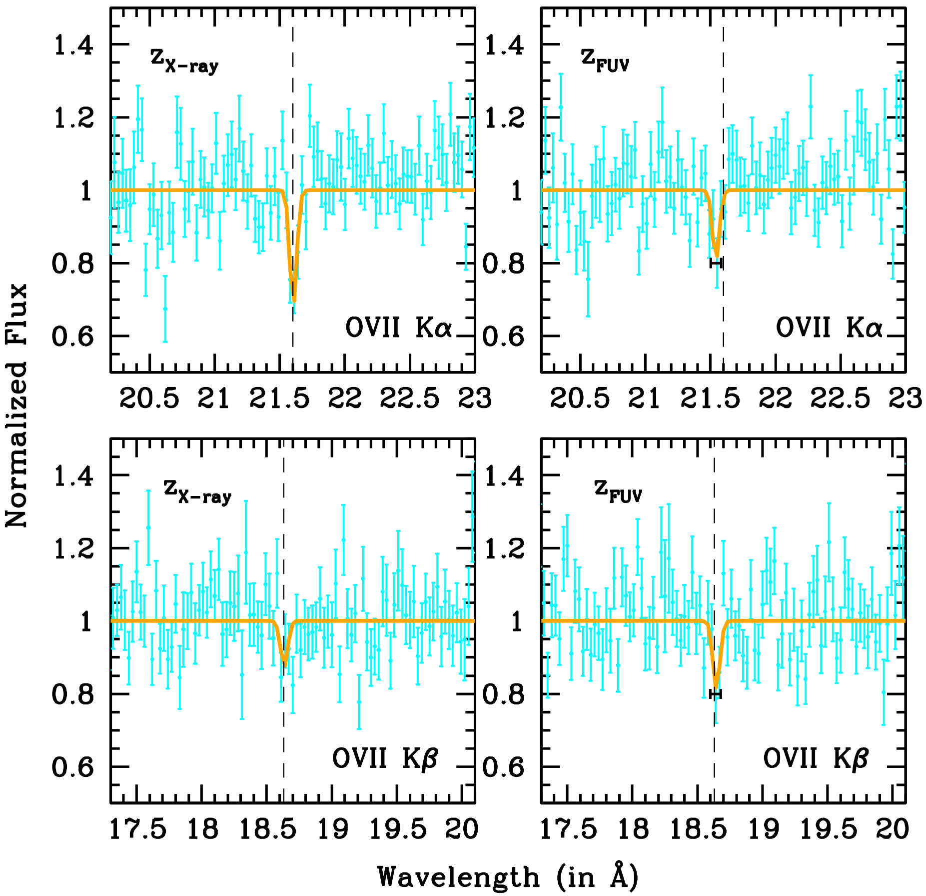


Table 2. *Best-fitting parameters of the X-ray halo absoprtion lines from the simultaneous fits*

Method	$<\lambda^{O\,vii\,K\alpha}_{LLS-frame}>$ (Å)	$<\lambda^{O\,vii\,K\beta}_{LLS-frame}>$ (Å)	$<EW^{O\,vii\,K\alpha}_{LLS-frame}>$ (mÅ)	$<EW^{O\,vii\,K\beta}_{LLS-frame}>$ (mÅ)	Δv km s^{-1}	Significance of the X-ray halo
A	21.54 ± 0.04	[a]18.58	39.1 ± 7.4	9.4 ± 5.2	$-(830 \pm 560)$	5.6σ
B	21.55 ± 0.04	[a]18.59	28.5 ± 6.7	16.4 ± 10.3	$-(690 \pm 560)$	4.6σ
C	21.55 ± 0.04	[a]18.59	26.4 ± 7.1	17.3 ± 8.7	$-(690 \pm 560$	4.2σ

[a] Linked to the Kα position through the ratio of the rest-frame line positions.

Stacked Spectrum



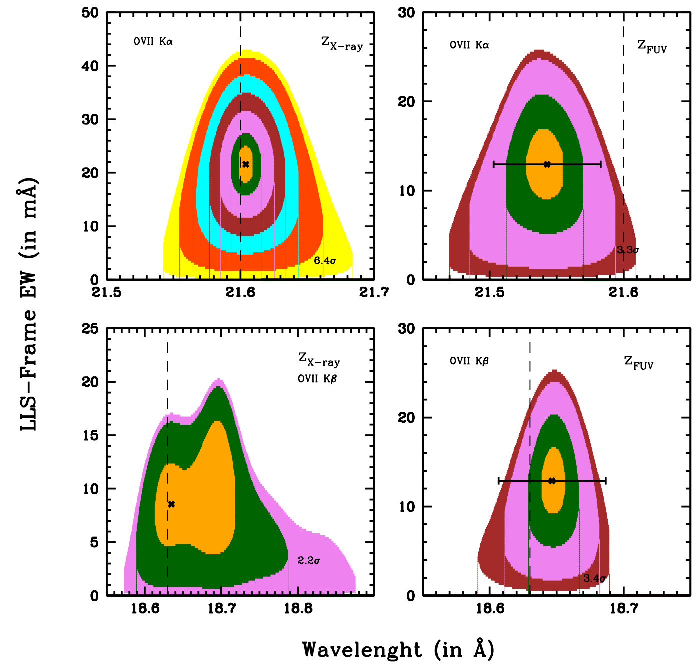


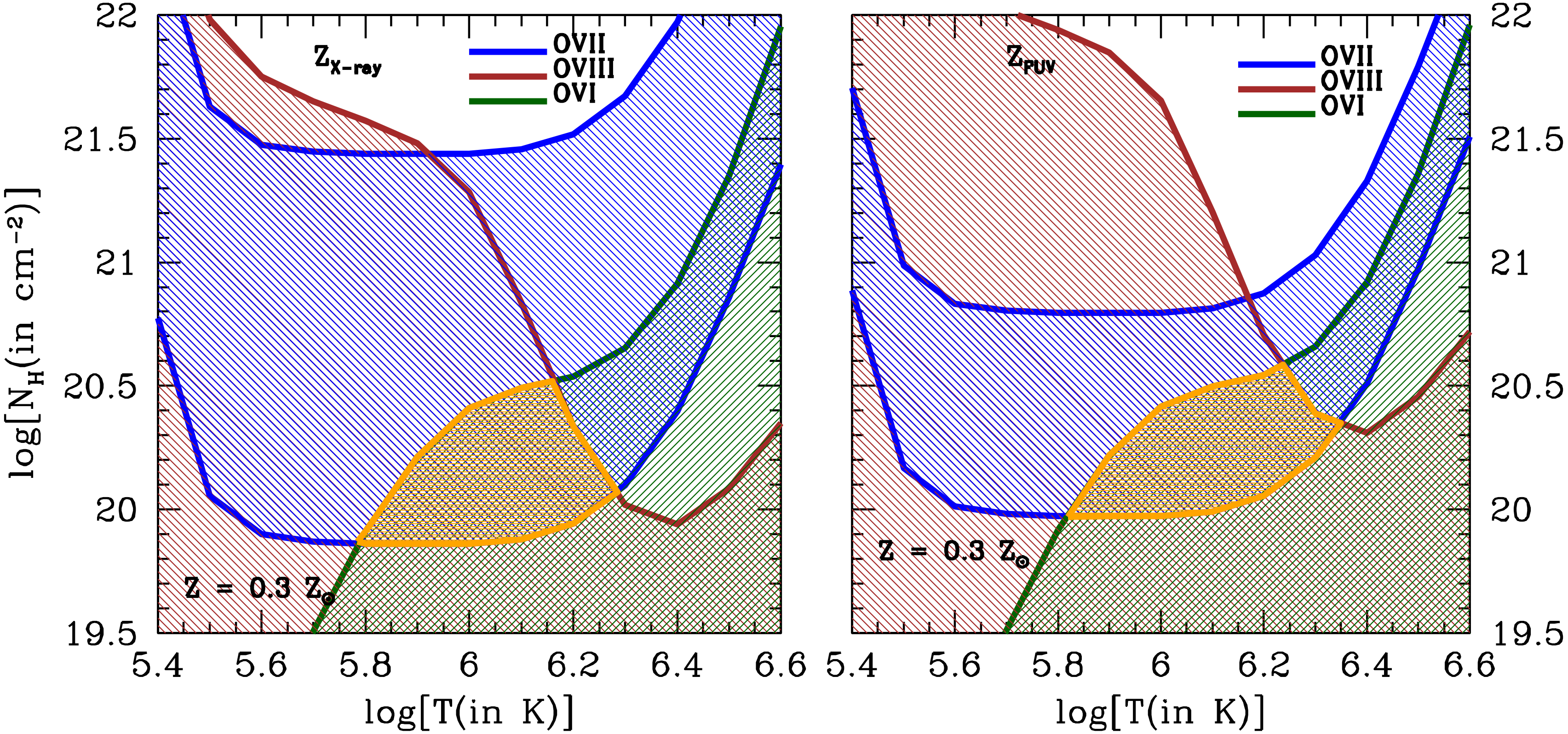
Table 5. *Best-fitting X-ray halo absorption line parameters*

Line Parameter	O VII Kα	O VII Kβ	O VIII Kα
X-Ray-LLS Spectrum			
Centroid (in Å)	$21.604^{+0.007}_{-0.006}$	$18.64^{+0.08}_{-0.02}$	[a]18.97
EW (in mÅ)	21.6 ± 3.4	8.6 ± 4.0	≤ 7.9
Significance	6.4σ	2.2σ	90%
Combined Significance		6.8σ	
FUV-LLS Spectrum			
Centroid (in Å)	$21.54^{+0.02}_{-0.01}$	$18.647^{+0.009}_{-0.010}$	[a]18.97
EW (in mÅ)	12.9 ± 3.9	12.9 ± 3.8	≤ 11.4
Significance	3.3σ	3.4σ	90%
Combined Significance		4.7σ	

[a] Frozen in the fit.

Equivalent-Hydrogen Column density

$$N_b \approx (10^{19.9} - 10^{20.6})\ (Z/0.3Z_\odot)^{-1}\ \mathrm{cm}^{-3}$$



Physical Conditions of the X-ray Halo

logT ≈ 5.8–6.3 K

This is consistent with the virial temperature of a $M_h = 10^{11.95} M_{\odot}$ halo,

$\log T_{vir} \approx 6.0$

$$n_b = \frac{N_b}{L} = \frac{N_b}{2 f_l \sqrt{R_{vir}^2 - \rho^2}} \approx (10^{19.9} - 10^{20.6})/9.2\times10^{23} \approx (0.8 - 4.3)\times10^{-4} \text{ cm}^{-3}$$

➔ $P_{Hot} = n_b T \approx 50 - 900 \text{ K cm}^{-3}$

For the cool-CGM and if photoionization is at work:

$P_{Cool} = n_b T \approx 5 \text{ K cm}^{-3}$

➔ Pressure equilibrium ⬄ Cool clouds > 10x denser ⬄ r_{cloud}~ 1-2 kpc, as Galactic HVCs if at 100 kpc

➔ Equilibrium-Photoionization probably not the main mechanism for the cool clouds

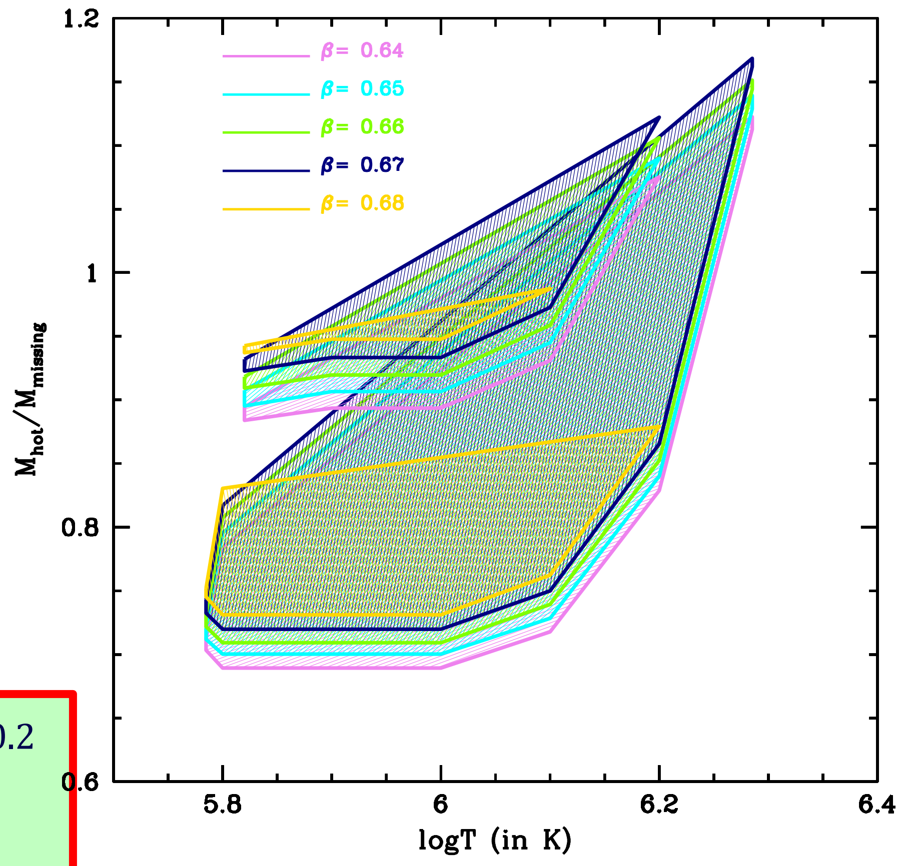
Baryon Mass of the X-ray-halo up to 1 R_{vir}

Integrates the density profile in a spherical geometry from the center of the halo to R_{vir} and imposes that, at ρ=115 kpc, N_H matches the range of observed values

$$Beta - Profile:$$
$$f(\beta; R_c, n_b^0) = n_b^0[1 + (r/R_c)^2]^{-3\beta/2}$$
β=0.64–0.68 (isothermal halo)
R_c = 1– 5 kpc
$n_b^0 = 0.0004 - 0.1\ \mathrm{cm}^{-3}$

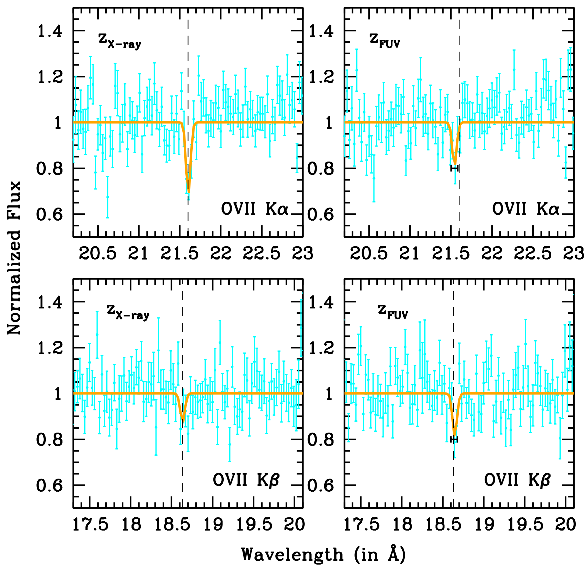
$$\xi_b(\beta = 0.64 - 0.68) = \frac{M_{hot-CGM}}{f_b M_h - M^* - M_{cool-CGM}} = 0.9 \pm 0.2$$

Close the galaxy baryon census

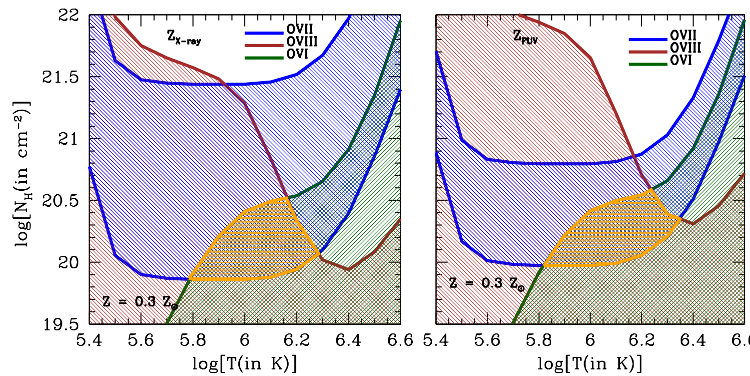


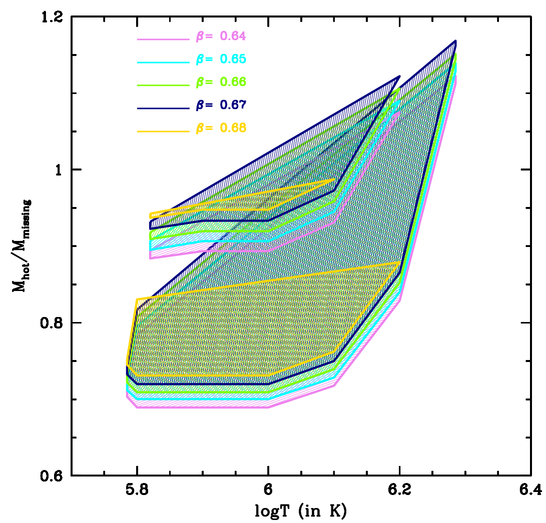
Summary

6.8σ (4.7σ @ FUV-LLS)



$\log N_H$(in cm^{-2}) ≈ 19.8-20.6
$\log T$(in K)=5.8–6.3





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