(Missing) Hot Baryons/Metals: in or out of halos?

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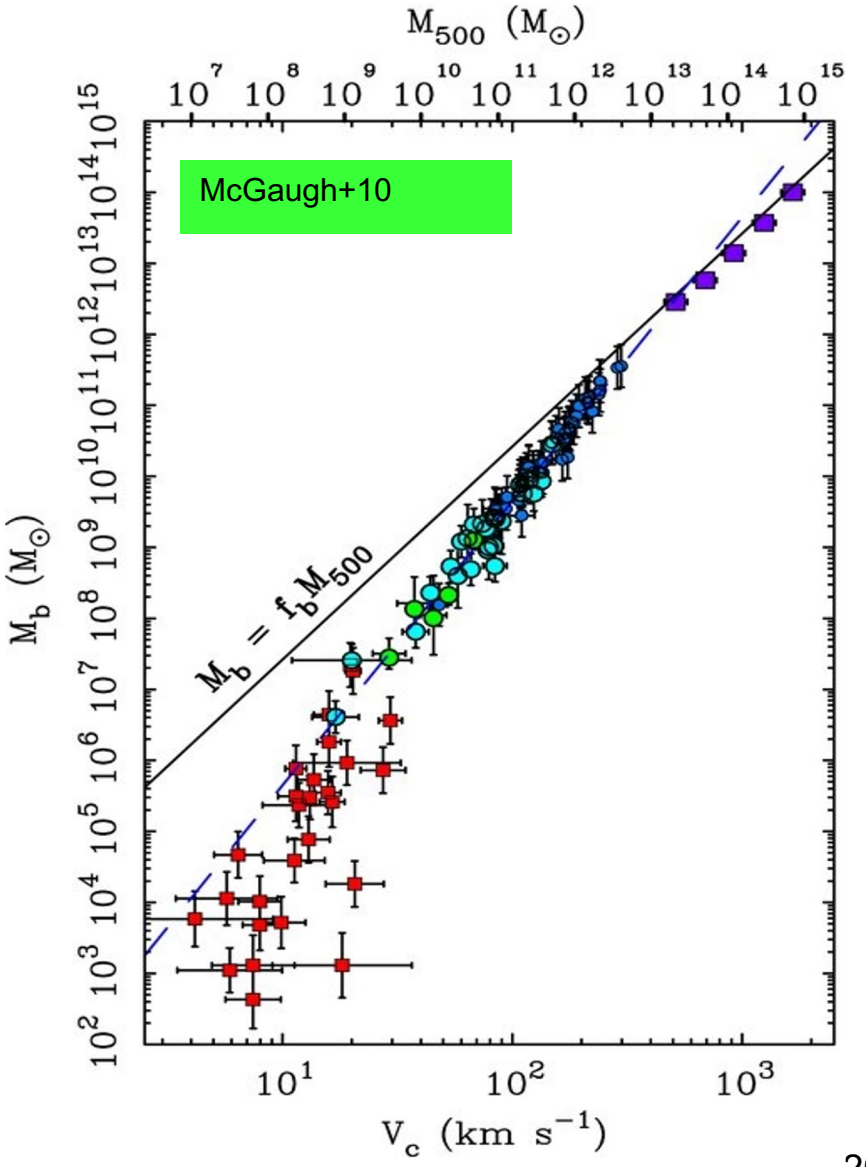
Outline

- The Universe and galaxy's missing baryons/metals: are they bound to or unbound from structures?
- (UV and) X-ray Observations of the Milky-Way and external galaxies' hot CGM
- Detectability and Study of LSS gas absorption with future X-ray instruments

The Galaxy Missing Baryon Problem



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

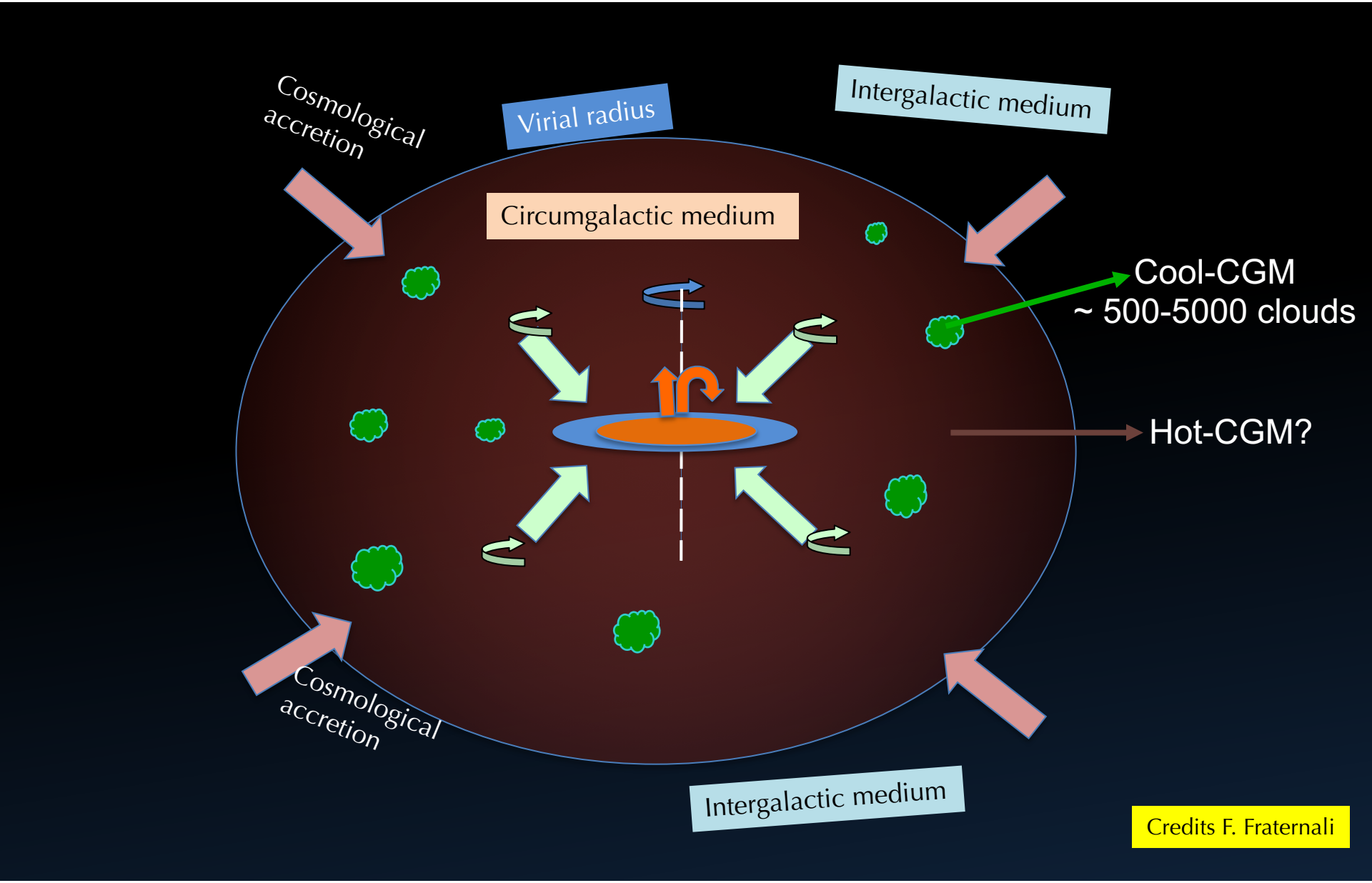
$f_b = \Omega_b / \Omega_m = 0.157$

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

should have $M_b \sim 1.6 \times 10^{11}\ M_\odot$

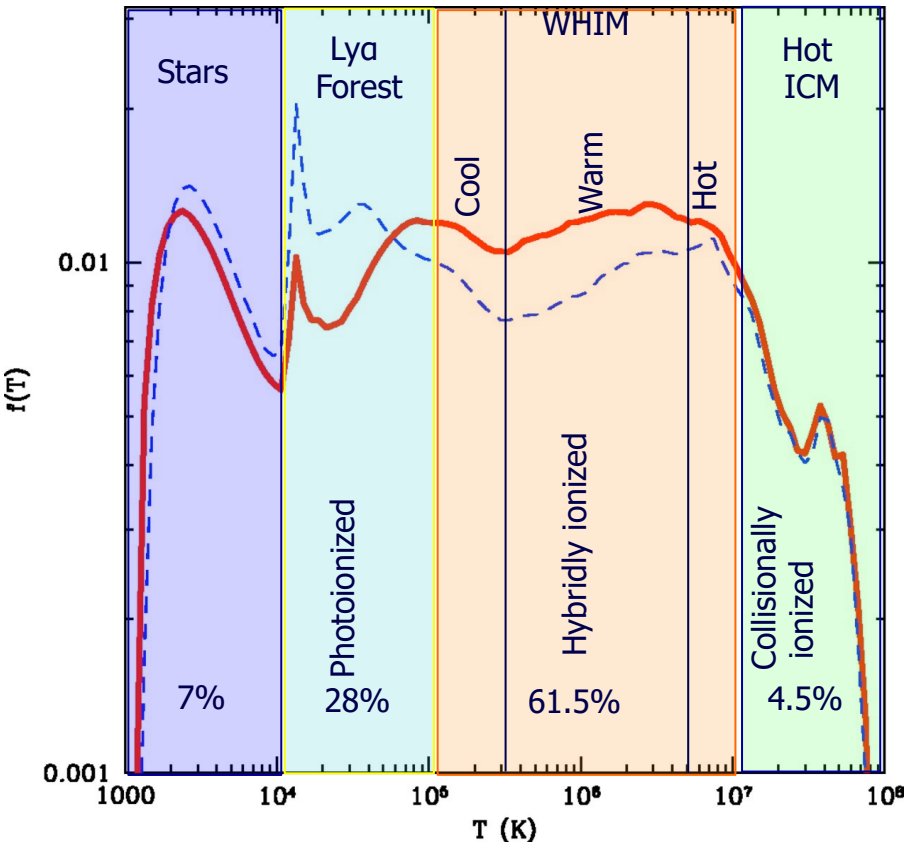
and have $M^* \sim 3 \times 10^{10}\ M_\odot$

i.e. $M_b(\text{missing}) \sim 4.3 \times M^*$


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

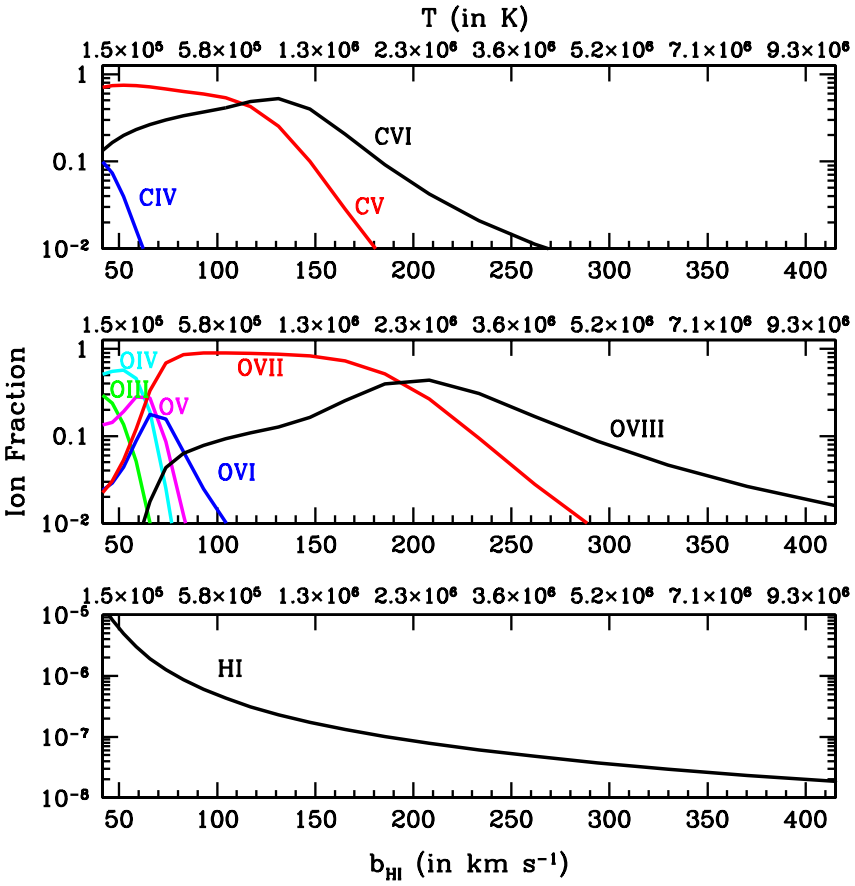
The Baryon Phases in HDS

Differential Mass Fraction vs T



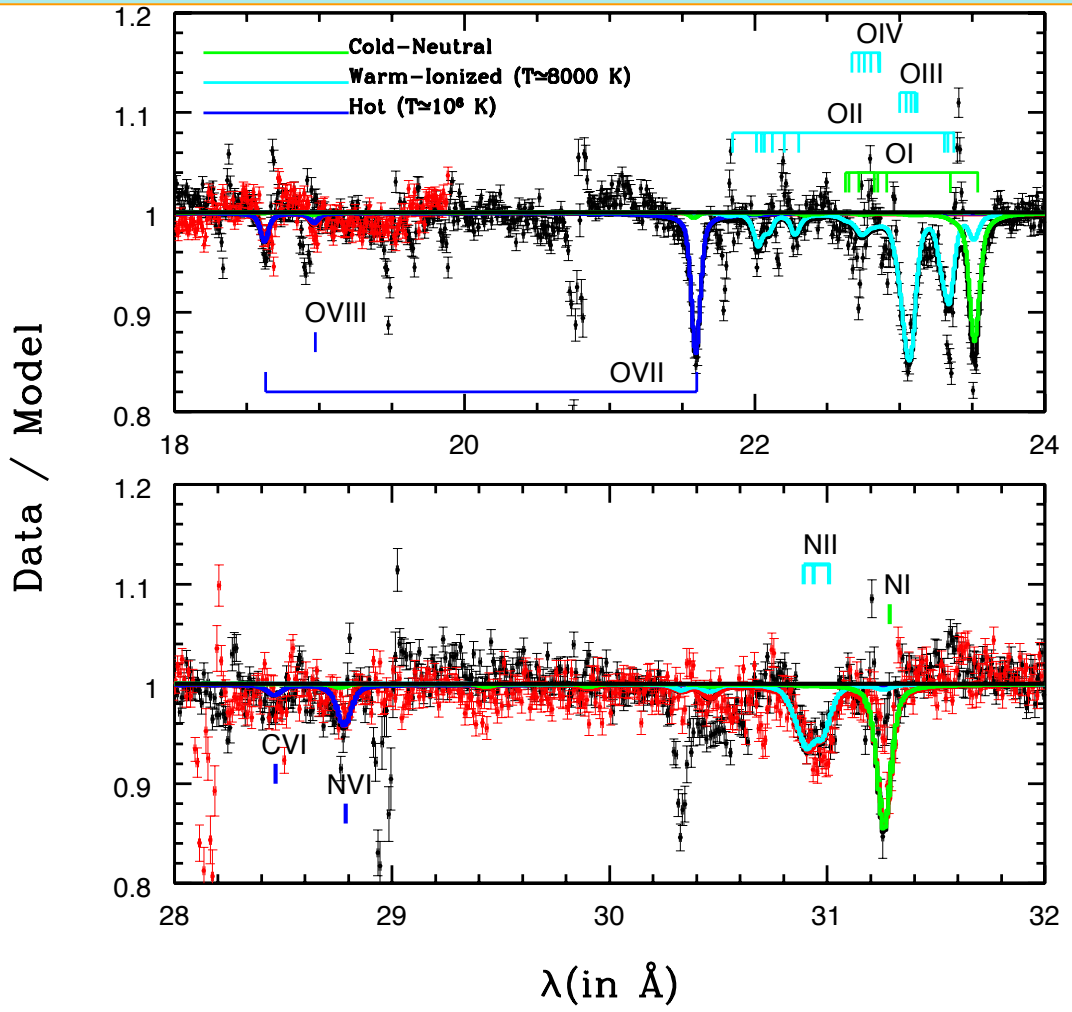
Cen & Ostriker 06

Hybridly Ionized IGM (δ=50)



The Hot Phase: All the X-Ray Colors of the Milky Way

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?

Q. Yu Z. Zheng

Submitted to Science

The Hot Phase of the Milky Way

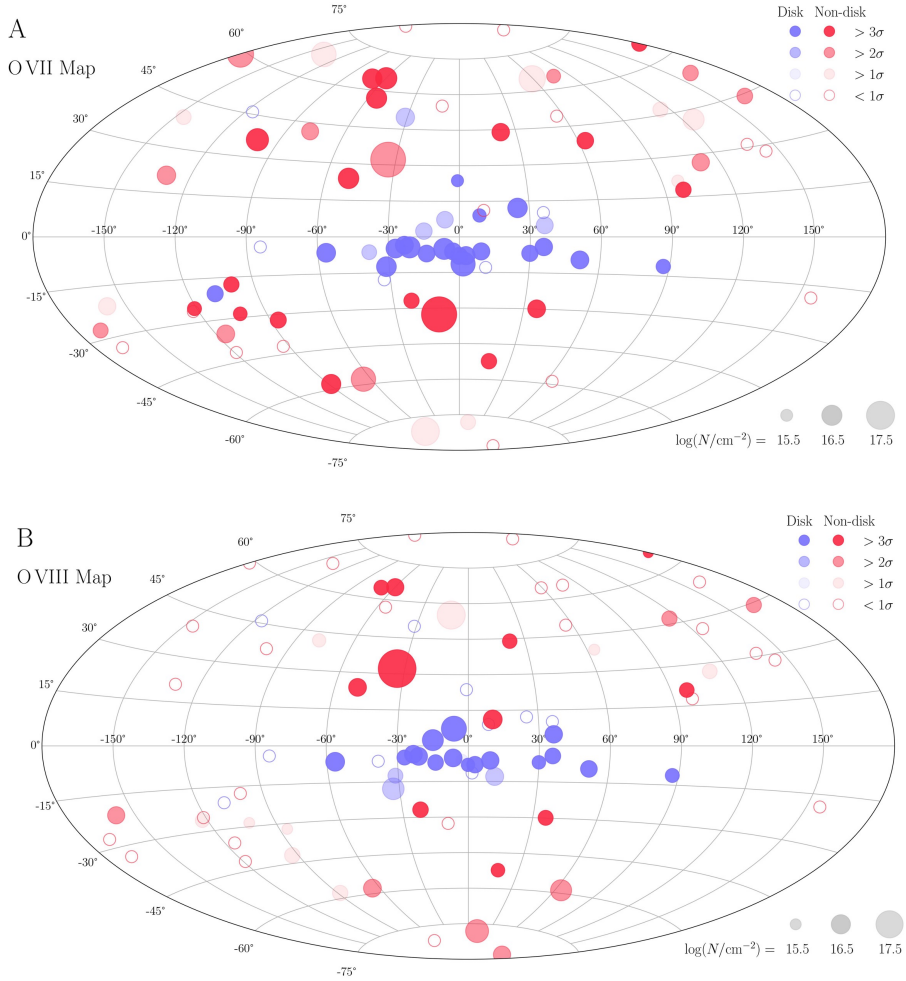
Motivation and sample selection

Motivation:

- Emission study, which is biased by the nearest and densest structures, hinted the presence of an extended hot halo;
- Detect the hot halo using absorption of Galactic OVII and OVIII lines, which is unbiased by the gas density and distance.

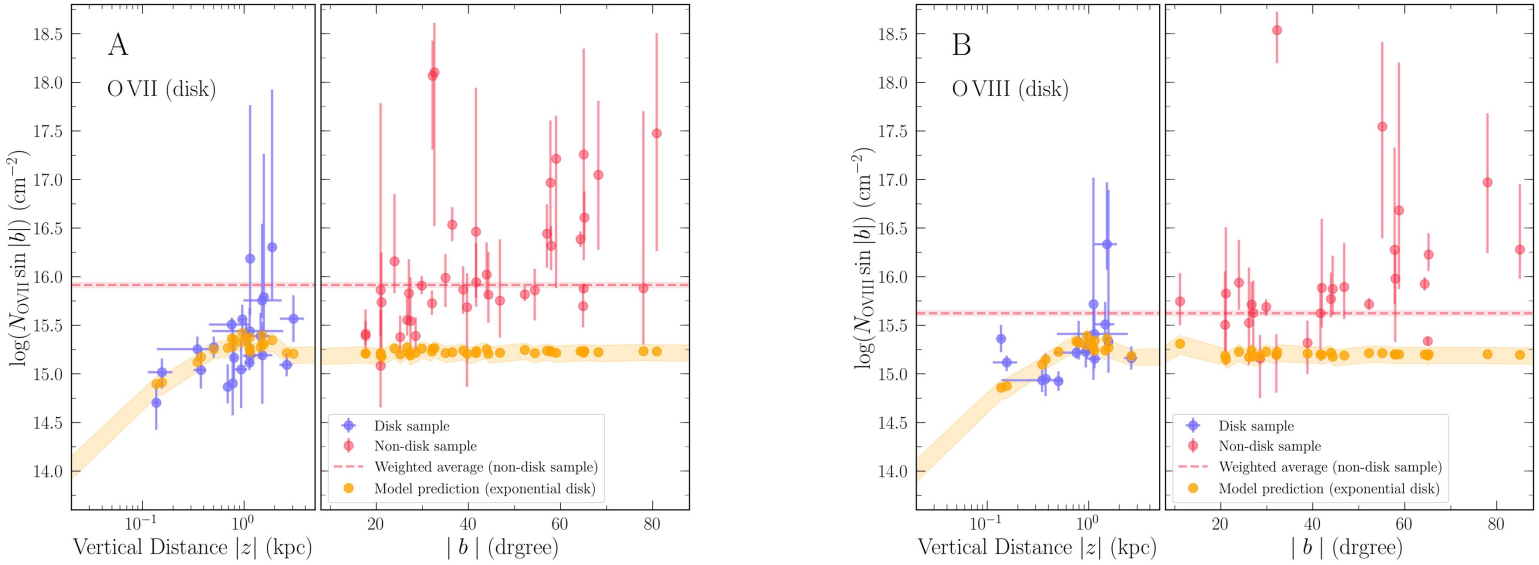
Sample selection:

- XMM-Newton/RGS data observed before Dec 2023;
- Bright AGNs and XRBs with CPRE>20 counts (SNRE>7.5) in the continuum at the wavelengths of OVII Kα, OVII Kβ, OVIII Kα, and OVIII Kβ;
- 30 disk (nearby XRBs) and 52 non-disk (distant XRBs and AGNs) LOSs are selected.



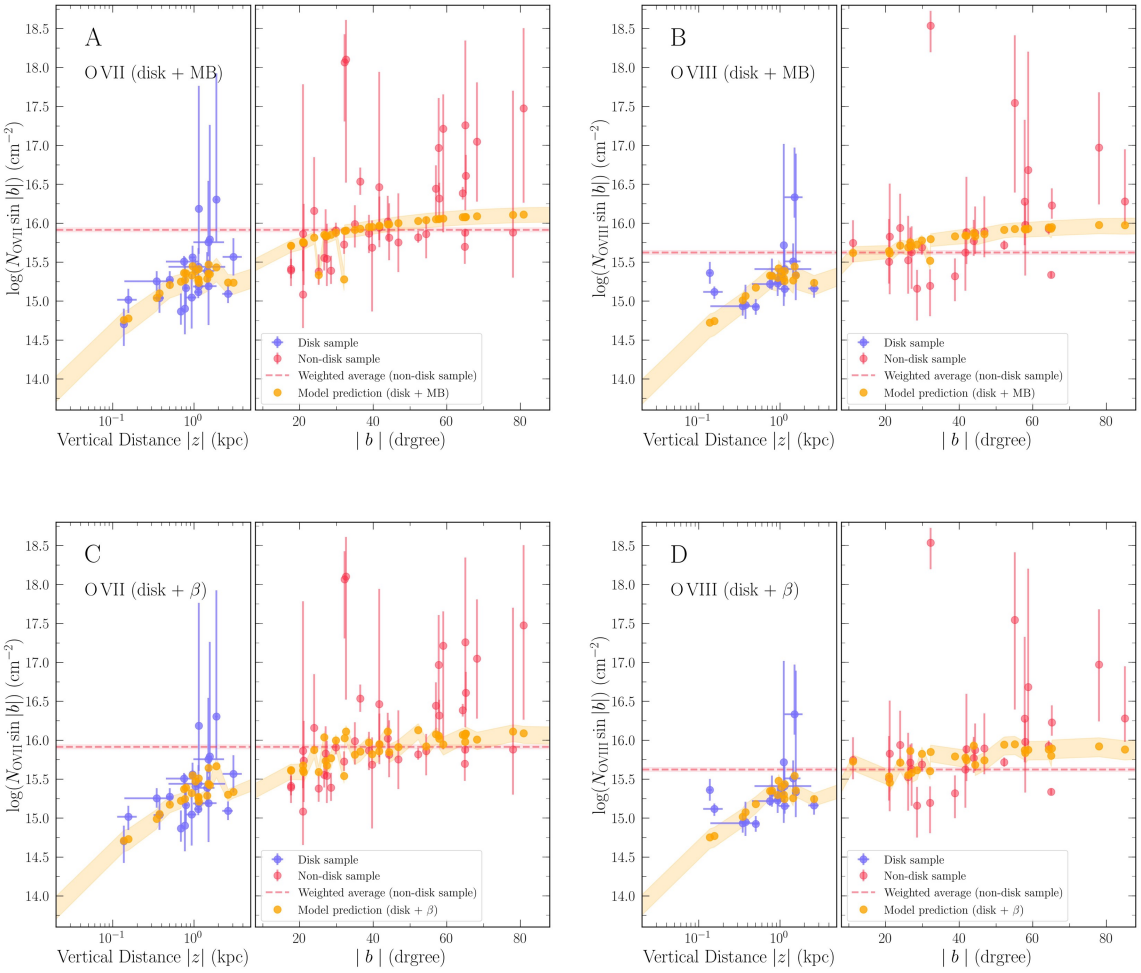
Zhou, Fang, Nicastro et al., 2024

Hot Gas in the halo: excess absorption against non-disk LOSs



- Exponential disk $n(R,z) = n_0\, exp(-R/R_0)\, exp(-z/z_0)$, jointly fit the OVII and OVIII data of the disk sample under CIE;
- A pronounced excess against the non-disk LOSs: $7.1\,\sigma$ for OVII and $4.2\,\sigma$ for OVIII, $8.2\,\sigma$ in combination;
- Indicating that the hot disk contributes to $20 \pm 4\%$ of the total Galactic OVII absorption against non-disk LOSs and $38 \pm 8\%$ of the OVIII absorption.

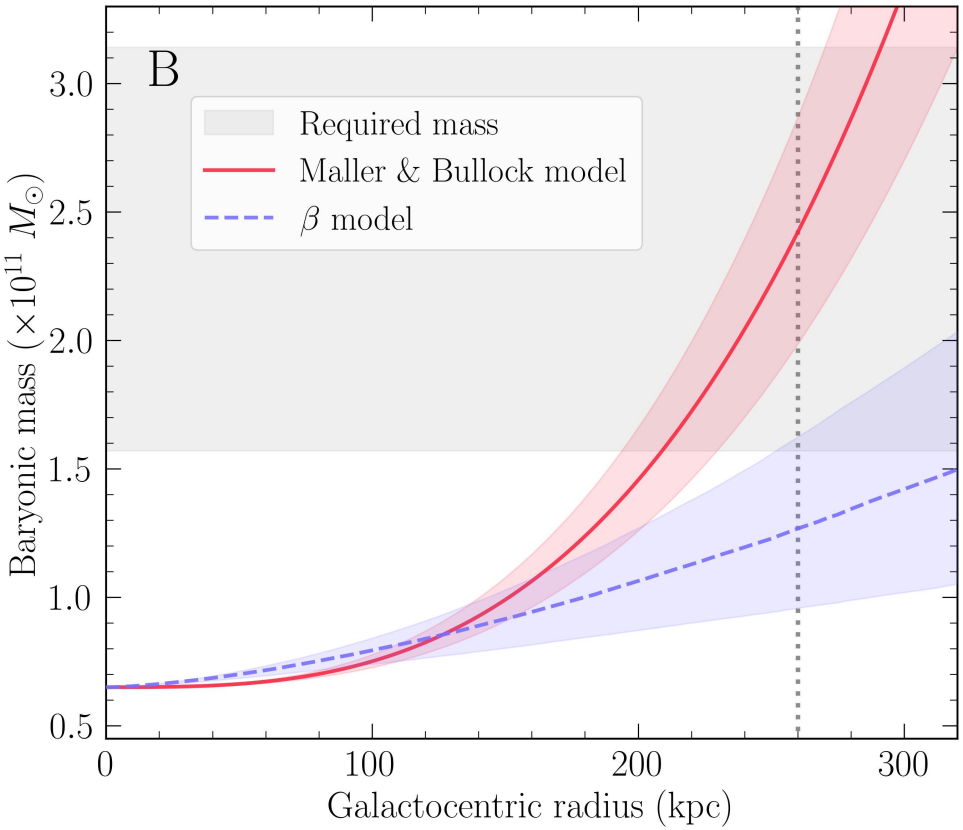
Modeling the Milky-Way’ s halo Hot Phase



- (A) and (B): Maller-Bullock profile (Maller & Bullock 2004).

- (C) and (D): β model

The Total Baryon Mass of the Milky Way



- Cold (6.5×10^{10} $M_\odot$) + hot gas;
- Gray shows the required baryonic mass predicted by the cosmological mean (assumed a DM halo of $(1-2)\times 10^{12}$ $M_\odot$)
- Integrating the β model to $1.3r_{\mathbf{vir}}$ could close the Galactic baryon census.

Nicastro+23

The Hot-CGM in external galaxies

- 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

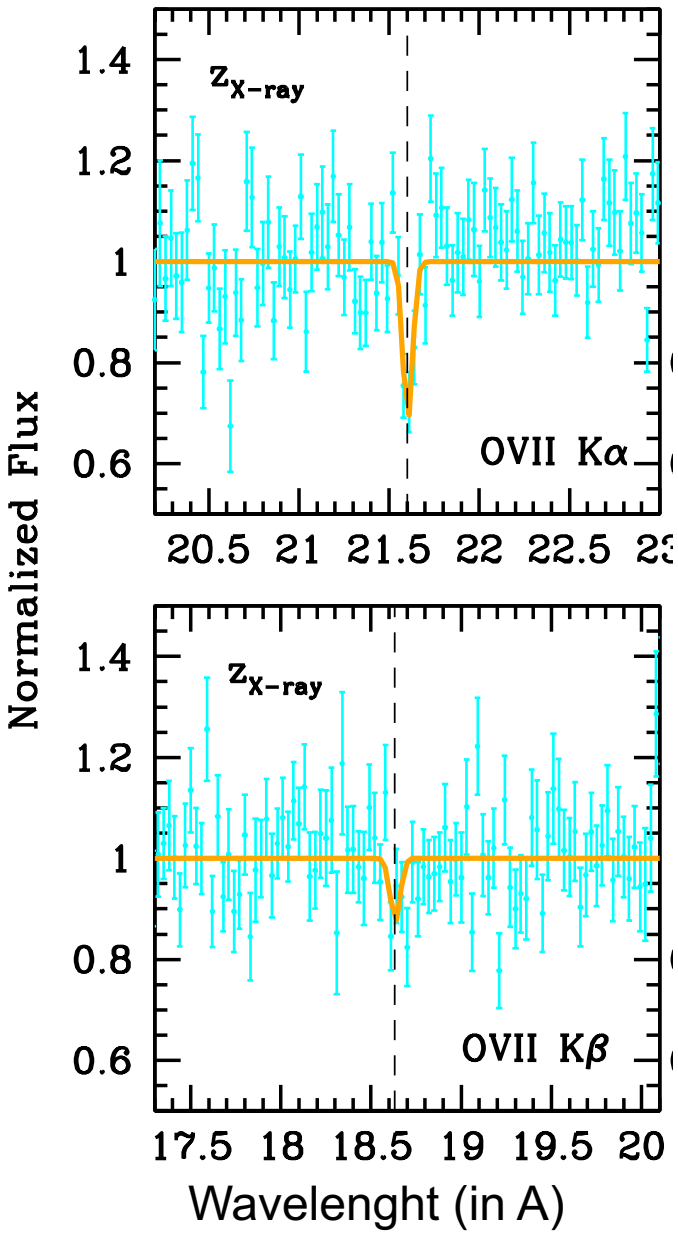
Galaxy-Halo properties

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

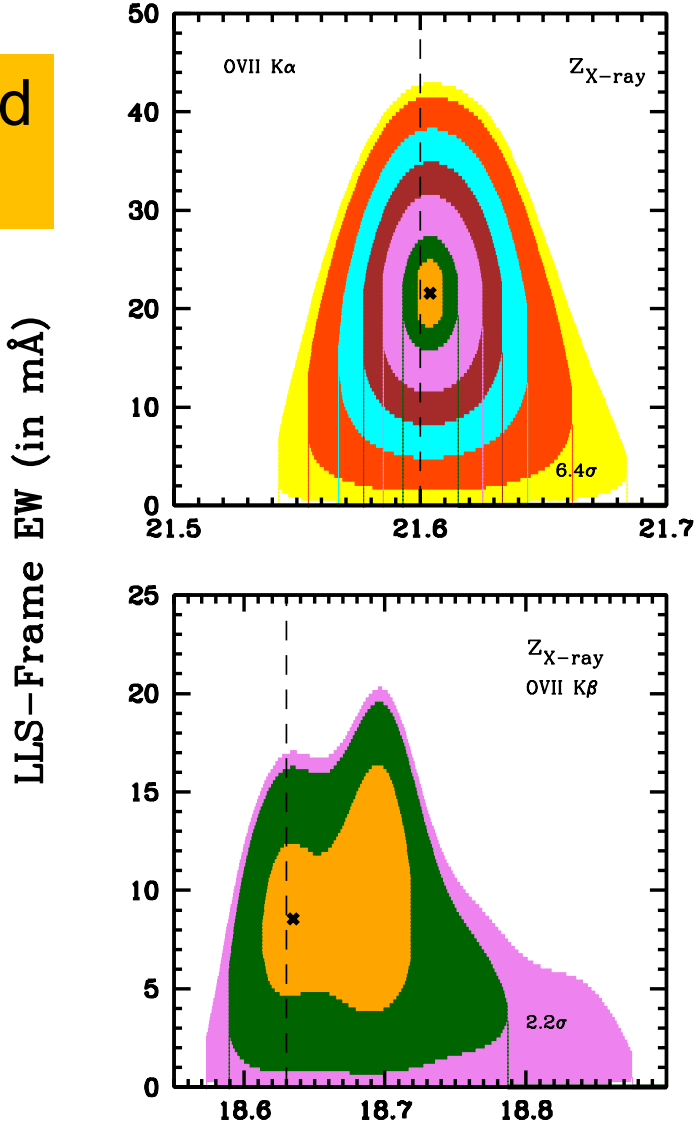
QSO (LLS #)	z_{LLS}	M_* (in $\log M_\odot$)	M_h (in $\log M_\odot$)	R_{vir} (in kpc)	ρ (in kpc)	[X/H]	$\log N_{OVI}$ (in cm^{-2})	b_{OVI} (in km s^{-1})
PG 1407+265 (#1)	0.6828	[a]10.9	12.4	[a]220	[a]91	[b]-1.66	[c]13.99 ± 0.06	[c]28 ± 10
PKS 0405-123 (#2)	0.1672	[d]10.3	[d]11.9	[d]183	[d]117	[b]-0.29	[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).

Stacked spectrum of the hot halo



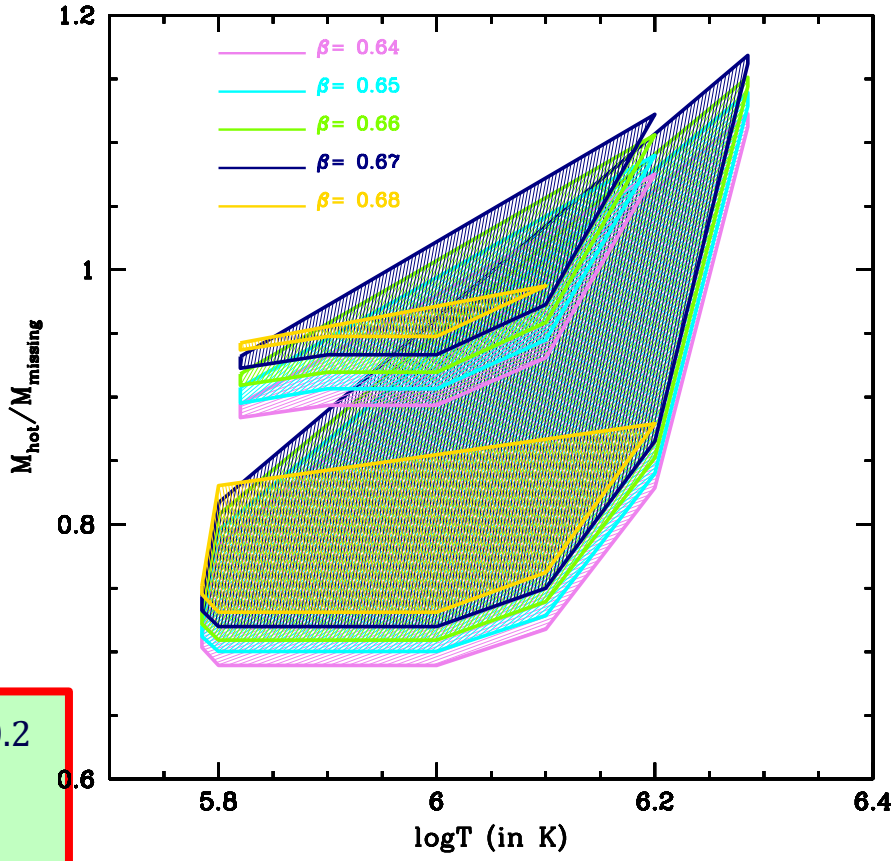
Combined
6.8σ



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

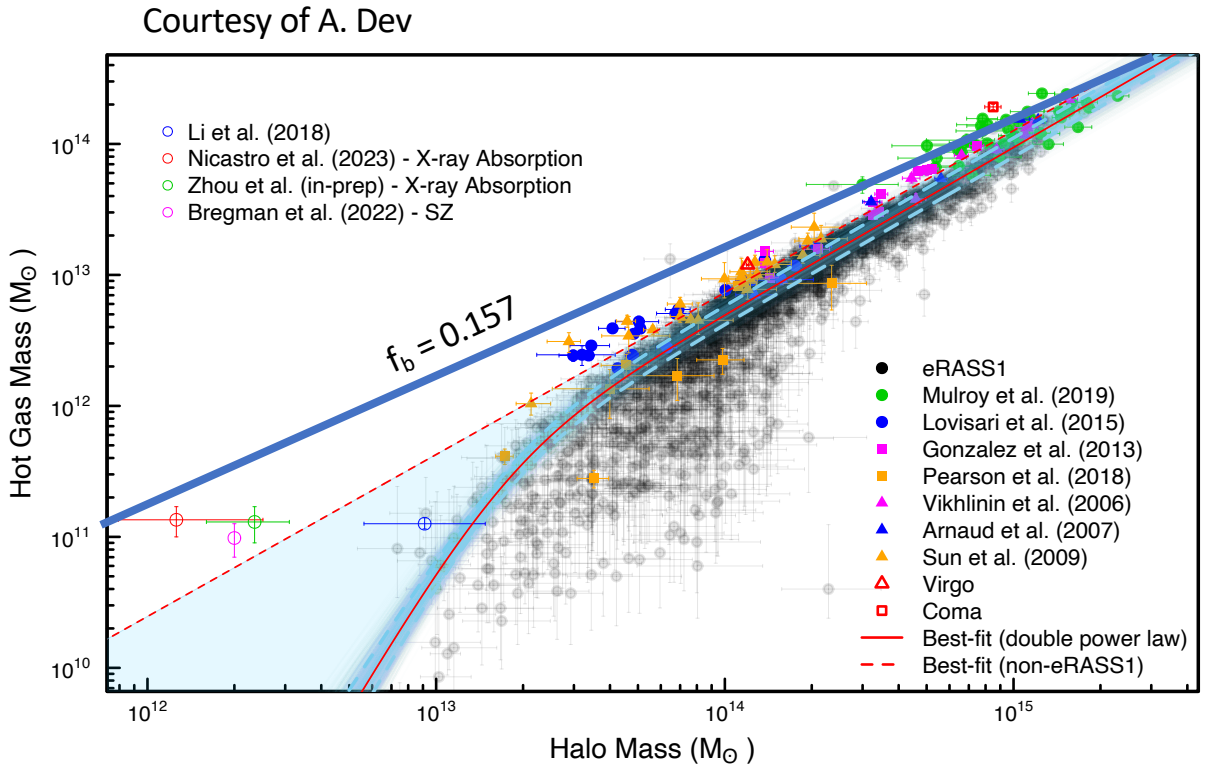
$$Beta-Profile:$$
$$f(\beta; R_c, n_b^0) = n_b^0[1+(r/R_c)^2]^{-3\beta/2}$$
β=0.64–0.68 (isothermal halo)
$R_c = 1-5$ kpc
$n_b^0 = 0.0004 - 0.1$ cm^{-3}



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

Close the galaxy baryon census

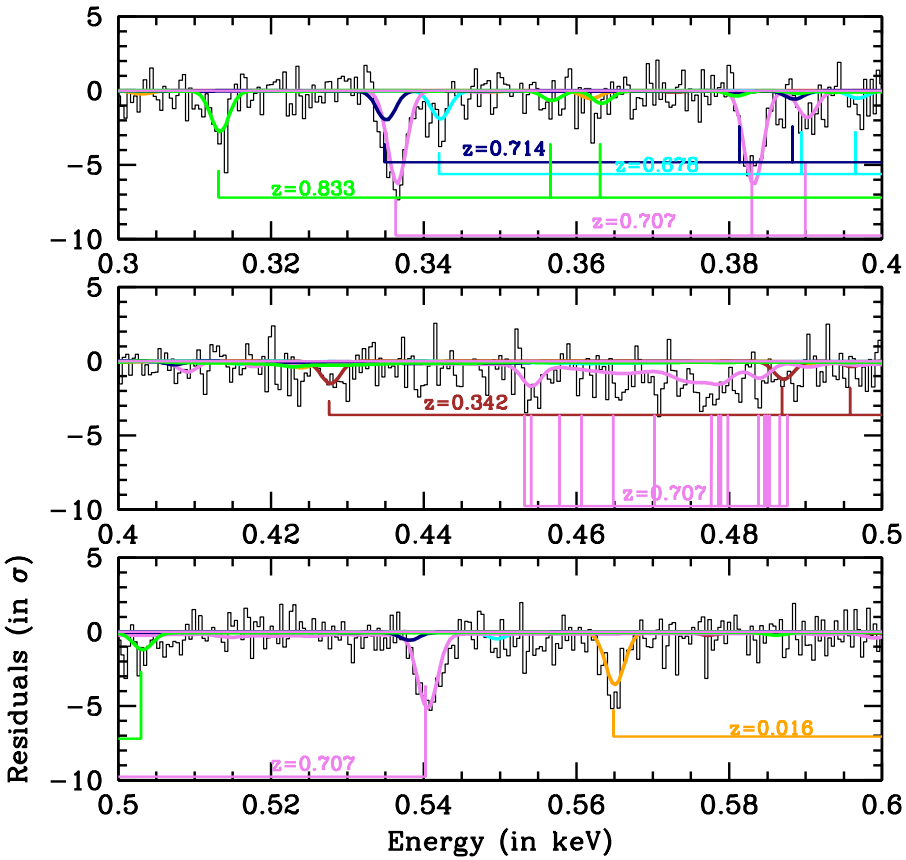
Majority of hot gas surrounding galaxies is gravitationally bound



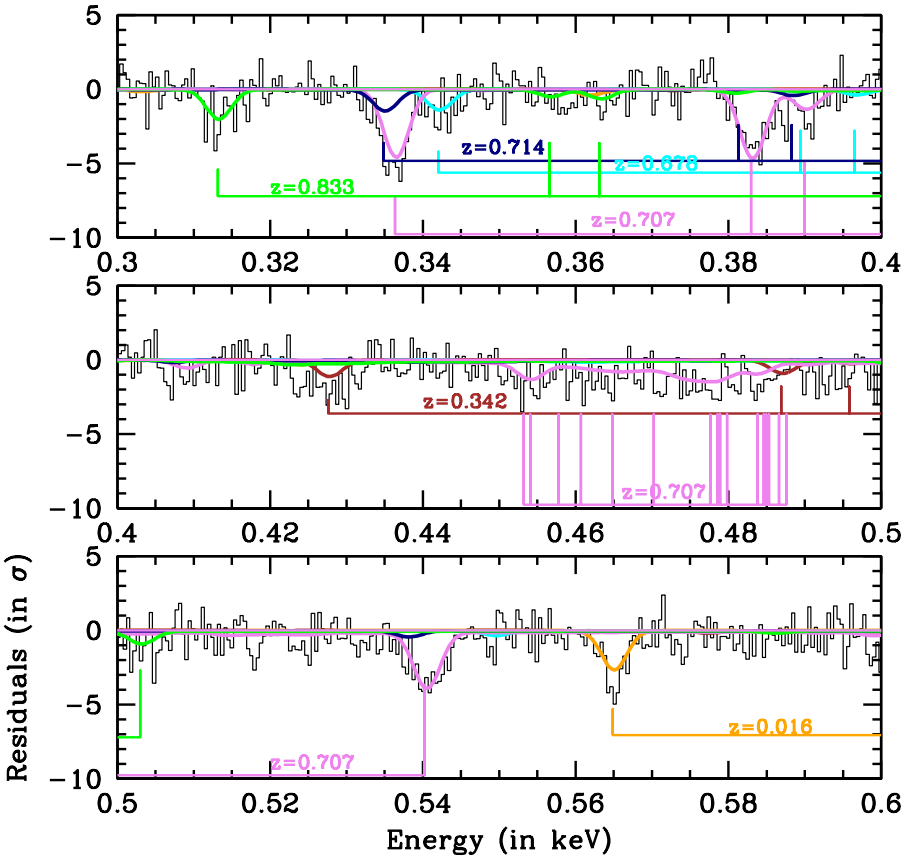
The Future of Hot X-ray Baryon Observations

WHIM/CGM Detections with NewAthena

Uncommonly WHIM-filament-rich l.o.s. out of 26 from Cen&Ostriker(06)



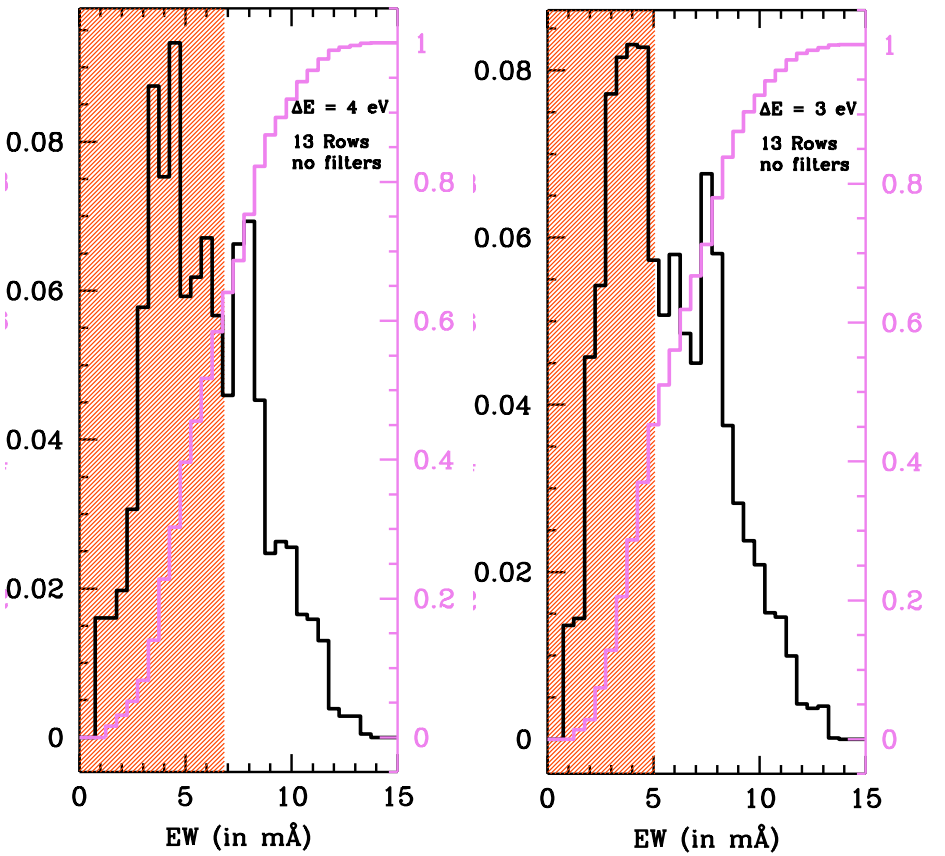
3 eV resolution

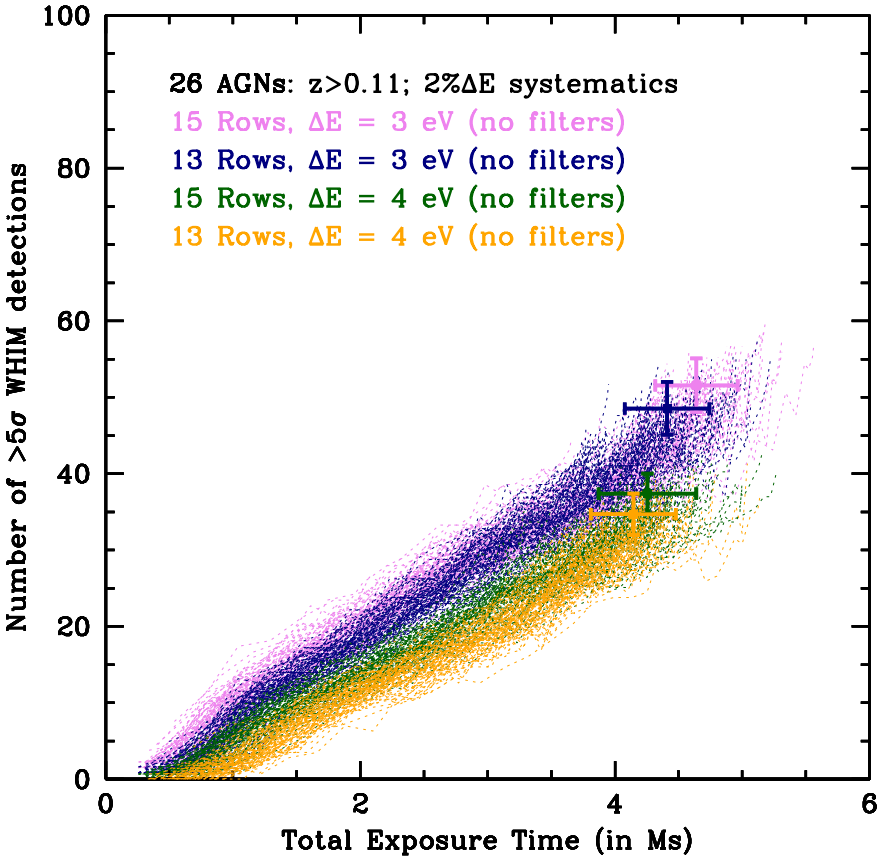


4 eV resolution

WHIM-filaments/CGM with NewAthena

of > 5-sigma WHIM-filament detections with NewAthena along 26 l.o.s.





Summary

1. >20yr data from the Chandra-LETG and XMM-Newton-RGS provide strong evidence for at least 2 phases (but also super-virial?) of hot CGM in the Milky Way. The amount of hot gas is probably sufficient to close the MW baryon census within ~1-2 galaxy's virial radius.

1. The HOT-CGM of external ~L* galaxies has finally been seen in X-ray absorption (Nicastro+23; Mathur+23) and, again, the full universal baryon fraction seems to be still relatively bound to the system (i.e. within one halo's virial radius or so).

2. This suggests that current hydrodynamical simulations use too strong AGN-feedback (thermal) recepies (blowing baryons and metals out to even 10 R_{vir}).

3. Athena (2032) will make a tomography of the WHIM/CGM and will detect ~100 filaments against bright AGNs and GRBs (absorption+emission)

4. NEW ATOMIC DATA OF X_RAY INNER-SHELL TRANSITIONS URGENTLY NEEDED TO PROPERLY IDENTIFY ALL ISM TRANSITIONS