X-ray Integral Field Unit

Missing Baryons and the WHIM

Current Evidence & Future Prospects

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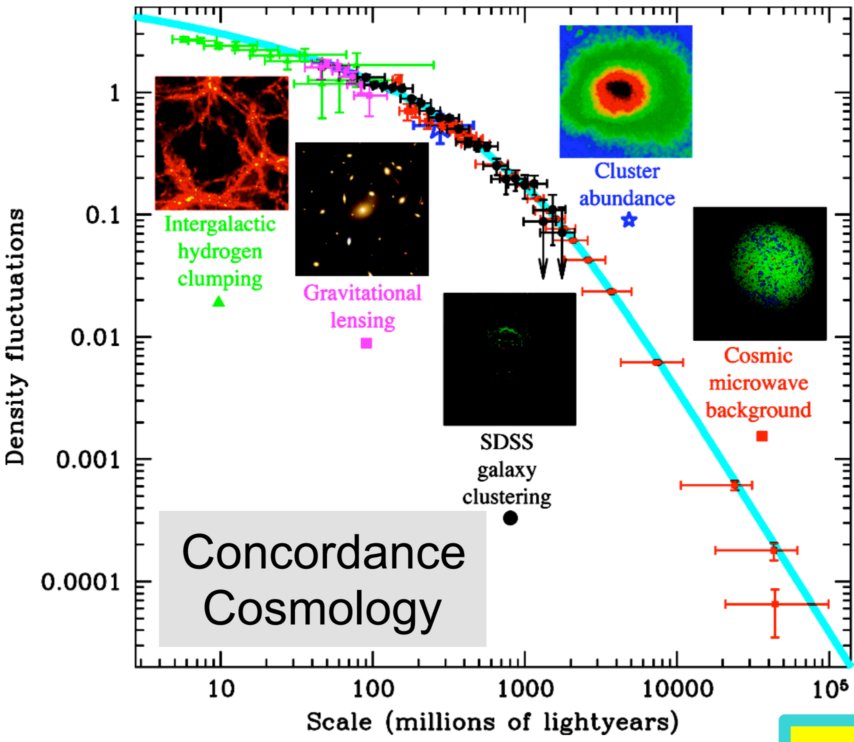
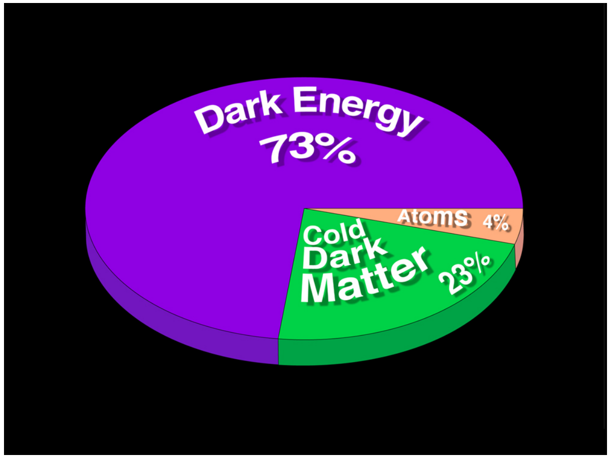
Outline

- The Missing Baryon Problem and its Theory Solution:
  - The Warm-Hot Intergalactic Medium & its Phases
- Current Evidence of the WHIM:
  - Serious flaws in recent (2009, 2014) claims of WHIM at redshift of super-structures
- First Determination of Ω_b^{WHIM} and Metallicity in X-rays
  - The Chandra observation of *“The best WHIM target in the Universe”*
- Future Prospects: the Athena X-IFU

The Era of Precision Cosmology

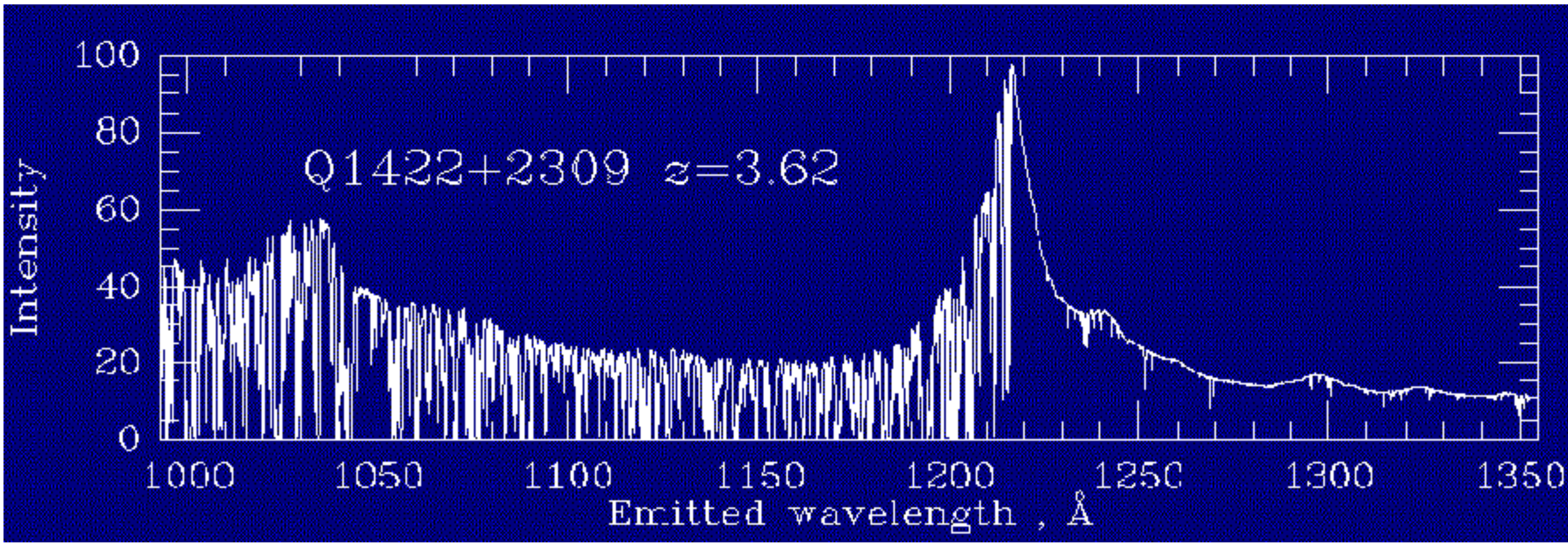




96% Unknown + 2% Missed…
…The Era of Ignorance Cosmology

Baryon Budget at z>2: the Ly α Forest

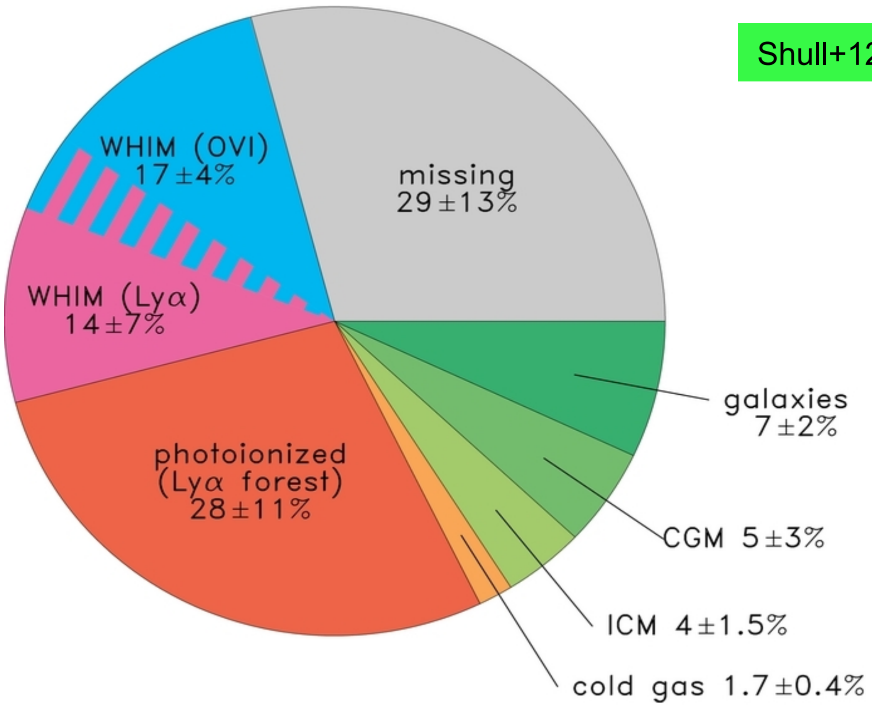
$\Omega_b^{WMAP} h^{-2} = 0.0226\ h^{-2} = 0.0456 \sim 5\%$: agrees with BBN



$\Omega_b(z>2) > 0.018\ h^{-2} = 0.034 \sim 75\%\ \Omega_b^{WMAP}$

The Missing Baryons Problem

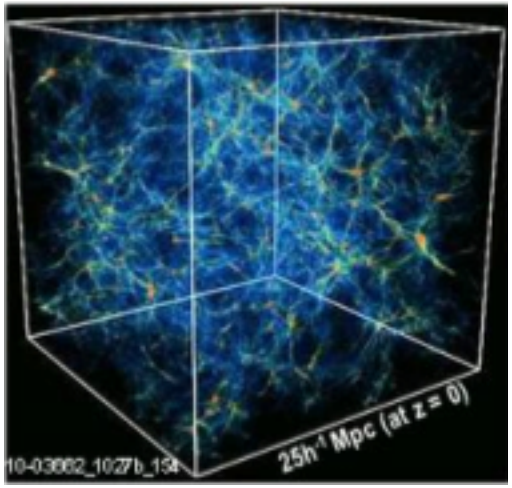
$\Omega_b^{WMAP} h^{-2} = 0.0226\ h^{-2} = 0.0456 \sim 5\%$



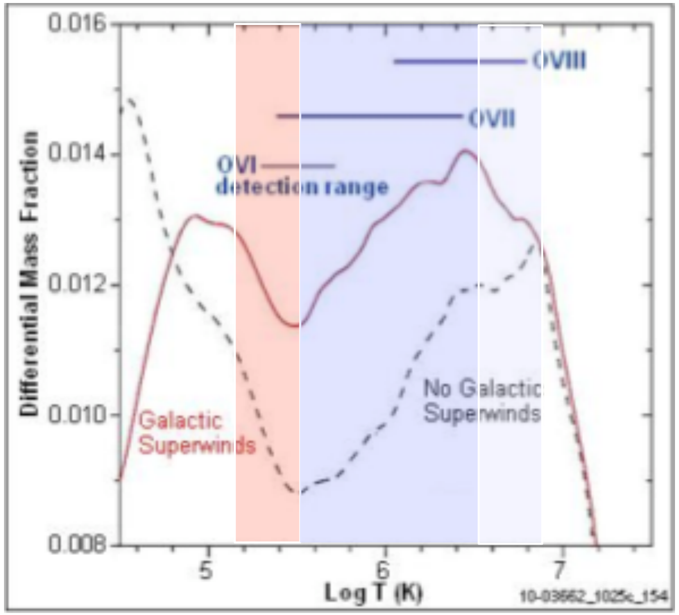
Shull+12

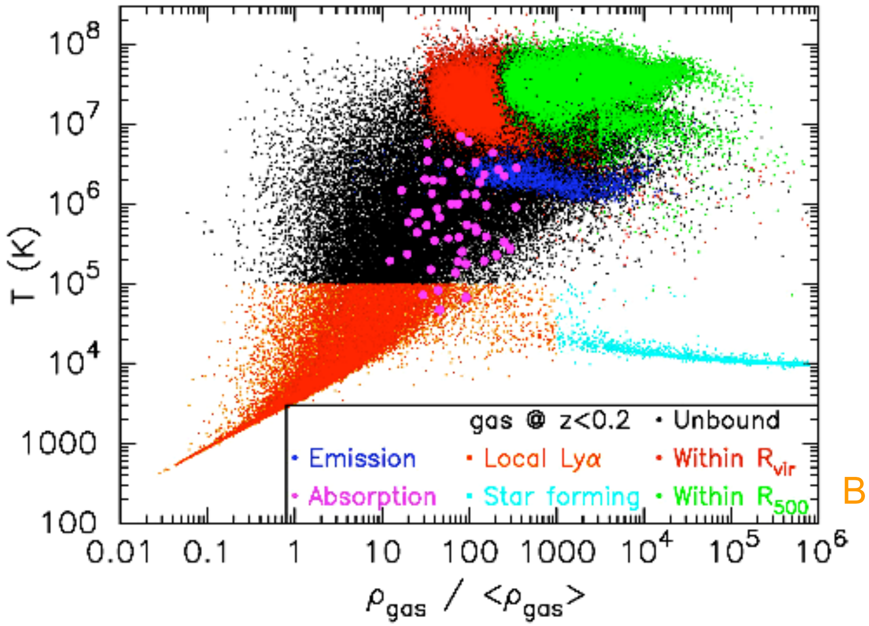
~ 30-40% (or more) of Baryons Still Missing at z~0

The Theory Solution: the WHIM



Britton+12





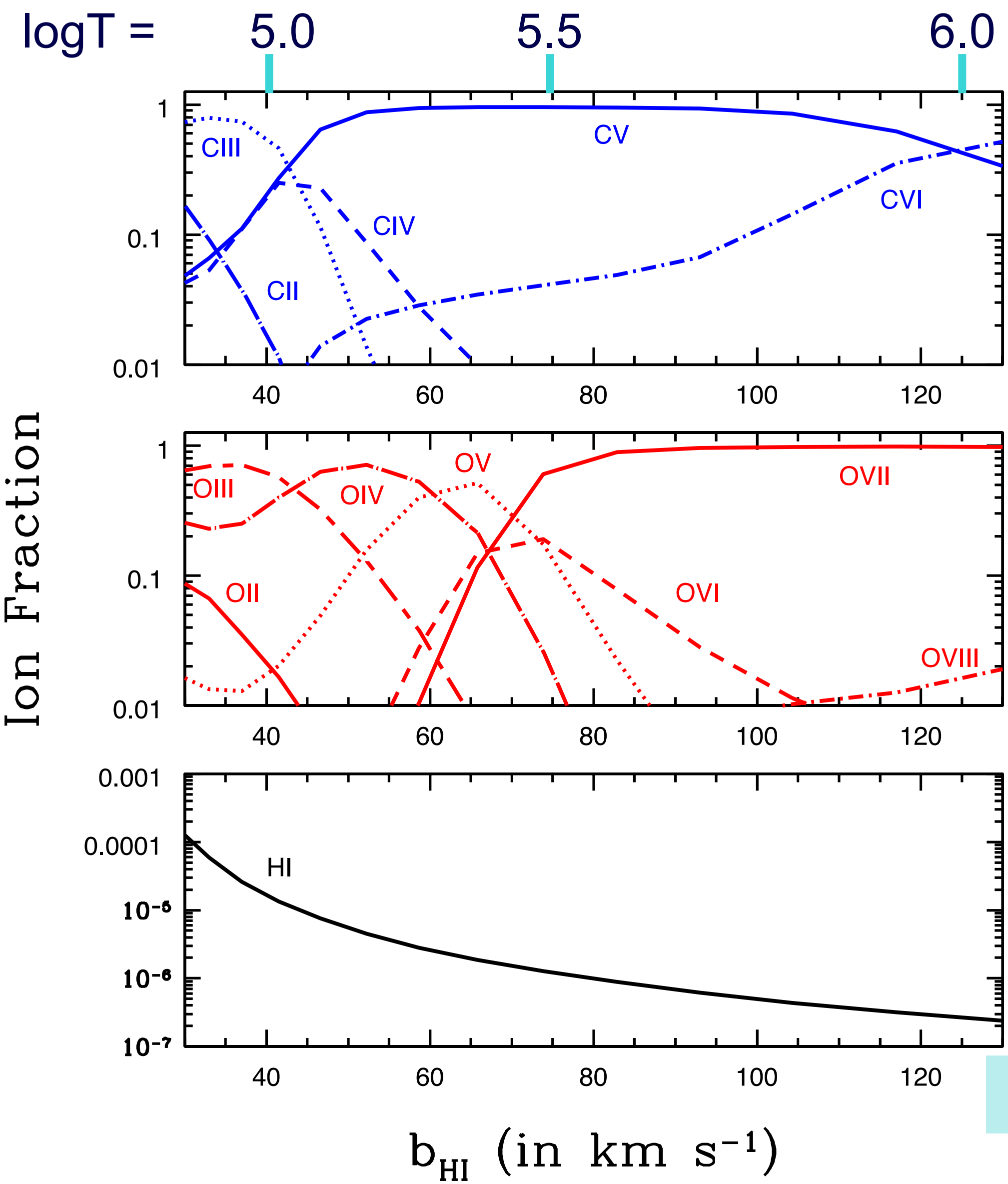
Branchini+10

Cool-Phase: ~20%

Warm-Phase: ~60%

Hot-Phase: ~20%

Most of the WHIM has to be searched for in the X-rays



@ logT = 5-5.5:
CV + OIV + OV

@ logT = 5.5-6:
OVII + CV

Problems:

dN/dz(OVII,CV) ~ 10 at N >10^{15} cm^{-2}

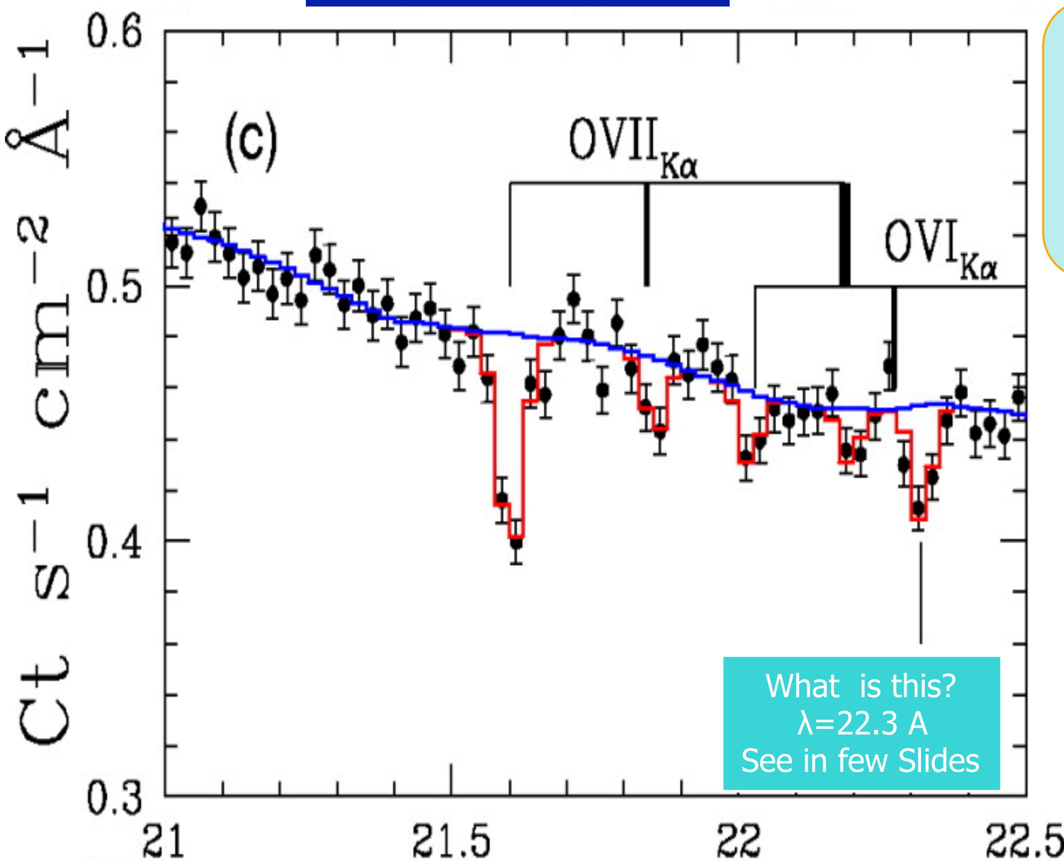
Current X-ray Spectrograph have
- Small Collecting Area (~20-40 cm2)
- Low Resolving Power (R~300)

➔ Tuned Observational Strategies

First Claimed WHIM Detections:

Exceptional Outburst State

(Nicastro+05, *Nature*, *ApJ*)



However:

- *z(Mkn 421) only 0.03*
- *Mkn 421 outbursts are unique*

+

Controversial:

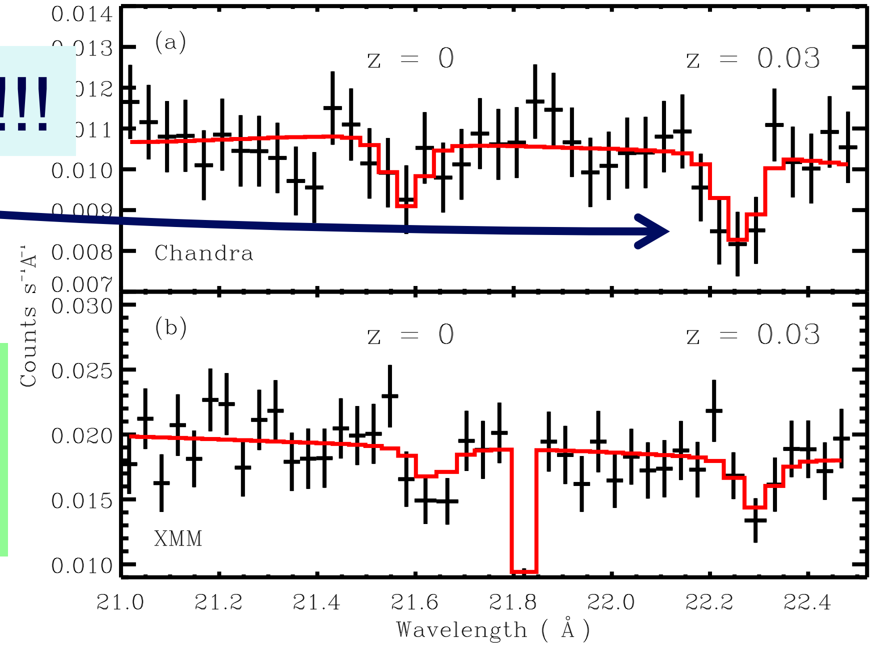
- *Not confirmed by XMM (though consistent with; Rassmussen+07)*
- *Close to instrument systematics (Kaastra+06)*

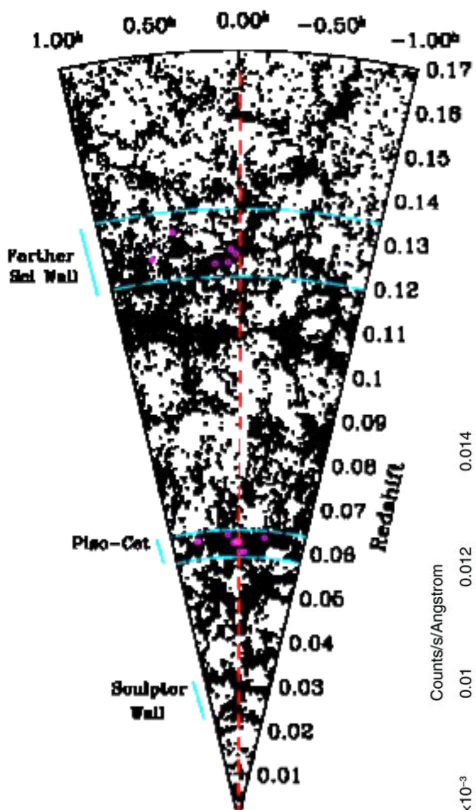
$$\Omega_b(N_{OVII} > 7*10^{14}) = 2.7^{+3.8}_{-1.9} * 10^{-[O/H]_{-1}}\% \sim \Omega_{Miss}$$

The Sculptor Wall: Buote+09, Fang+10

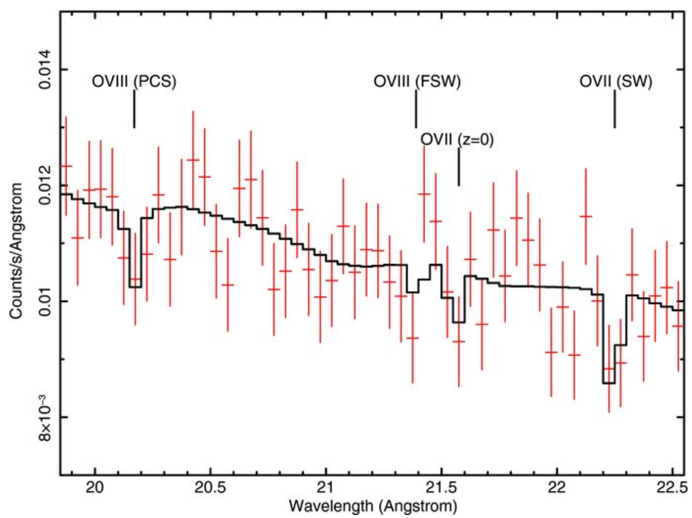
Galaxy concentrations as WHIM tracers

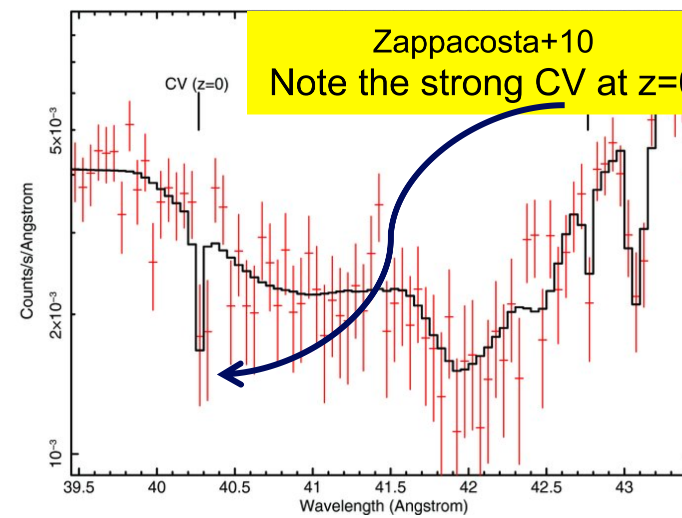
But: $N_{OVII} \sim 2 \times 10^{16}\ cm^{-2}$!!!





Also one of the Chandra highlights and discoveries (the only WHIM) In Tananbaum+14 ArXiv:1405.7487

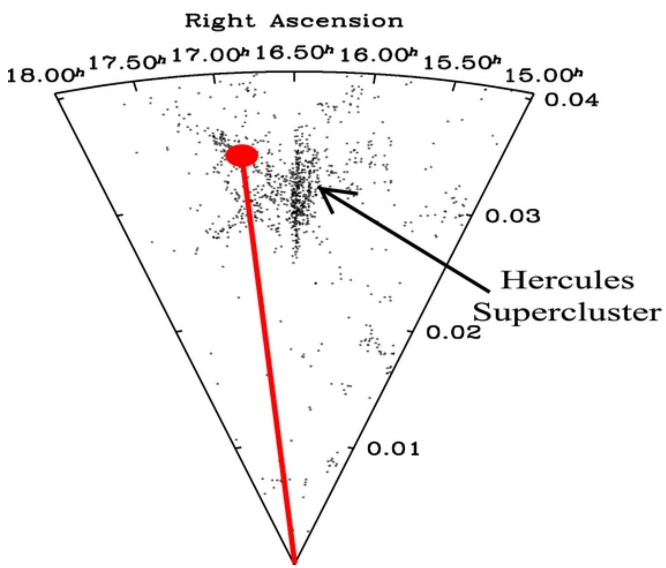


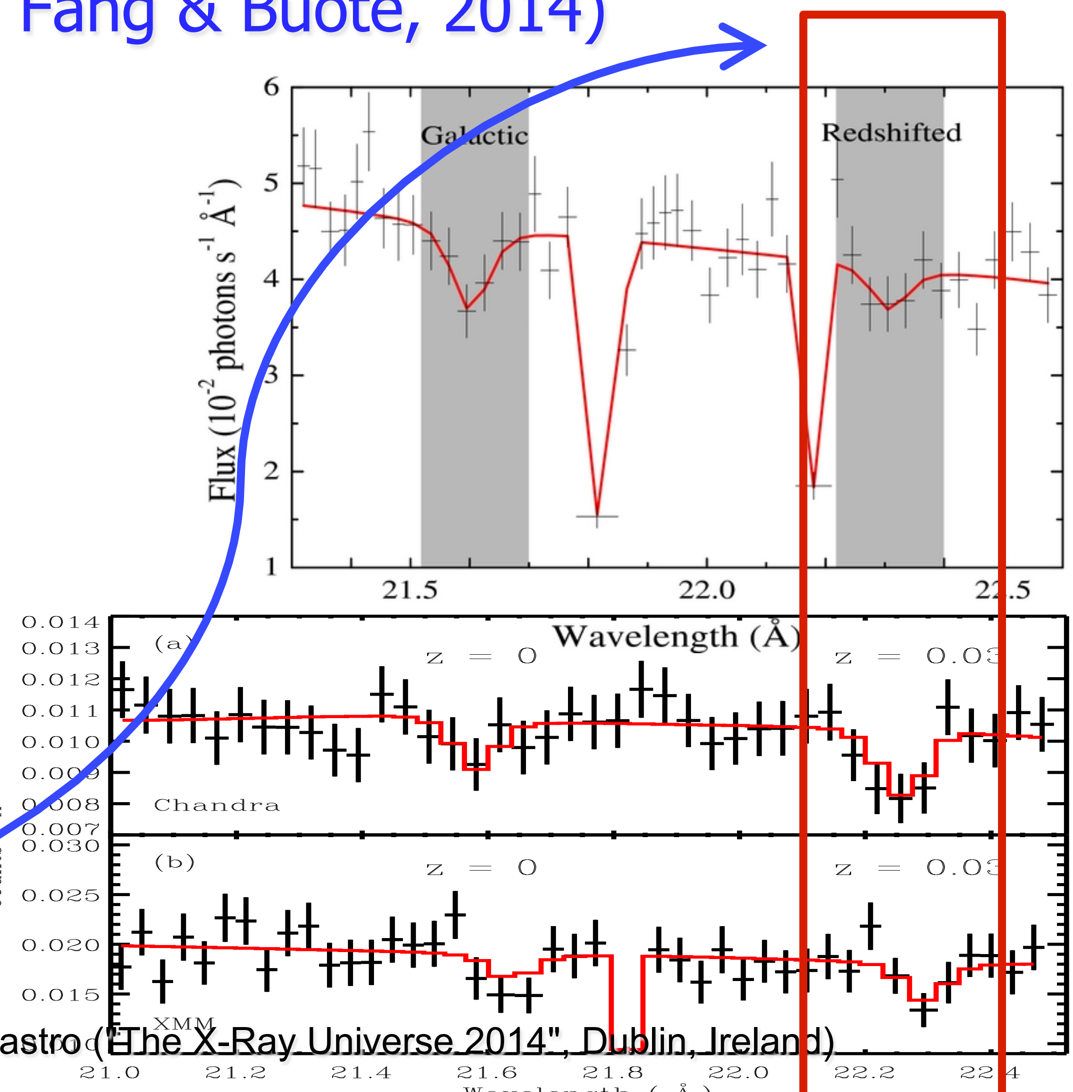


Zappacosta+10
Note the strong CV at z=0

"X-RAY ABSORPTION BY THE WARM-HOT INTERGALACTIC MEDIUM IN THE HERCULES SUPERCLUSTER"

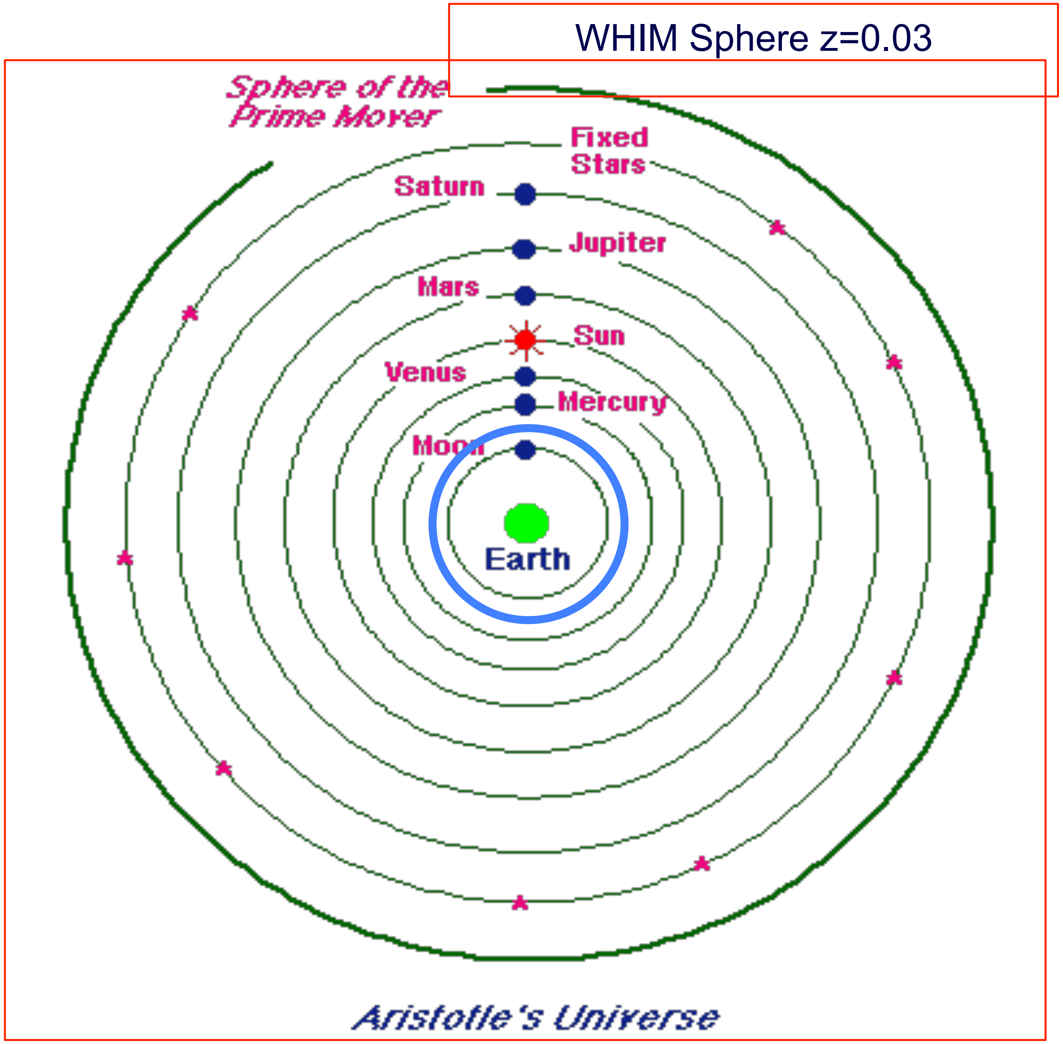
(Ren, Fang & Buote, 2014)



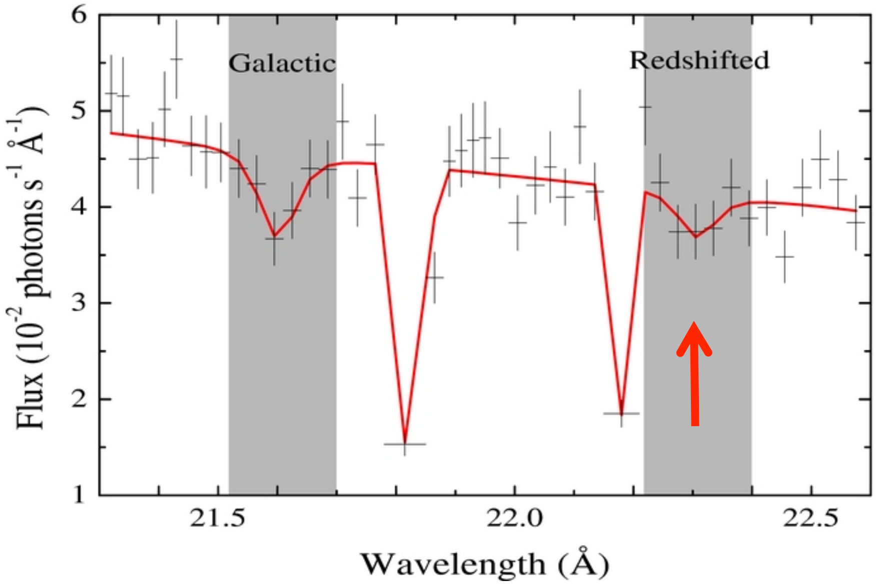


Note that both Structures are at z=0.03
This translate in OVII Ka redshifted
to λ=22.3 Å

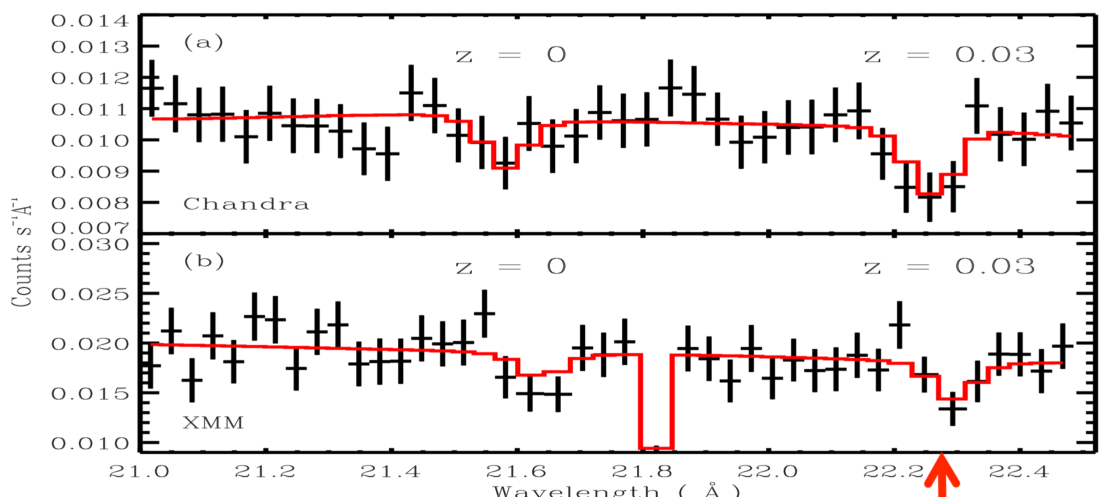
The Era of Dark-Age Cosmology:
A new Ptolemaic Universe ? ☺



The "Magic" of the z=0.03 WHIM in OVII: 1

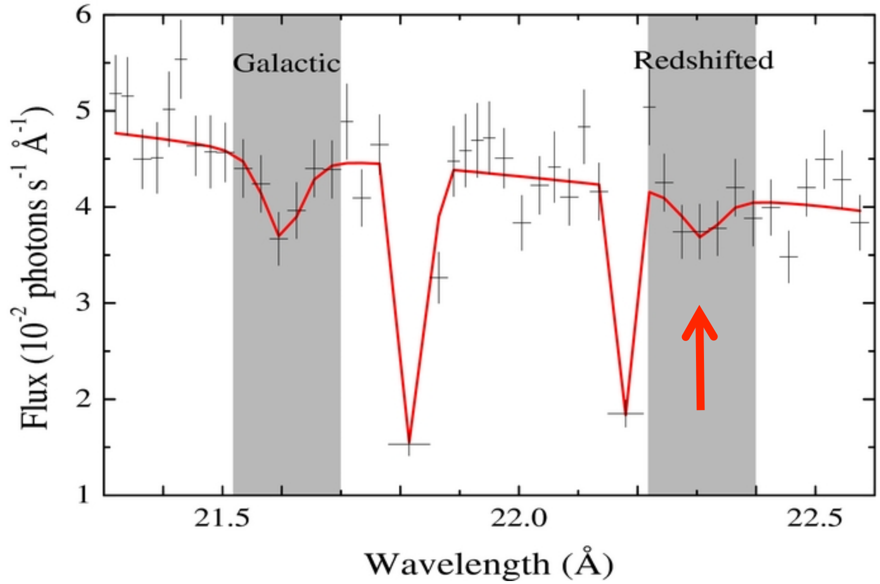


Mkn 501: z=0.033 !!!

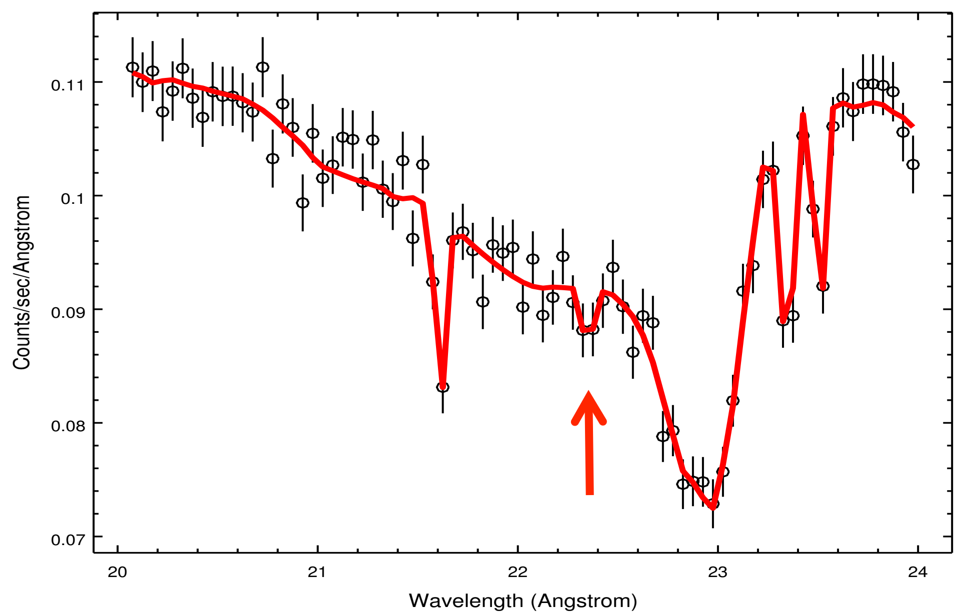


H 2356-309: z=0.165

The “Magic” of the z=0.03 WHIM in OVII: 2

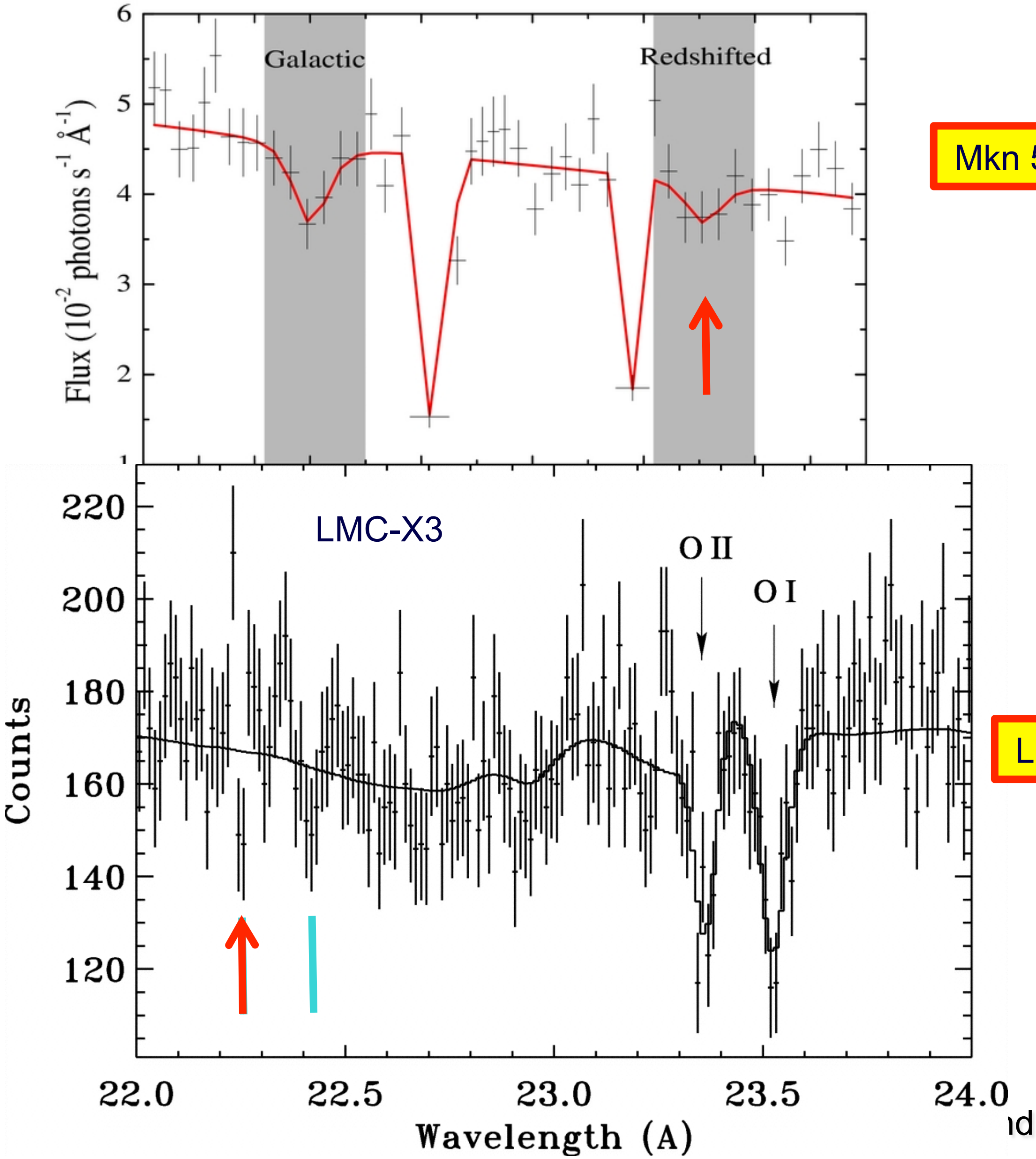


Mkn 501: z=0.033 !!!



PKS 2155-304: z=0.116

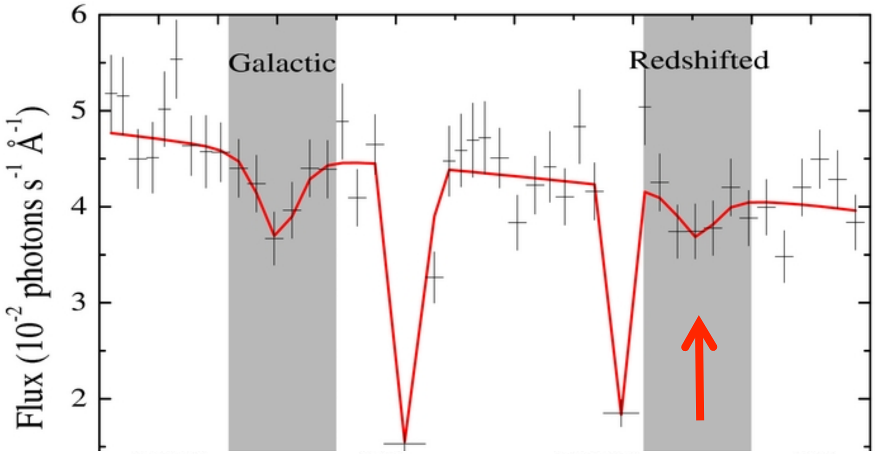
The "Magic" of the z=0.03 WHIM in OVII: 3



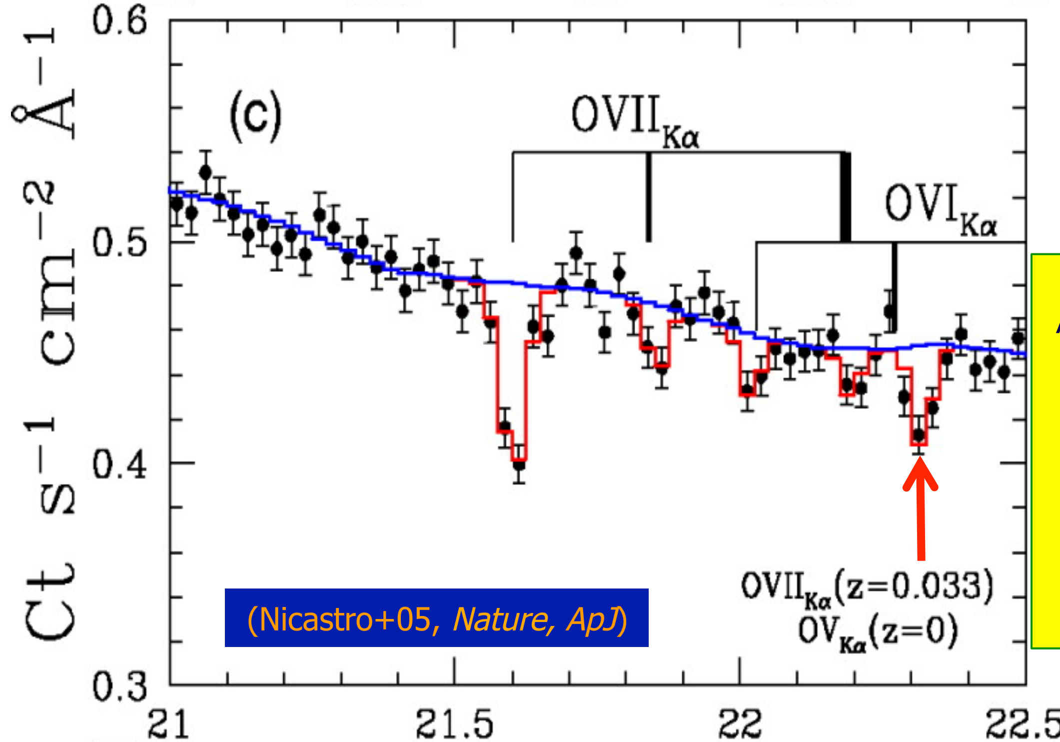
Mkn 501: z = 0.033 !!!

LMC X-3: z=0 !!!

The "Magic" of the z=0.03 WHIM in OVII: 4



Mkn 501: z = 0.033 !!!



Mkn 421: z=0.03

Panel of Figure 8 from Nicastro+05:
Already in that paper we identified this
λ=22.3 Å line as either OVII at the
Redshift of the blazar or (more likely
In our discussion) OV Kα at z=0

"Simply" an OV Kα
Inner-shell transition
From the MW or the CGM

The Beauty of the Inner-Shell Transitions

Kaastra+04

Table 1. Energy levels of O V. Energies are taken from Wiese et al. (1996). Levels 2–4 are the metastable levels discussed in this paper.

Level	Configuration	J	Energy (eV)
1	$2s^2\ ^1S$	0	0
2	$2s\,2p\ ^3P$	0	10.16
3		1	10.18
4		2	10.21
5	$2s\,2p\ ^1P$	1	19.69
6	$2p^2\ ^3P$	0	26.47
7		1	26.49
8		2	26.52
9	$2p^2\ ^1D$	2	28.73
10	$2p^2\ ^1S$	0	35.70

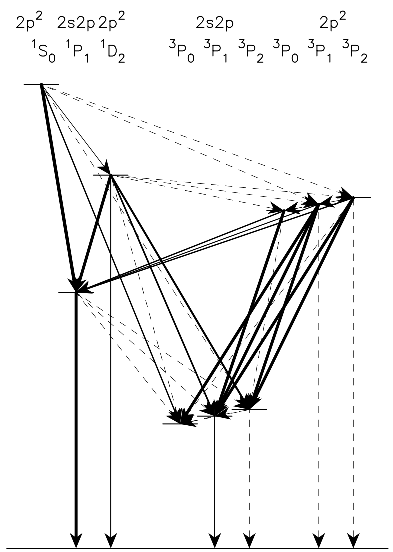


Fig. 1. Energy level diagram of O V. Only the $n = 2$ levels are shown. The energy differences within the ^3P triplets have been exaggerated for clarity. Solid lines: transitions with transition probabilities larger than 1 s^{-1}; the line thickness is proportional to the logarithm of the transition probability. Dashed lines: transitions with transition probabilities less than 1 s^{-1}.

Table 2. Strongest X-ray lines of O V. The values listed apply for the full multiplets (not splitted into sublevels).

Label	Initial state		Final state		f	λ
	Conf.	Term.	Conf.	Term.		(Å)
A2	$2s^2$	^1S	$1s\,2s^2 2p$	^1P	0.649	22.381
A3	$2s^2$	^1S	$1s\,2s^2 3p$	^1P	0.108	19.871
A4	$2s^2$	^1S	$1s\,2s^2 4p$	^1P	0.041	19.258
A5	$2s^2$	^1S	$1s\,2s^2 5p$	^1P	0.020	19.002
A6	$2s^2$	^1S	$1s\,2s^2 6p$	^1P	0.012	18.869
A7	$2s^2$	^1S	$1s\,2s^2 7p$	^1P	0.007	18.791
A8	$2s^2$	^1S	$1s\,2s^2 8p$	^1P	0.005	18.742
A9	$2s^2$	^1S	$1s\,2s^2 9p$	^1P	0.004	18.708
B1	$2s\,2p$	^3P	$1s\,2s\,2p^2$	$(^3S)^3P$	0.328	22.466
B2	$2s\,2p$	^3P	$1s\,2s\,2p^2$	$(^3S)^3D$	0.178	22.431
B3	$2s\,2p$	^3P	$1s\,2s\,2p^2$	$(^3S)^3S$	0.039	22.239
B4	$2s\,2p$	^3P	$1s\,2s\,2p^2$	$(^1S)^3P$	0.014	22.132
C1	$2s\,2p$	^1P	$1s\,2s\,2p^2$	$(^1S)^1D$	0.182	22.558
C2	$2s\,2p$	^1P	$1s\,2s\,2p^2$	$(^3S)^1P$	0.339	22.389
C3	$2s\,2p$	^1P	$1s\,2s\,2p^2$	$(^1S)^1S$	0.040	22.363
D1	$2p^2$	^3P	$1s\,2s^2\,2p$	^3P	0.005	23.643
D2	$2p^2$	^3P	$1s\,2p^3$	^3D	0.173	22.511
D3	$2p^2$	^3P	$1s\,2p^3$	^3S	0.151	22.474
D4	$2p^2$	^3P	$1s\,2p^3$	^3P	0.105	22.339
E1	$2p^2$	^1D	$1s\,2s^2\,2p$	^1P	0.006	23.598
E2	$2p^2$	^1D	$1s\,2p^3$	^1D	0.328	22.477
E3	$2p^2$	^1D	$1s\,2p^3$	^3P	0.002	22.457
E4	$2p^2$	^1D	$1s\,2p^3$	^1P	0.112	22.306
F1	$2p^2$	^1S	$1s\,2s^2\,2p$	^1P	0.002	23.855
F2	$2p^2$	^1S	$1s\,2p^3$	^1P	0.438	22.536

Ground Level

At logT=5.2 (where OV peaks) E=13.6 eV ➔ collisions may easily depopulate the ground level for the 1st excited

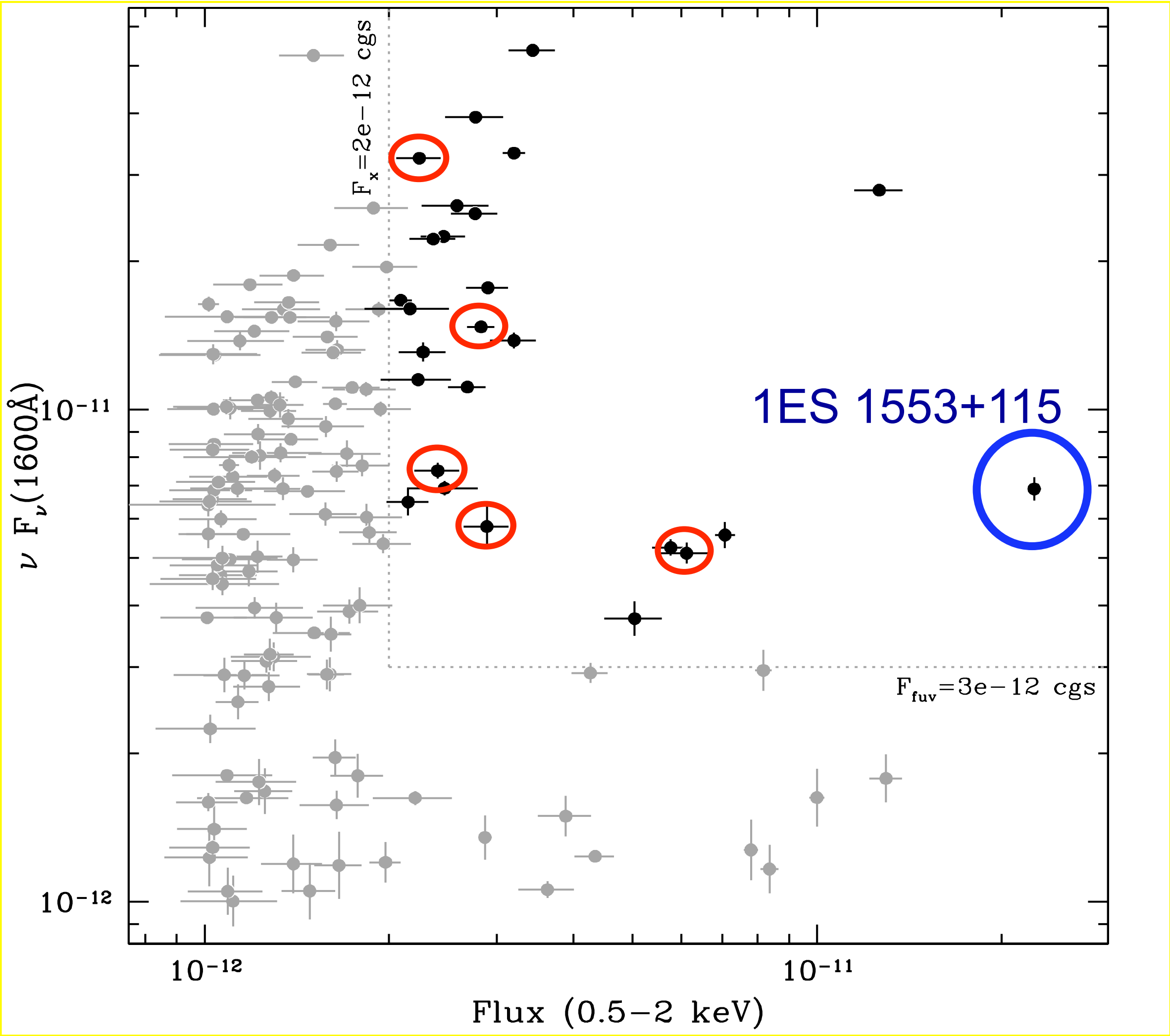
$\Delta E \sim 10$ eV ➔ FUV

1st Excited Level

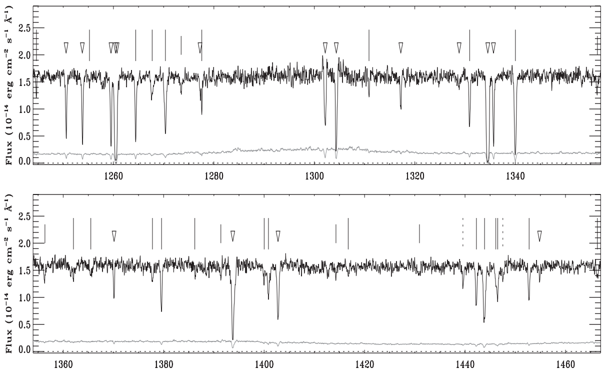
Also: Plenty of such photons in or near a galaxy to photo-pump OV at 1st excited from higher excitation levels.
➔ Position of the line great density and location diagnostics.

"Best WHIM Target in the Universe"

1ES 1553+113



- z > 0.4
- FX ~ 1-2 mCrab
- High S/N COS spectrum with 5 a-priori BLA signposts



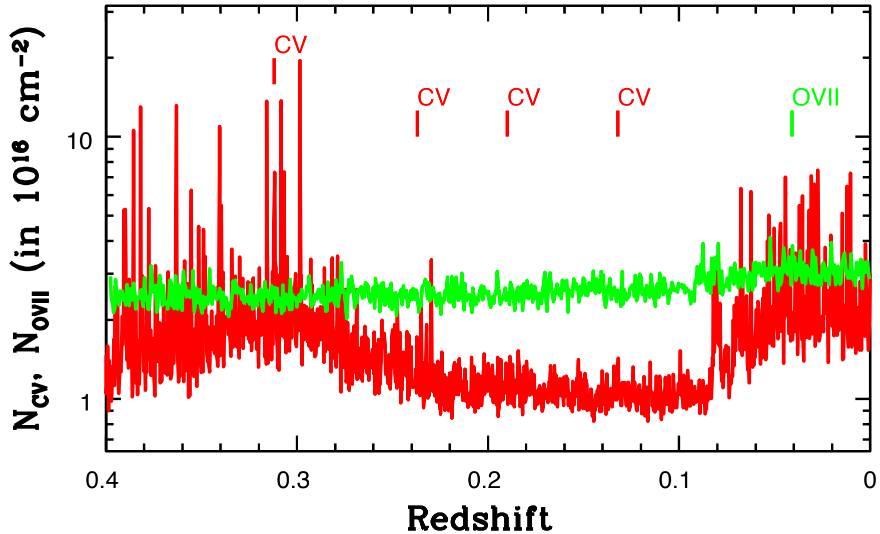
Tentative IGM IDs

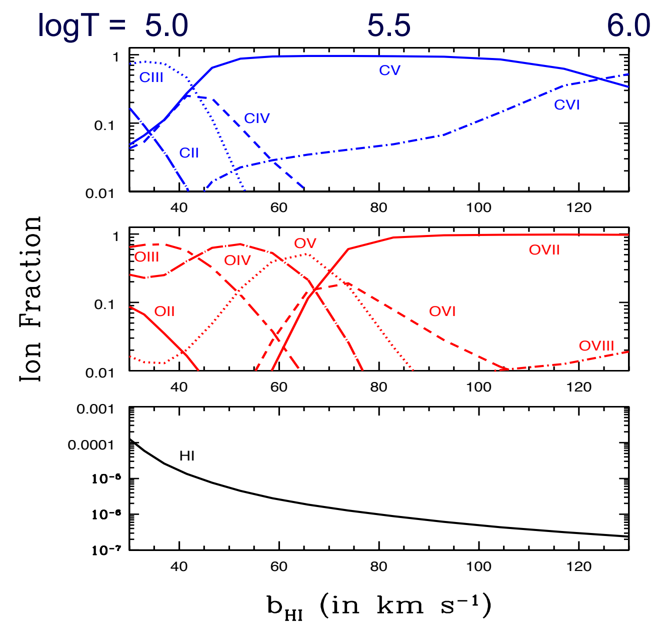
Nicastro+13

Redshift	CV	CVI	OIV	OV	OVII	BLA	OVI (mA)	CIV (mA)
0.041±0.002	NA	NA	NA	NA	2.3σ	9.6σ	<65	<13
0.133±0.002	3.8σ	2.7σ	NA	NA	NA	5.4σ	<14	<25
0.184±0.001	3.6σ	NA	NA	NA	NA	NA	<11	NA
0.190±0.001	2.2σ	NA	NA	1.7σ	NA	9.3σ	7.6σ	NA
0.237±0.001	3.9σ	NA	NA	?	NA	5,2.2σ	<13	NA
0.312±0.001	4.1σ	4.1σ	NA	?	NA	8.1σ	3.6σ	NA

Sensitivity of the Chandra Spectrum of 1ES 1553+113

$$N_{Ion} \geq 1.1\times10^{20}\,\frac{N_\sigma \Delta\lambda}{S/N}\, f_i^{-1}\lambda_i^{-2}(1+z)^{-1}$$



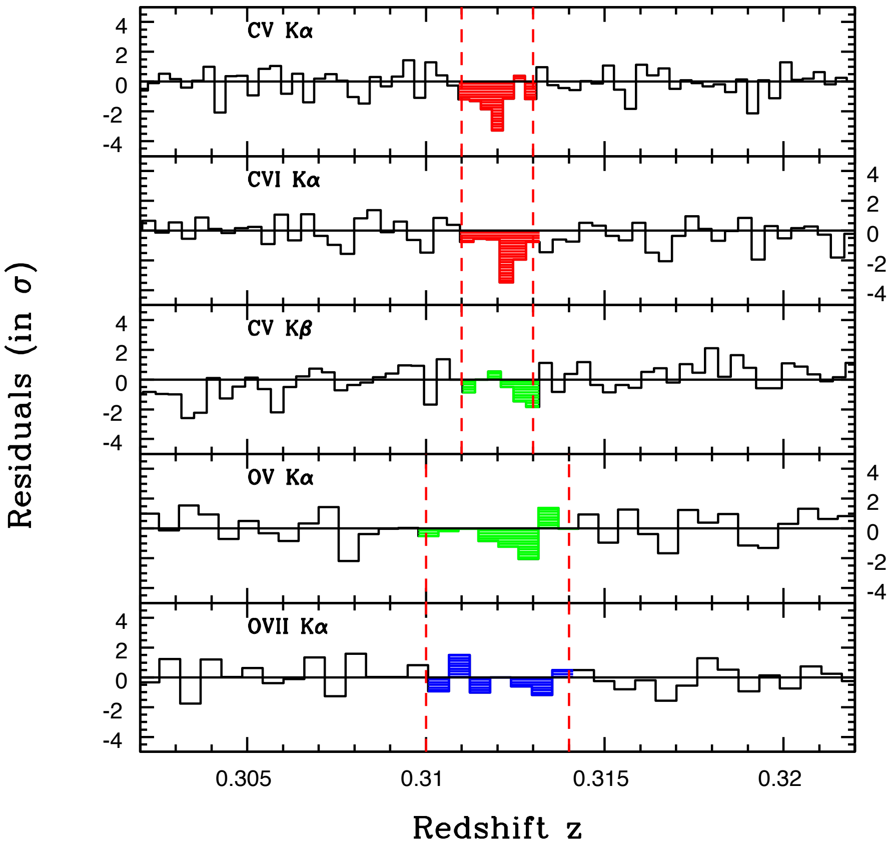


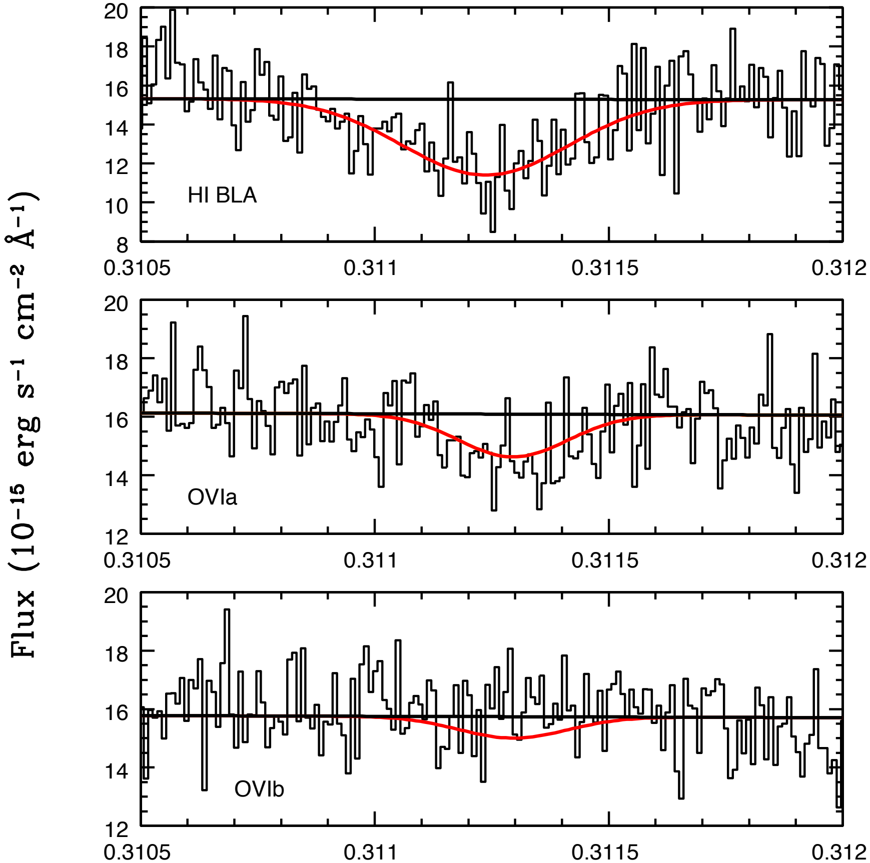
With the sensitivity of the current *Chandra* spectrum of 1ES 1553+113 bound to detect only the cool (logT < 5.6) WHIM in CV.

4x exposure with Chandra 1.6x with XMM ➔ 2x S/N ➔ $N_{OVII} > 10^{15}$-10^{16} cm^{-2} ➔ ~ 4 new systems sampling the hot WHIM

Cool WHIM at z=0.312:
(6.3σ X-ray only)

Nicastro+13





From COS BLA and OVI b:

➔ b_{th} = 52 ± 7 km s^{-1} (b_{turb} = 30 ± 14 km s^{-1}) ➔ logT = 5.2 ± 0.1

Fully Consistent with presence of CV, OV, probably not CVI: Multiphase gas? If so [C/O] super-solar; mis-identified? CV at z=0.100?

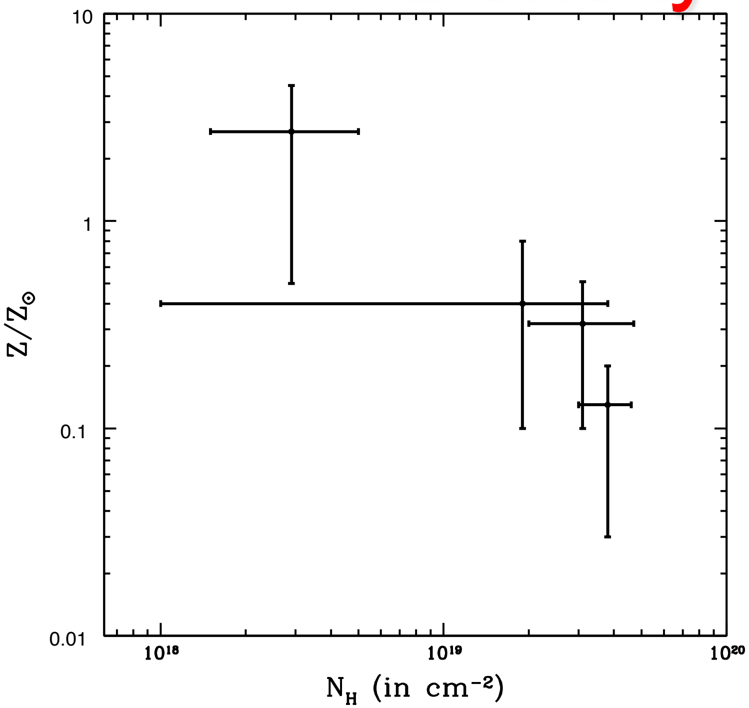
Best-Fitting WHIM Parameters

Redshift	logT	N_H (10^{19} cm^{-2})	n_b (10^{-6} cm^{-3})	$Z/Z_\odot$ [= $N_H(X)/N_H(FUV)$]
0.041±0.002	5.45 ± 0.05	3.8 ± 0.8	1.0	0.13, +0.07, -0.10
* 0.133±0.002	5.4, +0.2, -0.6	** 2.2	119	NA
0.190±0.001	5.25 ± 0.05	1.9 ± 1.8	128	0.4, +0.4, -0.3
0.237±0.001	5.3 ± 0.1	0.3, +0.2, -0.1	135	2.7, +1.8, -2.2
0.312±0.001	5.25 ± 0.05	3.1, +1.6, -1.1	146	0.32, +0.19, -0.22

* No consistent X-Ray-FUV solution: BLA is too narrow and shallow to be imprinted by the X-ray absorber and OVI should be visible if logT<5.2

** From $N_H(X)$ divided by the average $\langle Z/Z_\odot \rangle = 0.28 \pm 0.24$ determined for the z=0.041, 0.190, 0.312 systems

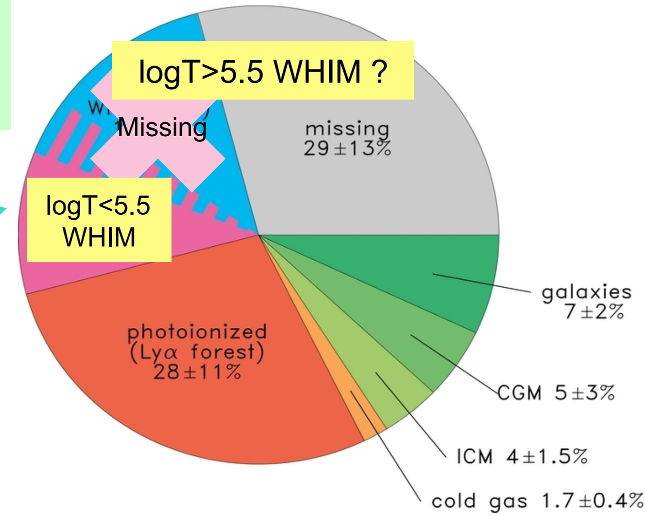
Metallicities and Cosmological Mass Density of the Cool WHIM



$$\Omega_b = \frac{1}{\rho_{cr,0}} \frac{\mu m_p \sum_i N_H^i}{\Delta l_{comoving}}$$

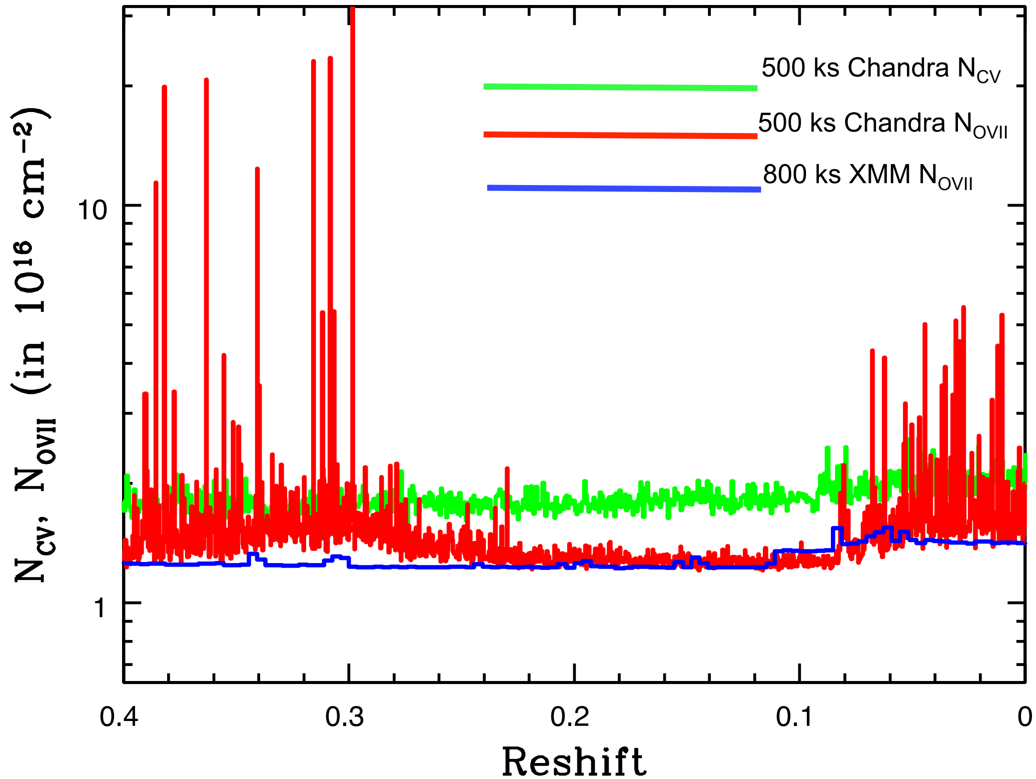
$$dl_{comoving} = {}^{c}\!/_{H(z)}\, dz$$

$$\sigma_{\Omega_b} = \frac{1}{[1-1/K]^{1/2}} \frac{1}{\rho_{cr,0}} \frac{\mu m_p \sqrt{\sum_{i=1}^{K} [N_H^i - < N_H^i >]^2}}{\Delta l_{comoving}}$$



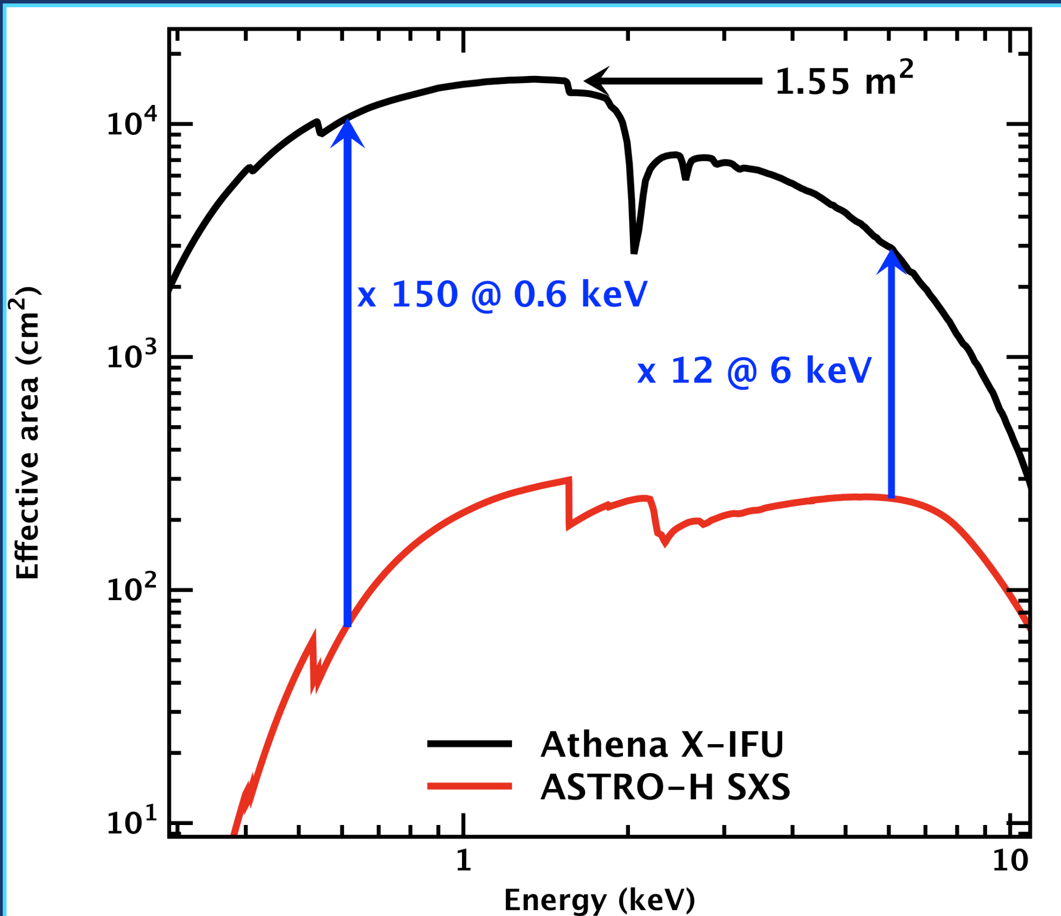
$$\Omega_b(5Sys; 5.0 < \log T < 5.5; EW_{CV,OVII} > 10\ m\overset{o}{A}) = 0.0069 \pm 0.0018 = (15 \pm 4)\%\ \Omega_b$$

The WHIM: Short-Term Prospects
Looking for OVII with the RGS



2 Ms (total) Chandra-LETG and 800 ks XMM-RGS would allow us to reach the sensitivity that the Chandra LETG Spectrum has for CV, and so to detect the OVII WHIM

X-IFU PERFORMANCE- EFFECTIVE AREA

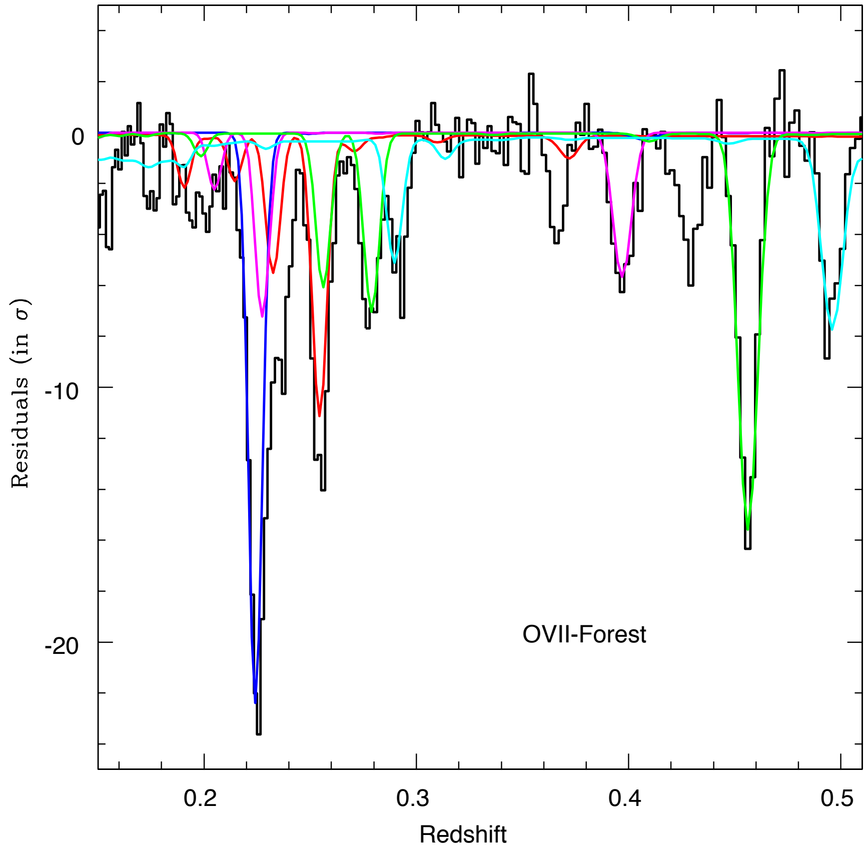


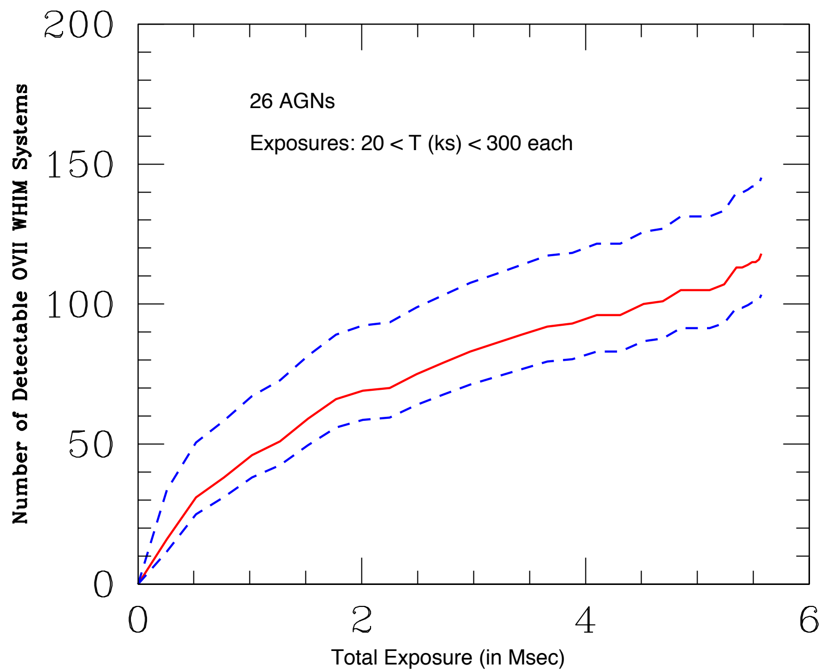
Effective area curve comparison of Athena-X-IFU versus ASTRO-H SXS, showing that at low energies the gain in sensitivity is about 150 and more than a factor of 10 at 6 keV

Ravera et al. (2014, SPIE)

The WHIM: Future Prospects Athena+

X-ray Integral Field Unit





500 ks for $F_{0.5\text{-}2}$ = 0.1 mCrab along a random WHIM LOS from Cen+06:
detects 5 Systems with logT = 5.2-6.4 K, logN_H = 18.7-19.4 $(Z/Z_\odot)^{-1}$ cm^{-2} at z<0.5
All in OVII-OVIII; 2 in CV + OIV-OVI (Cool-Phase): excellent Density Diagnostics

Summary and Future

- *The Missing baryons in the local Universe are likely to reside in hot tenuous medium in the IGM, as predicted by hydro-dynamical simulations*
- *The claimed (and most credited) detections of the WHIM toward weak sources along crowded lines of sight suffer serious flaws in the data interpretation: putative redshifted OVII Kα are most likely OV Kα at z=0.*
- *The first detection of the cool WHIM has instead finally been secured in the X-rays along the line of sight to the best WHIM target in the Universe 1ES 1553+113: only cool portion with current sensitivity.*
- *Metallicity is relatively high (~0.3 on average), consistent with feedback models and recent cluster outskirts observations.*
- *After proper ionization and metallicity correction, CV-OVI-BLA dominated WHIM (i.e. logT=5-5.5) contains ~ 15% of Baryons ➔ 40-50 % of Baryons are still missing and likely to reside in logT>5.5 WHIM, only detectable in X-rays*
- Deeper Chandra-LETG and XMM-RGS observations of 1ES 1553+113 will allow us to break the detection limits of OVII and so start detecting the majority of the baryons in the WHIM.