A Decade of WHIM search:

Where do We Stand…

…Where do We Go

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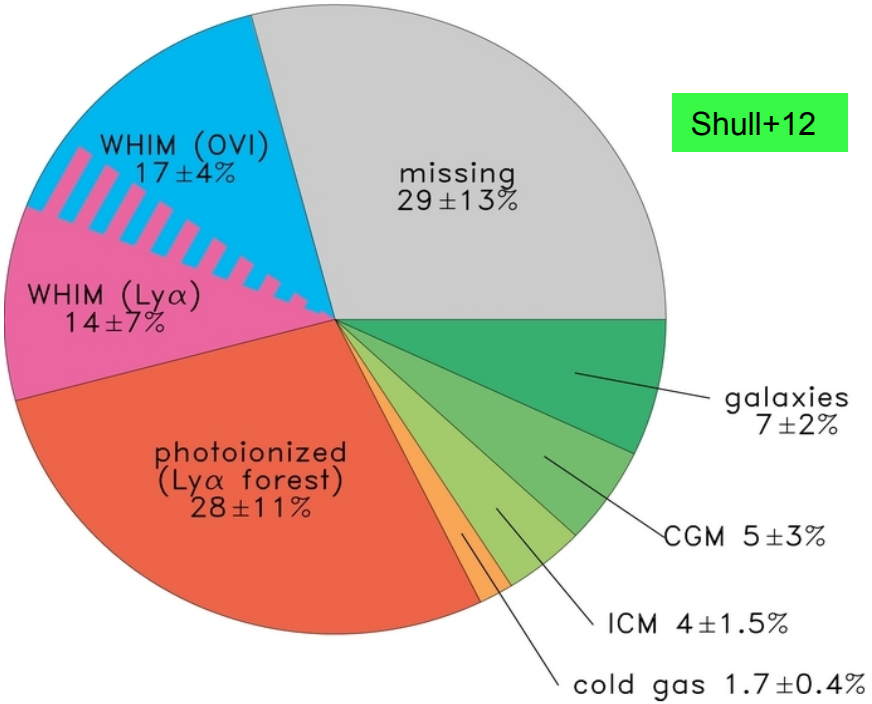
The Missing Baryons Problems

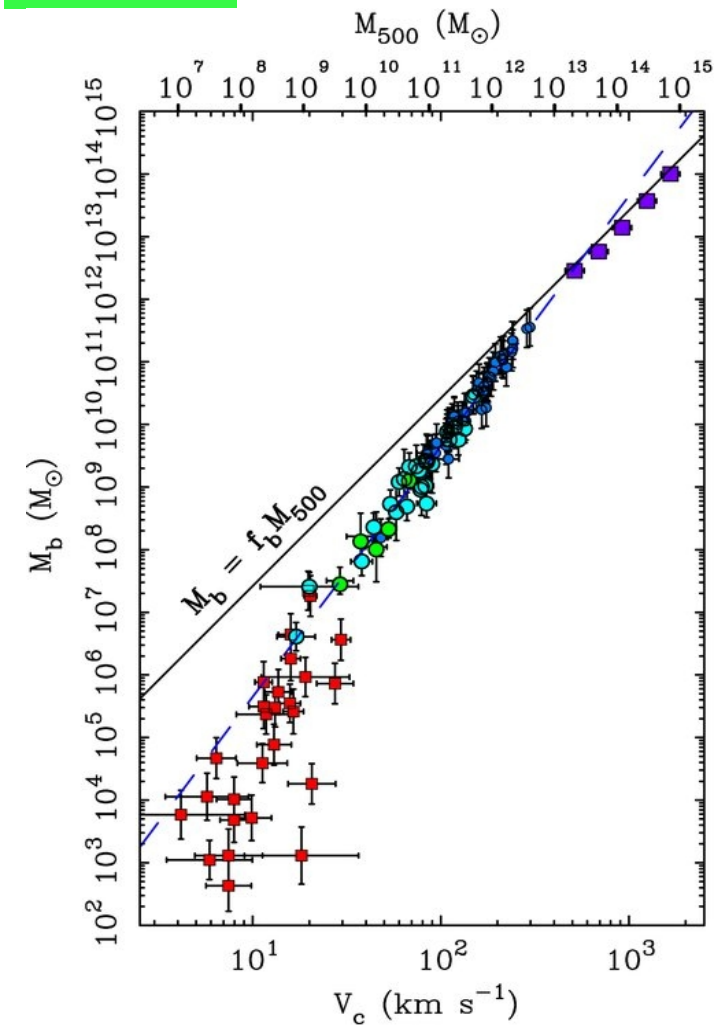
$\Omega_b^{WMAP} h^{-2} = 0.0226\ h^{-2} = 0.0456 \sim 5\%$



Shull+12

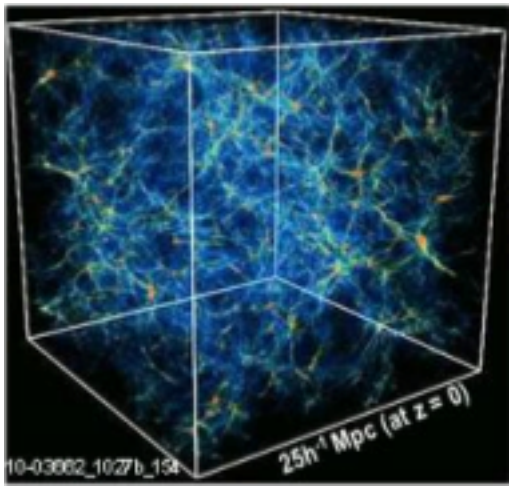
~ 30-40% (or more) of Baryons
Still Missing at z~0

McGaugh+10

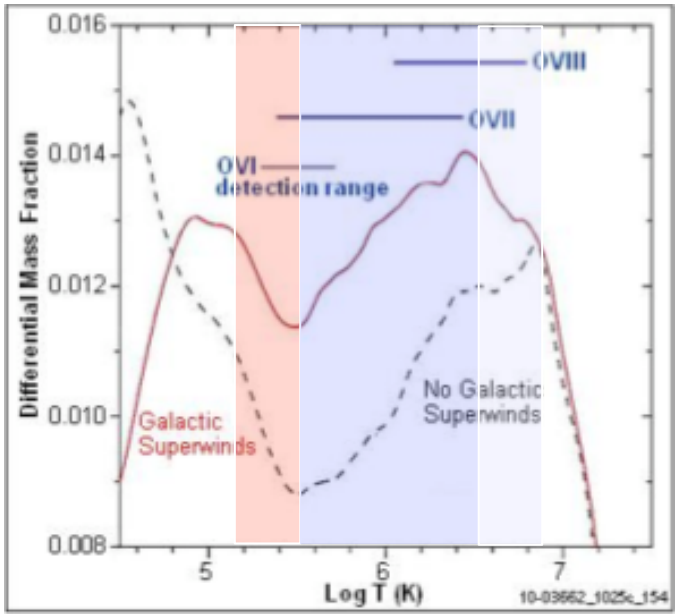


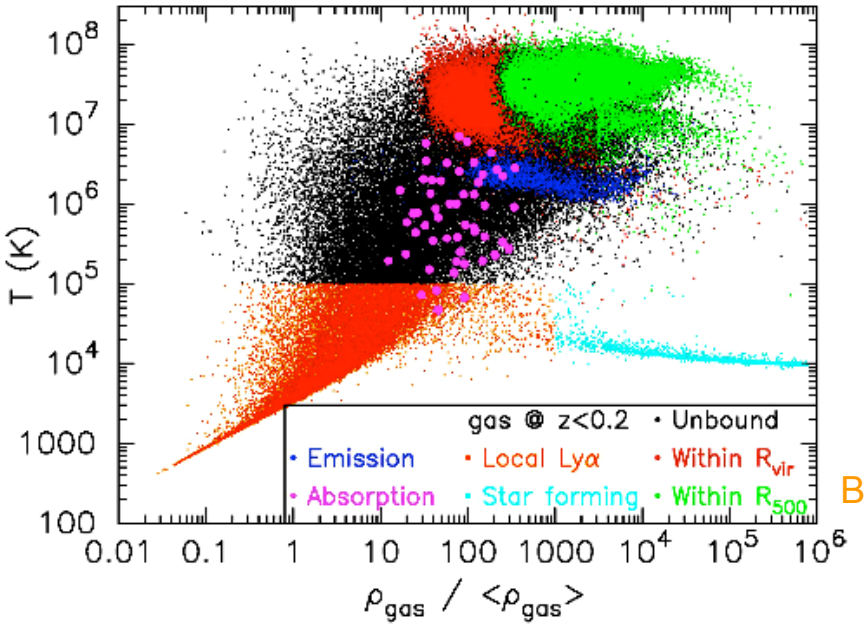
Cosmological Baryon Fraction $f_b = 0.17$

The WHIM in Hydro-dynamical simulations



Britton+12





Branchini+10

Cool-Phase: ~20%

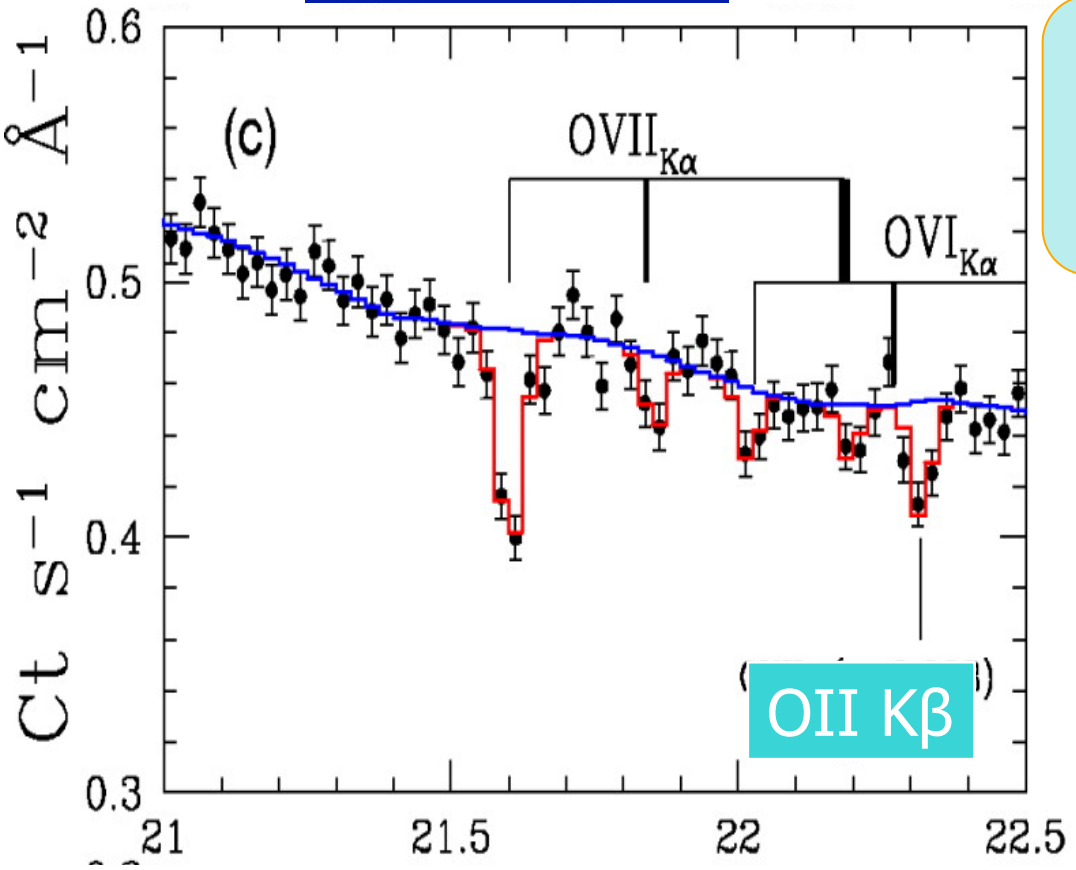
Warm-Phase: ~60%

Hot-Phase: ~20%

First Claimed WHIM Detections:

Exceptional Outburst State

(Nicastro+05, *Nature, ApJ*)



However:

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

+

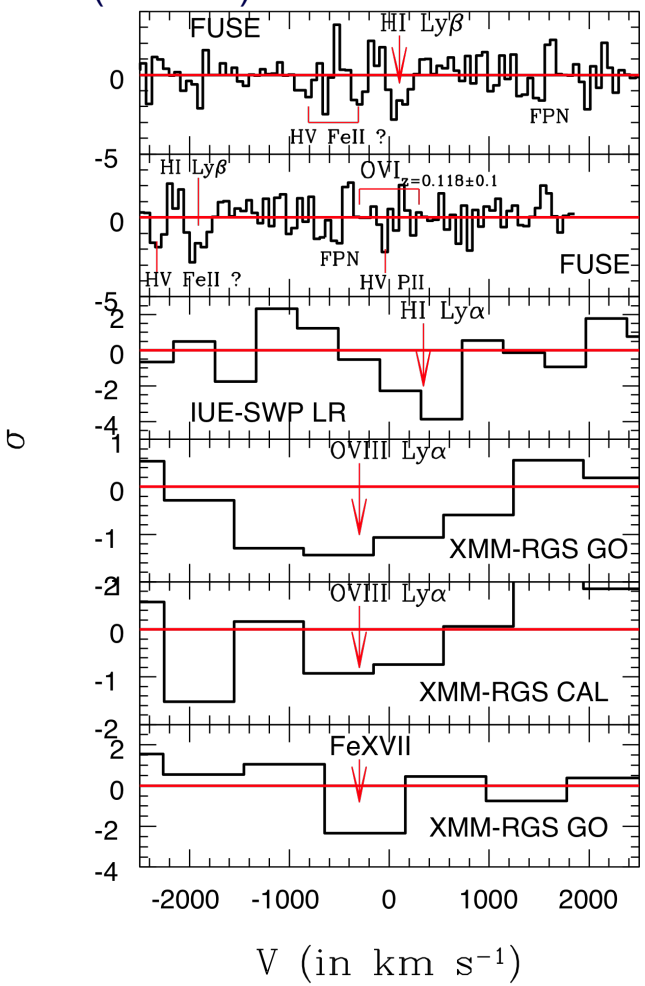
Controversial:

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

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

A Serendipitous hot X-Ray/BLA Filament at z=0.118?

PKS 0558-504
(z=0.137)



From X-rays ➔ $\log T < 6.75$; $\log N_H = 21.5 \pm 0.3\ (Z/Z_{0.01\odot})^{-1}$

From lack of OVI ➔ $\log T > 6.52$

From HI and T ➔ $Z = (1\text{-}4)\%\ Z_\odot$

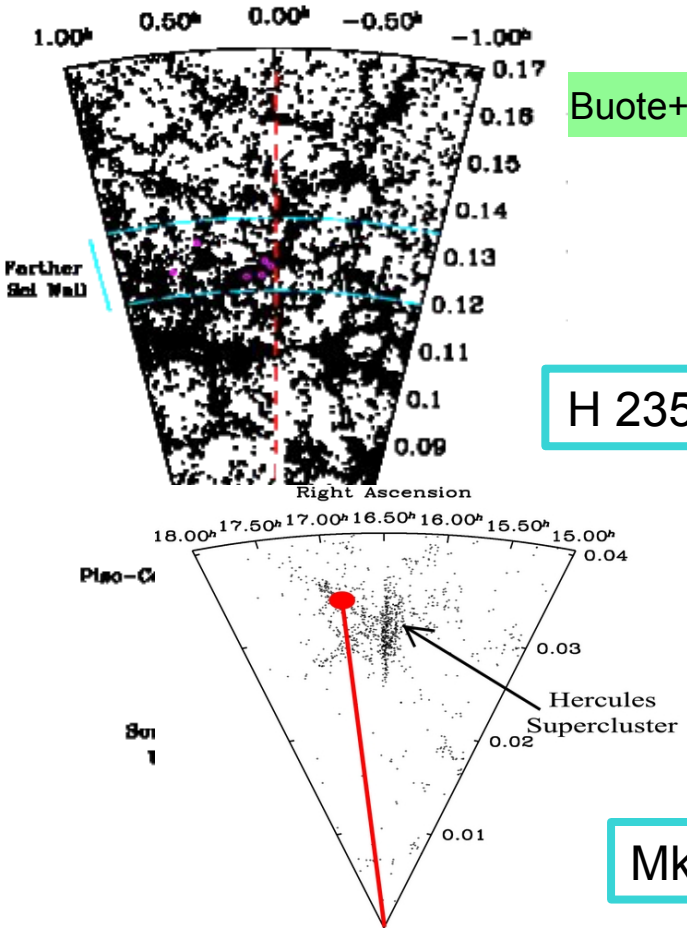
From Z and T and Theory ➔ $\delta \approx 300$

From δ and N_H ➔ D=4-7 Mpc

Combined Statistical Significance = 5.2σ
(5σ if FUSE systematics are included)
[Nicastro+10]

Galaxy concentrations as WHIM tracers

But: $N_{OVII} \sim 8 \times 10^{16}$ cm^{-2} !!!

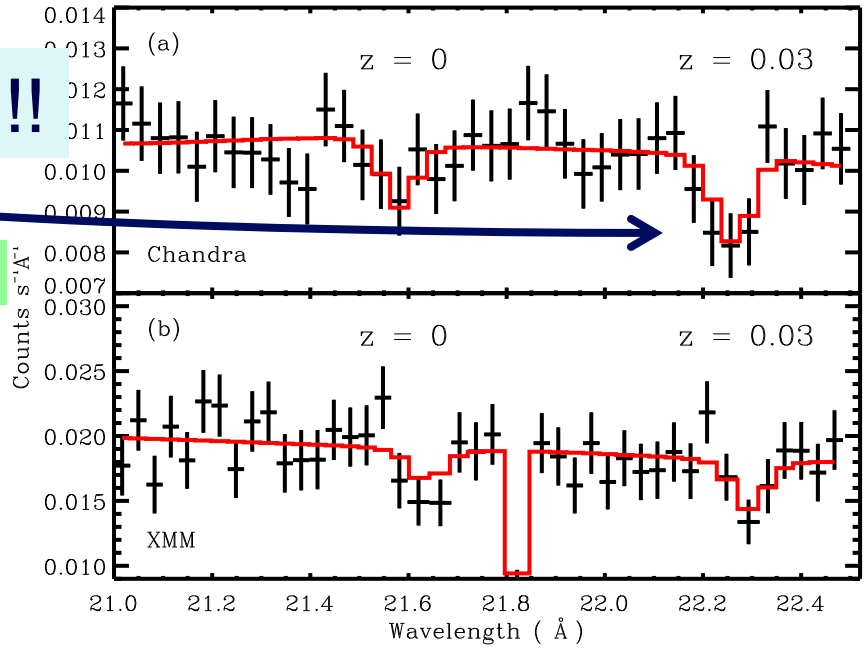


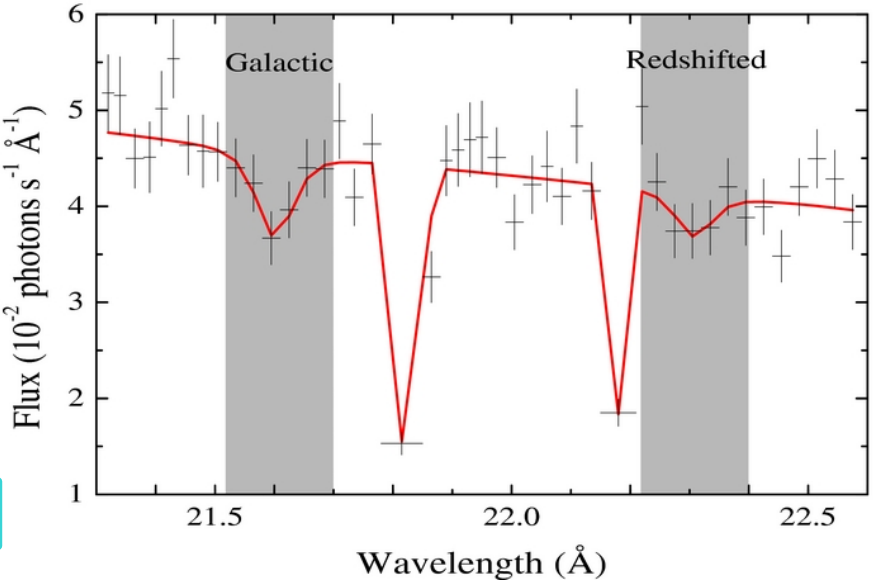
Buote+09, Fang+10

H 2356-309

Mkn 501

Ren, Fang & Buote, 2014



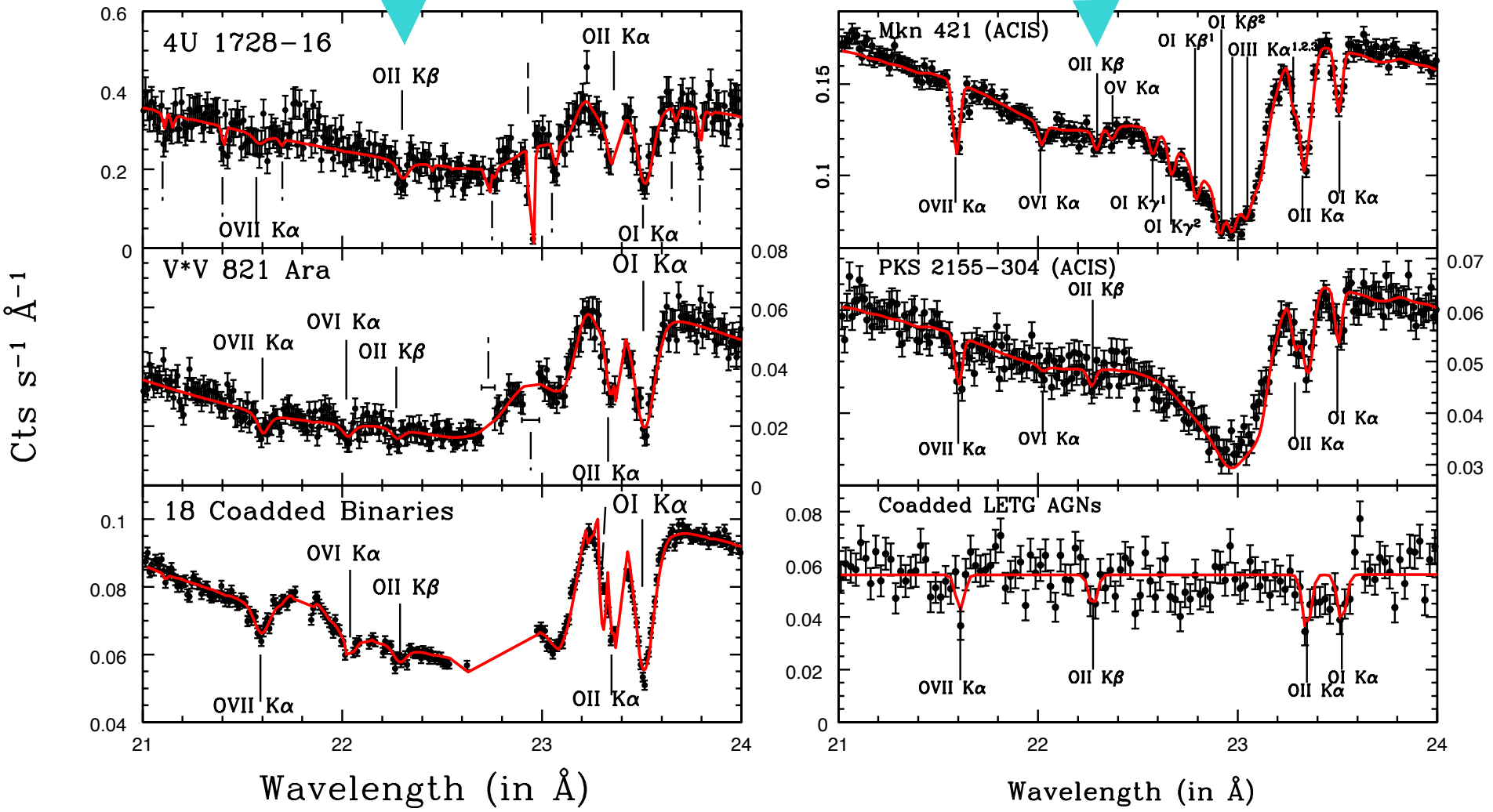


OII Kβ @ z=0 Not OVII @ z=0.03

<EW(OII Kβ)> = 14 ± 4 mÅ

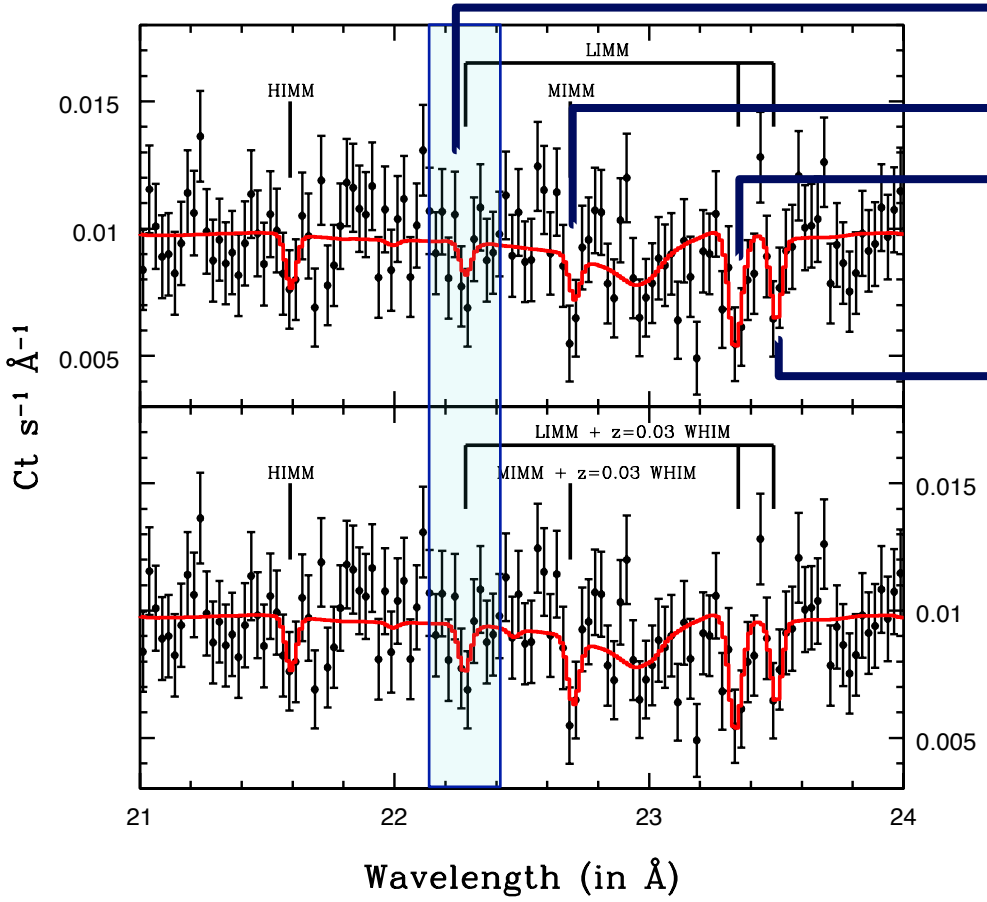
Nicastro+16, MNRAS, 457, 676

<EW(OII Kβ)> = 18 ± 5 mÅ



The Case of H 2356-309

& the z=0-LIMM / z=0.03-WHIM conspiracy



z=0 OII Kβ or z≈0.03 OVII Kα

z=0 OIV Kα or z≈0.03 OVI Kα

z=0 OII Kα

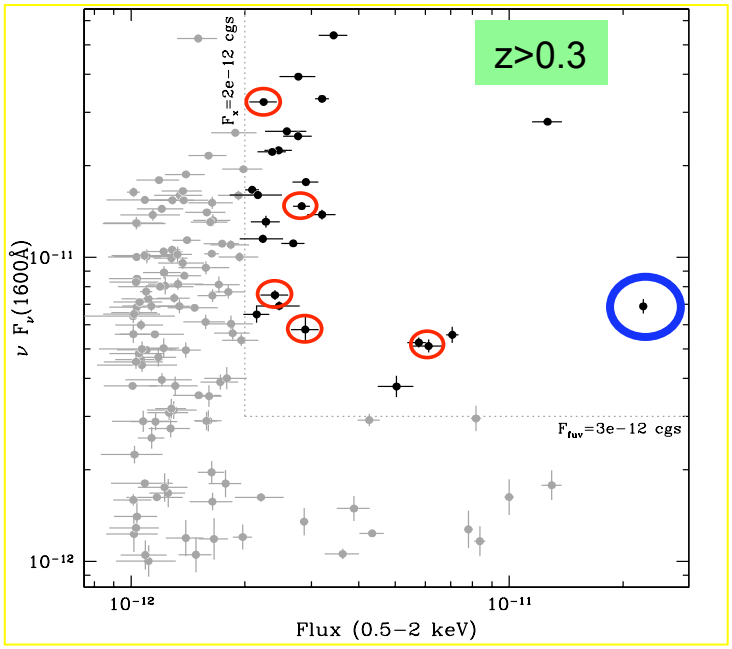
z=0 OI Kα or z≈0.03 OIV Kα

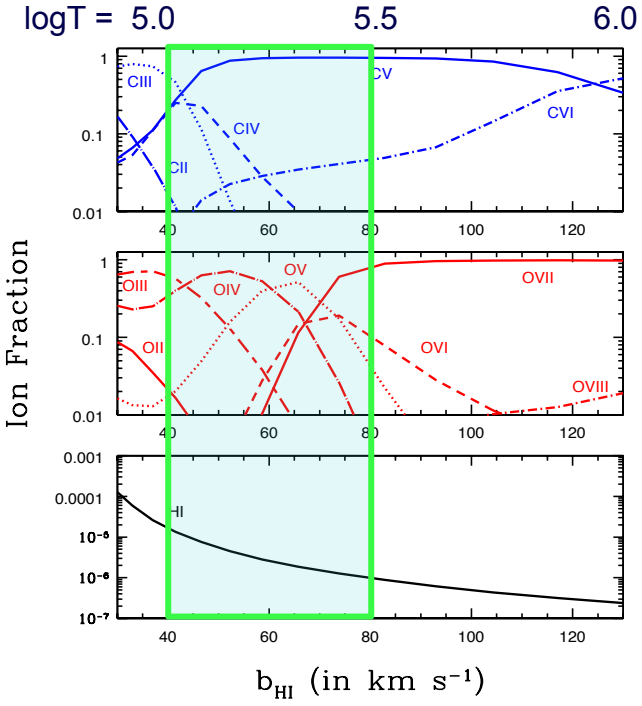
EW(OII Kβ) = 18 ± 5 mÅ
vs
<EW(OII Kβ)>^{AGN} = 18 ± 5 mÅ

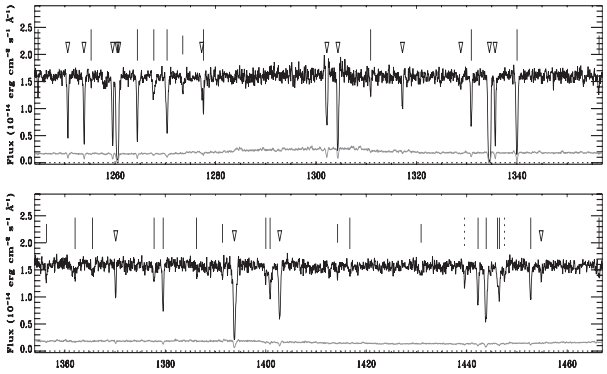
z≈0.03 WHIM not statistically required.
If present must have:
T ≈ 3x10^{5} K
b ≈ 100 km s-1
NOVII ≈ 4x10^{15} cm^{-2}
(<< 8x10^{16} cm^{-2} of Fang+10)

Nicastro+16, MNRAS, 485, L123

Best WHIM Target in the Universe: 1ES 1553+113







- z > 0.4
- F_X ~ 1-2 mCrab
- High S/N COS spectrum with 5 priors (HI Lyα with 40<b<80 km s^{-1} : BLAs
- ➔ 5.2 < logT < 5.5 ➔ Mostly CV)

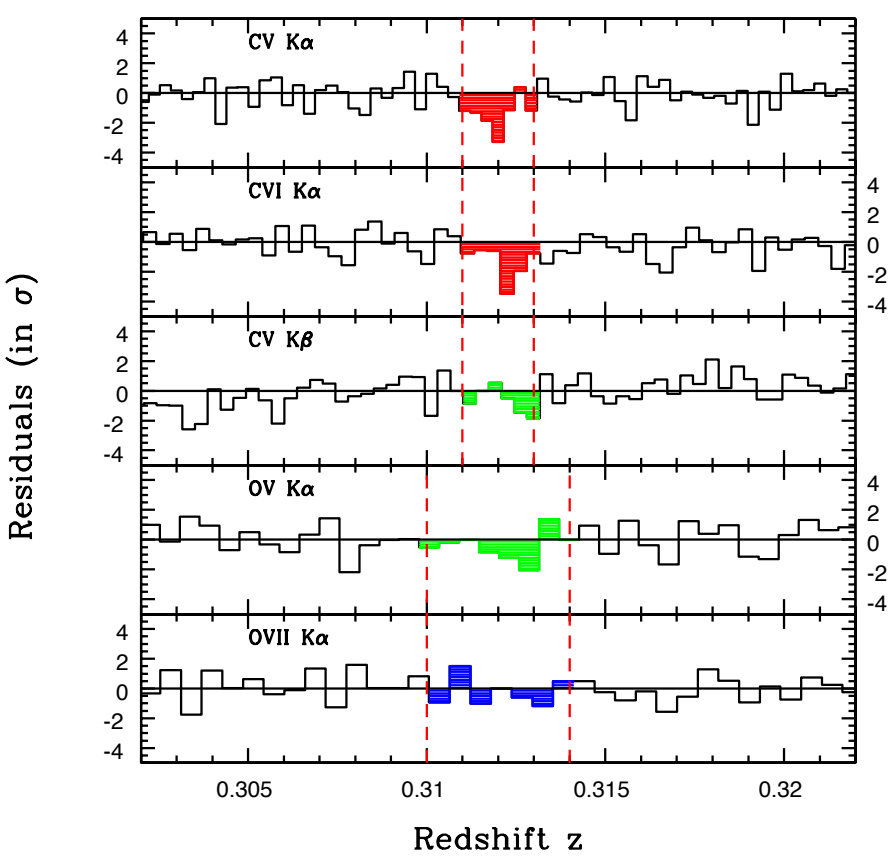
Tentative IGM IDs

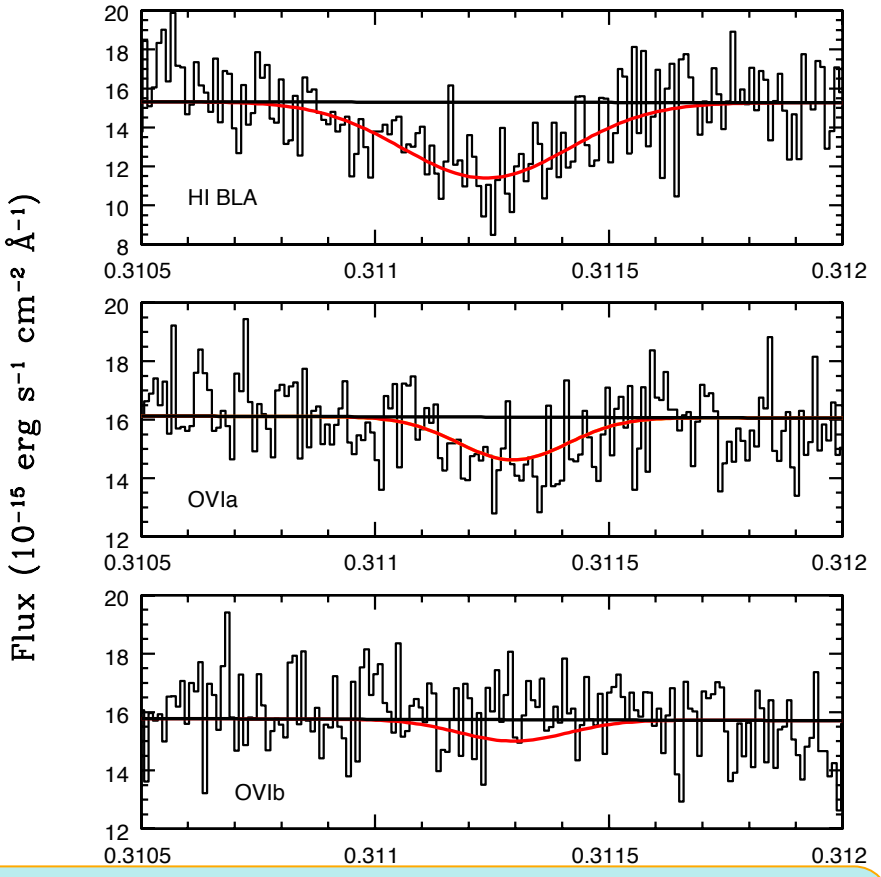
Nicastro+13

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

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, CVI, OV

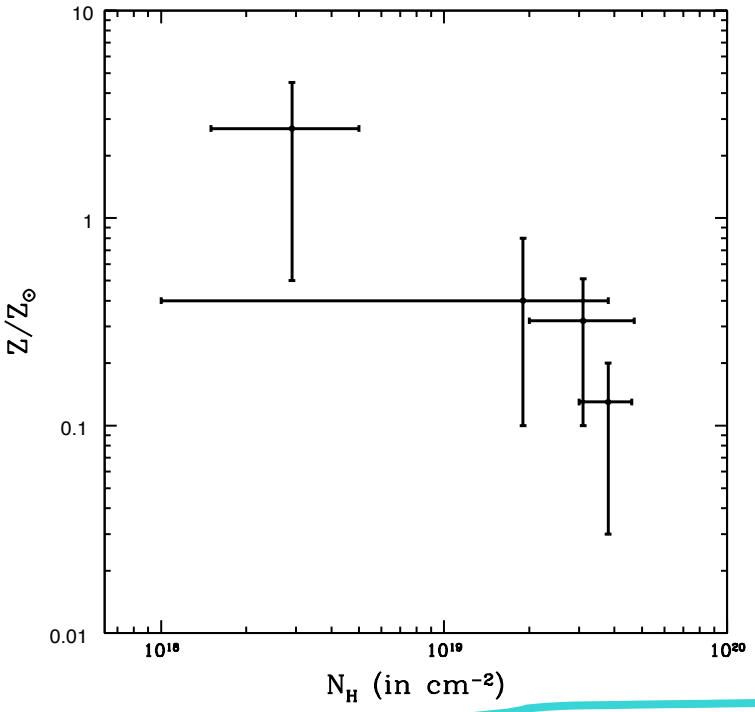
Best-Fitting WHIM Parameters

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	105	NA
0.190±0.001	5.25 ± 0.05	1.9 ± 1.8	107	0.4, +0.4, -0.3
0.237±0.001	5.3 ± 0.1	0.3, +0.2, -0.1	109	2.7, +1.8, -2.2
0.312±0.001	5.25 ± 0.05	3.1, +1.6, -1.1	112	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

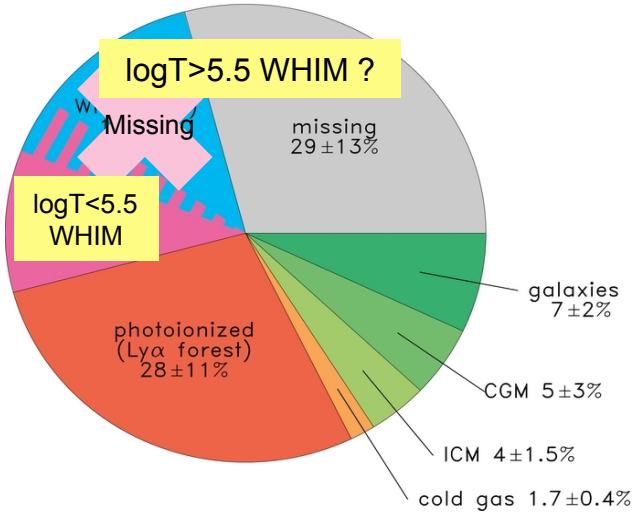
Cool WHIM contains 15% of MBs



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

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

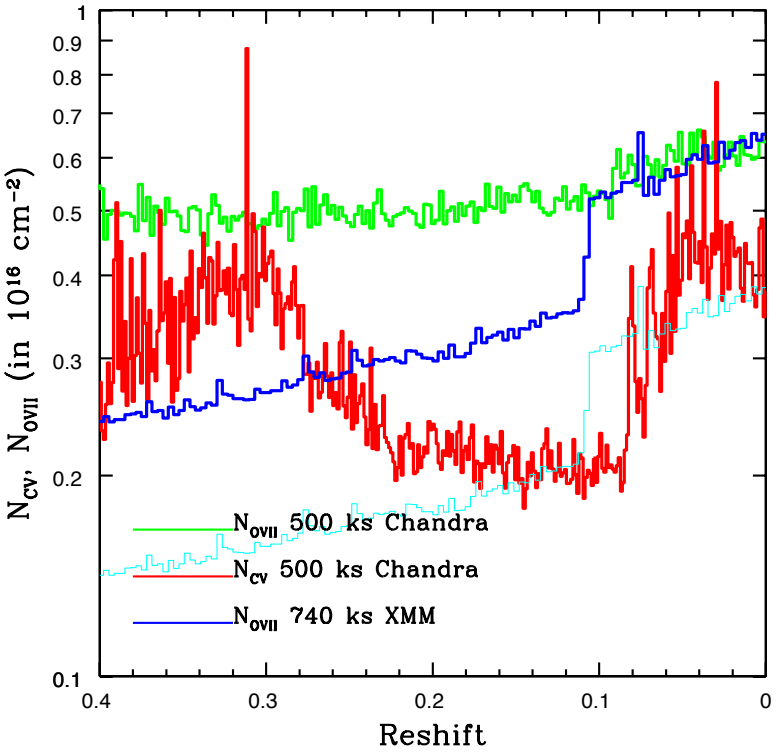
$$\sigma_{\Omega_b} = \frac{1}{[1-1/K]^{1/2}} \frac{1}{\rho_{cr,0}} \frac{\mu m_p \sqrt{\sum_{i=1}^{K} [N_H^i - < N_H^i >]^2}}{\Delta l_{comoving}}$$



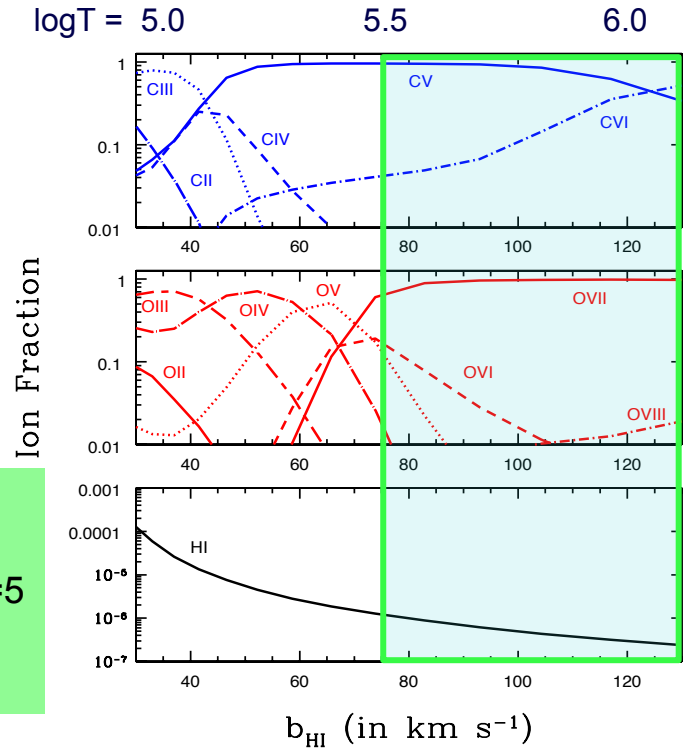
$$\Omega_b(5.0 < \log T < 5.5; EW_{CV,OVII} > 10\ m\mathring{A}) = 0.0069 \pm 0.0018 = (15 \pm 4)\%\ \Omega_b$$

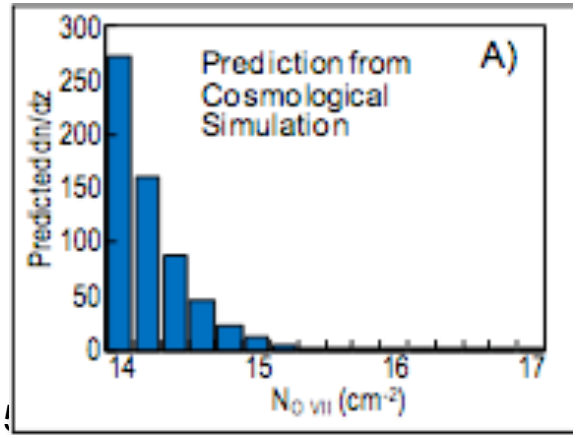
50% of Baryons are still Missing

XMM VLP: 1.6 Ms on 1ES 1553+113



9 h at GTC
SDSS u',g'r',I',z'
≤24.5 in r' @ S/N=5
(0.02L* at z=0.5)
Allows Δz=0.025

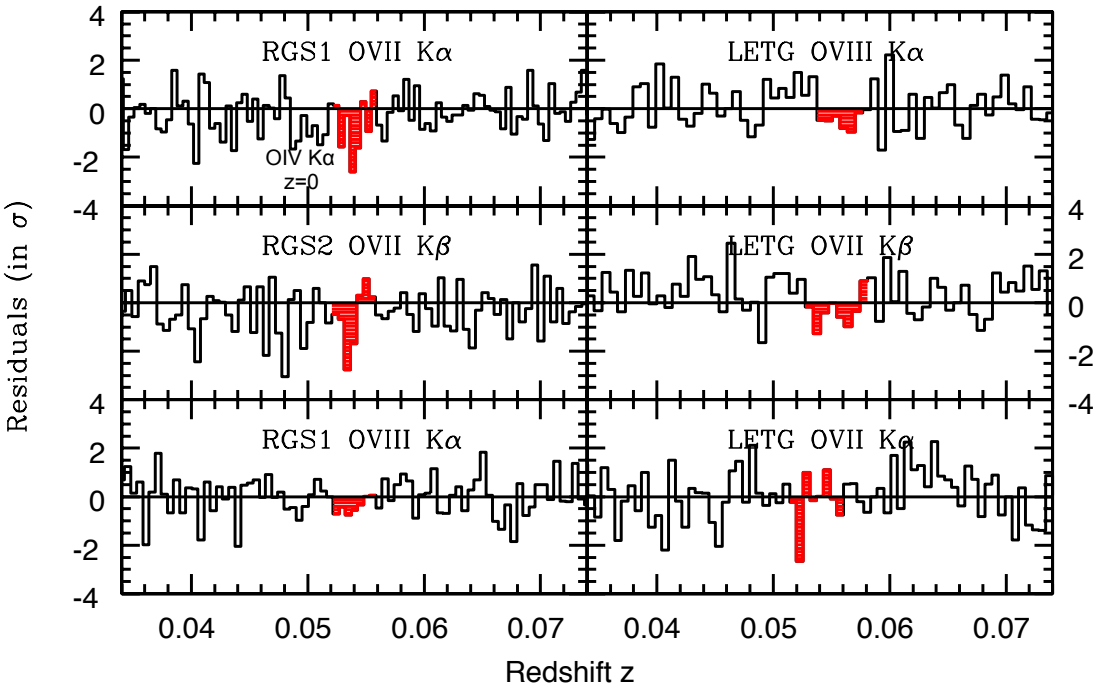




With the sensitivity of the current 500 ks *Chandra* bound to detect only the cool WHIM in CV.

~1.6 Ms XMM ➔ ~4x S/N in OVII ➔ $N_{OVII} > 10^{15}$ cm^{-2} ➔ ~5-10 systems sampling the hot WHIM

4σ Detection of logT>5.5 WHIM in Multiple Lines



z=0.054

$\log T = 5.7_{-0.1}^{+0.5}$ K

➔ $b_{HI} > 90$ km s^{-1}

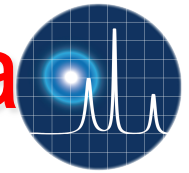
\+ Tentatively

confirms z=0.043 OVII

detects z=0.237 OVII

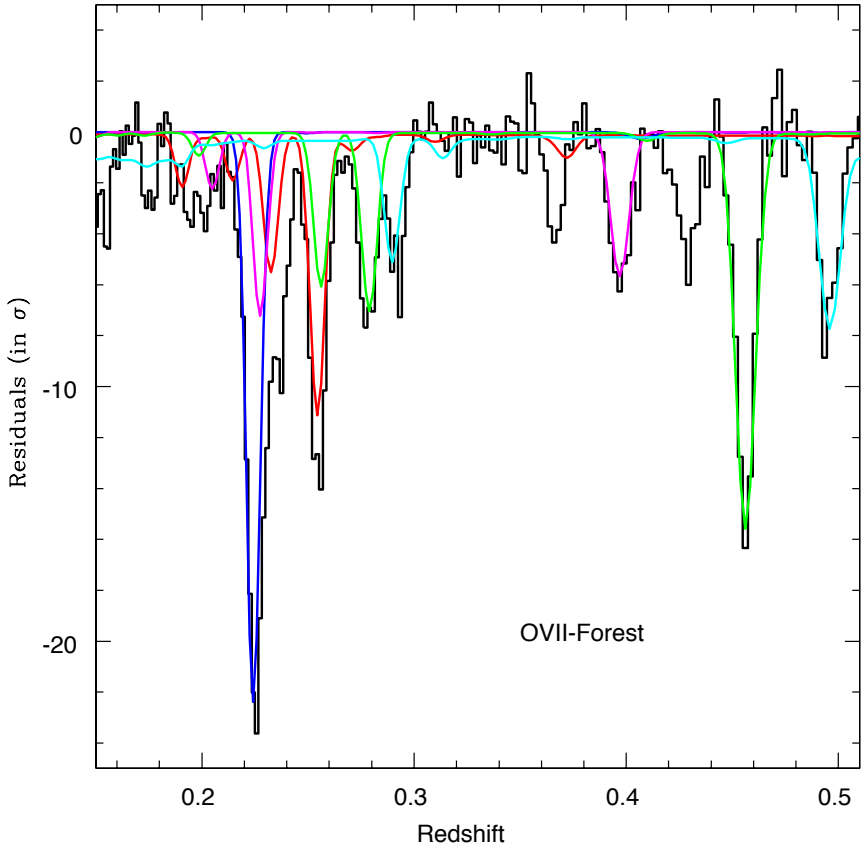
In the short-term, only ultra-deep XMM and Chandra observations can detect the missing 50% of baryons and solve the puzzle

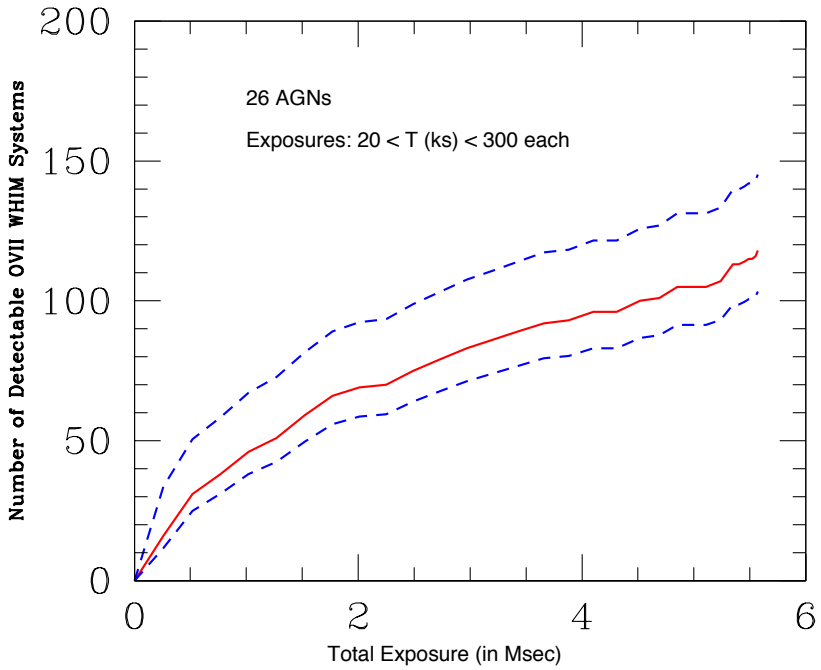
The Long-term Future: Athena



IFU

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, $\log N_H$ = 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

- *After proper ionization and metallicity correction, CV-OVI-BLA dominated "cool" WHIM contains ~ 15% of Baryons*
  - ➔ *40-50 % of Baryons still Missing and likely to reside in logT>5.5 WHIM:*

detectable only with ultra-deep XMM and Chandra pointings

- In the future Athena will enable:
  - (a) accurate (*few* %) measure of the Cosmological Mass Density of Baryons in the Universe
  - (b) study of the interplay between galaxy and AGN outflows and the IGM (feedback)
  - (c) understanding of the role of shocks in the formation of structures in the Universe
  - (d) mapping of the Universe's Dark-Matter concentrations