Detection of a WHIM filament towards PG 1116+215 with *Chandra* and *HST*

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How Chandra can help solve the Missing Baryons problem

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Missing baryons at low redshift

- Most of the baryons in the universe are in the intergalactic medium (IGM, e.g., Shull+12)
- At high z, most of baryons is in a photoionized phase that gives rise to the Lyman α forest
- At low z, most of baryons are in a warm-hot intergalactic medium (WHIM) at log T(K) = 5-7.

- Observations in the FUV have been very successful in measuring WHIM (e.g., Danforth & Shull 08; Tripp +08; Tilton+12; Shull +12)

- Typical estimates of the baryon density from FUV observations are short of the expected amount of baryons in the WHIM – this is the missing baryons problem at low z

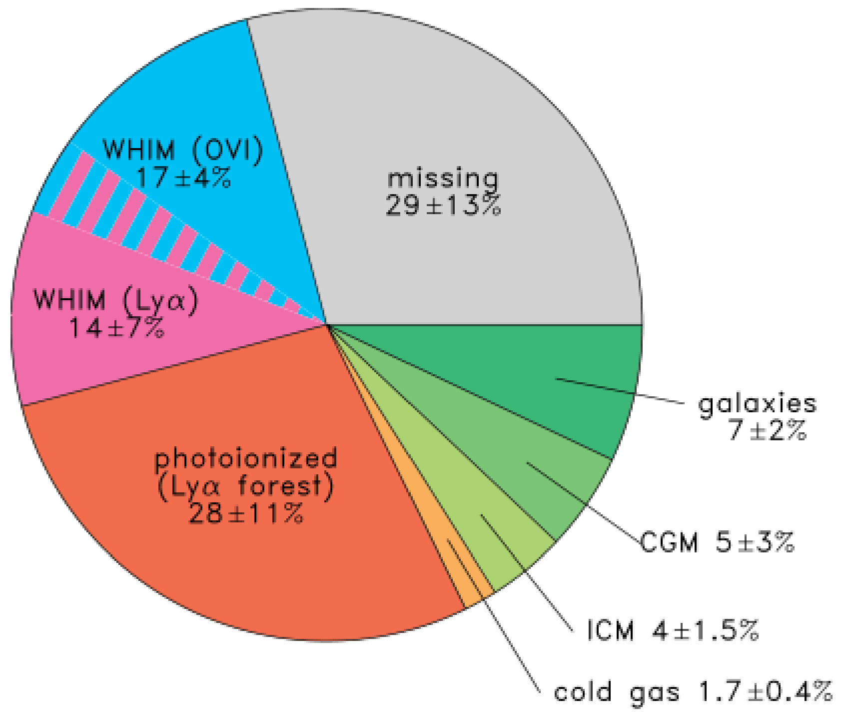


Figure 10. Compilation of current observational measurements of the low-redshift baryon census (Section 3.3). Slices of the pie chart show baryons in collapsed form, in the circumgalactic medium (CGM) and intercluster medium (ICM), and in cold gas (H I and He I). Primary baryon reservoirs include diffuse photoionized Lyα forest and WHIM traced by O VI and broad Lyα absorbers. Blended colors (BLAs and O VI) have a combined total of 25% ± 8%, smaller than their direct sum (17% plus 14%) owing to corrections for double-counting of WHIM at 10^5–10^6 K with detectable metal ions (Section 4.1). Collapsed phases (galaxies, CGM, ICM, cold neutral gas) total 18% ± 4%. Formally, 29% ± 13% of the baryons remain unaccounted for. Our simulations (Figure 3) suggest that an additional 15% reside in X-ray-absorbing gas at $T \geqslant 10^{6.3}$ K. Additional baryons may be found in weaker lines of low-column-density O VI and Lyα absorbers. Deeper spectroscopic UV and X-ray surveys are desirable.

(from Shull+12)

Challenges of detecting missing baryons

- Main challenges of the current estimates of cosmological density of WHIM are:

  (1) Knowledge of the metal abundance A of absorption-line systems.
  (2) Paucity of detections of log T(K)>6 WHIM in X--rays

- In the X-rays, there are only a handful of possible detections of WHIM ions (typically OVII/OVIII, but also NeIX/NeX, CIV/CV and NV/NVI at 11-40 Angstrom): H 2356-309 Fang+10),PKS 2155-304 (Fang+02,07; Yao+09), Mkn 421 (Nicastro+05; Rasmussen+07; Yao+12), Mkn 501 (Ren+14) and 1ES 1553+113 (Nicastro+13).
- All detections have limited S/N and some have been challenged.

- (It is easy to confuse genuine z>0 WHIM lines with other X-ray lines (think of OI through OVI X-ray lines from inner-shell transitions longward of 21.6 Angstrom) or detector artifacts and background fluctuations.)

- Need redshift priors to guide the search for z>0 WHIM

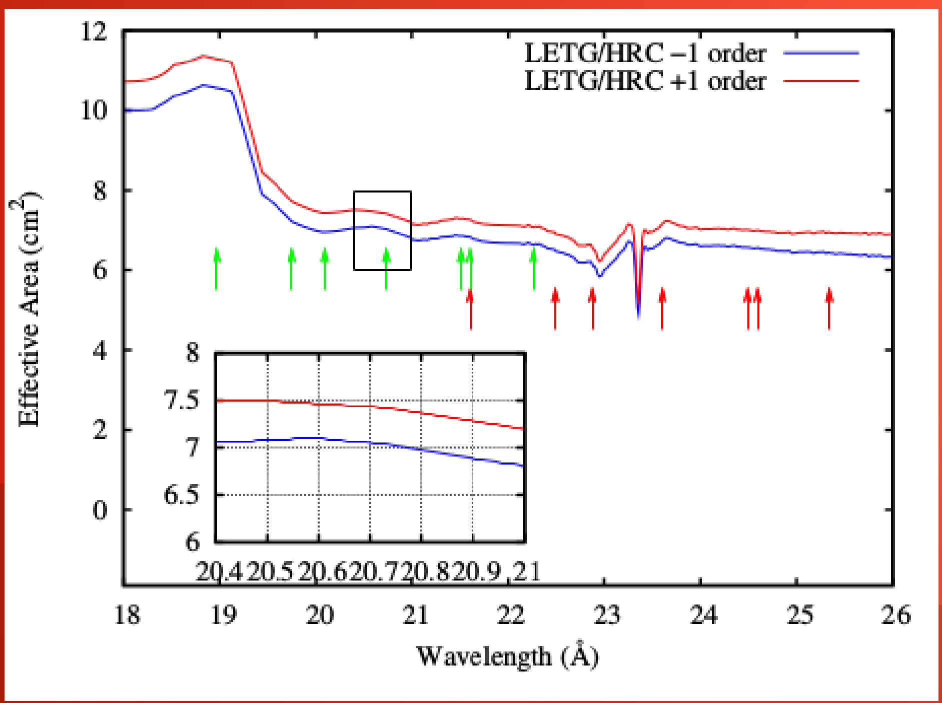
FUV observations of PG 1116+215

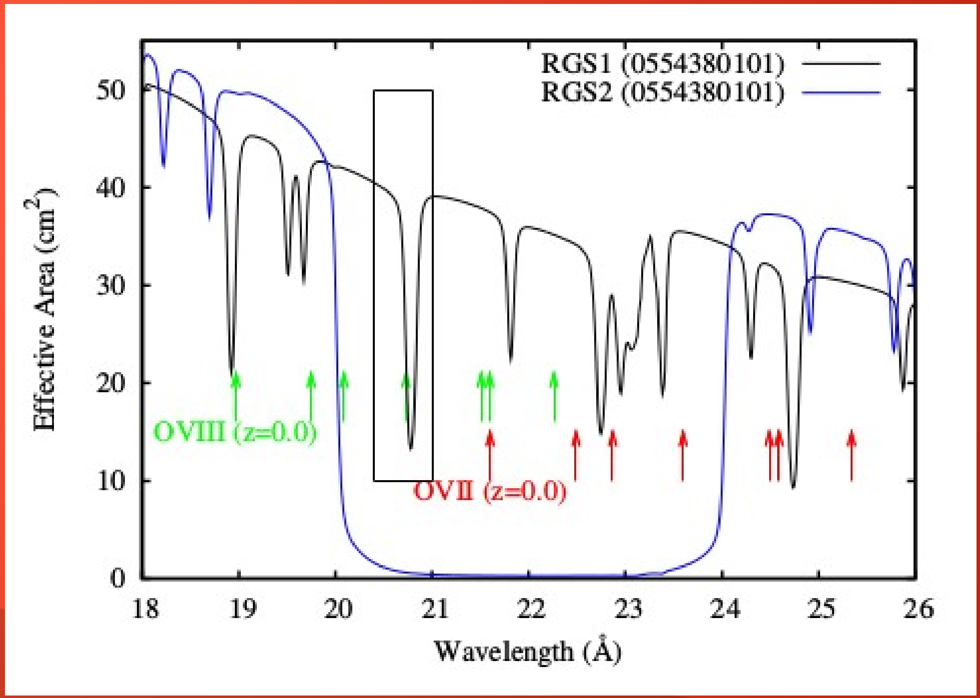
- PG 1116+215 (z=0.177) is well studied in the FUV. Tilton+12 used HST and FUSE data to detect a number of absorption lines from the WHIM at z>0.
- We followed up the OVI detections and the HI BLA with the largest Doppler b parameter (b>70 km/s).
- Notice in particular the HI BLA with b=133 km/s at z=0.09279. This is the highest-b BLA detected in Tilton+12.

Redshift	Line ID	Doppler b (km/s)	W_λ (mÅ)
0.13373	HI Lyman-α (BLA)	81 ± 6	82 ± 6
0.09279	HI Lyman-α (BLA)	133 ± 17	111 ± 14
0.04123	HI Lyman-α (BLA)	89 ± 10	73 ± 9
0.17340	OVI 1032,1038	$47 \pm 7, 24 \pm 13$	$60 \pm 10, 28 \pm 18$
0.13848	OVI 1032,1038	$24 \pm 8, 41$	$65 \pm 8, 43 \pm 10$
0.05927	OVI 1032,1038	$10 \pm 6, 17 \pm 12$	$25 \pm 5, 22 \pm 11$

X-ray observations of PG 1116+215

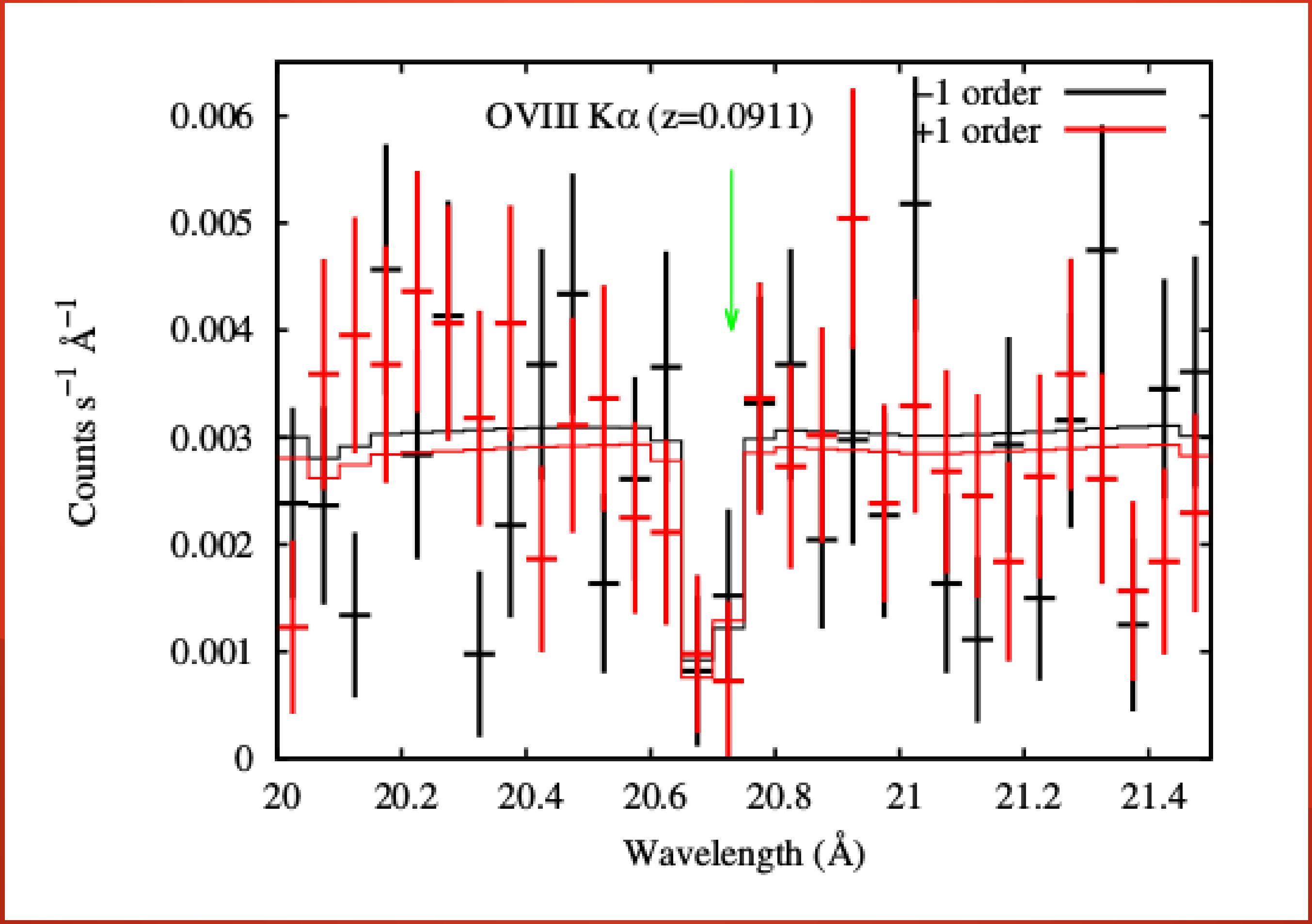
- PG 1116+215 was observed by both Chandra LETG and XMM-Newton RGS.
- Typical spectral resolution is 0.05 A in the soft X-ray band.
- XMM-Newton observations have too many detector edges that made most interesting absorption lines unaccessible.





Detection of a new OVIII absorption system

- Initial model was power-law model and fixed-wavelength absorption lines at the redshift of possible OVII and OVIII Kα lines (i.e., using redshift *priors*).
- Green arrow marks the position of the HI BLA from Tilton+12.



- We detect an absorption line: OVIII Kα at z=0.0911+-0.0004+-0.0005 at 5.2 σ (Bonamente+16)

Column density and non-thermal broadening

- EW=79+-15 mA for OVIII Kα corresponds to a column density of N=6.0+-1.1 x 10^{16} cm^{-2}. EW is larger than thermal broadening (6 mA at b=100 km/s)
- Line may be saturated if b<500 km/s. SPEX fits to Chandra spectra idicate that data are consistent with substantial non-thermal broadening (560+-400 km/s), so line may not be saturated after all.

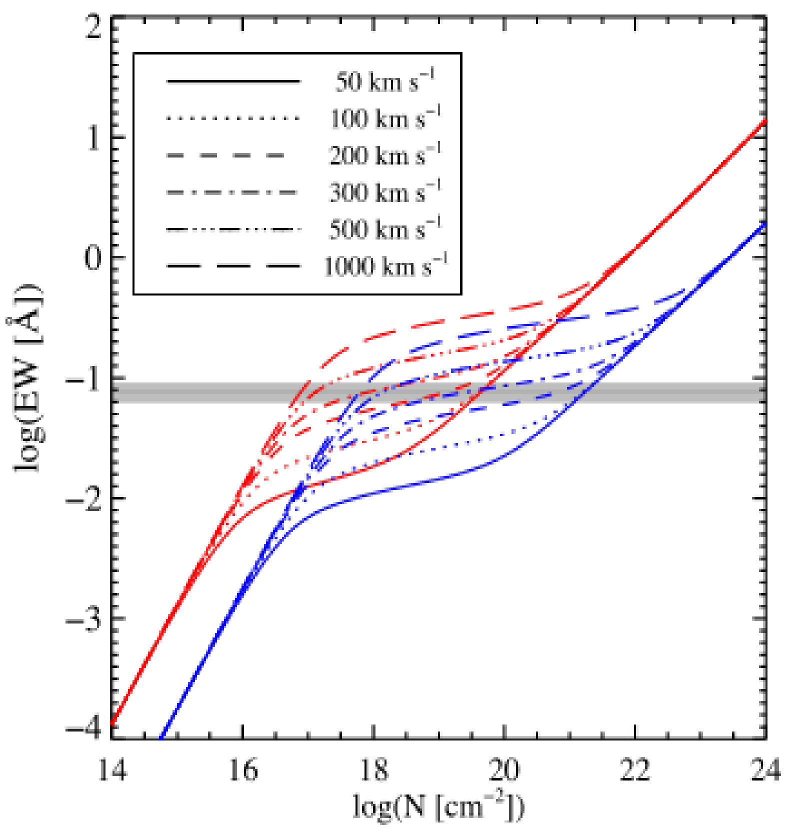
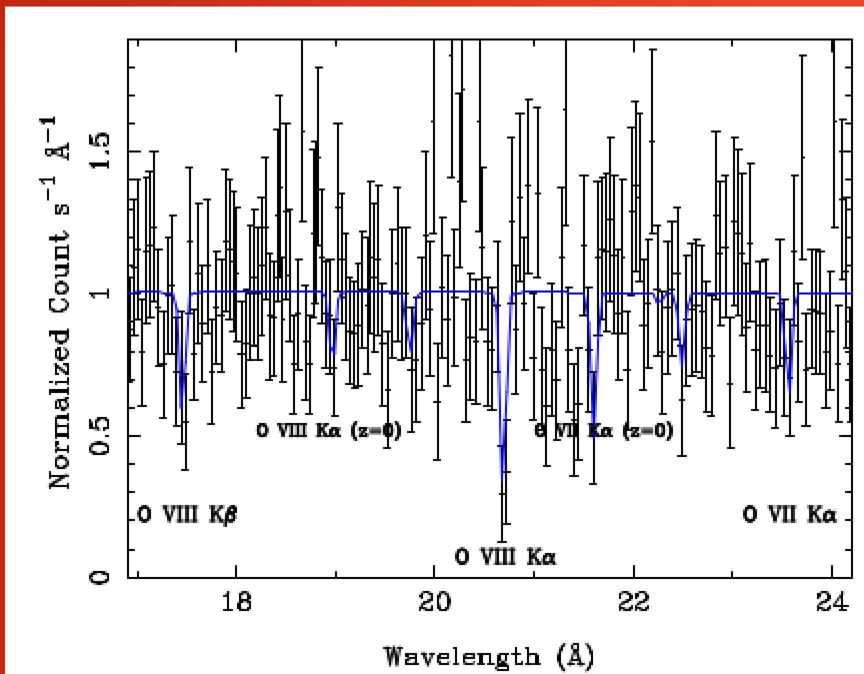


Figure 4. Curves of growth for the O VIII Kα (red) and Kβ lines (blue). The grey area marks the *Chandra* measurement of the O VIII Kα absorption line.

Maybe OVIII Kβ and OVII too?



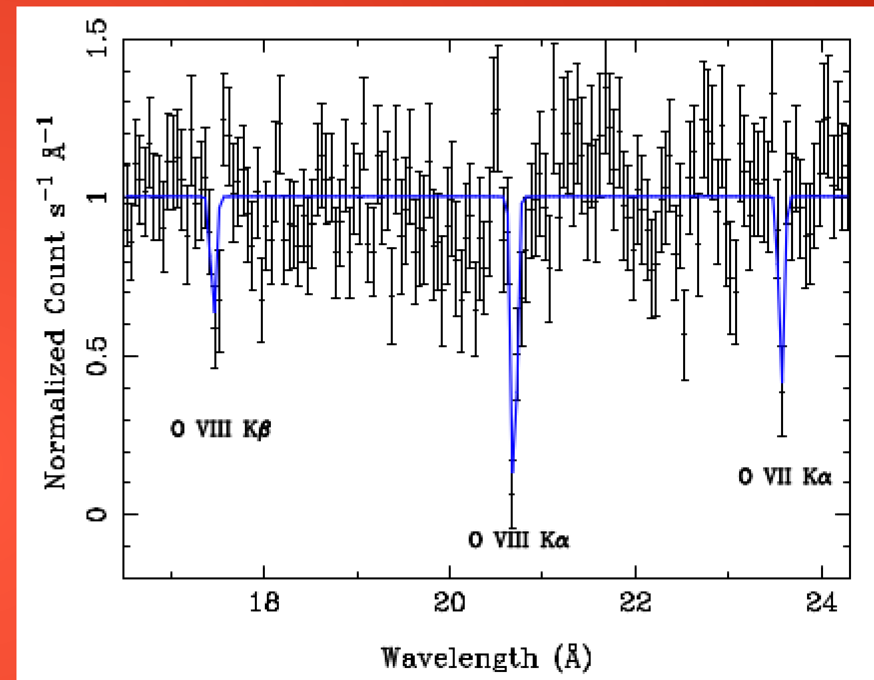
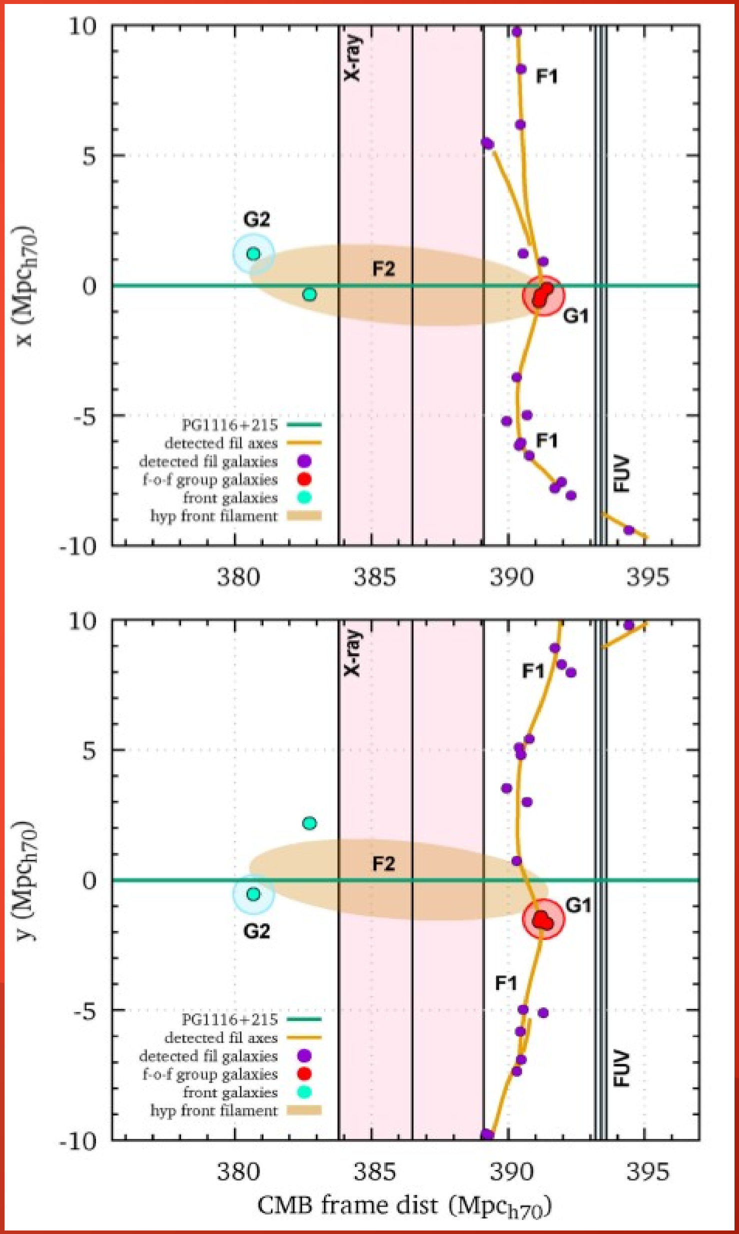


Figure 4: Sample simulated 280 ks LETGS spectrum of PG 1116+215 showing the three target lines. The coadded ±1 order spectrum is rebinned to 50 mÅ bins and normalized by the continuum.

- There is possible 2.4 σ absorption at same z for OVIII K-β and 1.5 σ absorption for OVII K-α at same redshift. This is potentially exciting if confirmed.
- Chandra cycle 18 approved 280 ks observation ... so we'll see.

Interpretation of X-ray/FUV observations

- Presence of WHIM at log T(K)>6 along the sightline.
- There are no viable galaxies in the redshift range z=0.091-0.093 whose circumgalactic medium can give rise to such an absorption line. (See Smita Matur's talk)
- Consistent with Stocke+14 hypothesis that warm absorbers (BLA at z=0.0928) are at the interface between cooler/photoionized gas and hotter gas (OVIII at z=0.0911) associated with galaxy groups.
- The Tilton+12 BLA at z=0.0928 and this OVIII Kα at z=0.0911 indicate the presence of a multi-temperature WHIM filament of few Mpc length towards PG 1116+215 (see figure: position and accretion velocities explain redshift difference between HI BLA and OVIII)



Upcoming Work on z>0 WHIM

- Future work includes the analysis of a large sample of Chandra/XMM sources that have FUV observations available. Work is in part supported by a Chandra archival grant.
- Analysis will make use of two key features: (1) a priori identification of WHIM filaments and (2) redshifts priors from FUV observations

Table 1: Sources and X–ray data used in this project. All sources have high S/N UV and FUV data from *FUSE* and *HST* (Tilton et al., 2012; Danforth et al., 2014).

Source	z	LETG	RGS
		(ks)	
Mrk 421	0.03	1,325	2,006
Mrk 478	0.0791	80	84
Mrk 509	0.0343	180	914
Ton S180	0.062	77	50
PH 1116+215	0.1765	88	277
1ES 1553+113	0.4140	645	77
PG1211+143	0.0809	134	878
H1821+643	0.297	470	67
PKS 2005-489	0.071	282	62
3C273	0.1583	244	998
PKS 2155-304	0.116	1,298	2,058
Akn 564	0.0247	100	666
Mrk 279	0.0305	279	191
1ES 1028+511	0.3604	149	312
NGC 5548	0.0172	939	897
MR 2251-178	0.0644	78	477
Total		6,368	10,014

Identification and characterization of foreground filaments

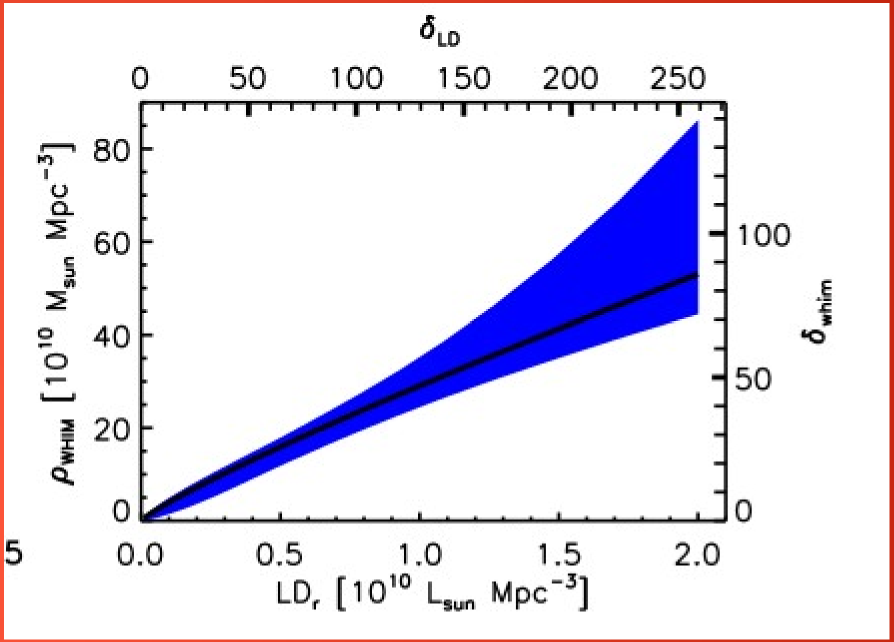
- New method to identify WHIM filaments from galaxy redshift surveys (such as SDSS) pioneered by Nevalainen+15:

- The Luminosity Density (LD) from galaxy surveys was calibrated with numerical simulations to predict the WHIM density

- Converts the observed LD to NH column densities for WHIM filaments. This leads to estimates of the WHIM temperature (assuming an abundance A) even with simple upper limits.

- If Doppler b parameters is available or if more than one ion of same element is detected, the availability of NH means the possibility to measure the abundance A.

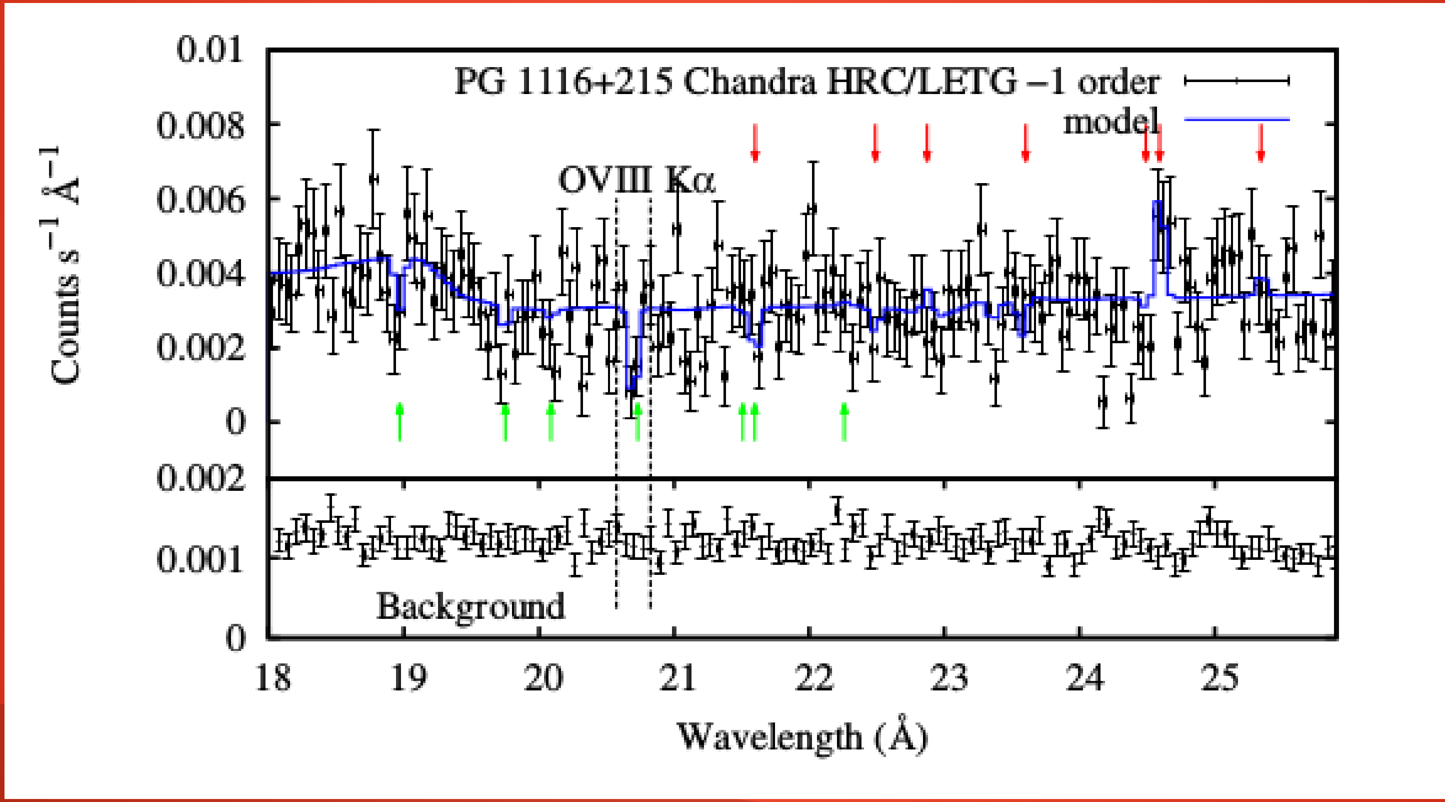
- Remember: Uncertainties in A are the dominant factor of uncertainty in the estimate of the cosmological density of WHIM (Tilton+12)



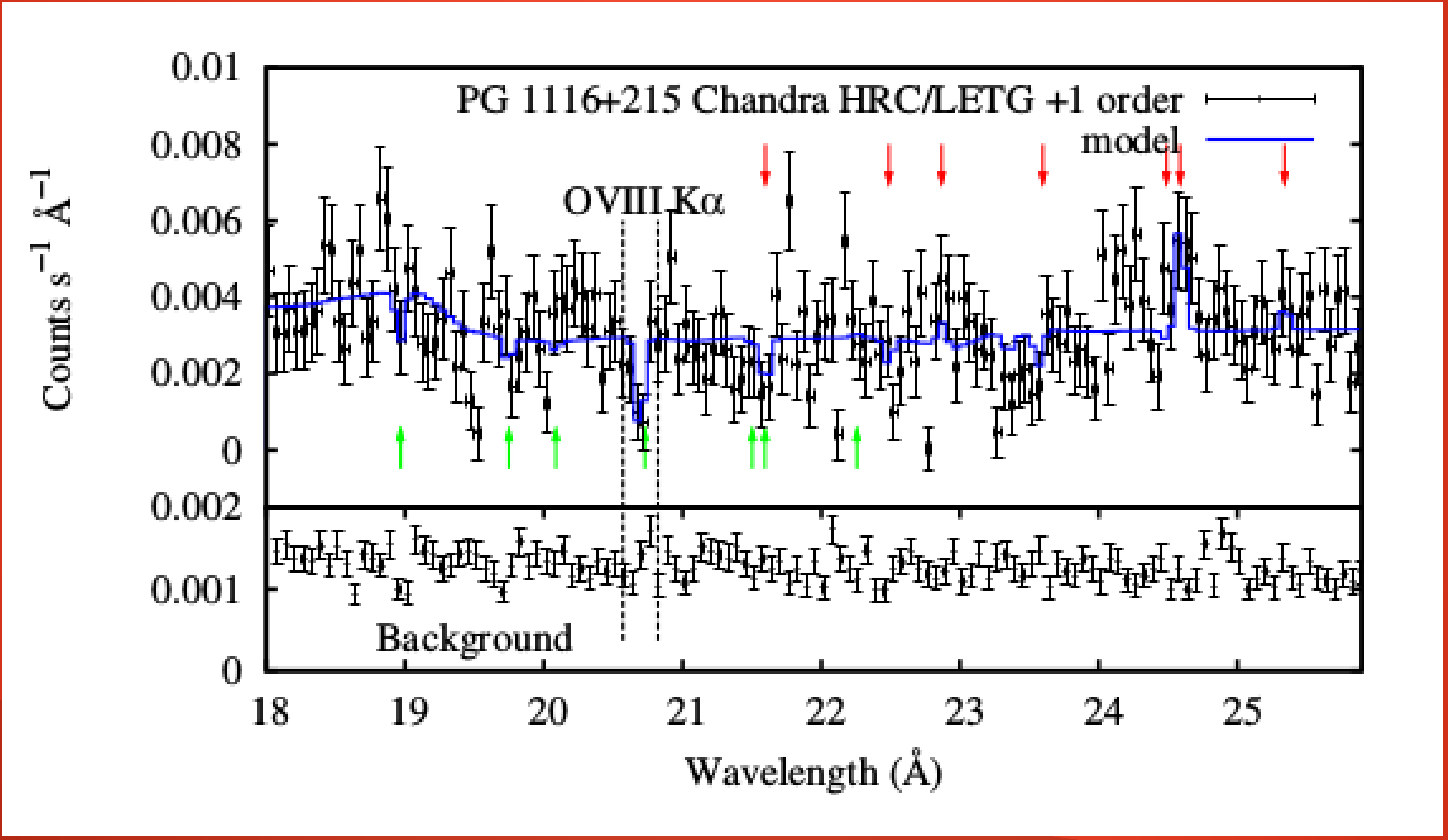
$$\log f_{ion}(kT) = \log\left(\frac{N_{ion}}{N_H}\right) - \log \frac{n_{el}}{n_H}\Big|_{\odot} - \log A$$

What can Chandra (and beyond) do for z>0 WHIM?

- Extensive archival work. There are >10 Ms of “free” grating data that need a consistent re-analysis. There is nothing easy about trying to detect X—ray WHIM lines at z>0.
- Integration with multi—wavelength efforts (HST/FUV, SDSS, etc. etc.). This will also emphasize the “relevance” of X—ray astronomy in the broader astrophysics community.
- Additional Chandra observations as needed. Notice that HRC is the main detector for LETG, so the loss of low—energy sensitivity of ACIS is not a factor.
- Bridge to new missions, such as *X—ray Surveyor* and *Arcus*. The key is to lower the typical sensitivity to WHIM column density to 10^{13}-10^{14} cm^{-2} from current 10^{15}-10^{16} cm^{-2} in a reasonable (few 100 ks) observation (see Brenneman poster).



PG 1116+215 Chandra HRC/LETG −1 order
model
OVIII Kα
Background
Counts s−1 Å−1
Wavelength (Å)



PG 1116+215 Chandra HRC/LETG +1 order
model
OVIII Kα
Background
Counts s^{-1} Å^{-1}
Wavelength (Å)
0.01
0.008
0.006
0.004
0.002
0
0.002
0.001
0
18
19
20
21
22
23
24
25