Missing Baryons at All Astronomical Scales

Current Evidence & Future Prospects

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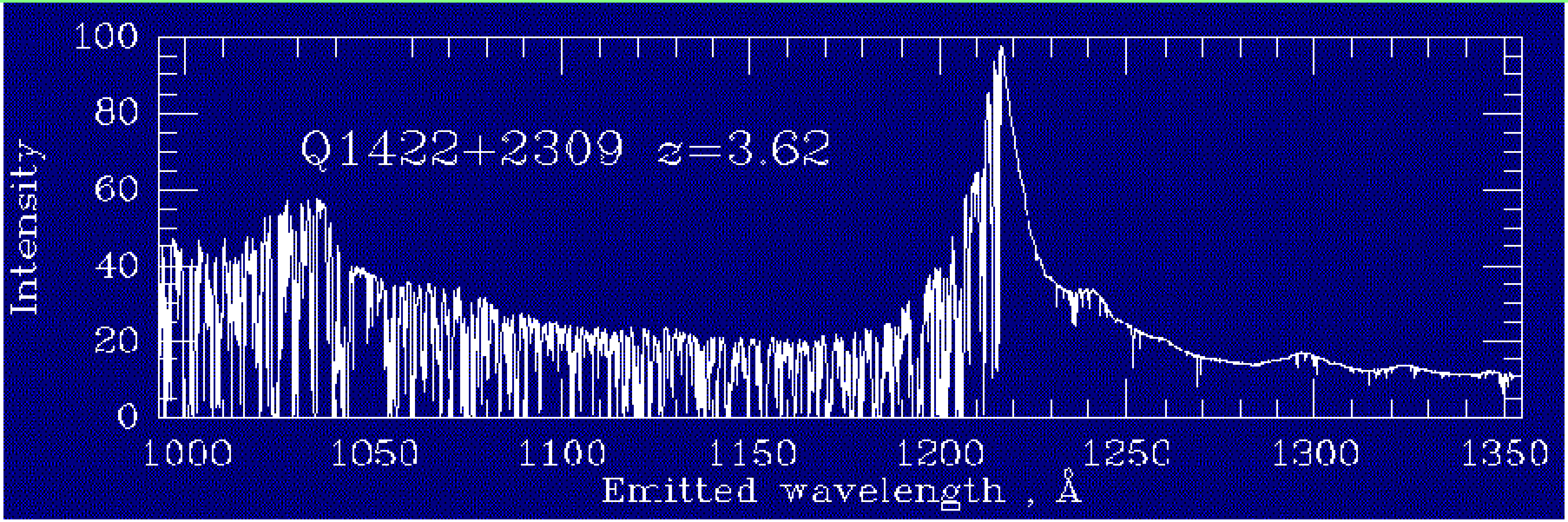
Outline

- The Missing Baryon Problems:
  - Universe & Galaxies
- Theory Solution & Predictions:
  - The Warm-Hot Intergalactic Medium & its Phases
- Current Evidence of the WHIM and First Determination of ΩbWHIM in X-rays
- Future Prospects

Baryon Budget at z>2: the Lyα Forest

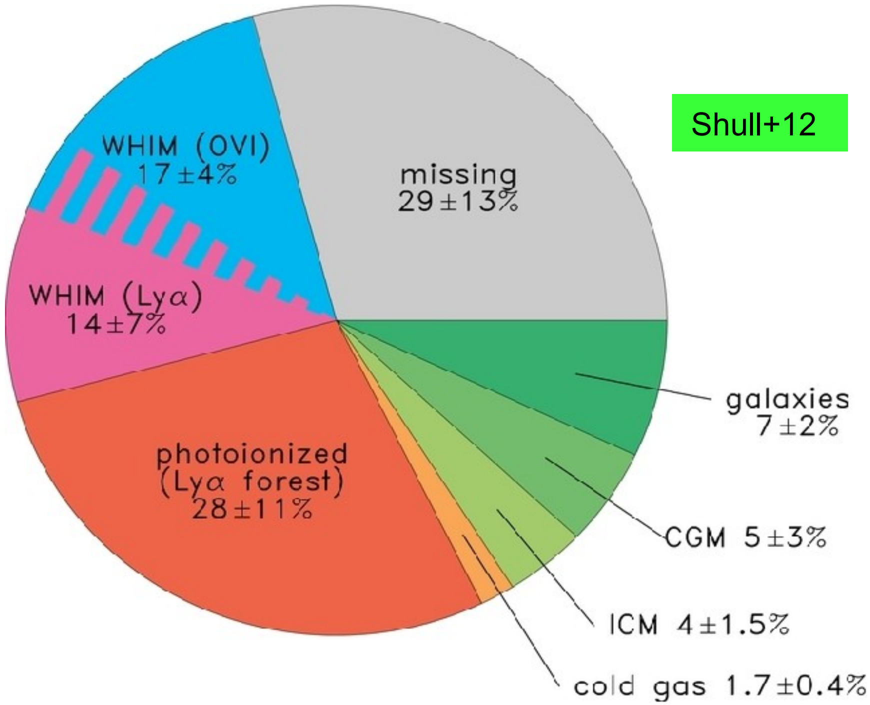
ΩbWMAPh-2 = 0.0226 h-2 = 0.0456 ~ 5%: agrees with BBN



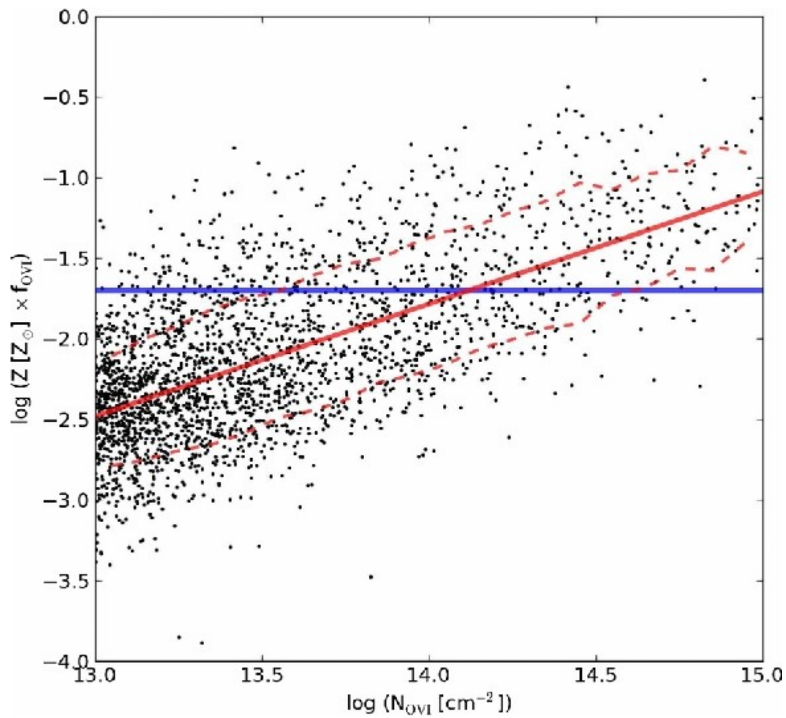
Ωb(z>2) > 0.018 h-2 = 0.034 ~ 75% ΩbWMAP

The Universe Missing Baryons Problem

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



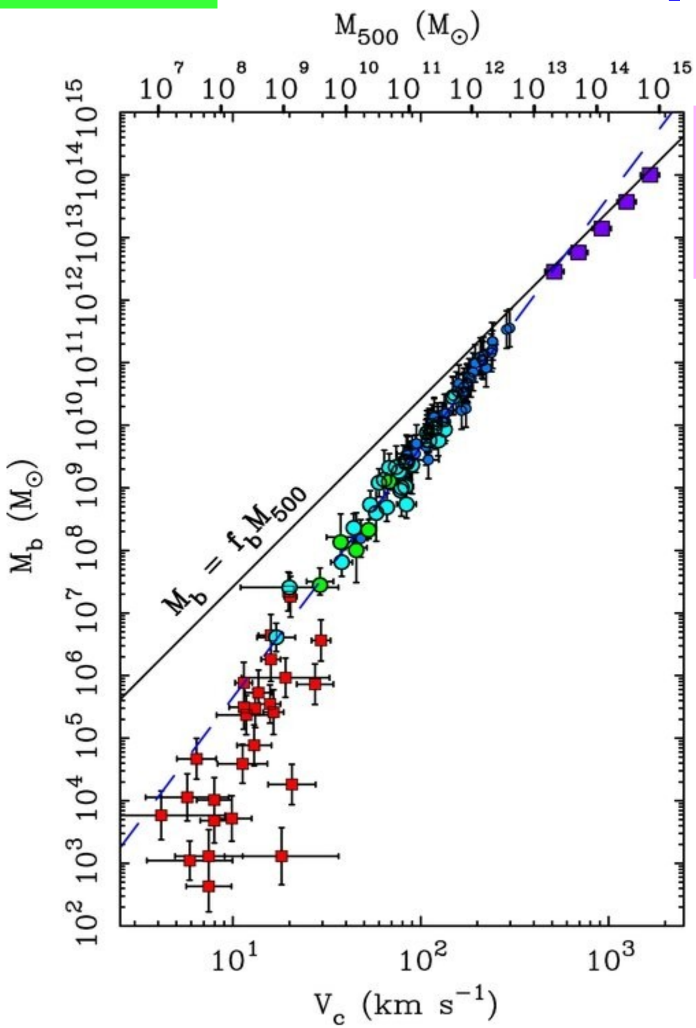
Shull+12



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

The Galaxy Missing Baryons Problem

McGaugh+10



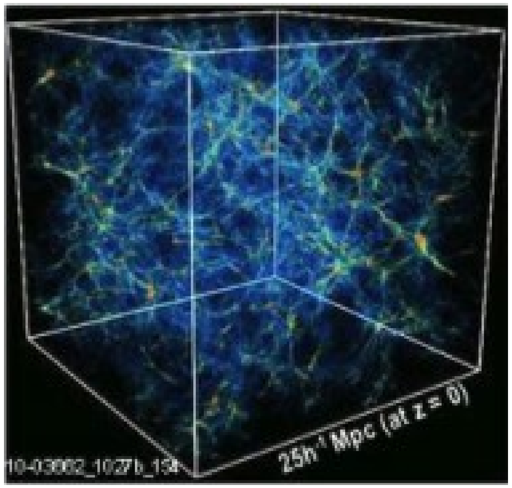
Cosmological Baryon Fraction
fb = 0.17

The baryon deficit is more severe in smaller galaxies

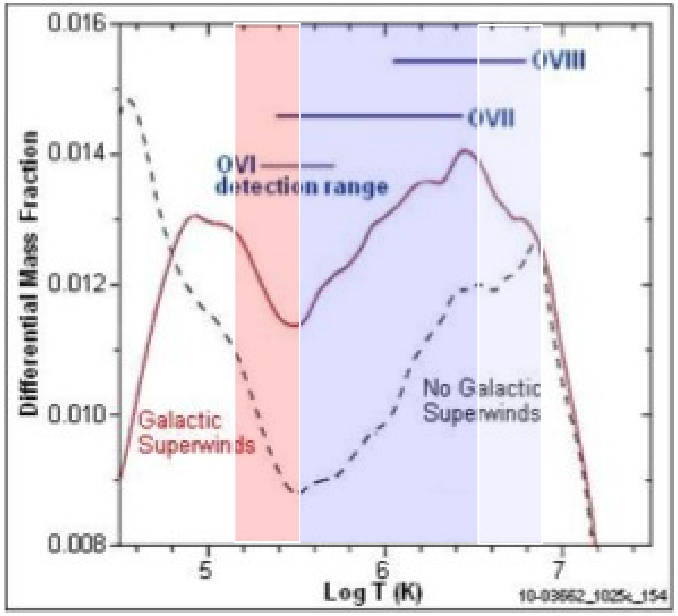
➔ Less massive objects are unable to retain baryons (and metals?) due to feedback processes (winds)?

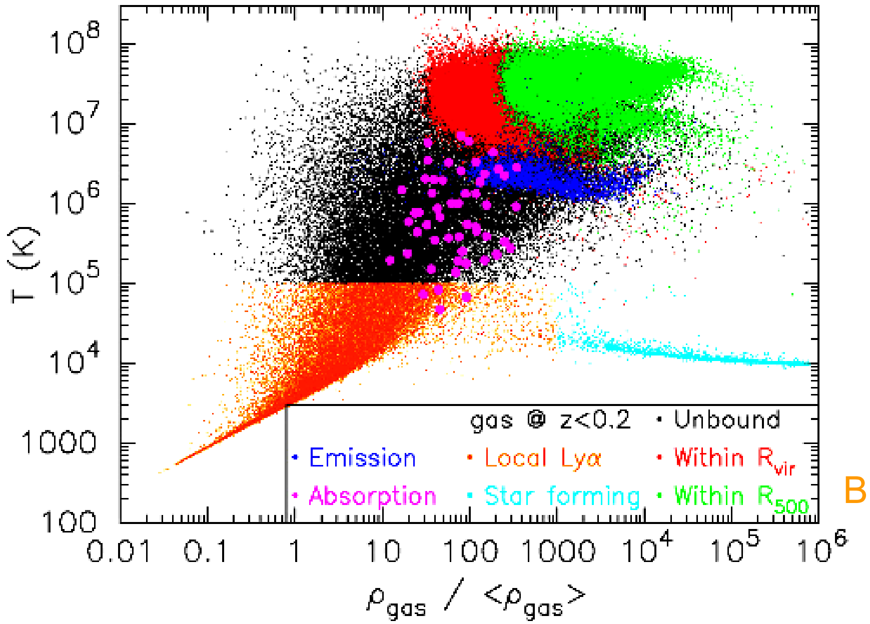
➔ Are these baryons in the surrounding CGM/IGM?

The WHIM in Hydro-dynamical simulations



Britton+12





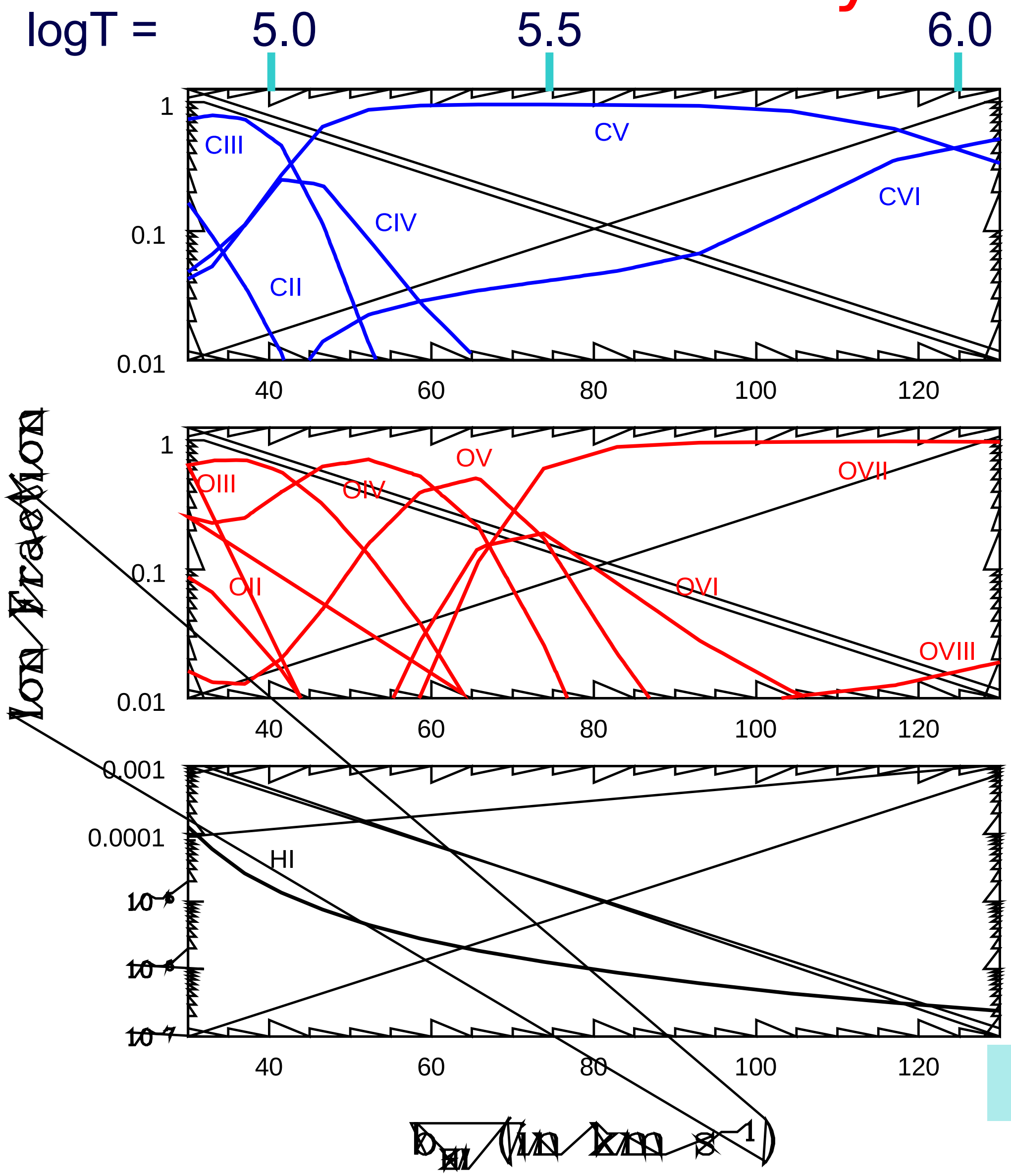
Branchini+10

Cool-Phase: ~20%

Warm-Phase: ~60%

Hot-Phase: ~20%

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

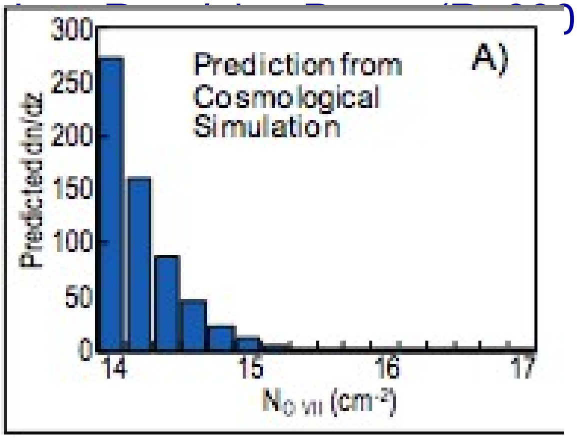


Problems:

dN/dz(OVII,CV) ~ 10 at NOVII>1015 cm-2

Current X-ray Spectrograph have

- Small Collecting Area (~20-40 cm2)
-))

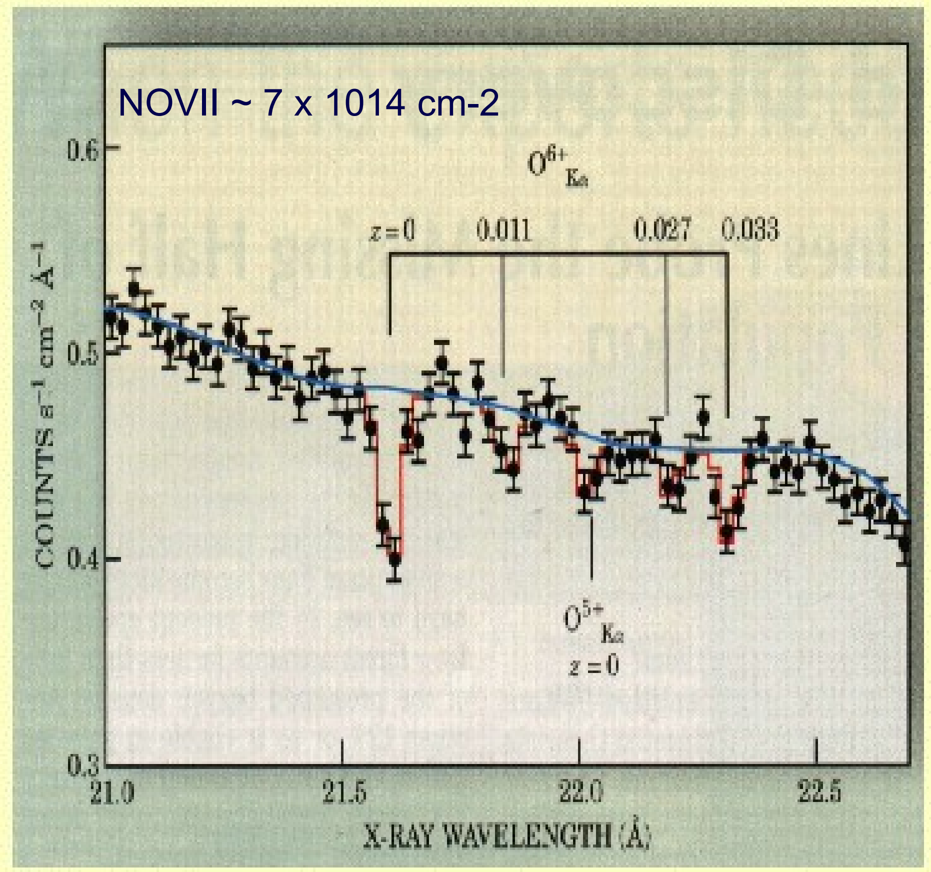


⇒ Tuned Observational Strategies

First Claimed WHIM Detections:

Exceptional Outburst State

(Nicastro+05, Nature)



However:

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

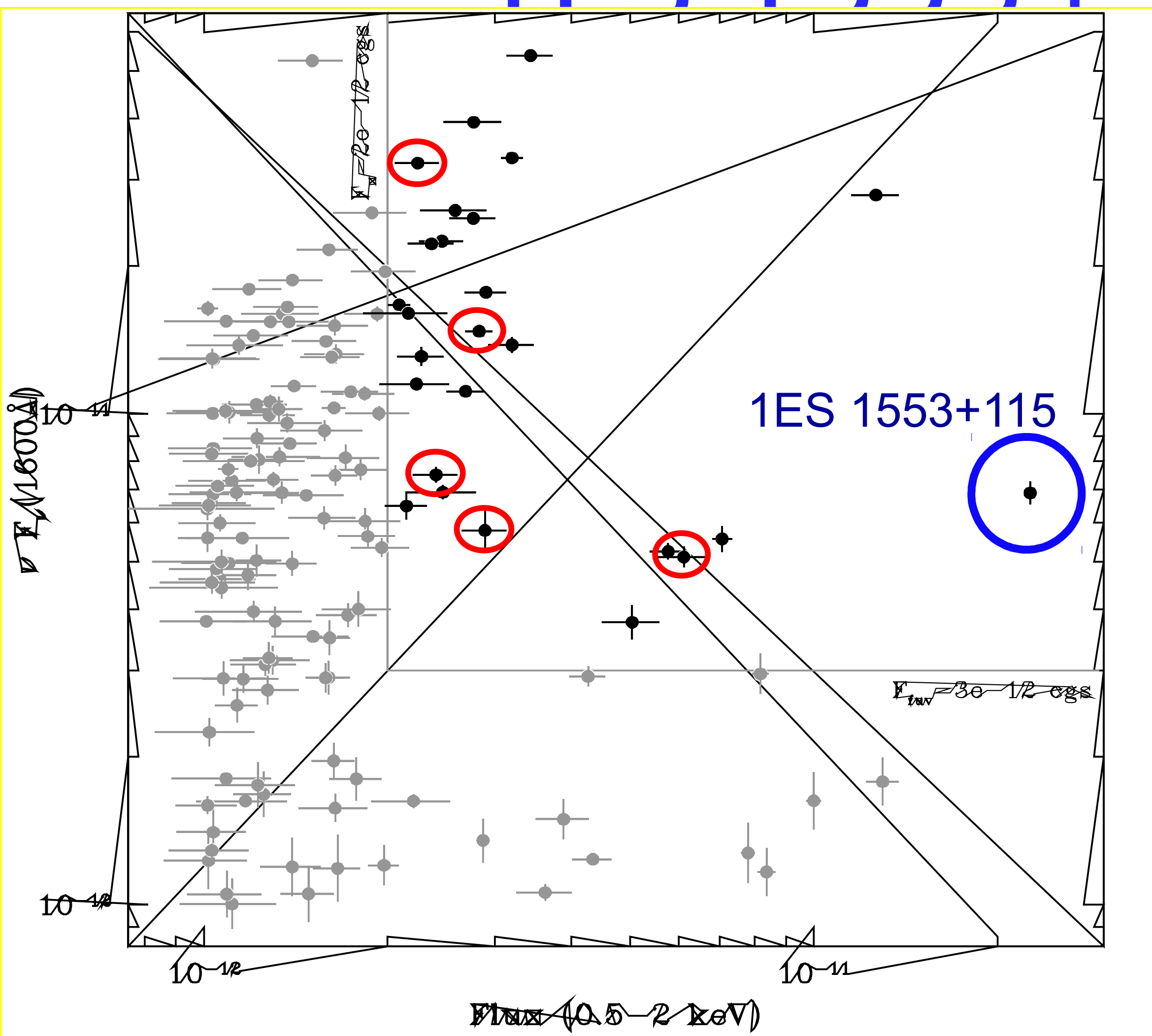
+

Controversial:

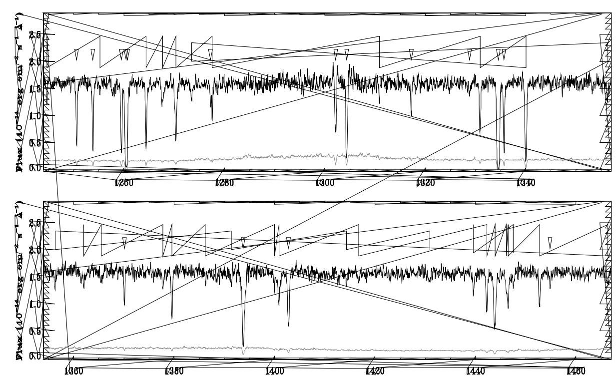
- *Not confirmed by XMM (though consistent with; Rassmussen+07)*
- *Close to instrument systematics (Kaastra+06)*

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

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

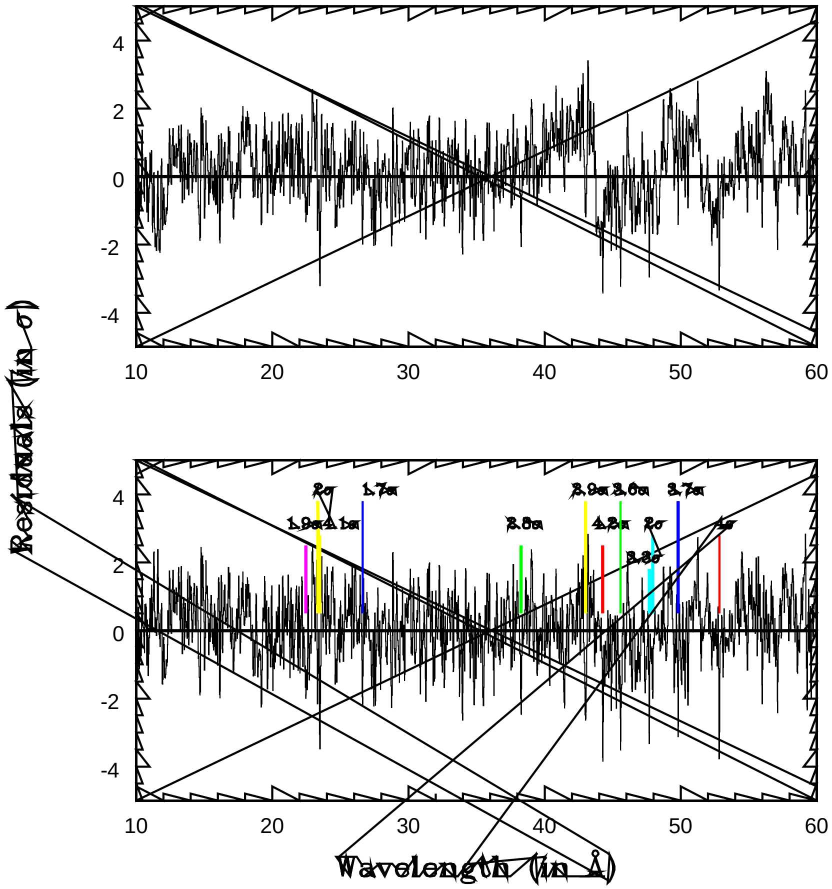


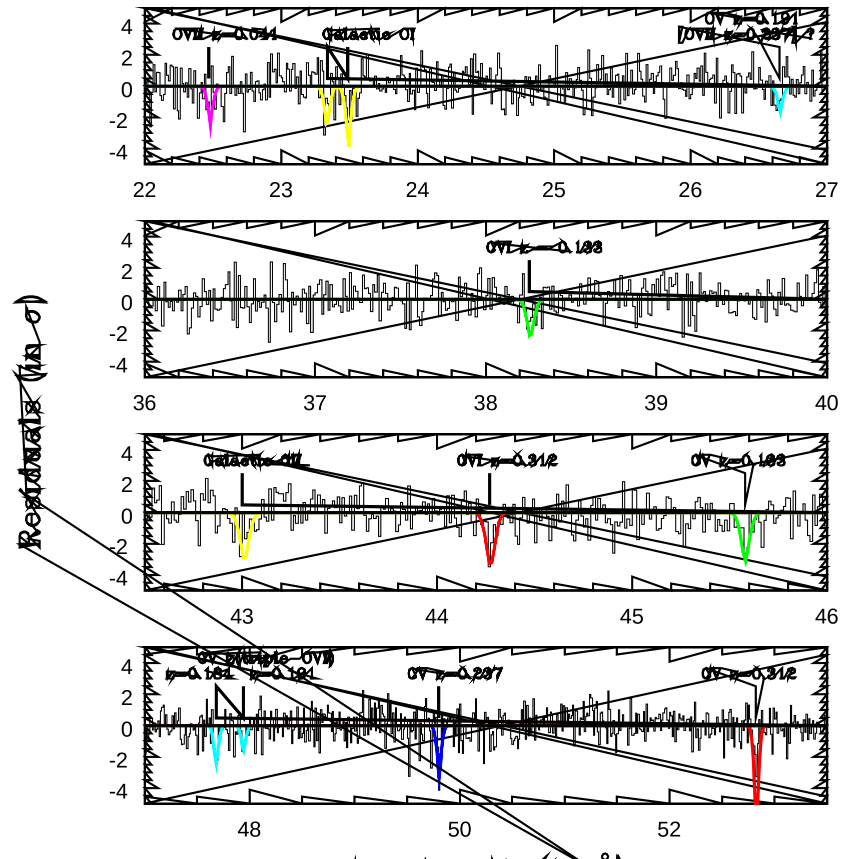
- z > 0.4
- FX ~ 1-2 mCrab
- High S/N COS spectrum with 5 a-priori BLA signposts



500 ks Chandra-LETG of 1ES 1553+113

Nicastro+13





Scanning routine finds only 6 LSF-shaped excesses (consistent with Poisson) and 50 deficits at >3σ

12 of the 50 LSF-shaped deficits are confirmed as unresolved absorption line candidates by fitting procedure
9 of them are tentatively identified with 5 intervening IGM systems

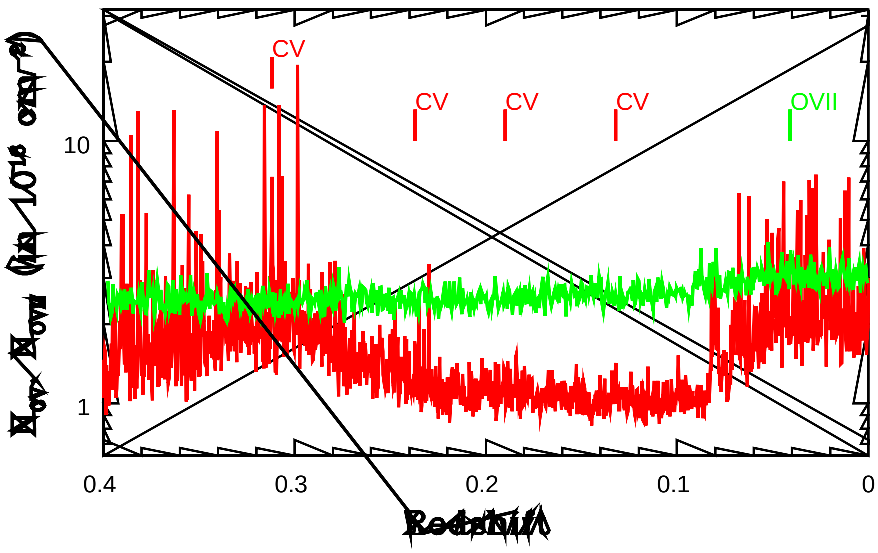
Tentative IGM IDs

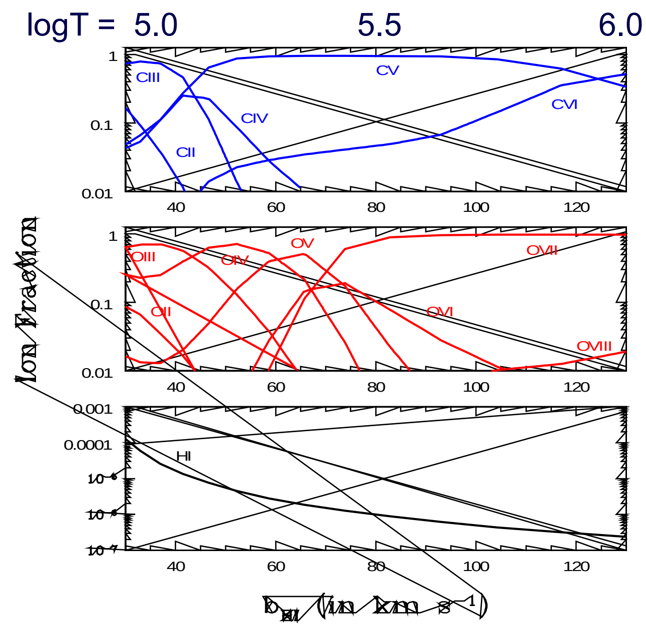
Nicastro+13

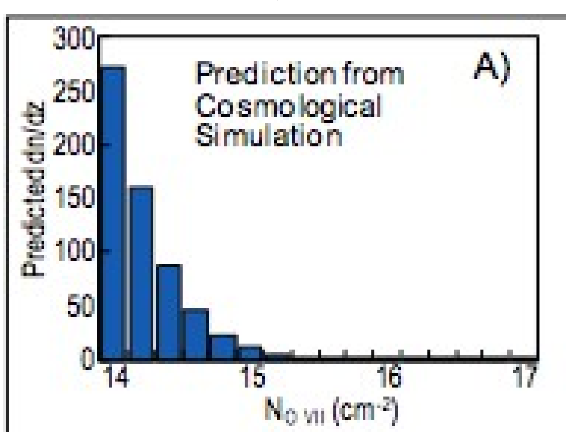
Redshift	CV	CVI	OIV	OV	OVII	BLA	OVI (mA)	CIV (mA)
0.041±0.002	NA	NA	NA	NA	2.3σ	9.6σ	<65	<13
0.133±0.002	3.8σ	2.7σ	NA	NA	NA	5.4σ	<14	<25

Sensitivity of the Chandra Spectrum of 1ES 1553+113

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





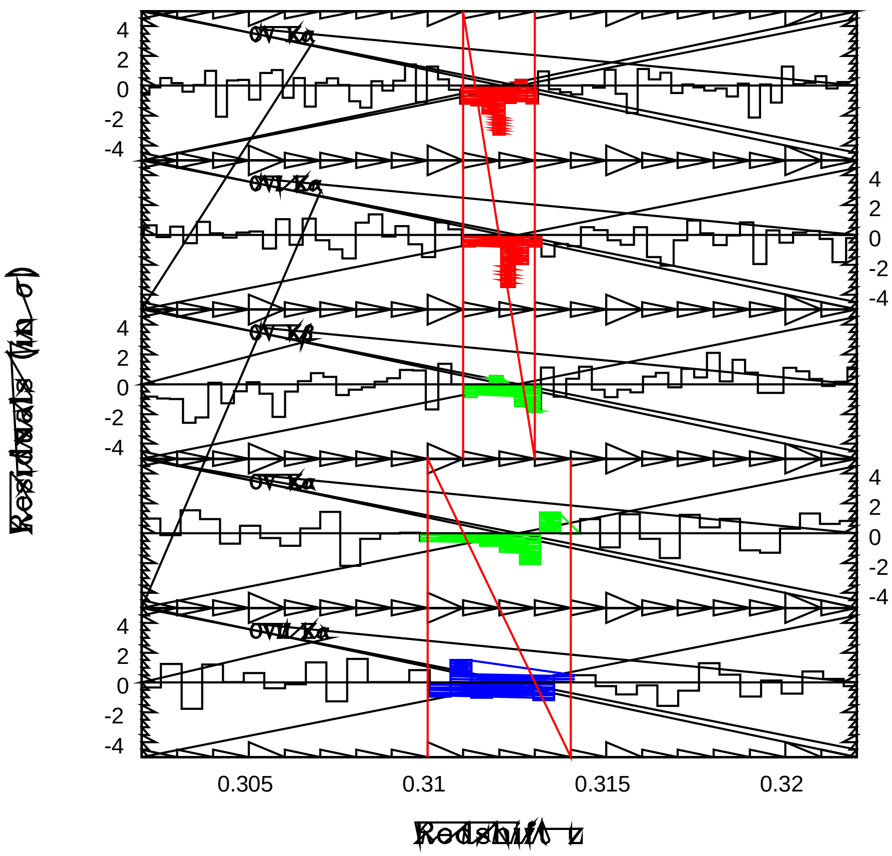


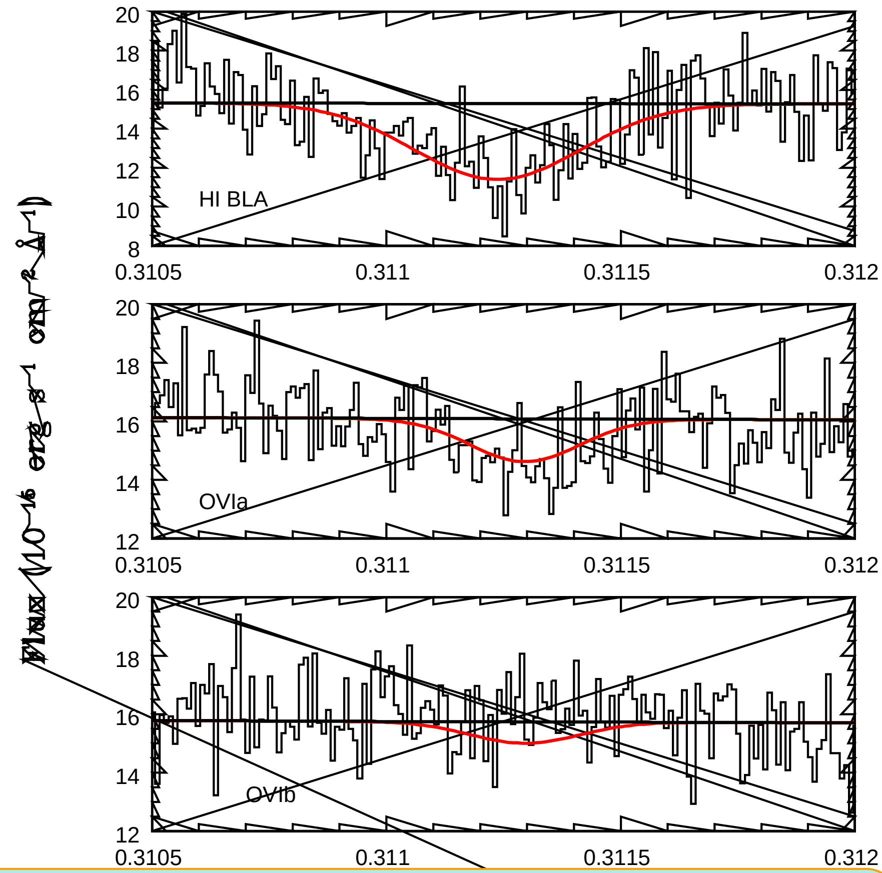
With the sensitivity of the current *Chandra* spectrum of 1ES 1553+113 bound to detect only the cool (logT < 5.6) WHIM in CV.

4x exposure ⇒ 2x S/N ⇒ NOVII > 1015 cm-2 ⇒ ~ 4 new systems sampling the hot WHIM

Cool WHIM at z=0.312:

(6.3σ X-ray only)



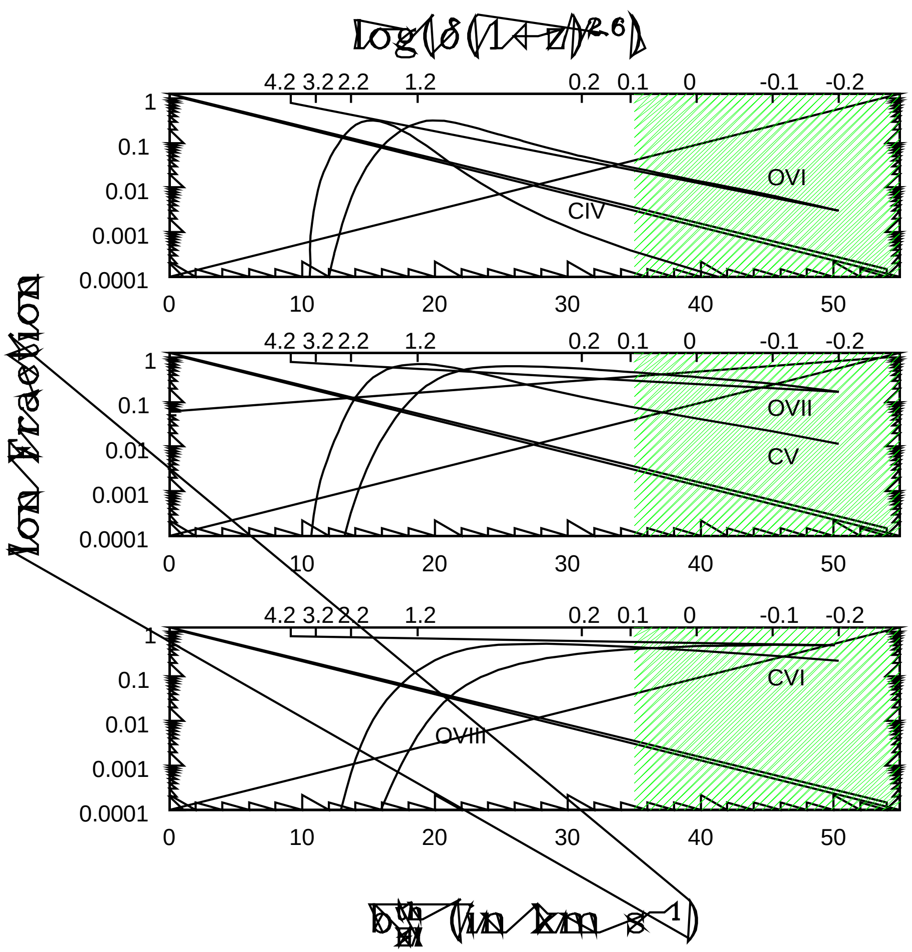


From COS BLA and OVI b:

⇒ bth = 52 ± 7 km s-1 (bturb = 30 ± 14 km s-1) ⇒ logT = 5.2 ± 0.1

Fully Consistent with presence of CV, CVI, OV

Photo-Ionized Lyα Forest or WHIM? (1)



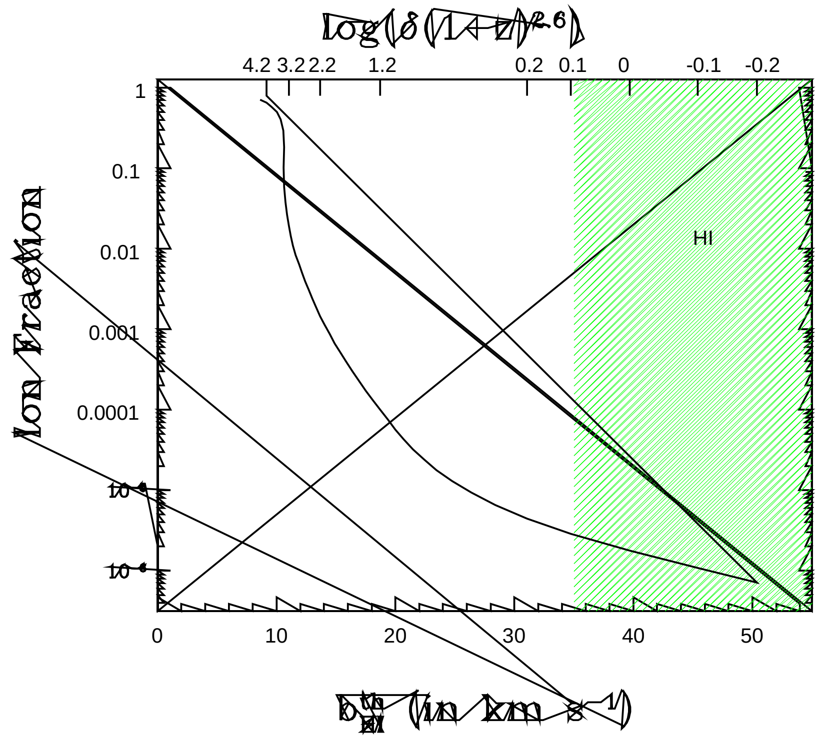
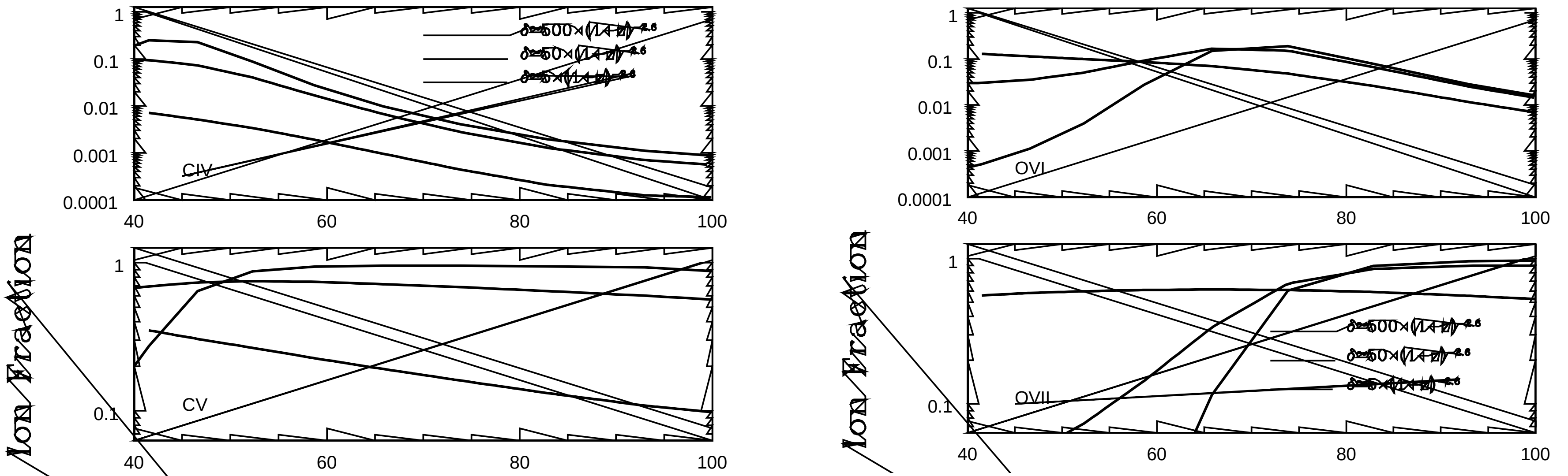
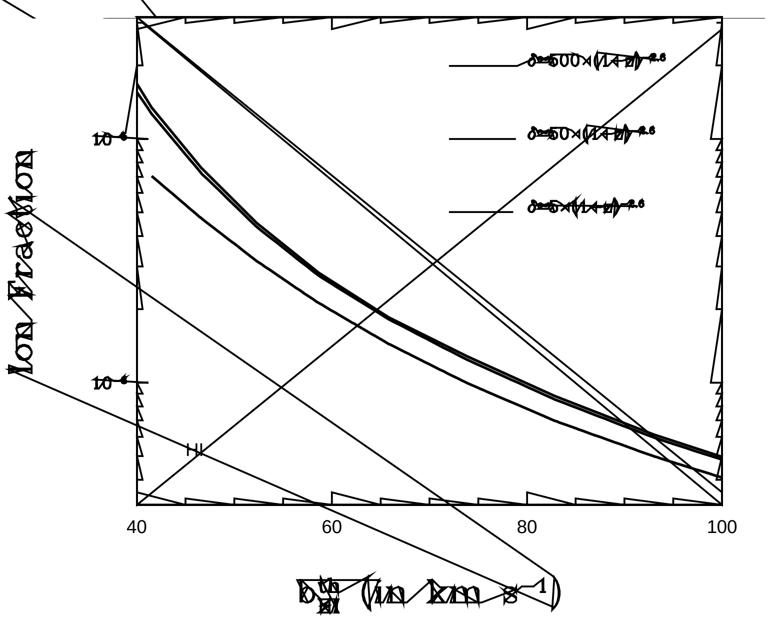


Photo-Ionized Lyα Forest or WHIM? (2)





Hybridly Ionized Gas can fit the FUV-X-ray data and constrain baryon densities

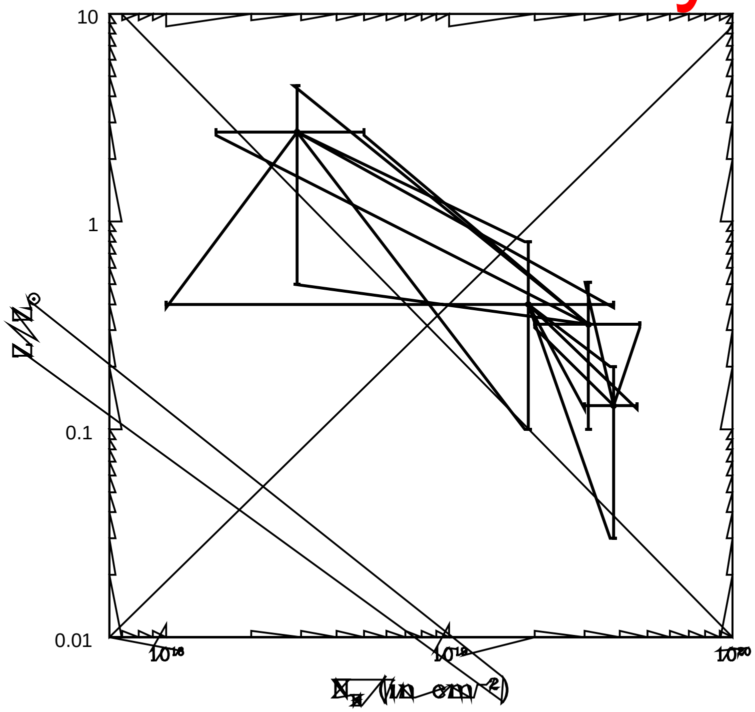
Best-Fitting WHIM Parameters

Redshift	logT	NH (1019 cm-2)	nb (10-6 cm-3)	$Z/Z_{\odot}$ [= NH(X)/NH(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

* 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 NH(X) divided by the average <$Z/Z_{\odot}$> = 0.28 ± 0.24 determined for the z=0.041, 0.190, 0.312 systems

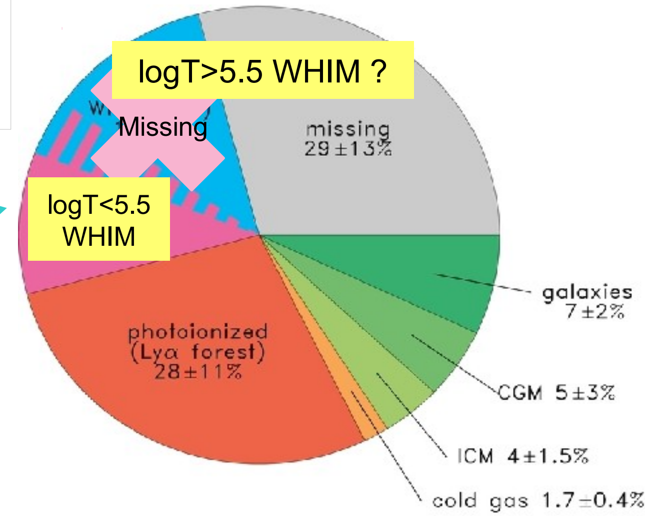
Metallicities and Cosmological Mass Density of the Cool WHIM



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

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

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



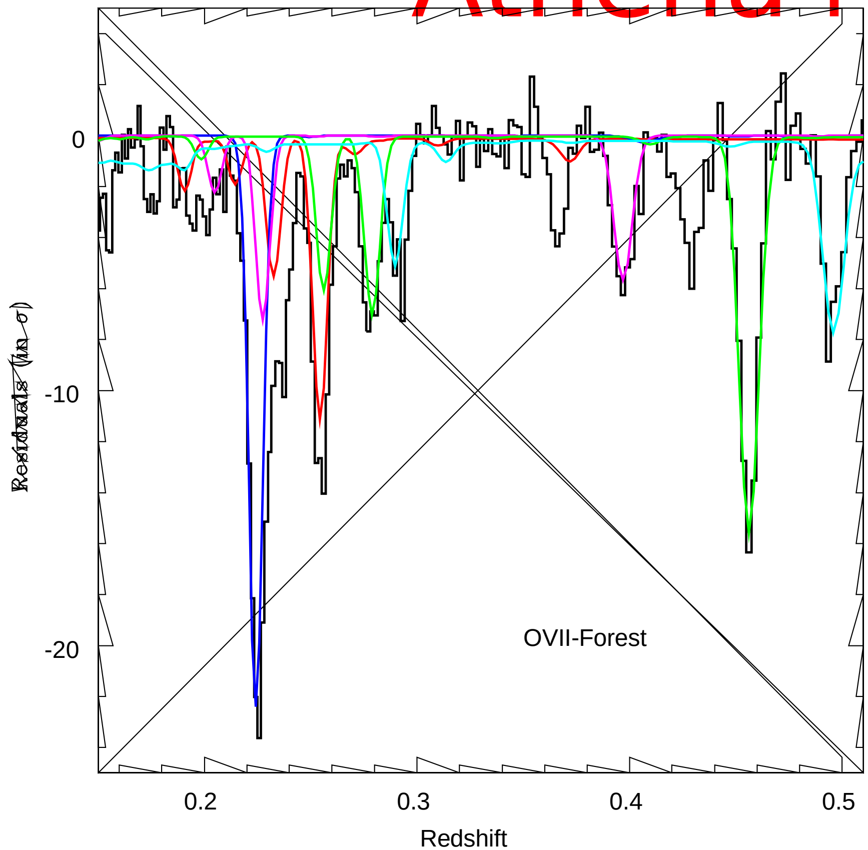
$$\Omega_b(5.0 < \log T < 5.5; EW_{CV,OVII} > 10\ \text{m}\mathring{A}) = 0.0055 \pm 0.0018 = (12 \pm 4)\%\ \Omega_b$$

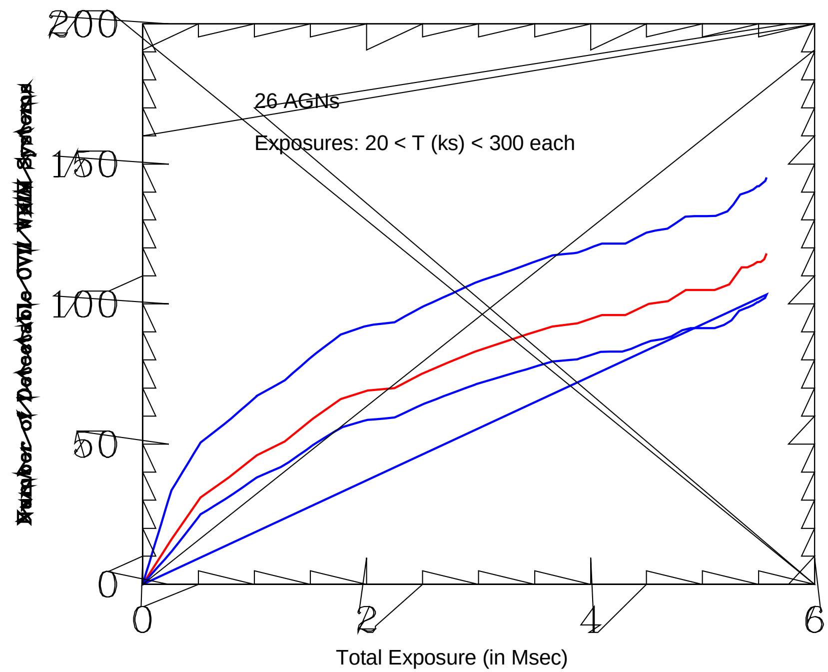
$$\Omega_b(5.0 < \log T < 5.5; EW_{CV,OVII} > 10\ \text{m}\mathring{A}) = 0.0069 \pm 0.0018 = (15 \pm 4)\%\ \Omega_b$$

The WHIM: Future Prospects

Athena+

X-ray Integral Field Unit





00 ks for F0.5-2 = 0.1 mCrab along a random WHIM LOS from Cen+06:
etects 5 Systems with logT = 5.2-6.4 K, logNH = 18.7-19.4 $(Z/Z_{\odot})^{-1}$ cm-2 at z<
ll in OVII-OVIII; 2 in CV + OIV-OVI (Cool-Phase): excellent Density Diagnostics

Summary and Future

IFU
X-ray Integral Field Unit

- *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 galaxy missing baryons are probably concentrated in enriched (because of galaxy-IGM feedback) extended (well beyond the galaxy virial radius) and massive (~1011 $M_\odot$) halos*
- *The first detections of the densest and coolest WHIM have finally been secured in the X-rays: 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 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*
- 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