

The Missing Baryons in a Warm-Hot Intergalactic Medium

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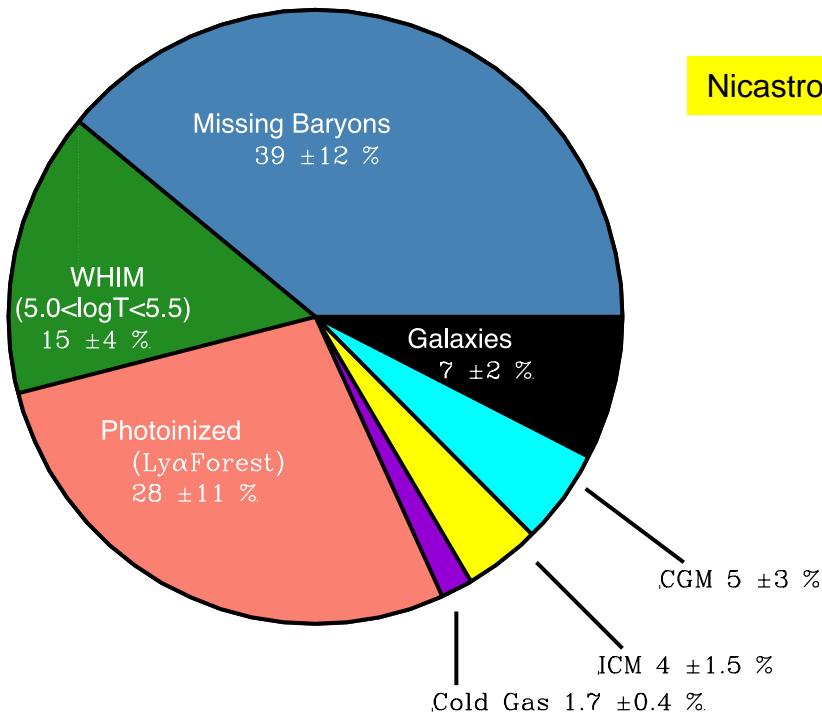
Outline

- The Missing Baryon Problem
- Results from the XMM-Newton VLP on 1ES 1553+113
- From current to next generation X-ray spectrometers.

The Missing Baryons Problems

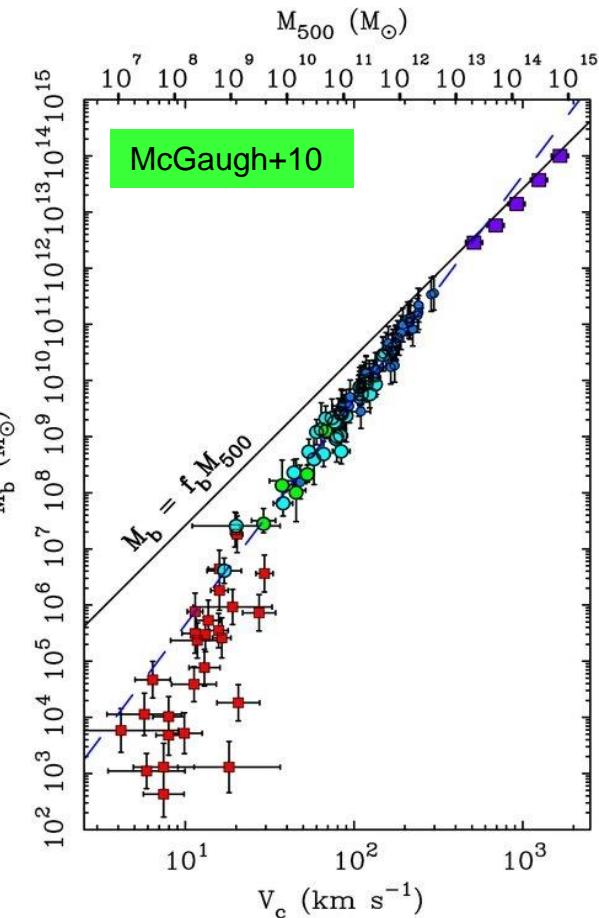
The Universe

$$\Omega_b^{\text{Planck+15}} = 0.0487 \sim 5\%$$



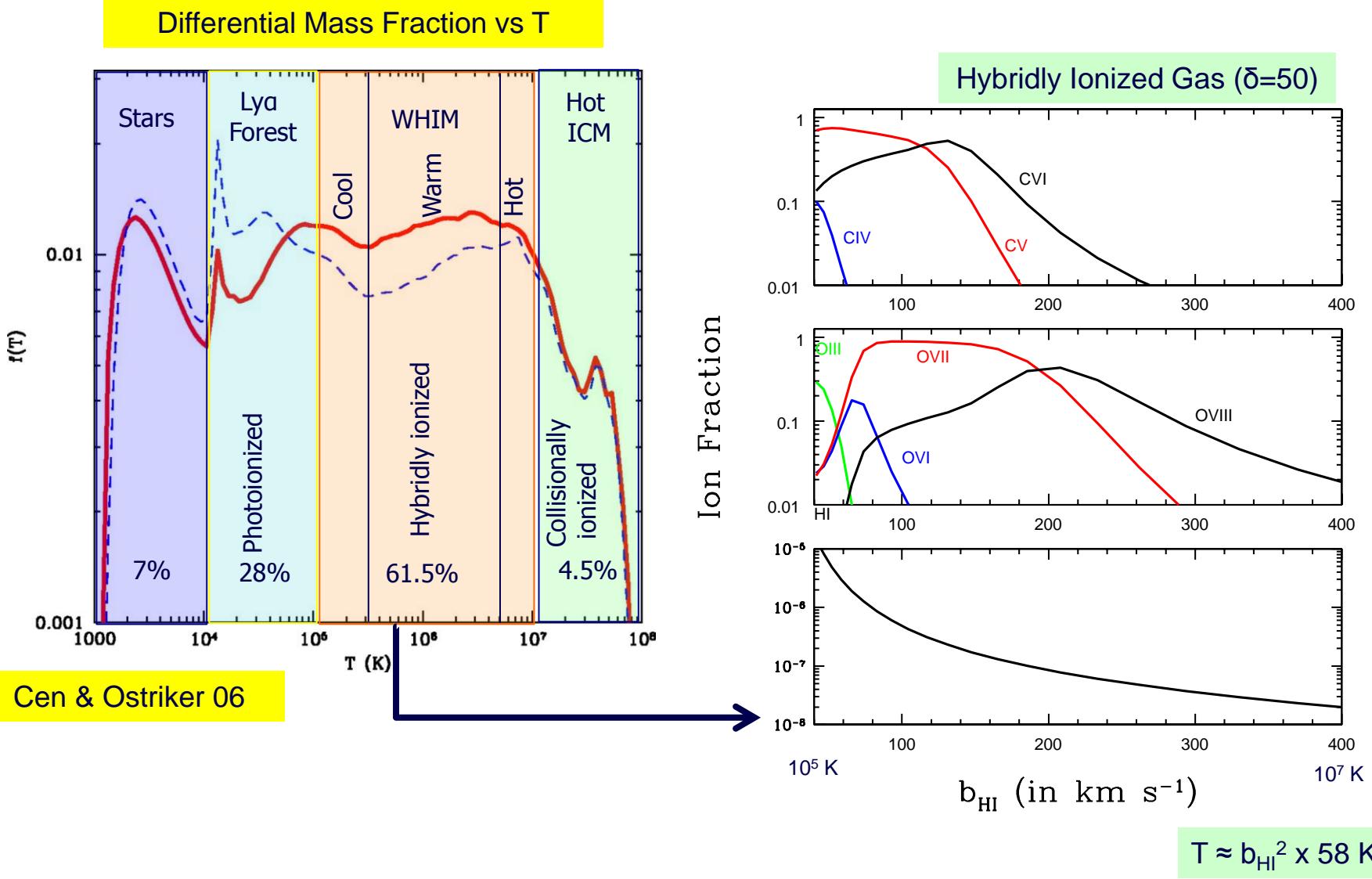
$\sim 30\text{-}50\%$ of Baryons missing at $z\sim 0$

The Galaxies



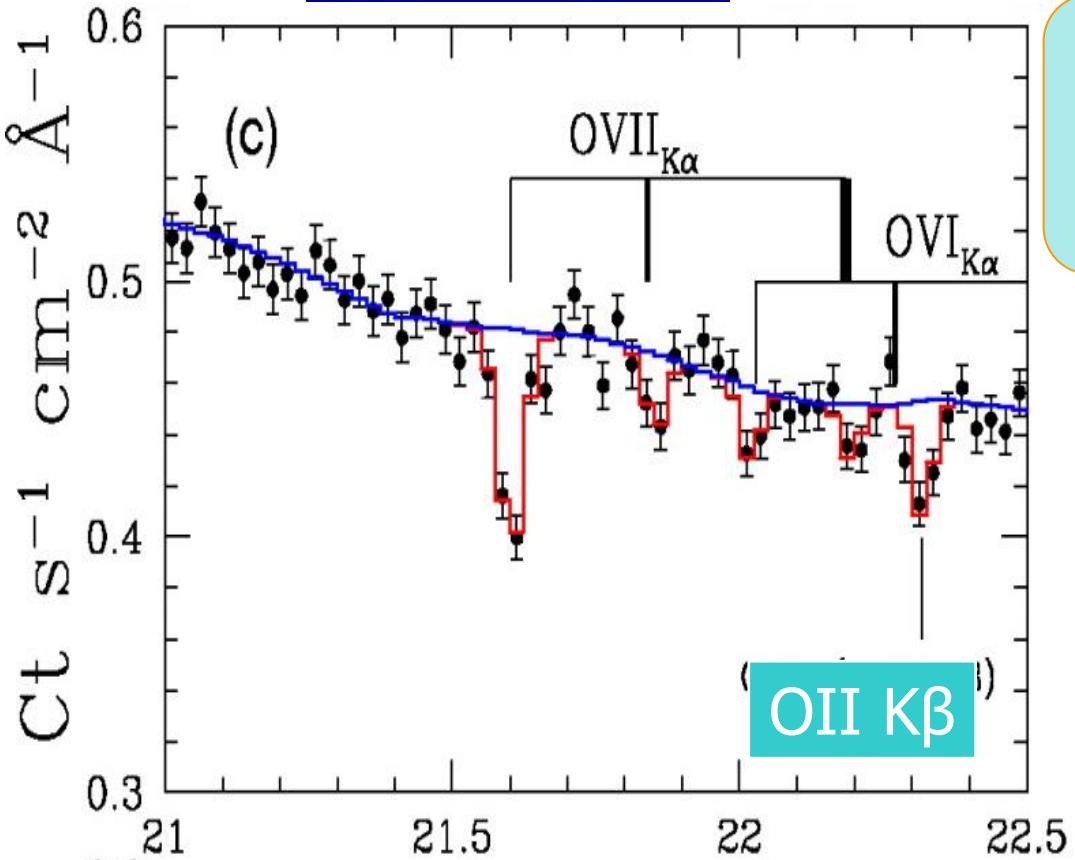
$$\Omega_m^{\text{planck+15}} = 0.3156 \rightarrow f_b = 0.154$$

The Baryon Phases in HDS



First Claimed WHIM Detections: Exceptional Outburst State

(Nicastro+05, *Nature, ApJ*)



However:

- $z(Mkn\ 421)$ only 0.03
- $Mkn\ 421$ outbursts are unique



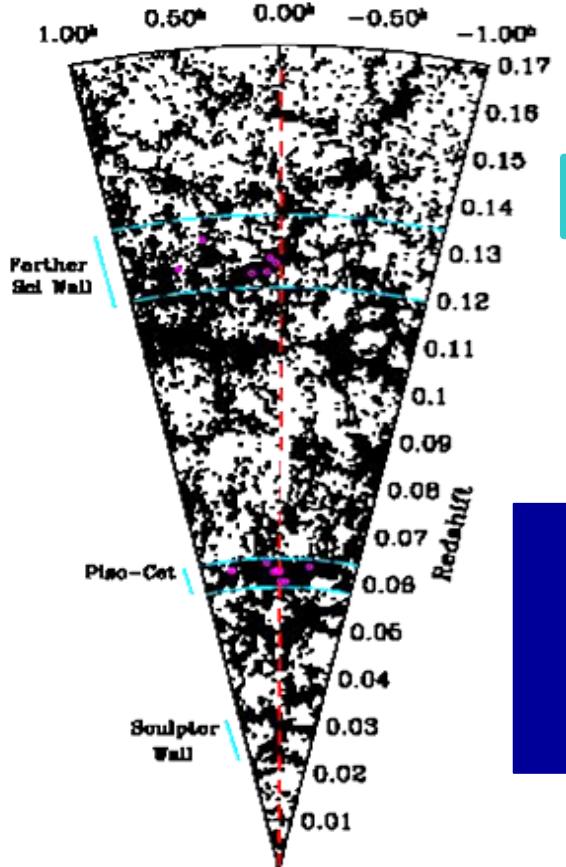
Controversial:

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

$$\Omega_b(N_{O\text{VII}} > 7 * 10^{14}) = 2.7_{-1.9}^{+3.8} * 10^{-[O/H]_1} \% \sim \Omega_{\text{Miss}}$$

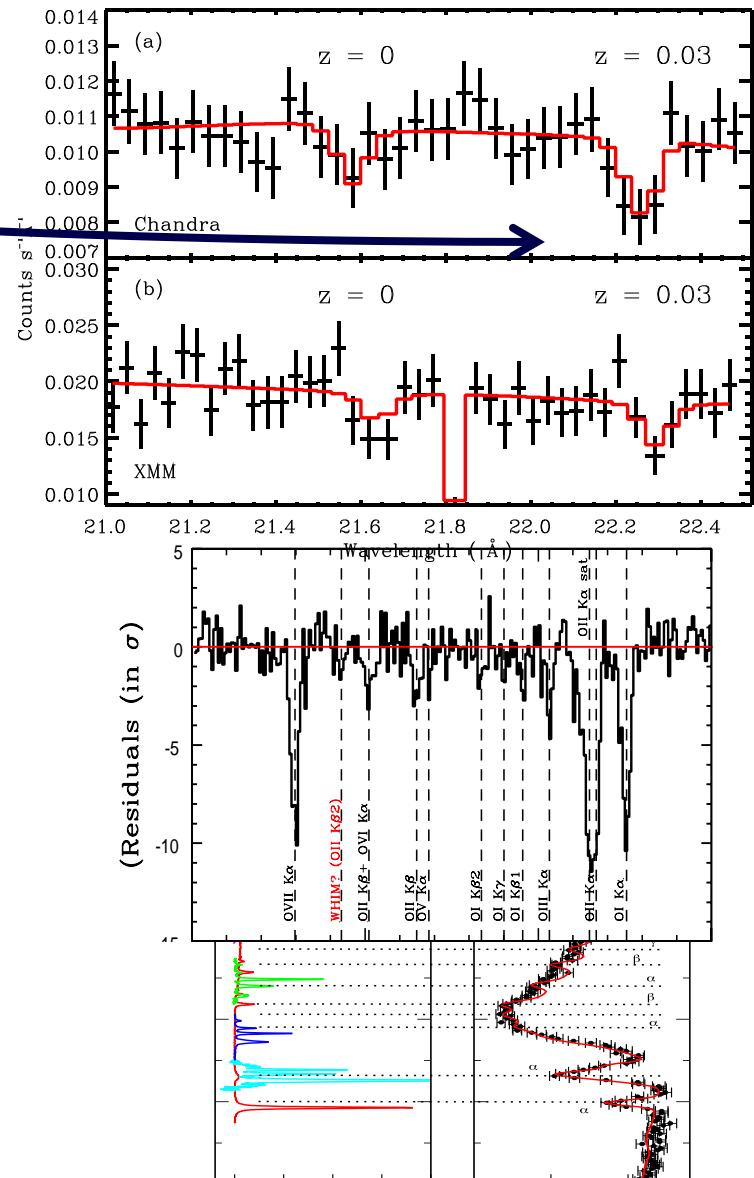
Galaxy concentrations as WHIM tracers

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



Buote+09, Fang+10

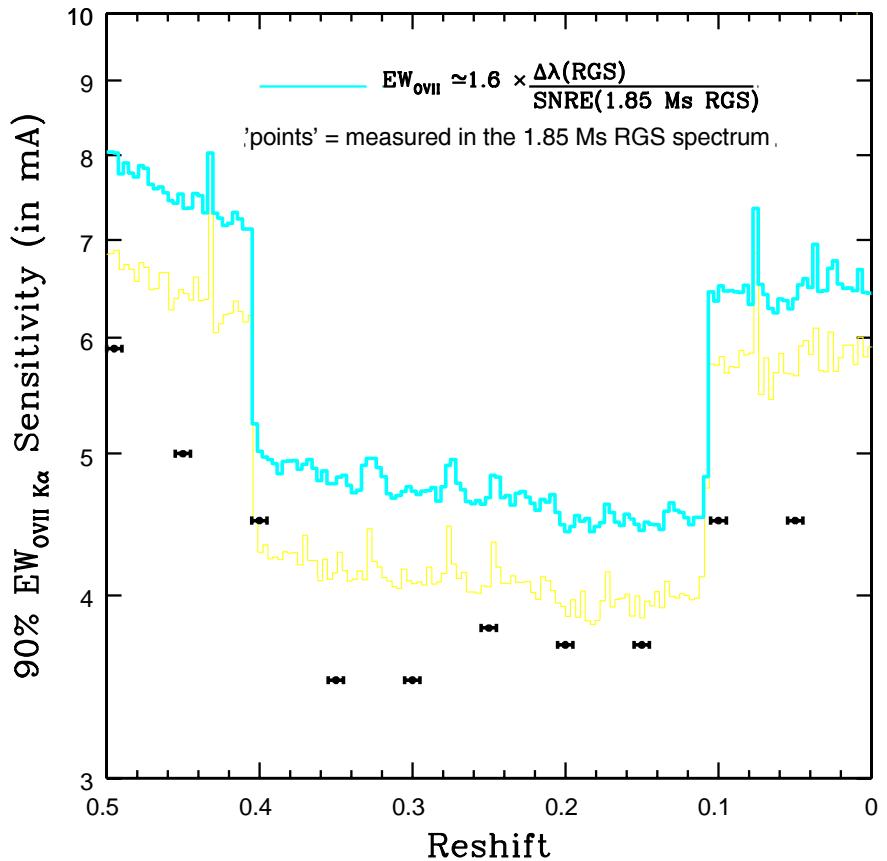
H 2356-309



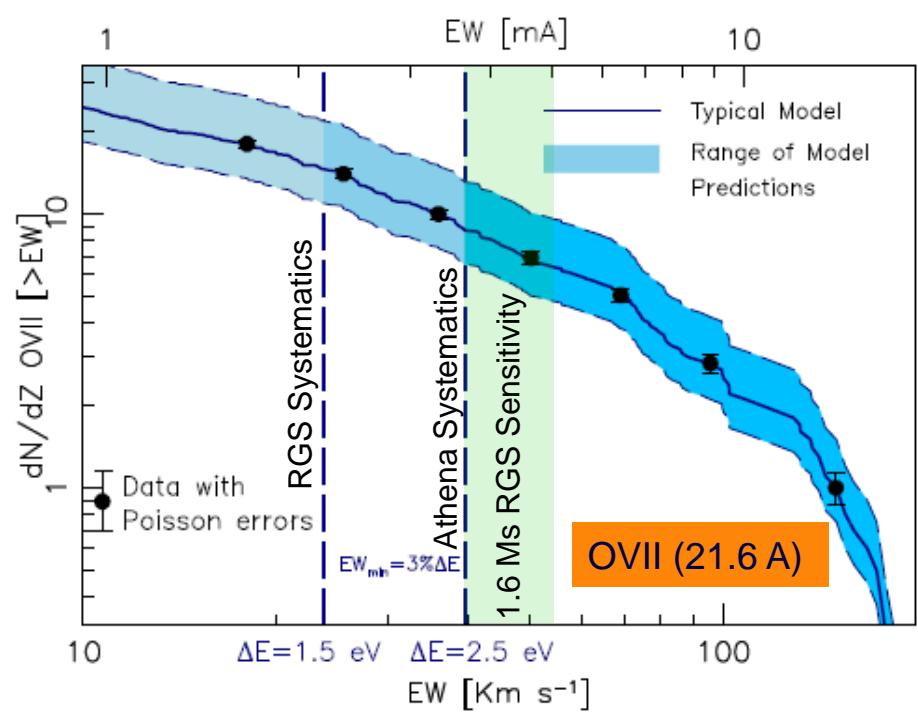
The Warm-Hot (OVII) IGM

XMM-Newton RGS Spectrum of 1ES 1553+113

RGS Spectra of 1ES 1553+113

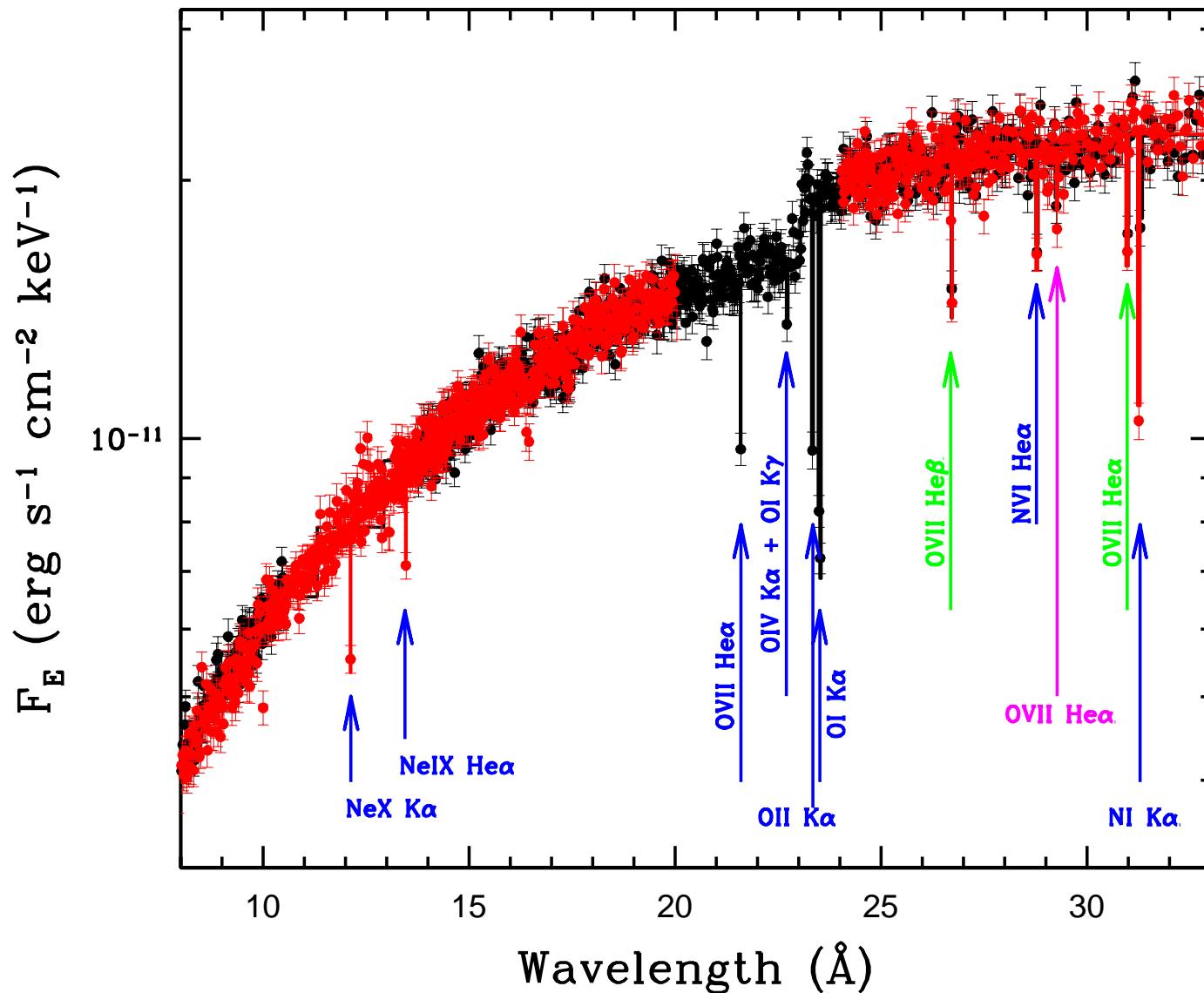


Athena WHIM White Paper (Kaastra+13)

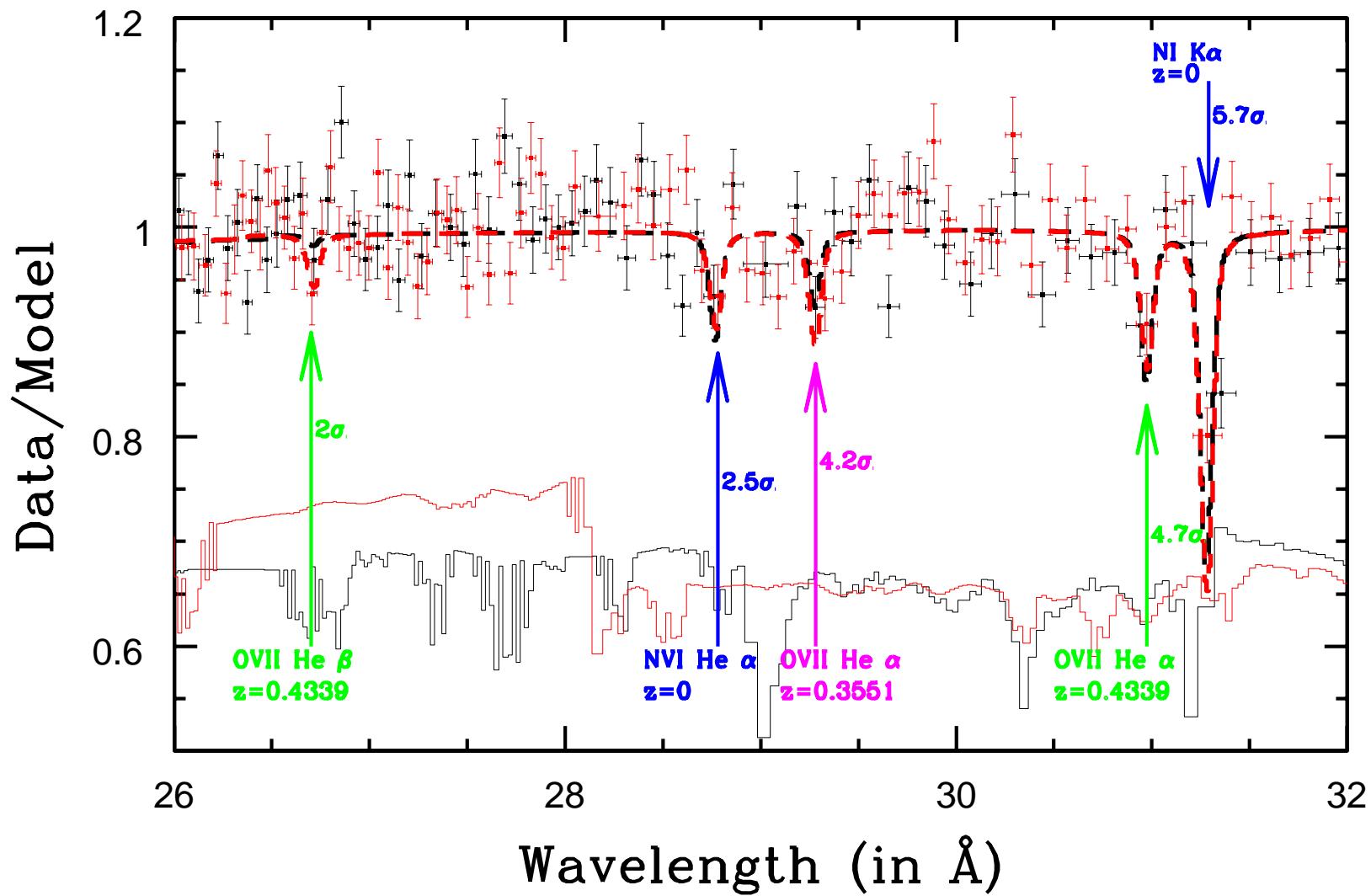


1.85 Ms RGS: $EW > 4-5$ mA @ >90%
i.e. ~600 cts per R.E.

Broad-band RGS Spectra of 1ES 1553+113

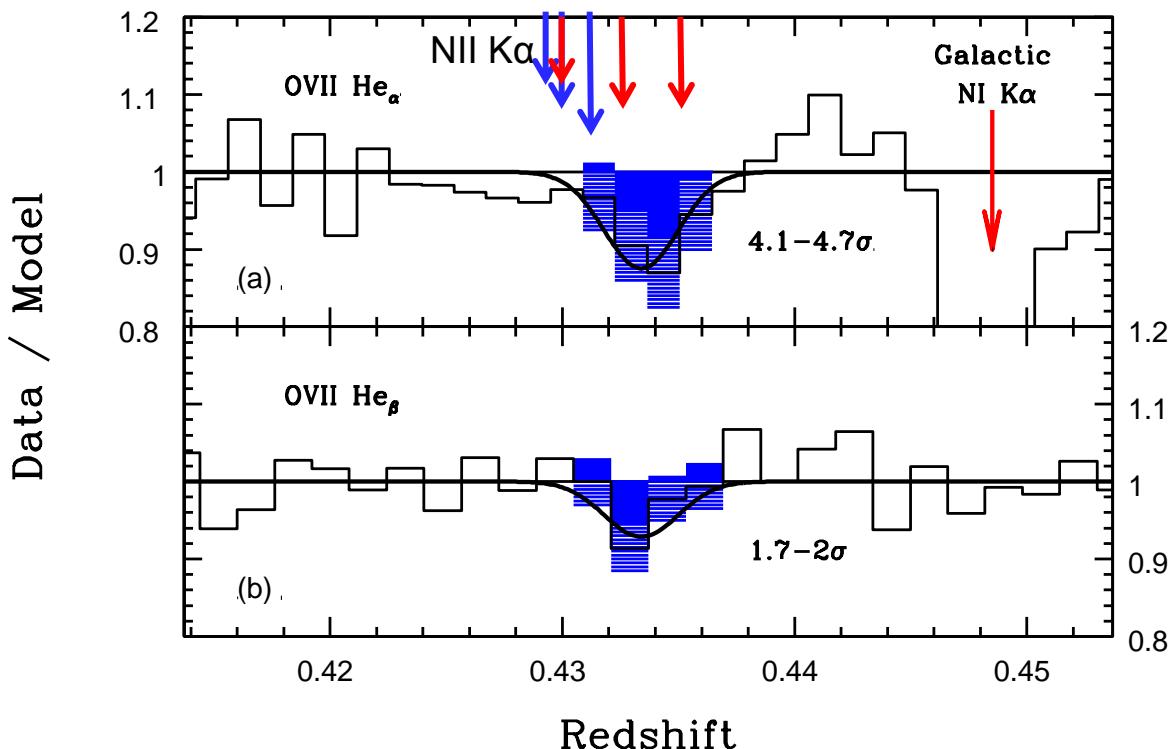


26-32 Å RGS Spectra



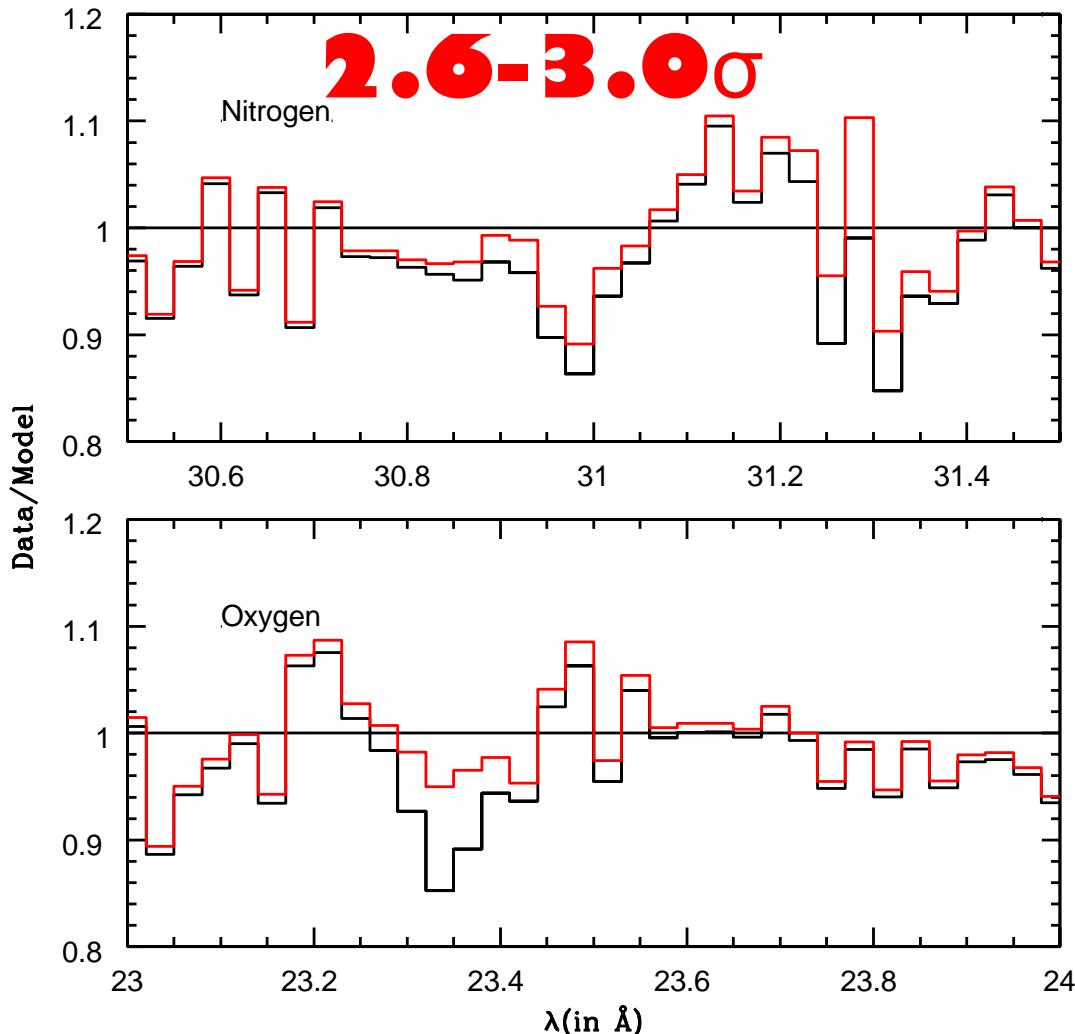
System-1

$$z_x = 0.4339 \pm 0.0008$$



Statistical Significance
(after accounting for
OVII blind redshift
search and RGS eff.-
area-induced
systematics): **3.9-**
4.5 σ

Contamination by ISM NII



2.6-3.0 σ

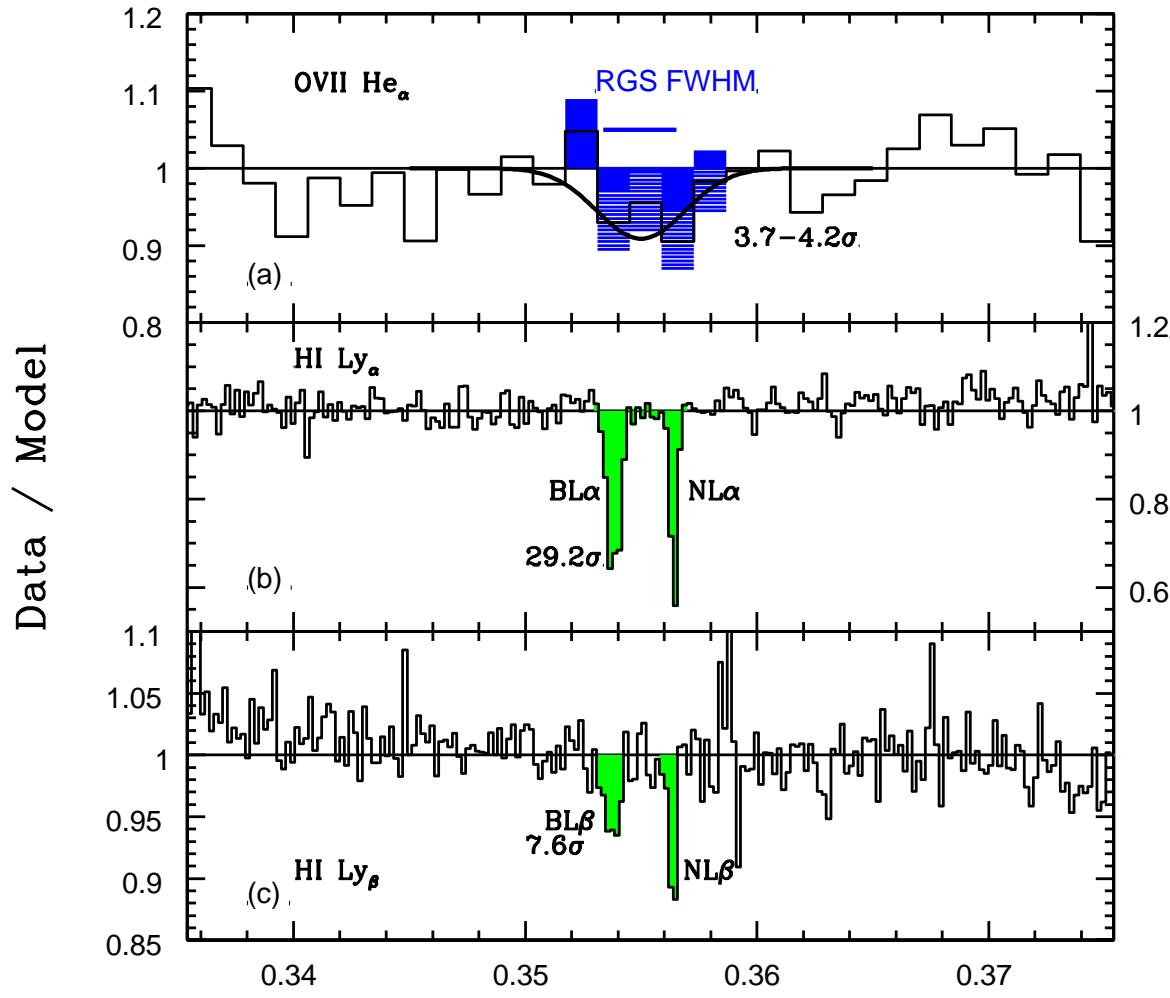
Nitrogen.

N_H (Neutral)= 3.7×10^{20} cm $^{-2}$
(agrees with 21 cm meas.)

N_H (T~5000 K)= 1.2×10^{20} cm $^{-2}$
 $Z/Z_{\odot}=0.46$

System-2

$$z_x = 0.35559 \pm 0.00016$$



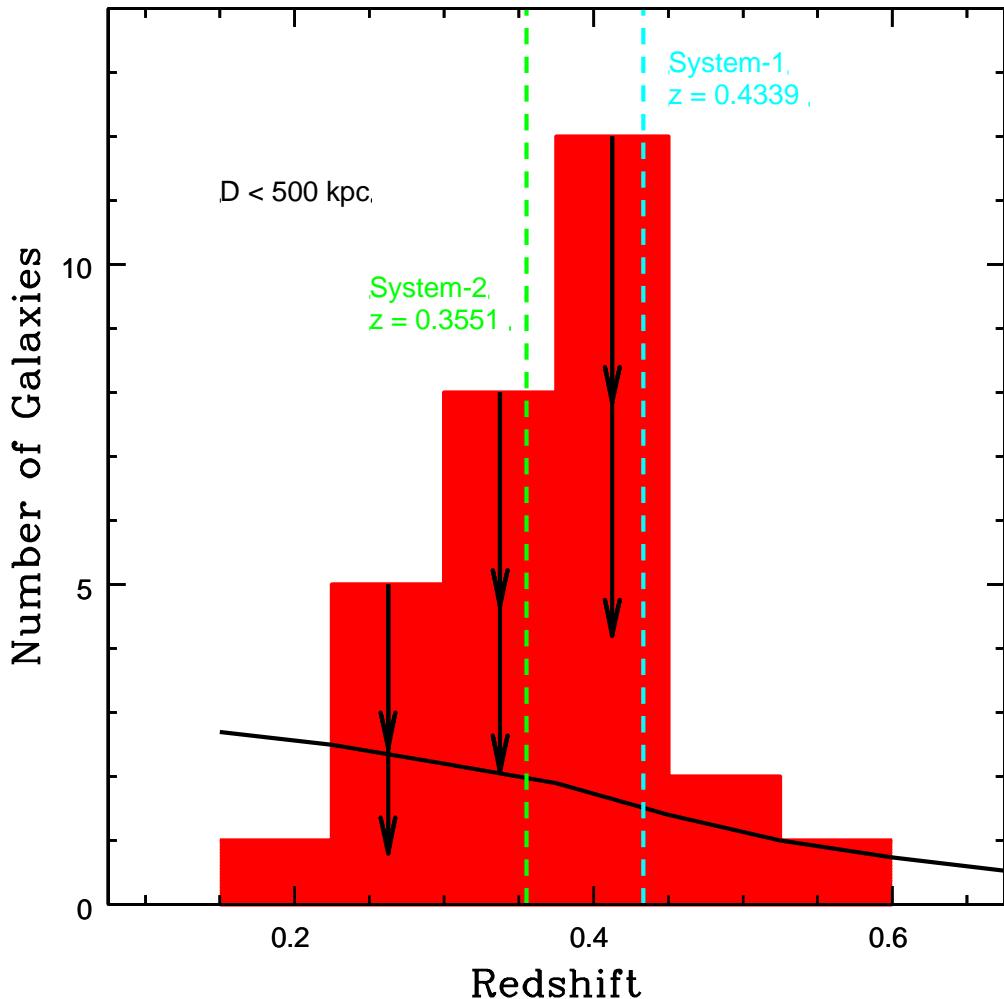
Statistical Significance
(after accounting for OVII blind redshift search and RGS eff.-area-induced systematics): 2.9-3.7 σ

Diagnostics

System	T (10^6 K)	N_O (10^{15} cm $^{-2}$)	$N_H(Z/Z_\odot)^{-1}$ (10^{19} cm $^{-2}$)	Z (Z_\odot)
1	1.2 ± 0.4	$7.8_{-2.4}^{+3.9}$	$1.6_{-0.5}^{+0.8}$	≥ 0.1
2	0.95 ± 0.45	$4.4_{-2.0}^{+2.4}$	$0.9_{-0.4}^{+0.5}$	≥ 0.1
1	1.0 ± 0.4	4.5 ± 1.5	$0.7, -0.2, +0.4$	> 0.02

$z=0.2-0.6$ Galaxy Distribution

(in cylindrical volumes: $\pi(0.5 \text{ Mpc})^2 \times (\Delta z=0.07)$)



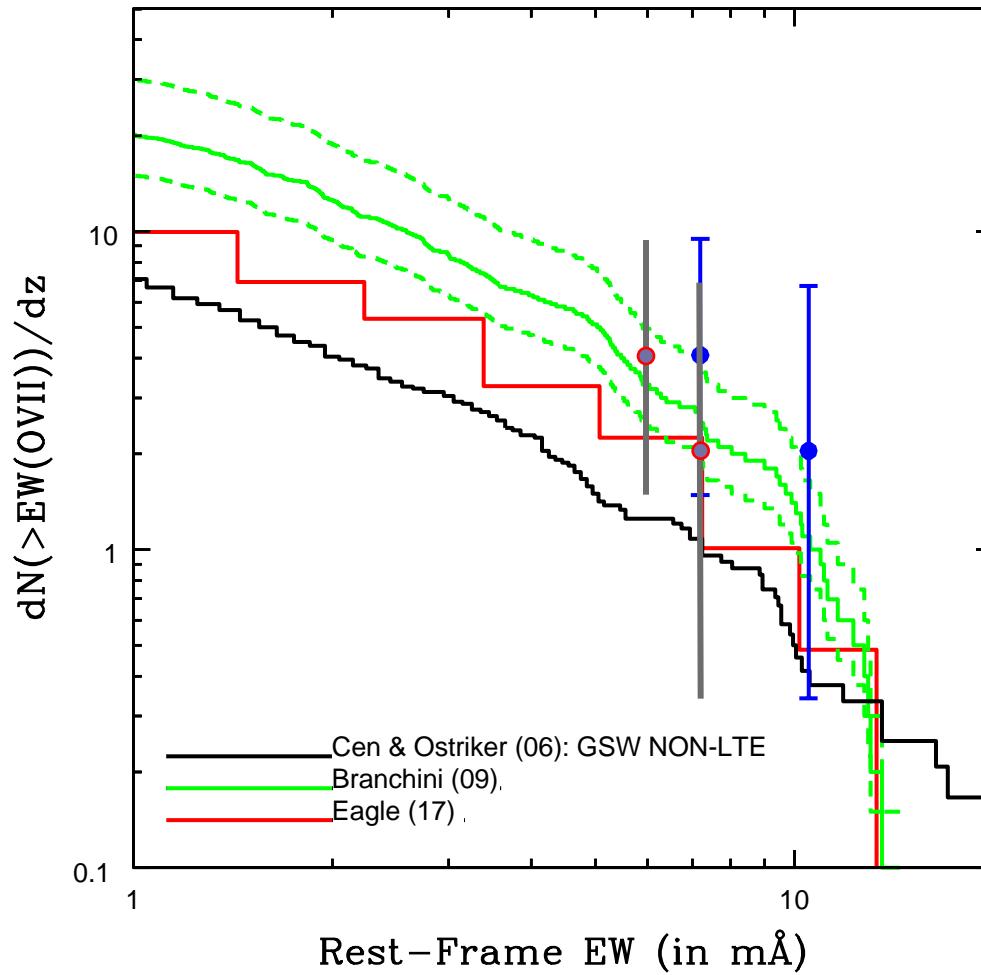
Galaxies photo-z redshifts obtained via deep ($r'>24$) SDSS-band imaging with the OSIIIS camera at GTC

Photo-z accuracy (and so bin width):
 $\Delta z = \pm 0.035$

Projected area: 0.5 Mpc radius circle
(at each z) centered on our line of sight to 1ES 1553+113

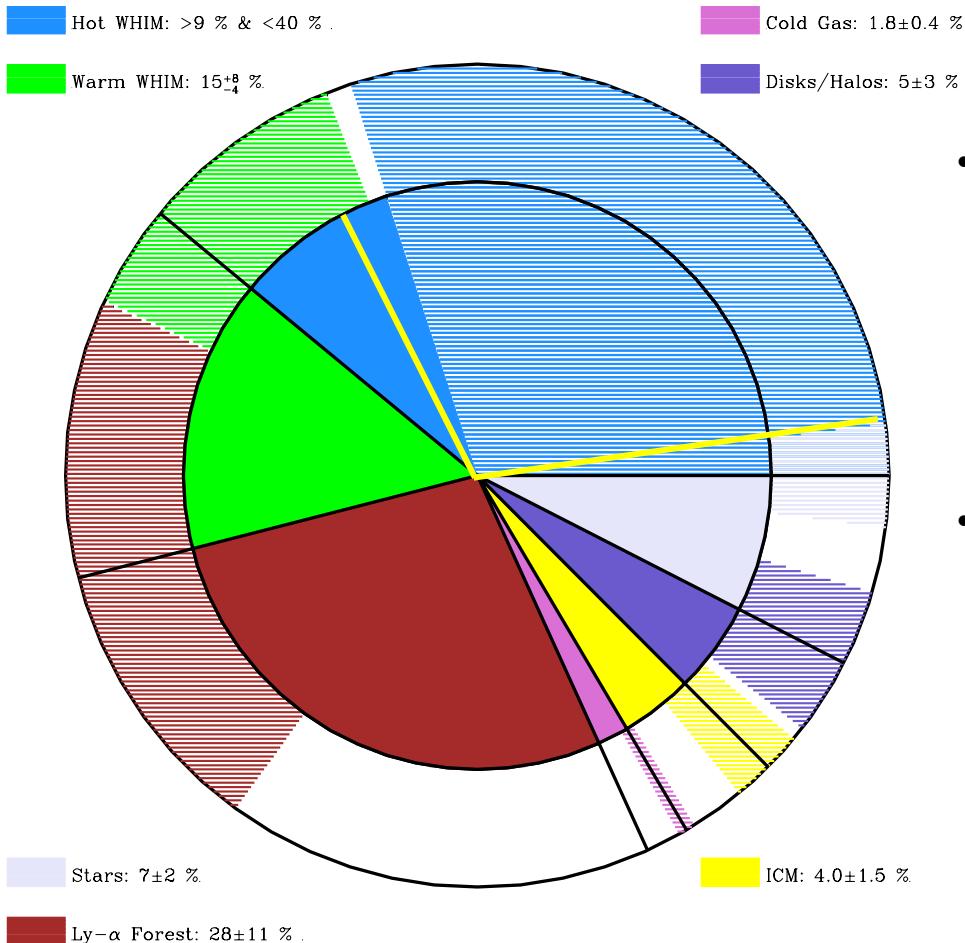
Black Curve: Expected average number of galaxies with $r'>24$ within each cylindrical volume, based on Wilmer+06

First data agree with predictions



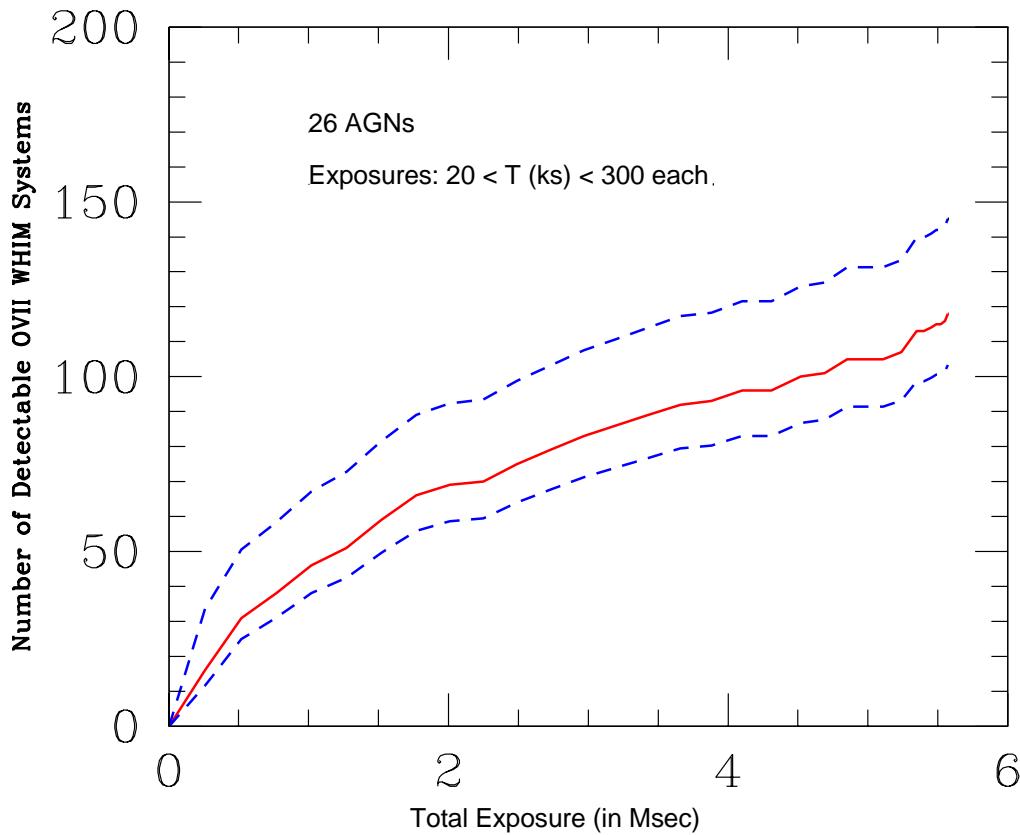
missing baryons to be found in OVII intervening absorbers.

Hot baryons close the census



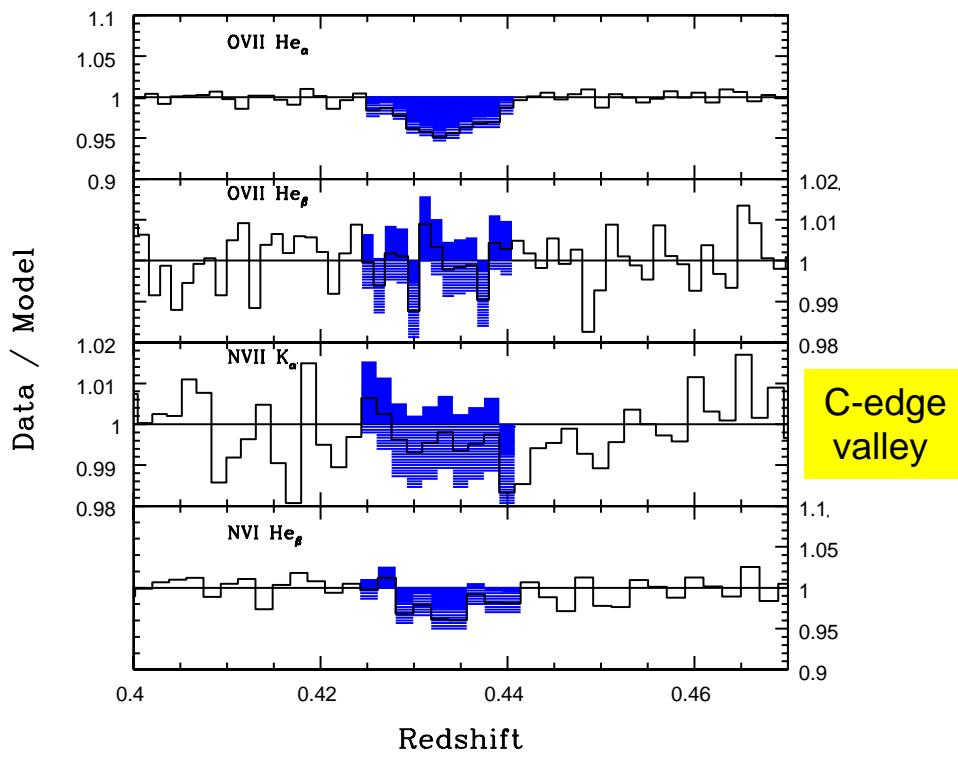
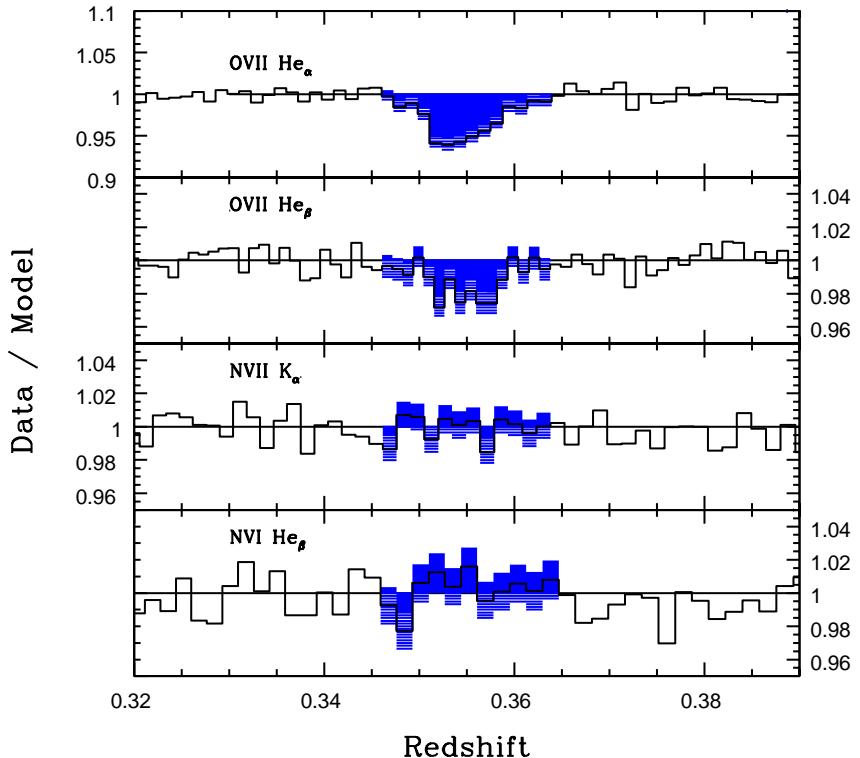
- HI lines are vital to evaluate metallicity and so derive mass: Athena's MOP targets should all be observed with the HST-COS at $\text{SNRE} \geq 50$ (requires ~ 500 HST orbits)
- Removing “directly” the degeneracy between b_{th} and b_{turb} , can only be done comparing HI and metal resolved lines. To do this by using O and Fe in the X-rays, would require a resolution of 4 km s^{-1} ($R > 75000$)!!! Simply not doable.

The WHIM with Athena: Measuring Ω_b



Athena will:
detect $\sim 100 + 100$ filaments against AGNs + GRBs
measure Ω_b with a precision of *few* %

The WHIM with Athena: Physics of the Missing Baryons



- Detecting 2 or more unresolved lines from the same ion (especially He-like) would allow us to infer the Doppler parameters and so (by comparing with X-ray T estimates) disentangle b_{th} and b_{turb} .

What do we learn from this

- The first data confirm predictions: missing baryons to be found in OVII intervening absorbers.
- MOPs for WHIM in absorption/emission are built up on realistic predictions: Athena will detect ~100 filaments against 26/39 bright AGNs
- HI lines are vital to evaluate metallicity and so derive mass: Athena's MOP targets should all be observed with the HST-COS at $\text{SNRE} \geq 50$ (requires ~500 HST orbits)
- Removing “directly” the degeneracy between b_{th} and b_{turb} , can only be done by comparing HI and metal resolved lines. To do this by using O and Fe in the X-rays, would require a resolution of 4 km s^{-1} ($R > 75000$)!!! Simply not doable.
- However, detecting 2 or more unresolved lines from the same ion (especially He-like), would allow us to infer the Doppler parameters and so (by measuring T through line ratio) disentangle b_{th} and b_{turb} .
- Synergy between Athena and ELT in mapping the galaxy fields of absorbers will be vital to study metallicity vs galaxy-environment
- **NEW ATOMIC DATA OF X_RAY INNER-SHELL TRANSITIONS URGENTLY NEEDED TO PROPERLY IDENTIFY ALL ISM TRANSITIONS**