The Missing Baryons in a Warm-Hot Intergalactic Medium

(Nature, 21 June 2018)

F. Nicastro (OAR-INAF)

Y. Krongold, J. Kaastra, S. Borgani, E. Branchini, R. Cen, M. Dadina, C. Danforth, M. Elvis, F. Fiore, A. Gupta, S. Mathur, D. Mayya, F. Paerels, L. Piro, D. Rosa-Gonzales, J. Schaye, M. Shull, J. Torres-Zafra, N. Wijers, L. Zappacosta

Outline

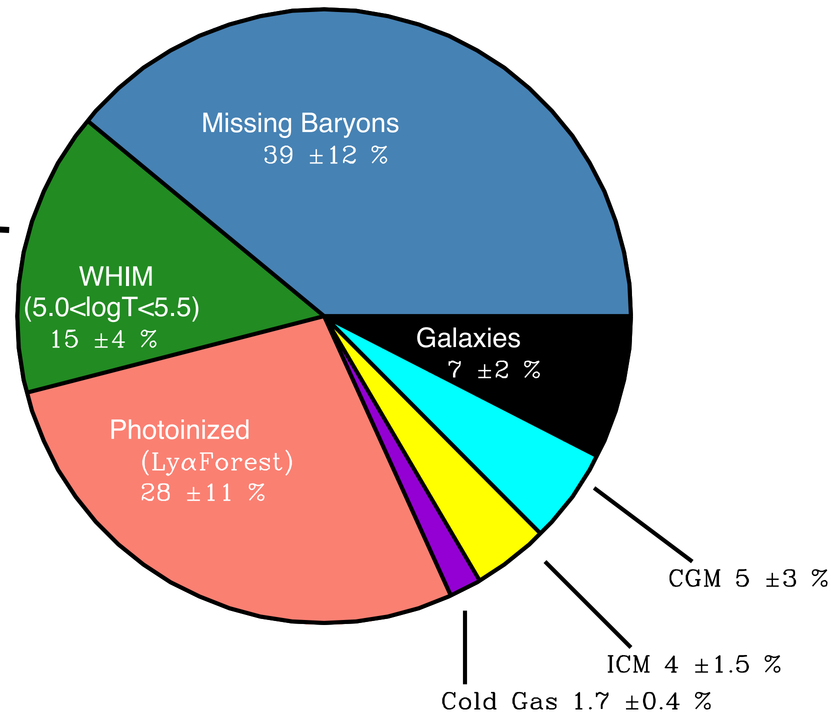
- The Missing Baryon Problem
- Results from the XMM-Newton VLP on 1ES 1553+113
- From current to next generation X-ray spectrometers.

The Missing Baryons Problem

Nicastro+16

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

HST-COS Obs of BLA+OVI & Chandra Obs of CV

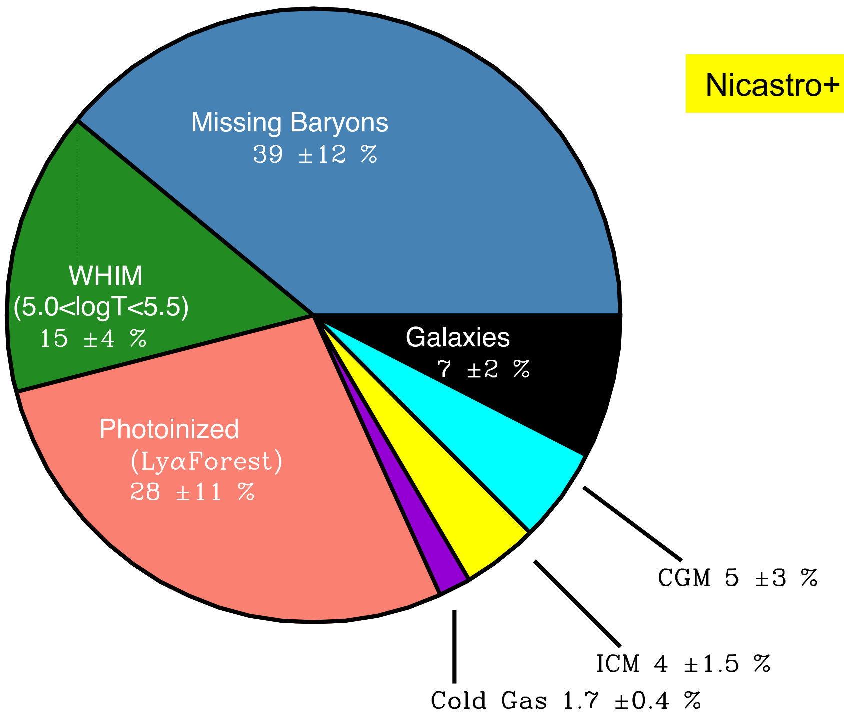


~ 30-50% of Baryons Still Missing at z~0

The Missing Baryons Problems

The Universe

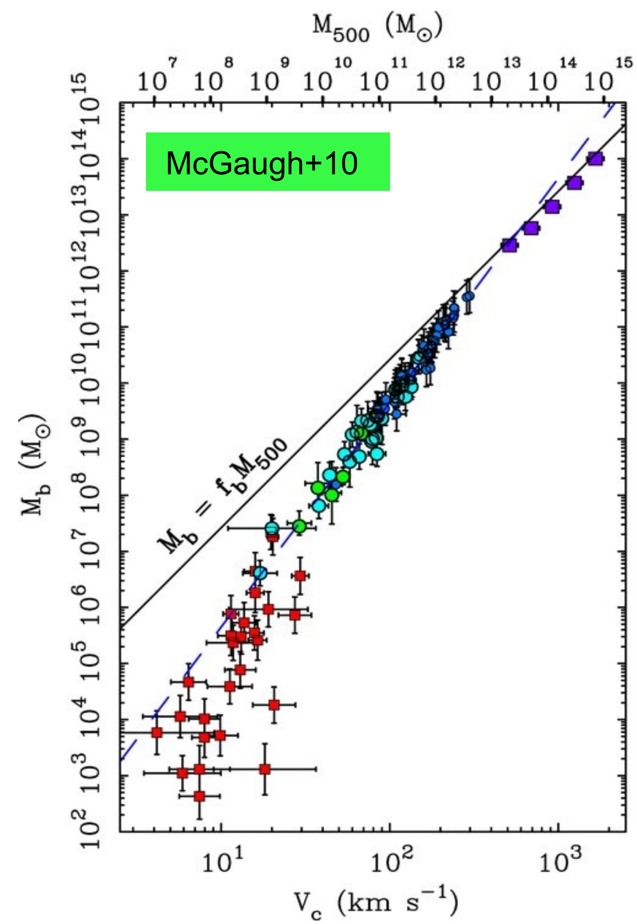
$\Omega_b^{Planck+15} = 0.0487 \sim 5\%$



Nicastro+16

~ 30-50% of Baryons missing at z~0

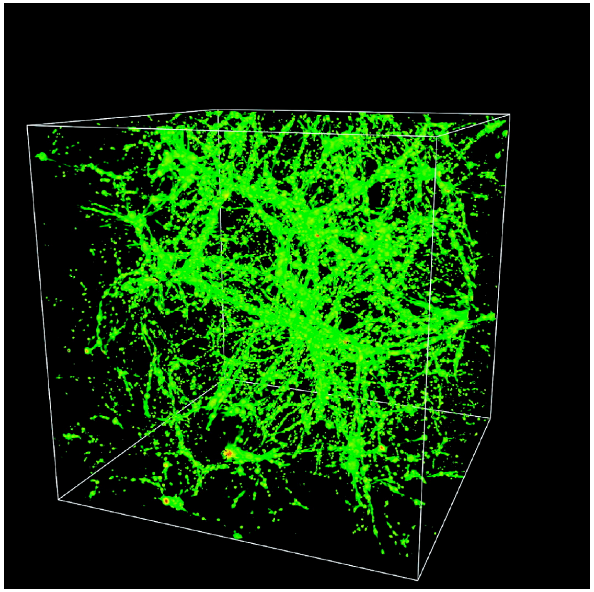
The Galaxies



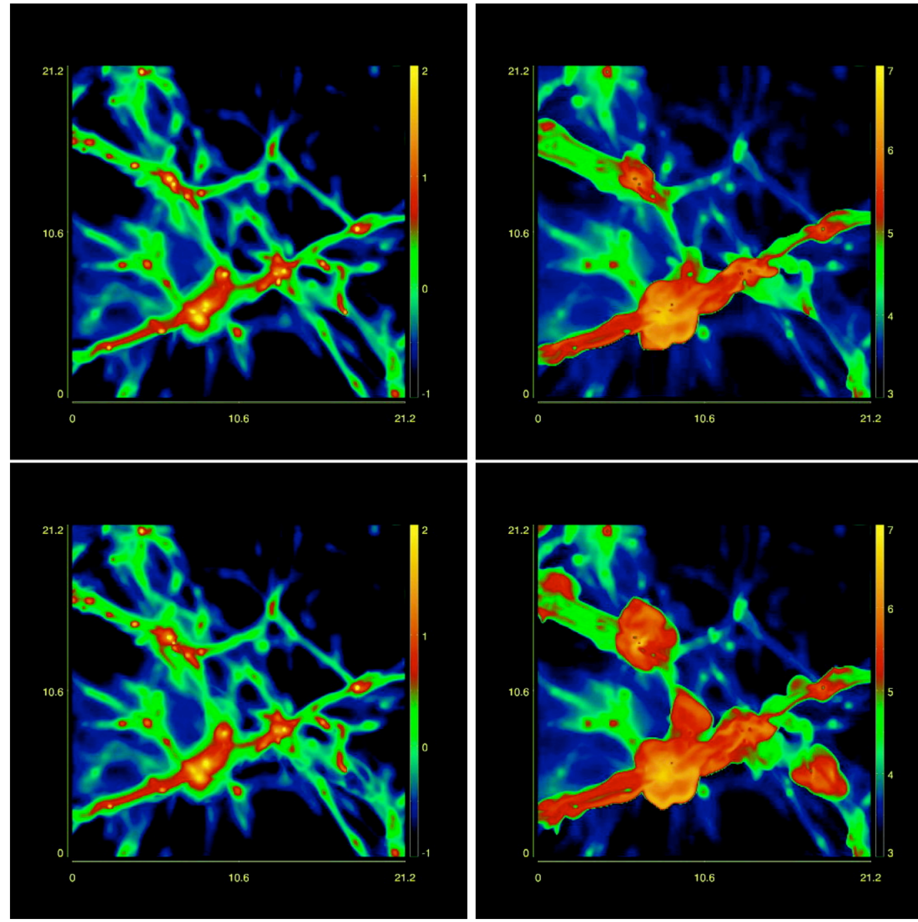
$\Omega_m^{planck+15} = 0.3156 \rightarrow f_b = 0.154$

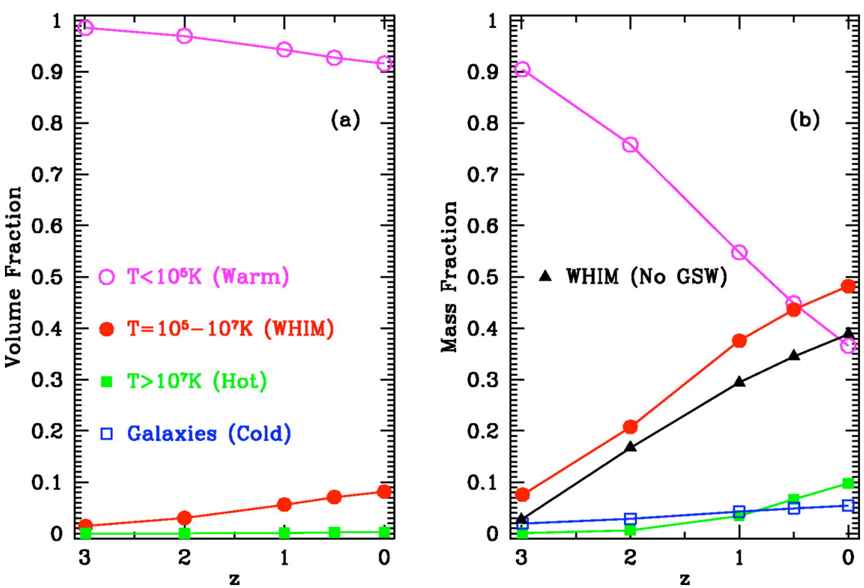
The Baryons in HD Simulations

85h^{-1} Mpc side
10^9 particles
z=0
T=10^5-10^7 K
Green=10-20 ρ_b
Red~1000 ρ_b



(21.2 x 21.2 x 1.75)h^{-1} Mpc
Without (top) and with (bottom) GSWs
Overdensity (left) Temperature (Right)

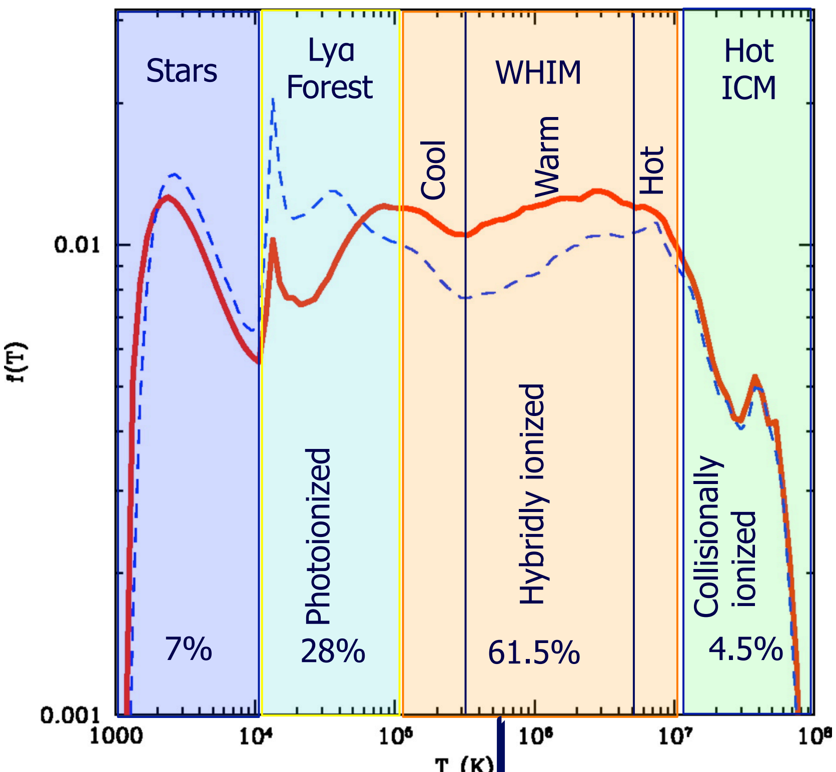




Cen & Ostriker, 2006

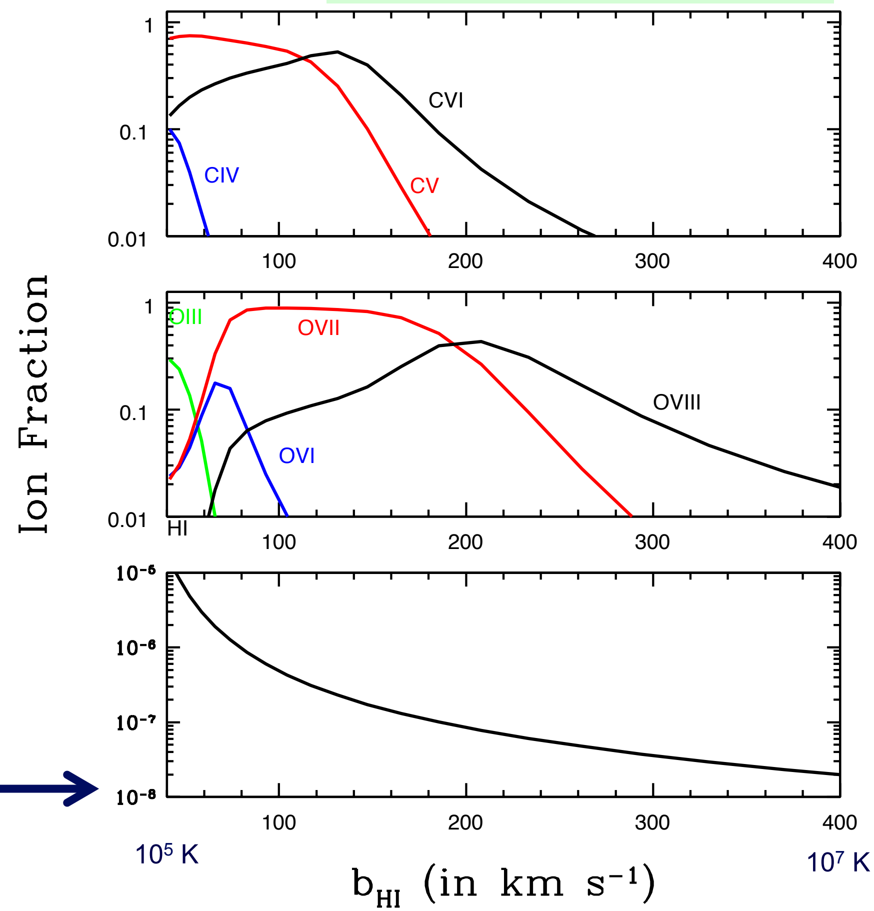
The Baryon Phases in HDS

Differential Mass Fraction vs T



Cen & Ostriker 06

Hybridly Ionized Gas (δ=50)

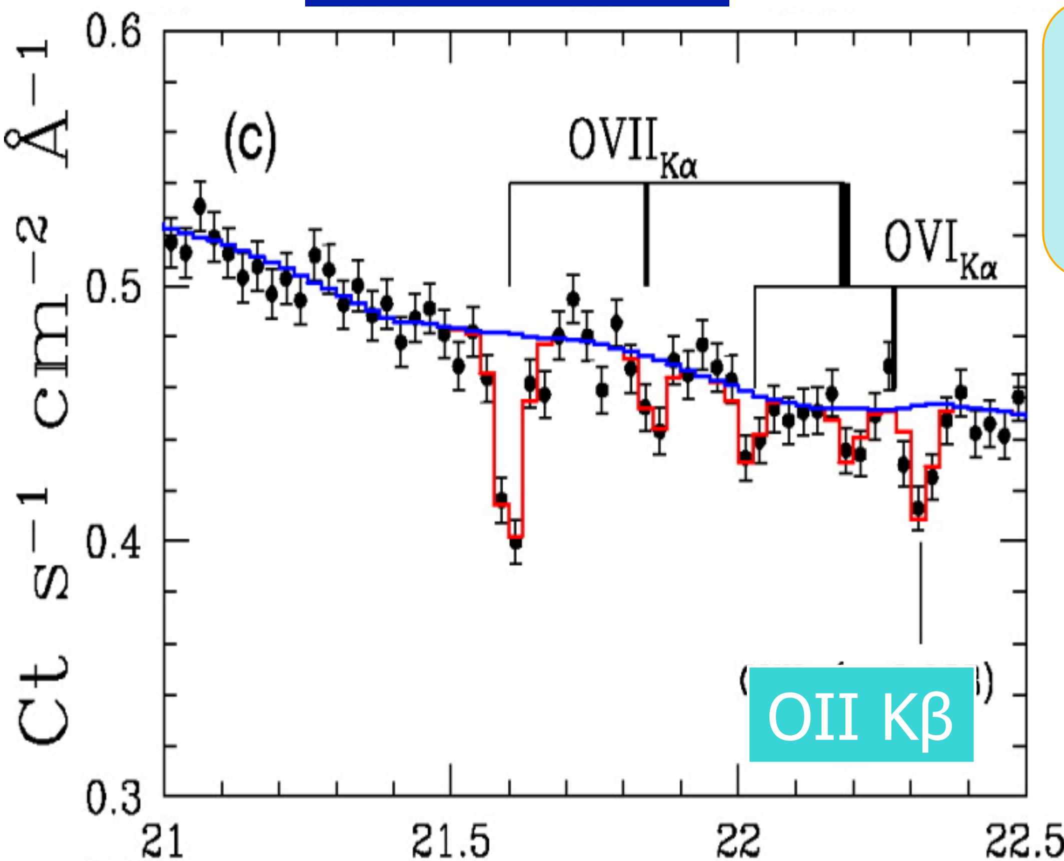


$T \approx b_{HI}^2 \times 58$ K

First Claimed WHIM Detections:

Exceptional Outburst State

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



However:

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

+

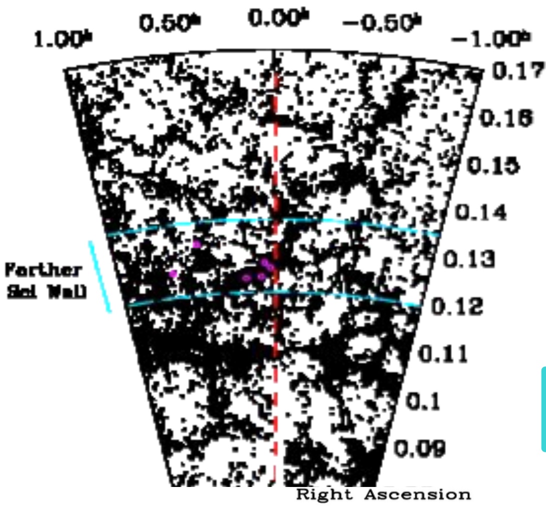
Controversial:

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

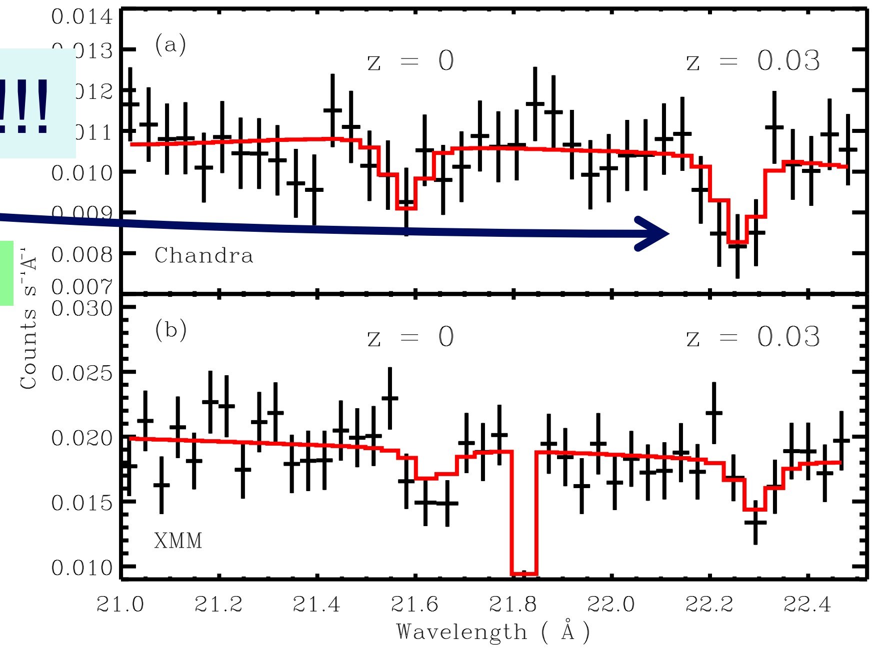
$$\Omega_b(N_{OVII} > 7*10^{14}) = 2.7^{+3.8}_{-1.9} * 10^{-[O/H]_{-1}}\% \sim \Omega_{Miss}$$

Galaxy concentrations as WHIM tracers

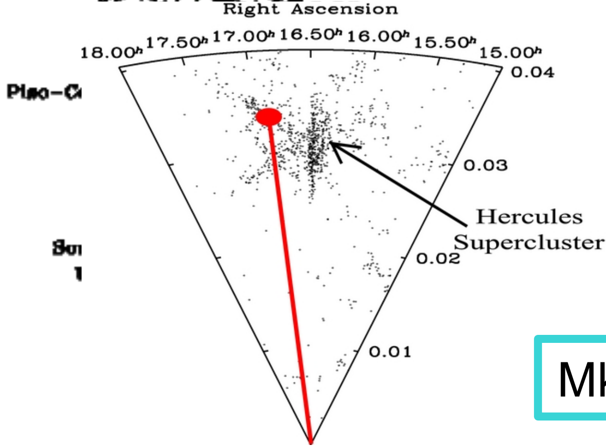
But: N_{OVII} ~ 8 x 10^{16} cm^{-2} !!!

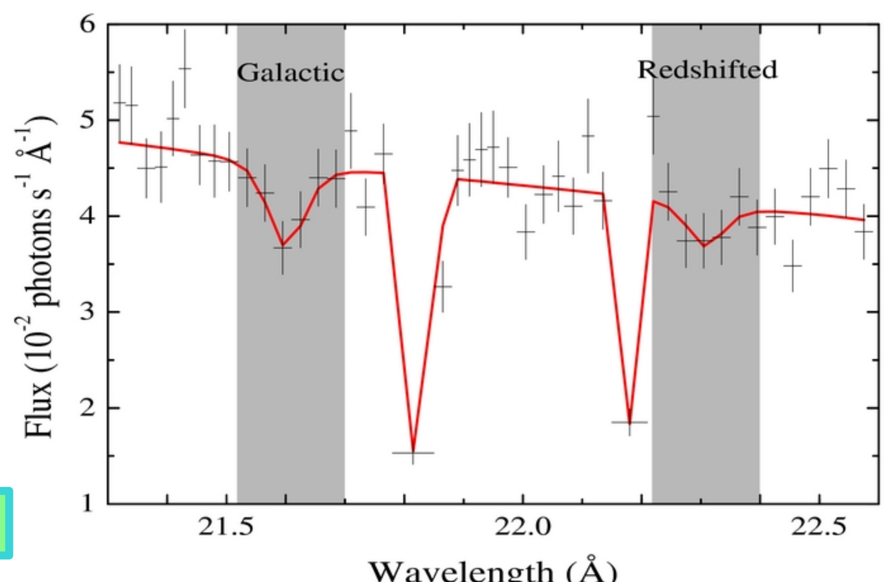


Buote+09, Fang+10



H 2356-309



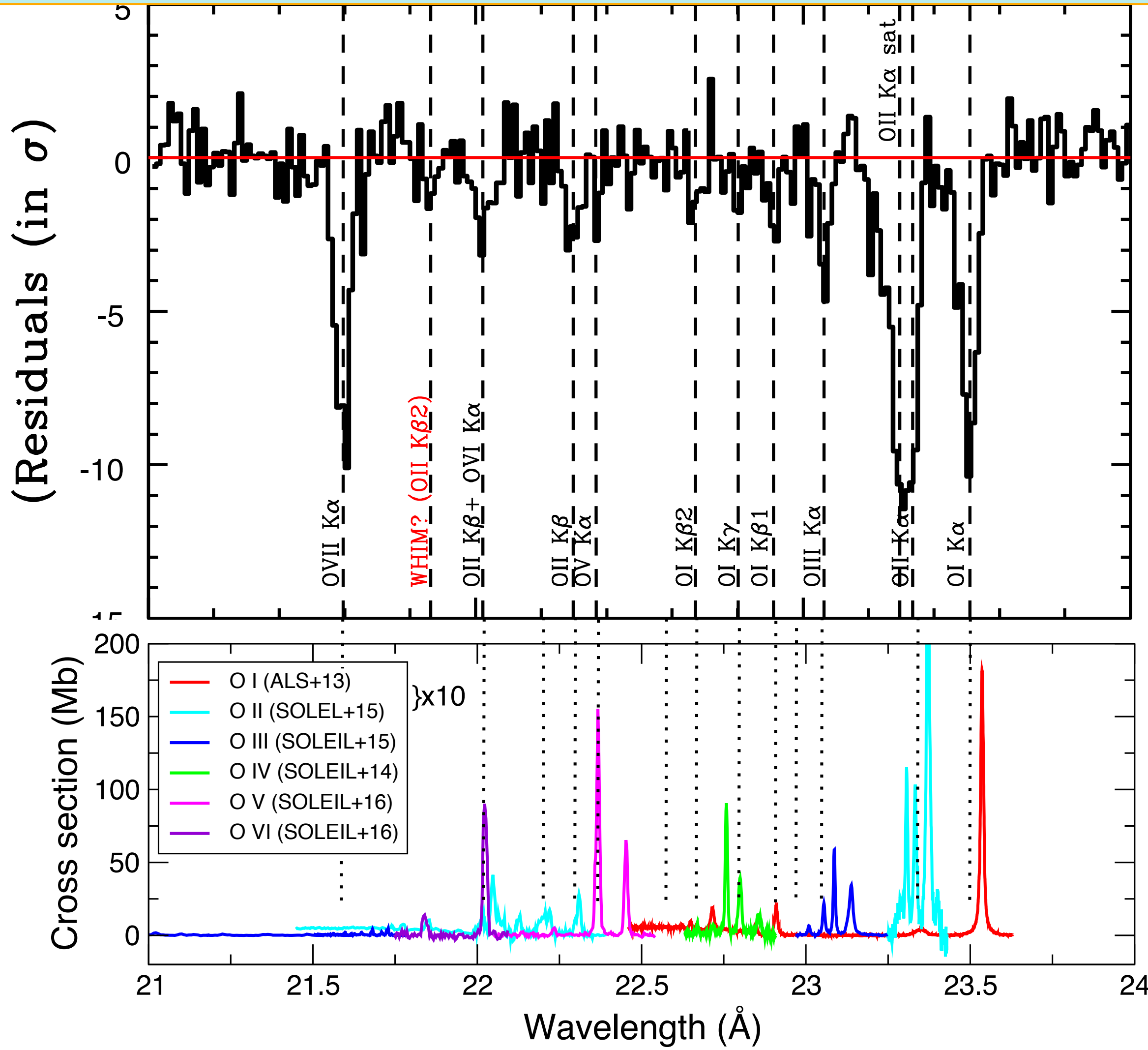


Mkn 501

Ren, Fang & Buote, 2014

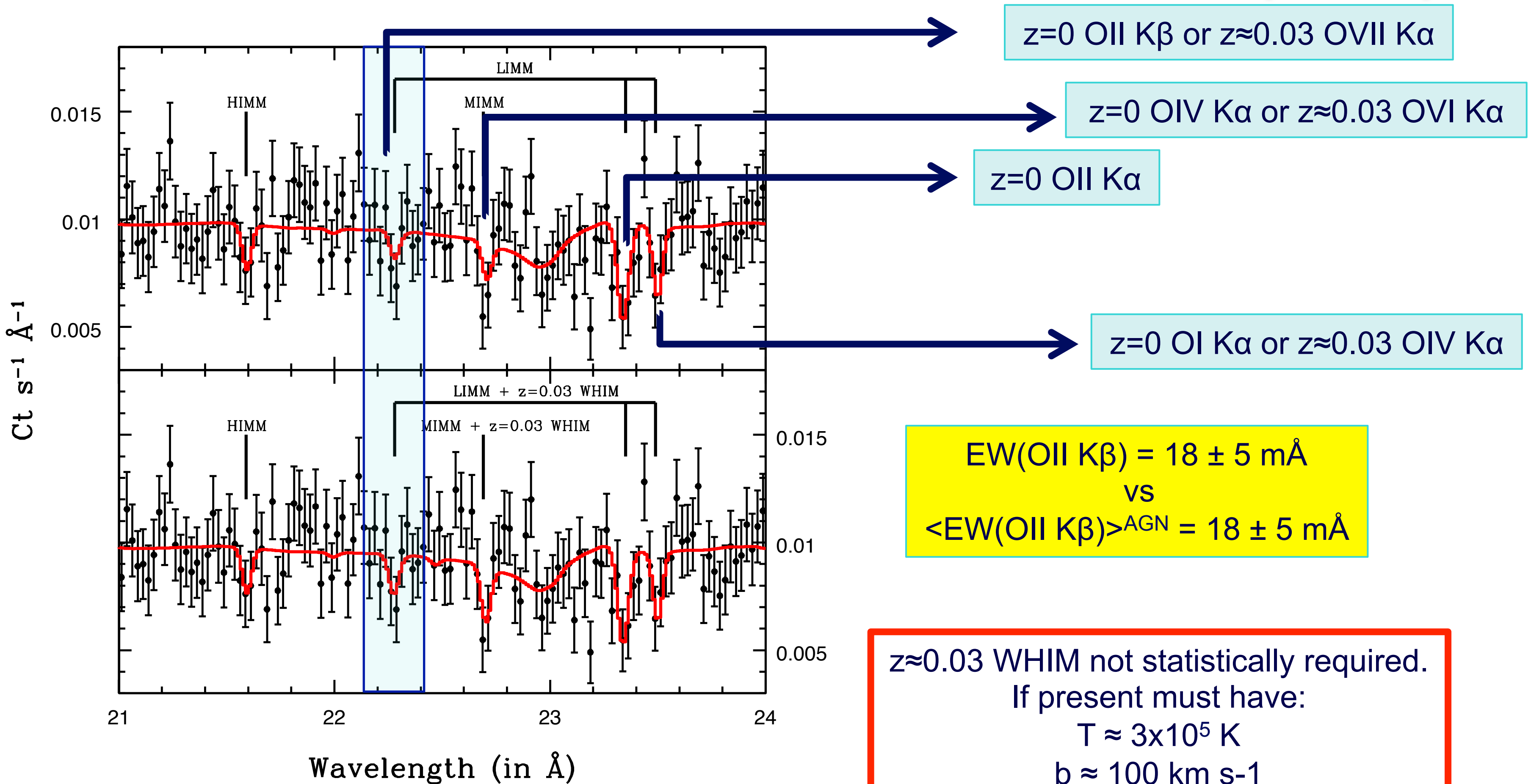
ISM/IGM Spectrum(Real Data)

Chandra-LETG Spectrum of Mkn 421 (z=0.03) Nicastro+05



The Case of H 2356-309

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



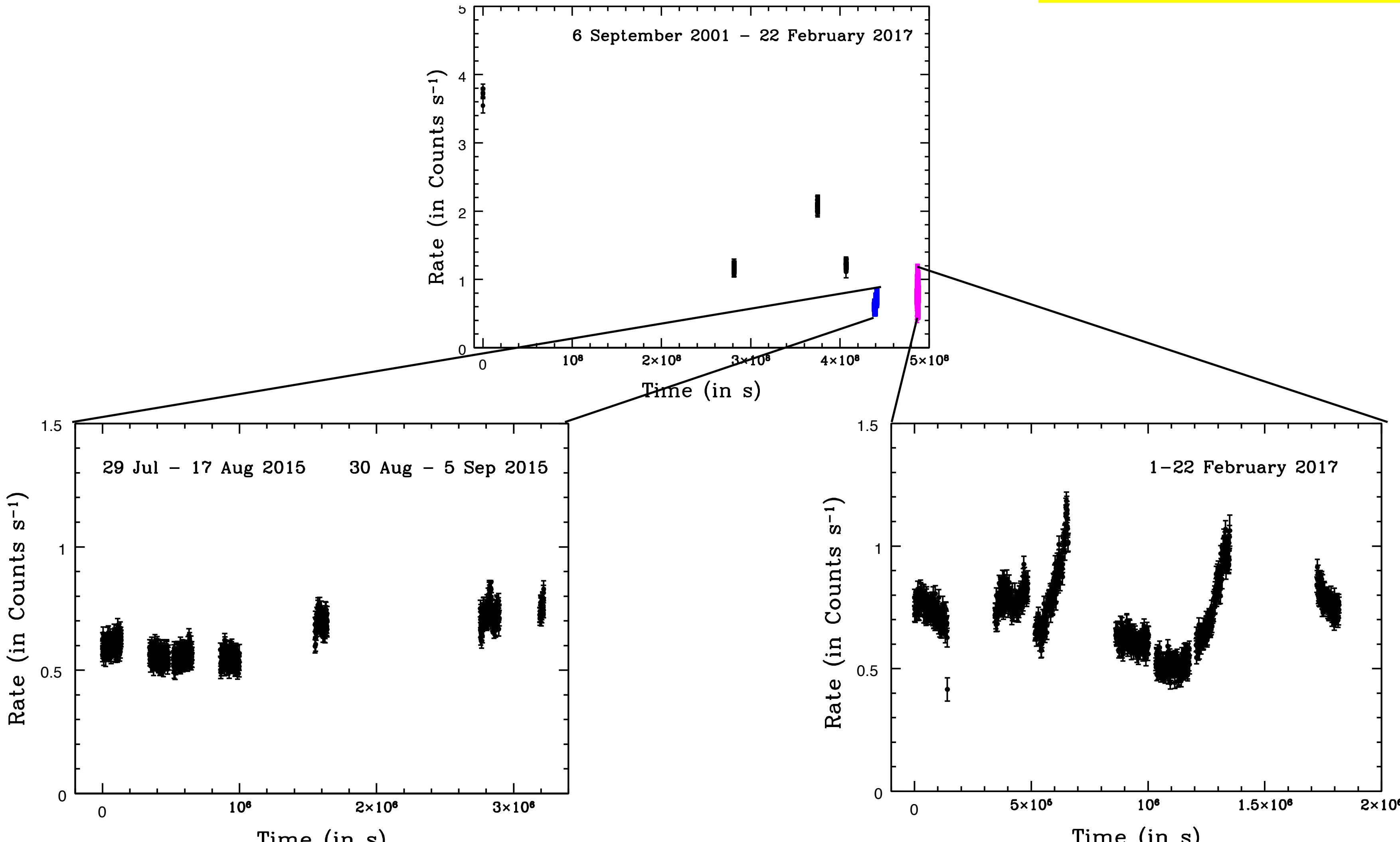
EW(OII Kβ) = 18 ± 5 mÅ
vs
<EW(OII Kβ)>^{AGN} = 18 ± 5 mÅ

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

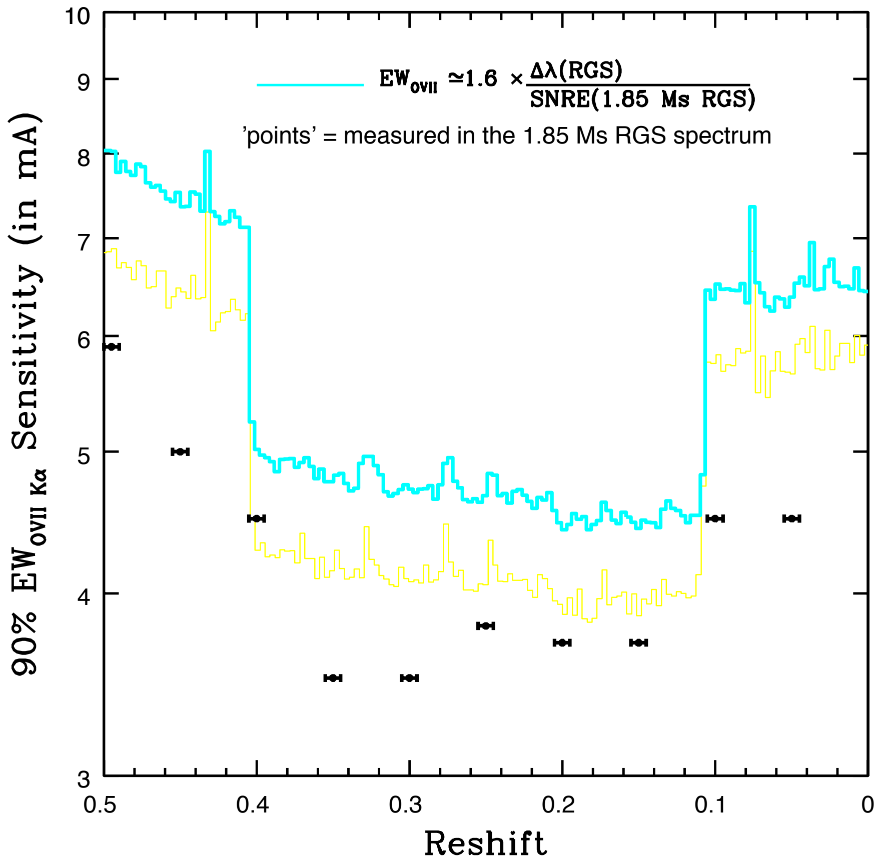
The XMM-Newton VLP on 1ES 1553+113

0.41 < z < 0.48 (COS)
z~0.49 ± 0.04 (Abramowski)

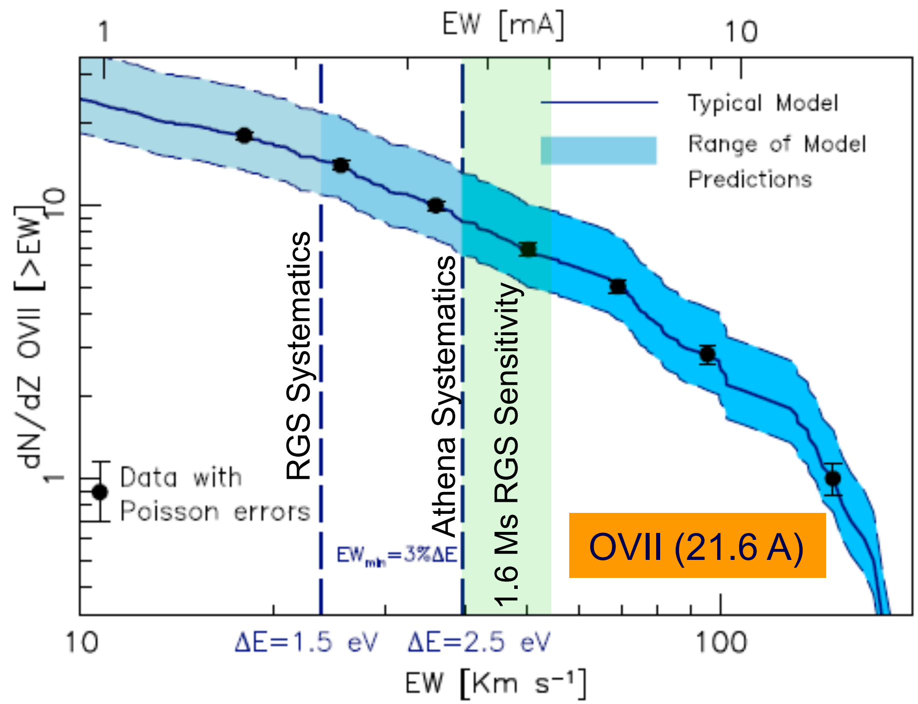


The Warm-Hot (OVII) IGM
XMM-Newton RGS Spectrum of 1ES 1553+113

RGS Spectra of 1ES 1553+113

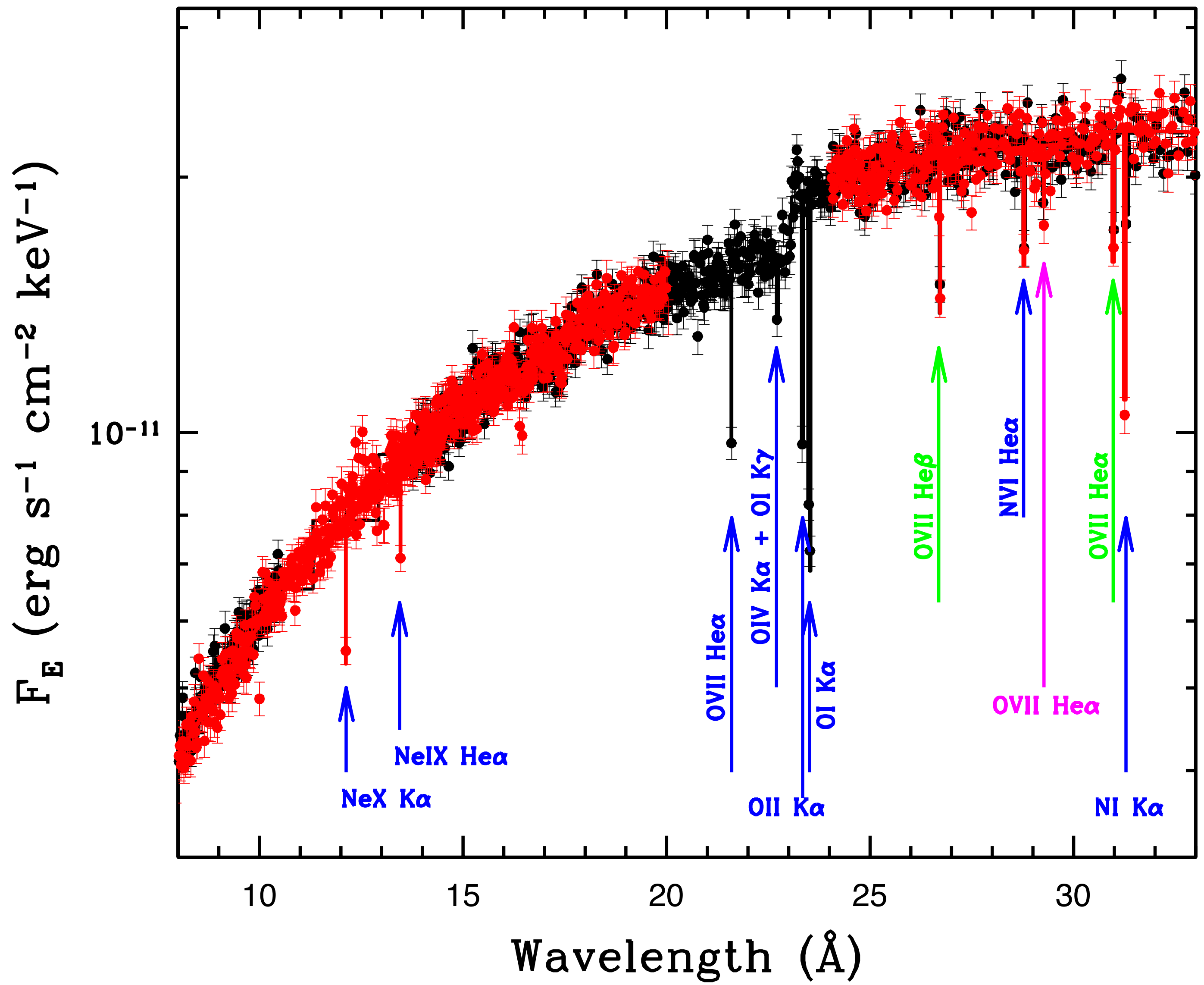


Athena WHIM White Paper (Kaastra+13)

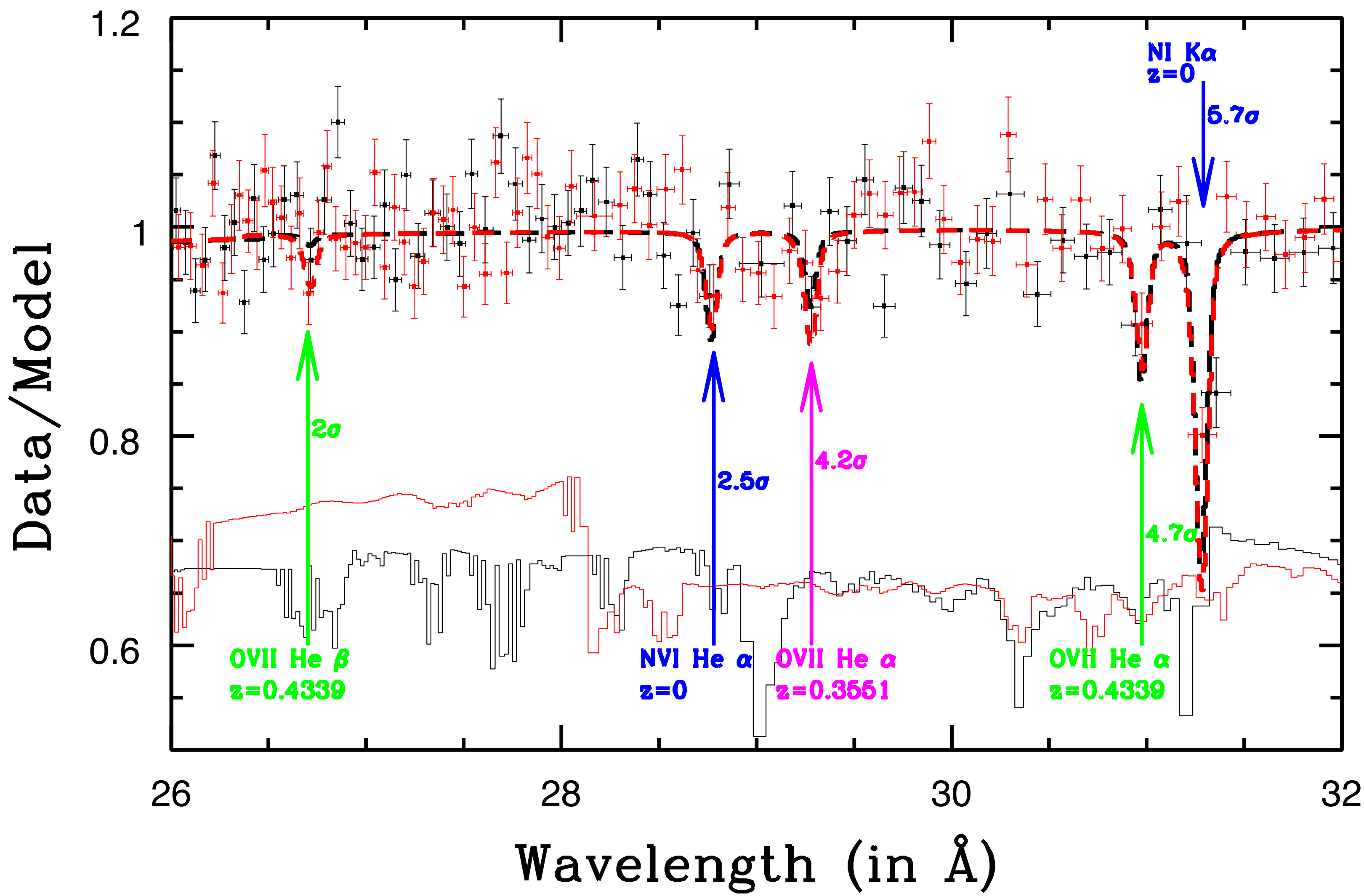


1.85 Ms RGS: EW>4-5 mA @ >90%
i.e. ~600 cts per R.E.

Broad-band RGS Spectra of 1ES 1553+113

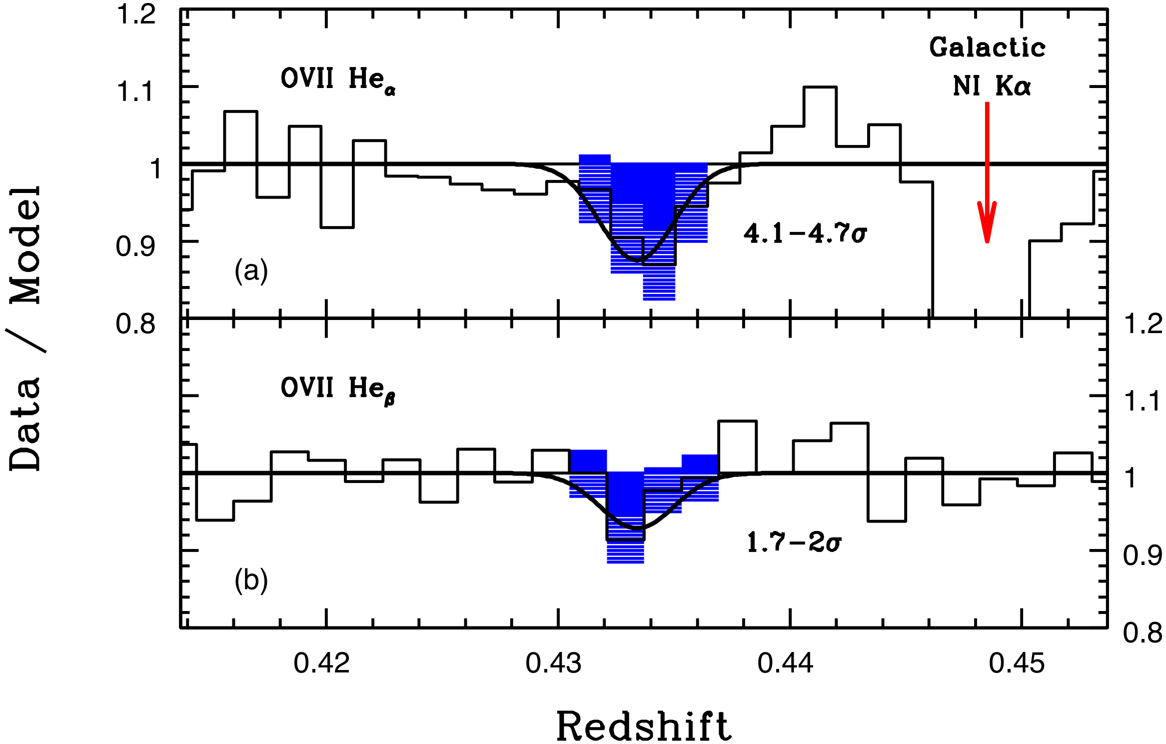


26-32 Å RGS Spectra



System-1

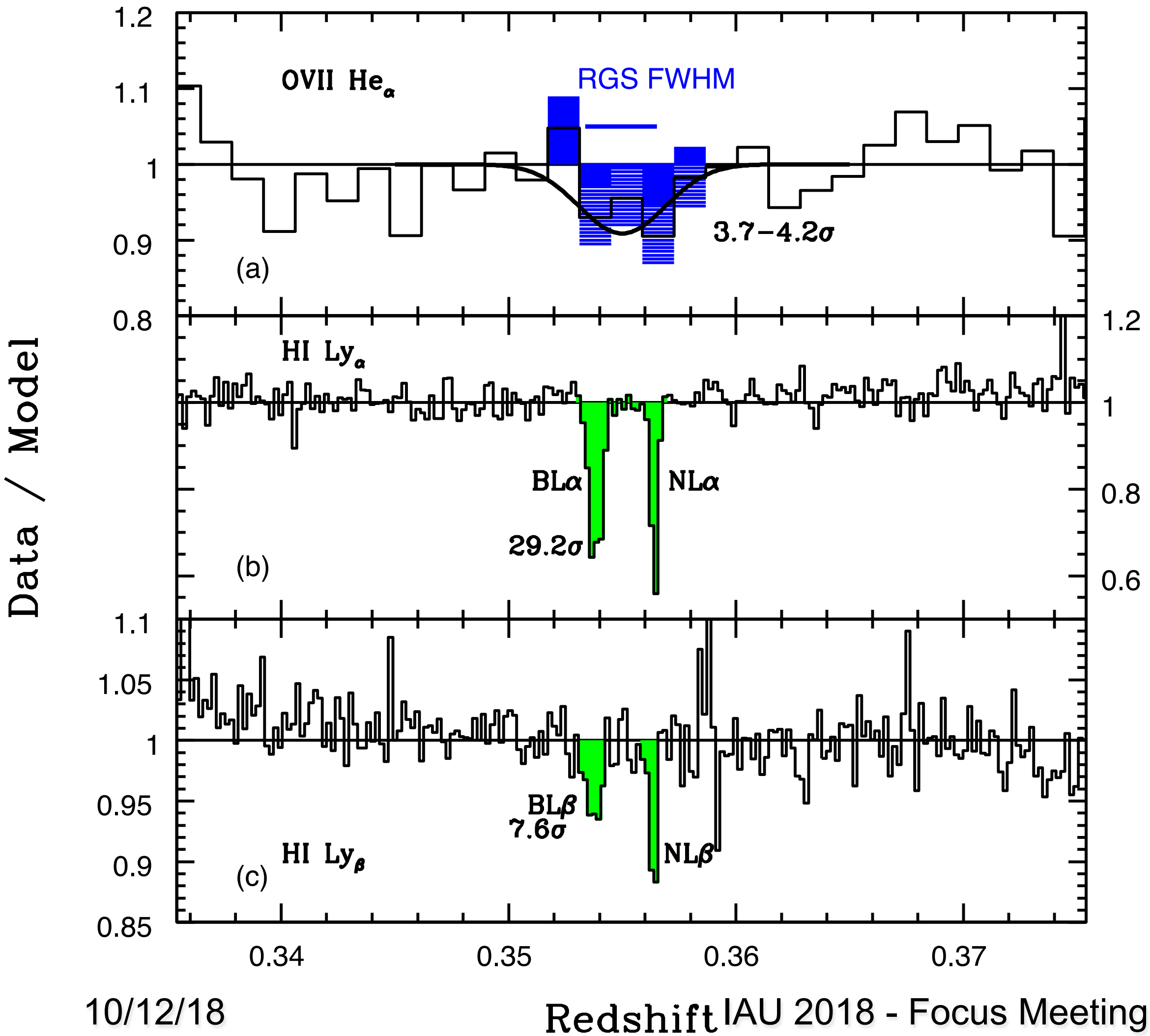
z_X=0.4339±0.0008



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

System-2

$z_X=0.35559\pm0.00016$

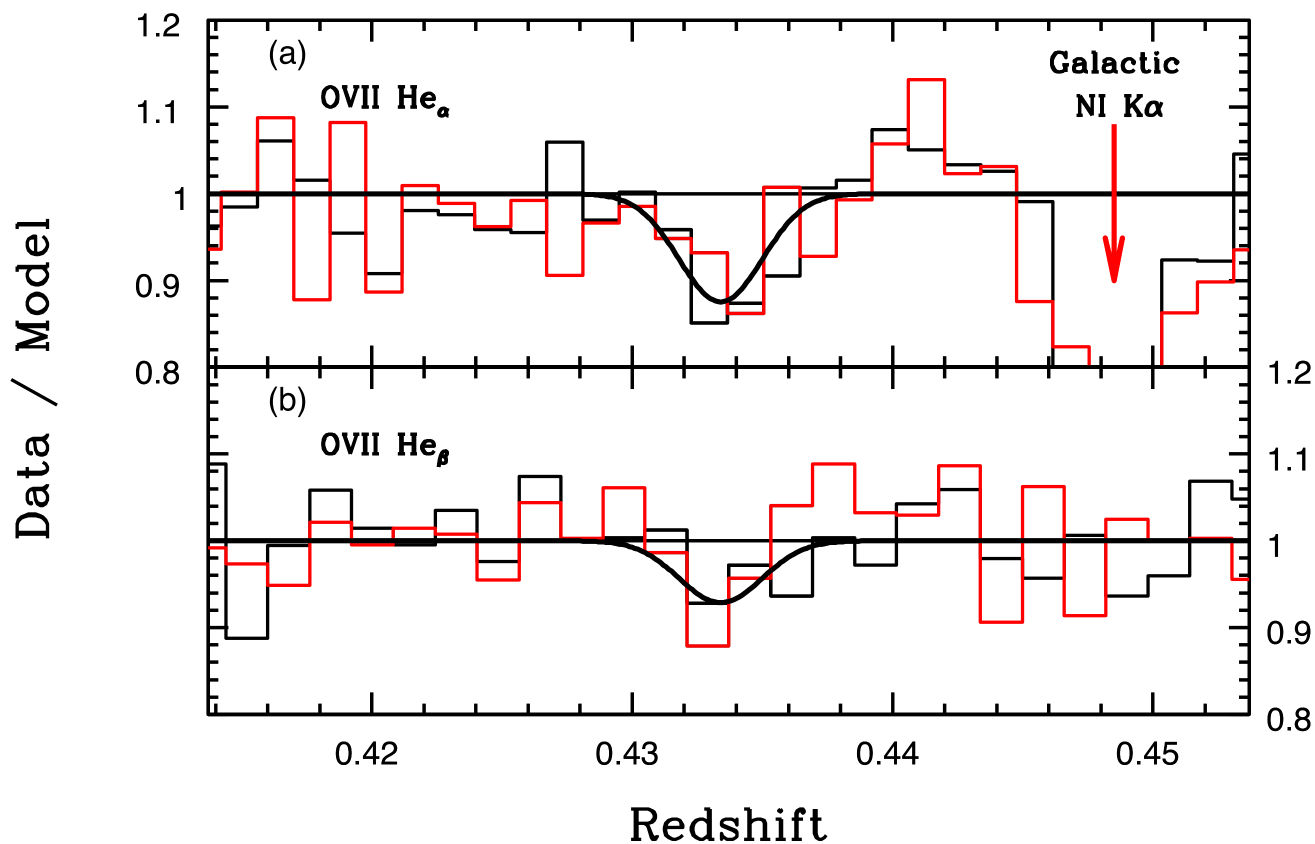


Statistical Significance (after accounting for OVII blind redshift search and RGS eff.-area-induced systematics): 2.9-3.7σ

Diagnostics

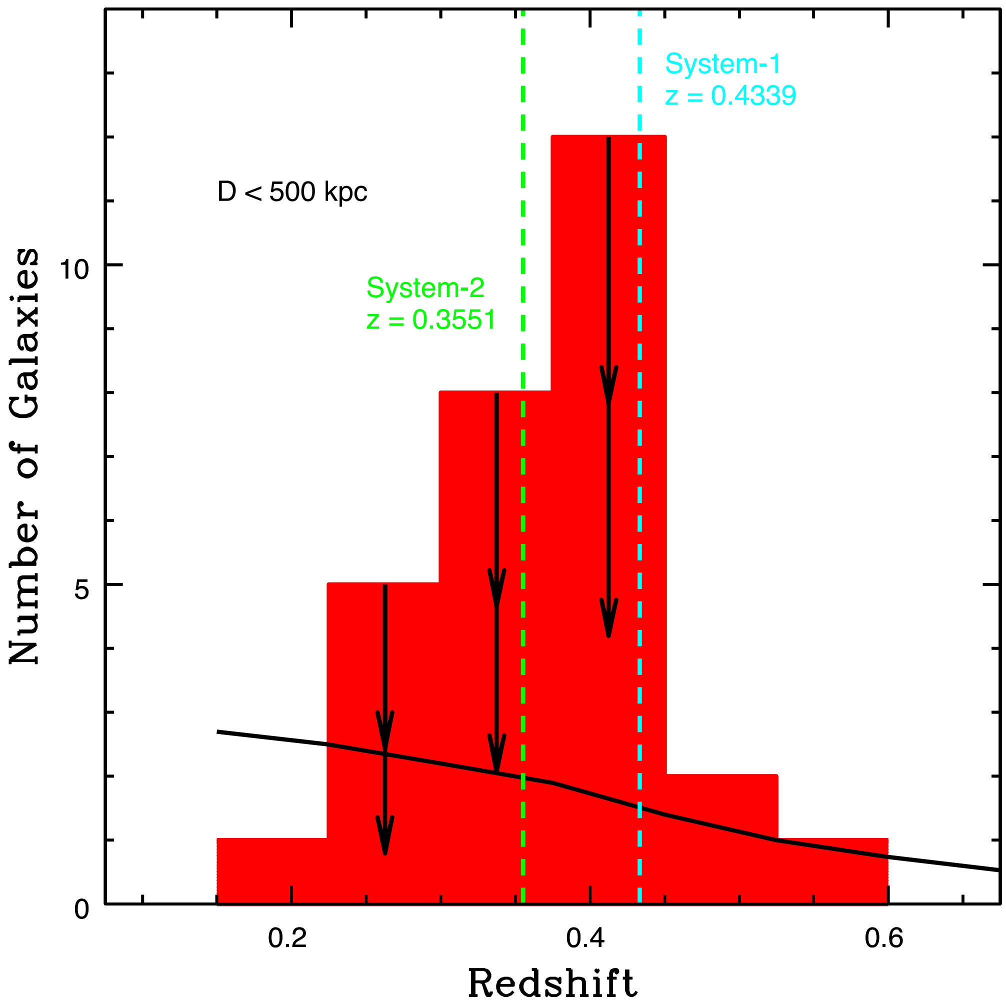
System	T (10^6 K)	N_O (10^{15} cm^{-2})	$N_H(Z/Z_\odot)^{-1}$ (10^{19} cm^{-2})	Z ($Z_\odot$)
1	1.2±0.4	$7.8^{+3.9}_{-2.4}$	$1.6^{+0.8}_{-0.5}$	≥0.1
2	0.95±0.45	$4.4^{+2.4}_{-2.0}$	$0.9^{+0.5}_{-0.4}$	≥0.1

IGM vs Intrinsic Absorption for System-1



z=0.2-0.6 Galaxy Distribution

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



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

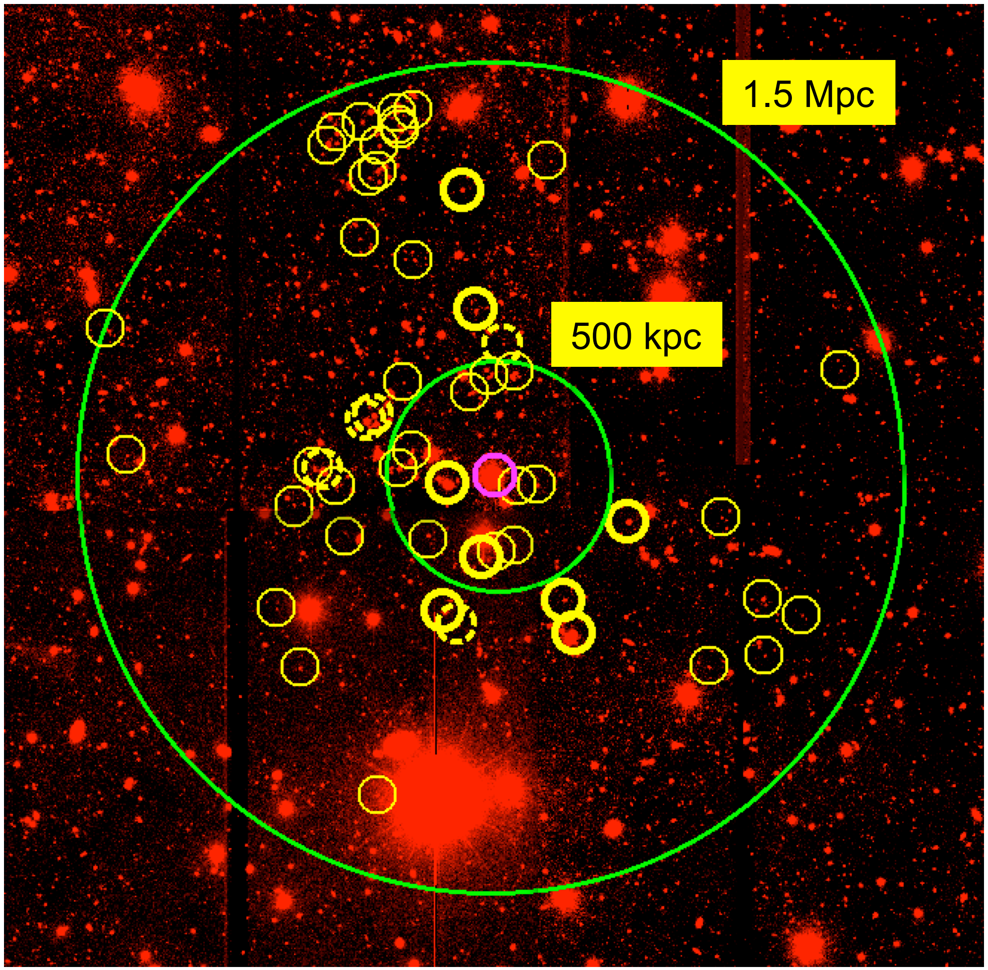
Photo-z accuracy (and so bin width): $\Delta z=\pm 0.035$

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

System-1: Galaxy Environment

at z=0.375-0.450 (5.7 kpc/arcsec)



8/13 spectroscopically confirmed galaxies within ±900 km s^{-1}

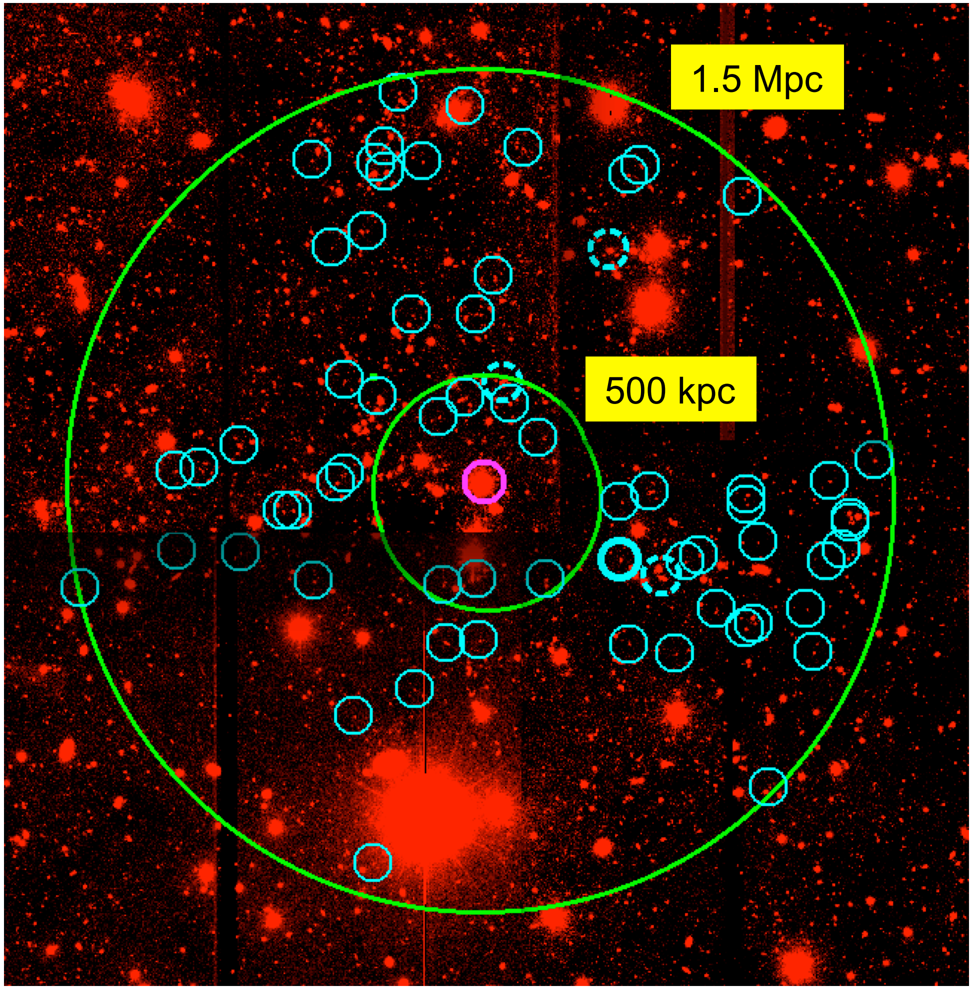
Nearest galaxy: i'=19.6 spiral at d=129 kpc and -15 km s^{-1}
➔ Galaxy's CGM?

500 kpc ~ 1.5 arcmin
1.5 Mpc _ 4.5 arcmin

Inner circle fits in Athena XIFU fov
Getting 5 PSF FWHM away from the background target still samples the filament ➔ emission+absorption (better at lower z)

System-2: Galaxy Environment

at z=0.320-0.390 (5 kpc/arcsec)



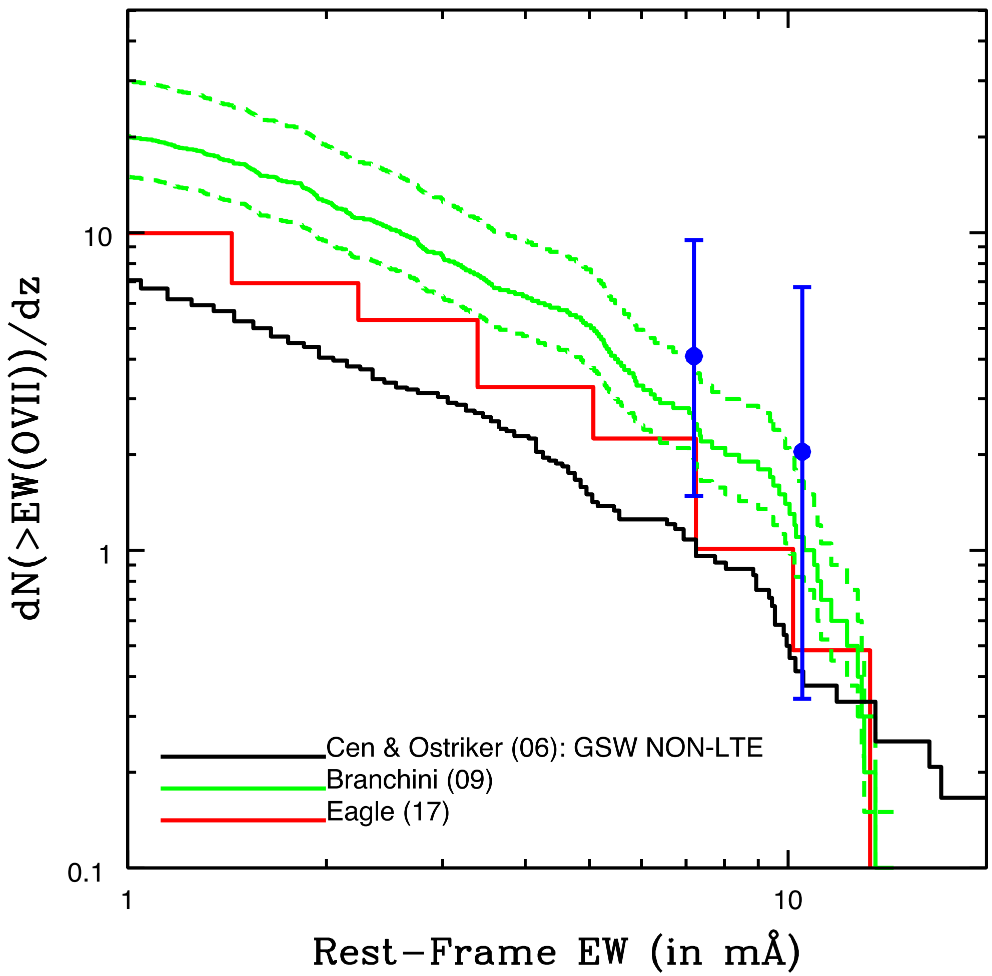
Only 4/72 galaxies within the 1.5 Mpc radius circle have spectroscopic redshifts

Only 1/4 is confirmed at the redshift of the absorber (a i'=20.5 elliptical), but lies at d=633 kpc and +370 km s^{-1}
➔ Diffuse filament?

500 kpc ~ 1.7 arcmin
1.5 Mpc _ 5 arcmin

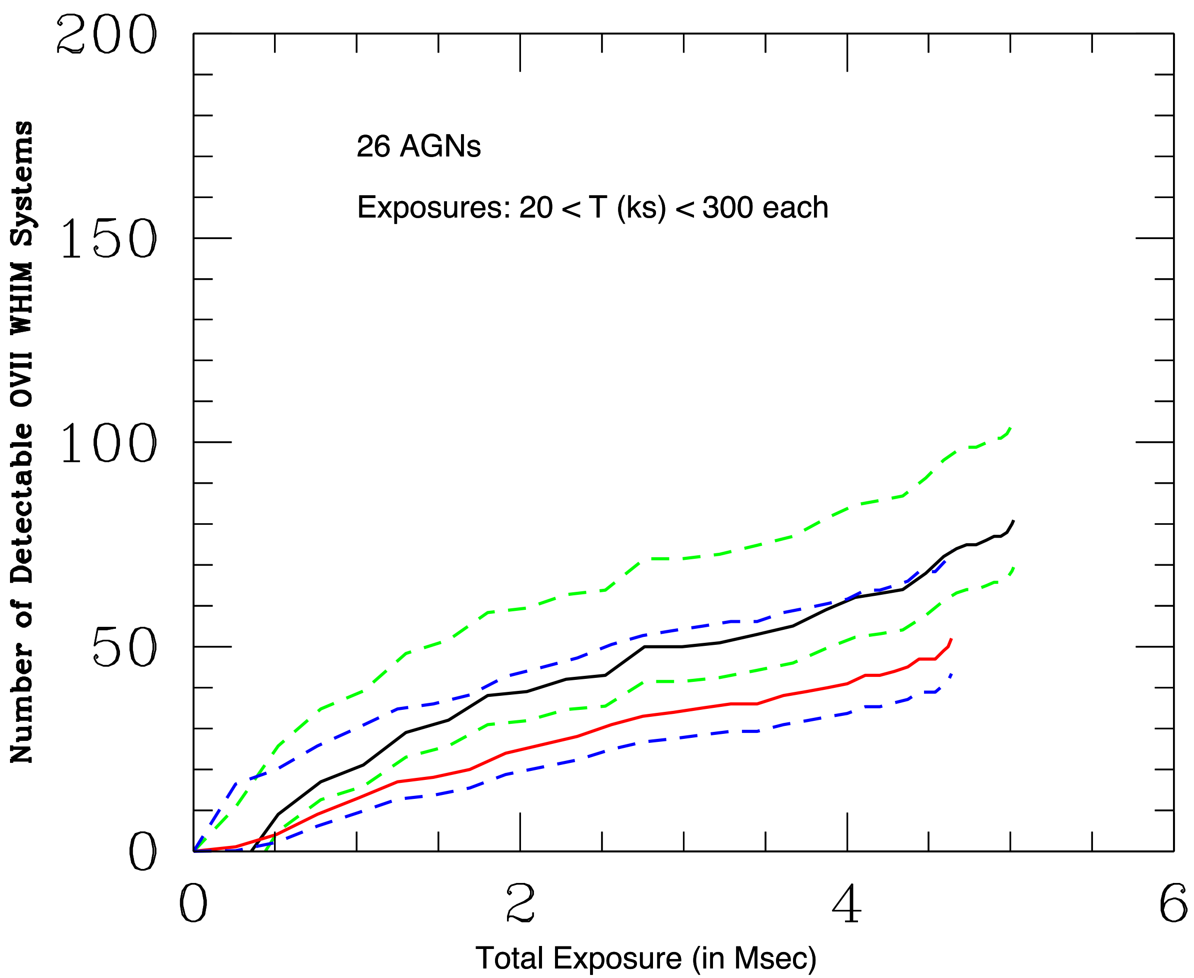
Entire inner circle still fits in Athena XIFU fov
➔ emission+absorption

First data agree with predictions



(once) missing baryons will be found in OVII intervening absorbers.

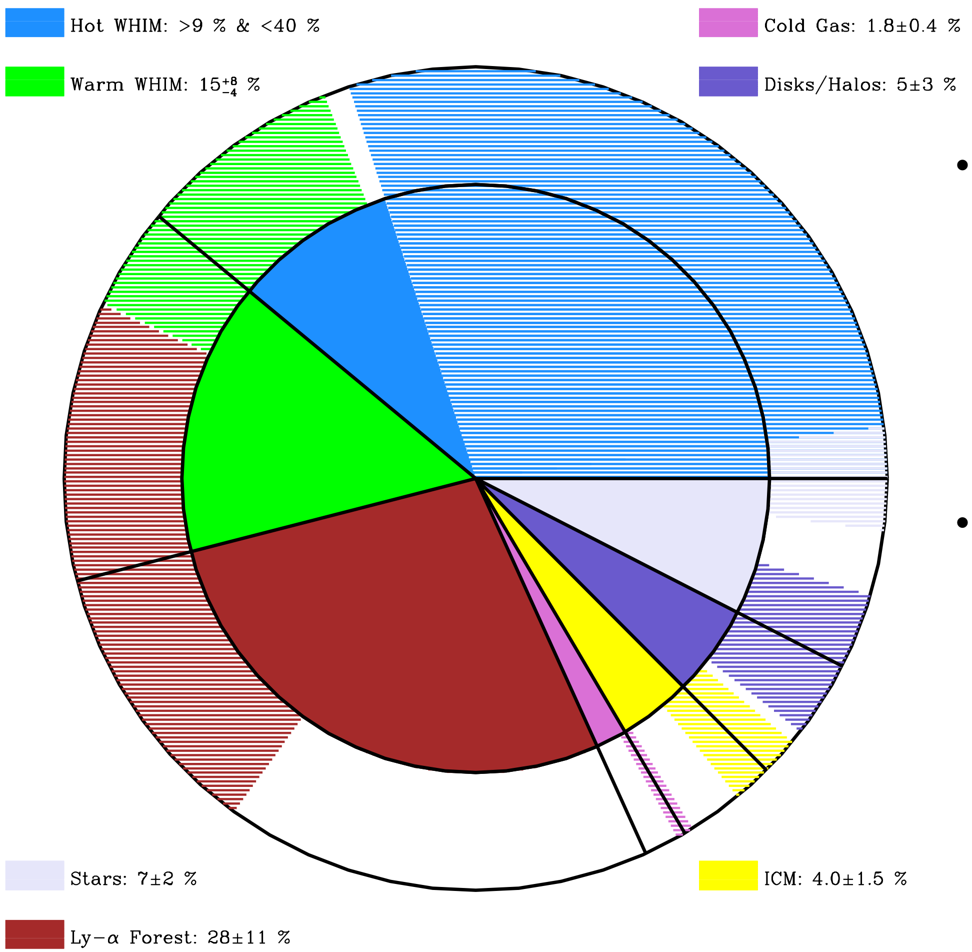
Athena vs Arcus: No. of Systems



- MOPs for WHIM are built up on realistic predictions:

  Athena(/Arcus) will detect about 100(/50) filaments against bright AGNs (R and A_{eff} compete)

Hot baryons close the census

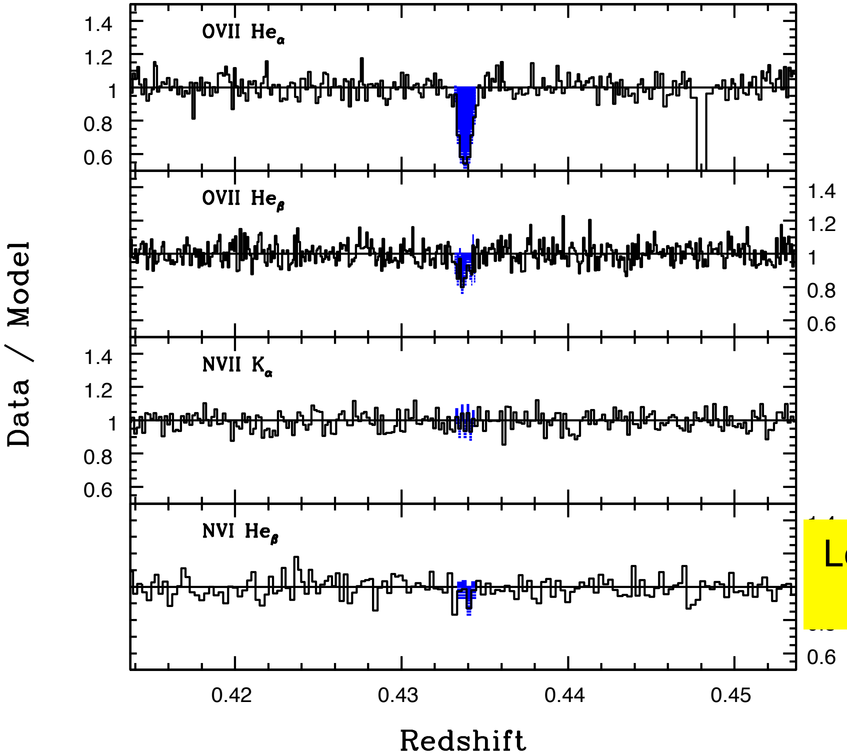


- HI lines are vital to evaluate metallicity and so derive mass: Athena's MOP targets should all be observed with the HST-COS at SNRE≥50 (requires ~500 HST orbits)

- 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.

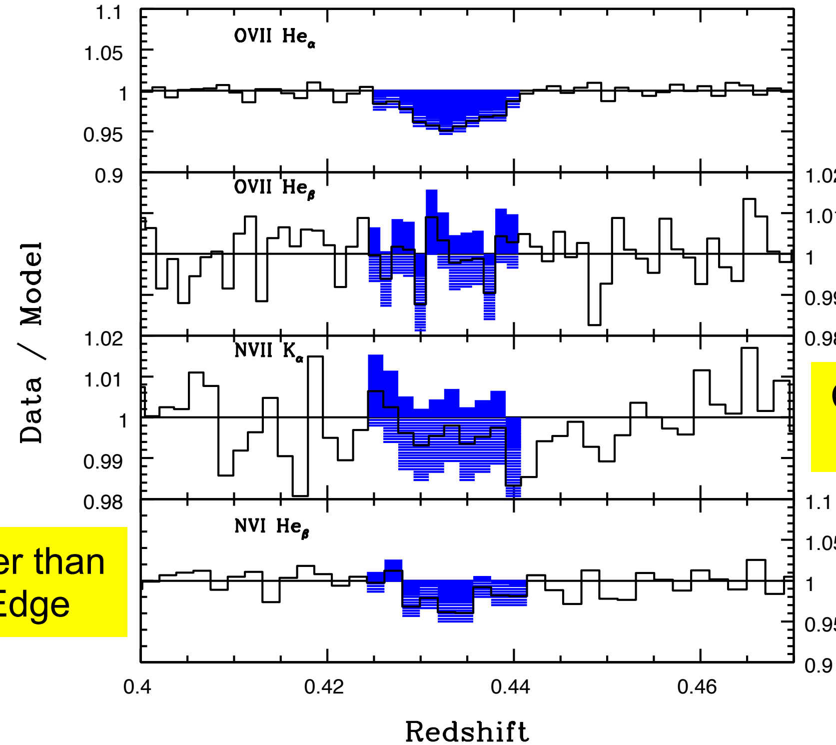
Athena vs Arcus: System-1

CAT-Gratings: $\Delta\lambda \sim \lambda$



Longer than C-Edge

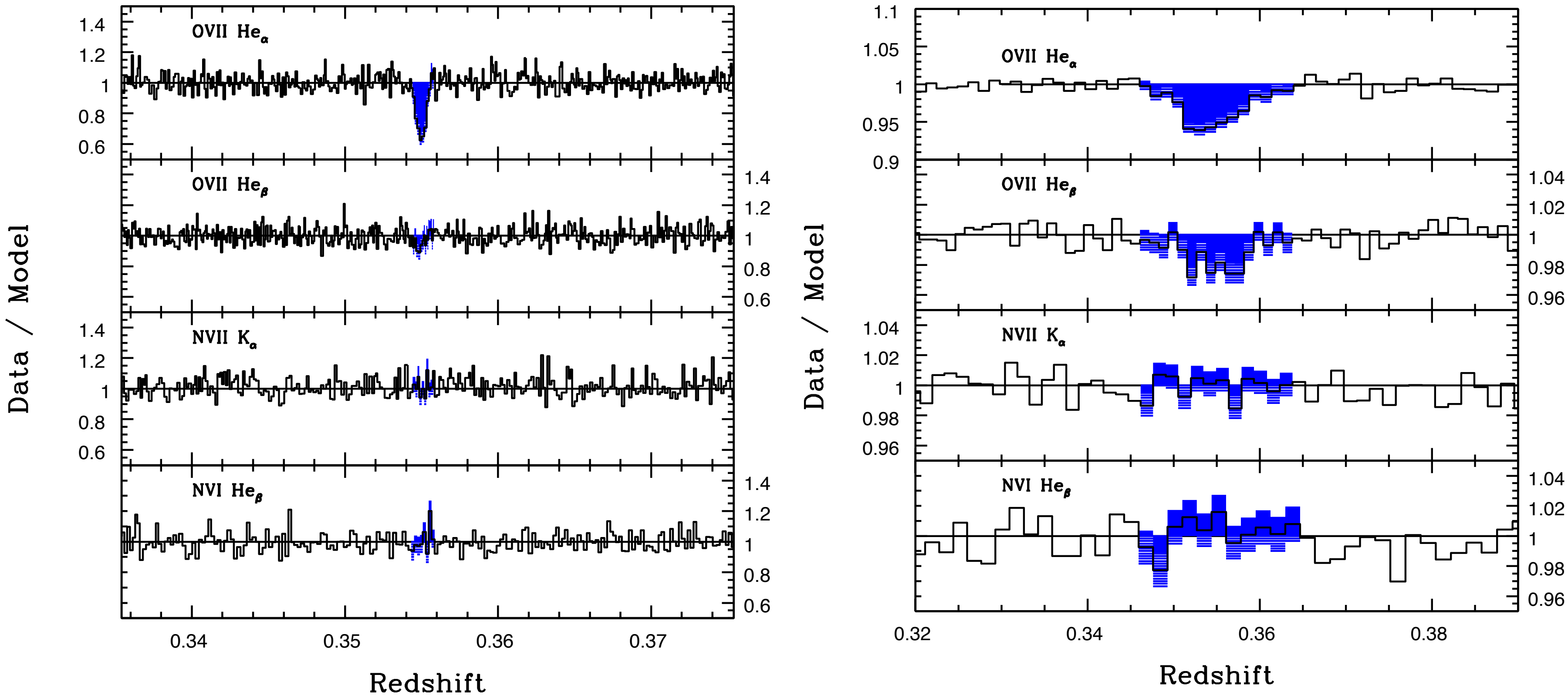
Calorimeter: $\Delta\lambda \sim \lambda^2$



C-edge valley

- Detecting 2 or more unresolved lines from the same ion (especially He-like), and for more than one metal (i.e. O and Ne or Fe) with high S/N would allow us to infer the Doppler parameters and so (by comparing them) disentangle b_{th} and b_{turb}.

Athena vs Arcus: System-2



- Filaments detected with Arcus-like machines before Athena, against targets fainter than ~ 1mCrab, can be followed up with Athena XIFU to detect associated emission, 5-PSFs away from target. This, compared with absorption measurements, will give densities.

What do we learn from this

- The first data confirm predictions: (once) missing baryons will be found in OVII intervening absorbers.
- MOPs for WHIM in absorption/emission are built up on realistic predictions: Athena/Arcus will detect about 50-100 filaments against bright AGNs (R and Aeff compete)
- HI lines are vital to evaluate metallicity and so derive mass: Athena's MOP targets should all be observed with the HST-COS at SNRE≥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 (and so, in the FUV). 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), and for more than one metal (i.e. O and Ne or Fe) with high S/N would allow us to infer the Doppler parameters and so (by comparing them) disentangle b_{th} and b_{turb}.
- z≤0.1 filaments detected with Arcus-like machines before Athena, against targets fainter than ~ 1mCrab, can be followed up with Athena XIFU to detect associated emission, 5-PSFs away from target. This, compared with absorption measurements, will give densities.
- Synergy between Athena and ELT in mapping the galaxy fields of absorbers will be vital to study metallicity vs galaxy-environment