Missing Baryons in the Universe: from kpc- to Mpc-scale

(ApJL, Nature, 21 June 2018)

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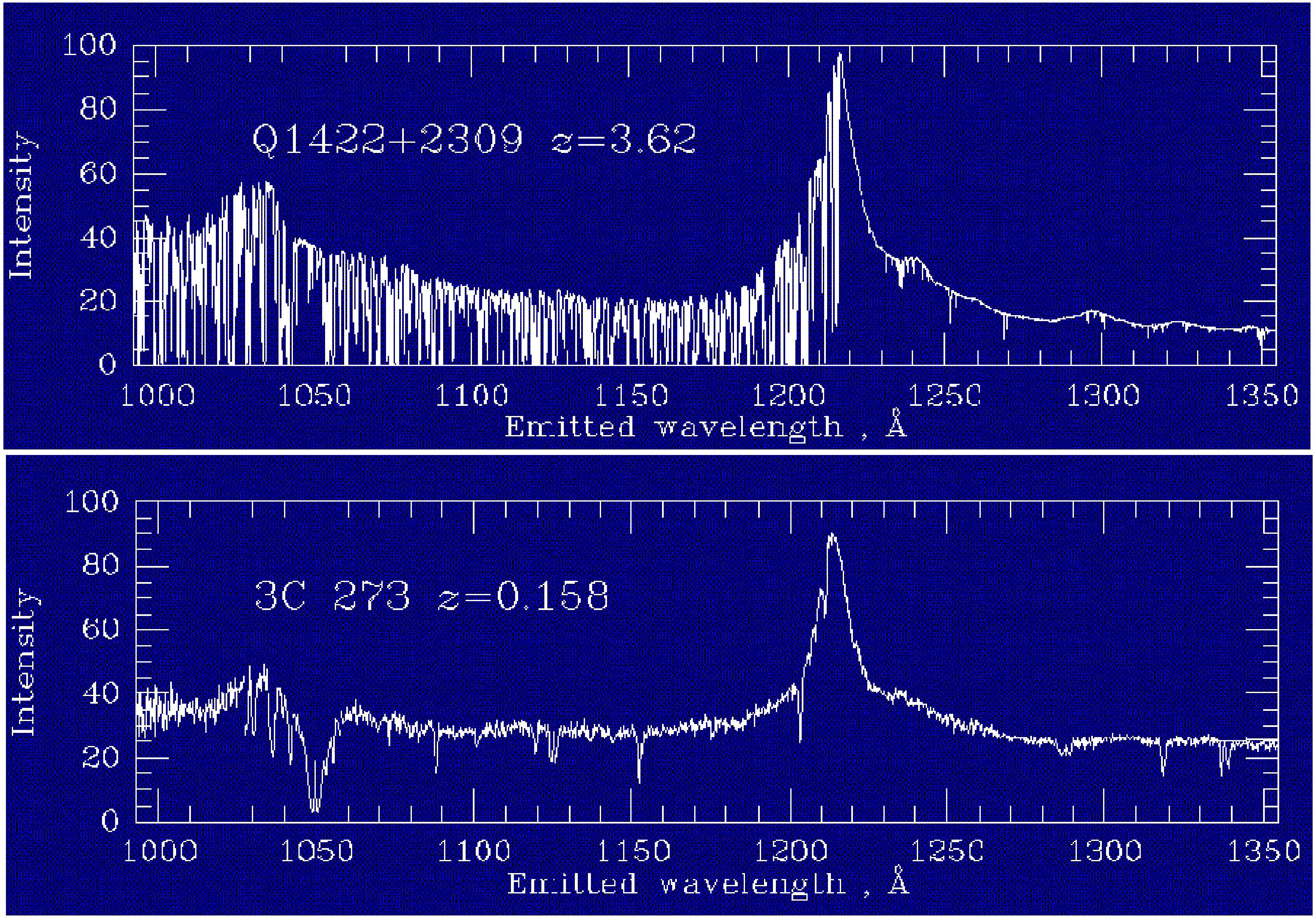
Outline

- The Missing Baryon Problem
- The Galaxy's Missing Baryons
- The Missing Baryons in a WHIM
- From current to next generation X-ray spectrometers.

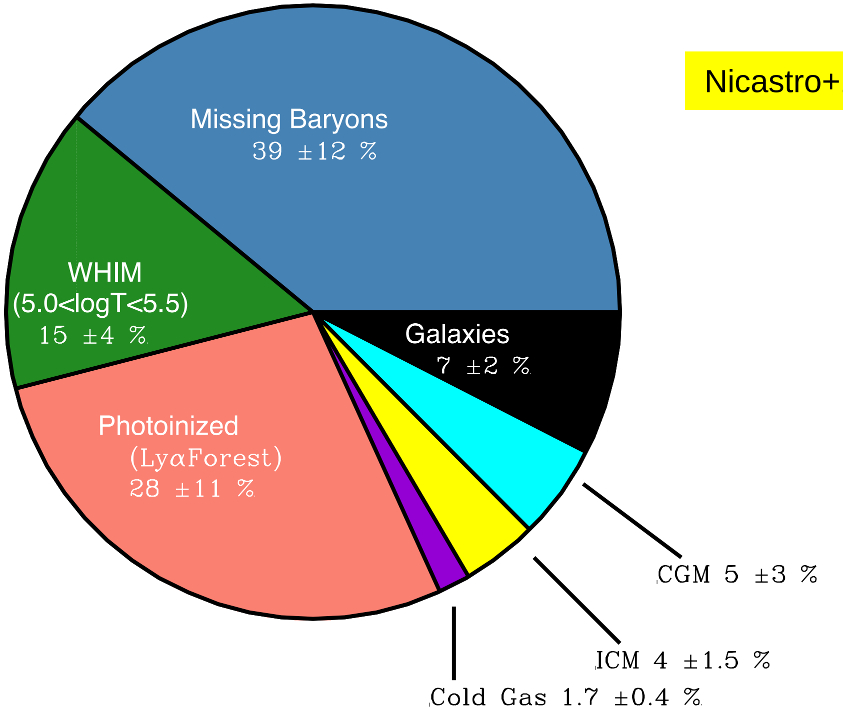
Where have all the baryons gone?



The Missing Baryons Problems

The Universe

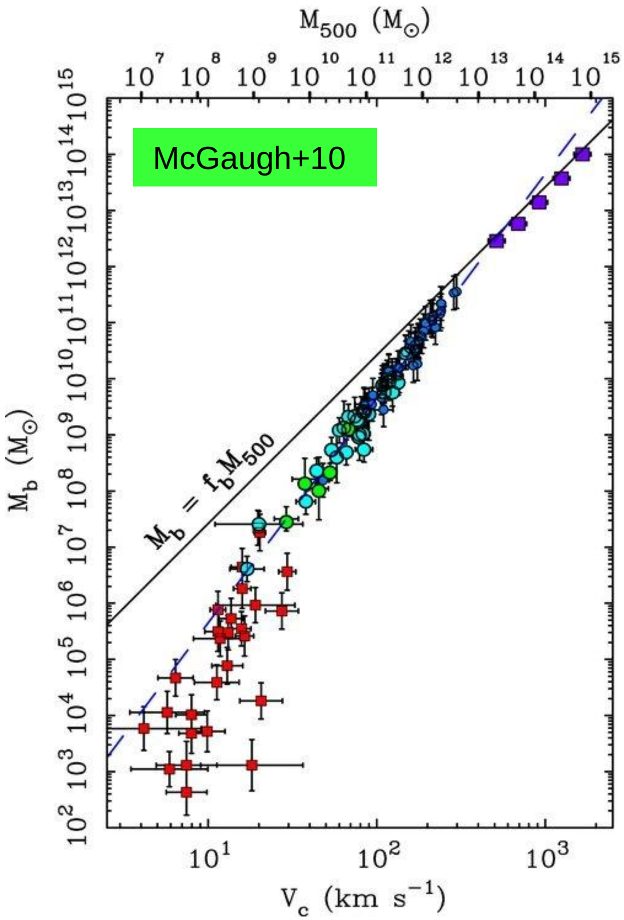
$\Omega_b^{Planck+15} = 0.0487 \sim 5\%$



Nicastro+16

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

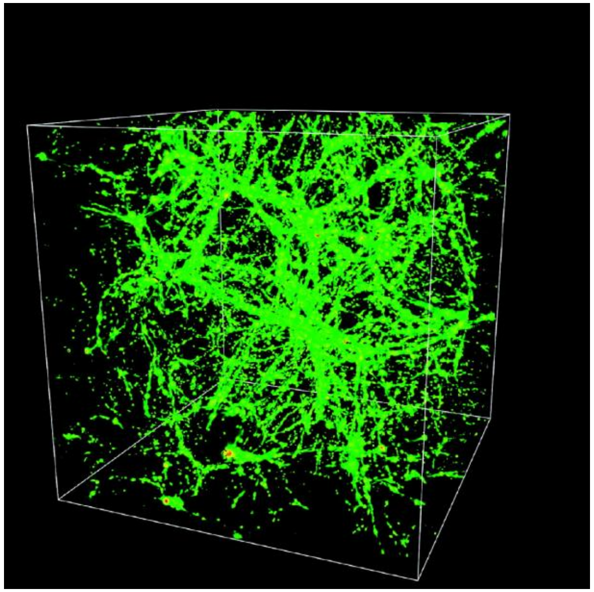
The Galaxies



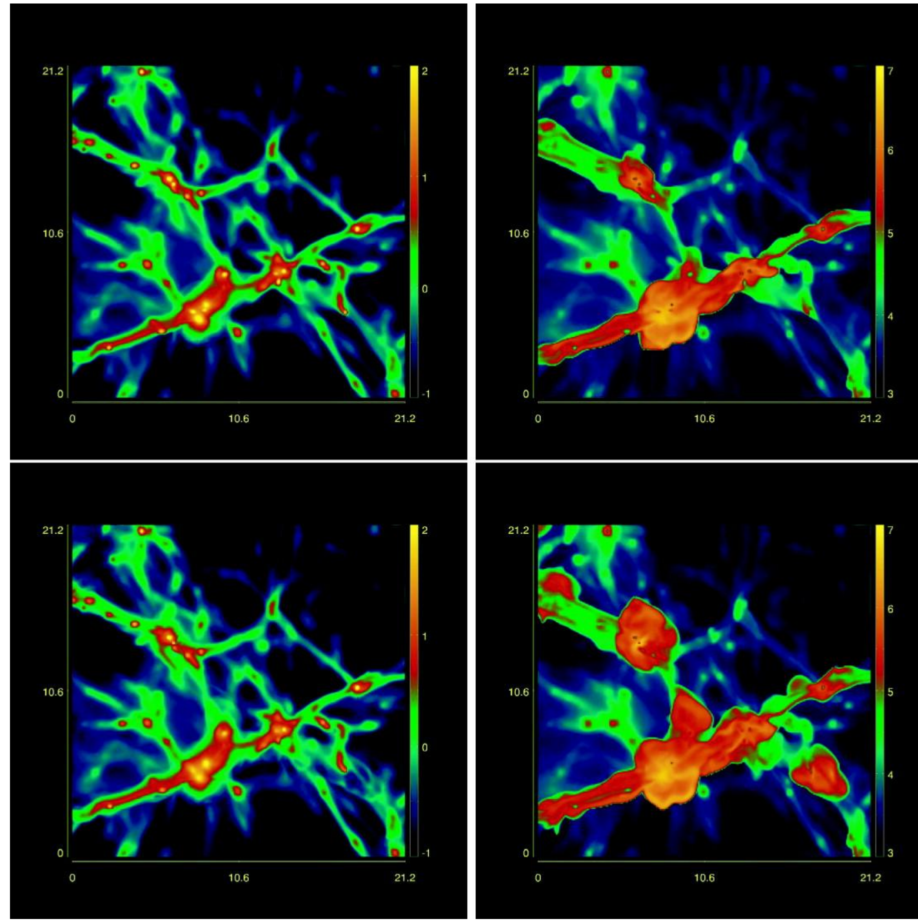
$\Omega_m^{planck+15} = 0.3156 \rightarrow f_b = 0.154$

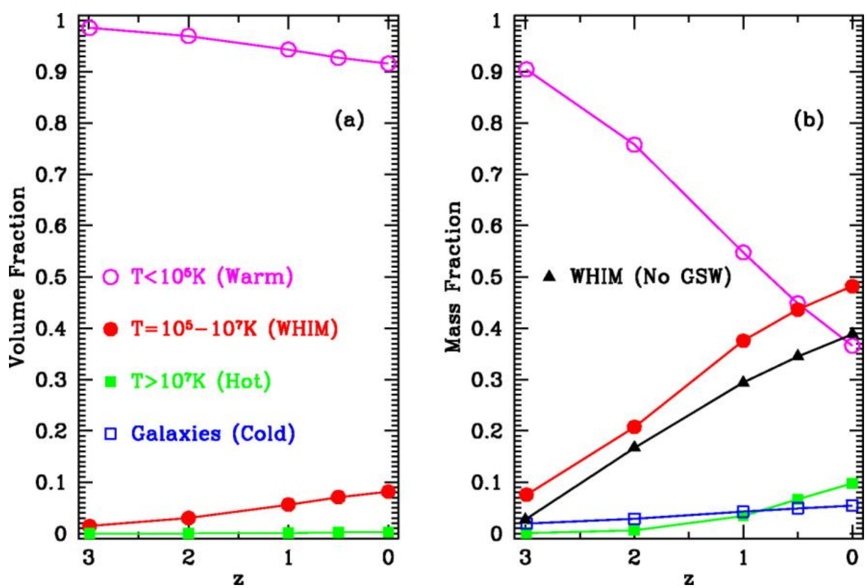
The Baryons in HD Simulations

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



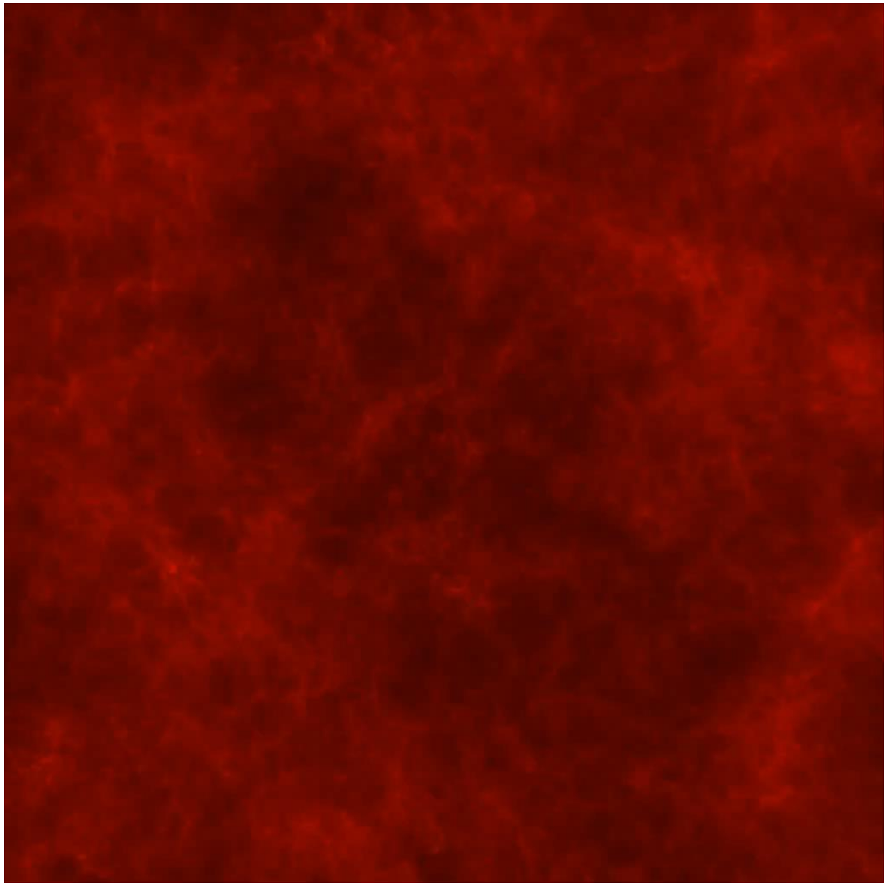
(21.2 x 21.2 x 1.75)h^{-1} Mpc
Without (top) and with (bottom) GSWs
Overdensity (left) Temperature (Right)

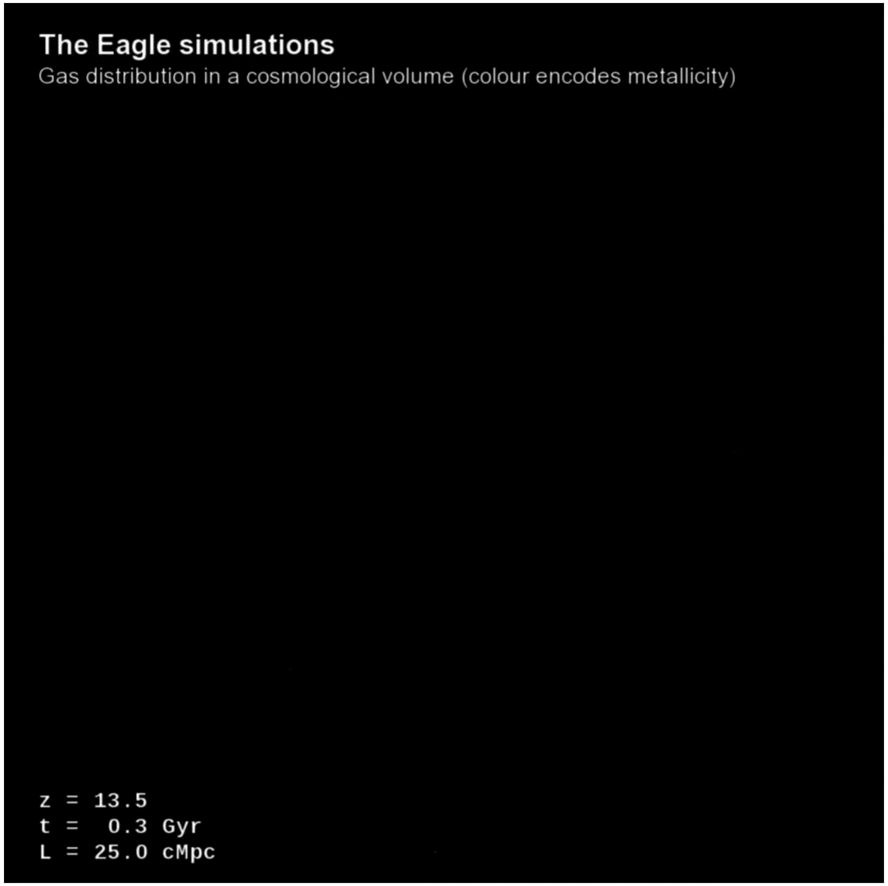




Cen & Ostriker, 2006

EAGLE T and Z evolution

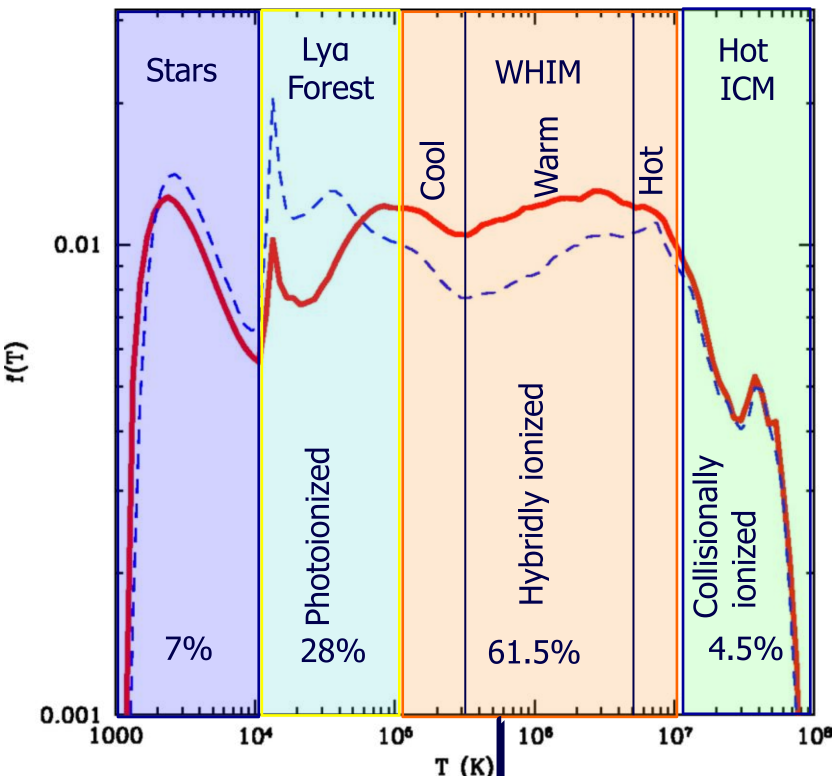




Schaye et al. (2015)

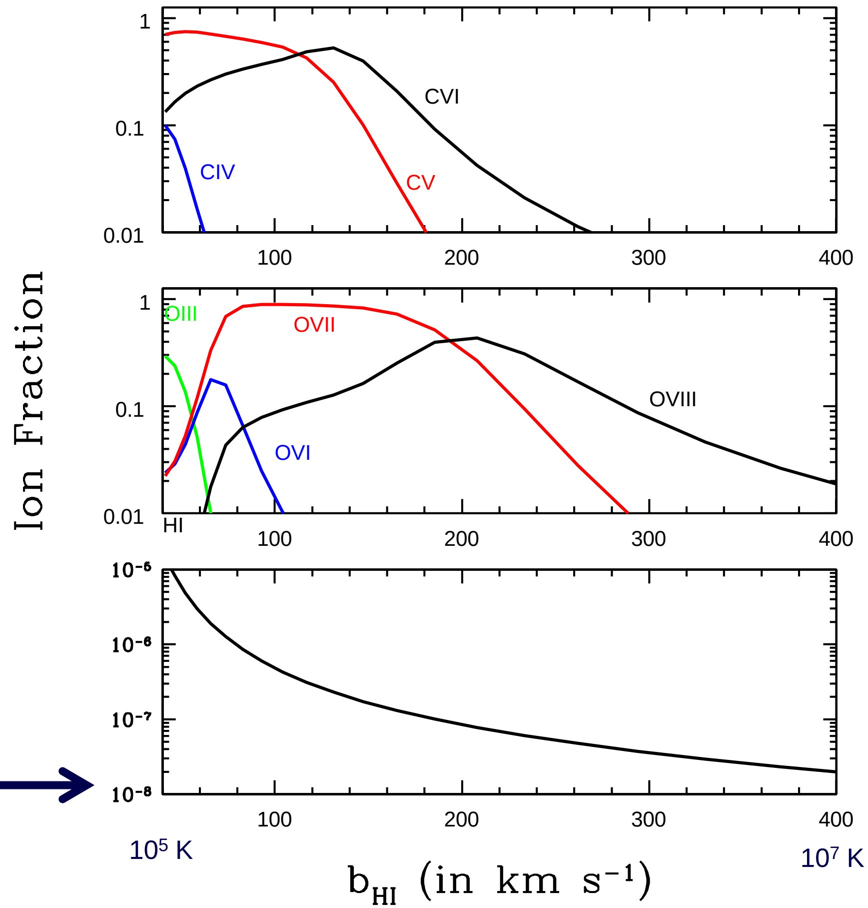
The Baryon Phases in HDS

Differential Mass Fraction vs T



Cen & Ostriker 06

Hybridly Ionized Gas (δ=50)



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

The Observables

Emission Measure (EM):

→ Product n_b^2R

Absorption Line Equivalent Widths:

→ Ion Column Densities: $N_{ion} \sim n_bR$

Equivalent Width Ratios:

→ Ionization Balance: T, n_b

The Milky Way's Baryon Problem

- $(M_b)^{Obs} = 6.5\times10^{10}\ M_\odot$ (McMillian & Binney, 2012)
- $M_{DM} = (1\text{-}2)\times10^{12}\ M_\odot$ (Boylan-Kolchin+12)
- $f_b = 0.157$ (The Plank Collaboration, 2015)

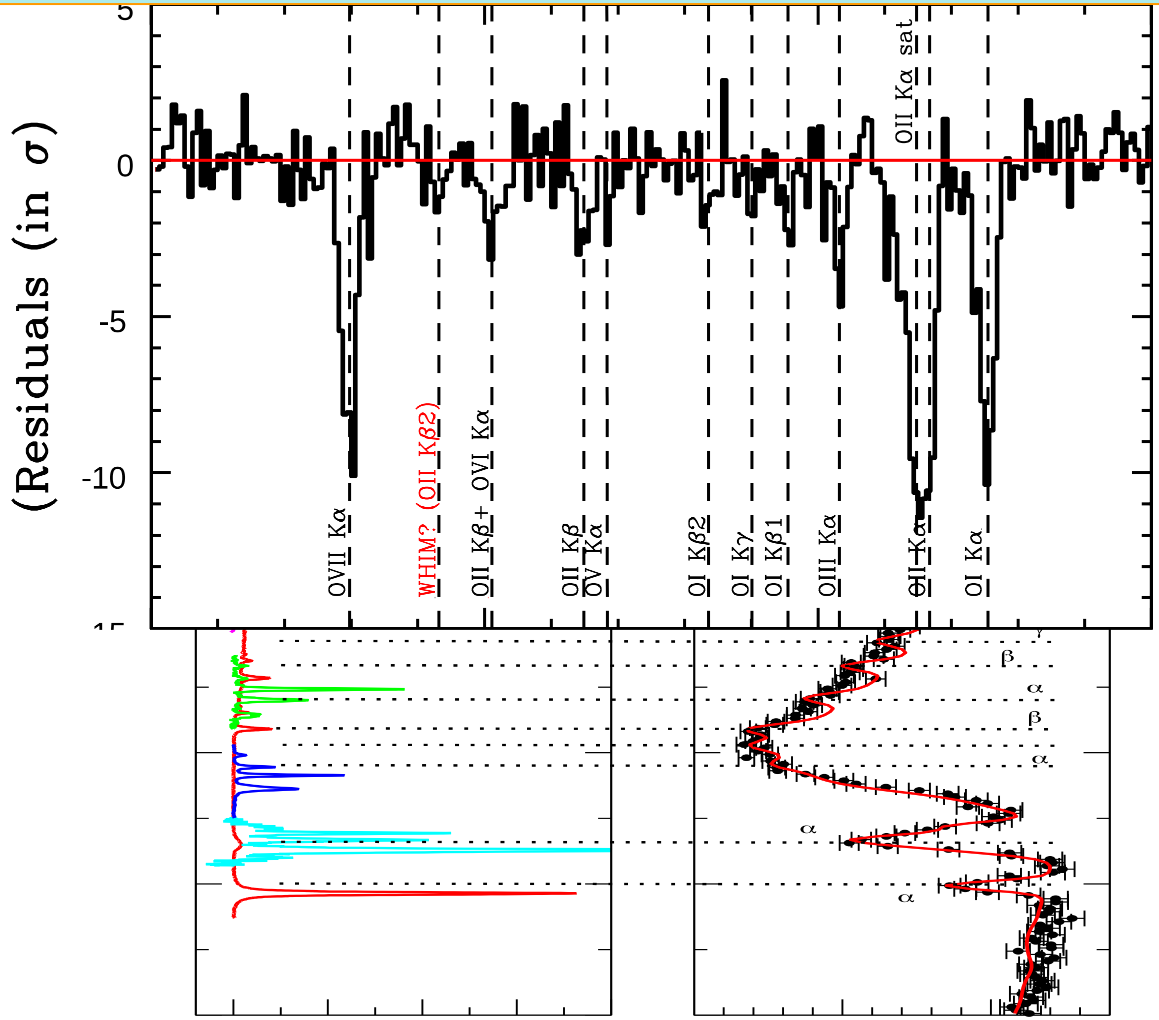
➔ $M_b/(M_b)^{Obs} \approx 2.5\text{-}5$

$$M_b^{Missing} \approx (1.5\text{-}3)\times10^{11}\ M_\odot$$

All the X-Ray Colors of the Milky Way

ISM/CGM Spectrum(Real Data)

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

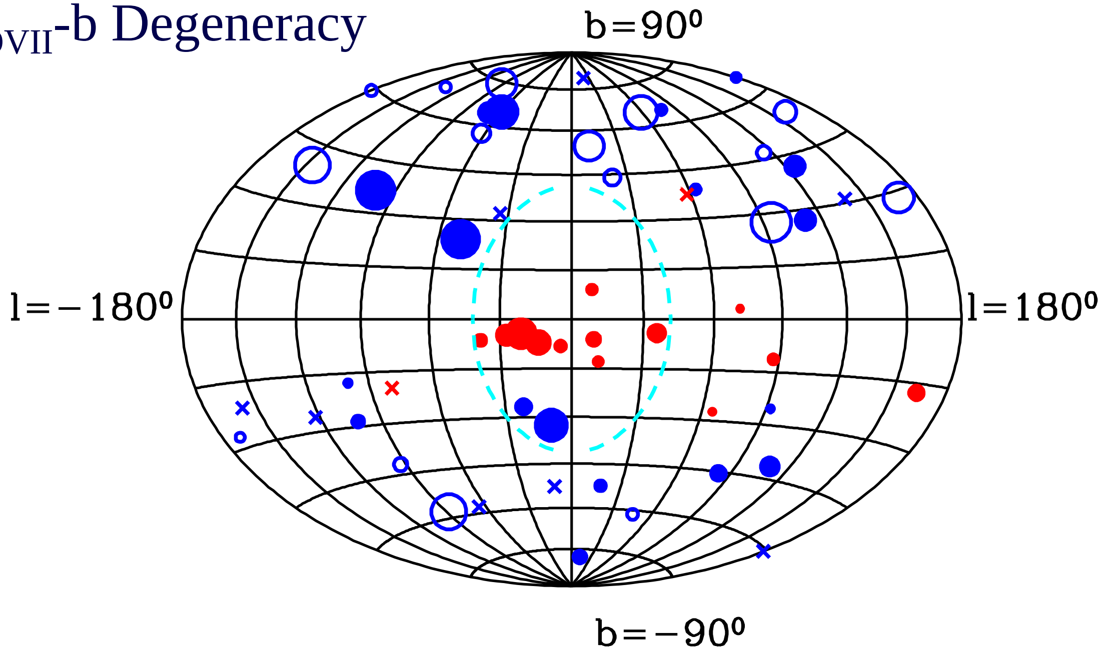


CNMM
LIMM
HIMM

The Optimal Galactic Sample

Differs from previous (e.g. Gupta+12, Miller&Bregman13):

- HGL + LGL
- Complete to SNRE>10 at 22 Å
- Remove N_{OVII}-b Degeneracy

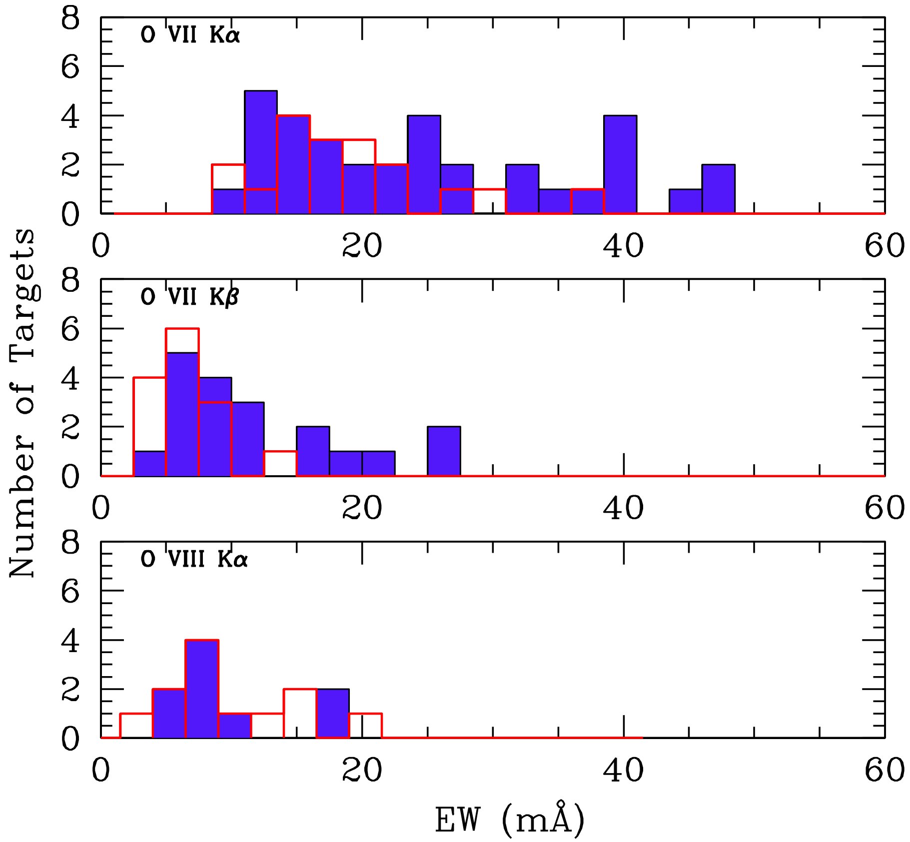


18/20 (90%) LGL have OVII, but only 14 known distance (1 contaminated)

51 HGL; 9 contaminated + 3 Instr.Feat.; 34/39 (87%) have OVII, but only 18 Kα & Kβ

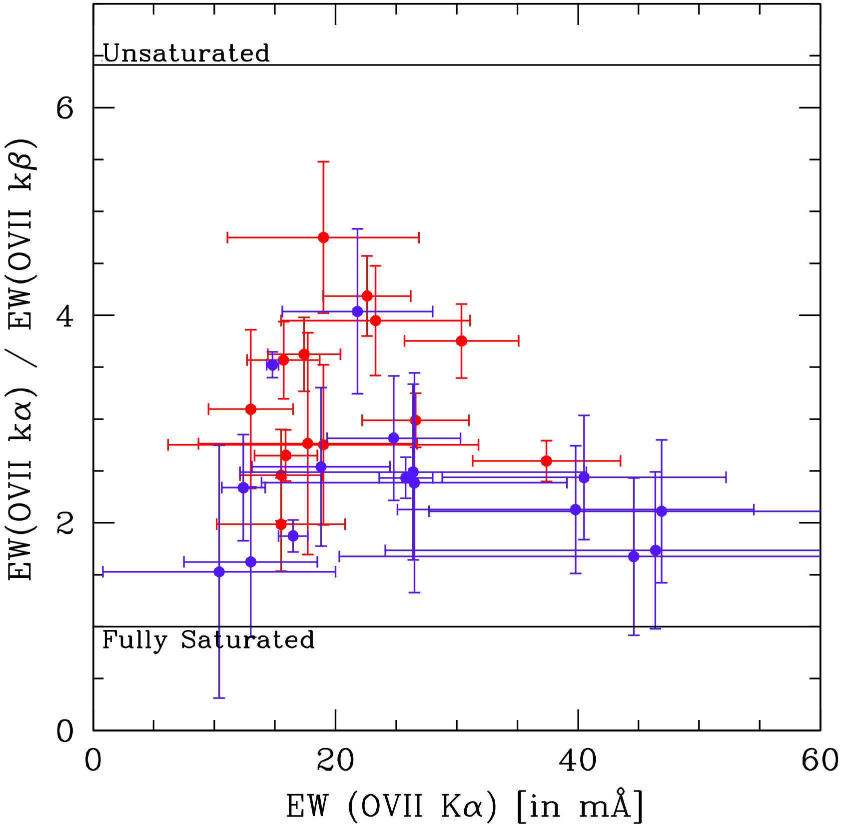
➔ 13 LGL (XRBs) + 18 HGL (AGNs) = 31 LoS

The High-Ionization Metal Medium Line Equivalent Widths



The High-Ionization Metal Medium

Line Saturation

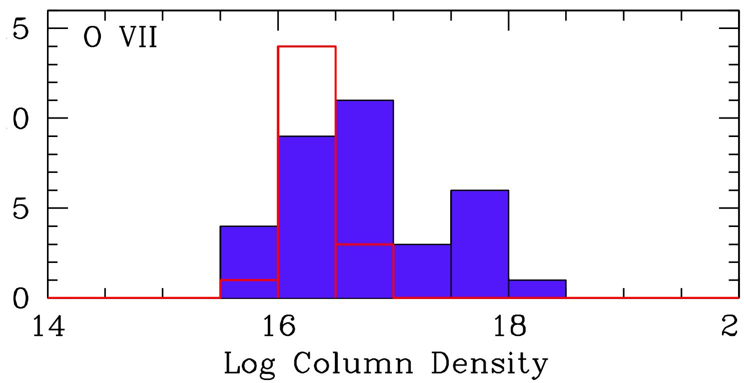


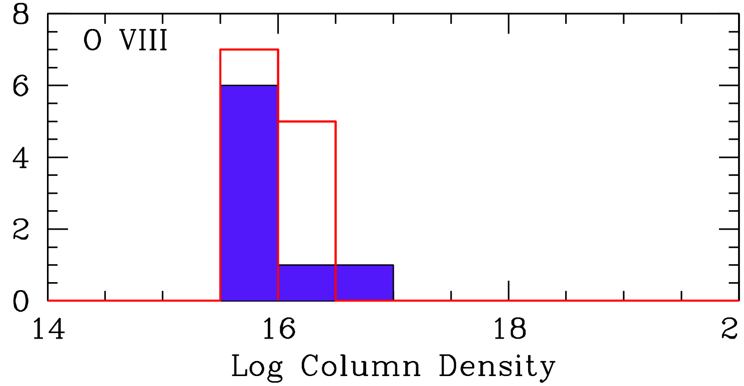
The High-Ionization Metal Medium

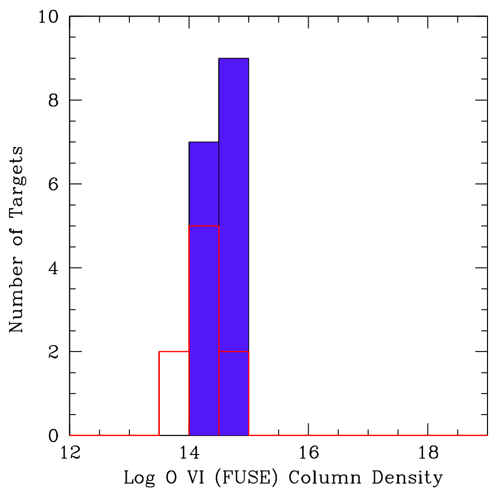
Column Density & Doppler Parameter: 2

$<N_{OVII}(LGL)> = (2.3^{+1.4}_{-1.2})\times10^{16}$ cm-2
$<b_{OVII}(LGL)> = (110^{+50}_{-40})$ km s^{-1}

$<N_{OVII}(HGL)> = (8 \pm 2)\times10^{16}$ cm-2
$<b_{OVII}(HGL)> = (100 \pm 50)$ km s^{-1}

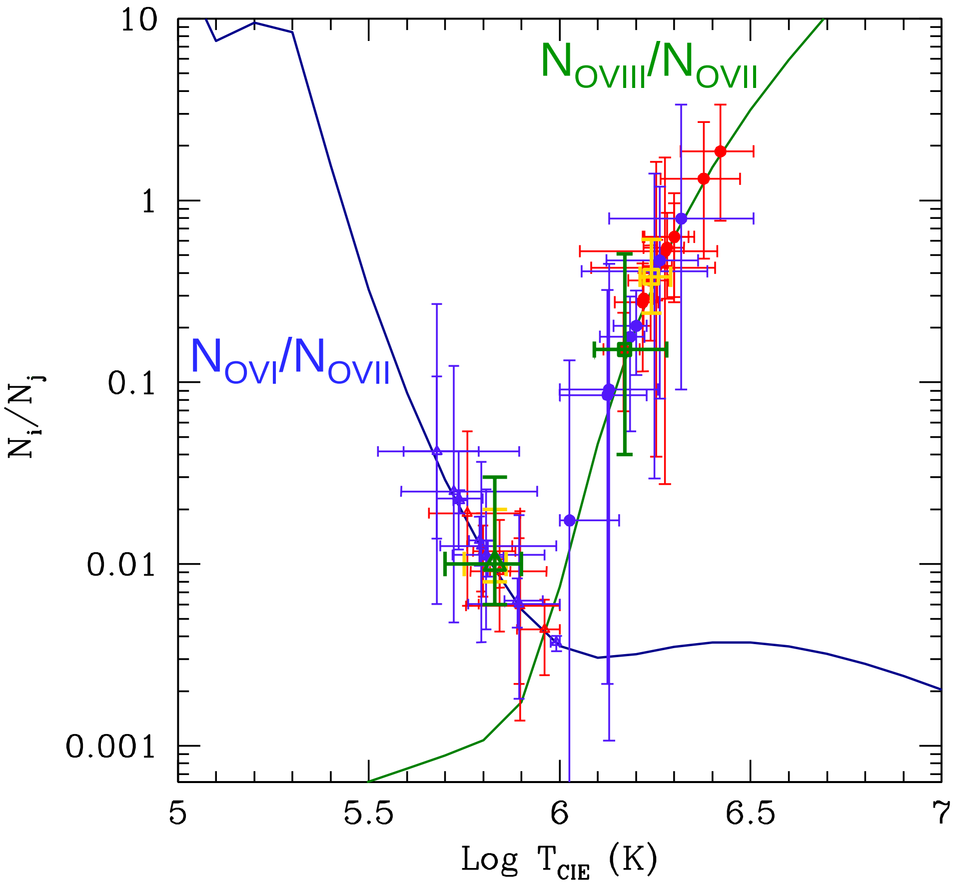


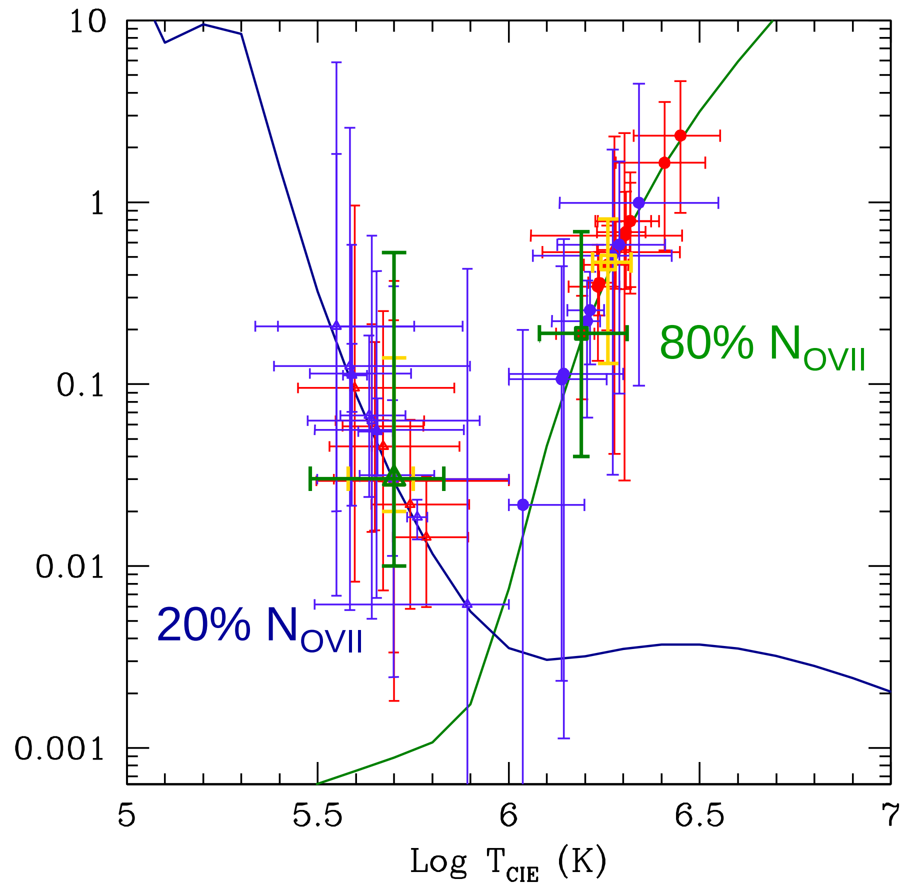




The High-Ionization Metal Medium

The Temperatures





Two Distinct Components both in the Disk and the Halo

1. Warm (OVI-traced): $T \sim 4 \times 10^5$ K
2. Hot (OVII,OVIII-traced): $T \sim 2 \times 10^6$ K (MW Virial Temperature)

The High-Ionization Metal Medium

N_{OVII}-(l,b) Fits: Density and Location

$\xi(R)$ = LoS coordinate, with $R^2 = \xi^2 + R_\odot^2 - 2\xi R_\odot \cos(b)\cos(l)$

$$n(R) = n_0 e^{-|R - R_s|/R_c};$$ (Exponential Sphere)

$$n(R) = n_0 e^{-\sqrt{(\rho/\rho_c)^2 + (z - h_s)/h_c)^2}};$$ (Exponential Disk)

$$n(R) = n_0 [1 + (R - R_s)^2/R_c^2]^{-3\beta/2};$$ (β-Sphere)

$$n(R) = n_0 [1 + \rho^2/\rho_c^2 + (z - h_s)^2/h_c^2]^{-3\beta/2}.$$ (β-Cylinder)

R_s and h_s = Offset Radius and Height

Separate LGL & HGL N_{OVII}-(l,b) Fits

Model Name	Model Type	n_0 (10^{-2} cm $^{-3}$)	R_c or ρ_c (kpc)	h_c (kpc)	R_s (kpc)	Halo Size (kpc)	Mass (10^9 $M_\odot$)	chi^2 (dof)
HGL	Exp-SS	$4.9^{+1.1}_{-0.4}$	$3.1^{+0.3}_{-0.2}$	N/A	$5.4^{+0.6}_{-0.4}$	> 46	$3.3^{+4.1}_{-1.4}$	10.9 (15)
LGL	Exp-CS	52^{+5}_{-15}	$2.4^{+0.3}_{-0.1}$	$0.16^{+0.04}_{0.03}$	N/A	N/A	$0.14^{+0.11}_{-0.06}$	12.8 (10)

LGL: χ^2_{flat}(dof) = 12.8(10) vs χ^2_{Sph}(dof) = 22.5(11)

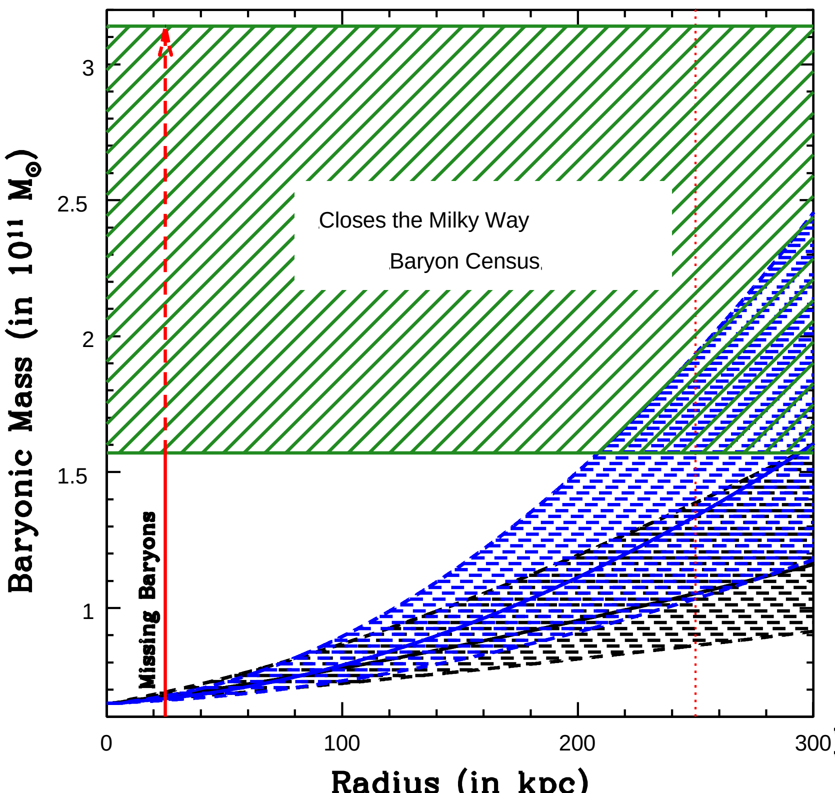
LGL to HLG: χ^2(dof) = 373(18) !!!

HGL to LGL: χ^2(dof) = 147(13) !!!

- LGLs trace the Galaxy's Disk: M_{OVII}(Disk)≈1.4×10^8 $M_\odot$
    - 2 distinct components or compromising solution

Combined LGL+HGL N_{OVII}-(l,b) Fits

Model Name	Model Type	n_0 (10^{-2} cm $^{-3}$)	R_c (kpc)	β	R_s (kpc)	Halo Size (kpc)	Mass (10^{11} $M_\odot$)	chi^2 (dof)
A	β-SS	$2.5^{+0.3}_{-0.3}$	$2.3^{+0.2}_{-0.2}$	$0.55^{+0.03}_{-0.03}$	$3.6^{+0.6}_{-0.6}$	> 110	$0.4^{+0.3}_{-0.2}$	62.9 (43)
B	LGL + β-SS	$1.4^{+0.2}_{-0.2}$	$1.0^{+0.2}_{-0.1}$	$0.38^{+0.02}_{-0.02}$	$6.4^{+0.2}_{-0.8}$	> 170	$0.7^{+0.2}_{-0.3}$	42.6 (43)
A1	β-SS	$8.2^{+0.9}_{-0.9}$	$1.6^{+0.4}_{-0.4}$	0.55 (frozen)	0 (frozen)	> 130	$0.7^{+0.4}_{-0.3}$	78 (45)
B1	LGL + β-SS	$4.5^{+0.5}_{-0.5}$	$1.2^{+0.4}_{-0.4}$	0.38 (frozen)	0 (frozen)	> 210	$2.5^{+1.4}_{-1.1}$	76 (45)



Sizes:
R(A)>110 kpc
R(B)>170 kpc

Masses at R_{vir}:
$M(A)=(1.0^{+0.3}_{-0.2})\times10^{11}\ M_\odot$
$M(B)=(1.3^{+0.6}_{-0.3})\times10^{11}\ M_\odot$

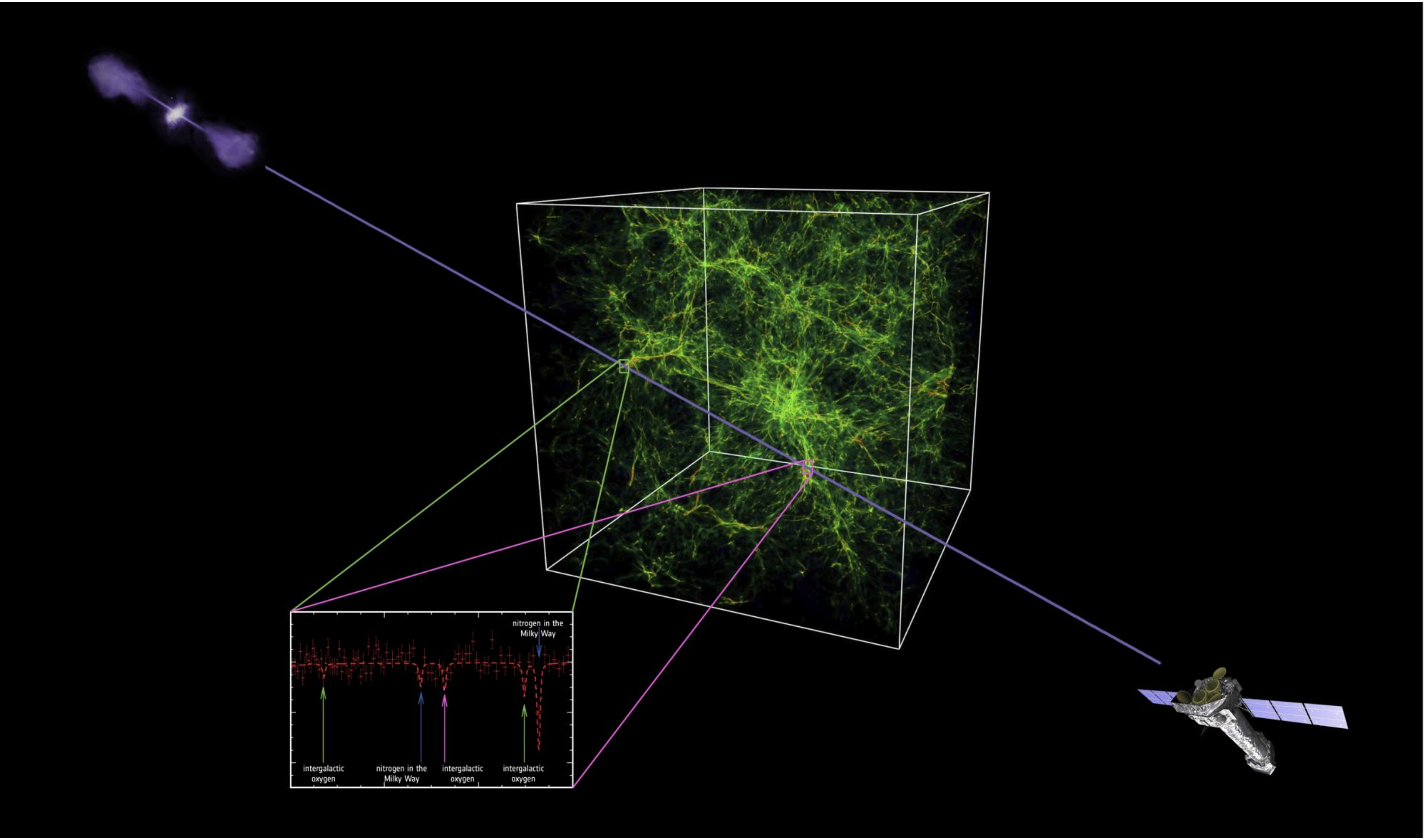
Actual Solution probably in between

The High-Ionization Metal Medium

Summary

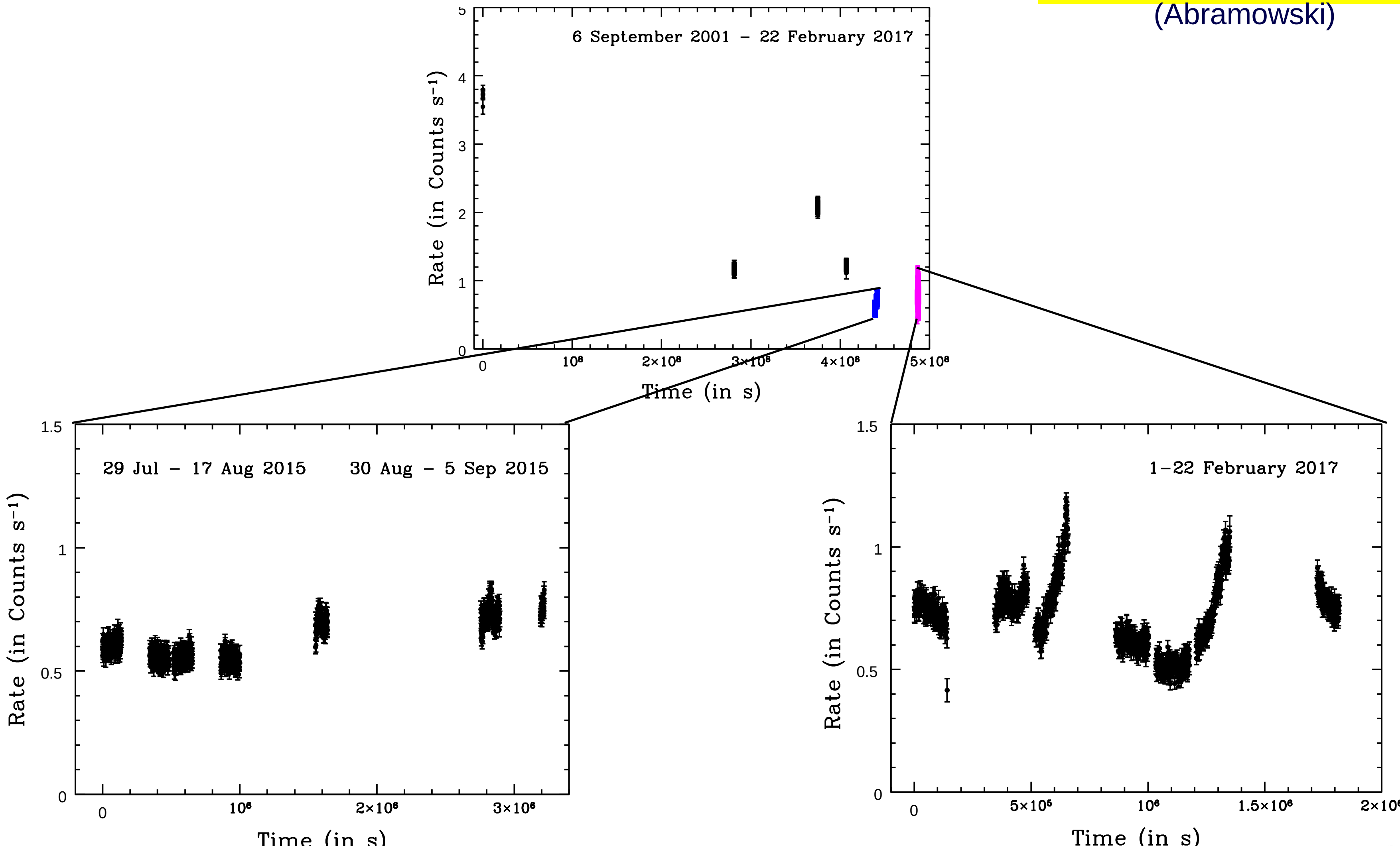
- Million-degree Gas permeates both the Disk and Halo of our Galaxy
- A spherically symmetric structure in the density profile of the million-degree halo gas tracks the current position of a shock-front generated 6 Million years ago by an energetic outflow powered by an AGN-like accretion episode
- The Mass of the OVII-bearing Gas may be sufficient to close the Galaxy's Baryon Census

The Missing Baryons in the WHIM



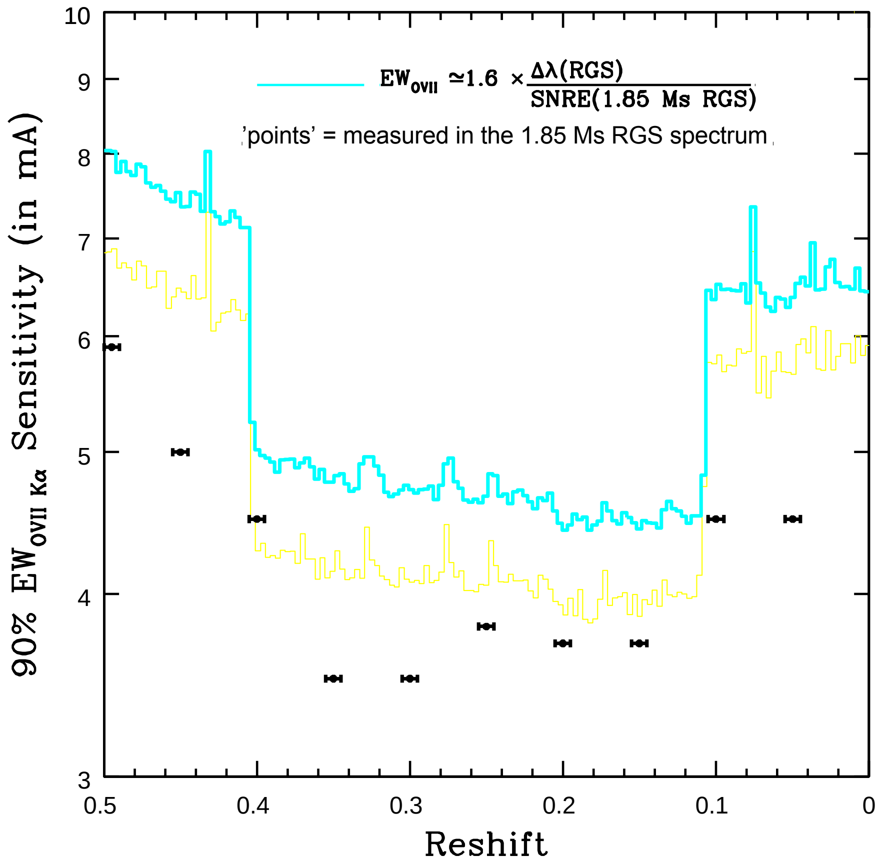
The XMM-Newton VLP on 1ES 1553+113

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

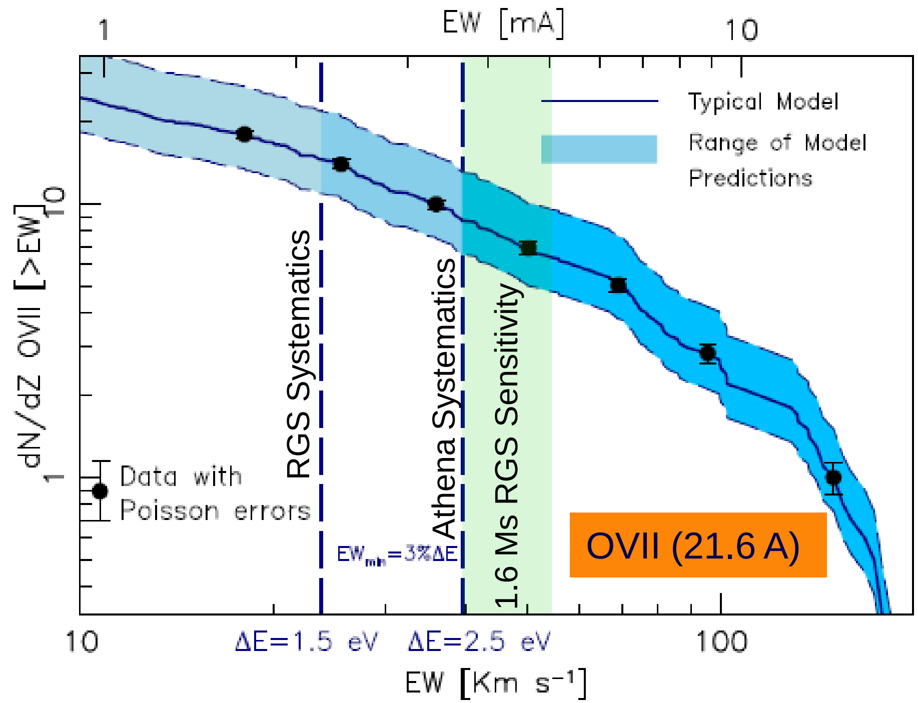


The Warm-Hot (OVII) IGM
XMM-Newton RGS Spectrum of 1ES 1553+113

RGS Spectra of 1ES 1553+113

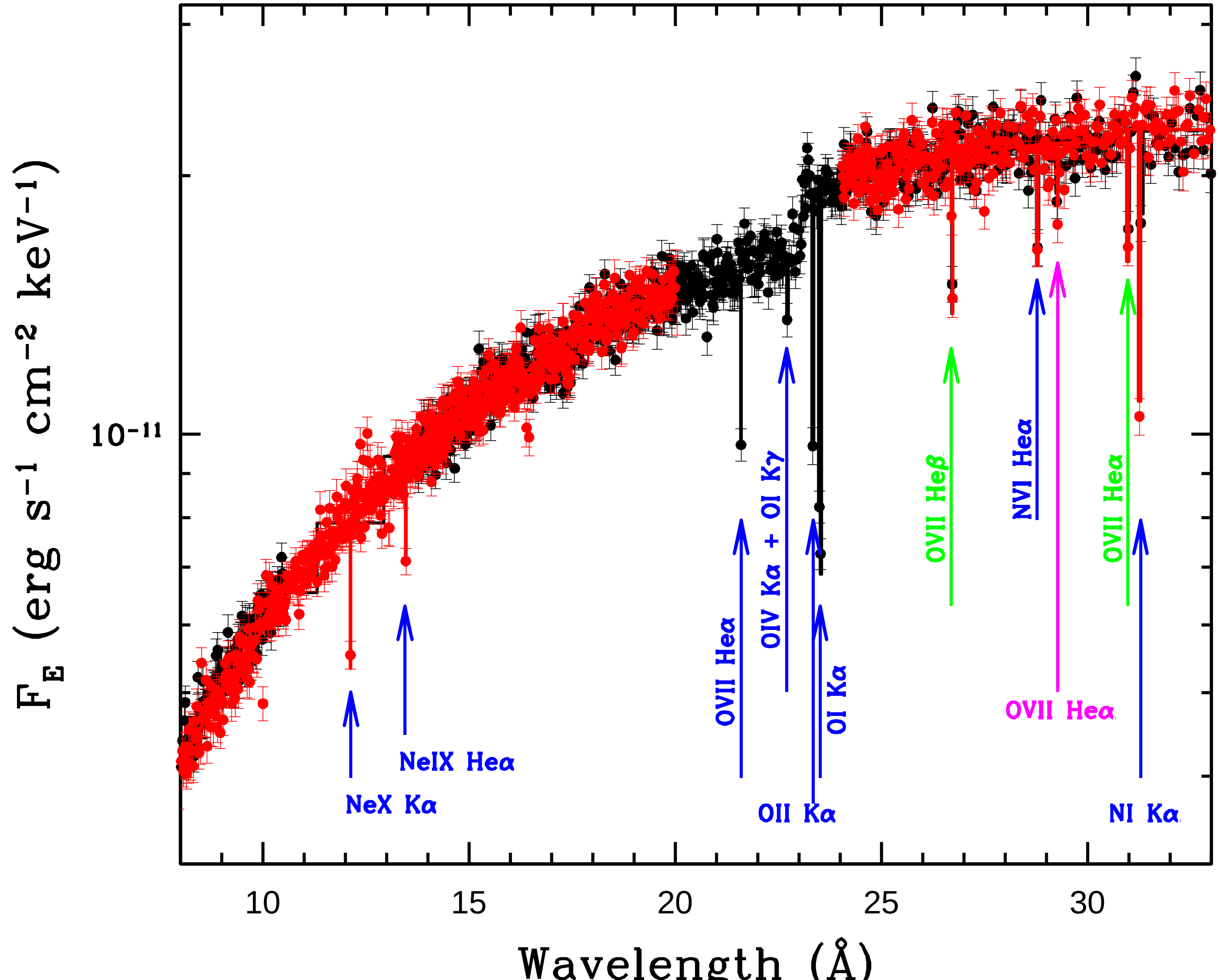


Athena WHIM White Paper (Kaastra+13)

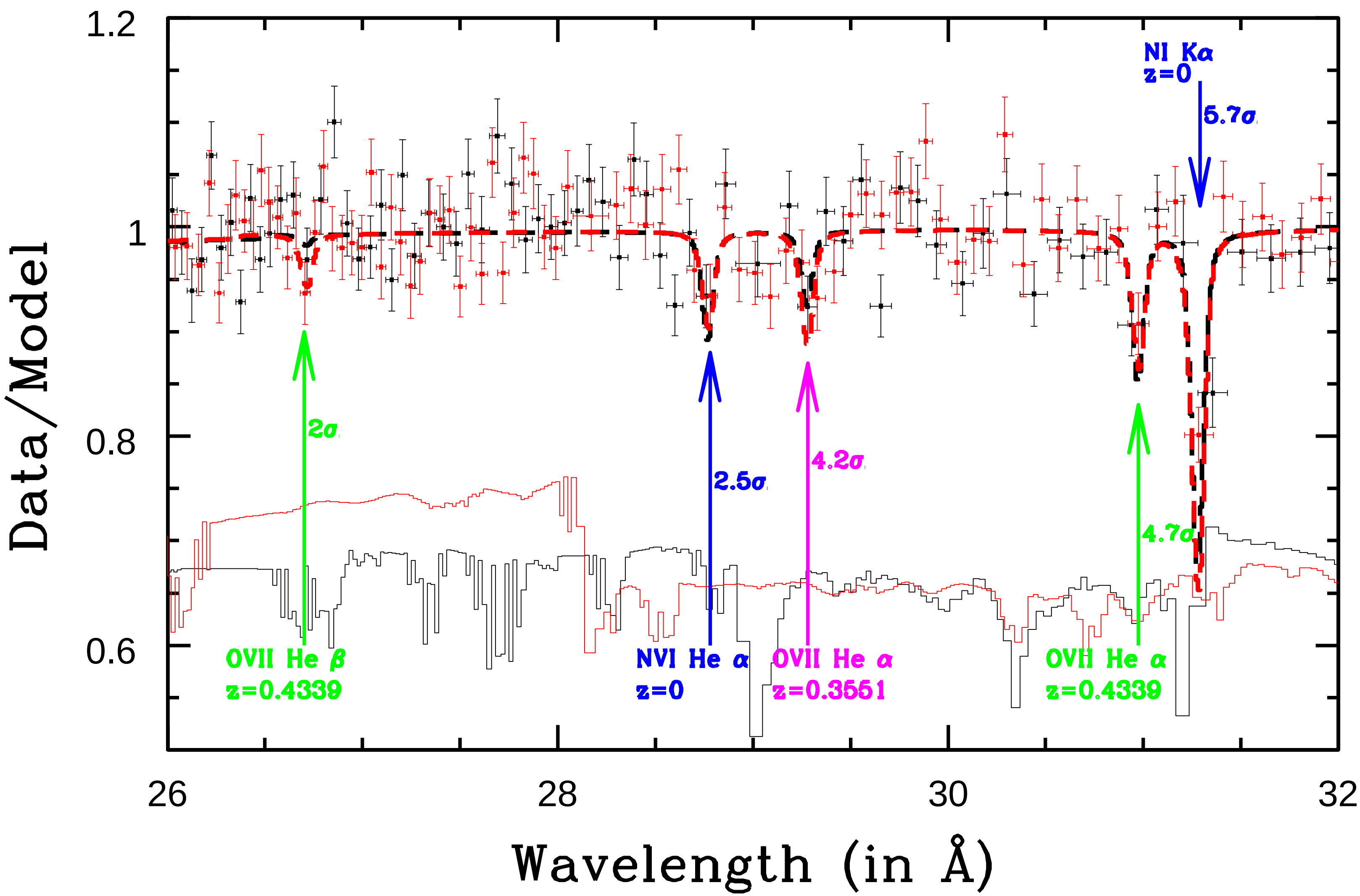


1.85 Ms RGS: EW>4-5 mA @ >90%
i.e. ~600 cts per R.E.

Broad-band RGS Spectra of 1ES 1553+113

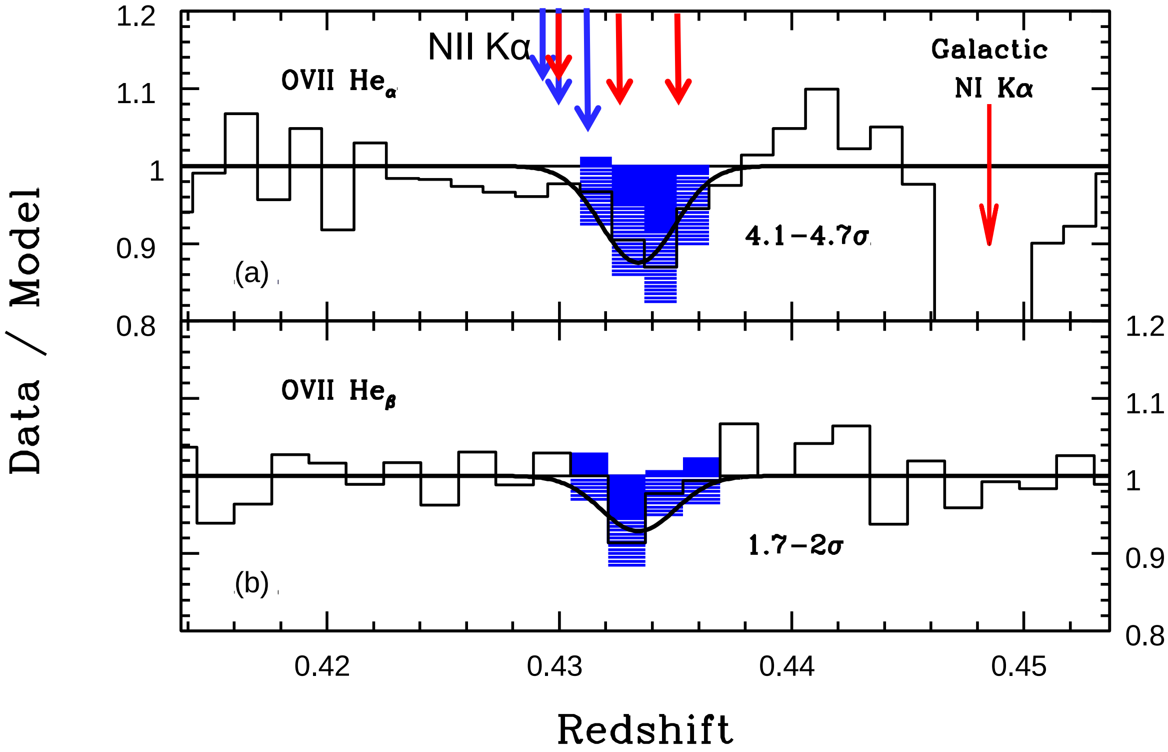


26-32 Å RGS Spectra



z = 0.4339 System

z_X=0.4339±0.0008



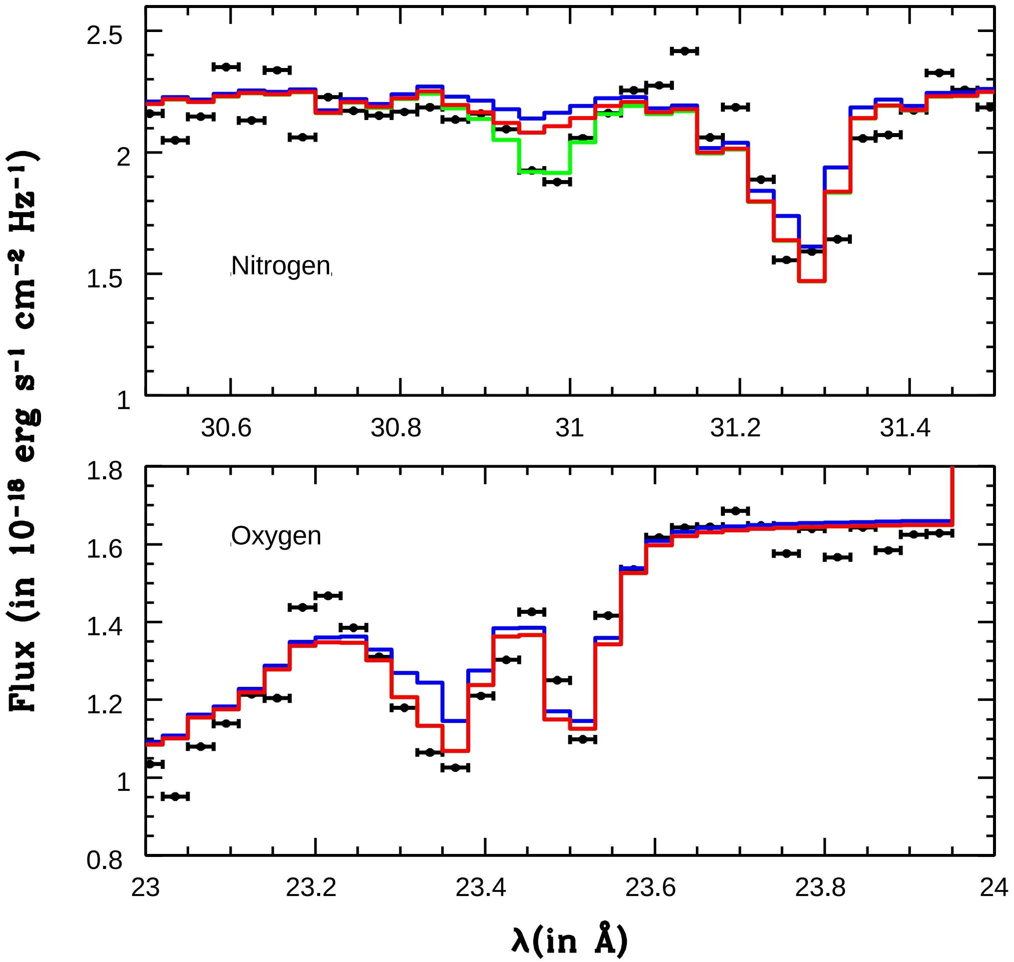
Statistical Significance

(after accounting for OVII blind redshift search and RGS eff.-area-induced systematics):

3.9-4.5σ

Contamination by ISM NII

2.7-3.1σ



CNMM

N_H(Neutral)=3.7x10^{20} cm^{-2}:

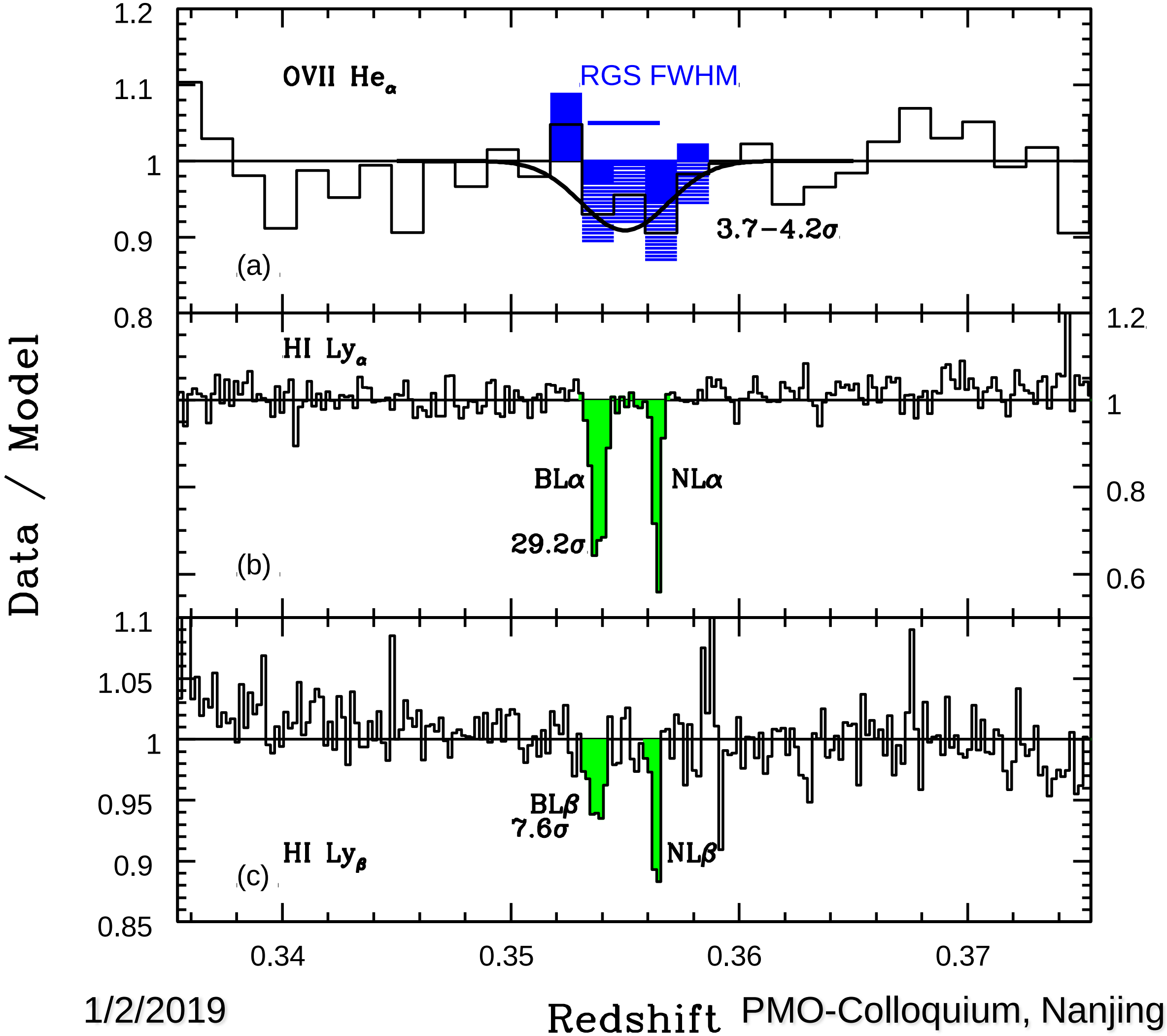
Fits well the curvature of the continuum, all OI Kα and most of the NI Kα
(and agrees with 21 cm meas.)

LIMM

N_H(T~5000 K)=1.2x10^{20} cm^{-2}
$Z/Z_\odot$=0.46

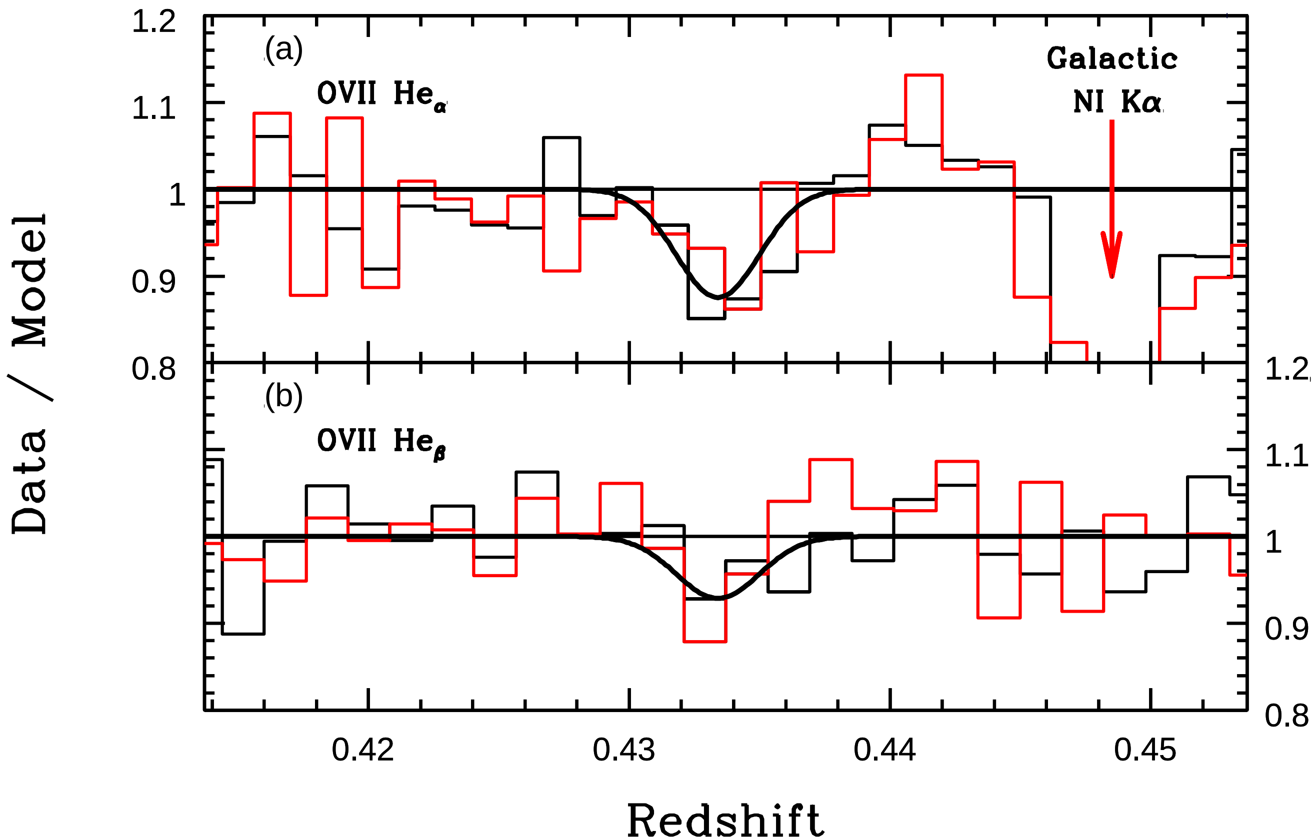
z=0.3551 System

z_X=0.35559±0.00016



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

IGM vs Intrinsic Absorption for System-1

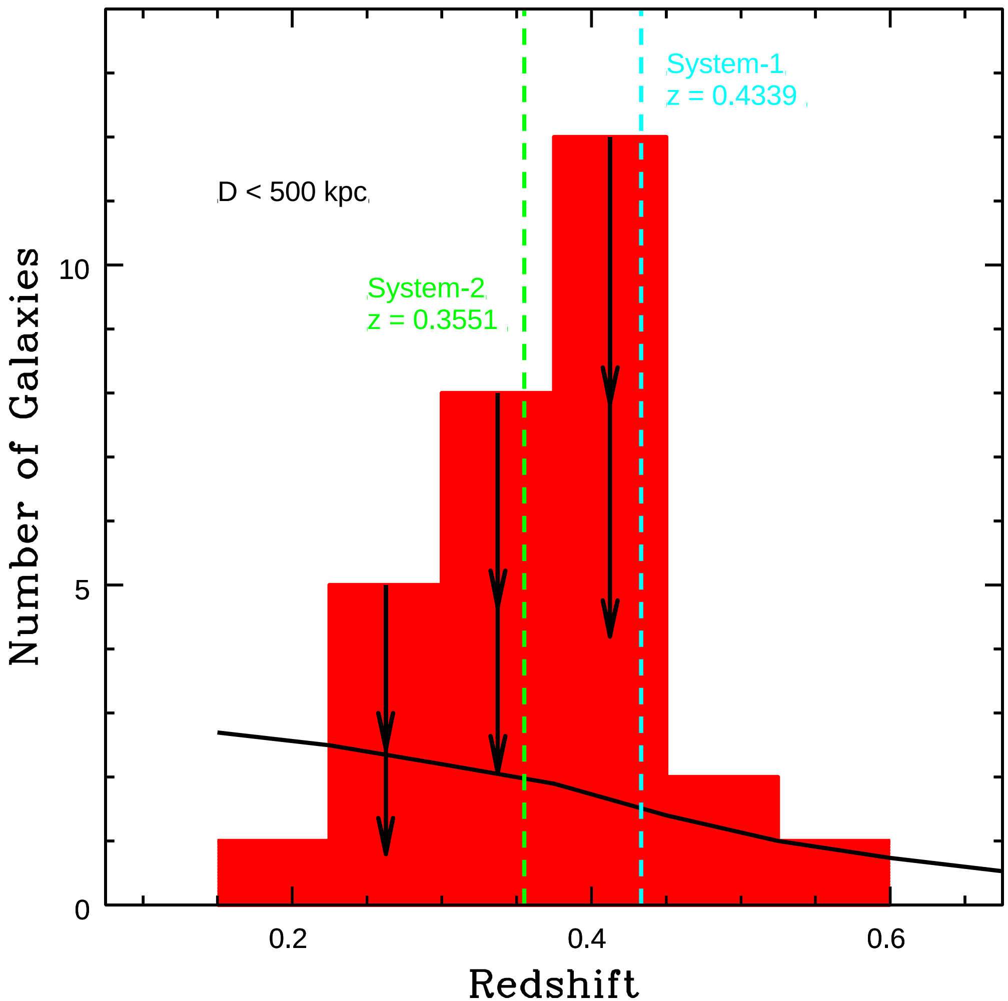


Diagnostics

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
1	1.0,-0.4,+0.9	3.6+/-1.5	0.7+/-0.3	>0.02

z=0.2-0.6 Galaxy Distribution

(in cylindrical volumes: $\pi(0.5\ \text{Mpc})^2$ x (Δz=0.07))



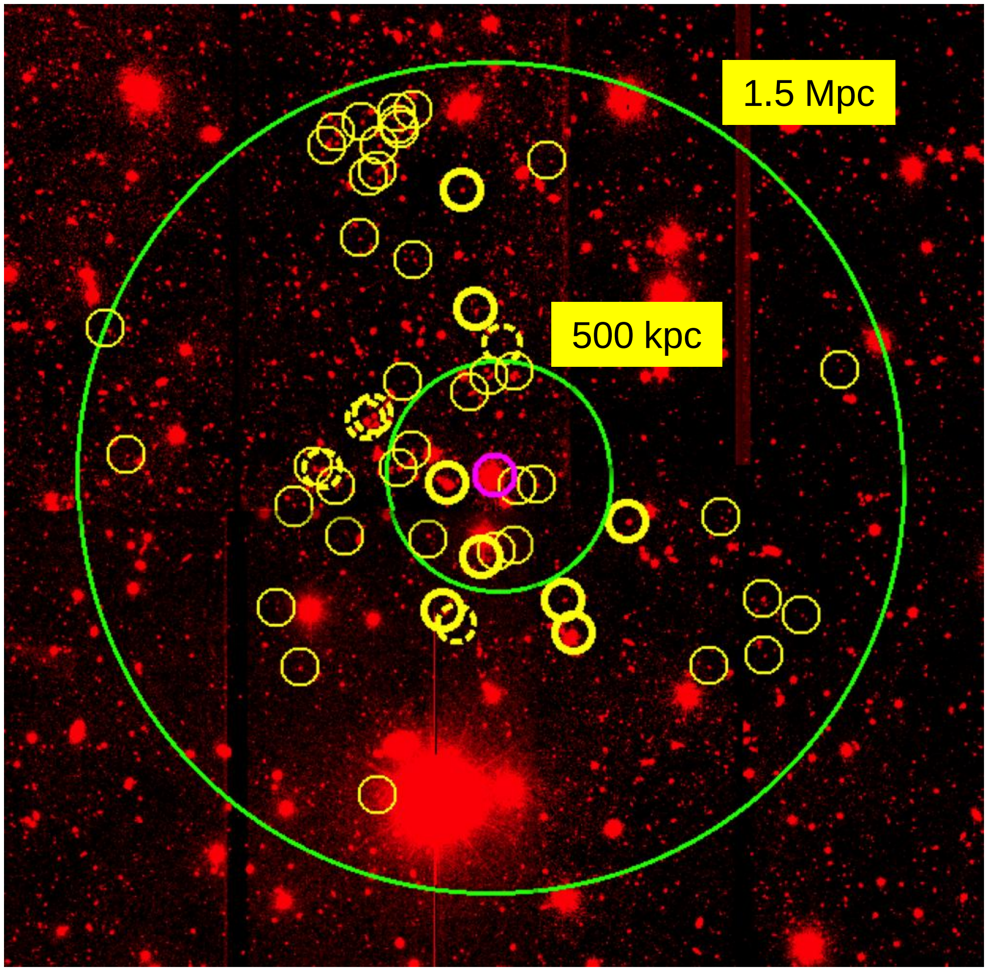
Galaxies photo-z redshifts obtained via deep (r'>24) SDSS-band imaging with the OSIIS camera at GTC

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}

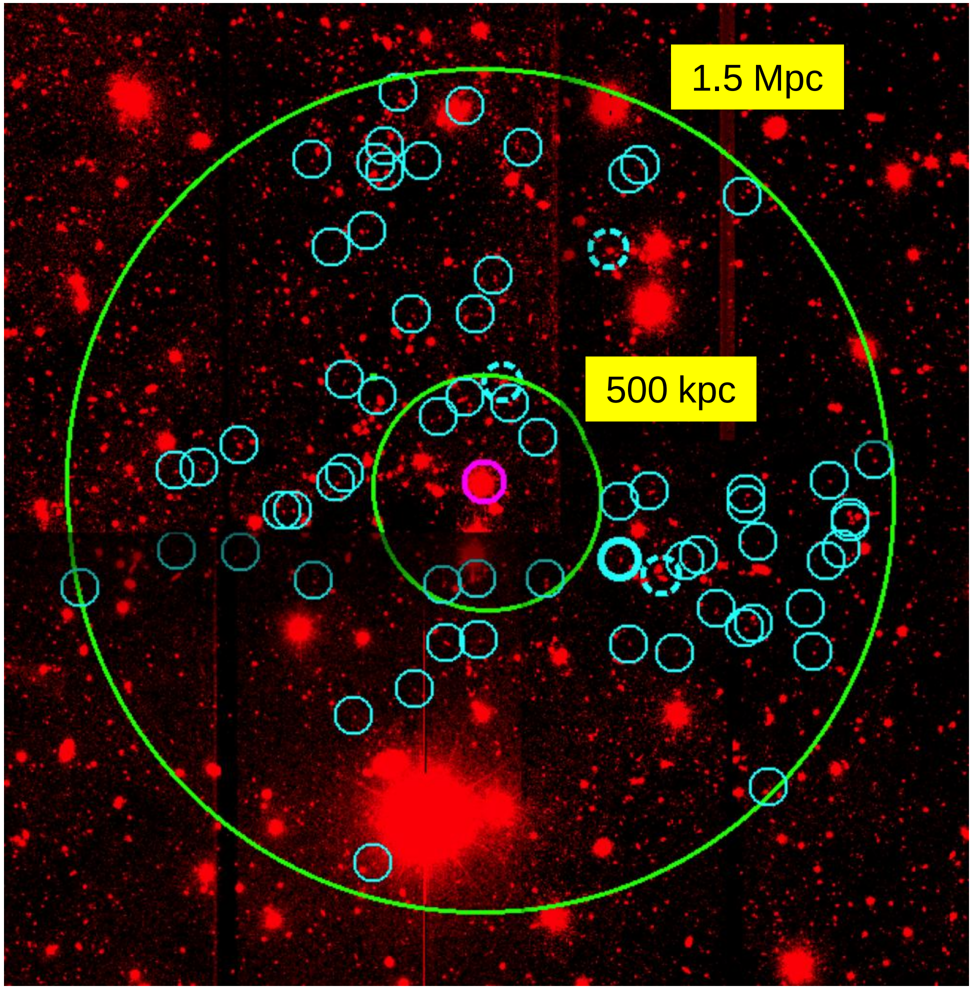
Nearest galaxy: i'=19.6 spiral at d=129 kpc and -15 km s^{-1}
➔ Galaxy's CGM?

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)



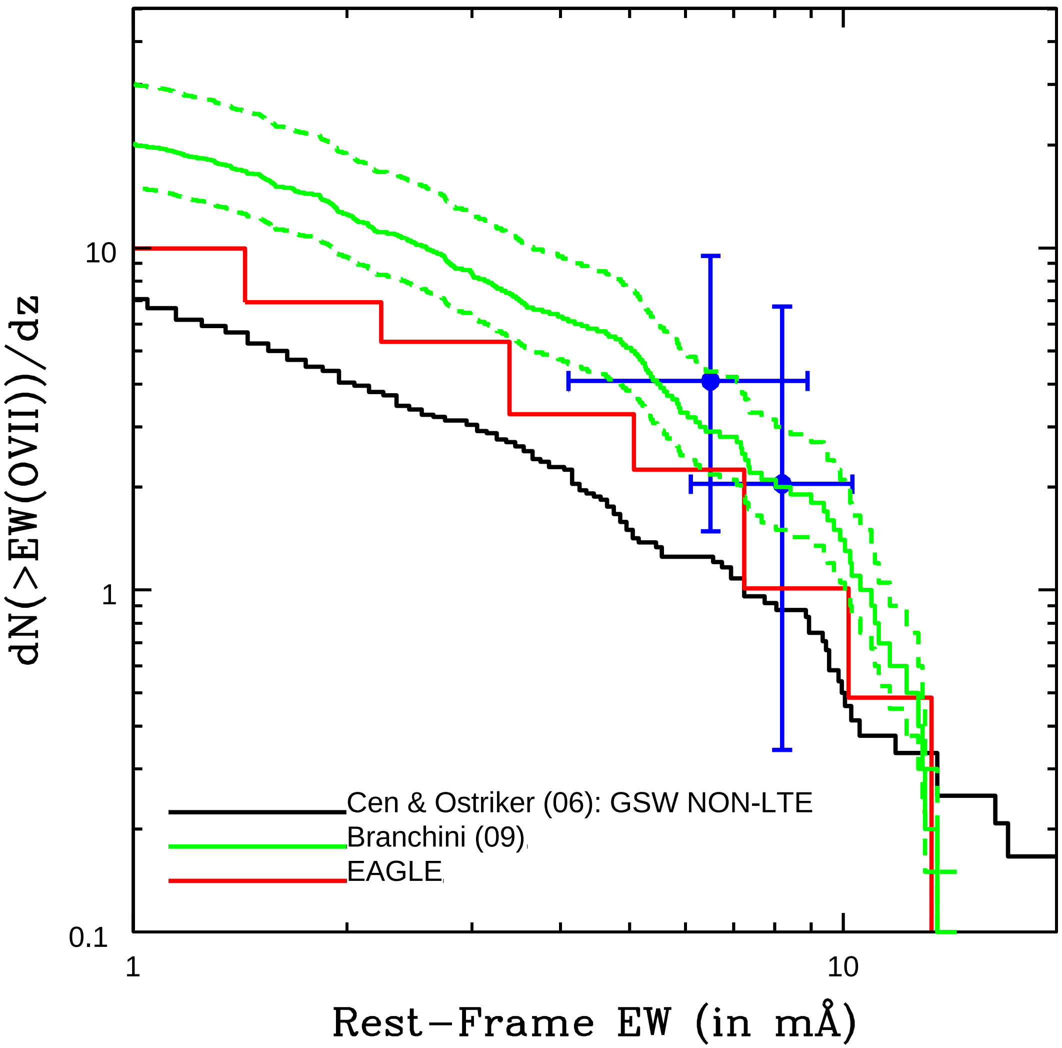
Only 4/72 galaxies within the 1.5 Mpc radius circle have spectroscopic redshifts

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

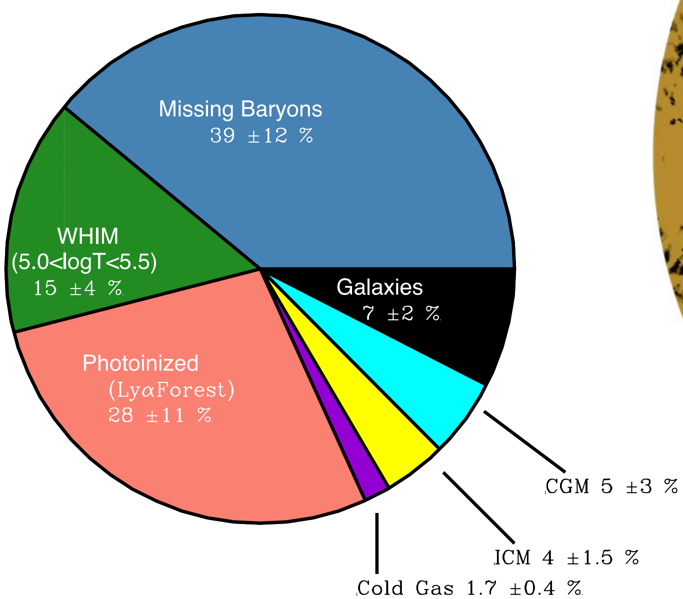
Entire inner circle still fits in Athena XIFU fov
➔ emission+absorption

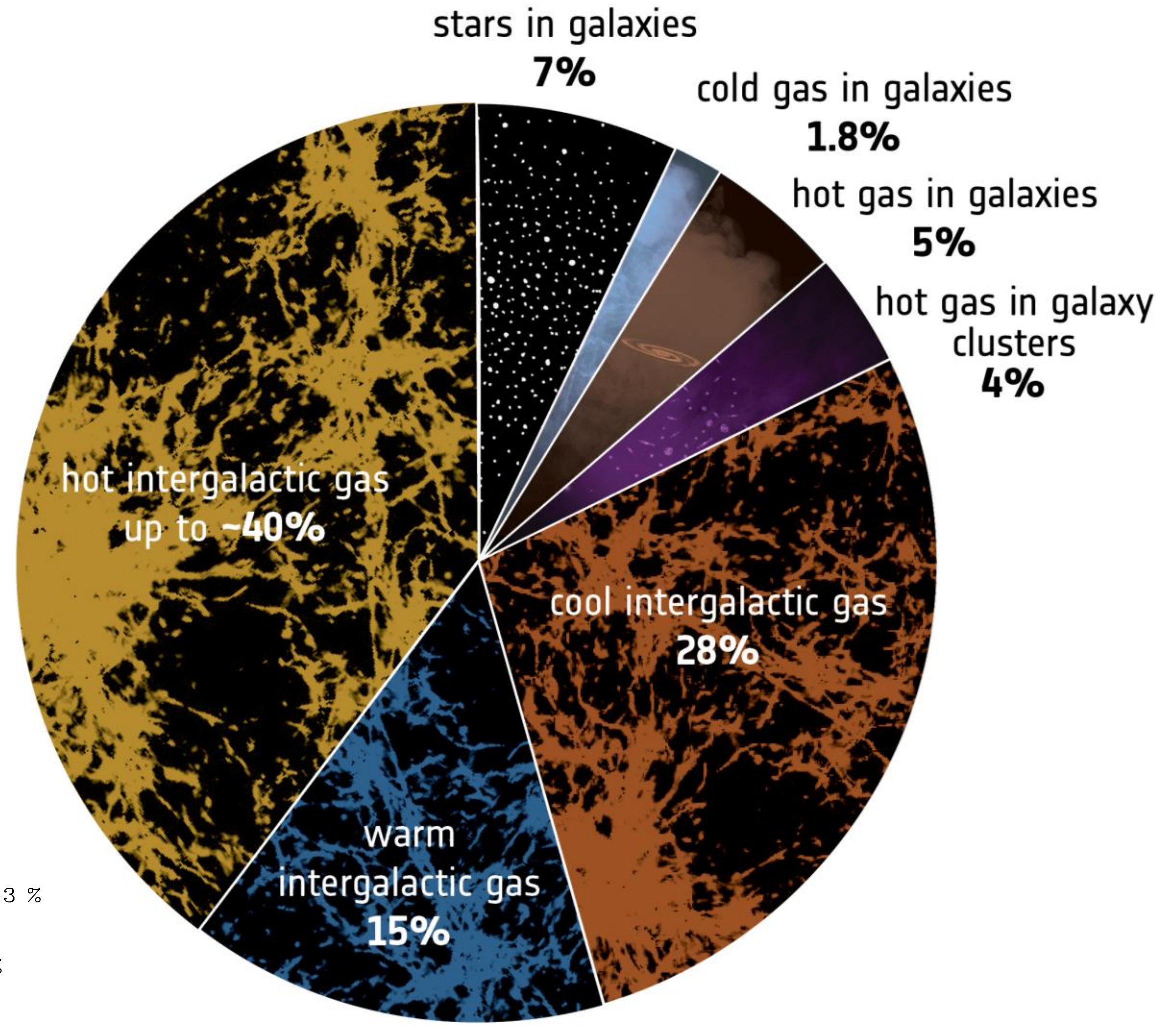
First data agree with predictions



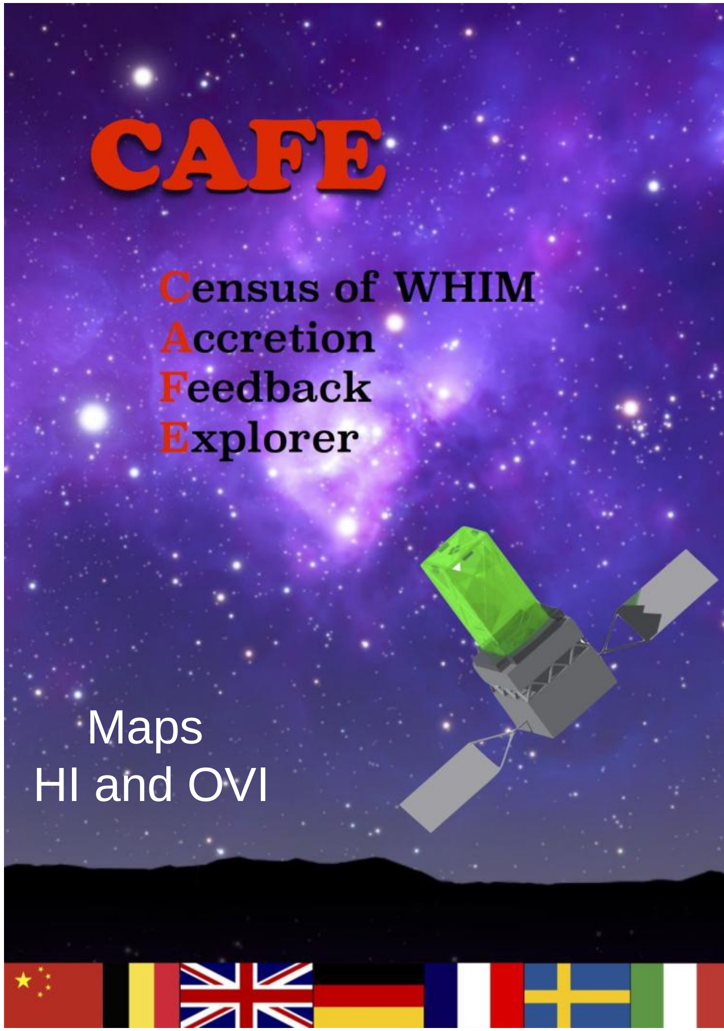
missing baryons to be found in OVII intervening absorbers.

Hot baryons close the census





Strong Momentum for China Space Astrophysics…and the Missing Baryons

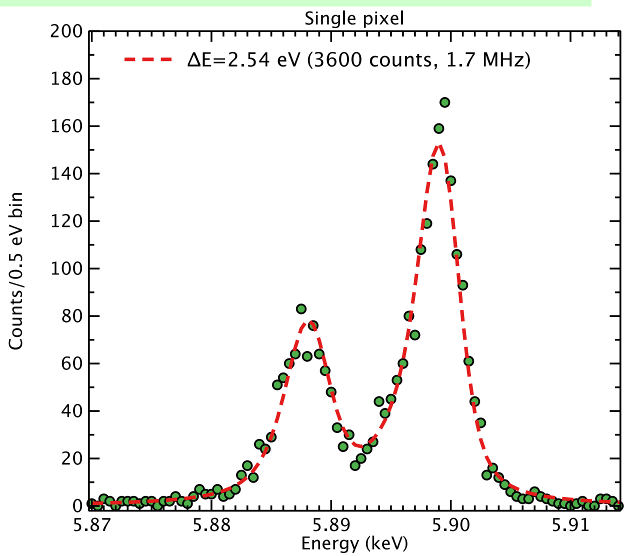


The Future: Athena X-IFU (2030)

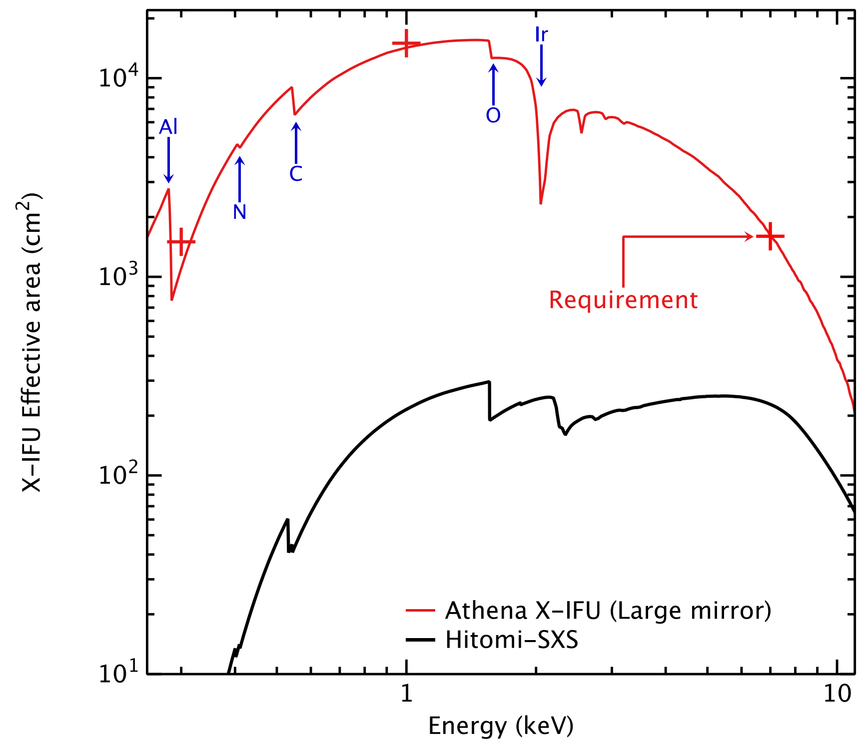
a Transition Edge Sensor (TES) microcalorimeter array with 3840 single pixels

Parameters	Requirements
Energy range	0.2 – 12 keV
Energy resolution[1]: E < 7 keV	2.5 eV
Energy resolution: E > 7 keV	$E/\Delta E = 2800$
Field of View	5′ (equivalent diameter)
Effective area @ 0.3 keV	> 1500 cm^2
Effective area @ 1.0 keV	> 15000 cm^2
Effective area @ 7.0 keV	> 1600 cm^2
Gain calibration error (RMS, 7 keV)	0.4 eV
Count rate capability – nominally bright point sources[2]	1 mCrab (> 80% high-resolution events)
Count rate capability – brightest point sources	1 Crab (> 30% throughput)
Time resolution	10 μs
Non X-ray background (2-10 keV)	< 5×10^{-3} counts/s/cm^2/keV (80% of the time)

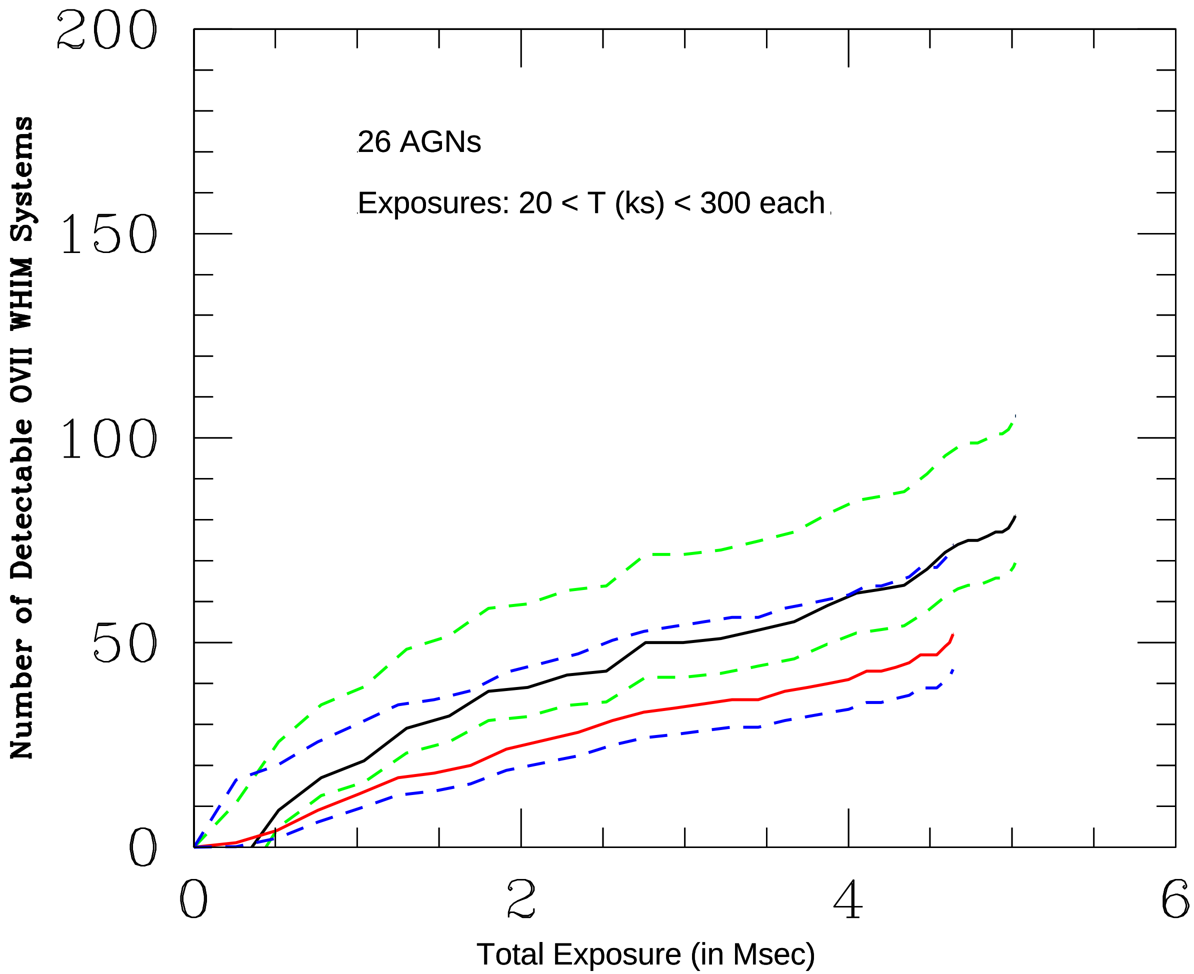
Athena X-IFU Measured Energy Resolution (2.5 eV)



Athena X-IFU Effective Area



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)

Summary

- 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.
- 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}.
- Cafe and HUBS (2025-2028?) will map the nearby (z<0.1) FUV (HI and OVI) and X-ray (OVII and OVII) WHIM and CGM. High synergy and complementarity.
- Athena (2032) will make a tomography of the WHIM and will detect ~200 filaments against 26/39 bright AGNs and GRBs.
- NEW ATOMIC DATA OF X_RAY INNER-SHELL TRANSITIONS URGENTLY NEEDED TO PROPERLY IDENTIFY ALL ISM TRANSITIONS