Missing Baryons and the WHIM

(Nature, 21 June 2018)

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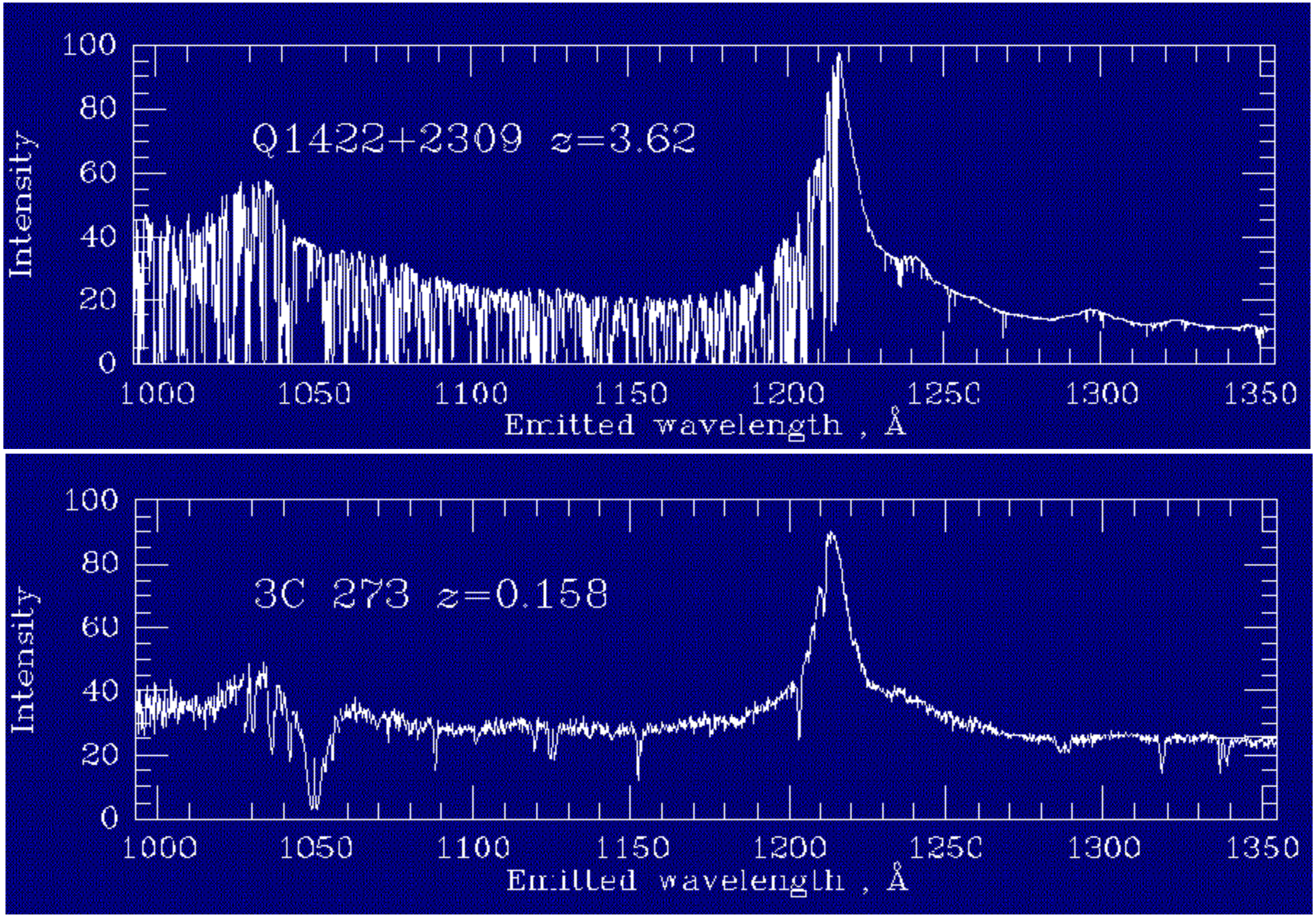
Outline

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

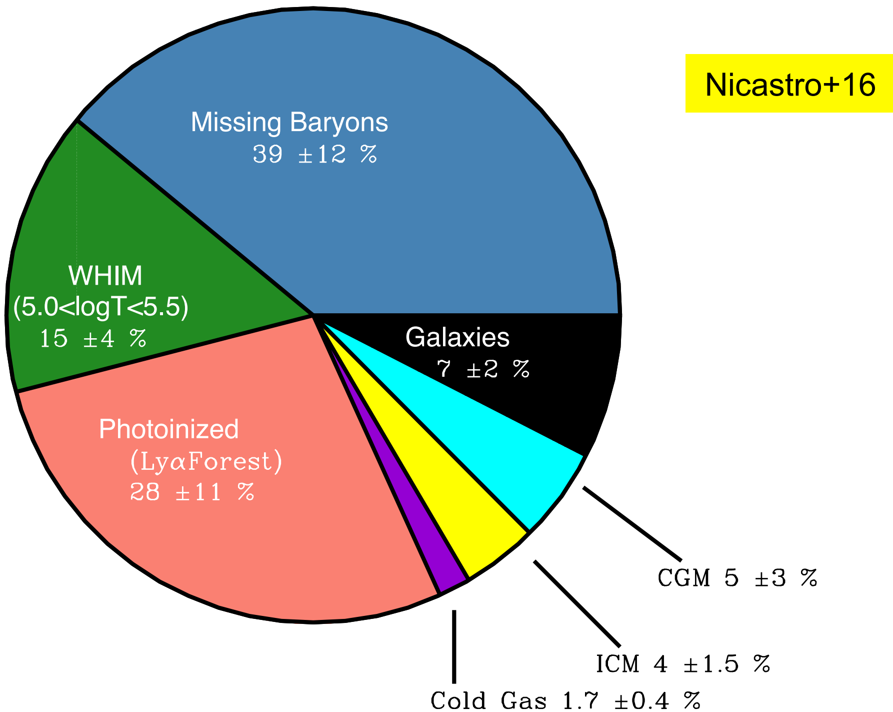
Where have all the baryons gone?



The Missing Baryons Problems

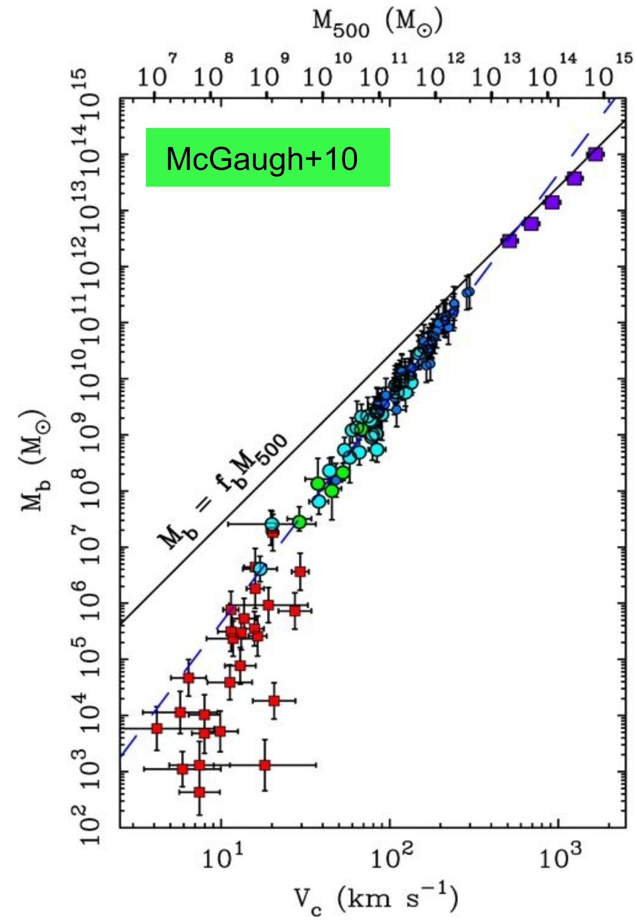
The Universe

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



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

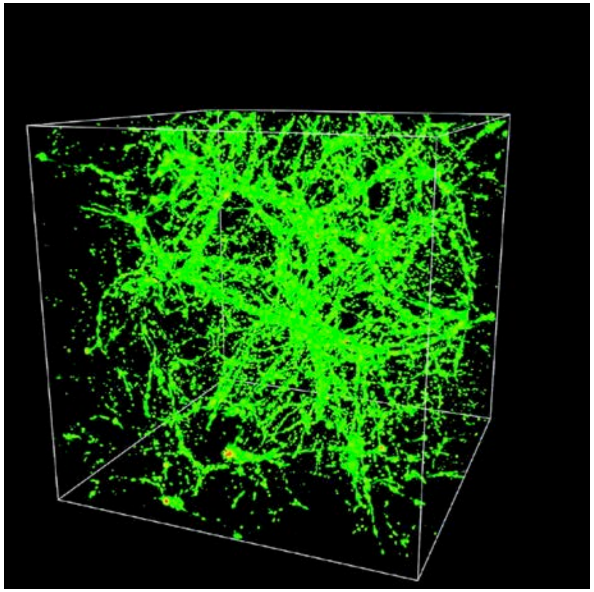
The Galaxies



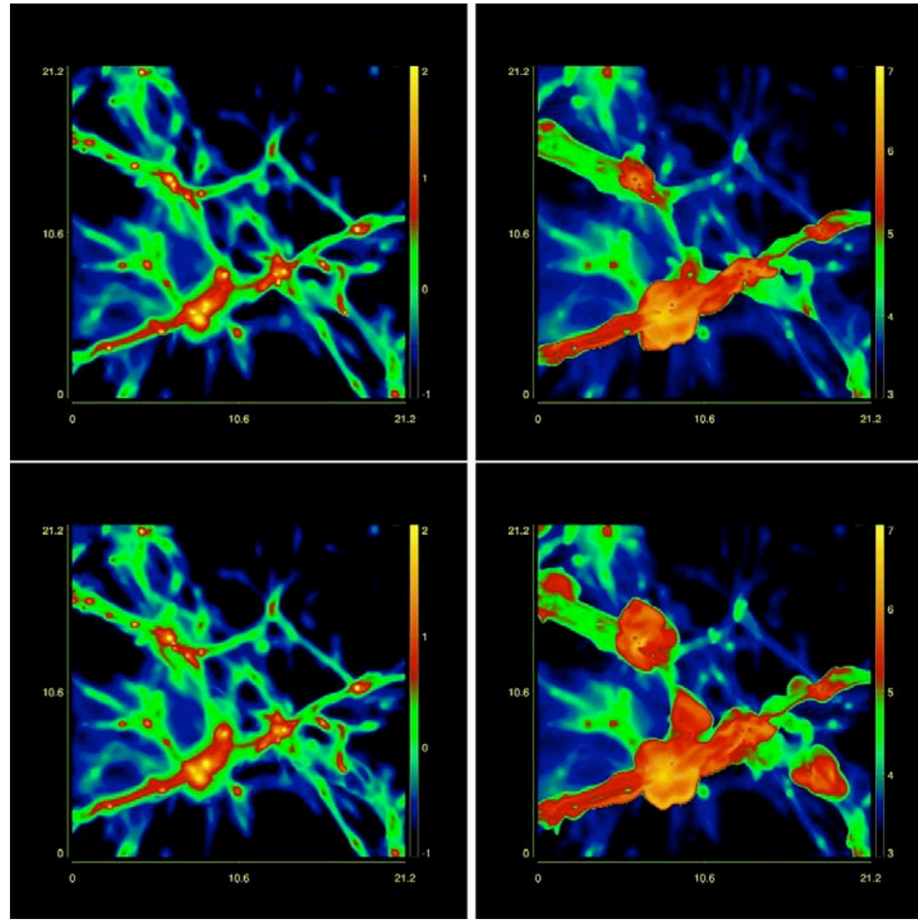
$\Omega_m^{planck+15} = 0.3156 \rightarrow f_b = 0.154$

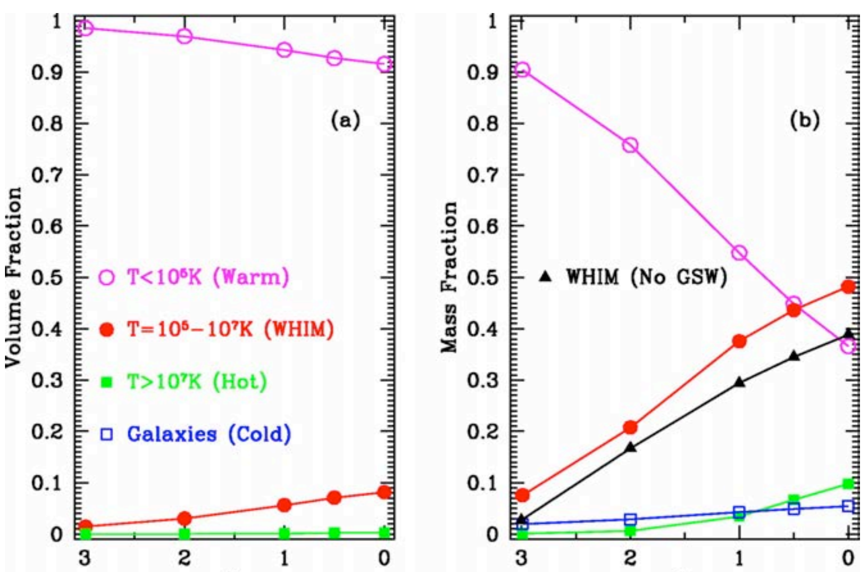
The Baryons in HD Simulations

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



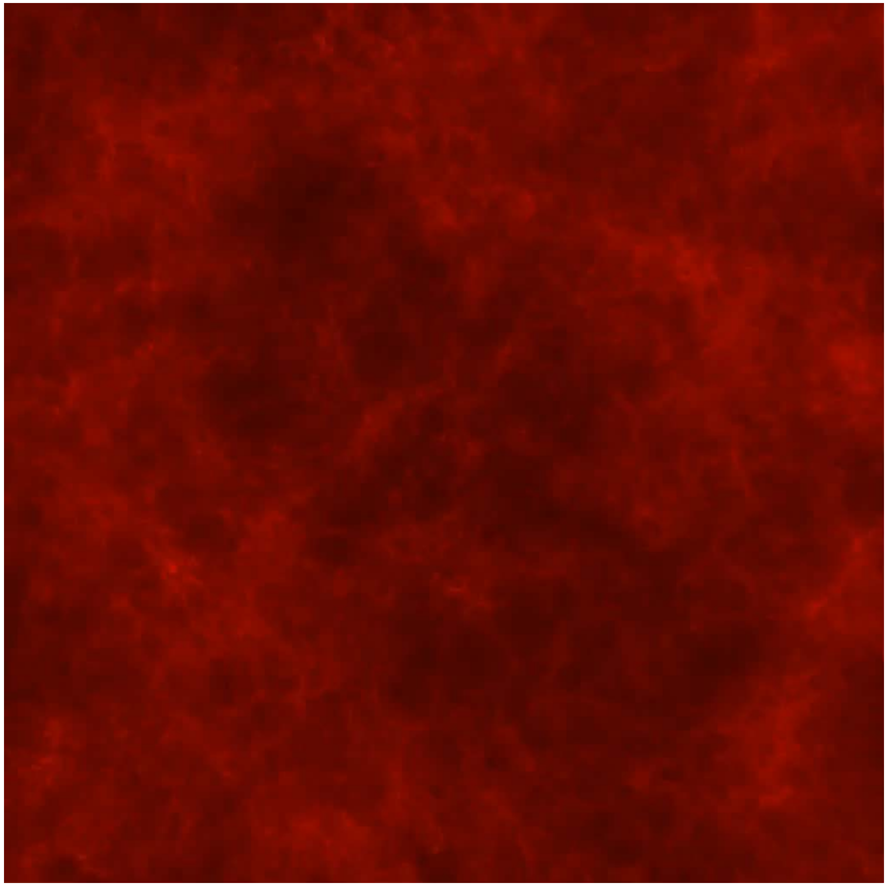
(21.2 x 21.2 x 1.75)h^{-1} Mpc
Without (top) and with (bottom) GSWs
Overdensity (left) Temperature (Right)

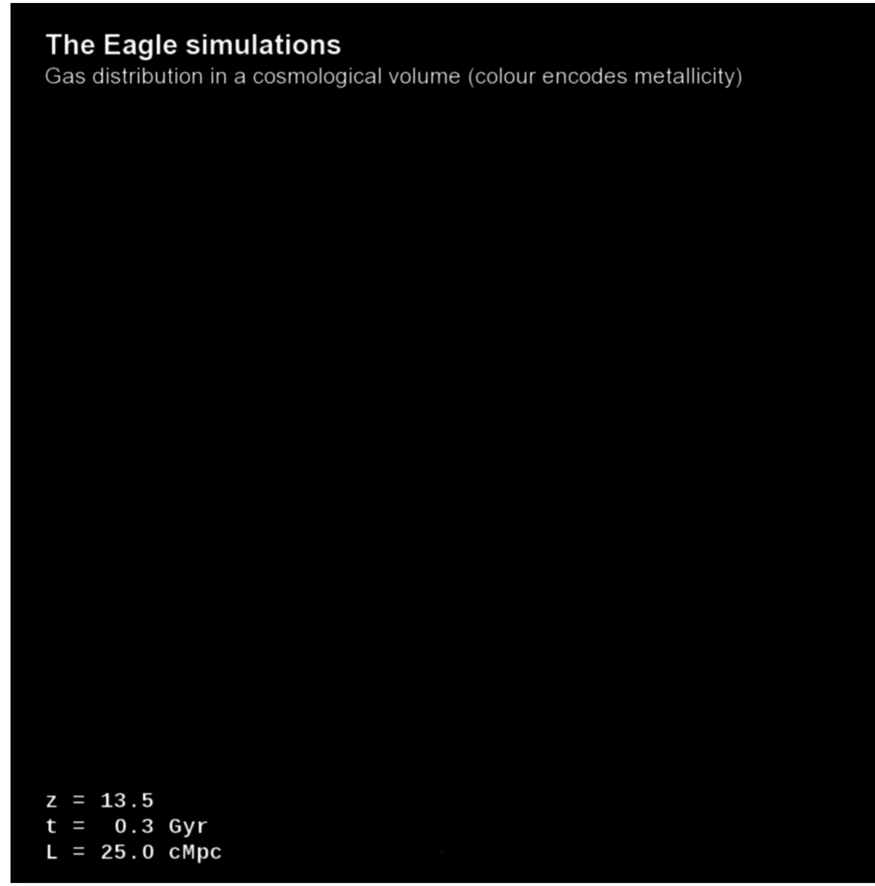




Cen & Ostriker, 2006

Why do we care?

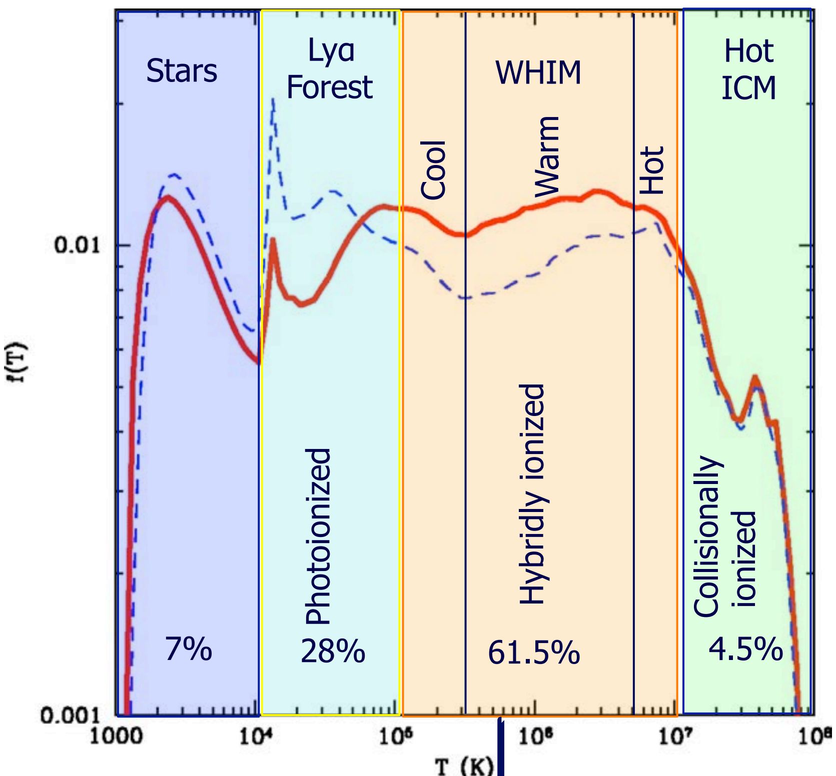




Schaye et al. (2015)

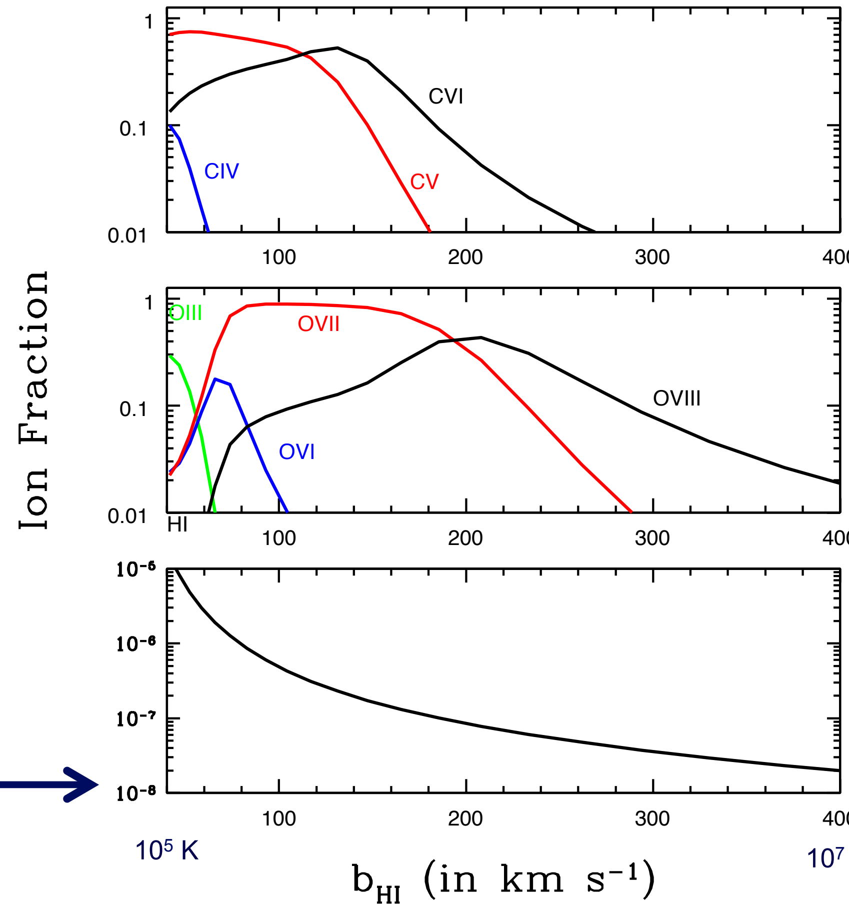
The Baryon Phases in HDS

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 $n_b^2 R$

Absorption Line Equivalent Widths:

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

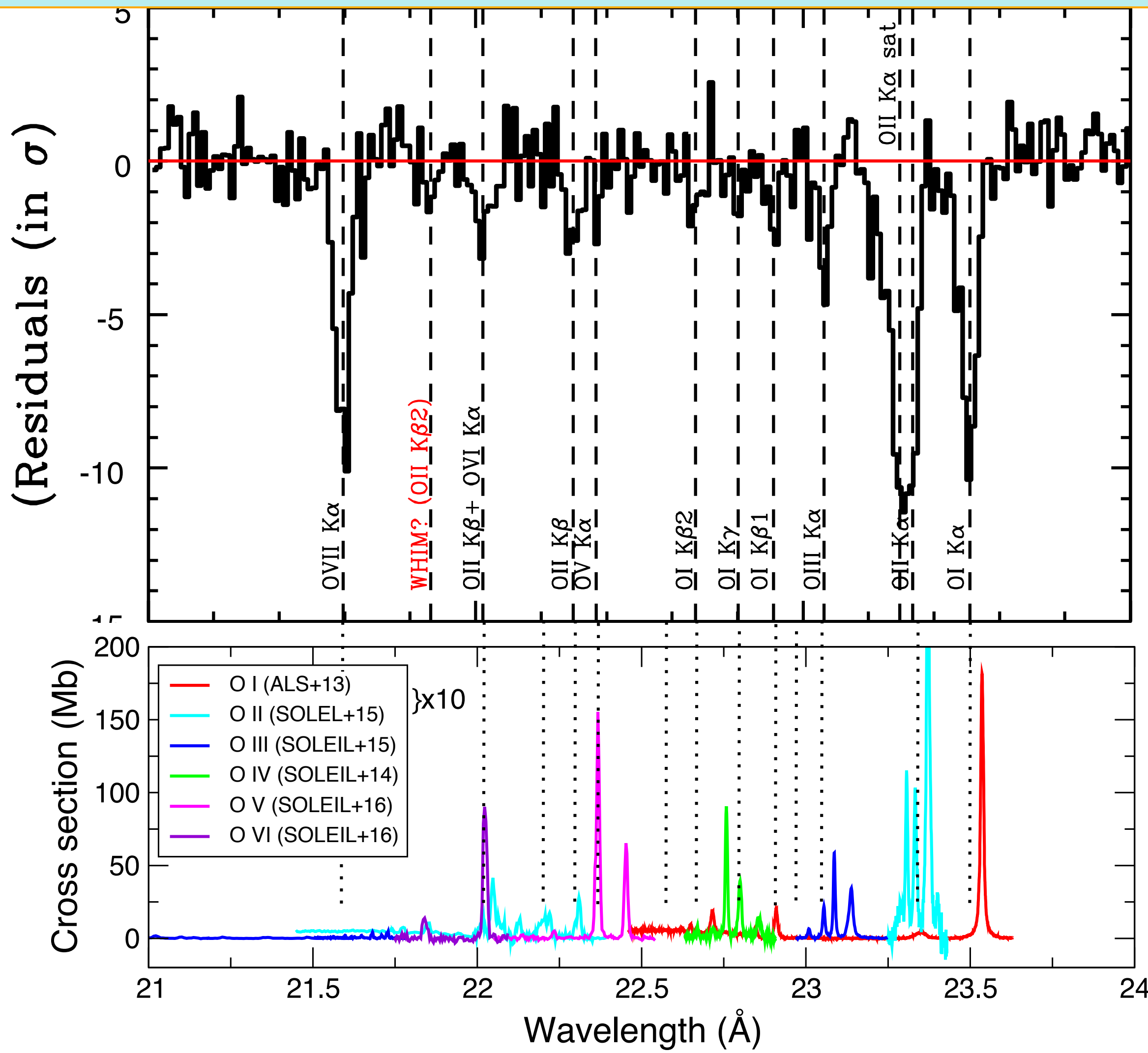
Equivalent Width Ratios:

→ Ionization Balance: T, n_b

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

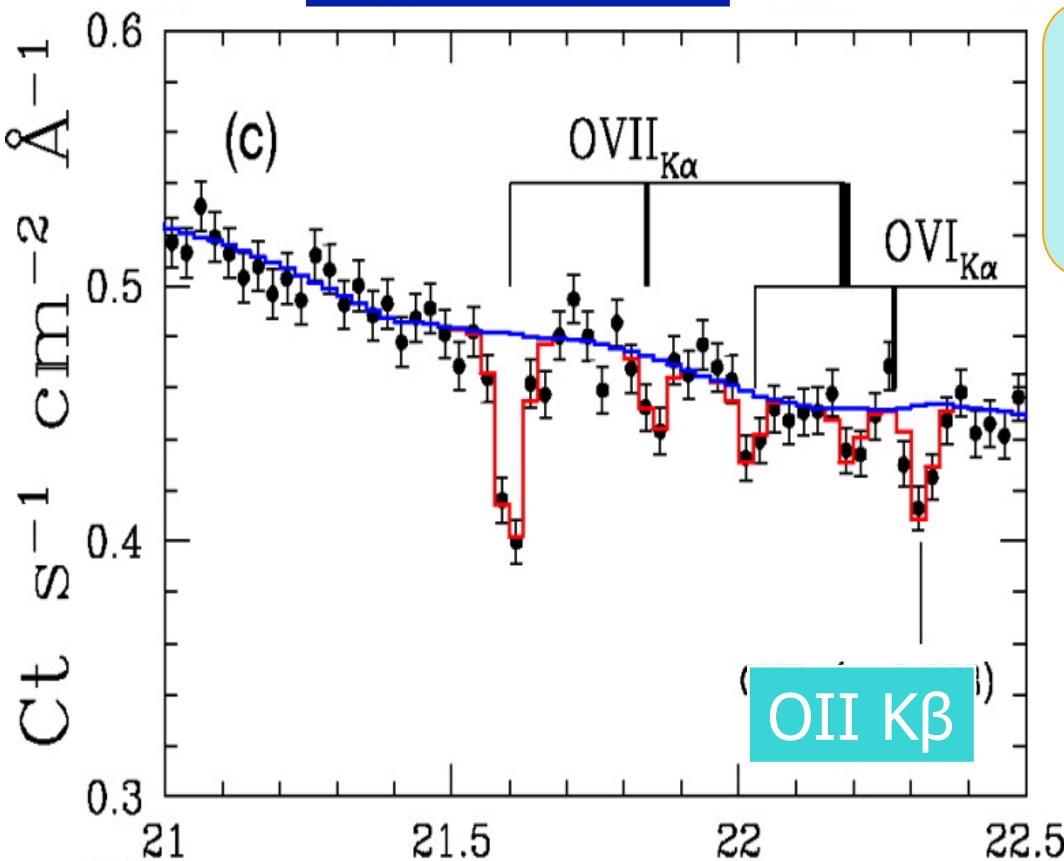
LIMM

HIMM

First Claimed WHIM Detections:

Exceptional Outburst State

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



However:

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

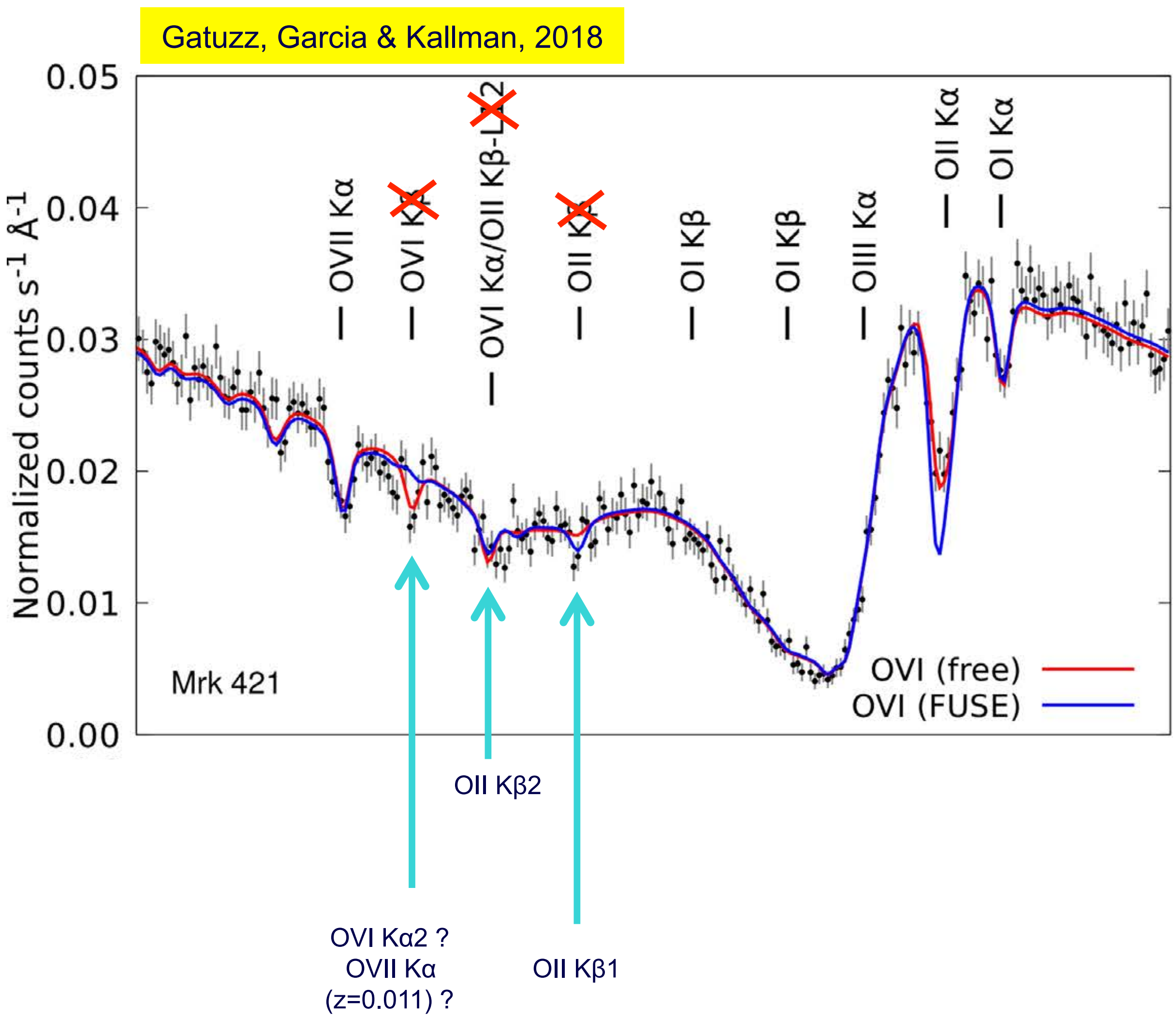
+

Controversial:

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

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

Confirmation of the line @ 21.85 Å



Mathur+16 show that line @22.02 Å is mostly due to OII Kβ2 with OVI Kα1 contributing at most 0.6 mÅ, so reconciling the OVI FUV-X-ray paradox.

Gatuzz+18 instead fit line @22.02 Å as OVI Kα1, line at 21.85 Å as an intrinsically very weak OVI Kα2 transition (f=0.0067), but doing so seriously underpredict the strongest OII Kβ1 line at 22.3 Å and does not solve X-ray FUV OVI paradox.

In either case, line at 21.85 Å is confirmed

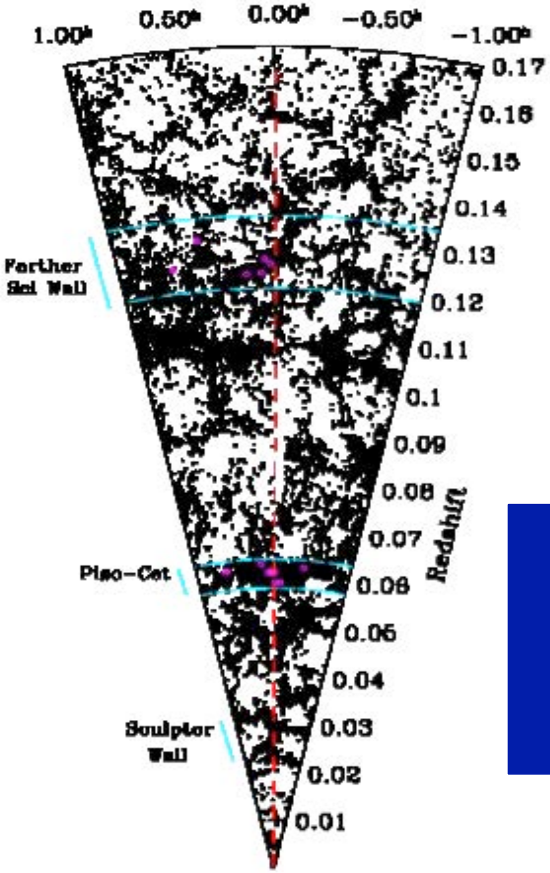
We prefer Mathur+16 explanation, with line at 21.85 Å being indeed intervening OVII Kα WHIM at z=0.011, as proposed by Nicastro+05

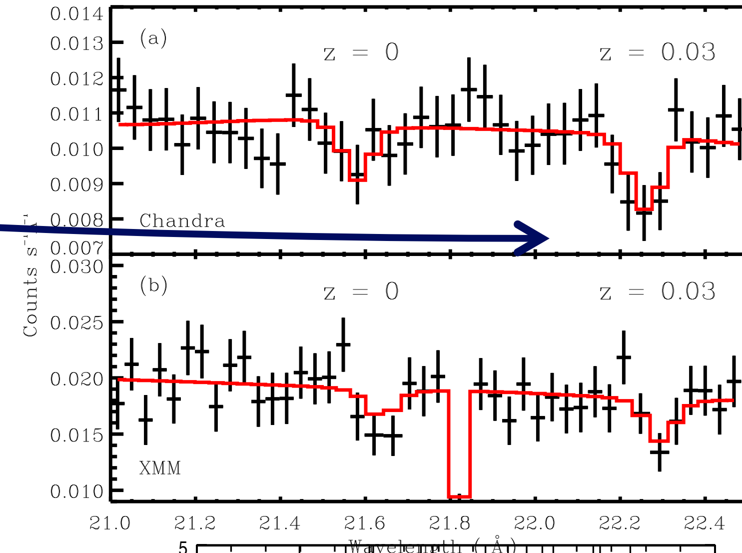
Galaxy concentrations as WHIM tracers

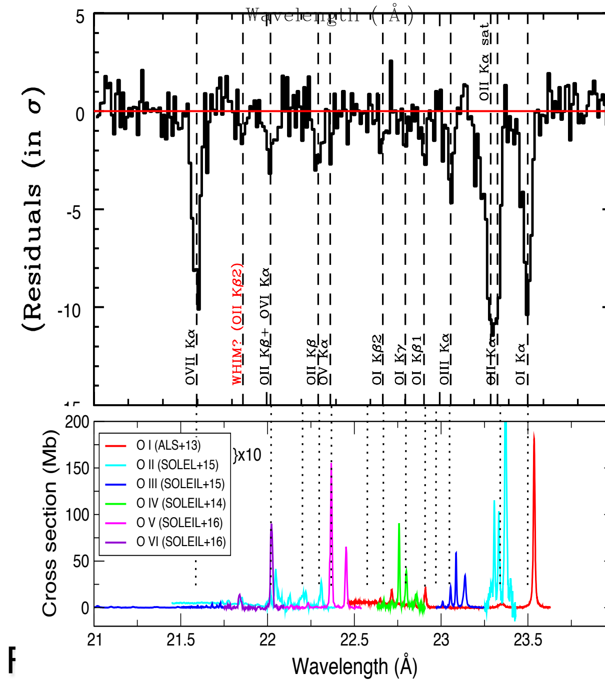
But: $N_{OVII} \sim 8 \times 10^{16}\ cm^{-2}$!!!

Buote+09, Fang+10

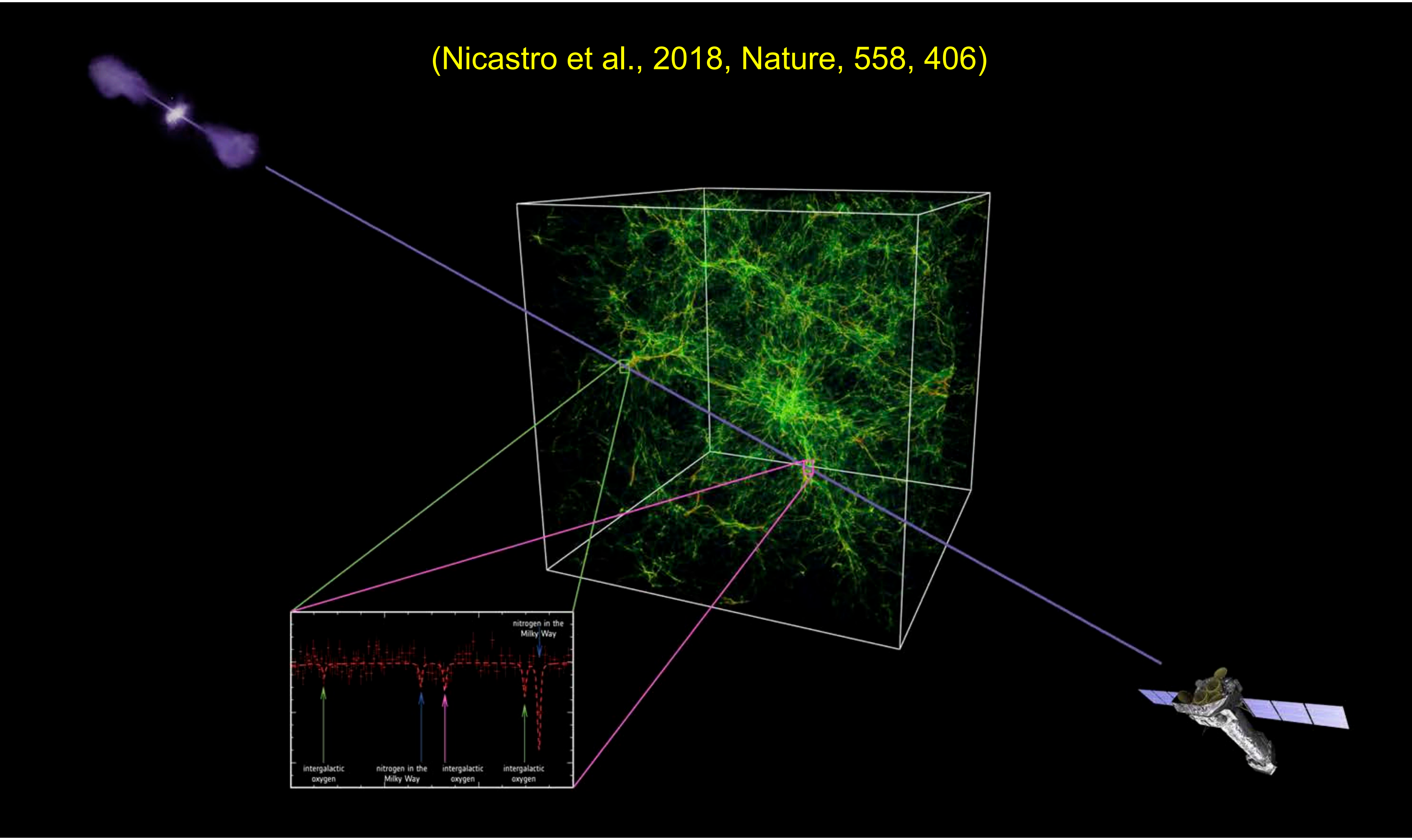
H 2356-309





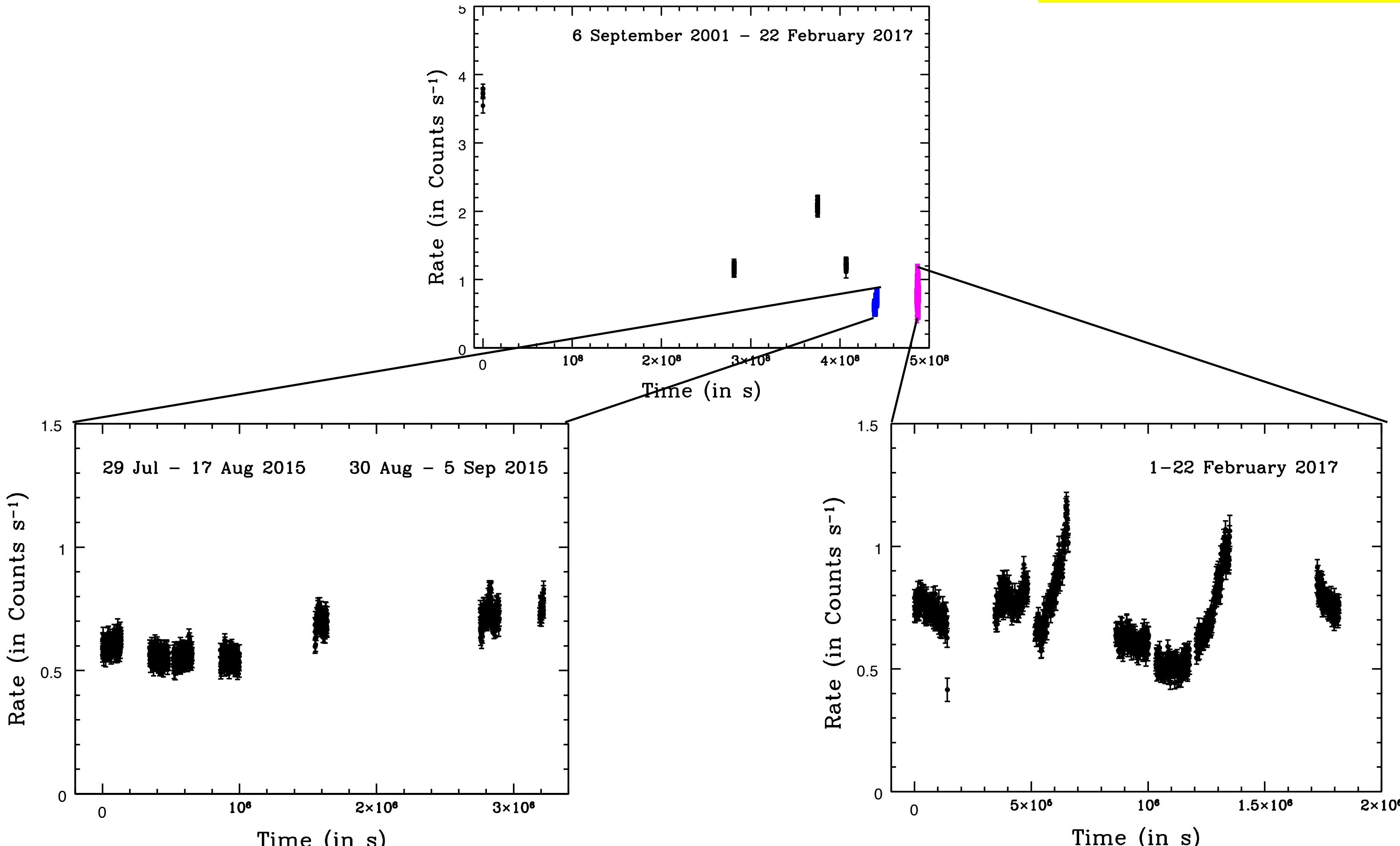


Detection of 2 WHIM Filaments



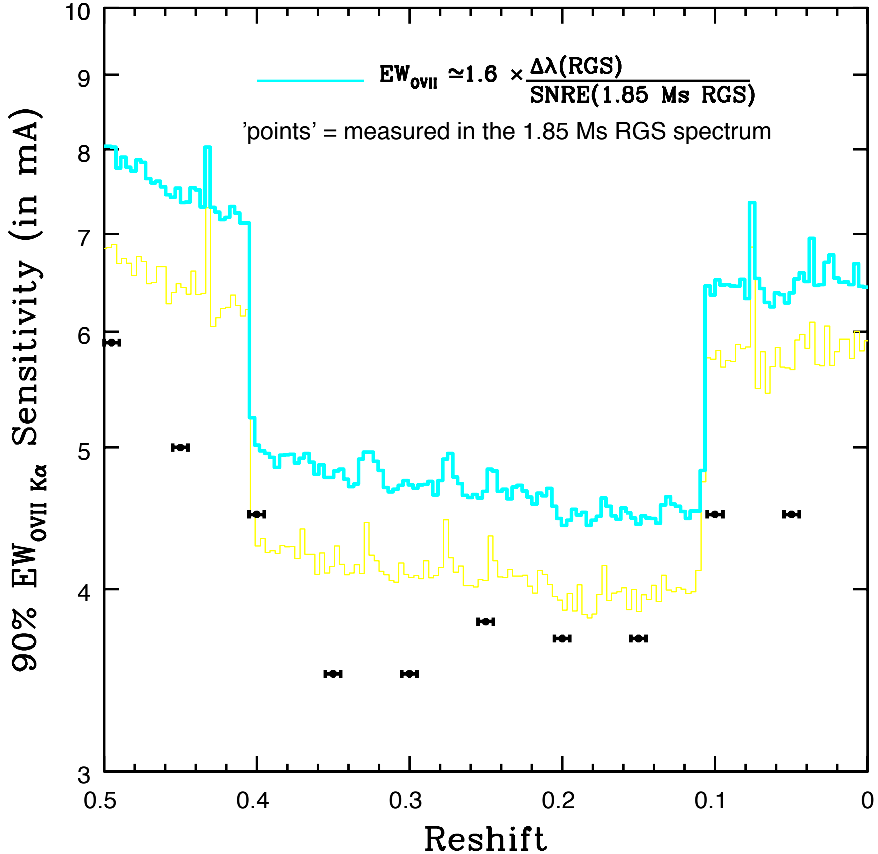
XMM-Newton Lightcurve of 1ES 1553+113

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

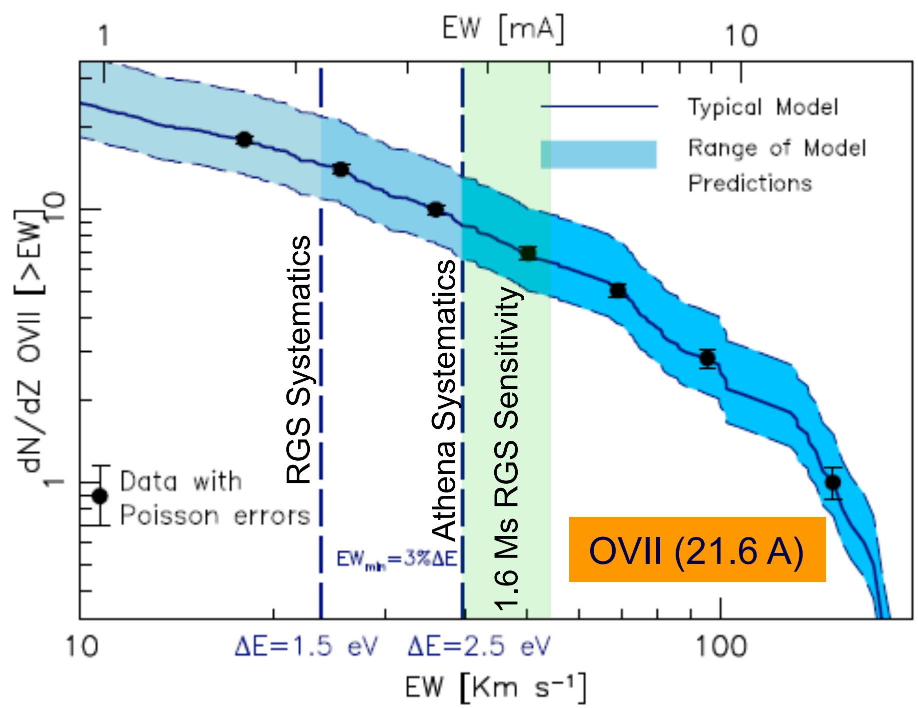


Sensitivity of RGS Spectrum of 1ES 1553+113

RGS Spectra of 1ES 1553+113

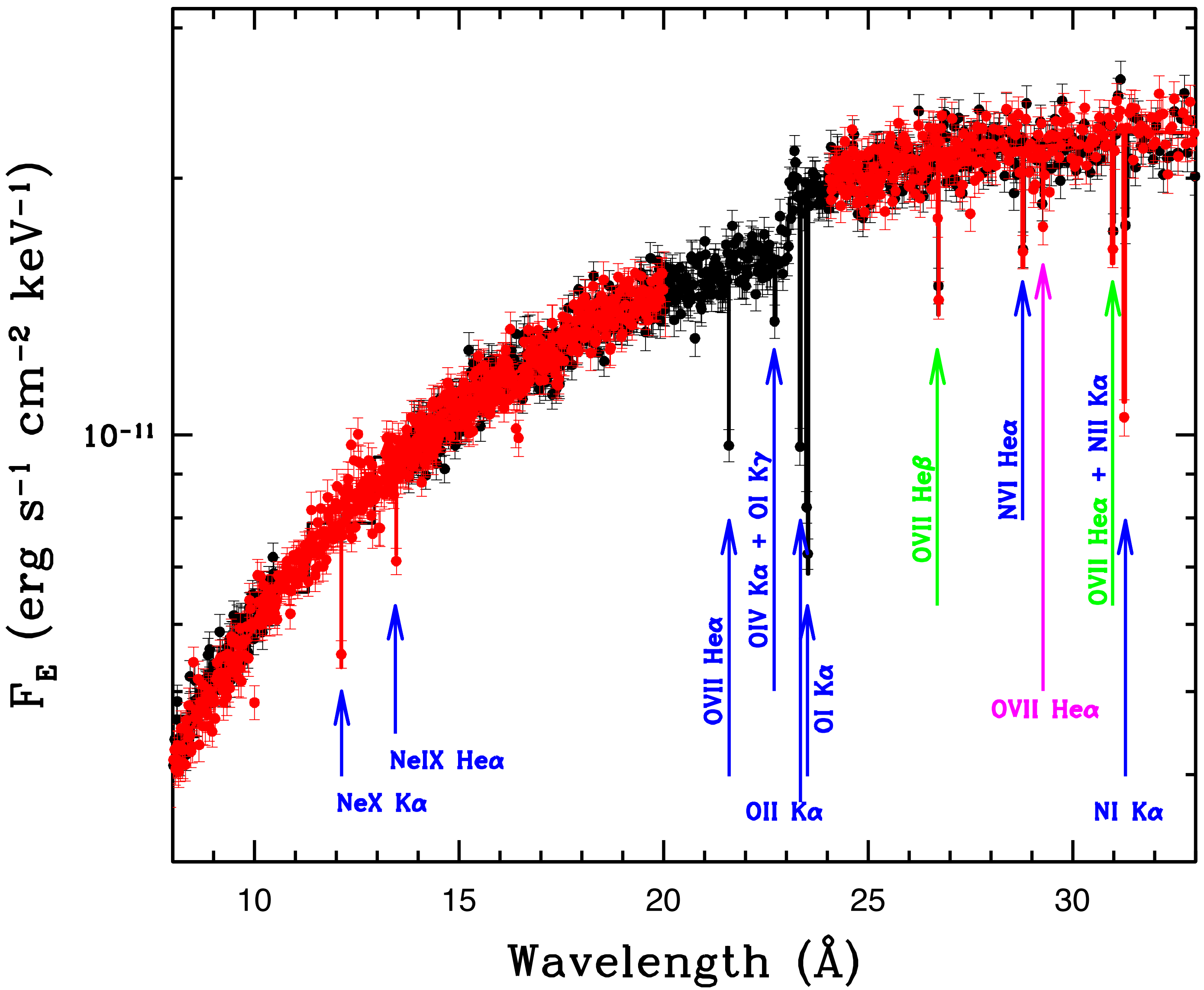


Athena WHIM White Paper (Kaastra+13)

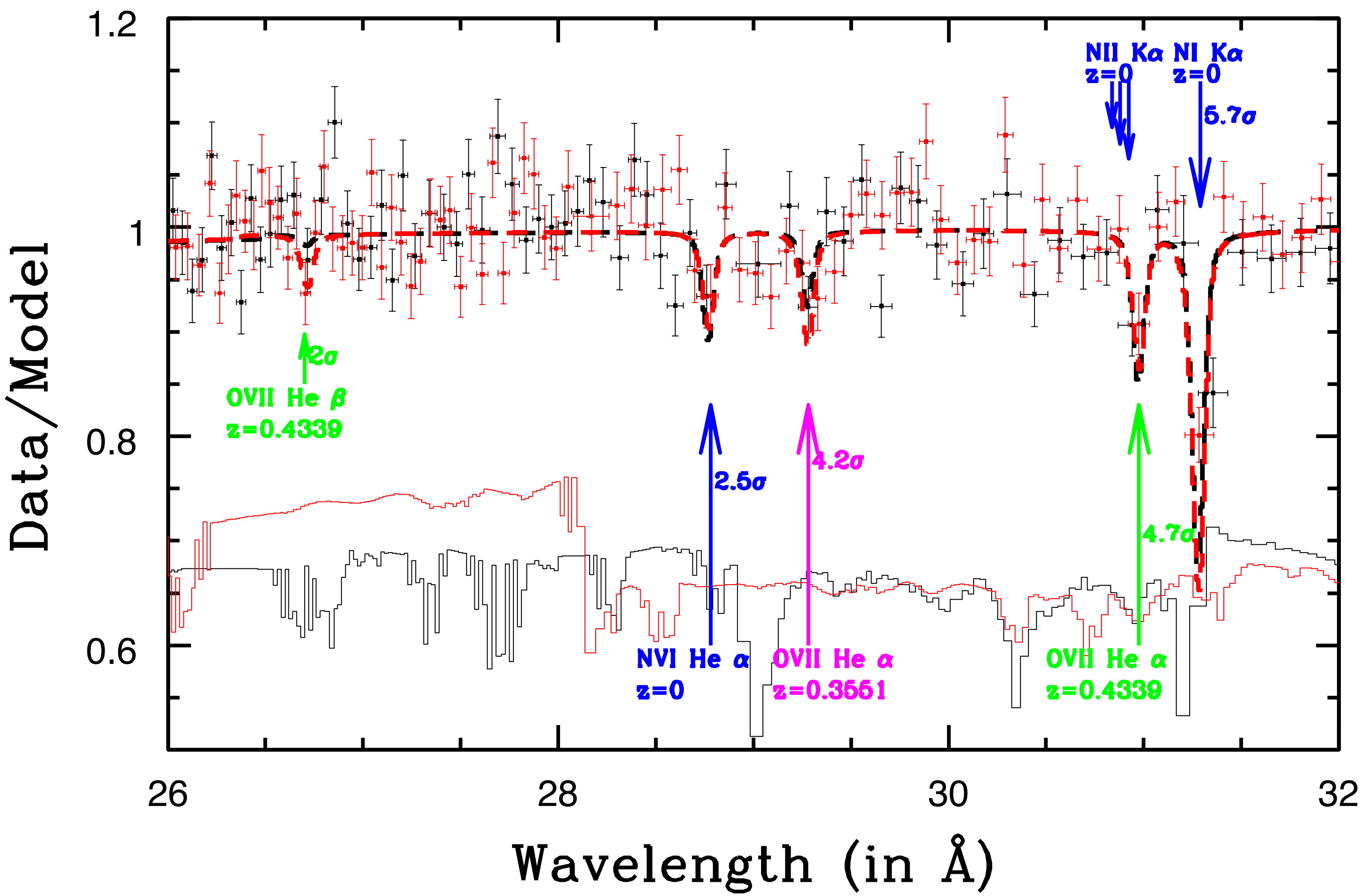


1.85 Ms RGS: EW>4-5 mA @ >90%
i.e. ~600 cts per R.E.

Broad-band RGS Spectra of 1ES 1553+113

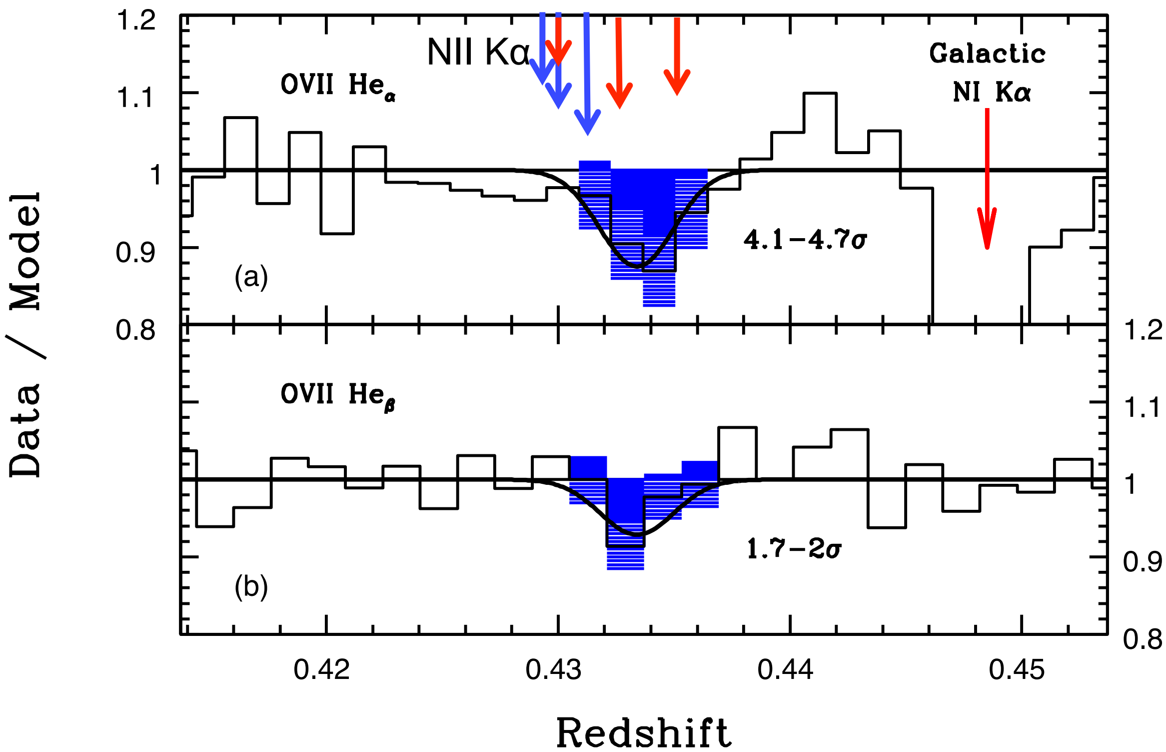


26-32 Å RGS Spectra



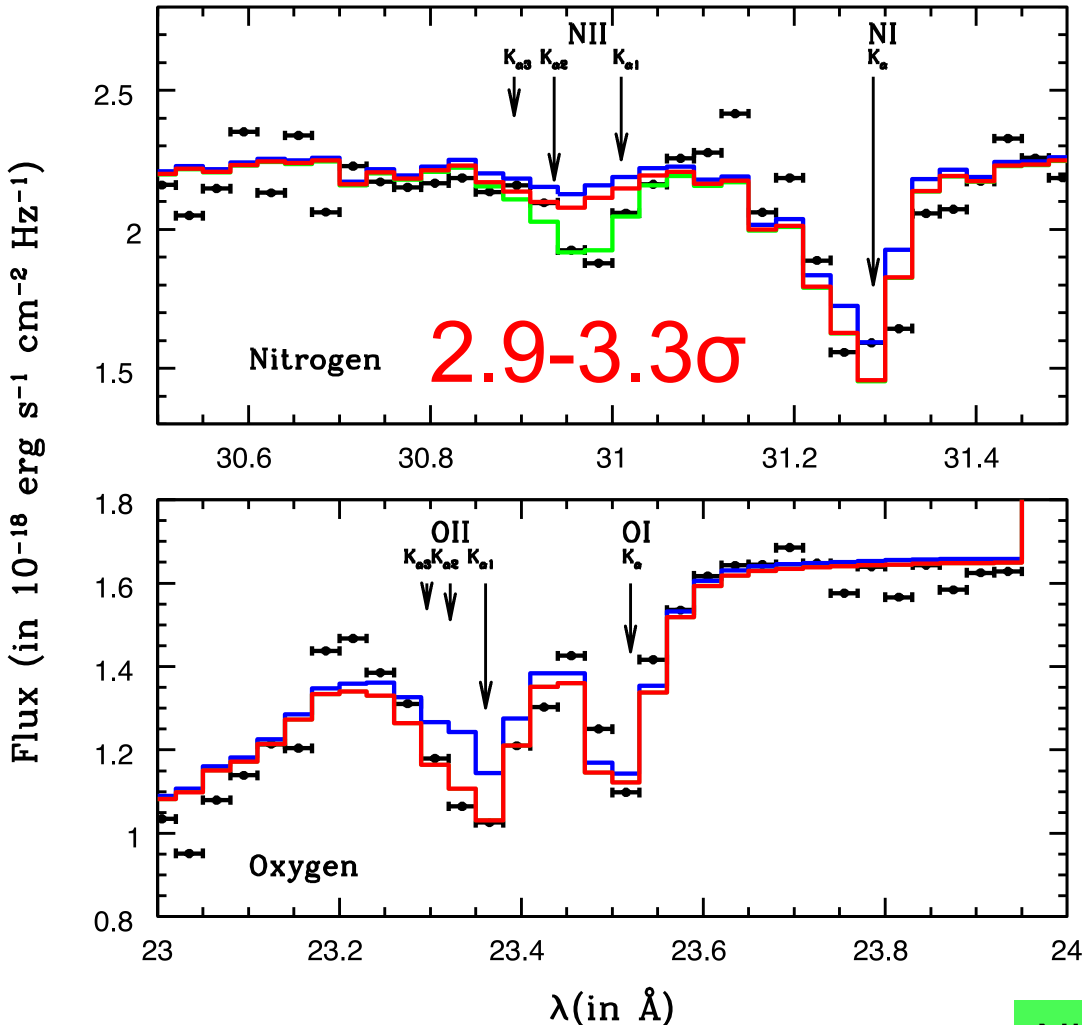
z = 0.4339 System

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

Modeling ISM CNMM & WIMM



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.)

WIMM

T≈3000-5000 K

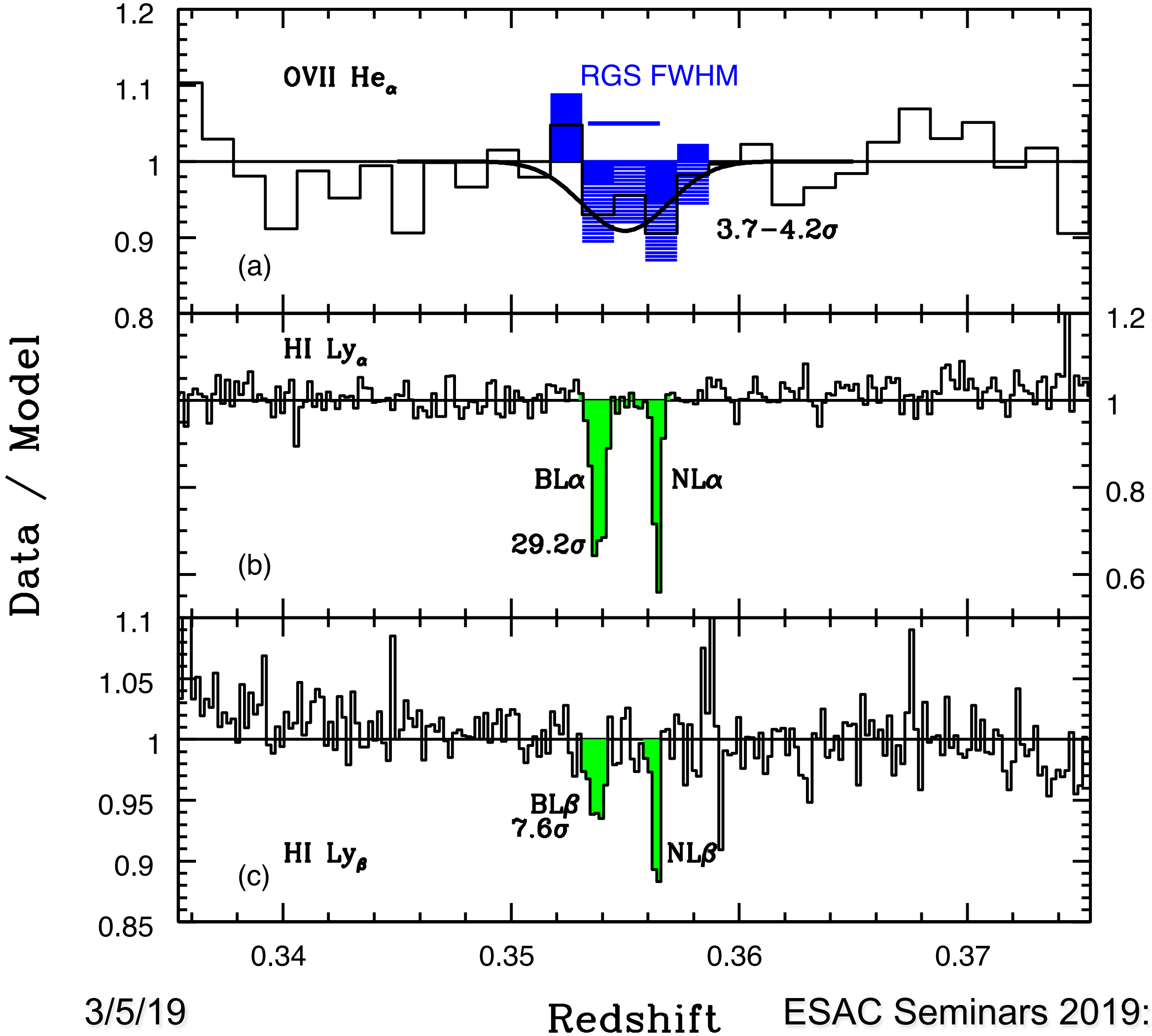
N_H=(1.85±0.07)x10^{20} cm^{-2}

$Z/Z_{\odot}$=0.52±0.09

Nicastro, 2018, ArXiV1811.03498

z=0.3551 System

z_X=0.35559±0.00016



Statistical Significance

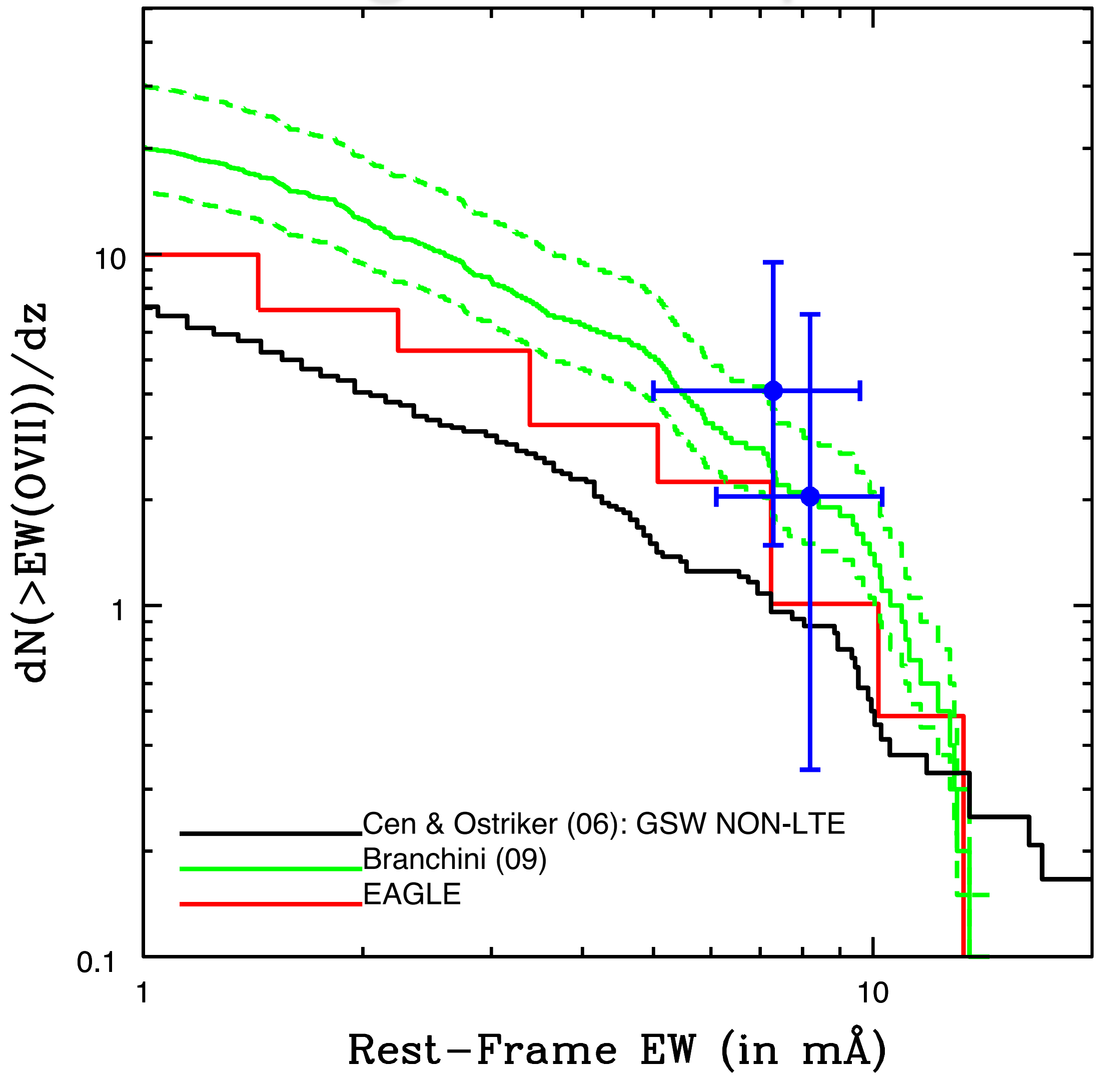
(after accounting for OVII blind redshift search and RGS eff.-area-induced systematics): 2.9-3.7σ

Diagnostics

z	T (10^6 K)	N_O (10^{15} cm^{-2})	$N_H(Z/Z_\odot)^{-1}$ (10^{19} cm^{-2})	Z ($Z_\odot$)
0.4339	1.0,-0.4,+0.9	3.5,+2.5,-1.5	0.7,+0.5,-0.3	>0.05
0.3551	0.95 ± 0.45	$4.4^{+2.4}_{-2.0}$	$0.9^{+0.5}_{-0.4}$	≥ 0.1

Physical parameters all in excellent agreement with WHIM predictions

First data agree with predictions

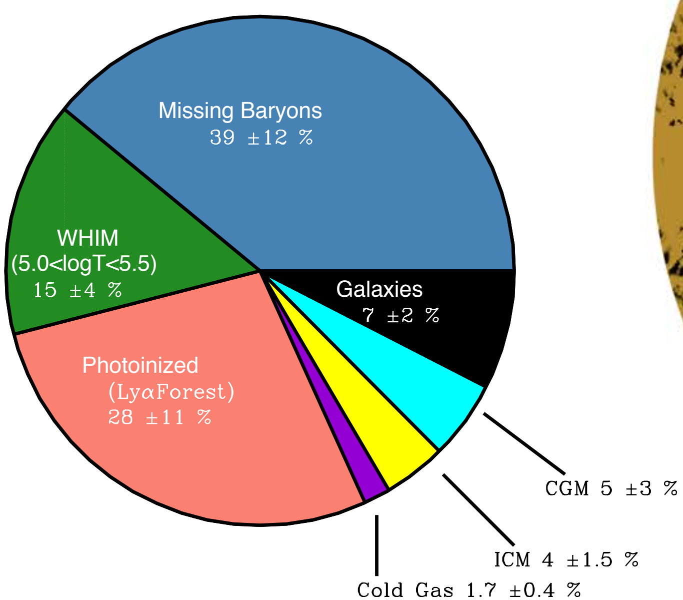


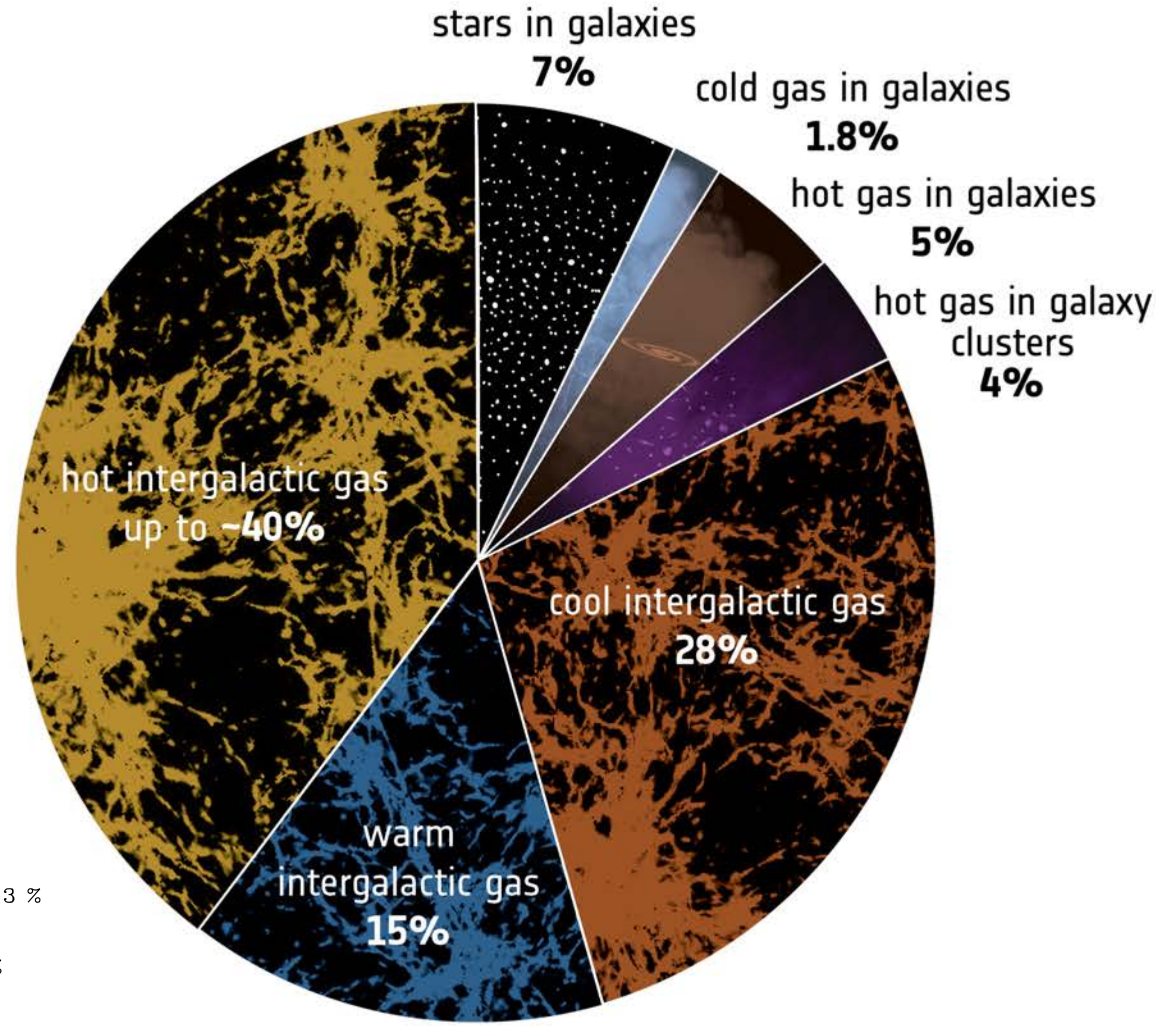
missing baryons to be found in OVII intervening absorbers.

Hot baryons close the census

$0.002 < \Omega_b^{WHIM} < 0.016$

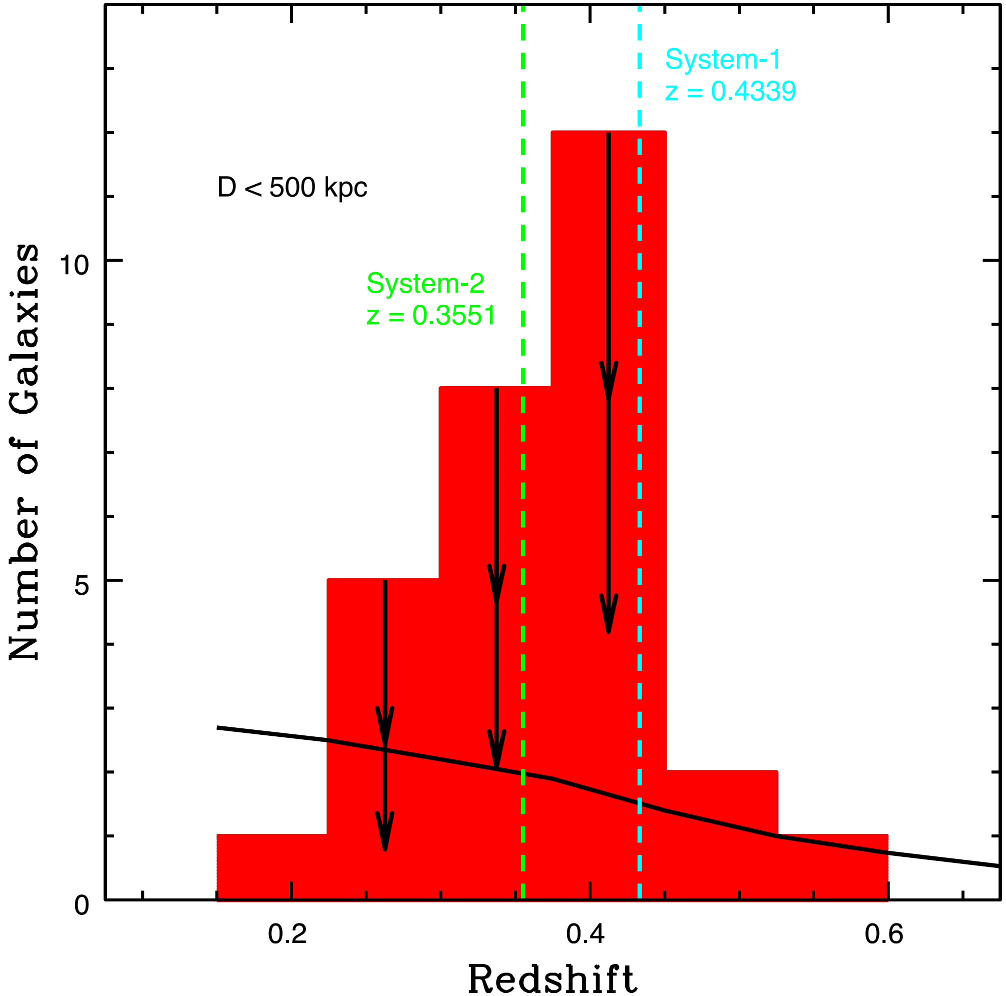
➔ $0.09\ \Omega_b < \Omega_b^{WHIM} < 0.7\ \Omega_b$





z=0.2-0.6 Galaxy Distribution

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



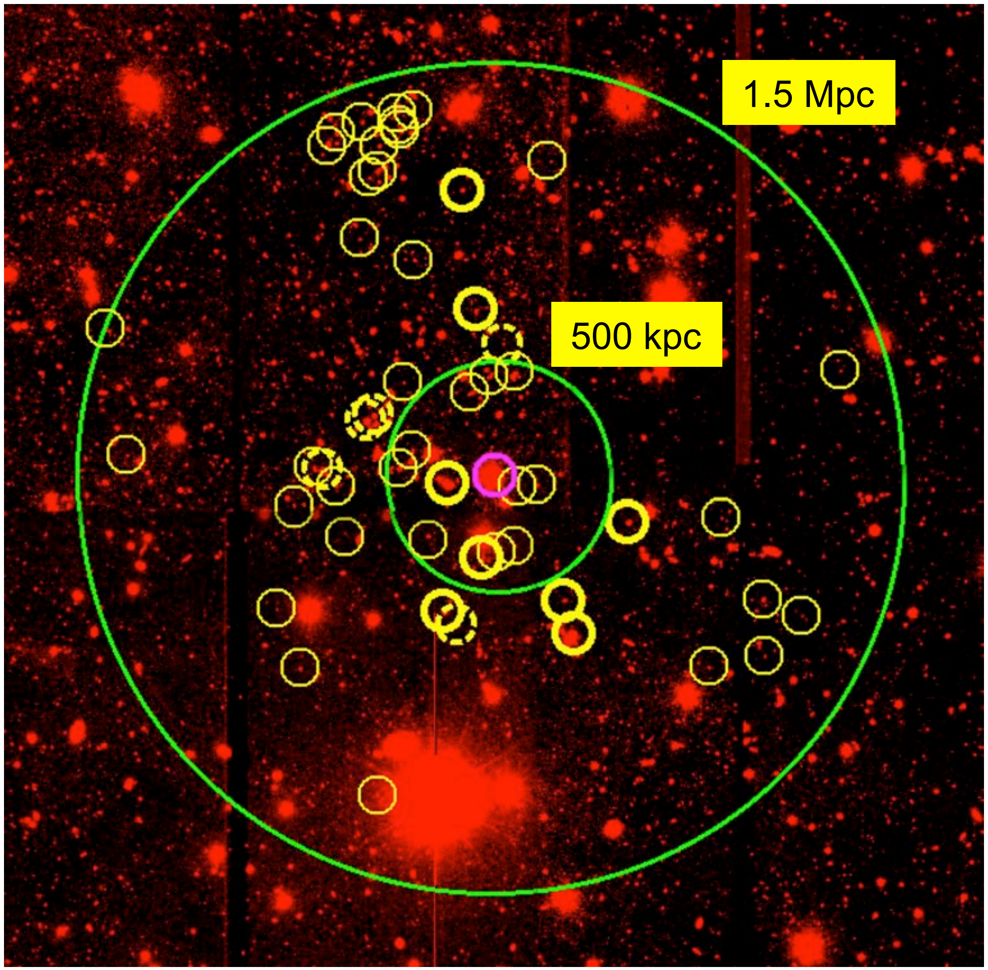
Galaxies photo-z redshifts obtained via deep (r'>23.5) SDSS-band imaging with the OSIIS camera at GTC

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'>23.5 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}

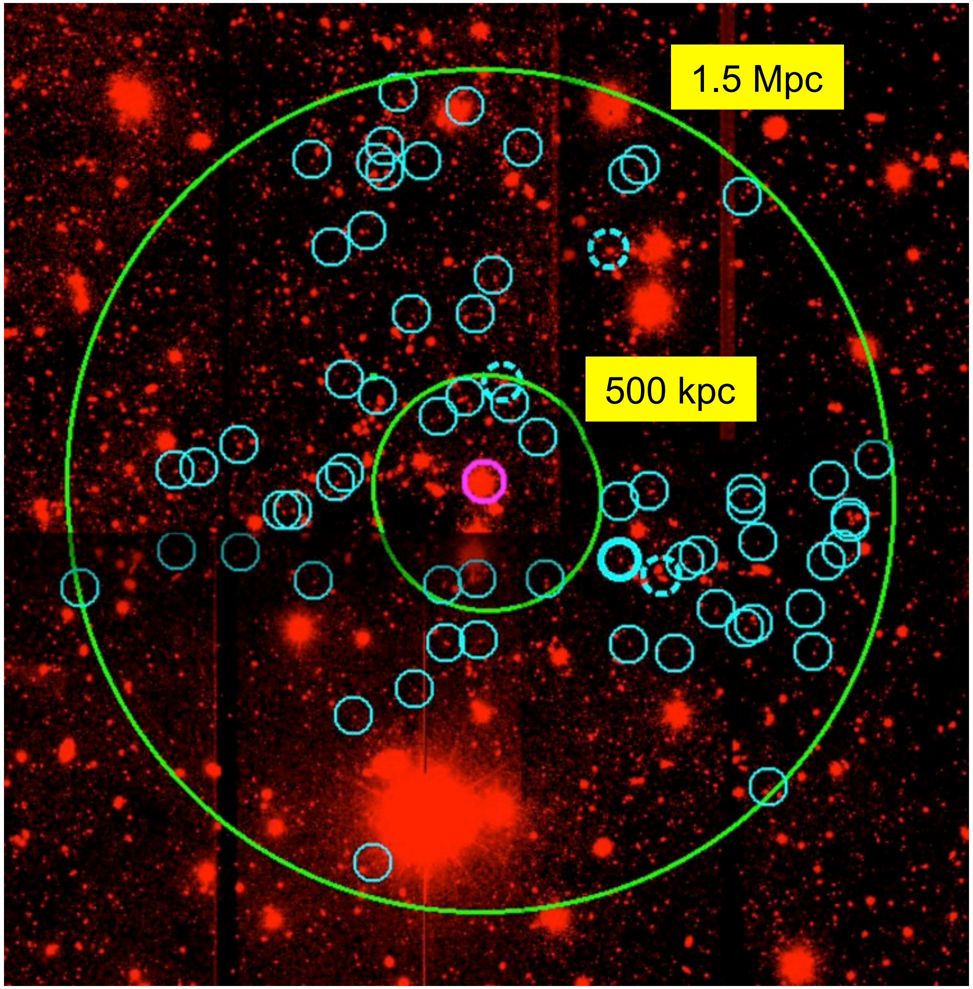
Nearest galaxy: i'=19.6 spiral at d=129 kpc and -15 km s^{-1}
➔ Galaxy's CGM?

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

Short-term Future: XURBE
(XMM-Newton Ultimate Roaming baryon Exploration)

XMM-Newton can provide invaluable contribution by:

observing (in a multi-cycle program) 6 opportunely selected, additional lines of sight to cover a total $\Delta z=3.5$ (cf. with explored $\Delta z=0.4$) down to a 3σ sensitivity of EW_{rf}(OVIIKα)>9 mÅ, in a total of 4.85 Ms (cf. with 1.9 Ms on 1ES 1553+113)

This would allow us to:

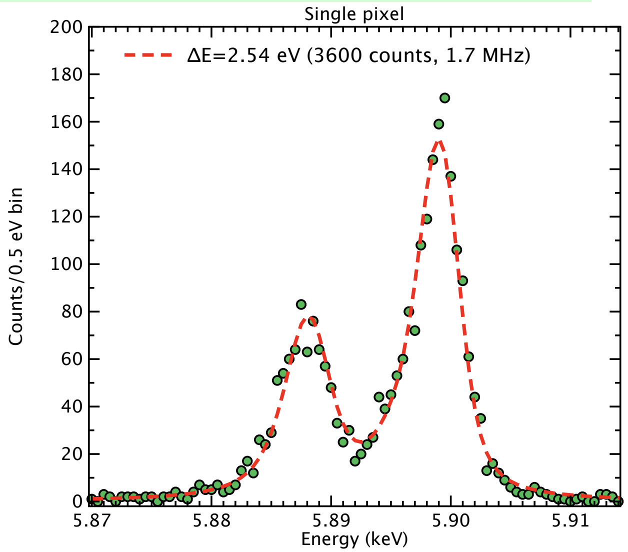
(1) effectively address WHIM cosmic variance over ~130 independent LSS elements;
(2) measure dN/dz(EW_{rf} > 9) and Ω_b(logT~ 6) with precisions of 15-40%;
(3) study the galaxy-environment around OVII-WHIM intervening absorbers;
(4) refine theoretical predictions.

Long-term Future: Athena X-IFU (2030)

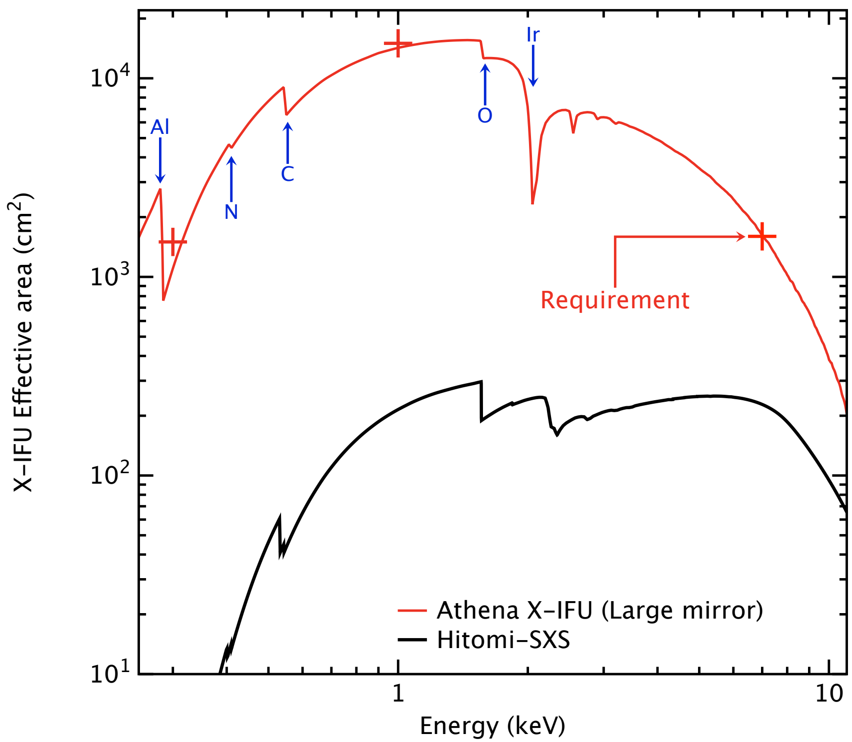
a Transition Edge Sensor (TES) microcalorimeter array with 3840 single pixels

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)	$< 5 \times 10^{-3}$ counts/s/cm^2/keV (80% of the time)

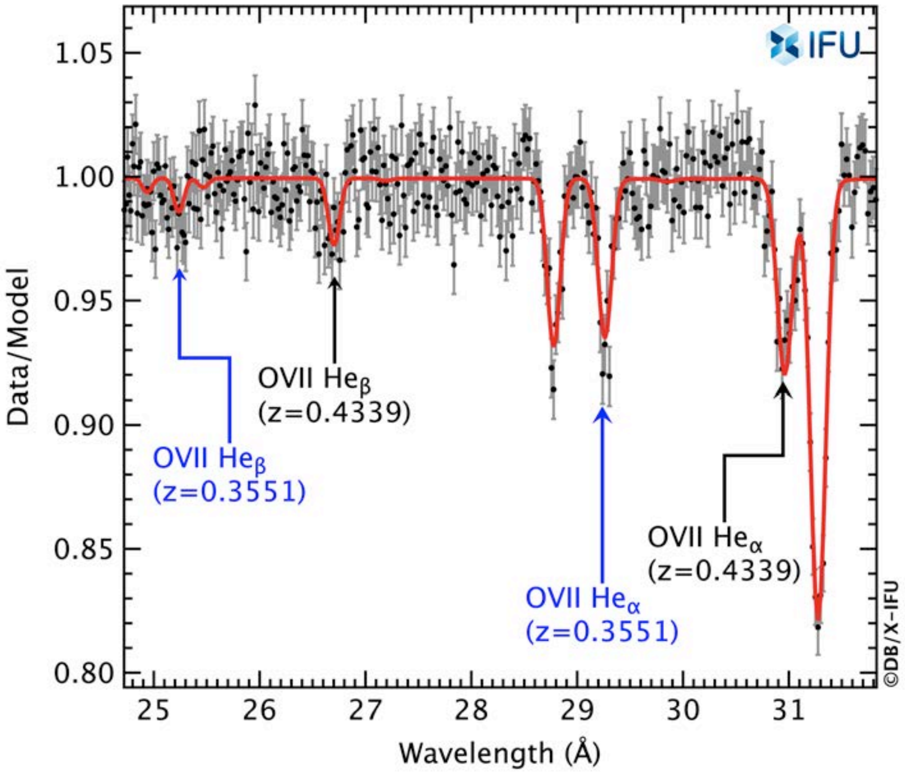
Athena X-IFU Measured Energy Resolution (2.5 eV)



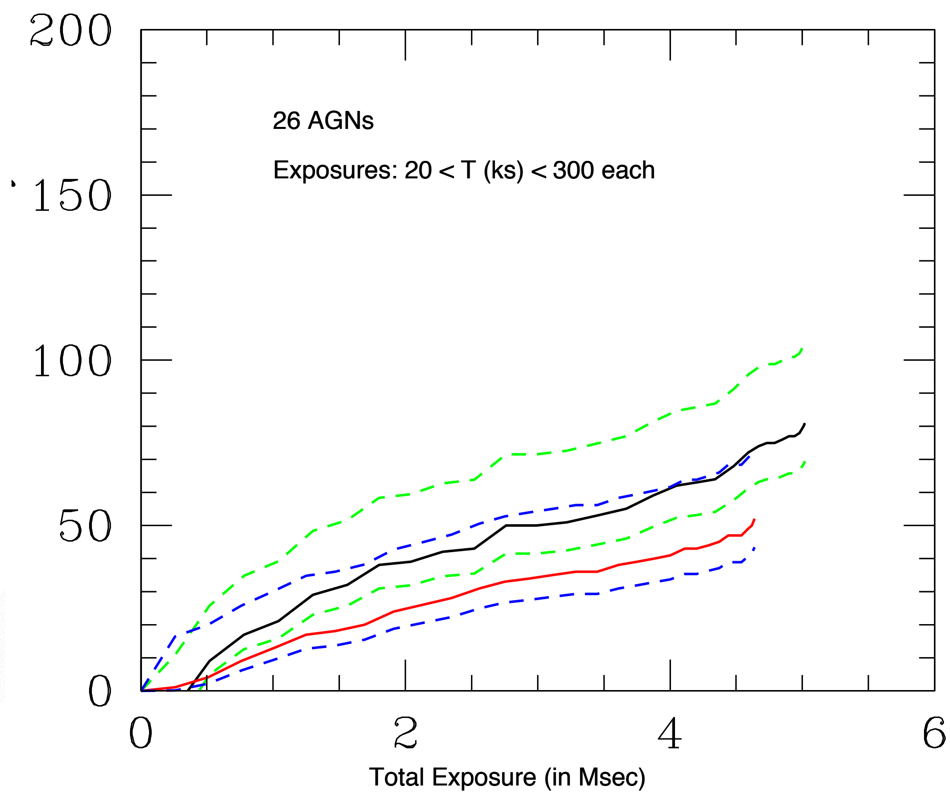
Athena X-IFU Effective Area



Athena (& Arcus): No. of Systems

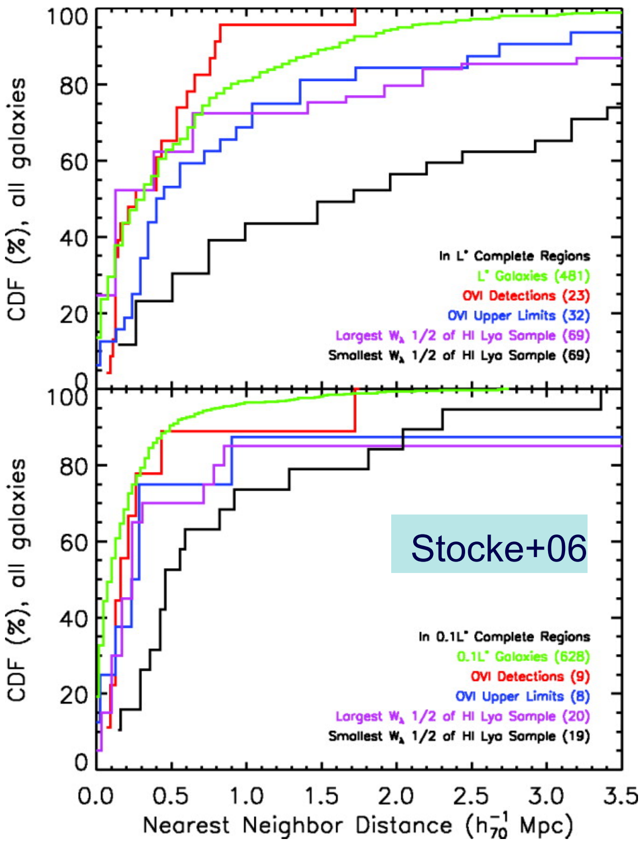


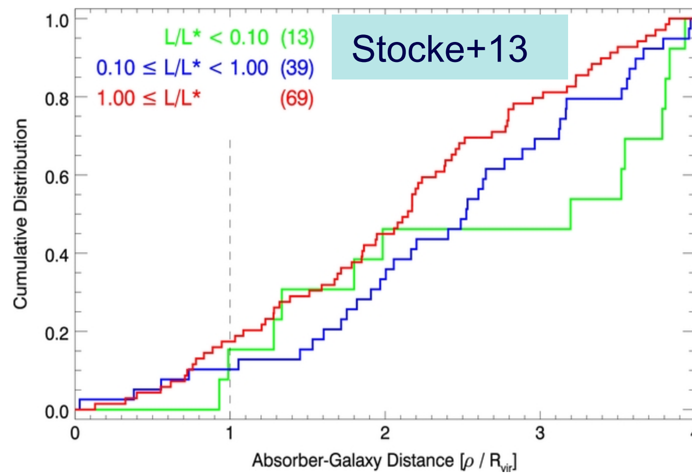
160 ks Athena-XIFU on 1ES 1553+113

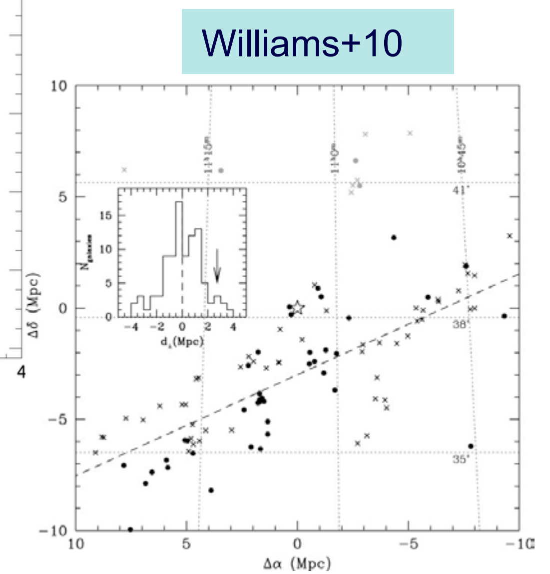


Athena(/Arcus) will detect about 100(/50) filaments against bright AGNs
(R and A_{eff} compete)

Galaxy Environment of WHIM Filaments (LSS Formation)
Synergies with mm/O/IR (1)





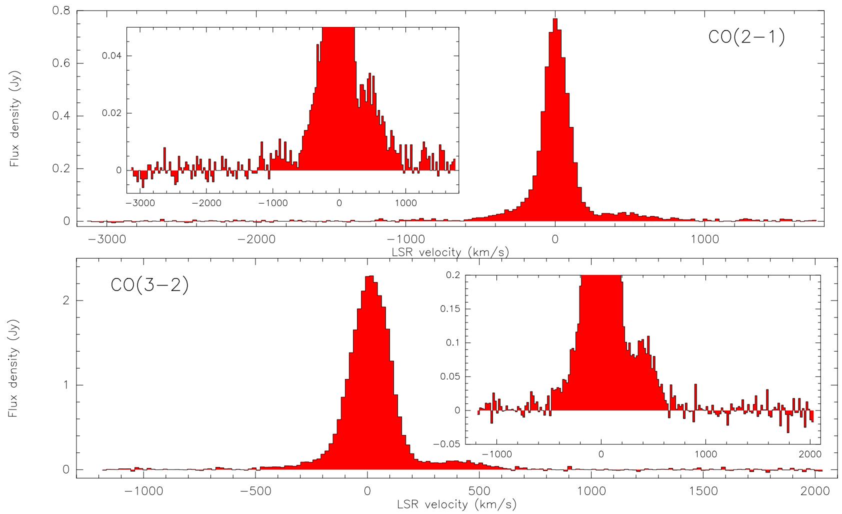


ELT:

- identify galaxies within 5-10 Mpc from Athena's WHIM prior at least down to 0.01 L*
- Measure relative distances and clustering properties (filamentary structure or groups)
- Distance to nearest AGNs

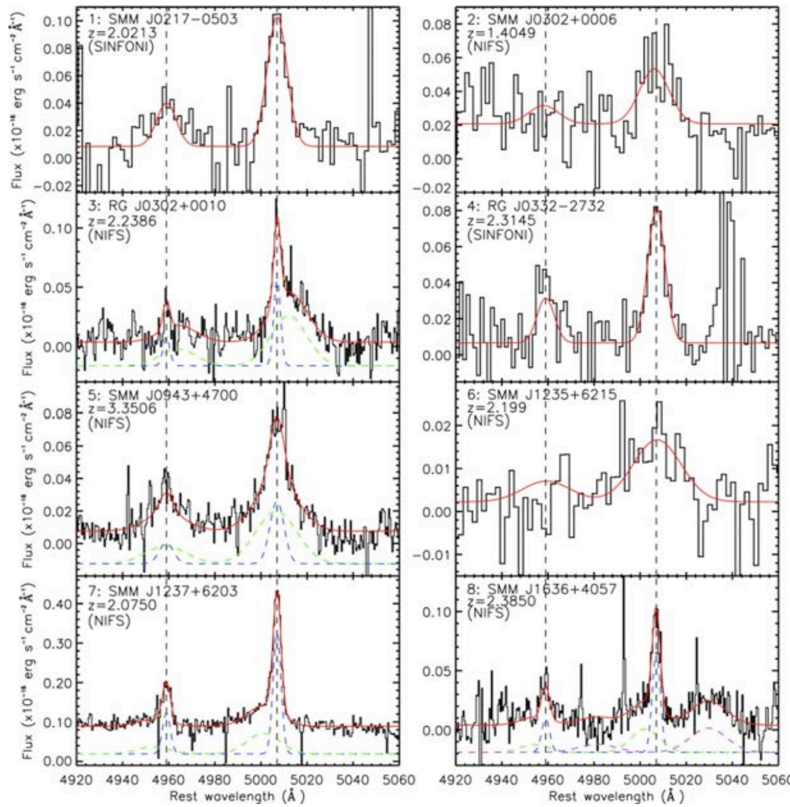
Feedback between virialized and non-viriliazed structures
Synergies with mm/O/IR (2)

kpc-scale molecular outflow in Mkn 231 (Feruglio+15)



ELT (HARMONY) + ALMA (bands 2-10):

- Detect atomic and molecular outflows in galaxies surrounding Athena's prior
- Measure outflow energetic to assess galaxy/IGM feedback potential
- Athena-XIFU/WFI spectra of galaxies in the field can detect high-ionization Ultra-Fast Outflows



Broad (FWHM= 900-1500 km s-1) and red/blue-shifted components of [OIII] doublet in 8 ULIRGs (Harrison+12)

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.
- Athena (2032) will make a tomography of the WHIM and will detect ~200 filaments against 26/39 bright AGNs and GRBs.
- Strong synergies with mm/O/IR will allow us to (a) identify WHIM-galaxy associations and map the structure of galaxy (and so DM) clustering; (b) study the interplay between galaxy and AGN outflows and the IGM (feedback)
- NEW ATOMIC DATA OF X_RAY INNER-SHELL TRANSITIONS URGENTLY NEEDED TO PROPERLY IDENTIFY ALL ISM TRANSITIONS