The Universe Missing Mass

Physics, Metallicity and Kinematics

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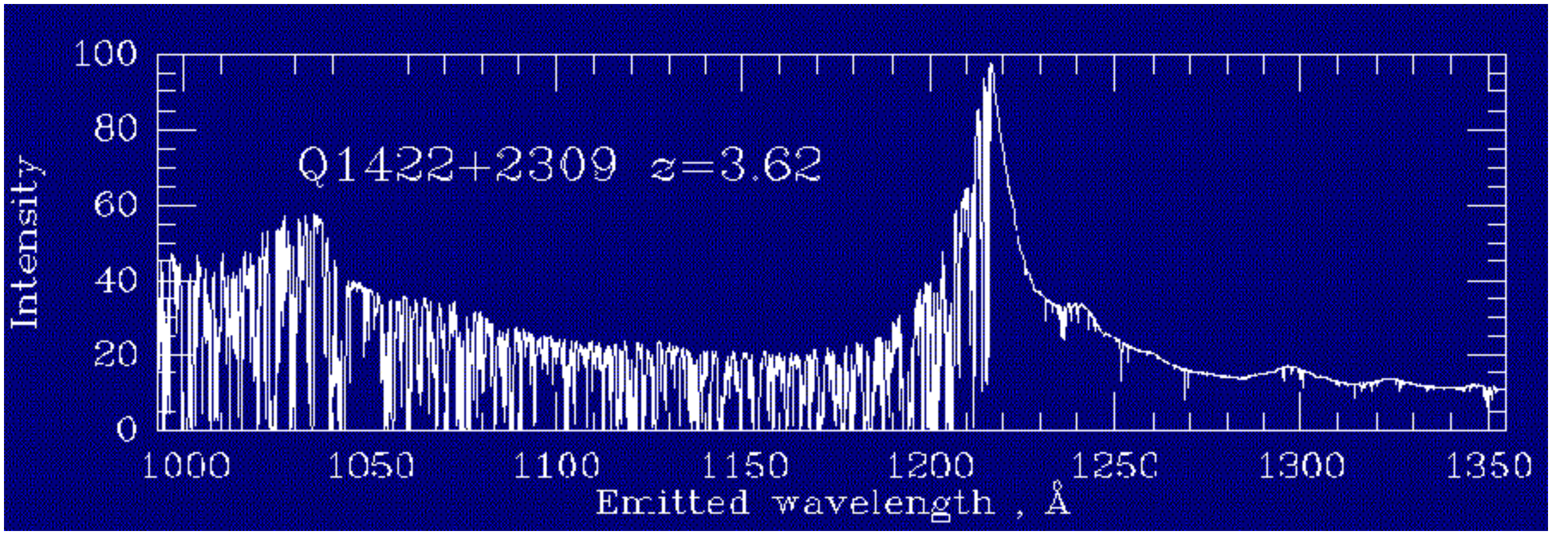
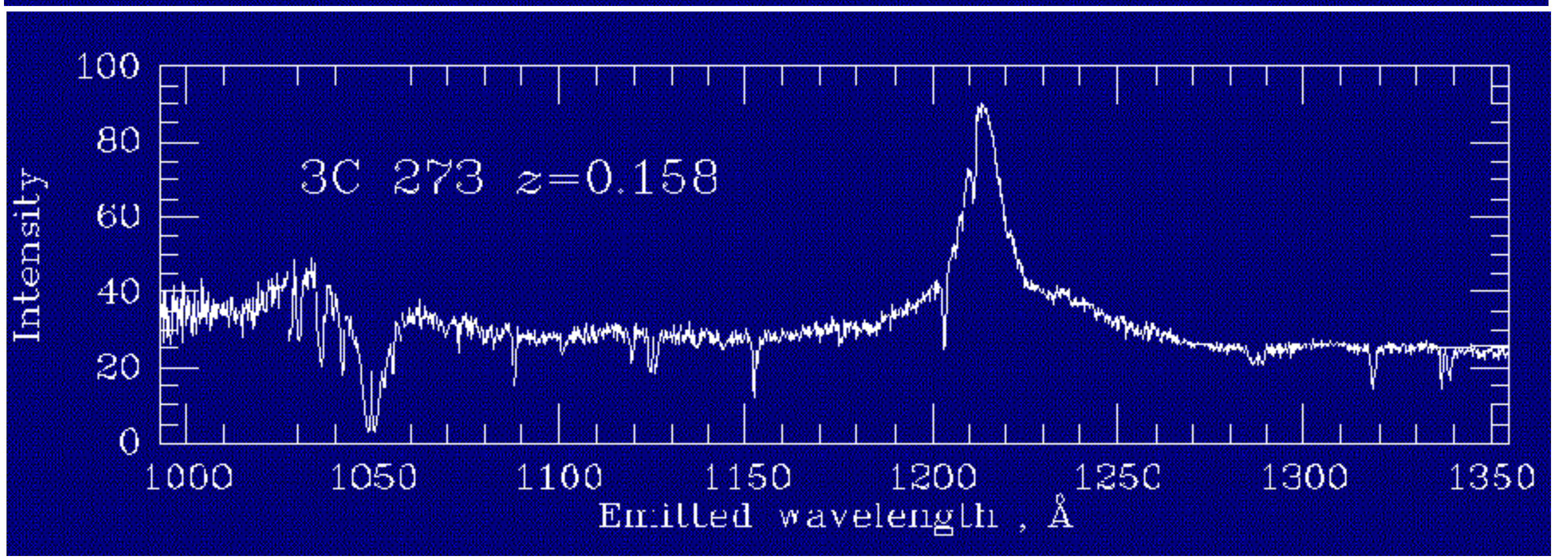
Outline

- 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?



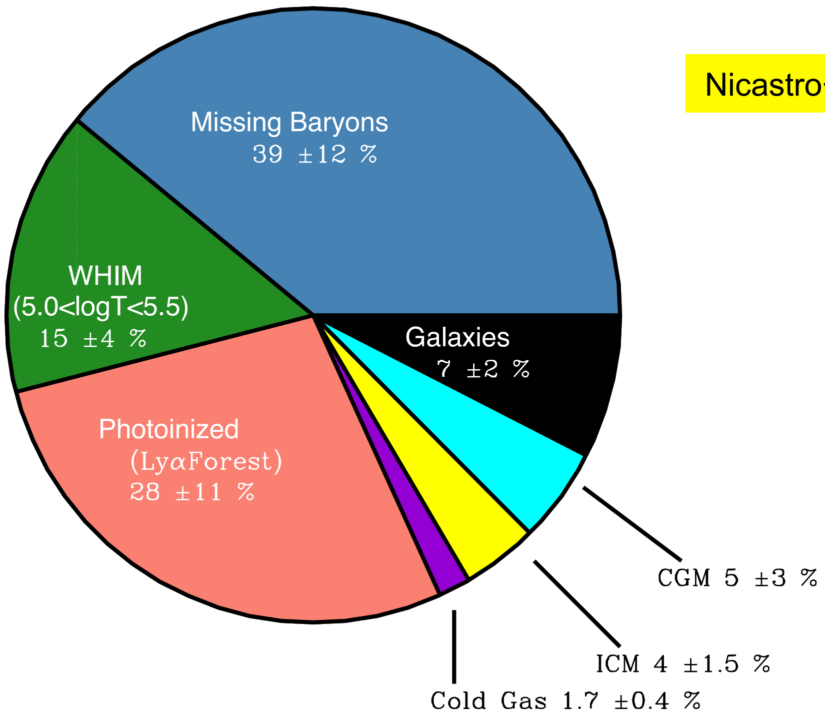


The Missing Baryons Problems

The Universe

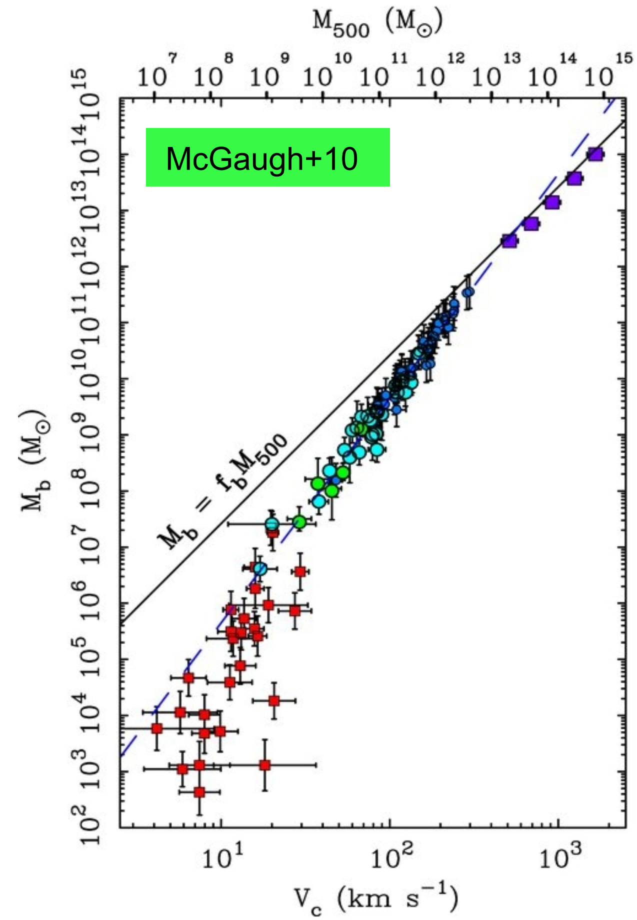
$\Omega_b^{Planck+15} = 0.0487 \sim 5\%$

Nicastro+16



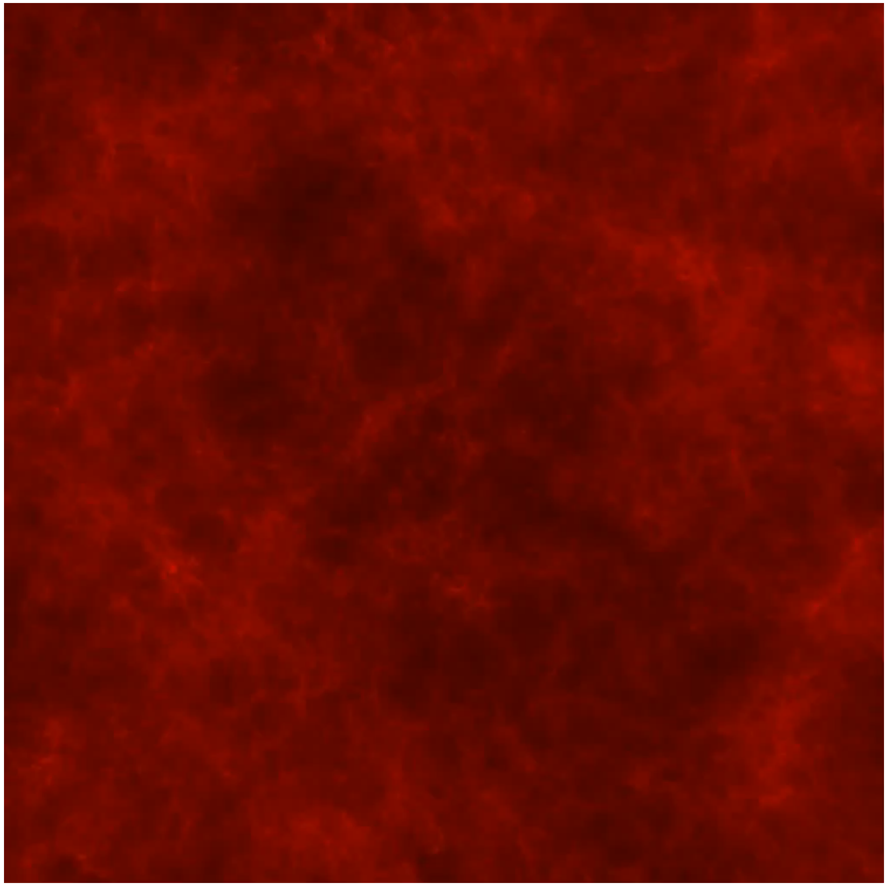
~ 30-50% of Baryons missing at z~0

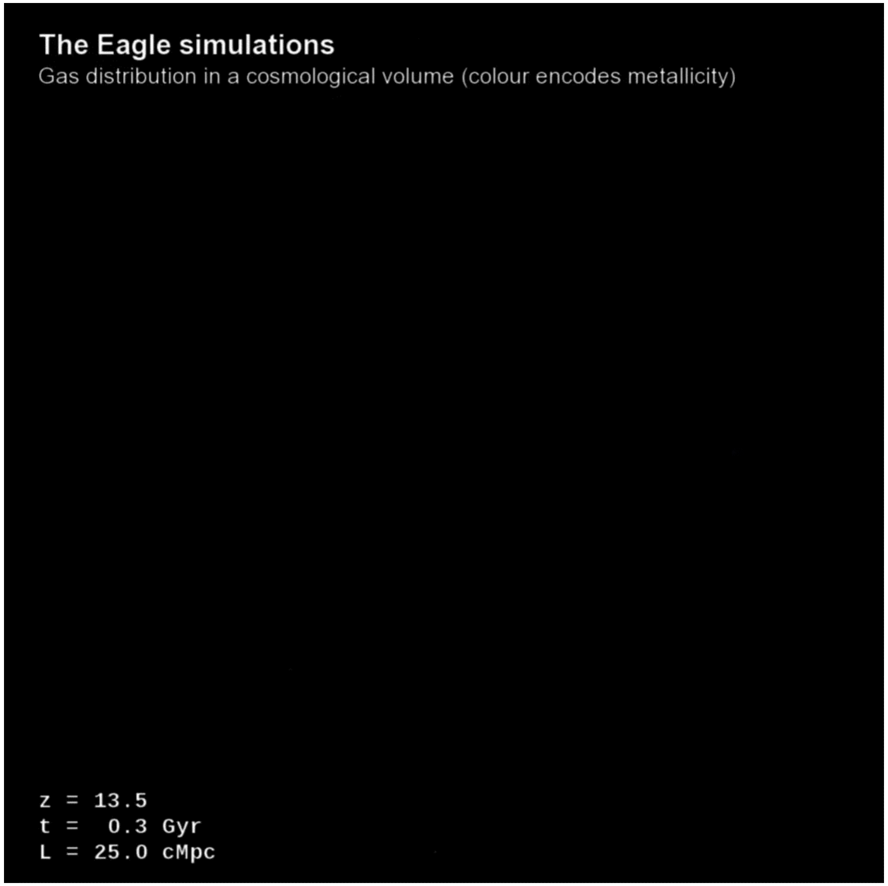
The Galaxies



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

Why do we care?



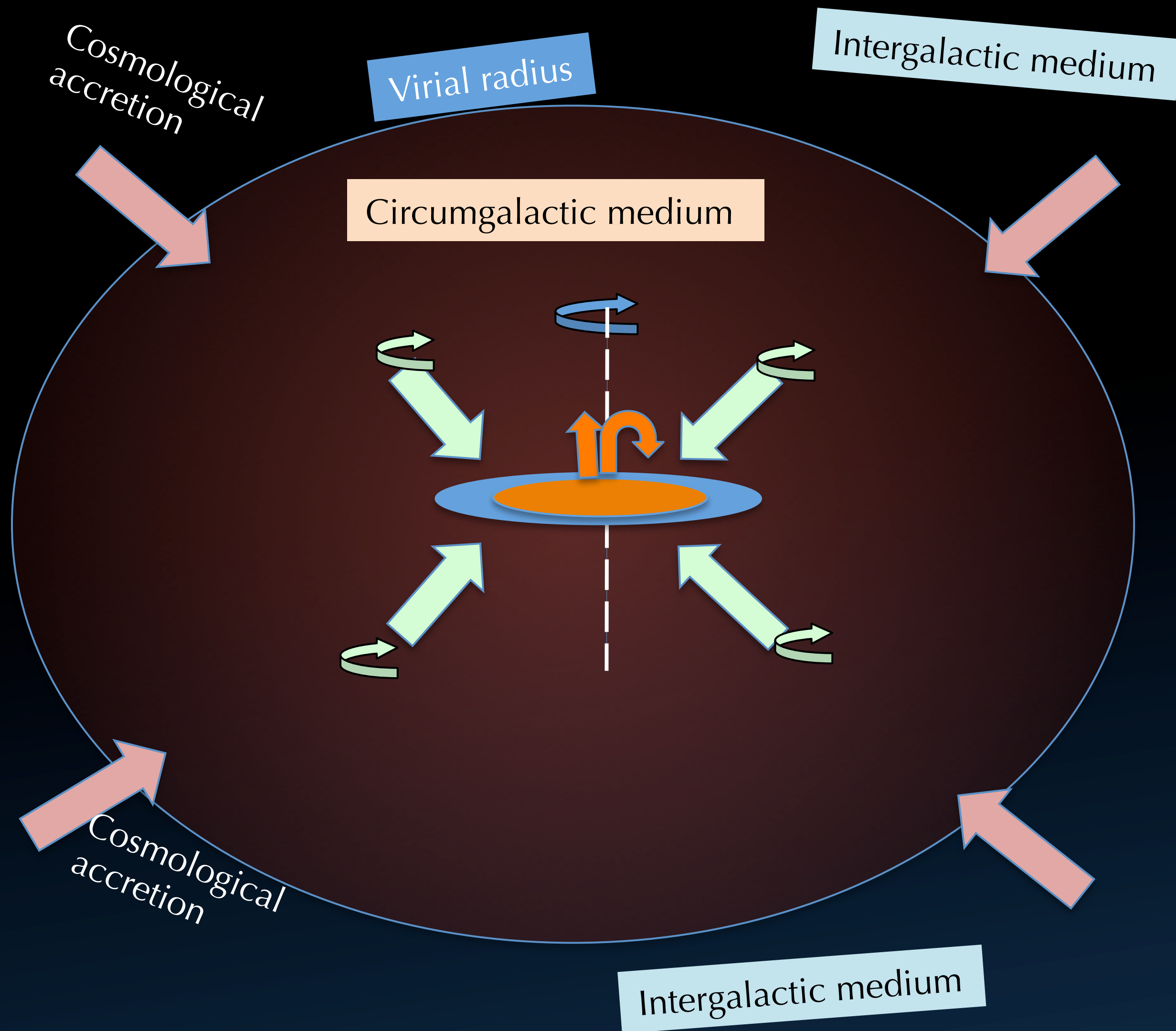


Temperature

Metallicity

Schaye et al. (2015)

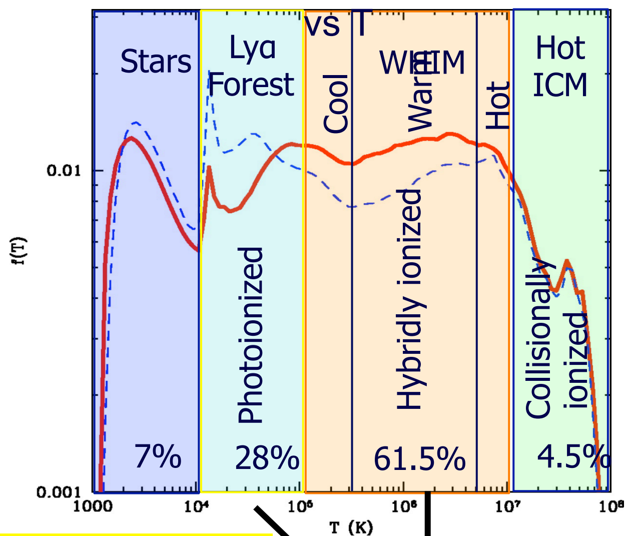
Close to the nodes: Galaxy growth



Credits F. Fraternali

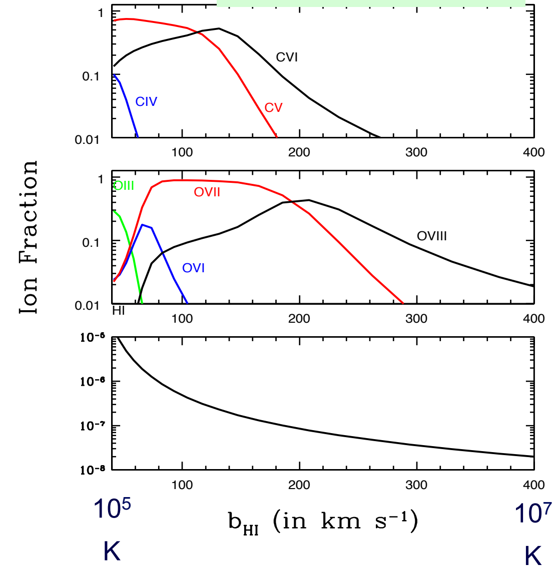
The Baryon Phases in HDS

Differential Mass Fraction

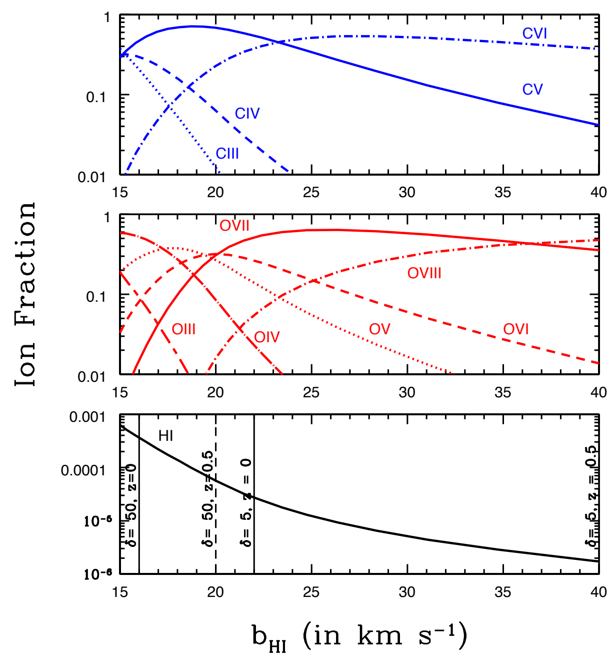


Cen & Ostriker 06

Hybridly Ionized IGM (δ=50)



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



Photoionized IGM

The Milky Way's Baryon Problem

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

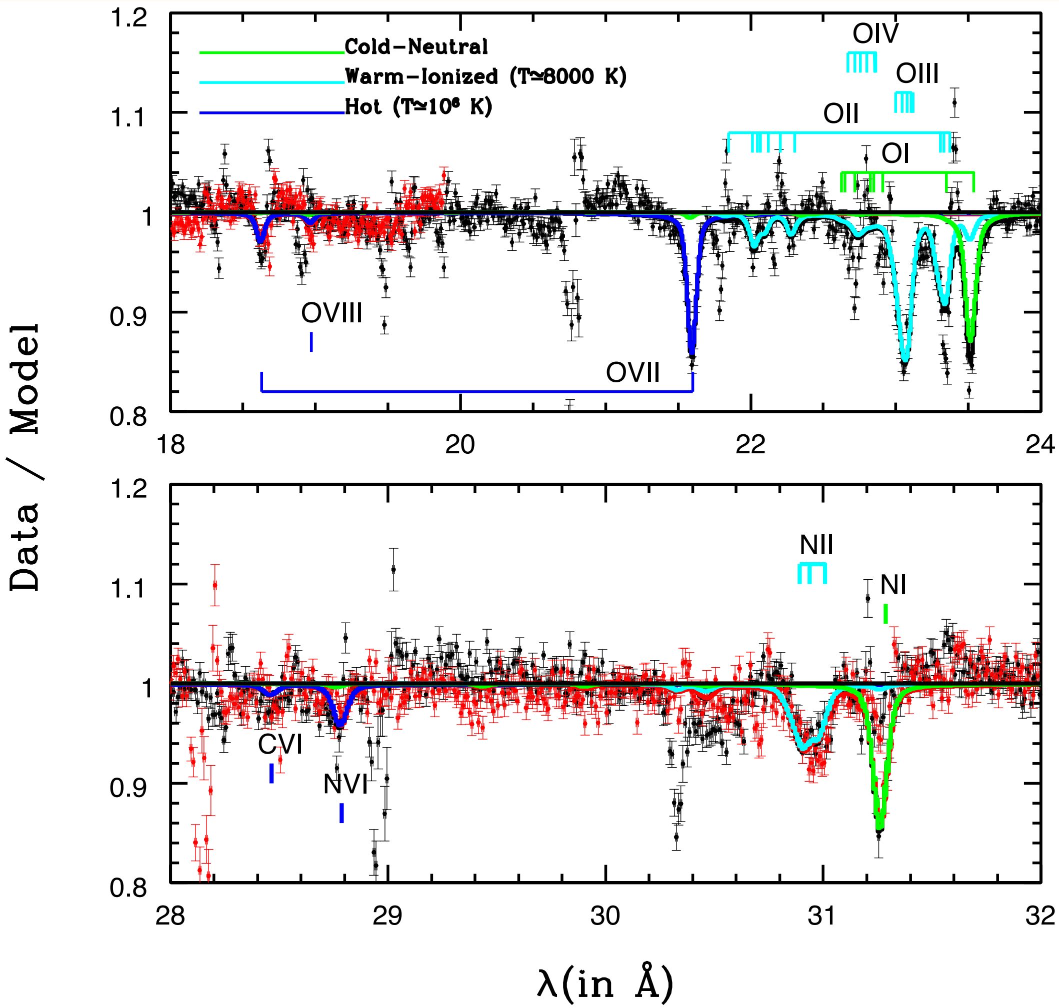
➔ $M_b/(M_b)^{Obs} \approx 2.5\text{-}5$

$$M_b^{Missing} \approx (1.5\text{-}3) \times 10^{11}\ M_\odot$$

Milky Way: Gaseous baryons in all phases

ISM/CGM Spectrum

XMM-Newton RGS Spectrum of Mkn 421 (z=0.03) Nicastro+19, in prep.

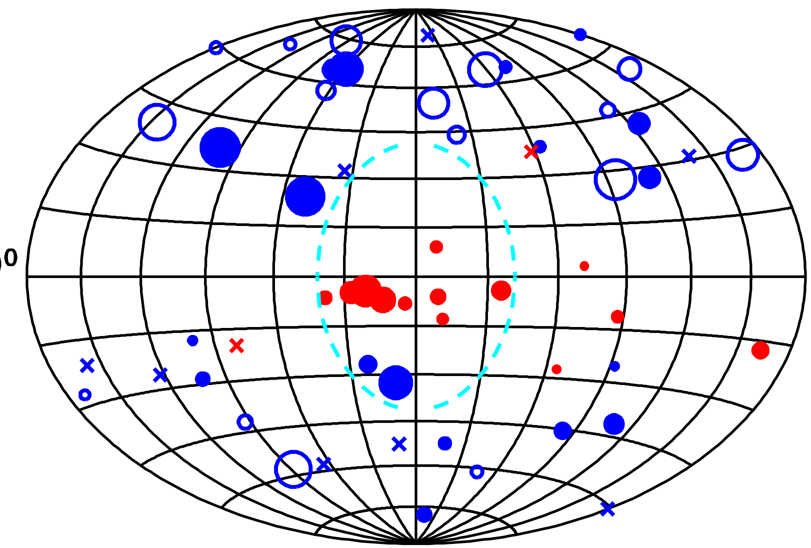


CNMM and LIMM are (mostly) confined in the thin and thick disks.

Where is the HIMM?

The Optimal HIMM Sample

- High Galactic Latitude (HGL) + Low Galactic Latitude (LGL)
- Complete to SNRE>10 at 22 Å
- Remove N_{OVII}-b Degeneracy through Kα-Kβ CoG comparison



Nicastro+16a,b
Nicastro+19, in prep.

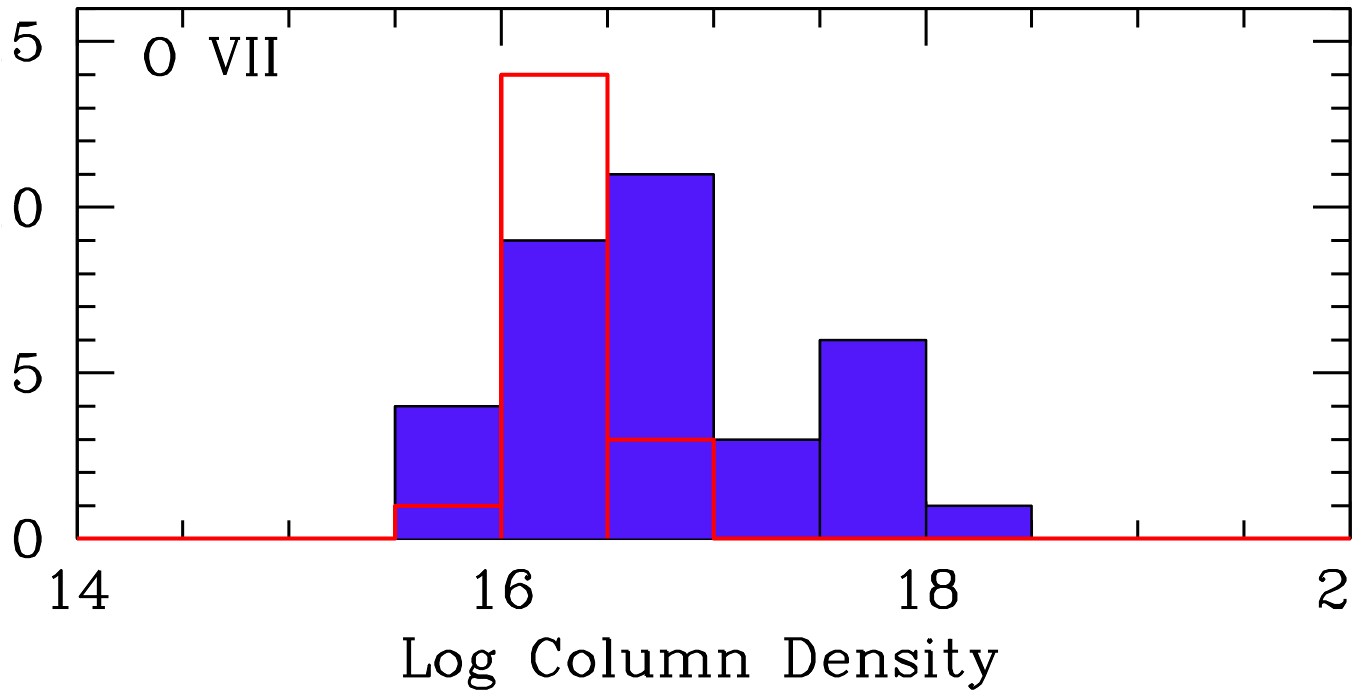
18/20 (90%) LGLs have OVII, but only 14 known distance
34/39 (87%) HGLs have OVII, but only 18 Kα & Kβ

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

➔ HIMM surely in the Disk

➔ If HGL and LGL's HIMM properties differ ➔ both in the Disk and Extended Halo

Hot Plasma Permeates a Large Galactic Volume



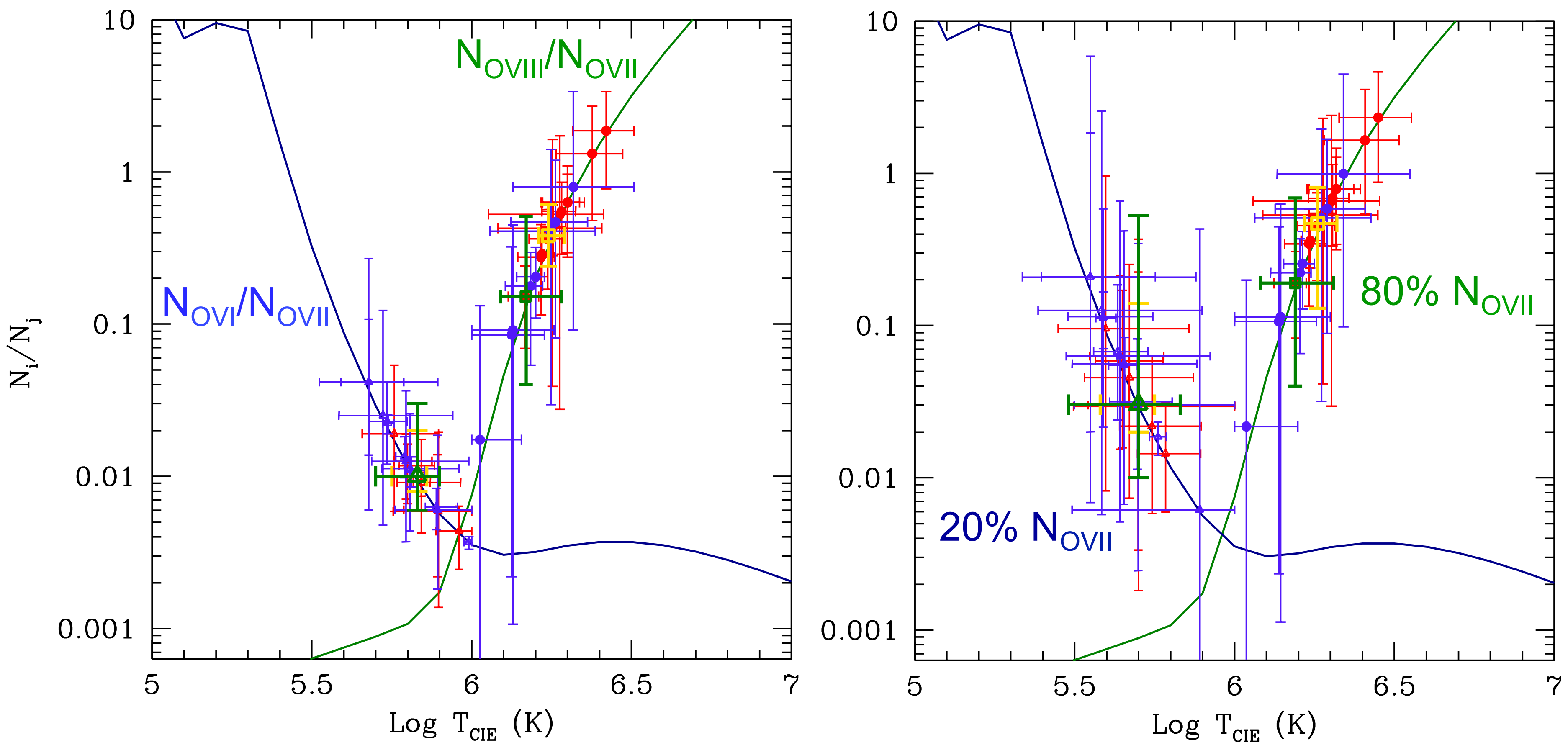
$<N_{OVII}(LGL)> = (2.3^{+1.4}_{-1.2})\times10^{16}$ cm^{-2}; $<b_{OVII}(LGL)> = (110^{+50}_{-40})$ km s^{-1}

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

HGL-HIMM Significantly Thicker then LGL-HIMM

➔ The HIMM permeates both the Galactic Disk and Halo

HIMM: at least 2 Phases



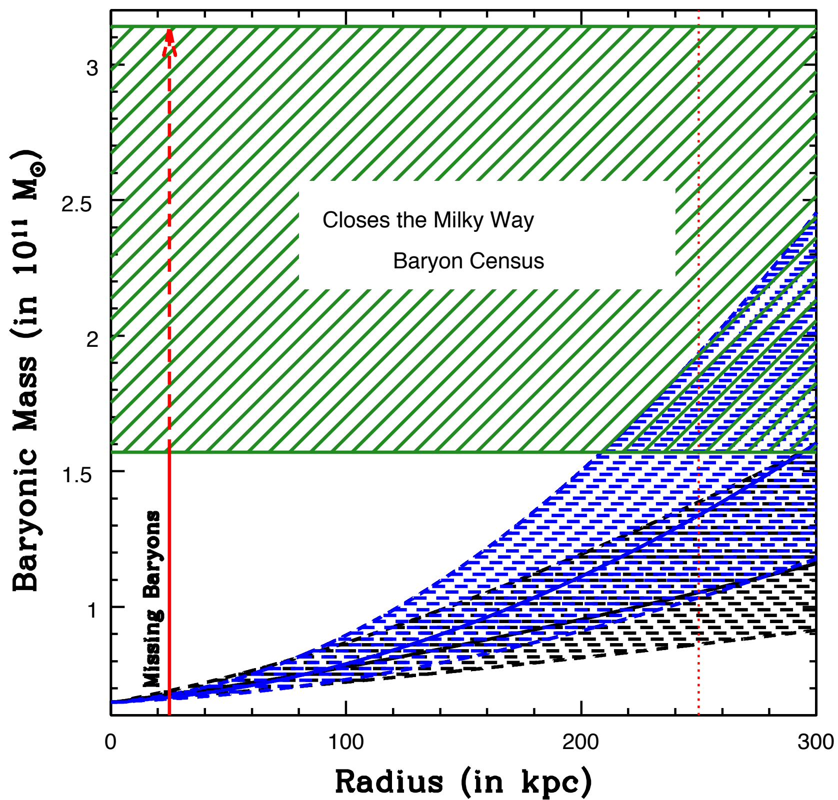
Two Distinct Components both in the Disk and the Halo

1. Warm (OVI-traced): T~4x10^5 K (if coll. Ionized)
2. Hot (OVII,OVIII-traced): T~2x10^6 K (MW Virial Temperature)

HIMM Mass Profile

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)



Size: R(B)>170 kpc

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

- May close the Galaxy's Baryon Census
- 6-kpc central cavity traces Fermi Bubble and Plank-Haze (highly multiphase) and echoes last AGN activity 6 Myrs ago

The Galaxy's Gaseous Baryons
Summary

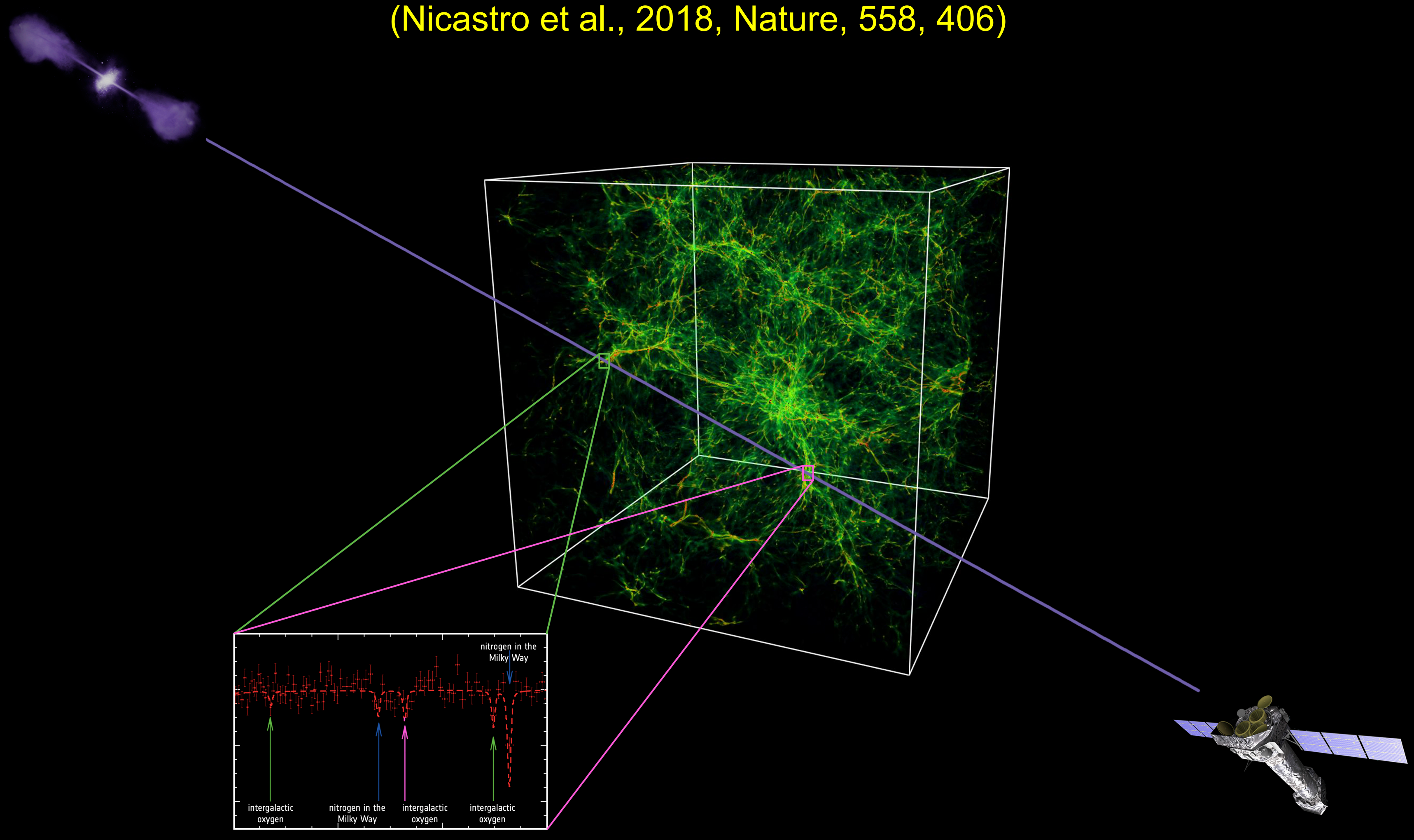
- Million-degree Gas permeates both the Disk and Halo of our Galaxy and co-exist with dense cold and cool gas

- 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

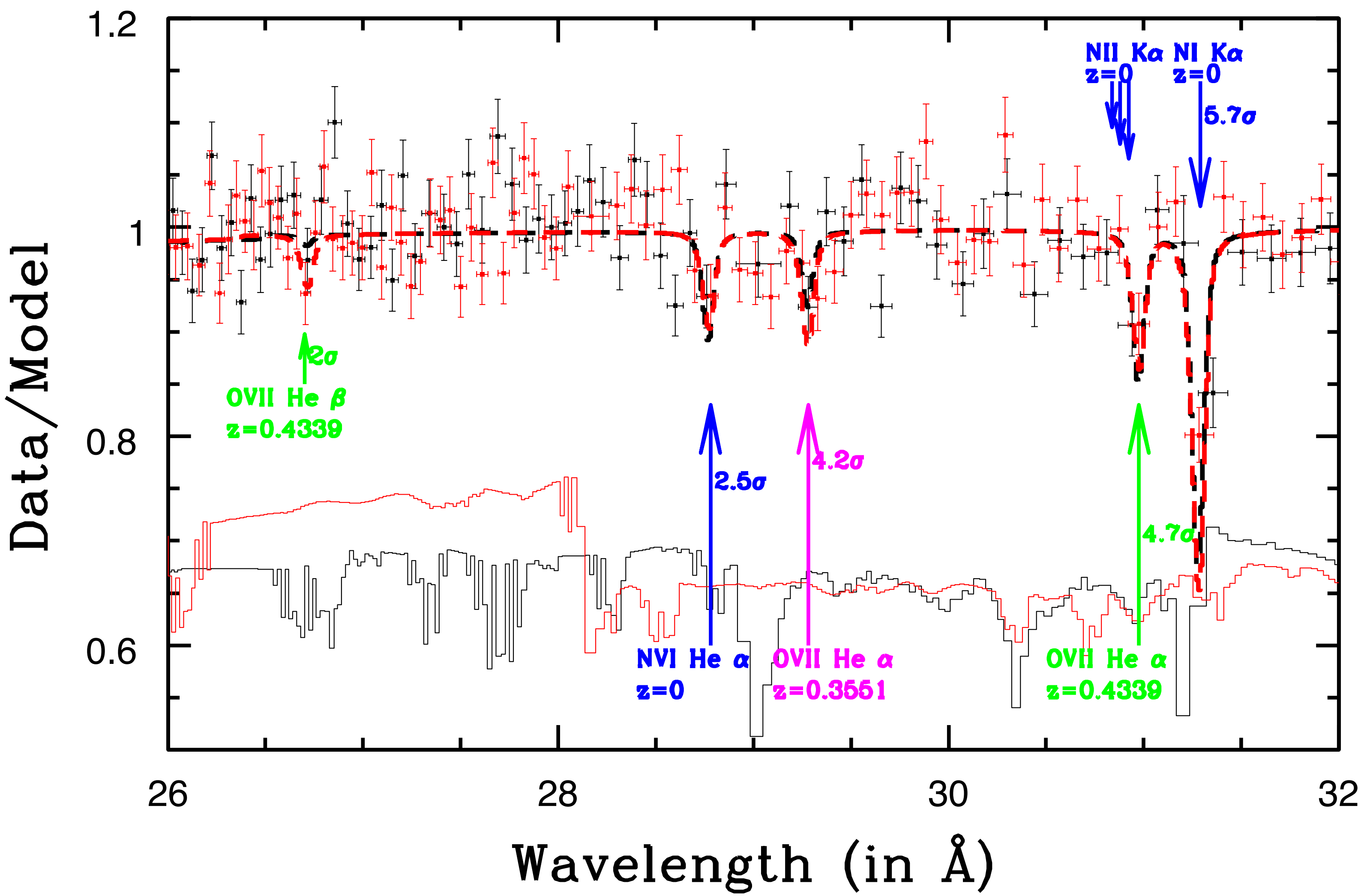
- The Mass of the OVII-bearing Gas may be sufficient to close the Galaxy's Baryon Census

The Universe Missing Baryons

(Nicastro et al., 2018, Nature, 558, 406)



26-32 Å RGS Spectra

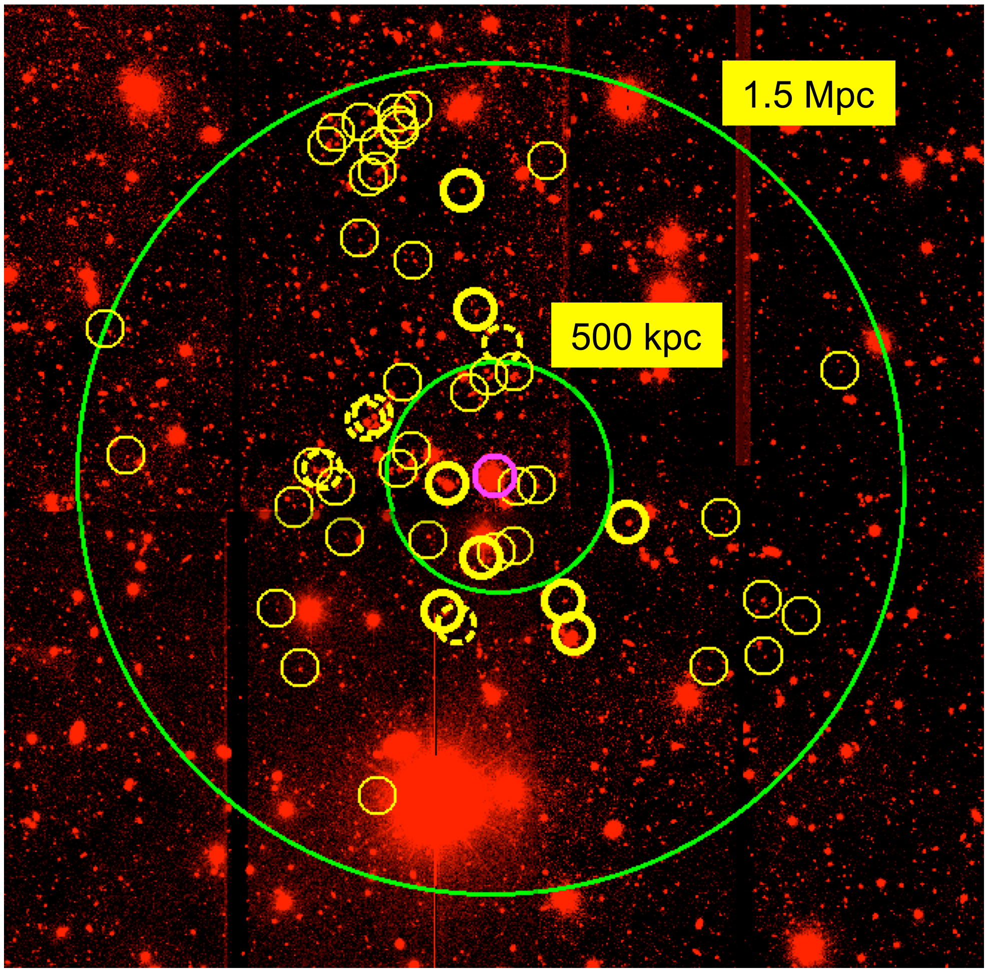


Diagnostics

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

System-1: Large Galaxy Overdensity



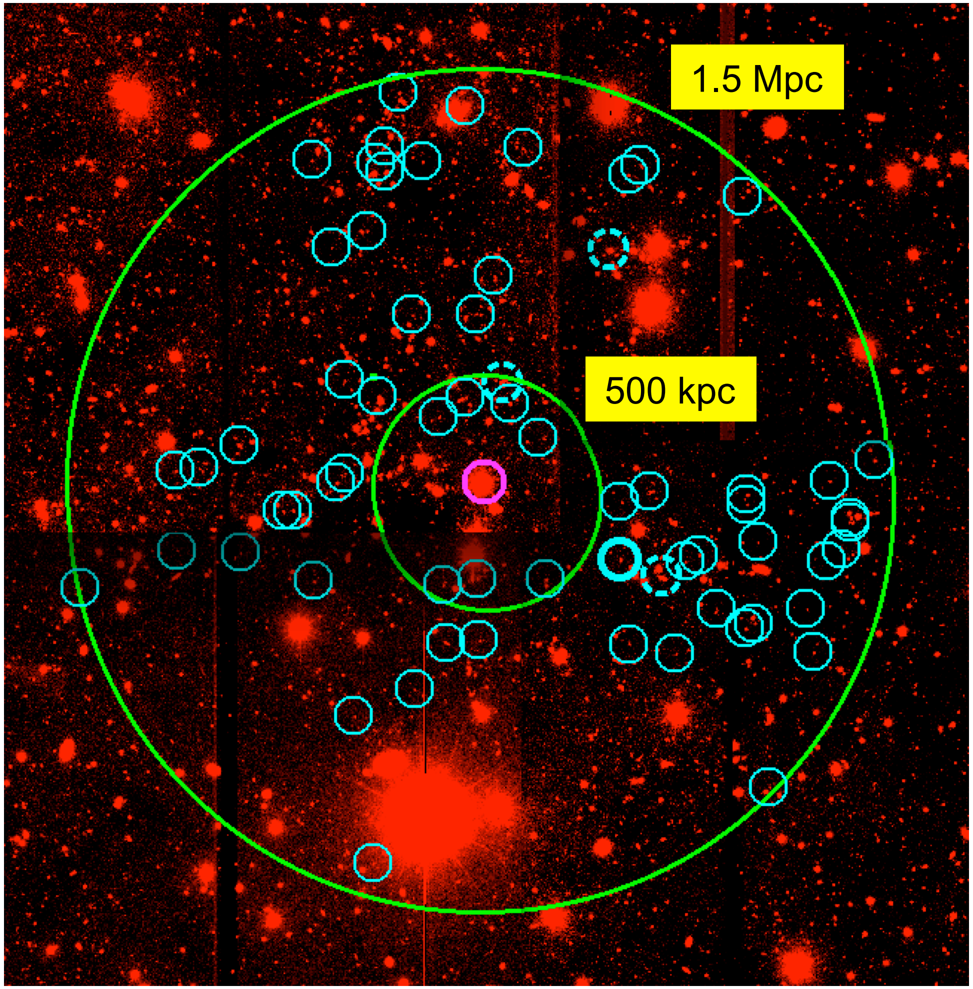
8/13 spectroscopically confirmed galaxies within ±900 km s^{-1}

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: 0.5 Mpc Void



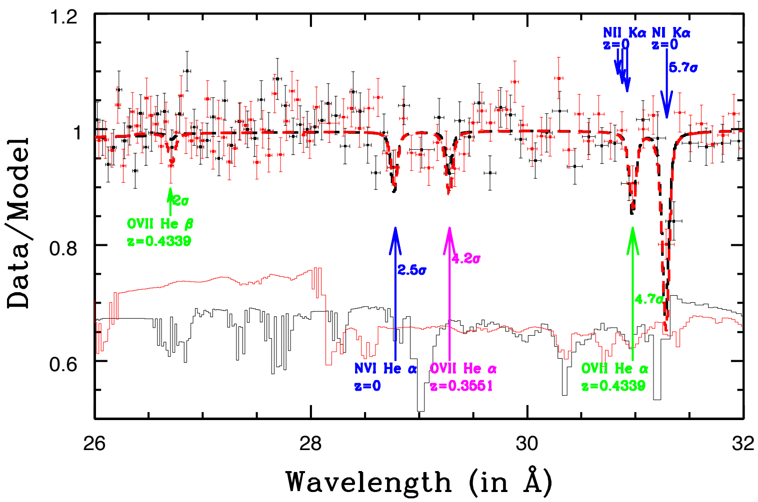
Only 4/72 galaxies within the 1.5 Mpc radius circle have spectroscopic redshifts

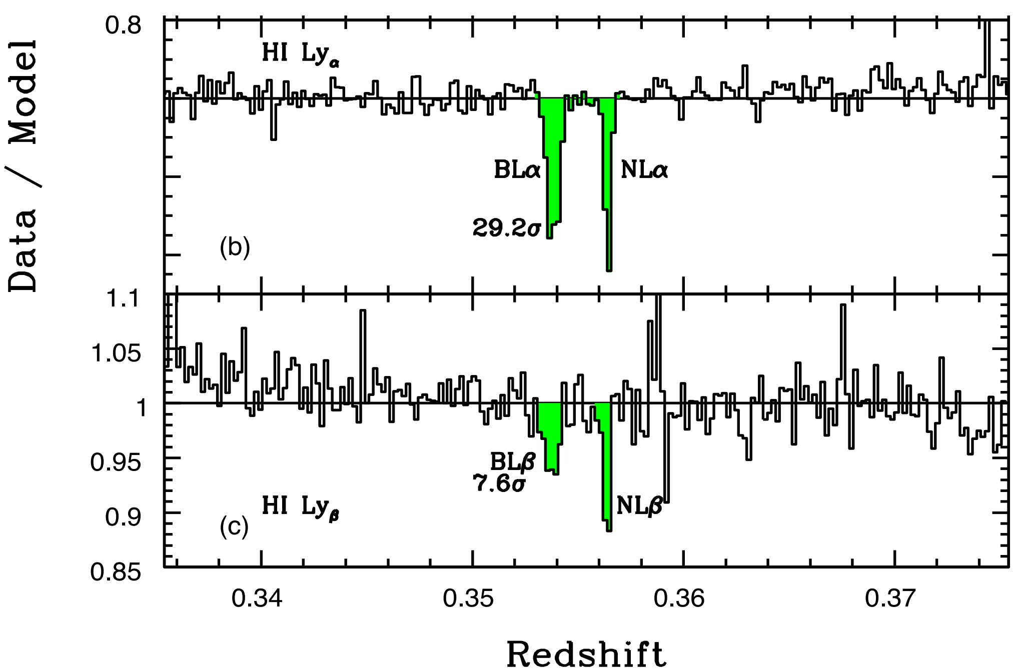
Only 1/4 is confirmed at the redshift of the absorber (a i'=20.5 elliptical), but lies at d=633 kpc and +370 km s^{-1}

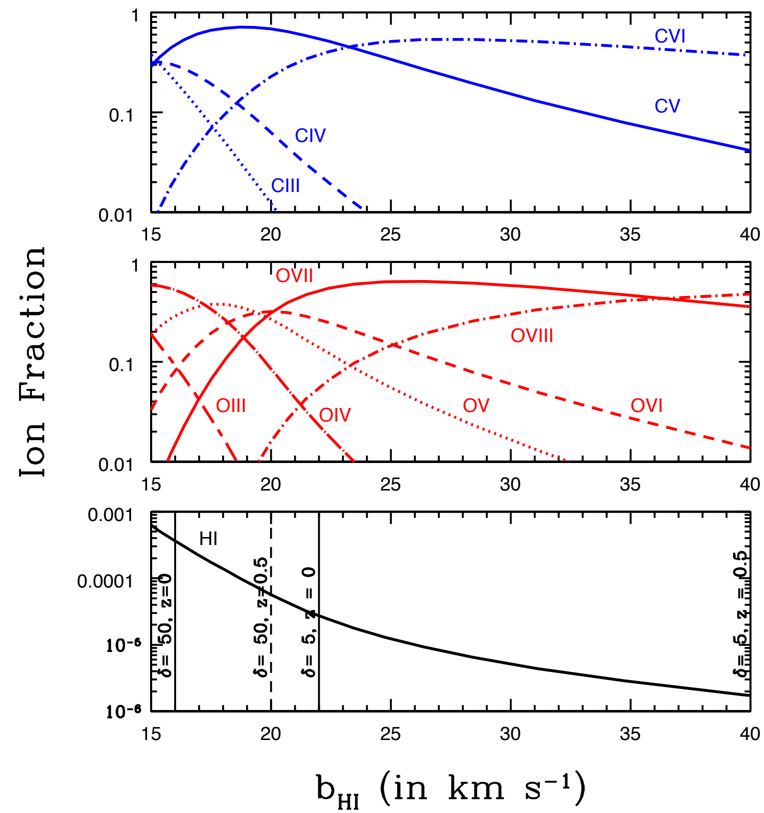
➔ Low Density Photo-Ionized IGM?

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

Photoionized IGM?





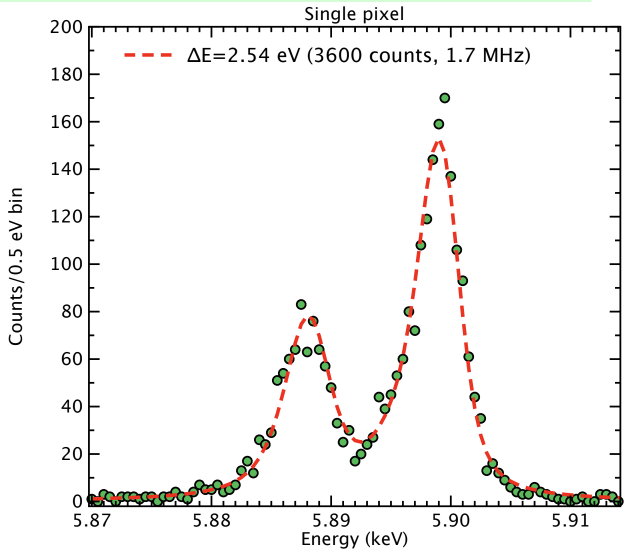


Long-term Future: Athena X-IFU (2030)

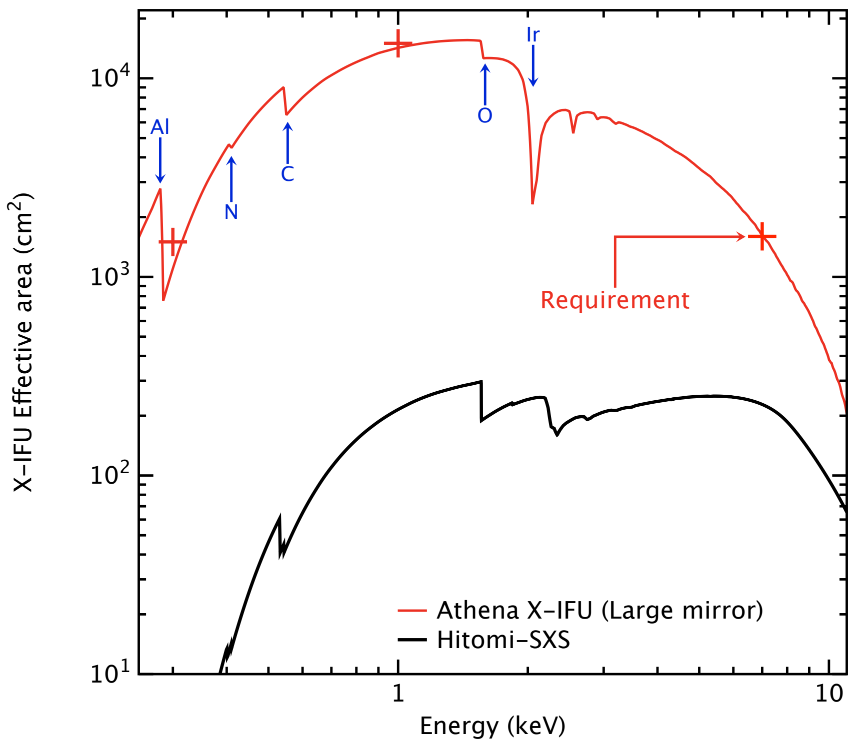
a Transition Edge Sensor (TES) microcalorimeter array with 3840 single pixels

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)

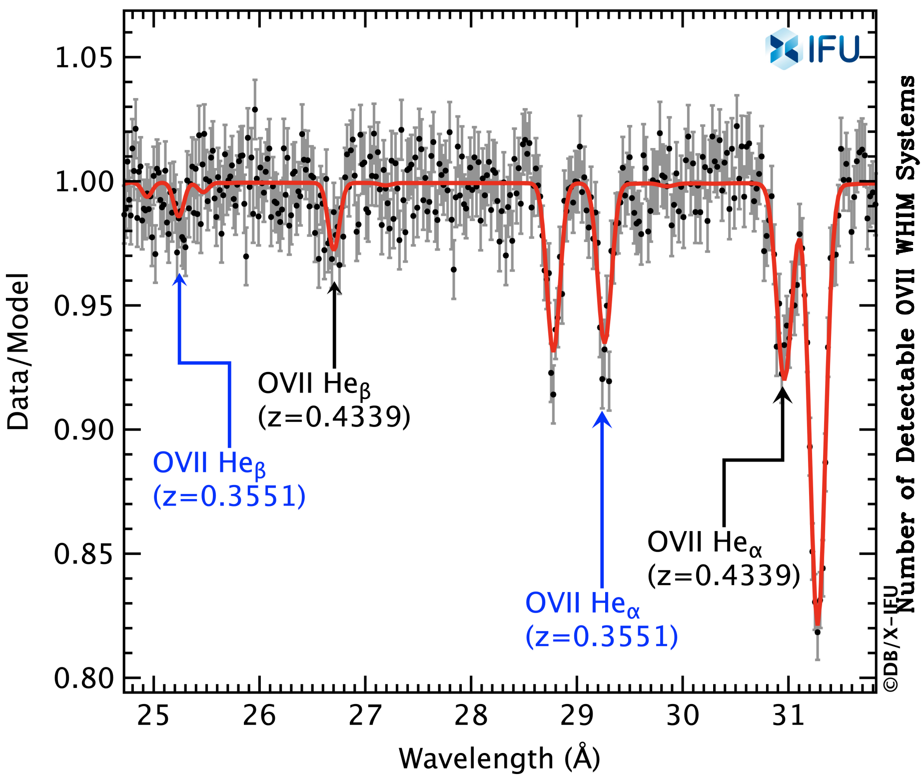
Athena X-IFU Measured Energy Resolution (2.5 eV)



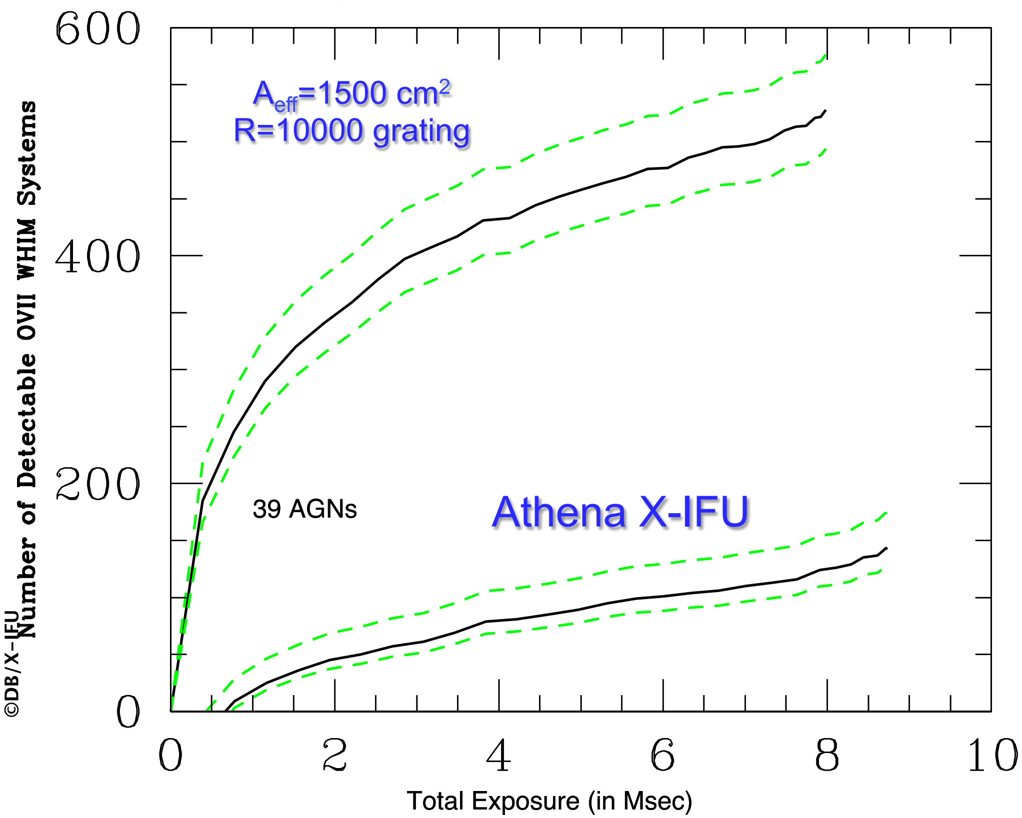
Athena X-IFU Effective Area



Athena: No. of Systems

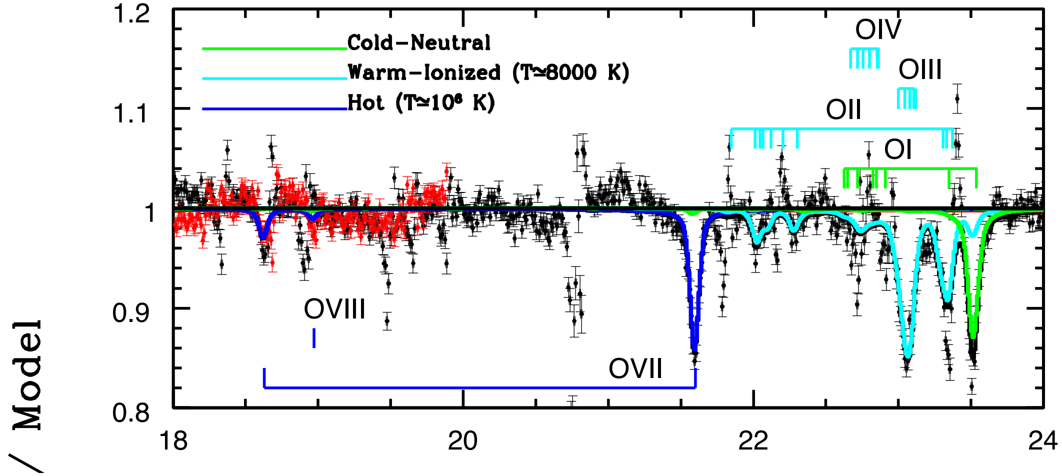


160 ks Athena-XIFU on 1ES 1553+113

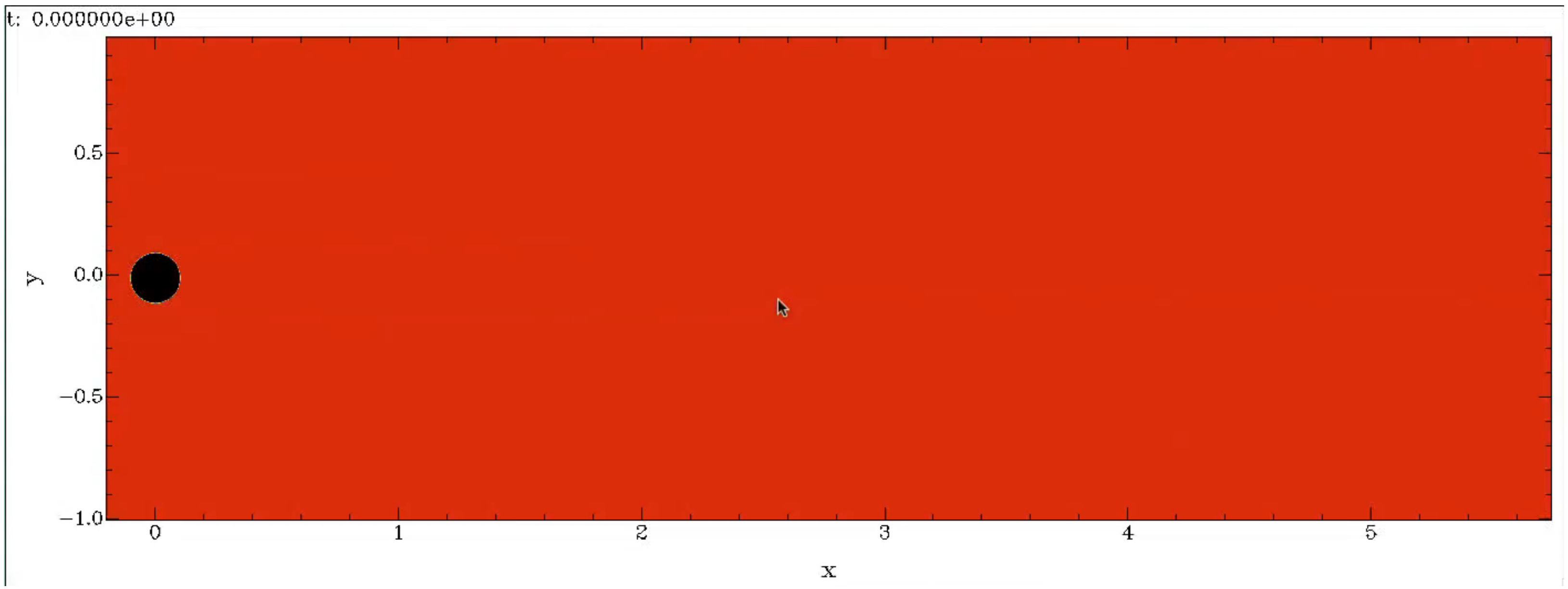


Athena will detect about 100 filaments against bright AGNs

Cold Cloud Traveling in Hot Halo



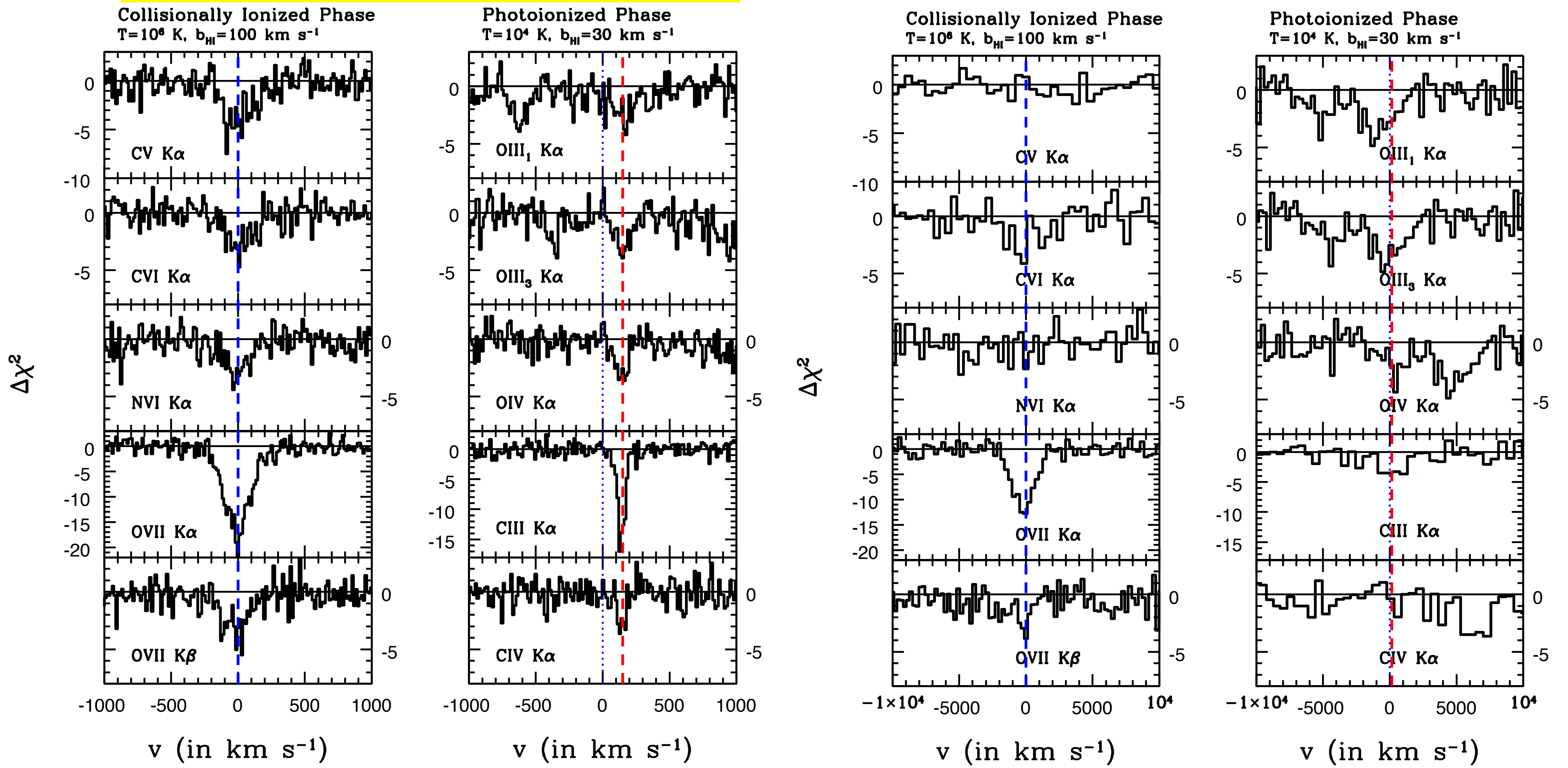
Armillotta+16 (Credit: F. Fraternali)



Physics, Kinematics and Metallicity of the IGM/CGM

LLS System in Lehner+13 at z=0.1672; v_{rel} = 150 km s^{-1}

HiReX (A_{eff}=1500 cm2; R=10000) — **Athena-XIFU (A_{eff}=10000 cm2; R=200)**



10x X-axis scale

Summary

- The first data confirm predictions: missing baryons to be found in Hot Intergalactic/ Circumgalactic Enriched Plasma

- Athena (2032) will make a tomography of the WHIM and will detect ~200 filaments.

- 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)

- To study in details, physics, kinematics and metallicity of the IGM/CGM, much higher resolutions are needed (ESA White-Paper for VOYAGE-2050 Science Themes)