The IGM at High Spectral Resolution

Physics, Metallicity and Kinematics of the Universe's Missing Mass with Future Spectrometers

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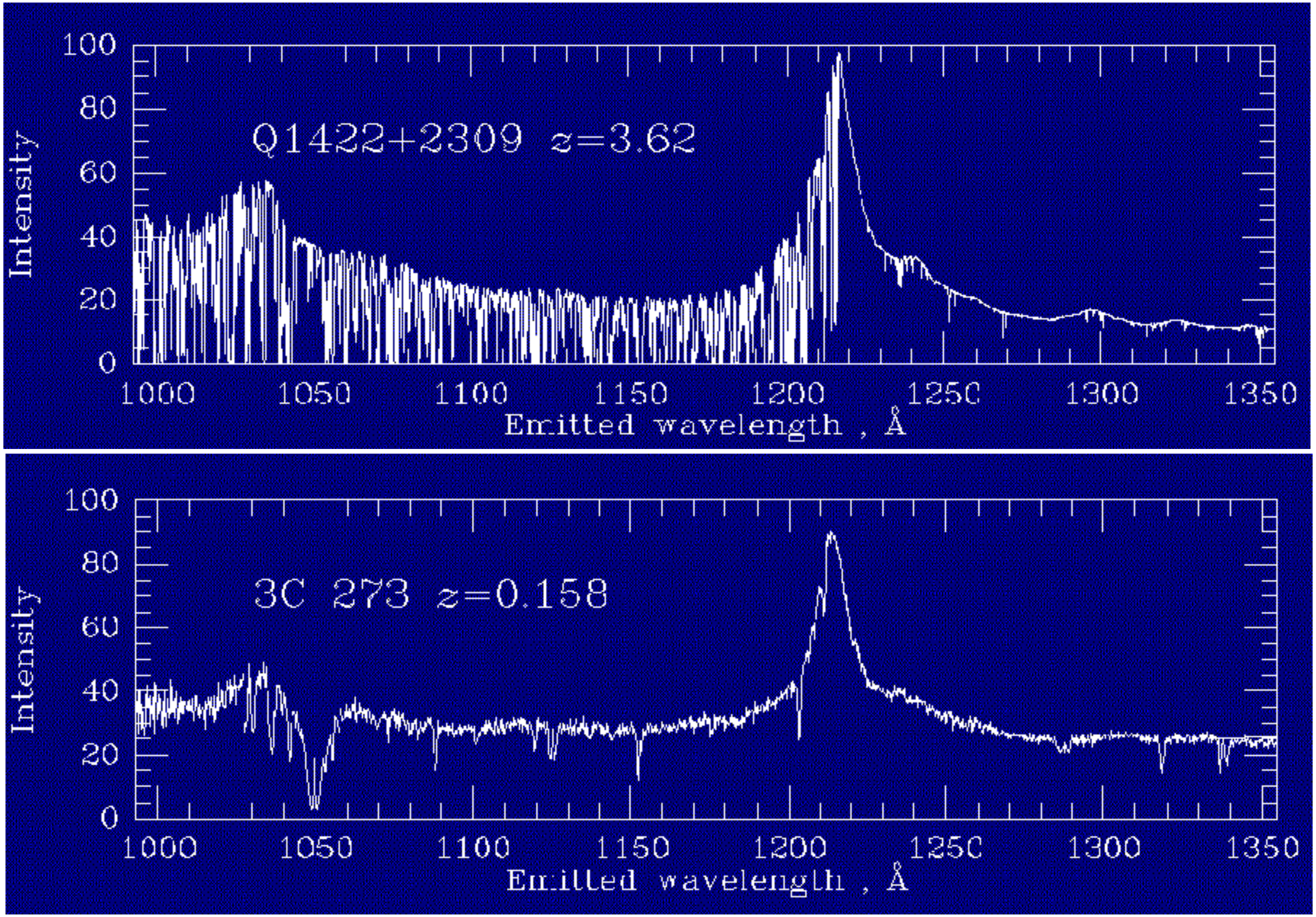
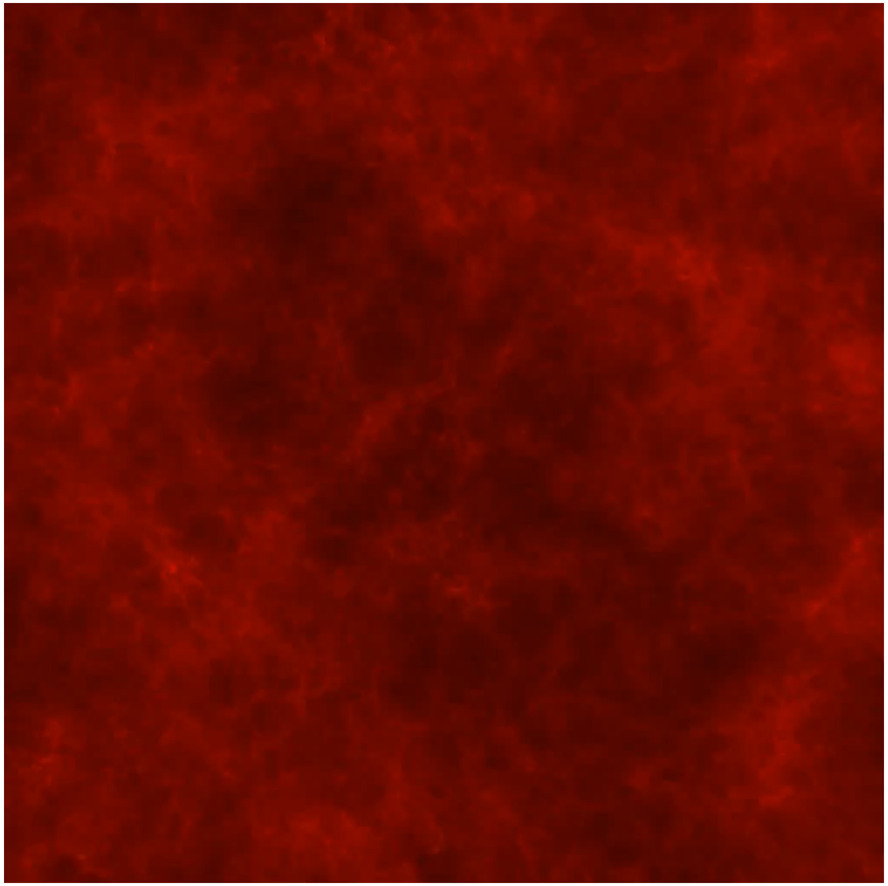
Outline

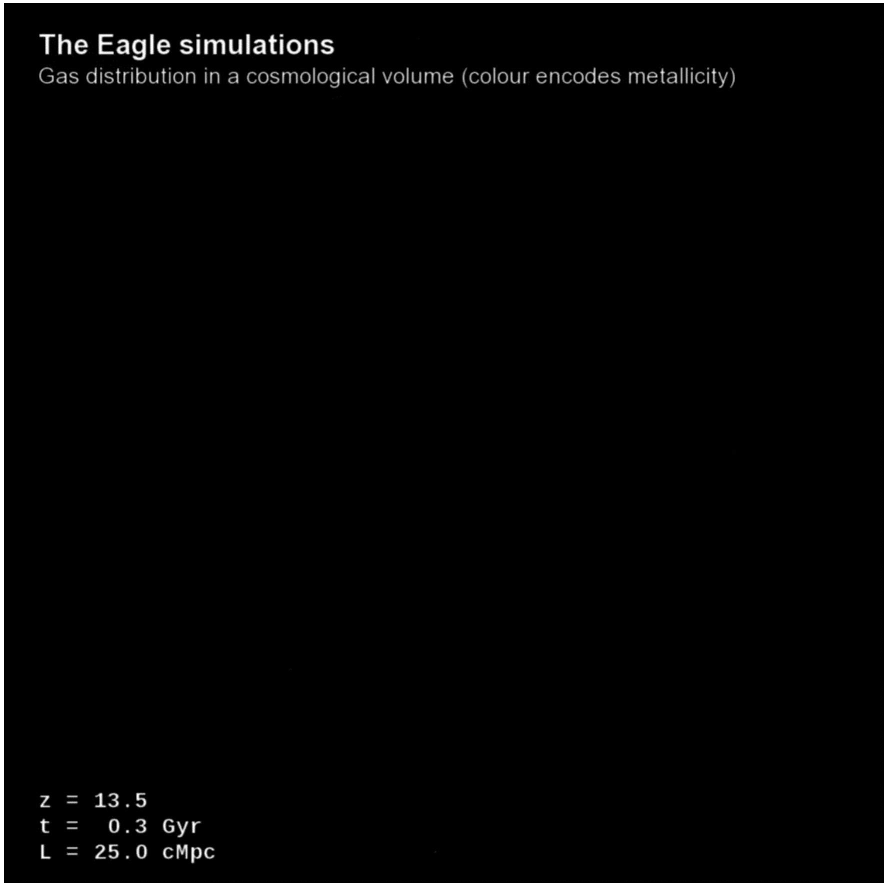
- The Missing Baryon Problems
- The Galaxy's Missing Baryons
- The Missing Baryons in a WHIM
- From current to next generation X-ray spectrometers.

Where have all the baryons gone?



Why do we care?



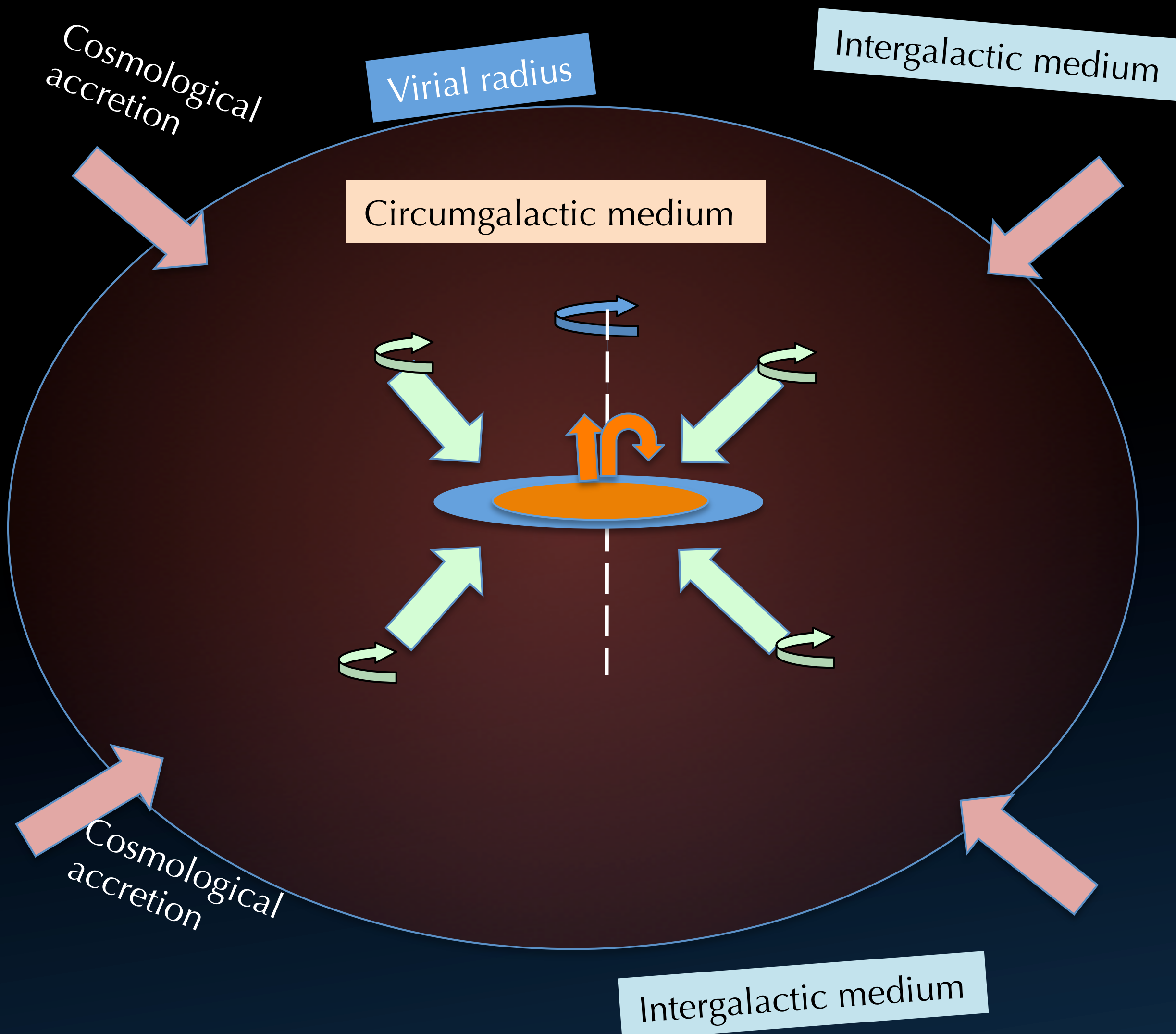


Temperature

Metallicity

Schaye et al. (2015)

Close to the nodes: Galaxy growth and IGM/CGM-Galaxy Feedback



Credits F. Fraternali

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)

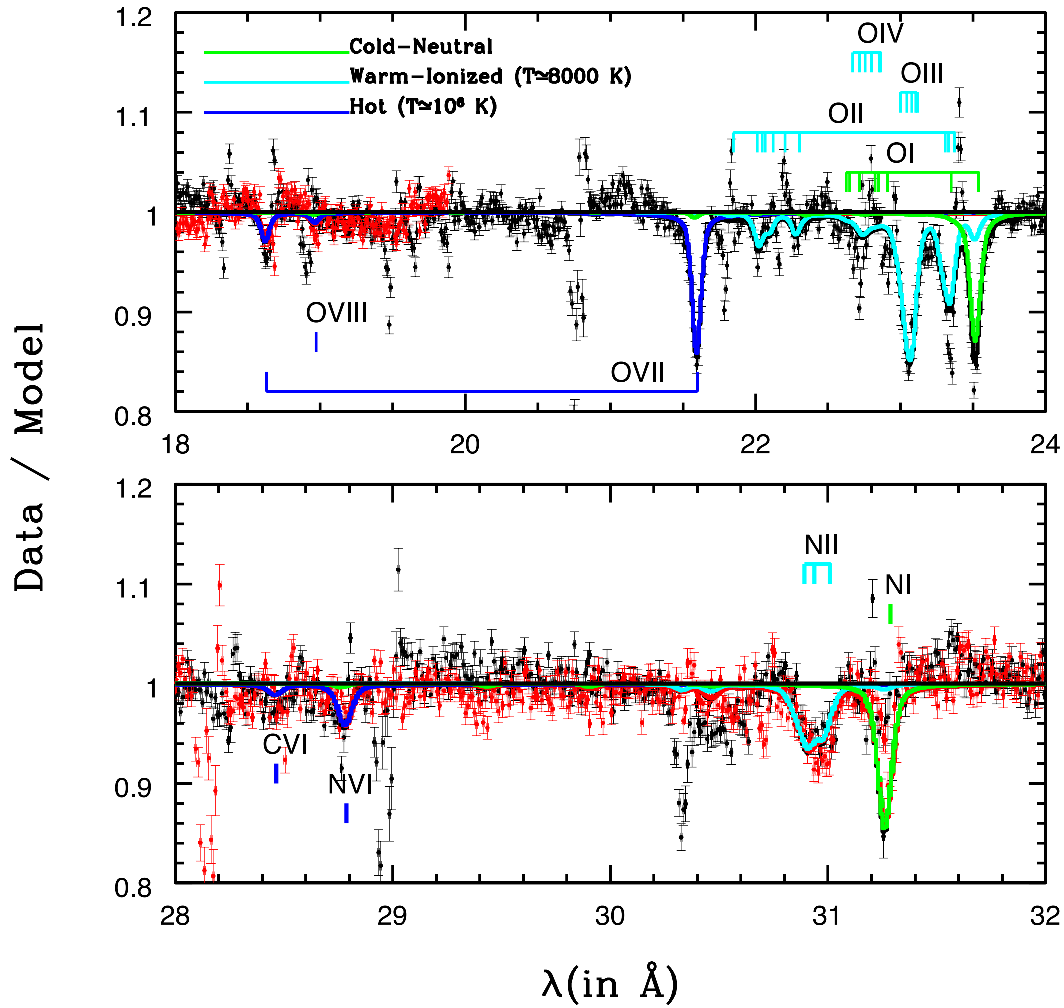
$$\rightarrow M_b/(M_b)^{Obs} \approx 2.5\text{-}5$$

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

Milky Way: Gaseous baryons in all phases

ISM/CGM Spectrum

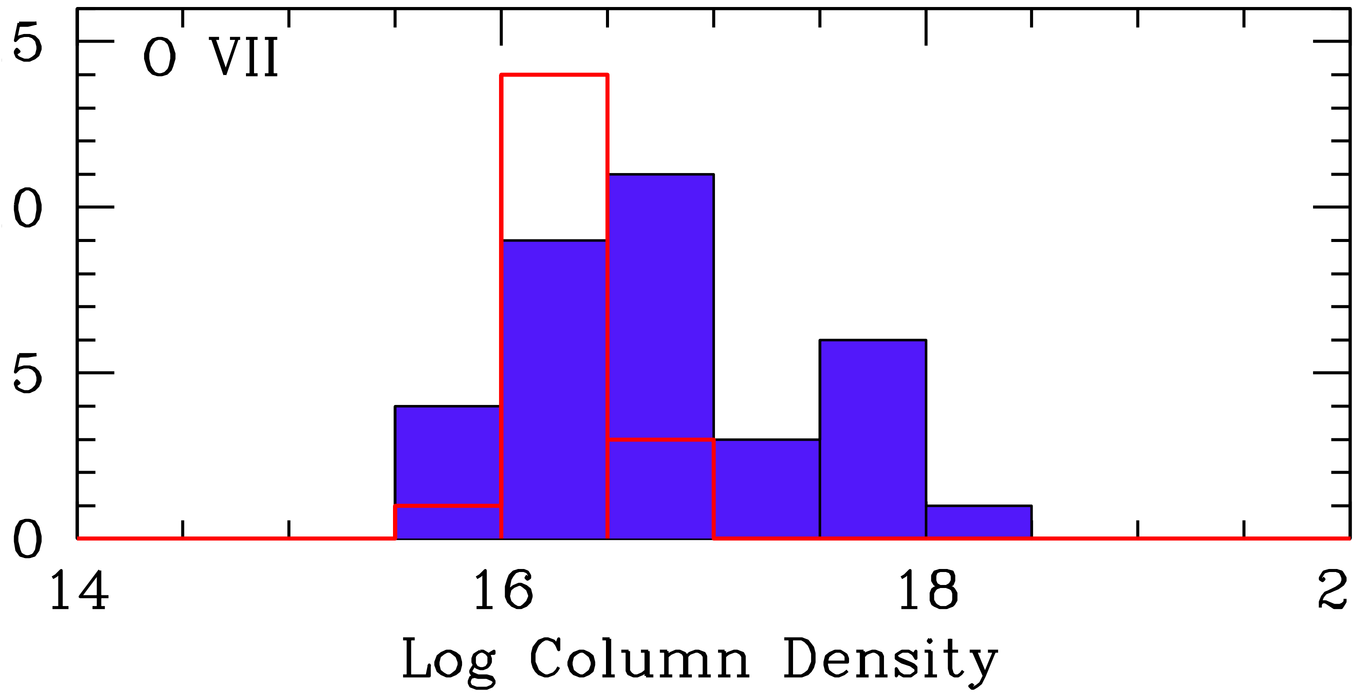
XMM-Newton RGS Spectrum of Mkn 421 (z=0.03) Nicastro+19, in prep.



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

Where is the HIMM?

Hot Plasma Permeates a Large Galactic Volume



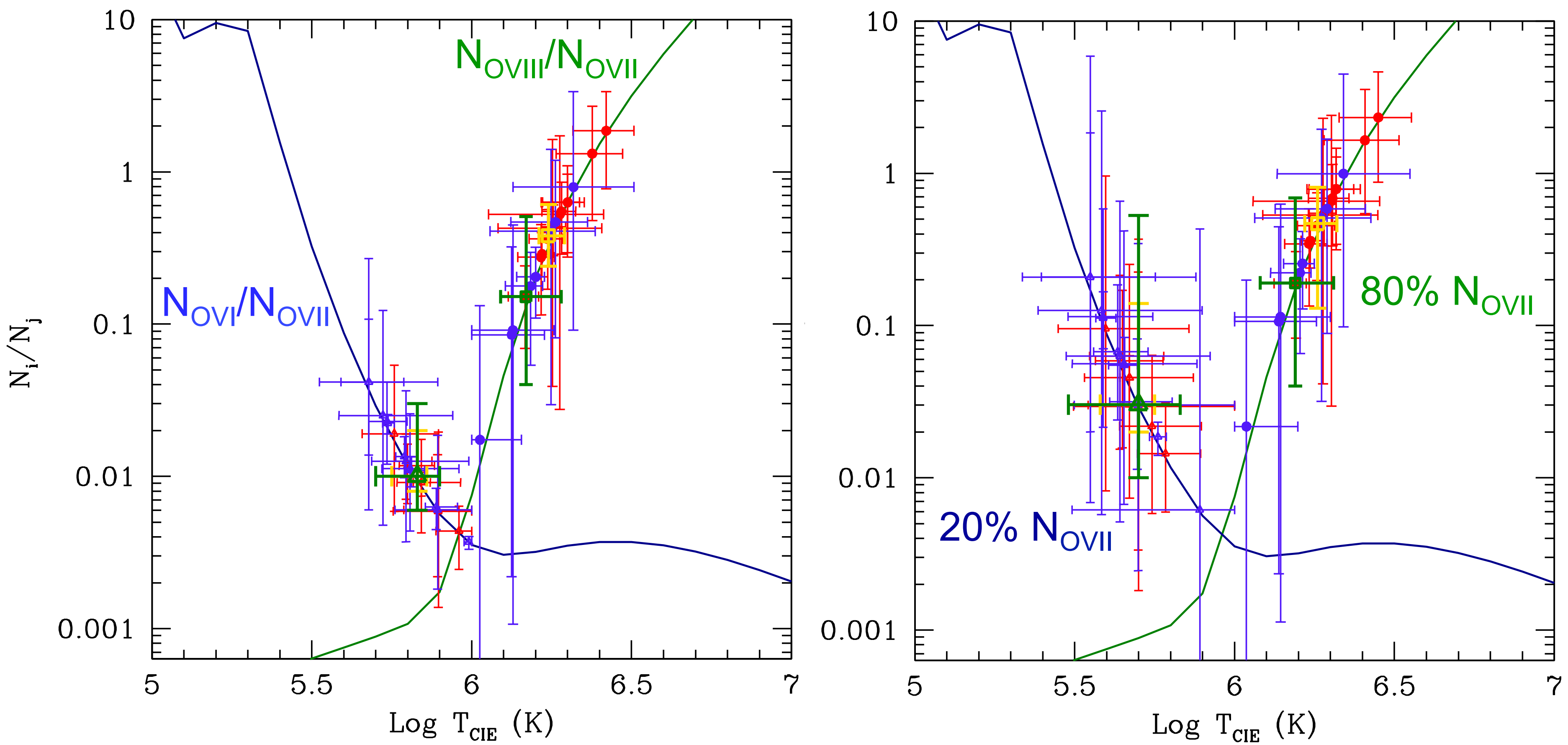
$\langle N_{OVII}(LGL)\rangle = (2.3^{+1.4}_{-1.2})\times10^{16}$ cm^{-2}; $\langle b_{OVII}(LGL)\rangle = (110^{+50}_{-40})$ km s^{-1}

$\langle N_{OVII}(HGL)\rangle = (8 \pm 2)\times10^{16}$ cm^{-2}; $\langle b_{OVII}(HGL)\rangle = (100 \pm 50)$ 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)

The Galaxy's Gaseous Baryons

Summary

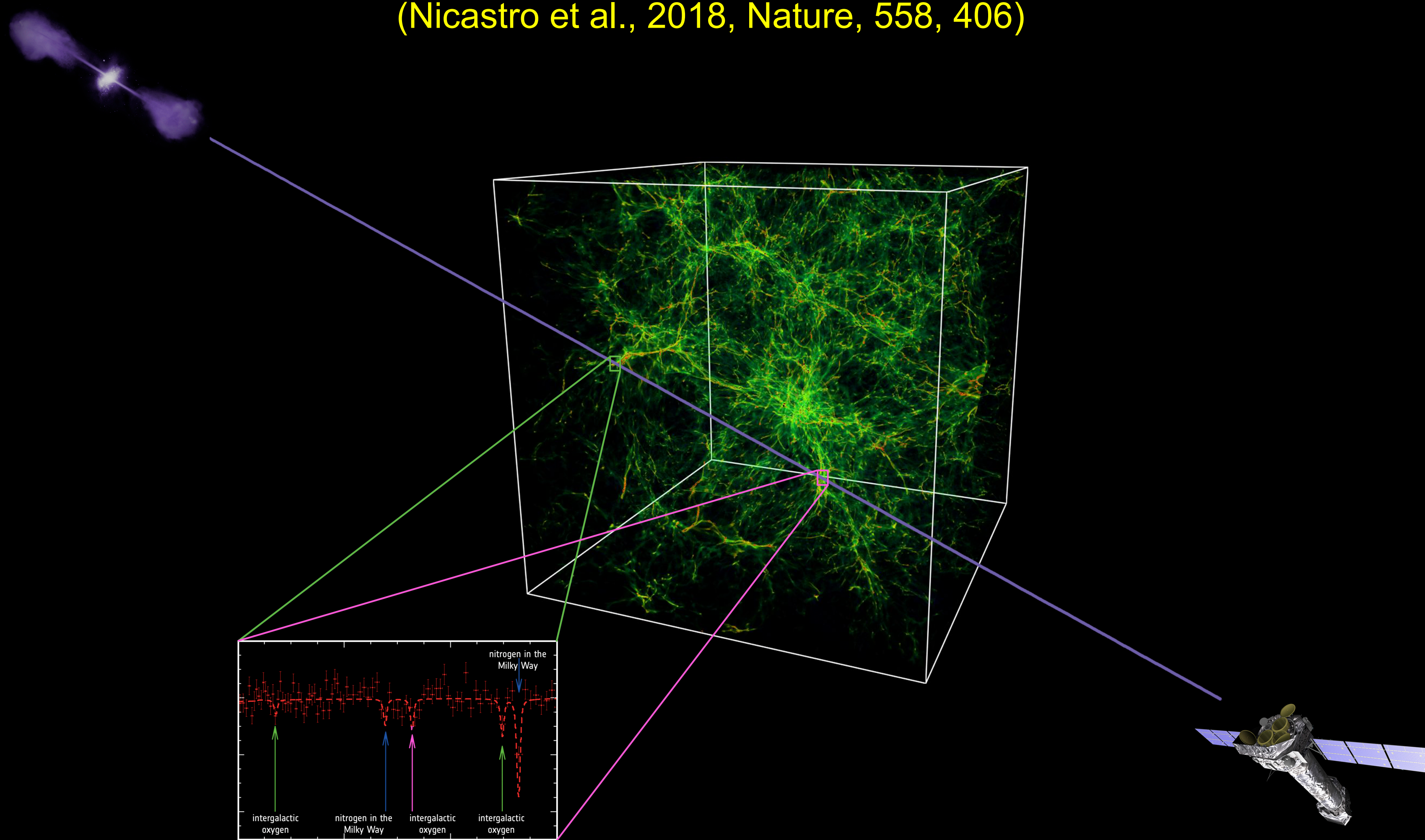
- Million-degree Gas permeates both the Disk and Halo of our Galaxy and co-exist with dense cold and cool gas

- Feedback in action: 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

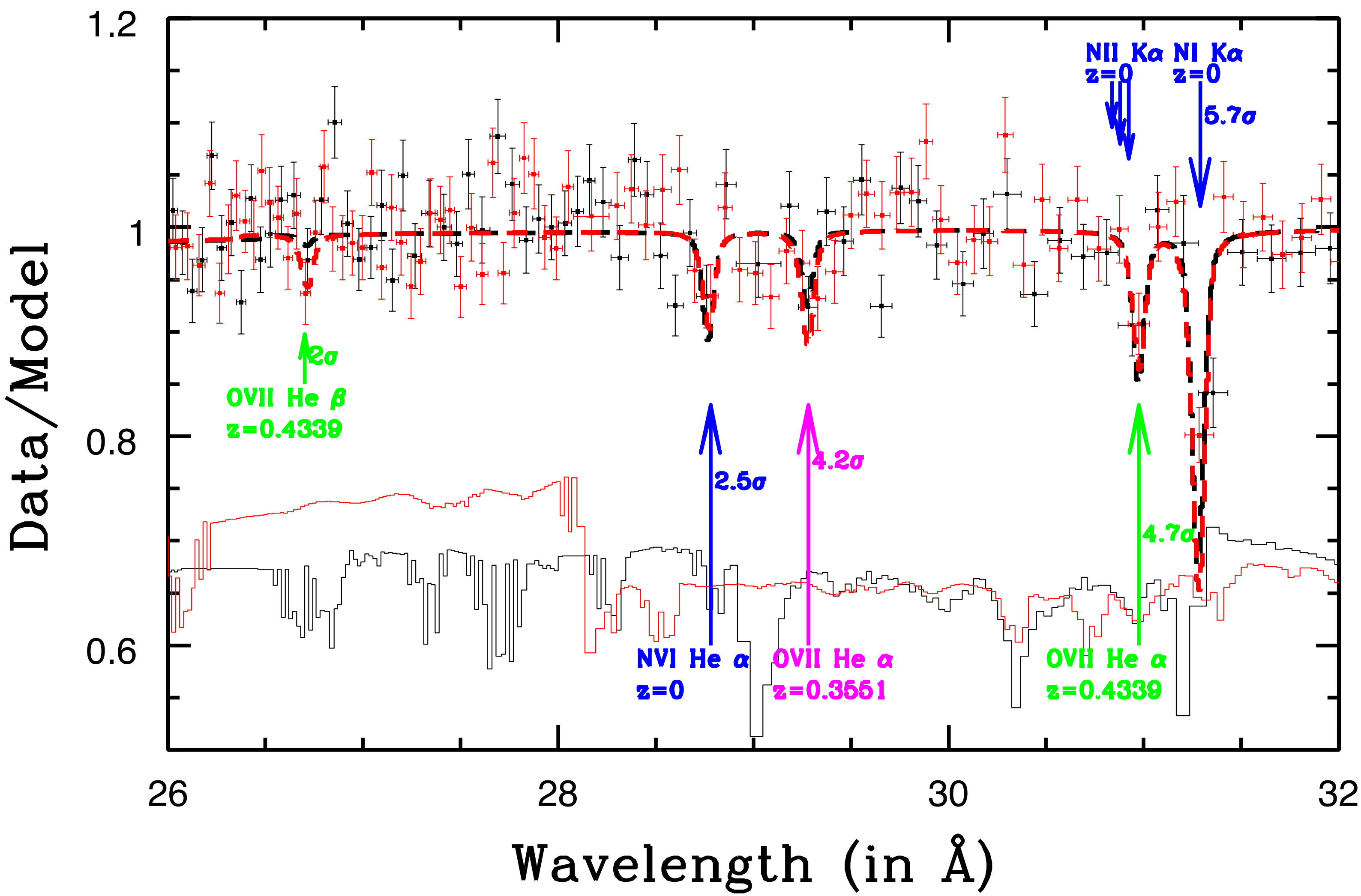
- The Mass of the OVII-bearing Gas may be sufficient to close the Galaxy's Baryon Census

The Universe Missing Baryons

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



26-32 Å RGS Spectra



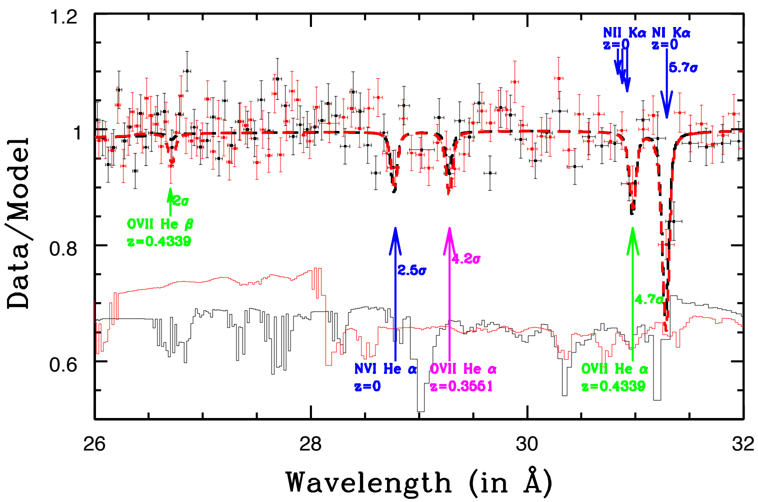
Diagnostics & Galaxy Association

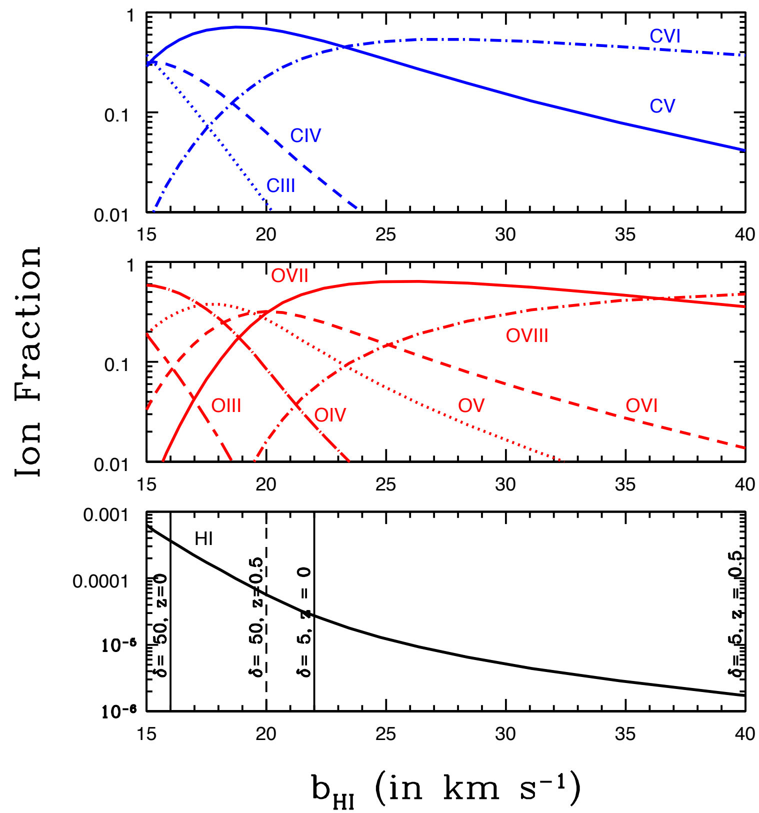
z	T (10^6 K)	N_O (10^{15} cm^{-2})	$N_H(Z/Z_\odot)^{-1}$ (10^{19} cm^{-2})	Z ($Z_\odot$)
$\boxed{0.4339}$	$\boxed{1.0,-0.4,+0.9}$	$\boxed{3.5,+2.5,-1.5}$	$\boxed{0.7,+0.5,-0.3}$	$\boxed{>0.05}$
0.3551	0.95 ± 0.45	$4.4^{+2.4}_{-2.0}$	$0.9^{+0.5}_{-0.4}$	≥ 0.1

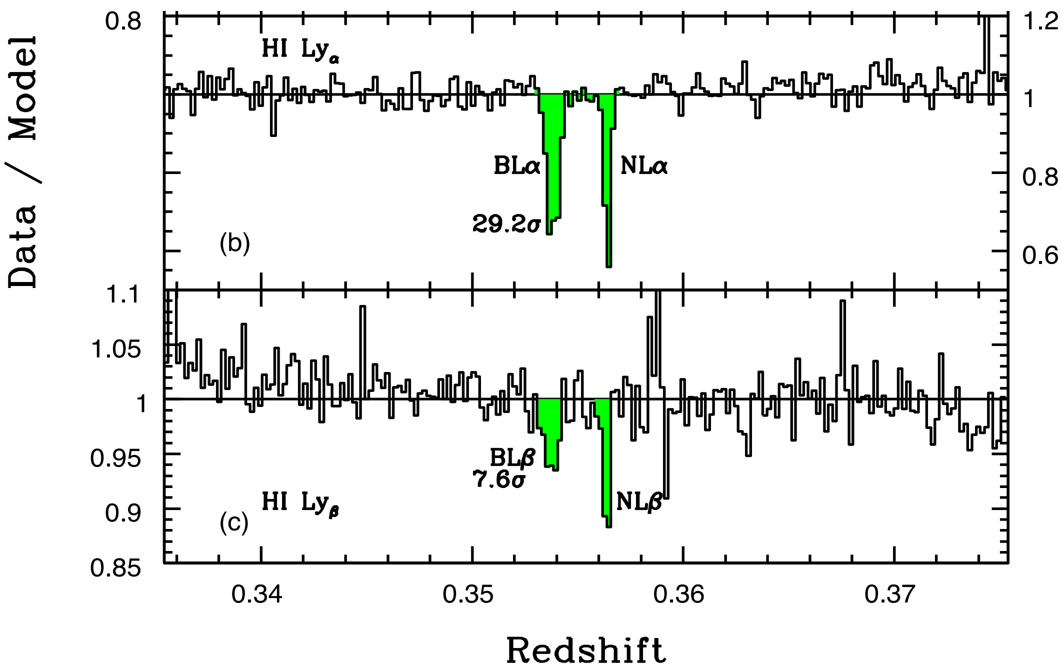
Physical parameters all in excellent agreement with WHIM predictions

z=0.4339: CGM of an i'=19.6 spiral at IP=129 kpc
z=0.3551: low-density photoionized IGM in a void

z=0.3551: Photoionized IGM







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:

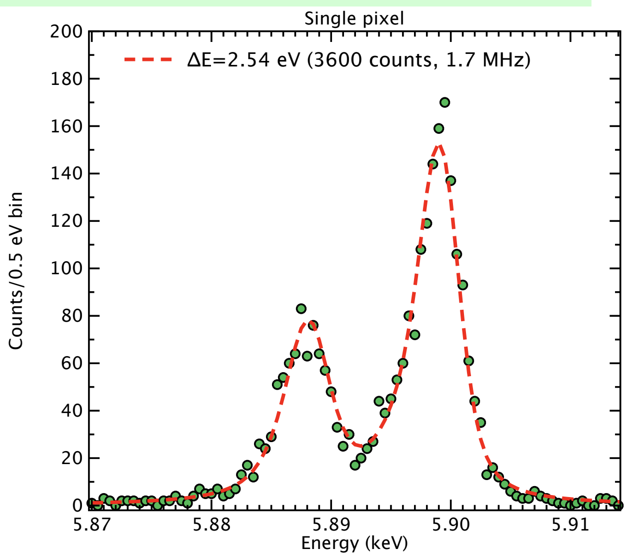
(1) effectively address WHIM cosmic variance over ~130 independent LSS elements;
(2) measure dN/dz(EW_{rf} > 9) and Ω_b(logT~ 6) with precisions of 15-40%;
(3) study the galaxy-environment around OVII-WHIM intervening absorbers;
(4) refine theoretical predictions.

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

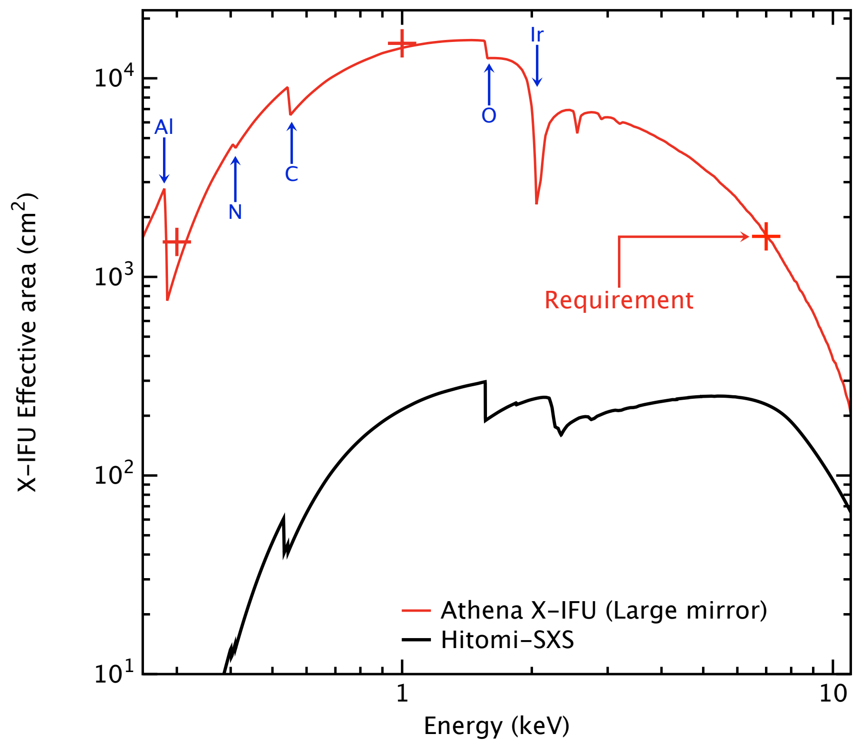
a Transition Edge Sensor (TES) microcalorimeter array with 3840 single pixels

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)



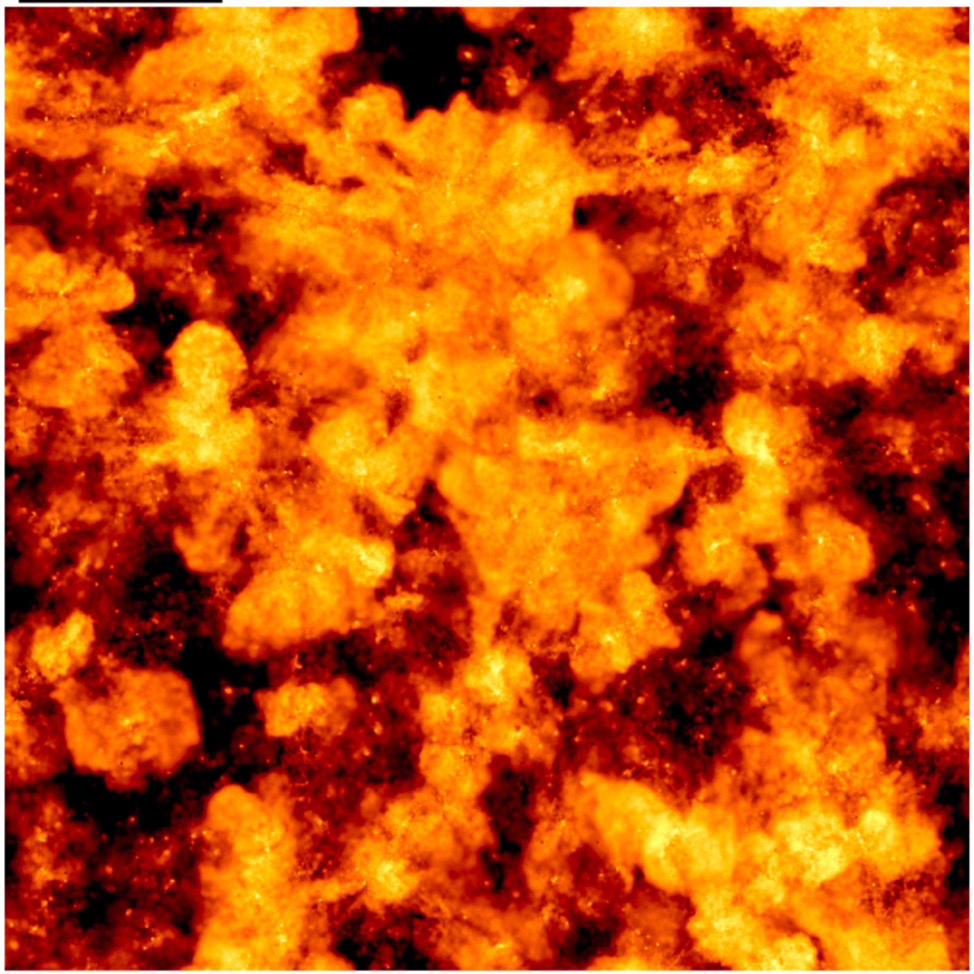
Athena X-IFU Effective Area



The Voyage of Metals in the Universe from Cosmological to Planetary Scales

the need for a Very High-Resolution,
High Throughput Soft X-ray Spectrometer

5 Mpc Gas metallicity (Eagle)

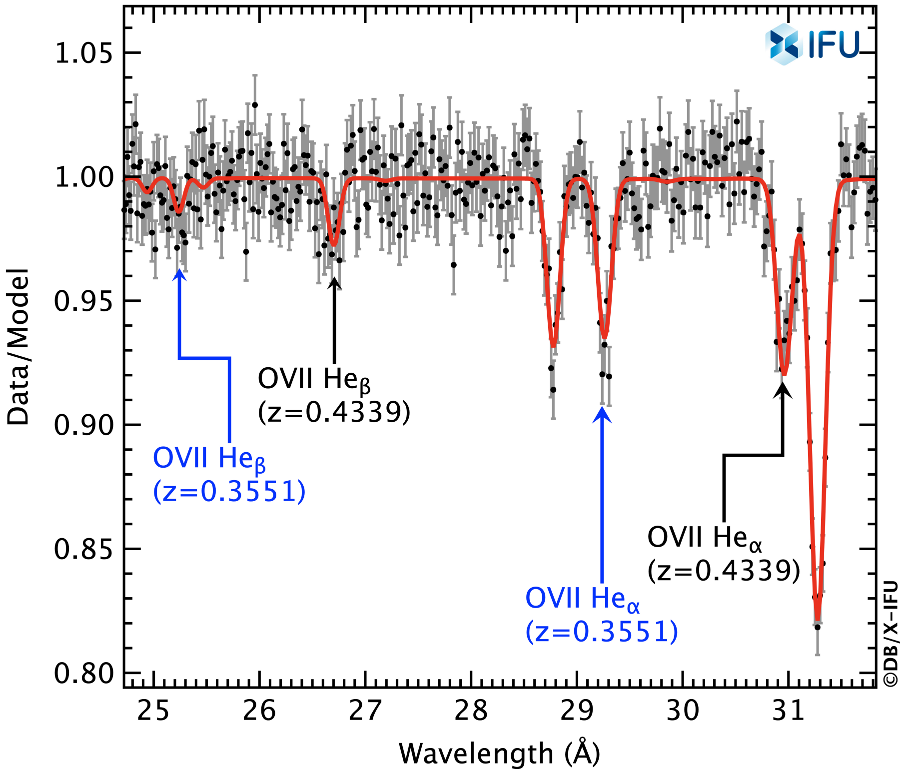


F. Nicastro[1] & J. Kaastra[2]

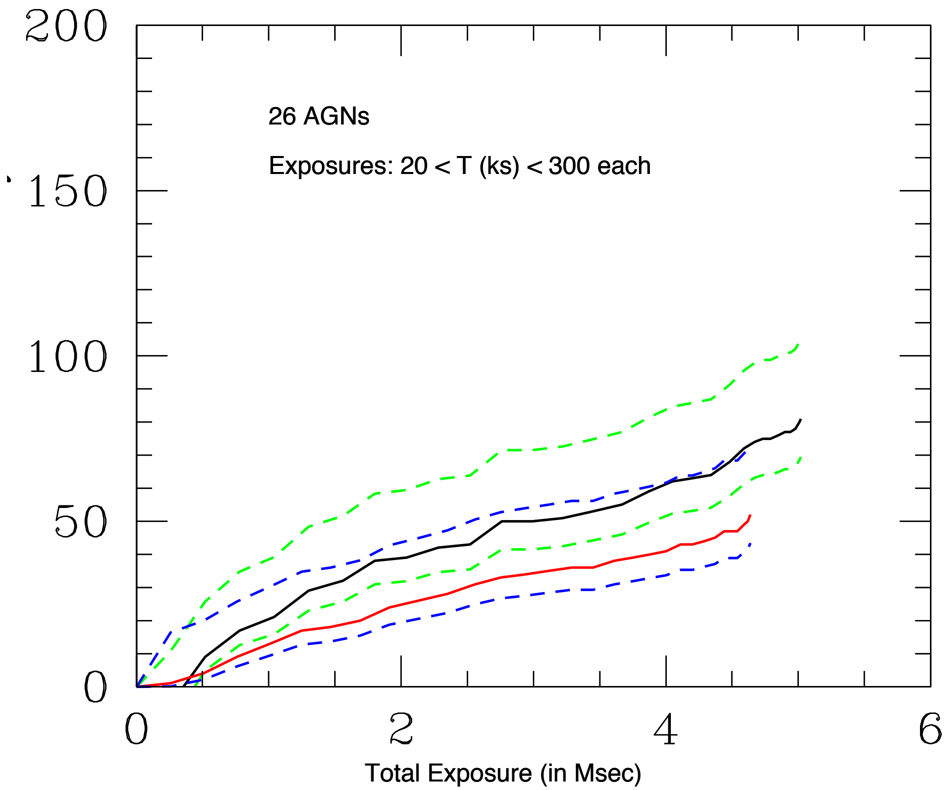
FoM: $(A_{eff} x R)^{(1/2)}$

Mission	Instrument	$A_{\rm eff}$ (cm^2)	R	FoM
HiReX		1 500	10 000	$\equiv 1$
Chandra	*LETGS*	12	500	0.02
XMM-Newton	*RGS*	90	400	0.05
XRISM	*Resolve*	125	100	0.03
Athena	*X-IFU*	5 900	200	0.28

Athena: No. of Systems



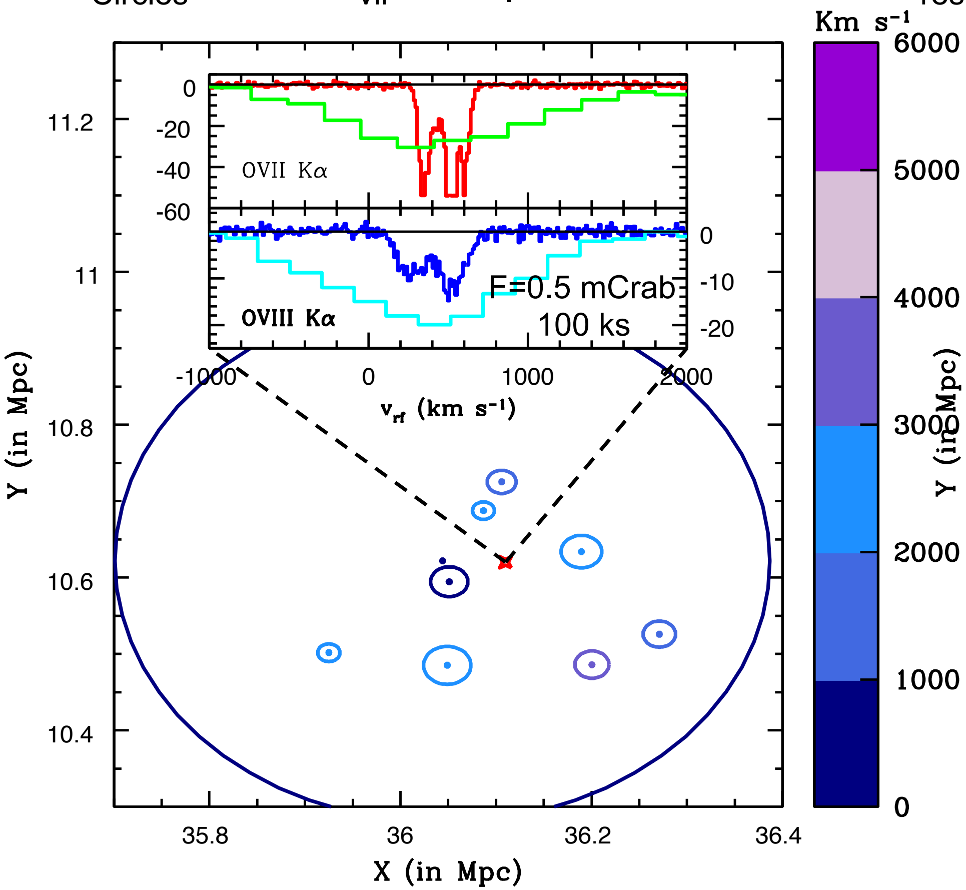
160 ks Athena-XIFU on 1ES 1553+113

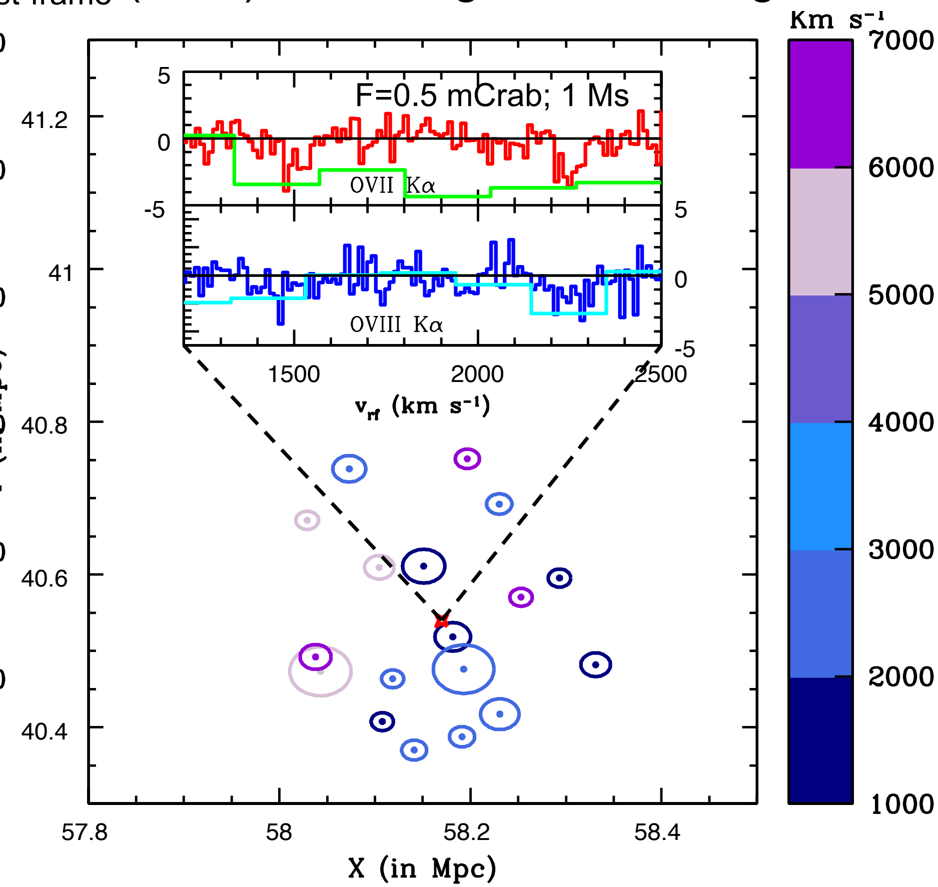


Athena will detect about 200 filaments against bright AGNs and GRBs

The WHIM in Eagle with Athena & HiReX

Extracted from a 100 Mpc^3 periodic box from Eagle simulations:
All halos with $M_{200c} \geq 10^9$ $M_\odot$ and d<200 ckpc from the lines of sight.
$R_{Circles} = 0.5\ R_{vir}$ in ckpc; color-coded in $v_{rest\text{-}frame}$ (i.e. z) according to the bar-legend

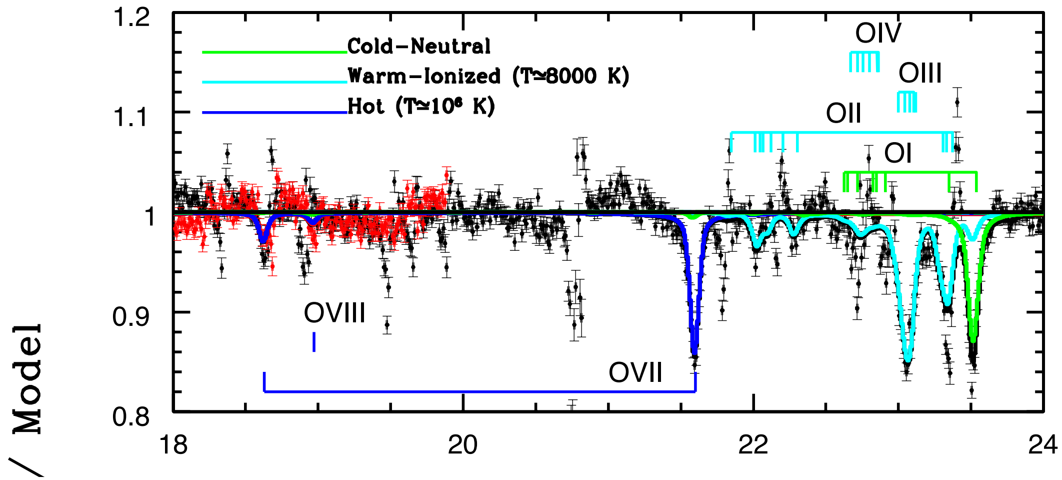




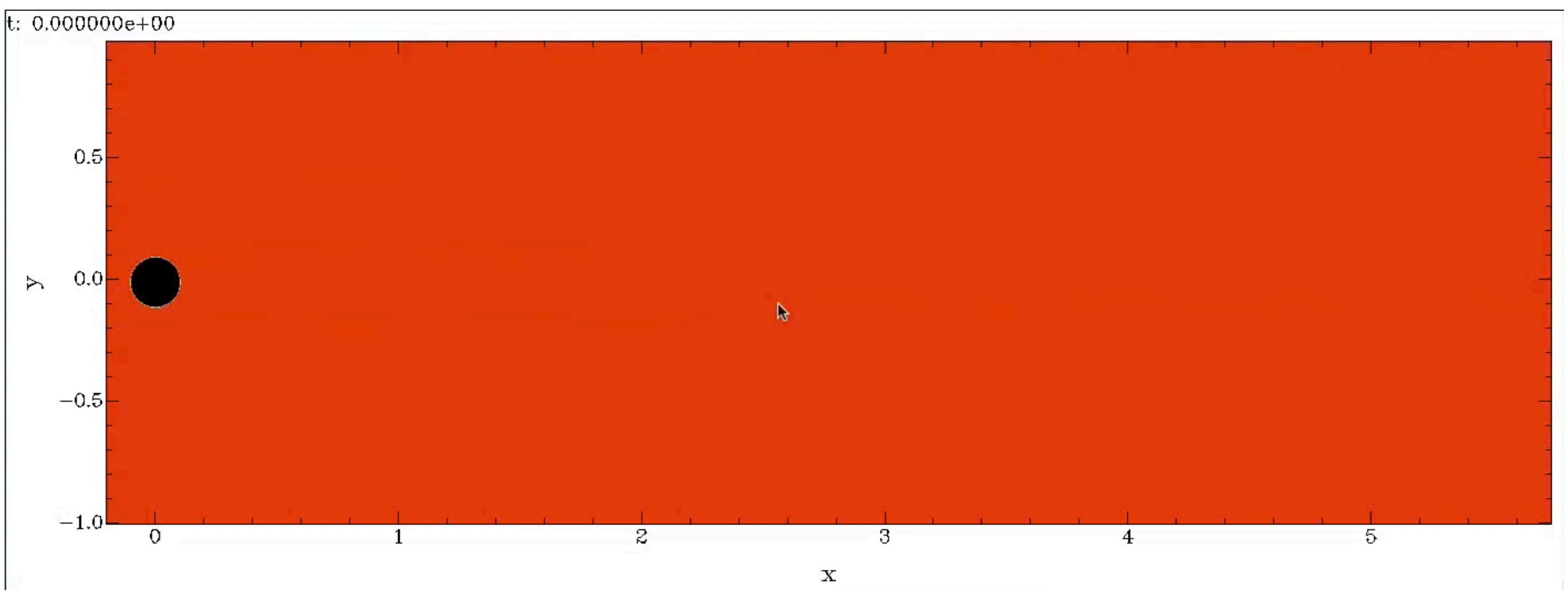
EW_{OVII}=50 mA; EW_{OVIII}=25 mA
$M_{200c}=3\times10^{13}$ $M_\odot$; IP=0.1 R_{vir}

EW^1_{OVII}=0.5 mA; EW^2_{OVIII}=0.4 mA
EW^2_{OVII}=0.6 mA; EW^2_{OVIII}=0.5 mA
$M^1_{200c}=5\times10^9$ $M_\odot$; IP=0.7 R_{vir}
Abs2 in Void: true WHIM filament

Cold Cloud Traveling in Hot Halo



Armillotta+16 (Credit: F. Fraternali)

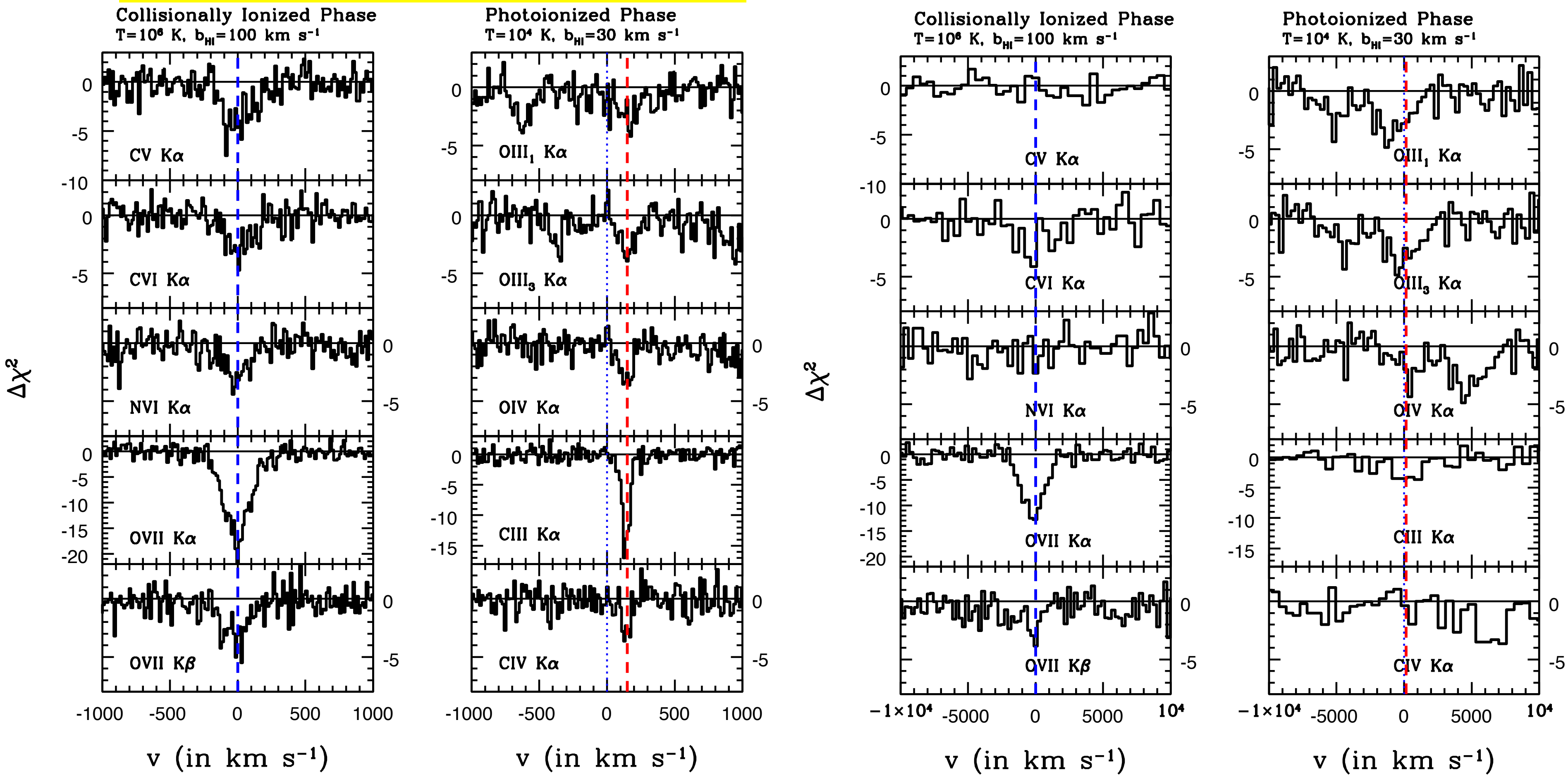


The Multiphase LLS-CGM with Athena & HiReX

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 the physical, kinematical and chemical details of the IGM/CGM, higher resolutions are needed (ESA White-Paper for VOYAGE-2050 Science Themes)