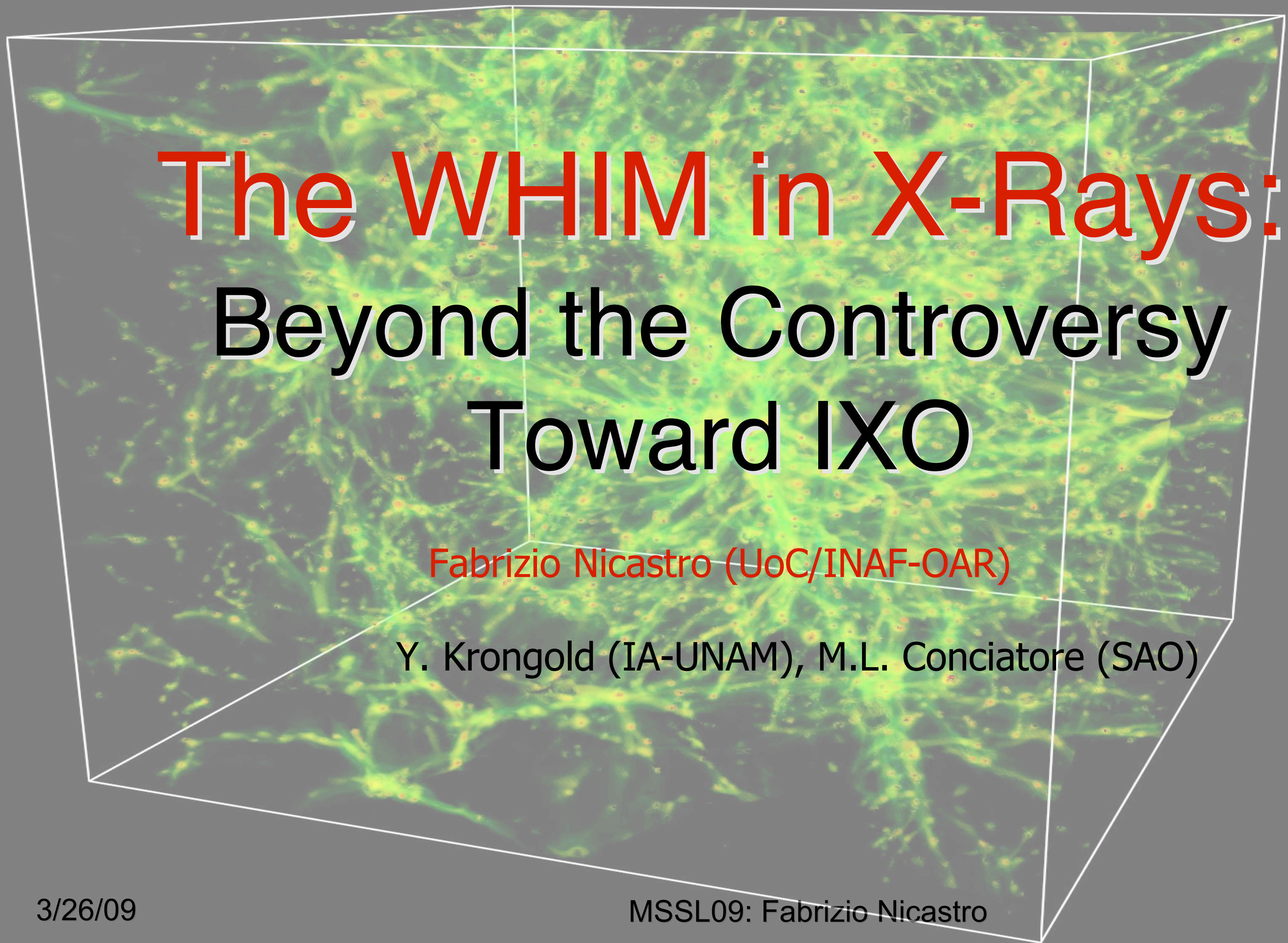

The WHIM in X-Rays:

Beyond the Controversy Toward IXO

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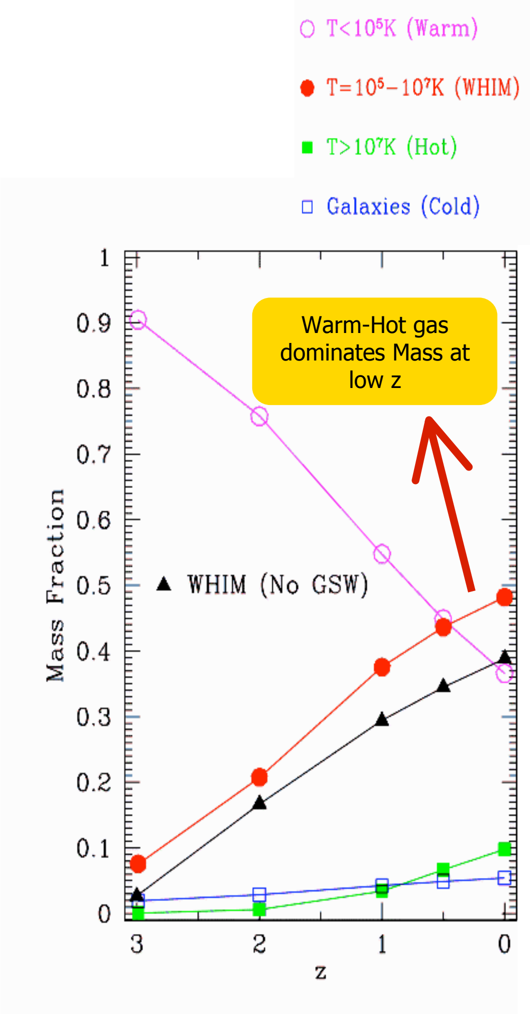
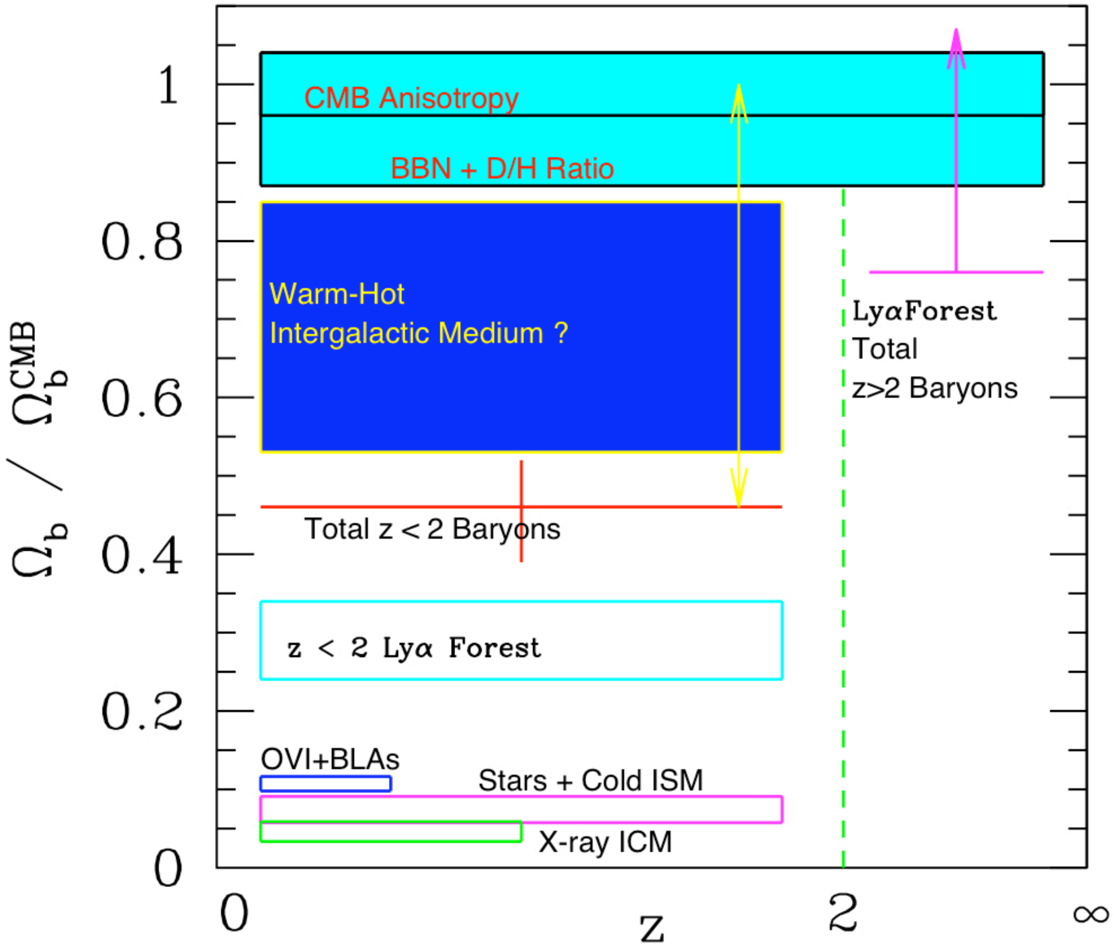
Y. Krongold (IA-UNAM), M.L. Conciatore (SAO)

Outline

- The Missing Baryons problem
- WHIM Observables: FUV (HI) & X-rays (T, Z) needed
- Current Evidence: the X-ray Controversy
- Looking Forward:
  - Chandra & XMM Legacy Program ?
  - HST-COS, IXO …et al.

Where are the Baryons?





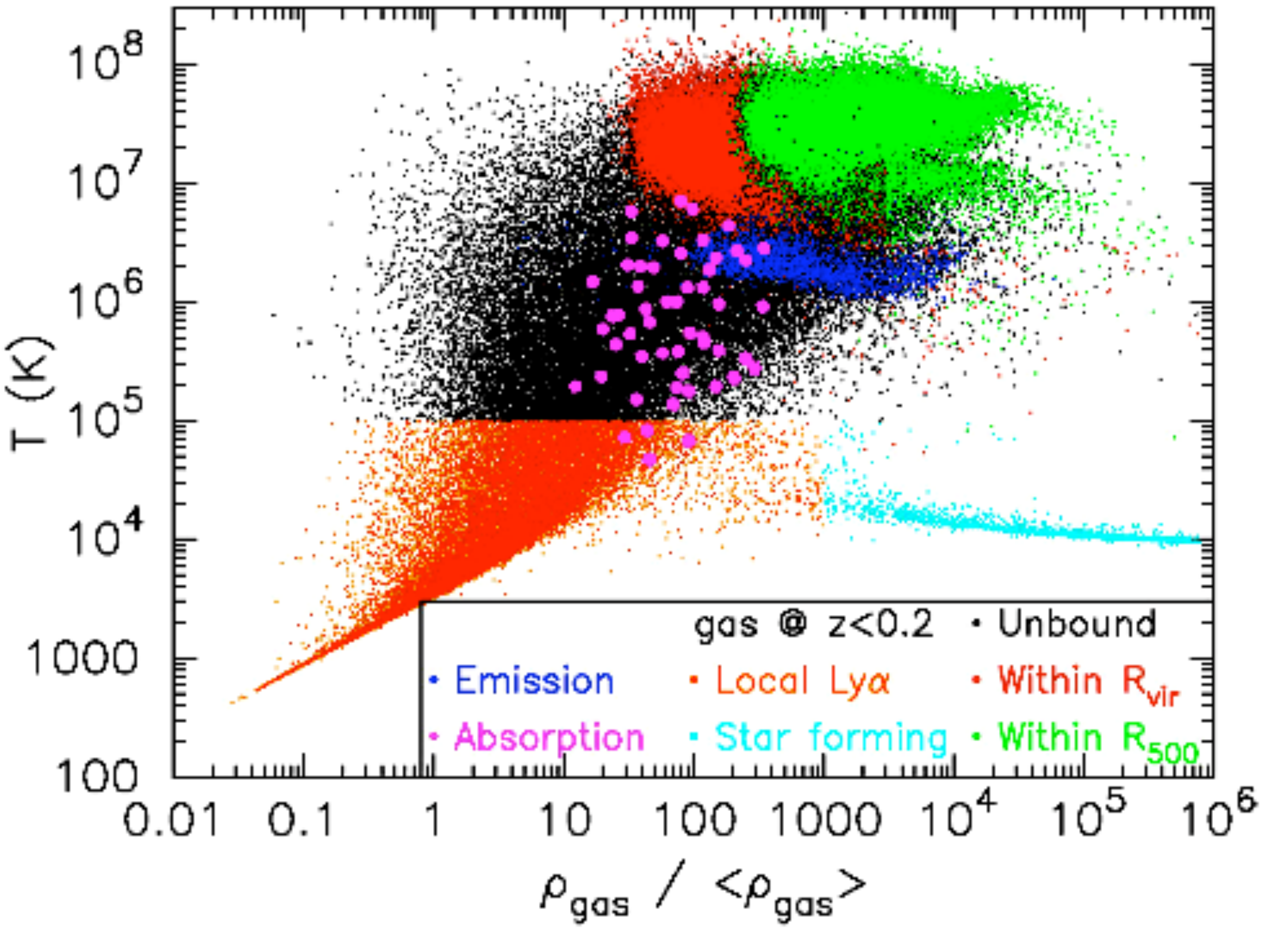
Not “just” Baryon Census

According to SCM: (54 ± 9) % of Baryons are missing!

- Find the ‘Missing Baryons’ to test SCM
- Enrichment History of the Universe: dZ/dz
  - Absolute (needs UV) and Relative Metallicities
  - Galaxy Superwinds (SN) vs AGN winds, jets
  - Nucleosynthesis
- Heating History of the Universe: dT/dz
  - Role of shocks in LSS formation
- Cosmological parameters: > 10^3 systems needed
- Local Group WHIM and Galaxy formation

Baryons ρ vs T at z=0

Branchini et al., 2009, in press



WHIM Observables: T, Z, n_b $\Rightarrow$ Ω_b

$$\Omega_b = \left(\frac{1}{\rho_c}\right)\left(\frac{\mu m_p \sum_i N_H^i}{d_{Tot}}\right)$$

$$N_H = N_{ion} \times A_{element}^{-1} \times \xi_{ion}^{-1}$$

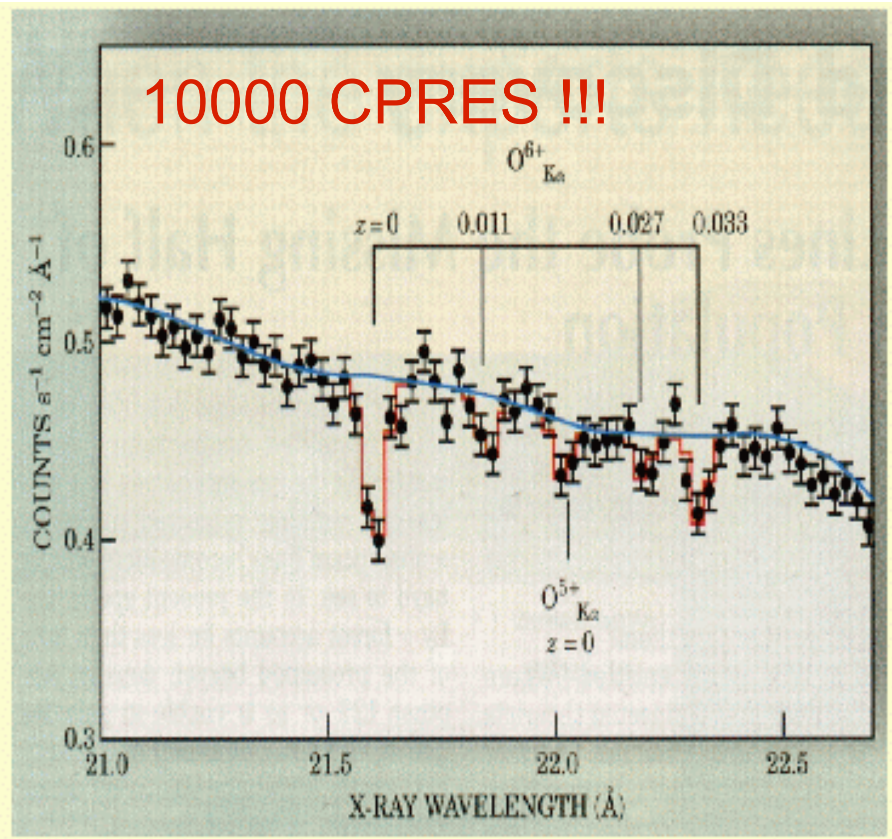
FUV | X

FUV & X

X

The WHIM in X-Rays:
80-90 % of the Missing Mass

(Nicastro+05, Nature)



Controversial

We stand by our Result:
(Nicastro+08, Science; Nicastro+07, ApJ)

1. XMM-*Newton* does ***NOT*** rule out *Chandra* detections (Rasmussen+07, ApJ)
2. Chances of falsely detecting the two systems are 0.05 % and < 0.01 %, ***NOT*** 40 % and 6 % (Kaastra+06, ApJ)

Statistical Significance

- N05a,b claim statistical significances of 3.5σ and 4.8σ, i.e. P^{chance}=0.05 % & 0.005 %
- K06 perform MonteCarlo and conclude that: P=40 % and P=6 % of falsely detect the two systems.
- N08n perform new MonteCarlo and confirm P=0.05 % and P < 0.01 % for the two systems (i.e. 3.5σ and > 3.9σ respectively):

differences due to different assumptions

A Simple Gaussian Argument (z=0.011; 2 lines @ 3.8σ & 2σ)

λ(OVII)=21.602; z(Mkn 421)=0.03 ==> $\Delta\lambda$= λ(OVII)xz(Mkn 421) = 648 mA

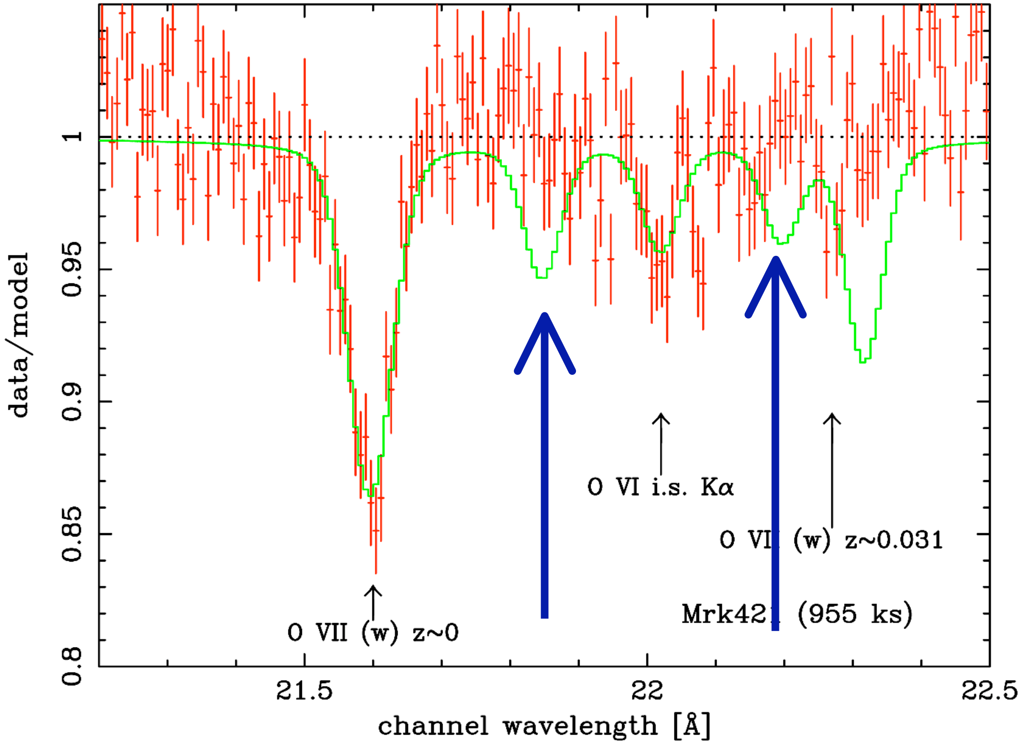
$\Delta\lambda$(LETG)=50 mA ==> 13 Ind. Elem.; Over-sampling by 4 ==> 52 bins

$$\Rightarrow P_{Gauss} \sim \{[(1-P(3.8\sigma)) \times 52] / 2\} \times \{[(1-P(2\sigma)) \times 59] / 2\} = 0.02\ \%$$

XMM-RGS Spectrum of Mkn 421
…as seen by R07+

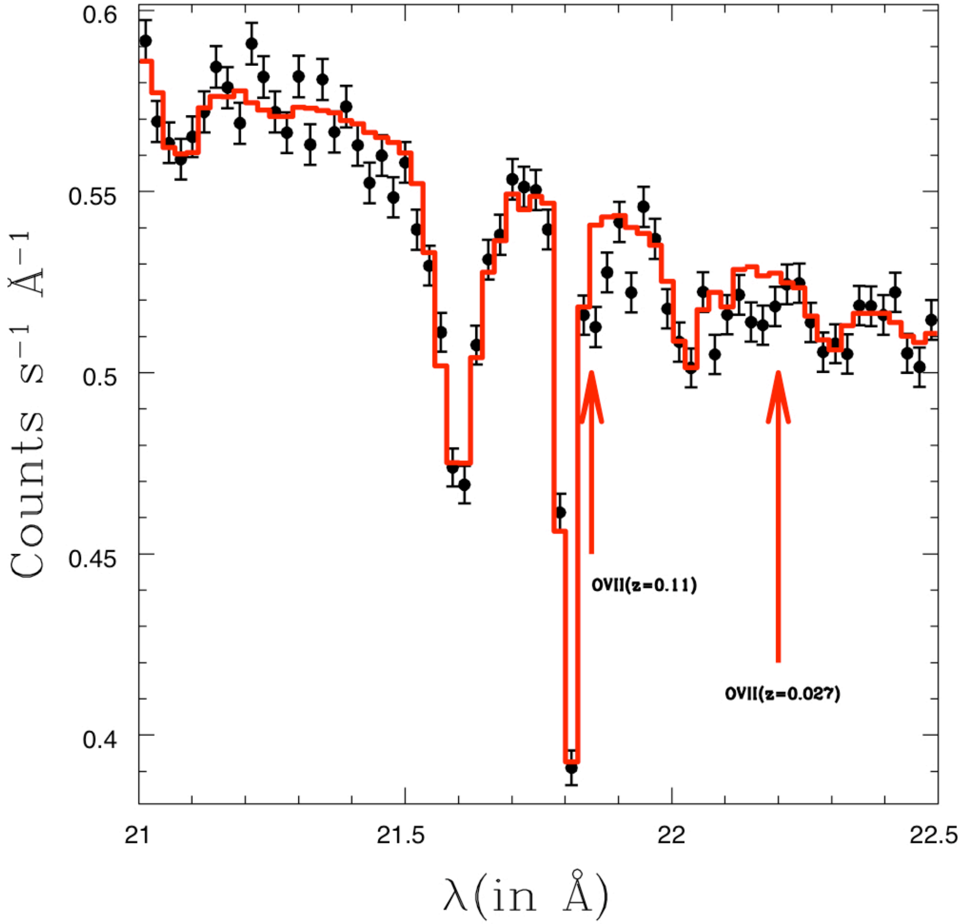
Rasmussen+07 claim no evidence, in XMM-RGS, of the absorption lines seen by *Chandra*

5-10 bins per resolution element

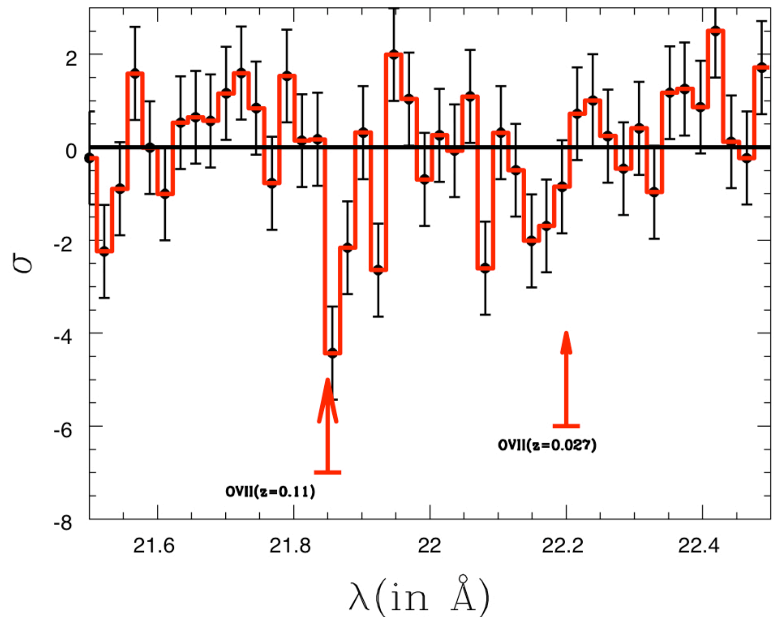


Continuum is too low!

XMM-RGS spectrum of Mkn 421 ...as seen by us

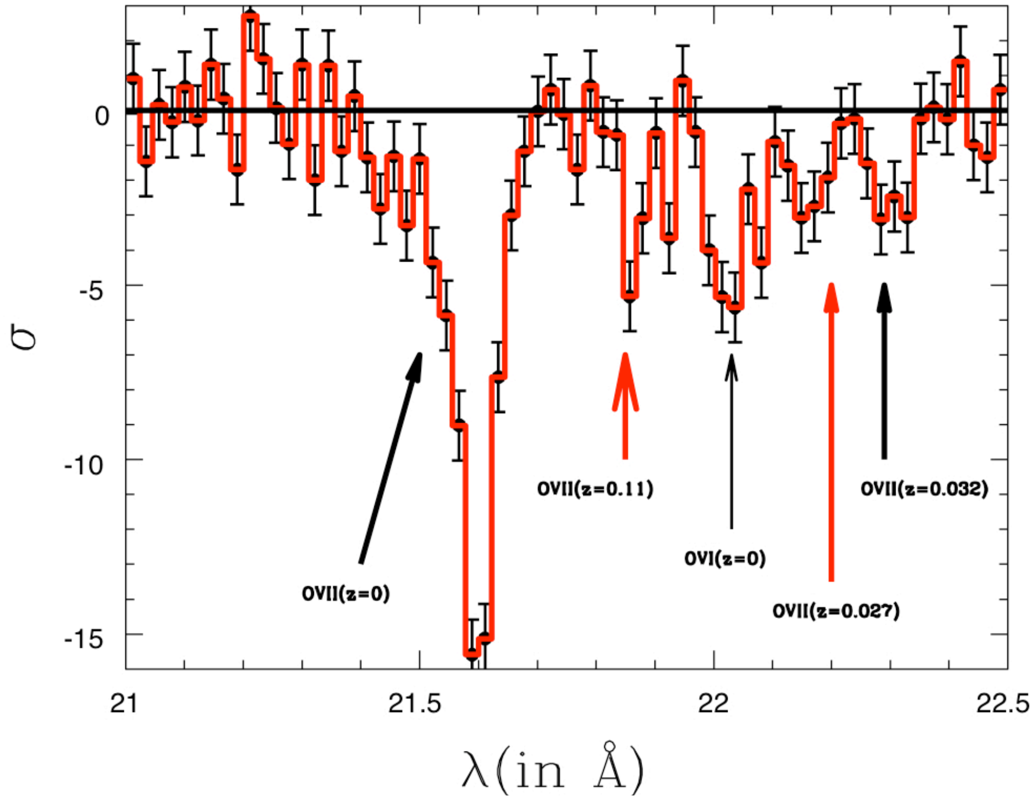


2-4 bins per resolution element

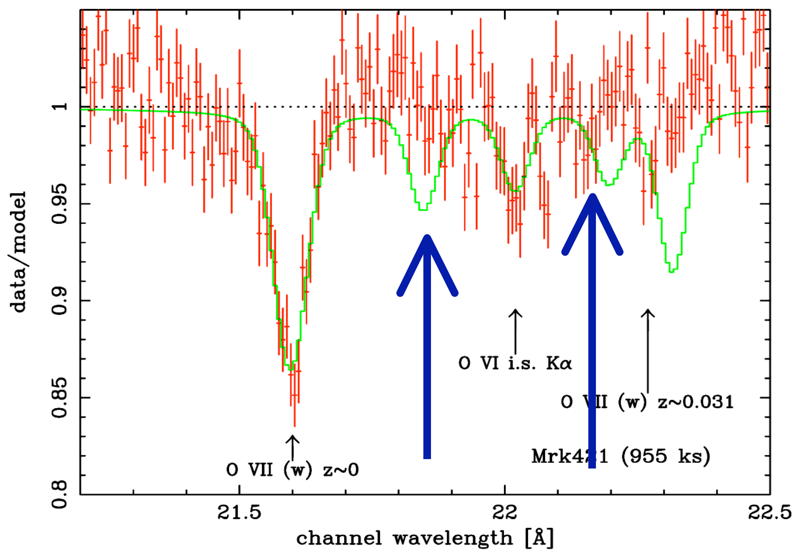


Placing the continuum where it should be: N08+ vs R07+

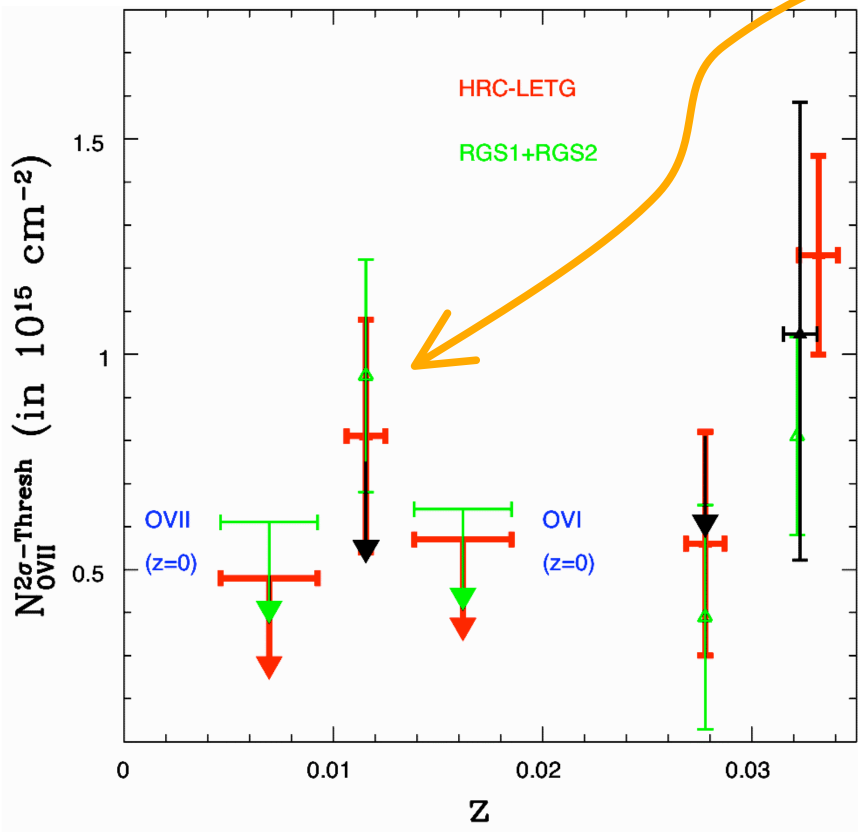
2-4 bins per resolution element



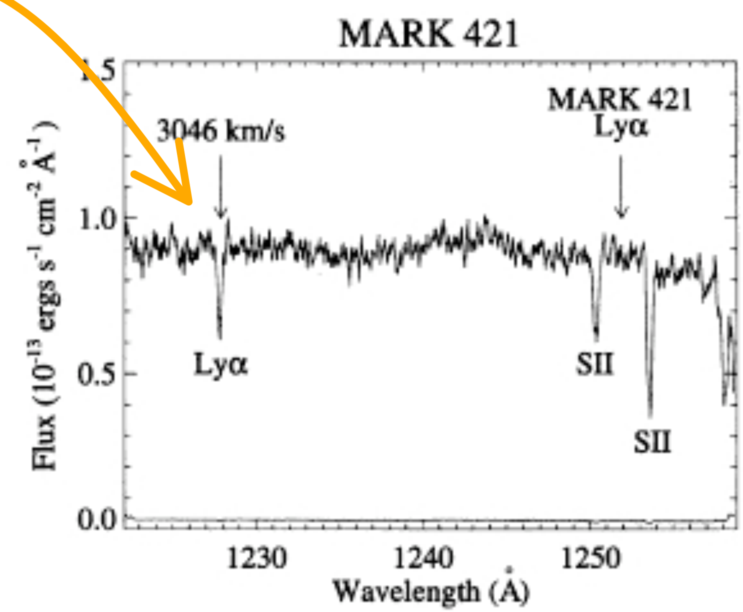
5-10 bins per resolution element



XMM-RGS confirmation(s) of LETG detections of WHIM



Shull+96



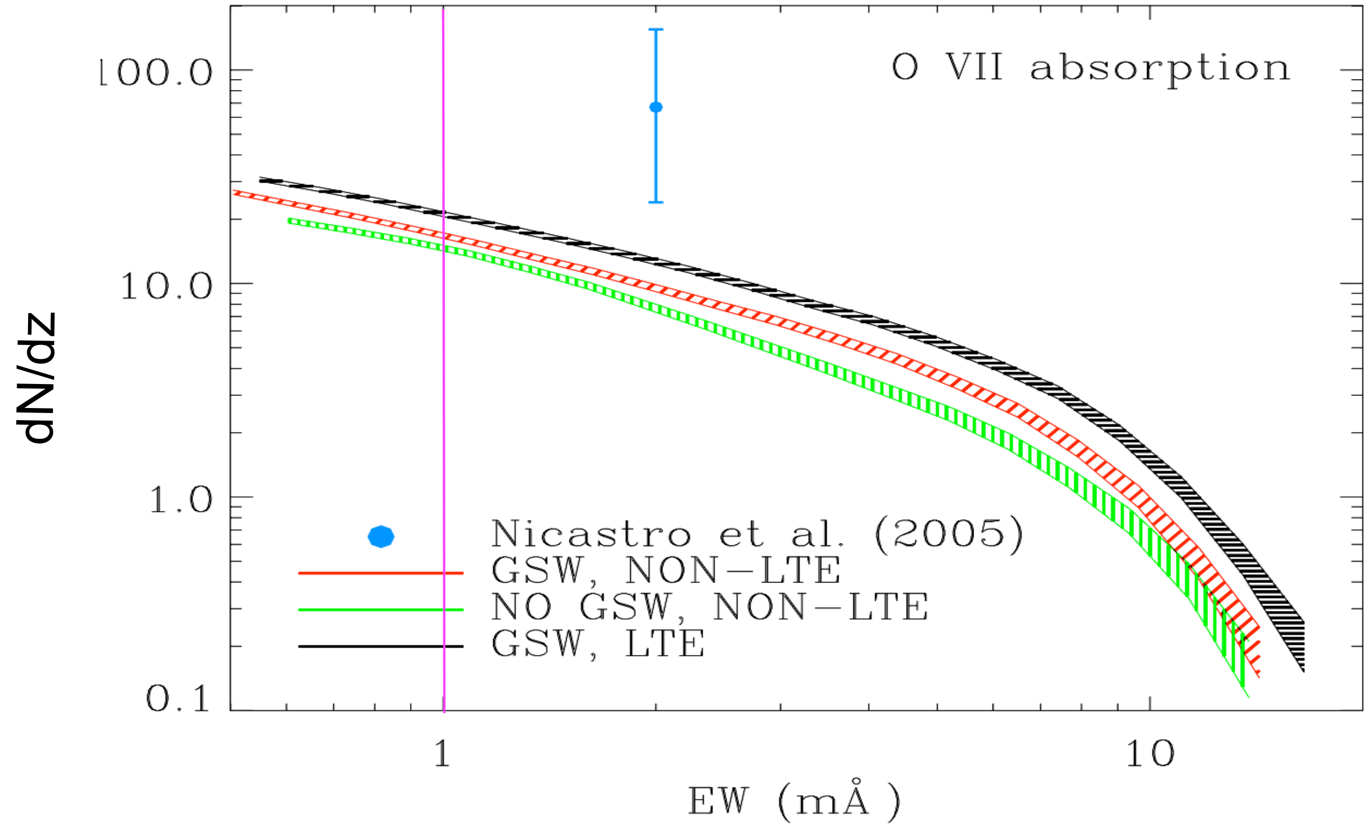
$$\Omega_b(N_{OVII} > 7 * 10^{14}) =$$
$$= 2.7^{+3.8}_{-1.9} * 10^{-[O/H]_{-1}}\% \sim \Omega_{Miss}$$

Beyond the Controversy

- Short Term: *Chandra* and XMM-*Newton* Msec (Metal) + deep HST-COS (HI) observations of optimal targets:
  - uncontroversial detection of WHIM
  - Ω_b to better than ~30-50%
- Long Term: hundreds of lines of sight for thousands of metal systems (IXO, Pharos); HI (HST-COS):
  - Ω_b to better than ~1%
  - Enrichment history of the Universe
  - heating-history of the Universe
  - Cosmological parameters from cross-correlation
  - 3D Dark Matter maps

Expected Number of Systems

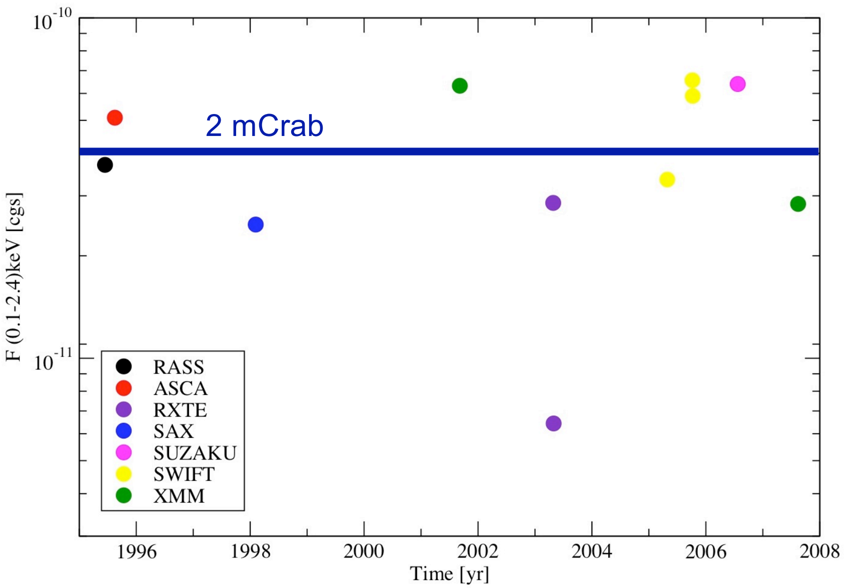
> 3-10 Systems down to $N_{OVII} = 4 \times 10^{14}$ cm^{-2} at $z > 0.3$



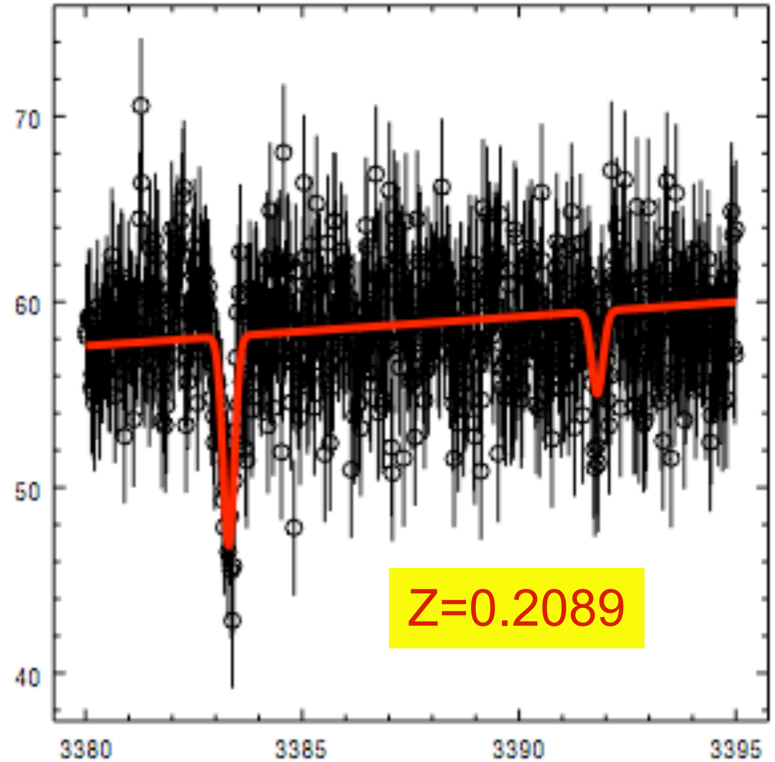
EW_{OVII} = 1 mA <=> $N_{OVII} = 4 \times 10^{14}$ cm^{-2}

The WHIM with Chandra/XMM
The Best WHIM Target in the Universe

0.25 < z < 0.42



15 minutes VLT-UVES Blue Arm



2 Msec XMM-Newton RGS

The WHIM with IXO: Why Gratings and not Calorimeter?

$$EW(CAL)^{5\sigma}_{Thresh} \geq \frac{5(125mA)}{(S/N)_{RE}}$$

$$EW(GRAT)^{5\sigma}_{Thresh} \geq \frac{5(10mA)}{(S/N)_{RE}}$$

to detect at 5σ OVII with EW(OVII)=2 mA

$(S/N)_{RE(CAL)} \geq 310$

$(S/N)_{RE(GRAT)} \geq 25$

Factor of 12 in S/N

Factor of ~12 in A_{Eff} nedeed vs Factor of <~ 10 actual

Resolution: Detection Efficiency

Grating vs Calorimeter

Typical OVII EW: $W_{OVII} \sim 0.8\text{-}8\ (1+z)$ mA (X-Rays)

Detection Efficiency: $$\eta = \frac{R}{(\lambda / EW)} = \frac{(\lambda / \Delta\lambda)}{(\lambda / EW)}$$

η(OVII) = R_{Grat} /22/(0.0008-0.008) > (0.1-1)

η(OVII) = R_{cal} /22/(0.0008-0.008) ~ (0.01-0.1)

Cf with:

η(OVII;Chandra,XMM) ~ (0.01-0.1)
η(OVI;FUSE,HST) ~ (1-10)
η(HI;FUSE,HST) ~ (0.1-1)

And...Kinematics and Multiphase: WHIM lines are narrow!

$V_{th}(O, T=10^6 \text{ K}) \sim 33 \text{ km s}^{-1}$

→ FWHM(OVII) ~ 6 mA @ 0.5 keV

Cf w FWHM(Grat) = 10 mA

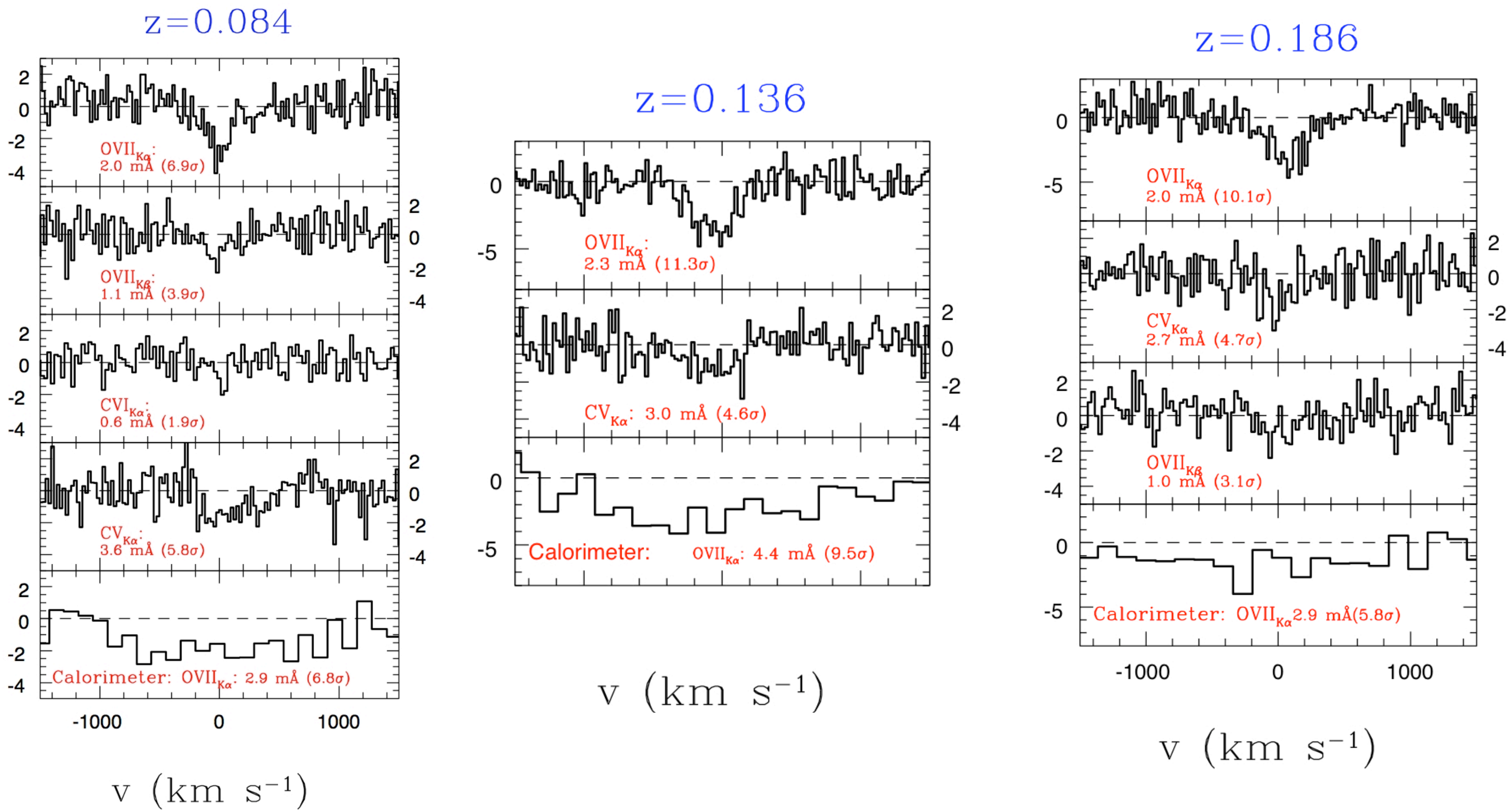
FWHM(Cal) = 125 mA @ 0.5 keV

+ WHIM is multiphase with typical 10-100 km s-1 separation (e.g. Danforth&Shull+08)

→ Ω_b measurements need secure identification of BLAs with Metal Lines

The WHIM with IXO: 600 ksec

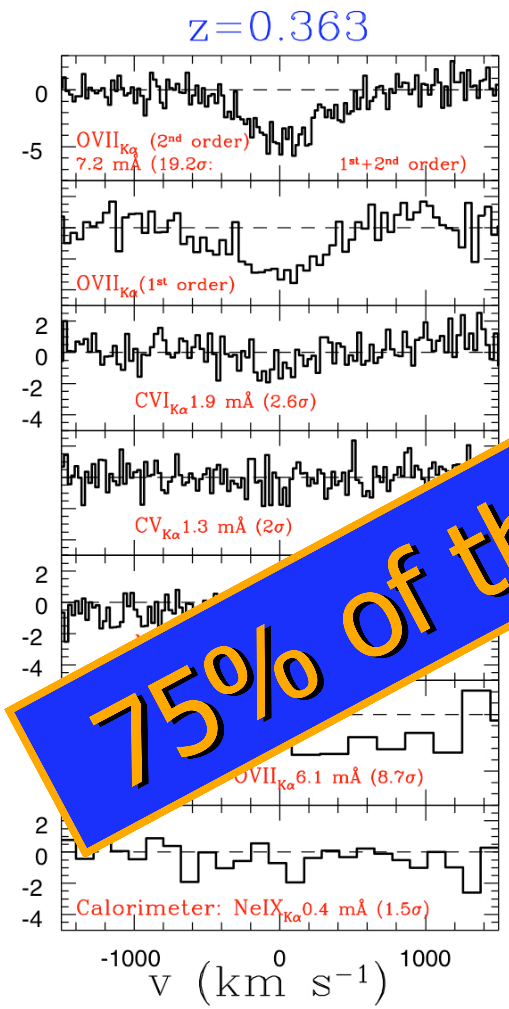
6 filaments down to $N_{OVII}>10^{14}$ cm^{-2} and up to z<0.5

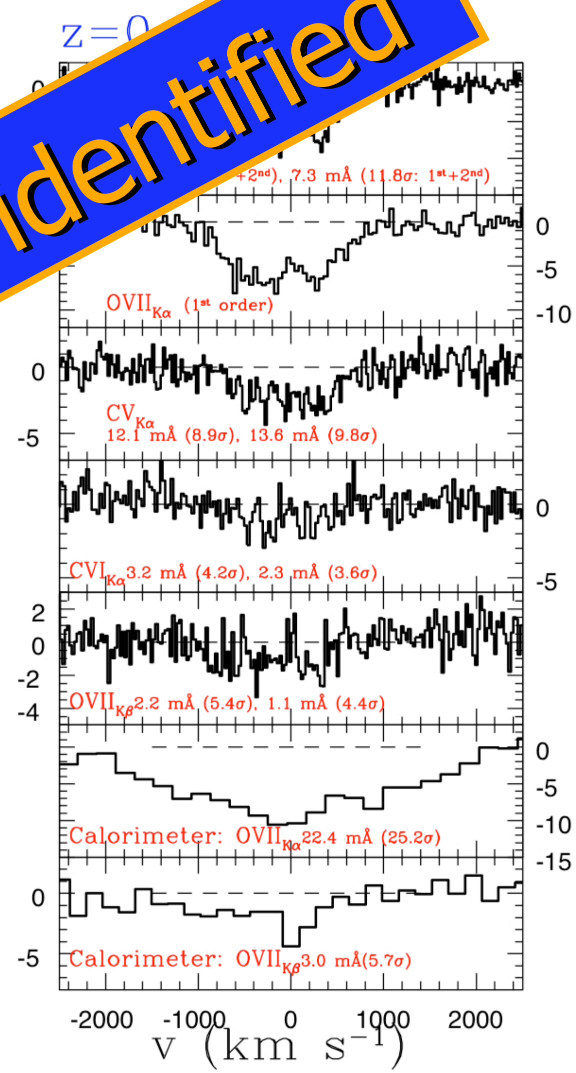


The WHIM with IXO: 200 ksec

2 of the 6 filaments are multi-phase…and res…d!

75% of the 8 Systems identified





Optimal WHIM Sample for IXO

- F(0.1-2.4 keV) > 0.2 mCrab
- $z > 0.3$
- N_H(Gal) < 3×10^{20} cm^{-2}
- Mostly BL-LAC

→ Gives 69 AGNs

~ 3-10 Metal Systems per line of sight in 200-300 ks with IXO Gratings

→ 200-700 OVII WHIM systems in 0.7 yrs

…….BUT…Needs HI to derive Metal Content & Mass

Conclusions

- The WHIM has been found in OVI. But only 10 % of the missing mass
- X-ray detections of the WHIM are few and highly controversial: needs independent confirmation: current X-ray mission must be exploited to their limits: deep observations (or TOOs) of the BEST TARGET
- Future WHIM studies must exploit the strong synergy between FUV and X-Ray spectroscopy: FUV vital to measure HI column and metallicity, X-Ray needed to obtain ionization correction
- IXO gratings (or dedicated X-Ray WHIM missions) will allow the detections of ~ thousand WHIM metal systems at $z<1$, down to $N_{OVII} > 10^{14}$ cm^{-2}
- This will enables:
  - Precise measure of Ω_b, and test of the SCM
  - Enrichment and heating history of the Universe
  - Cosmological Parameters from WHIM filaments CCF ?
  - 3D-Map of DM