Bulk of the IGM Missing Baryons:

Current Evidence and Future Prospects

Overview

- The Warm-Hot Intergalactic Medium in X-rays
- Detectability with Current Instrumentation
- Current Evidence: tentative Ω_b^{OVII} and $(dN/dz)^{OVII}$ estimates
- The Best Observational Strategy: Gaseous Signposts, FUV, X-Ray and Radio bright sources
- The Pilot Chandra Observation of "The Best WHIM Target in the sky"
- The "Missing Baryons" around the Milky Way: Local-Group WHIM, Extended Galactic Halo, or WHIM in local LSS
- The Future for the X-ray WHIM

1

Summary and Baryon Budget at z < 2

Baryon Budget at z<2

$$\Omega_b^{WMAP} h^{-2} = 0.0226\ h^{-2} = 0.0456$$

$$\Omega_b^{z<2} = \Omega_b^{Stars} + \Omega_b^{HI+HeI+H2} + \Omega_b^{Clusters} + \Omega_b^{Ly\alpha} + \Omega_b^{OVI} + \Omega_b^{BLA} =$$

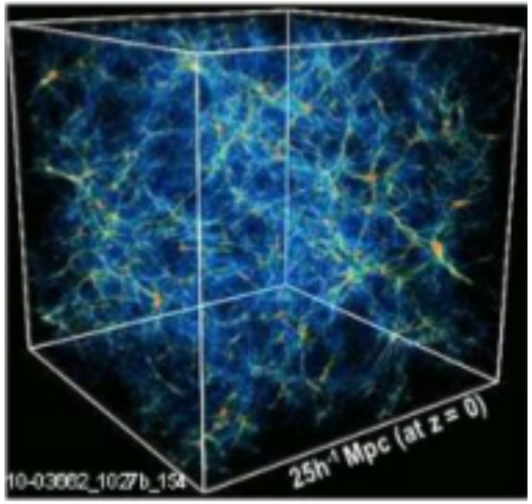
$$= 0.0287 = 64\%\ \Omega_b^{WMAP}$$

→ ~ 35% of Baryons Still Missing at z~0

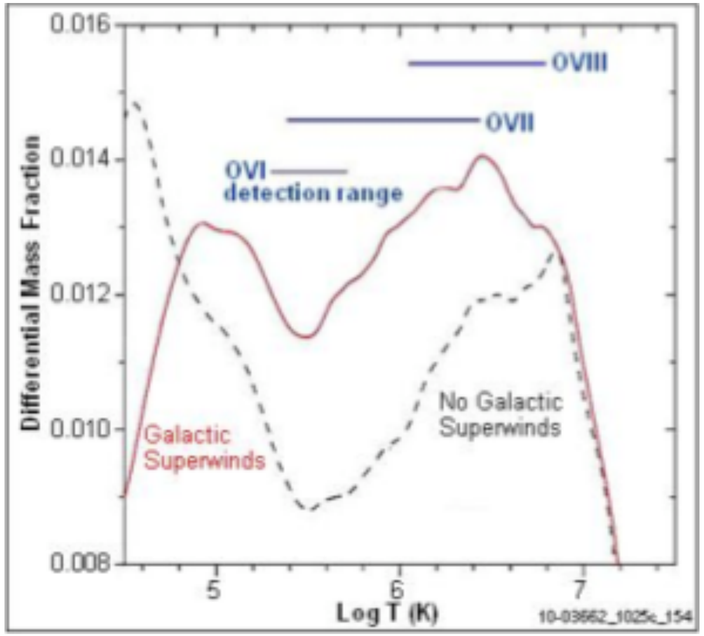
2

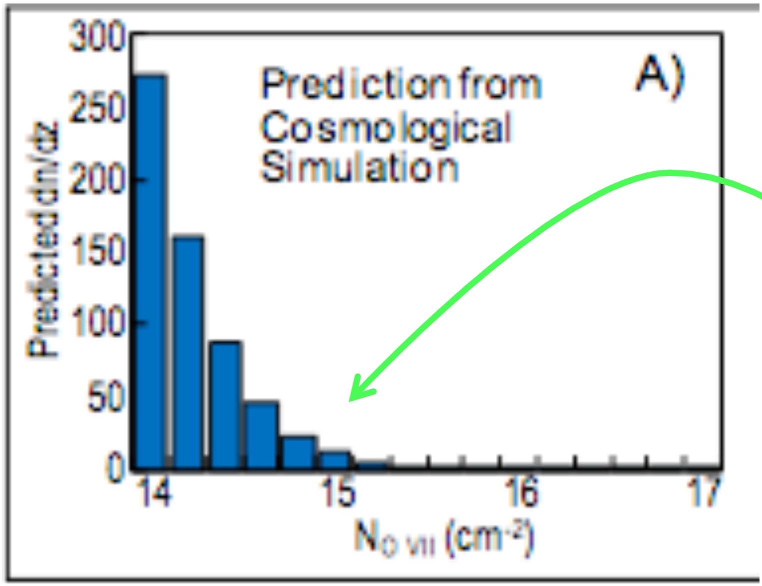
Searching for the Missing Baryons in the X-Ray WHIM

The WHIM in Hydro-dynamical simulations



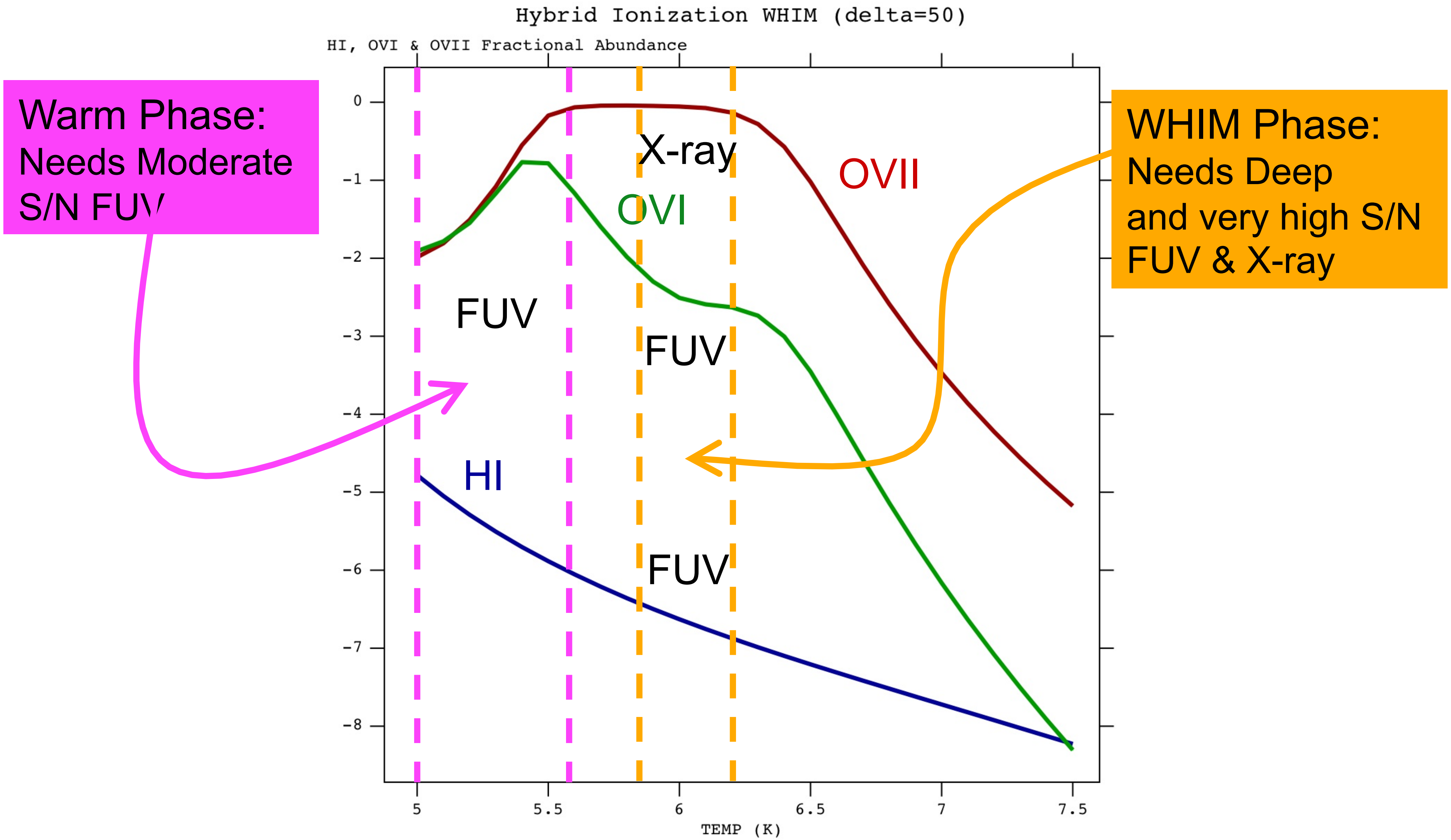
Britton+11





$dN/dz(N_{OVII}>10^{15}\ cm^{-2}) = 10$

Ionization Balance in the WHIM

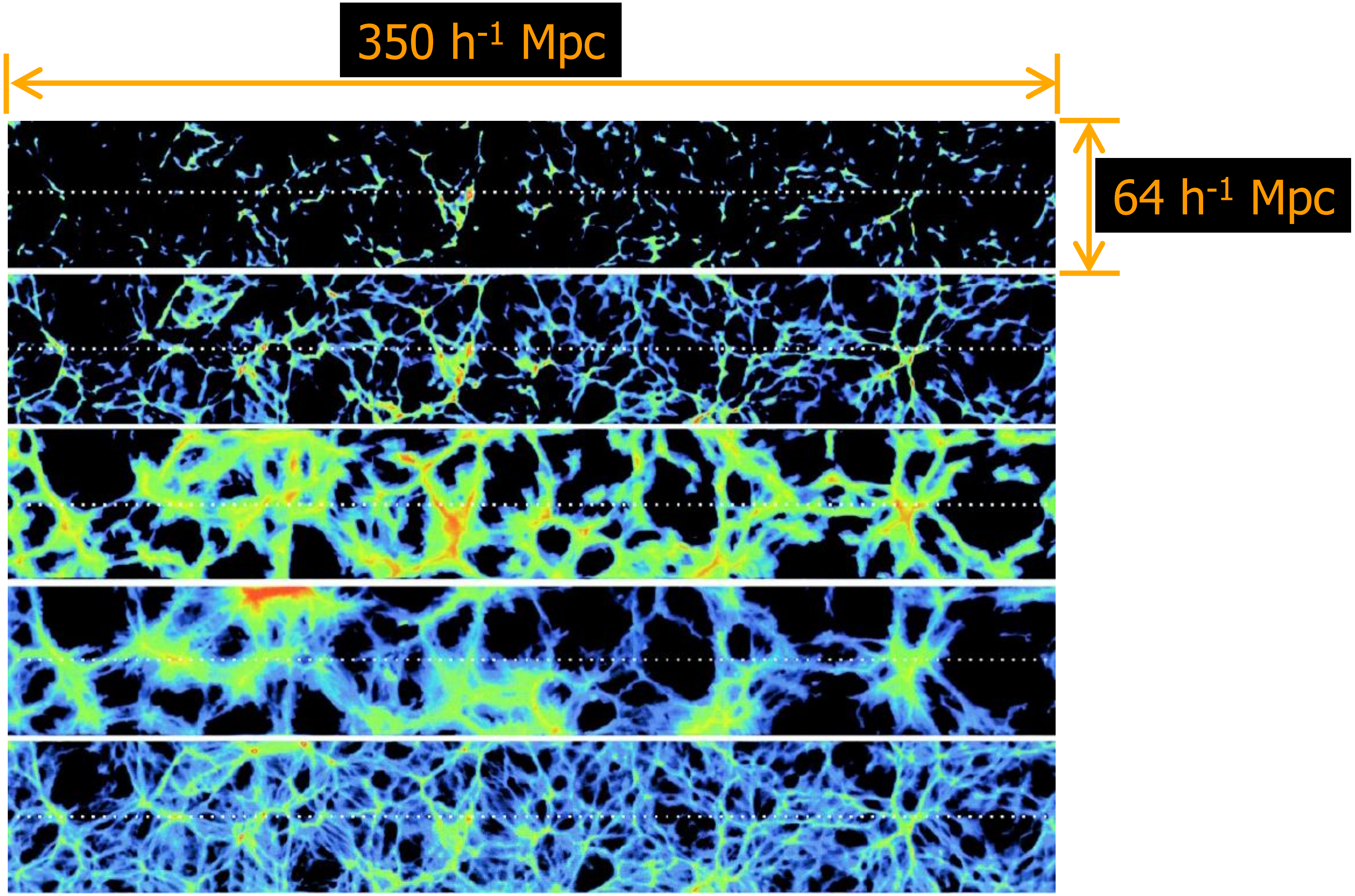


Why in X-Rays

$$f_{12} = \frac{g_2}{g_1} \frac{mc}{2\pi e^2 \nu^2} A_{21}$$

Ion	Transition	Wavelength (Å)	Energy (eV)	f
OI	$K\alpha$	23.52	527.1	0.118
OII	$K\alpha$	23.29	532.3	0.198
OIII	$K\alpha$	23.01-23.08	538.8-537.2	0.292
OIV	$K\alpha$	22.76	544.7	0.409
OV	$K\alpha$	22.37	554.2	0.533
OVI	$K\alpha$	22.03	562.8	0.538
OVII	$K\alpha$	21.60	574.0	0.696
OVII	$K\beta$	18.63	665.5	0.146
OVIII	$K\alpha$	18.97	653.6	0.416

The X-Ray Forest



$N_{OVII} \sim 10^{14\text{-}15}$ cm^{-2}

$N_{OVIII} \sim 10^{14\text{-}15}$ cm^{-2}

$Z/Z_{\odot} \sim 0.05\text{-}0.3$

$T \sim 10^{5.5} - 10^{7}$ K

$n_b \sim 10^{-6}\text{-}10^{-5}$ cm-3

(Hellsten et al., 1998)

WHIM Strength in X-Rays

Transverse Size: $\Delta R \sim 0.5$ Mpc,

Density: $n_b \sim 10^{-5}$ cm^{-3} ($\delta \sim 50$)

Temperature: $T \sim 10^6$ K,

Metallicity: $Z \sim 0.1\, Z_\odot$ (A_O=8.5x10^{-4})

Ion Fraction: ξ_{OVII}=0.87, ξ_{OVIII}=0.13, ξ_{OVI}=0.003, ξ_{CV}=0.27, ξ_{CVI}=0.53

$\Rightarrow N_{OVI} \sim n_b \xi_{OVI} Z \Delta R \sim 8\times10^{13}$ cm^{-2}

$\Rightarrow N_{OVII} \sim n_b \xi_{OVII} Z \Delta R \sim 10^{15}$ cm^{-2}

$\Rightarrow N_{OVIII} \sim n_b \xi_{OVIII} Z \Delta R \sim 2\times10^{14}$ cm^{-2}

$\Rightarrow N_{CV} \sim n_b \xi_{OVIII} Z \Delta R \sim 4\times10^{14}$ cm^{-2}

$\Rightarrow N_{CVI} \sim n_b \xi_{OVIII} Z \Delta R \sim 2\times10^{14}$ cm^{-2}

Line Saturation

Line Saturates when: $\Delta \lambda \sim W_\lambda$

$\Delta \lambda = \lambda (\Delta v/c) \sim \lambda (100/c) \sim 3\times10^{-4} \lambda$

➔ $\Delta \lambda$ (O) ~ 5-7 mÅ (20-25 Å)

➔ $\Delta \lambda$ (C) ~ 12-13 mÅ (40-45 Å)

WHIM Strength & Detectability in X-Rays

$$EW_{X^i} \cong 8.9 \times 10^{-21} (N_H A_X \xi_{X^i}) f_{lu} \lambda^2 \quad \overset{o}{\mathrm{A}}$$

$W_{OVI} \sim 0.2\,(1+z)$ mA

$W_{OVII} \sim 3\,(1+z)$ mA

$W_{OVIII} \sim 0.3\,(1+z)$ mA

$W_{CV} \sim 2\,(1+z)$ mA

$W_{CVI} \sim 2\,(1+z)$ mA

Contrast:

$20/0.003 \sim 7000 \sim 175 \times R_{chandra/XMM}$

$40/(0.002) \sim 20000 \sim 250 \times R_{chandra}$

OVII/CV/CVI Need High-Contrast Spectra

For a Dispersive Spectrometer with FWHM Resolution of $\Delta\lambda^{Spect}$, and an absorption line with FWHM $\Delta\lambda^{Line}$:

$$EW^{N\sigma}_{Thresh} \geq \frac{N\,\Delta\lambda^{Spect}}{(S/N)_{RE}}$$

$$EW(BLA)^{3\sigma}_{Thresh} \geq \frac{3(50mA)}{(S/N)_{RE}}$$

(Chandra LETG)

$(S/N)_{RE(LETG)} \geq 50 \Rightarrow \sim 2500$ CPRE

to detect at 3σ CV/OVII with EW=3 mA

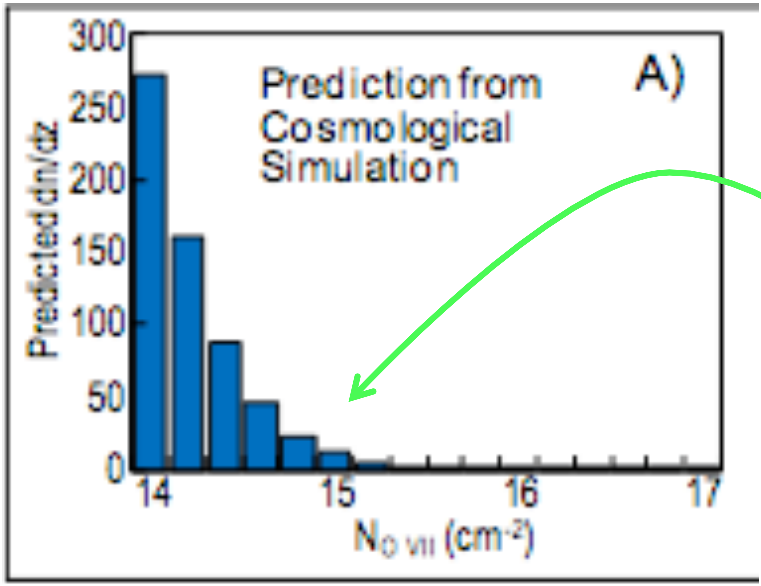
Extremely Demanding with Current Spectrometers

Chandra LETG A_{eff} = 10 cm^2 at 20 Å (XMM: 30 cm^2)
Chandra FWHM Resolution: $\Delta \lambda$ =0.05 Å (XMM: 0.075 Å)

Brightest extragalactic targets $F_{20Å}$ = 0.001 ph s^{-1} cm^{-2} $Å^{-1}$, typically at z<0.1

$$(S/N)_{RE} = (F_{20Å}\ \Delta\lambda\ A_{eff}\ T)^{0.5} = 50$$

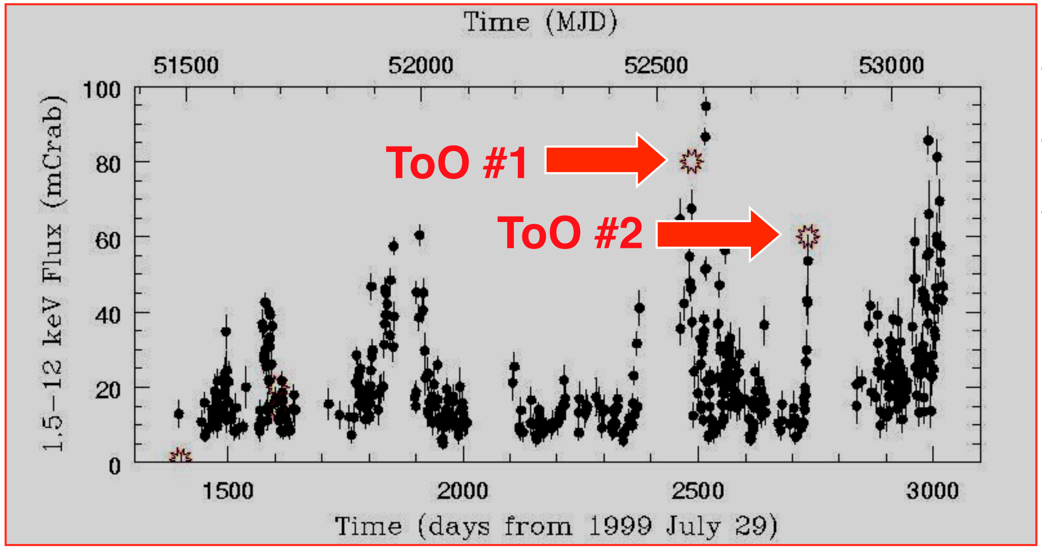
T =5 Ms !!! (about half with XMM)



dN/dz(N_{OVII}>10^{15} cm^{-2}) = 10

Waiting for Outbursts

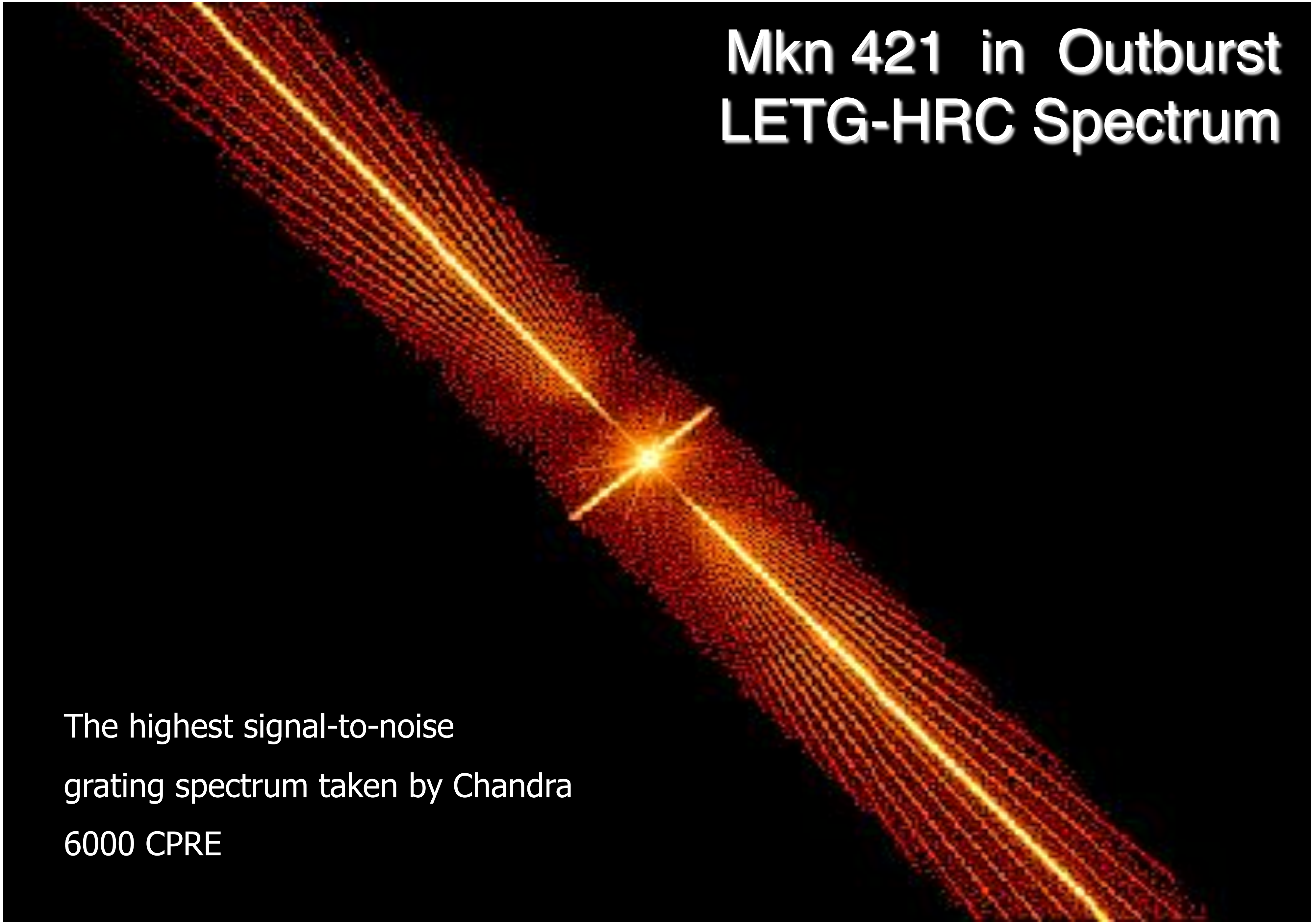
Mkn 421 (z=0.03)
RXTE ASM (0.5-12) keV light curve



- Blazars flare to > 10 times normal
- Trigger ToO (from Rossi-XTE ASM)
- Outbursts last days to 1-2 weeks

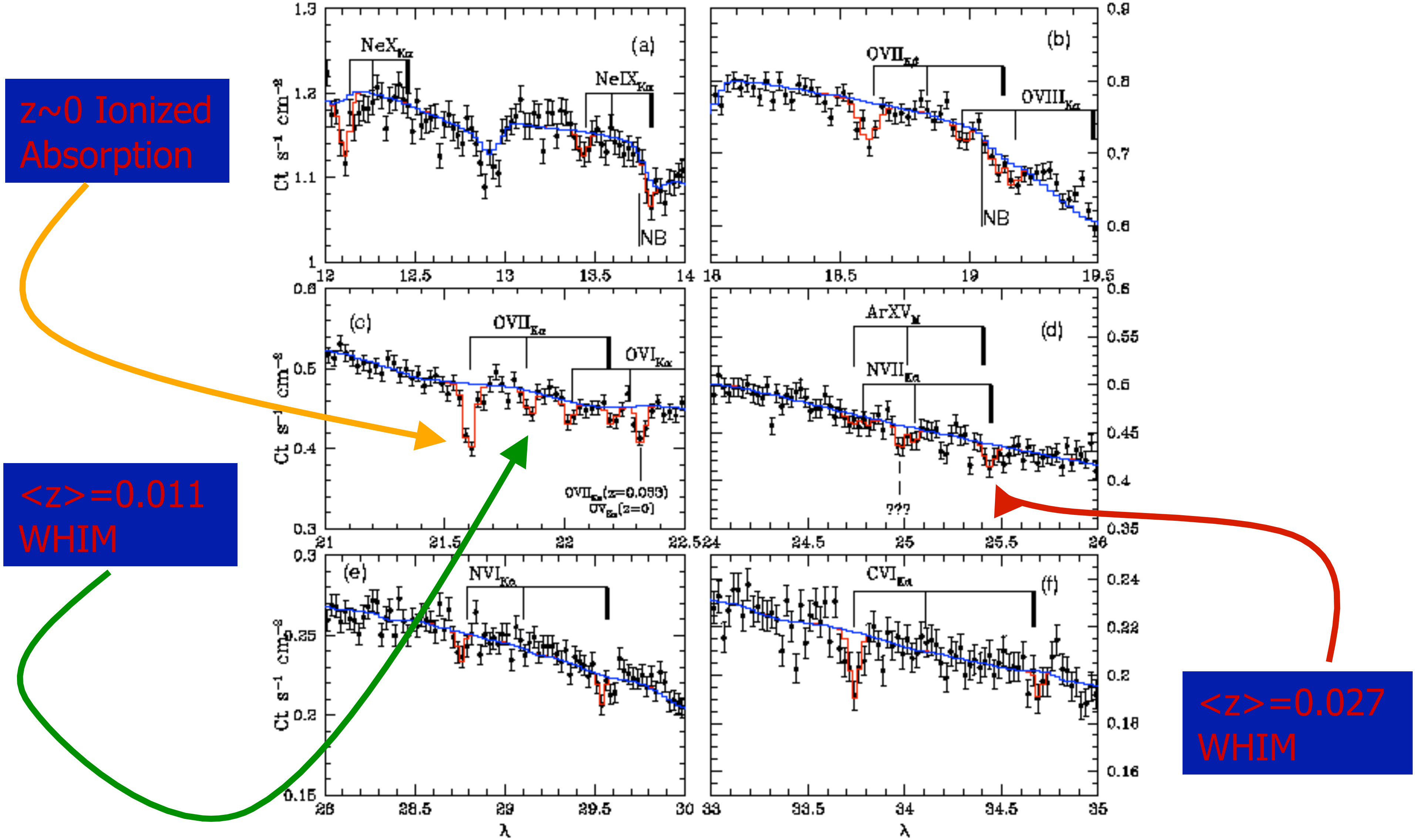
✓1st ToO ***80mCrab*** 2002 October 27: 100 ks ACIS-LETG
✓2nd ToO ***60mCrab*** 2003 June 6: 100 ks HRC-LETG

Mkn 421 in Outburst LETG-HRC Spectrum



The highest signal-to-noise
grating spectrum taken by Chandra
6000 CPRE

WHIM and ISM Absorption



(Nicastro+05a; Nicastro+05b; Williams+05)

WHIM Observables

Absorption Line Equivalent Widths:

→ Ion Column Densities: N_{ion}

Equivalent Width Ratios:

→ Ionization Balance: T, n_b

Equivalent Widths and Saturation

- Same-Ion Line ratios: direct check
- Curve of Growth technique:

$$W_{X^i} = \int_0^\infty (1 - e^{-\tau_\nu}) d\nu \approx \int_0^\infty \tau_\nu d\nu + \frac{1}{2} \int_0^\infty \tau_\nu^2 + \ldots$$

$$\tau_\nu = N_{X^i} \frac{\pi e^2}{mc} f_{lu} \Phi(\nu)$$

$$\Rightarrow W_{X^i} \approx \frac{\pi e^2}{mc} f_{lu} N_{X^i} + \frac{1}{2} \left(\frac{\pi e^2}{mc} f_{lu} N_{X^i} \right)^2 \int_0^\infty \Phi^2(\nu) d\nu + \ldots$$

Ionization Balance

- Most metal absorption Lines fall in the linear branch of the Curves of Growth (CoG)

➔ EW ∝ Ion Column Density :

$$EW_{X^i} \cong 8.9 \times 10^{-21} (N_H A_X \xi_{X^i}) f_{lu} \lambda^2 \quad \overset{o}{\mathrm{A}}$$

➔ EW ratios ∝ Ionization Balance:

For 2 ions from the same element

$$\frac{\xi_{X^i}}{\xi_{X^{[i+n]}}} = \frac{EW_{X^i}}{EW_{X^{[i+n]}}} \times \frac{f_{lu}(X^{[i+n]})}{f_{lu}(X^i)} \times \left(\frac{\lambda_{X^{[i+n]}}}{\lambda_{X^i}}\right)^2$$

For 2 ions from different elements

$$\frac{\xi_{X^i}}{\xi_{Y^j}} = \frac{EW_{X^i}}{EW_{Y^j}} \times \frac{f_{lu}(Y^j)}{f_{lu}(X^i)} \times \frac{A_Y}{A_X} \times \left(\frac{\lambda_{Y^j}}{\lambda_{X^i}}\right)^2$$

Mass and Metal Content of the WHIM

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

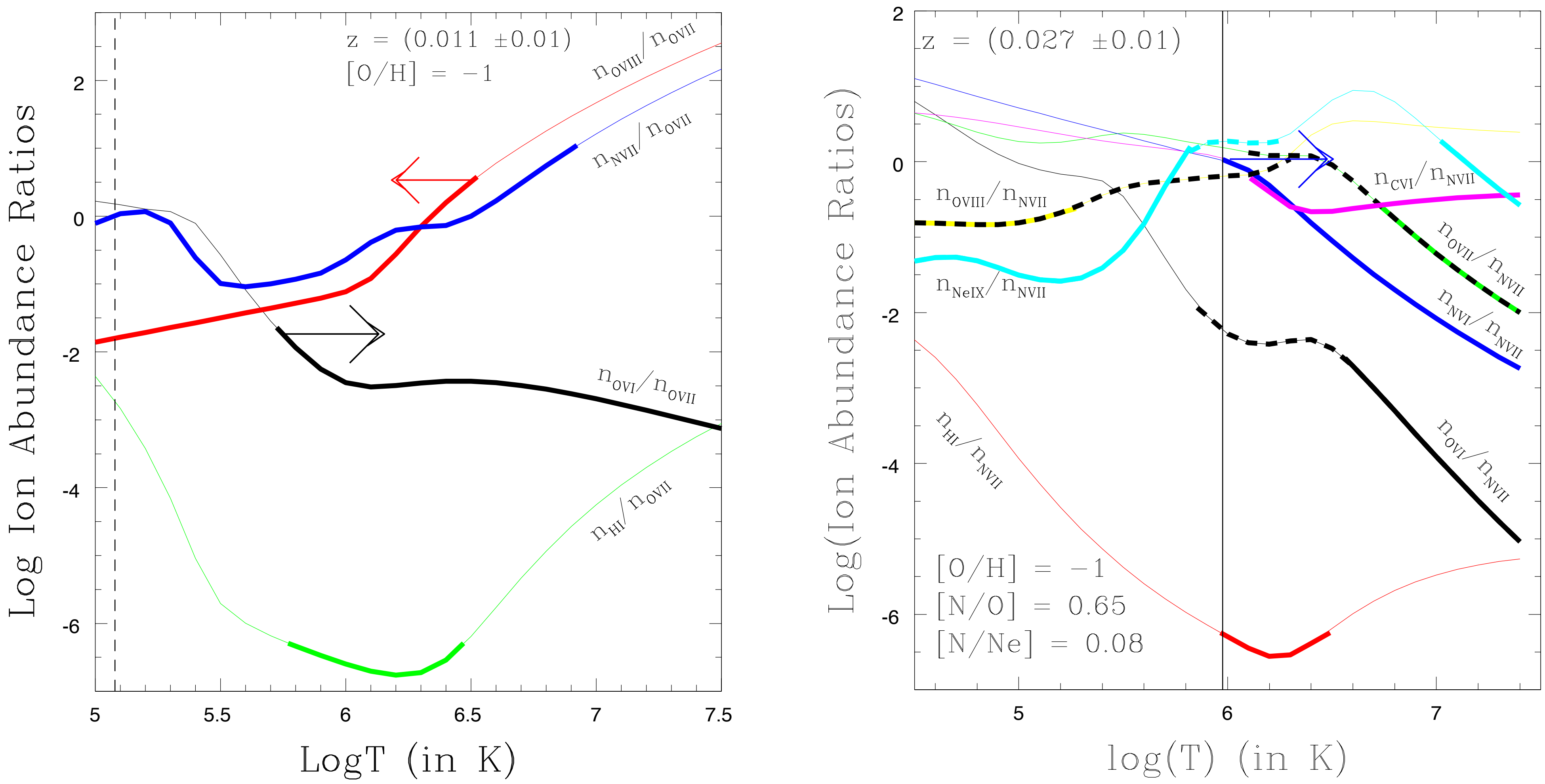
$$N_H = N_{ion} \times A_{element}^{-1} \times \xi_{ion}^{-1}$$

FUV | X

FUV & X

X

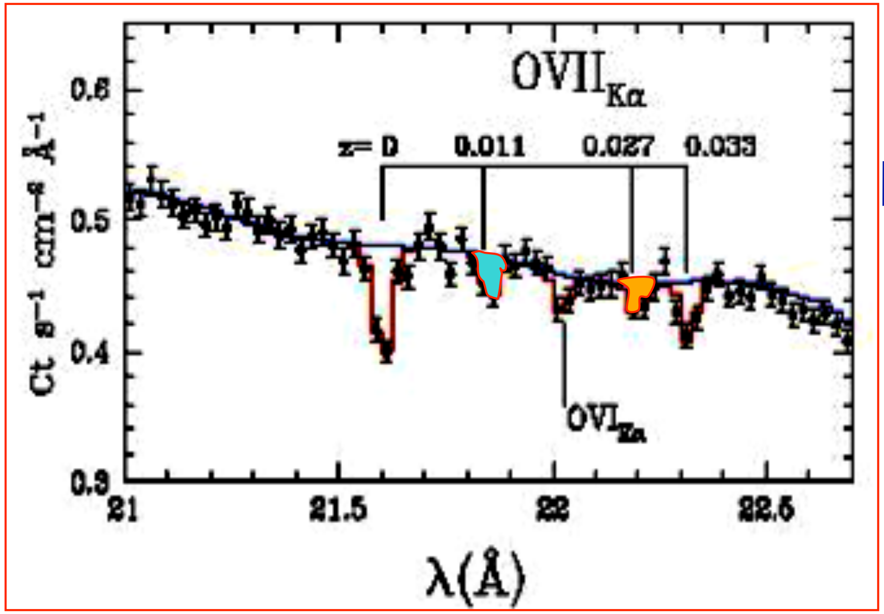
Modeling the WHIM with Hybrid-Ionization Models

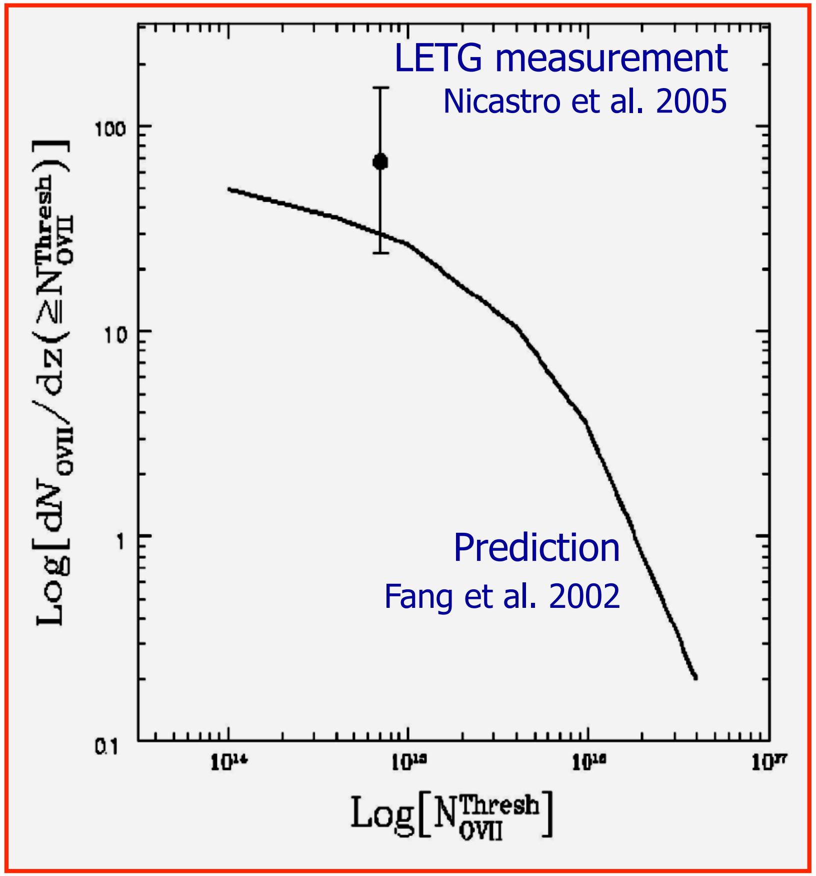


X-Ray WHIM toward Mkn 421

Nicastro+05, *Nature*

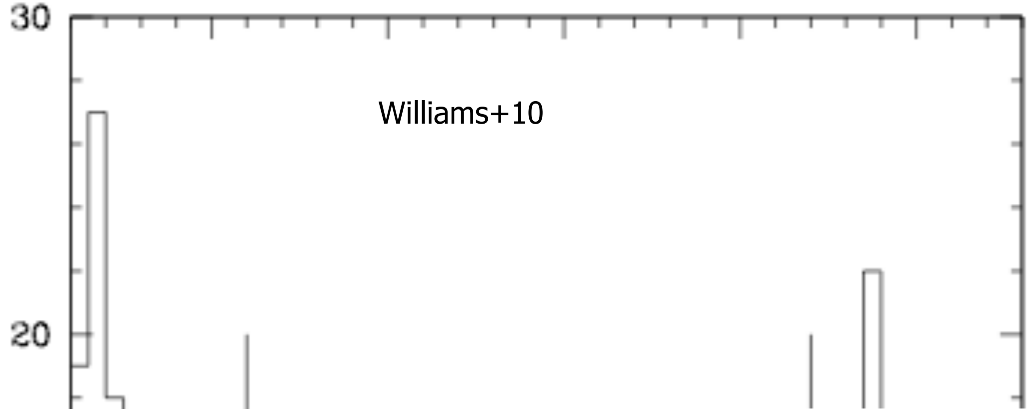
9 z>0 lines: 2 systems
z=0.011 (3.5σ), 0.027 (4.9σ)

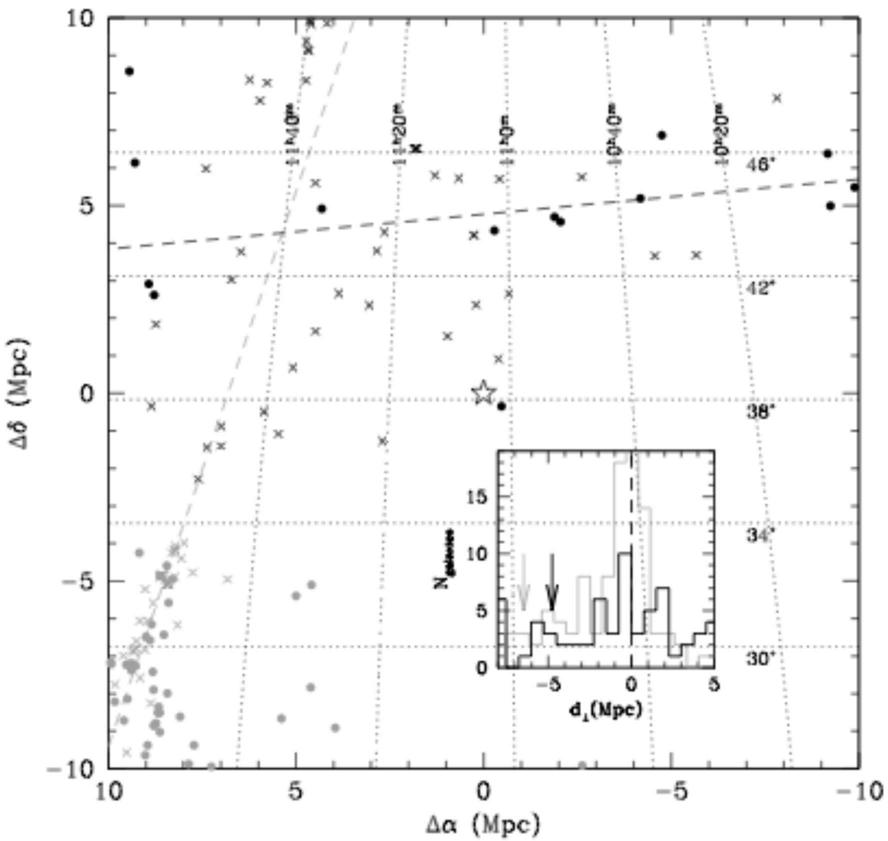


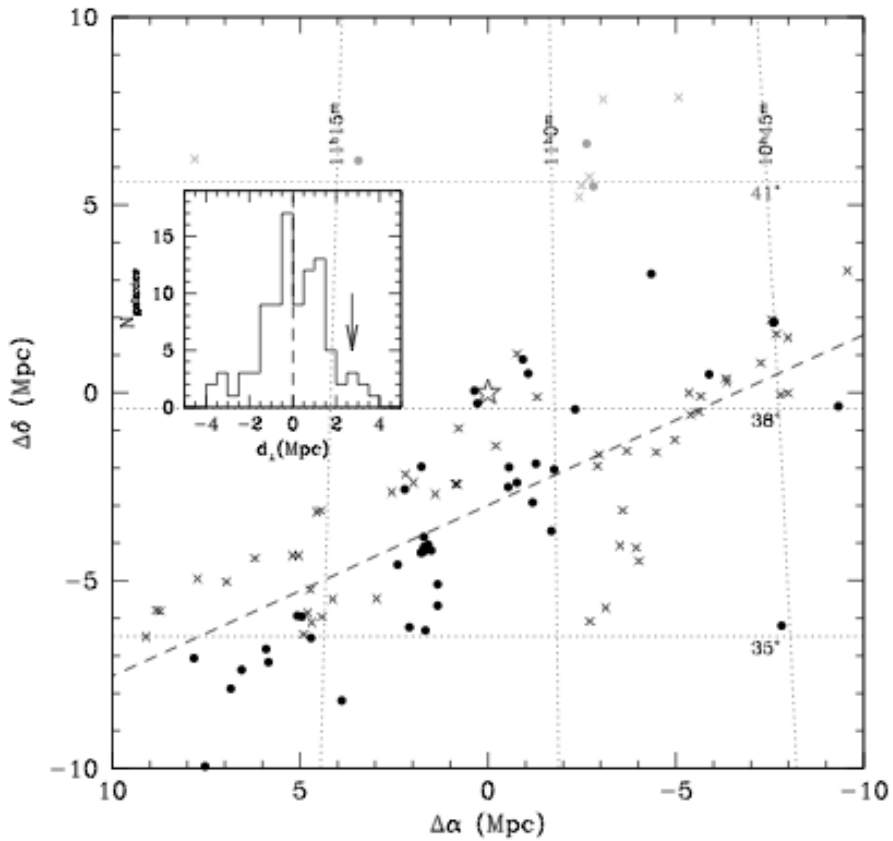


$$\Omega_b(N_{OVII} > 7*10^{14}) = \left(\frac{1}{\rho_c}\right)\left(\frac{\mu m_p \sum_i N_H^i}{d_{Mkn421}}\right) = 2.7^{+3.8}_{-1.9} * 10^{-[O/H]_{-1}}\%$$

Galaxy Environment of Mkn 421 Absorbers



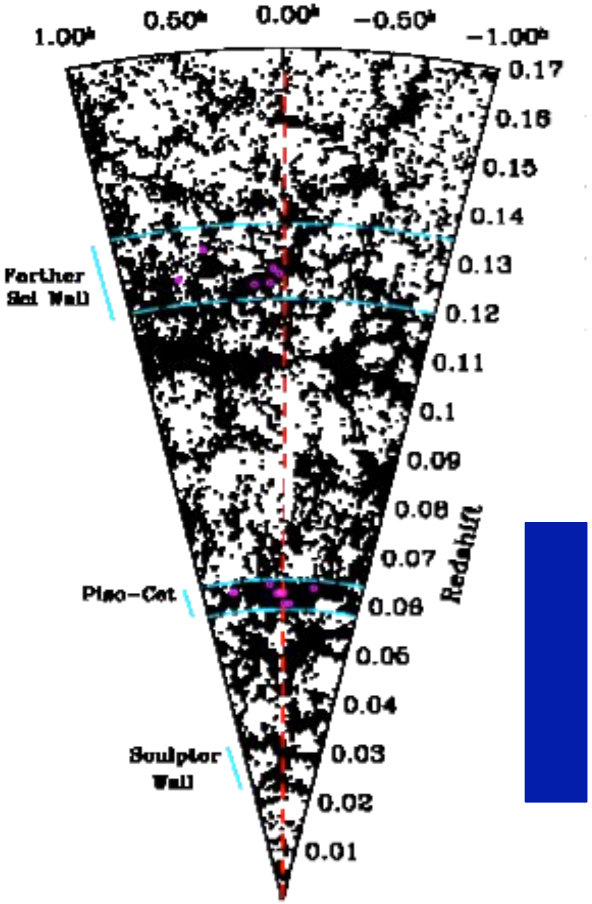


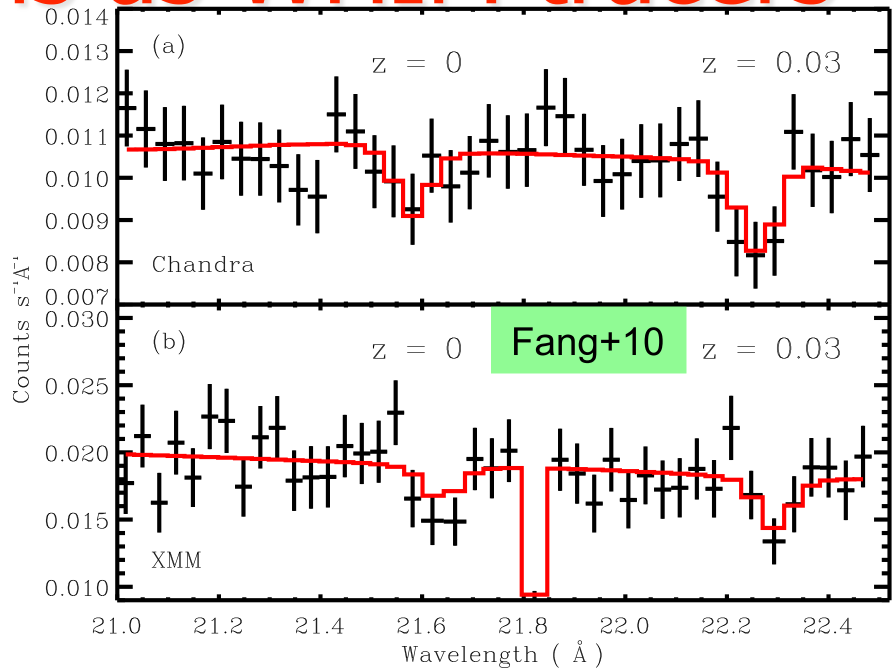


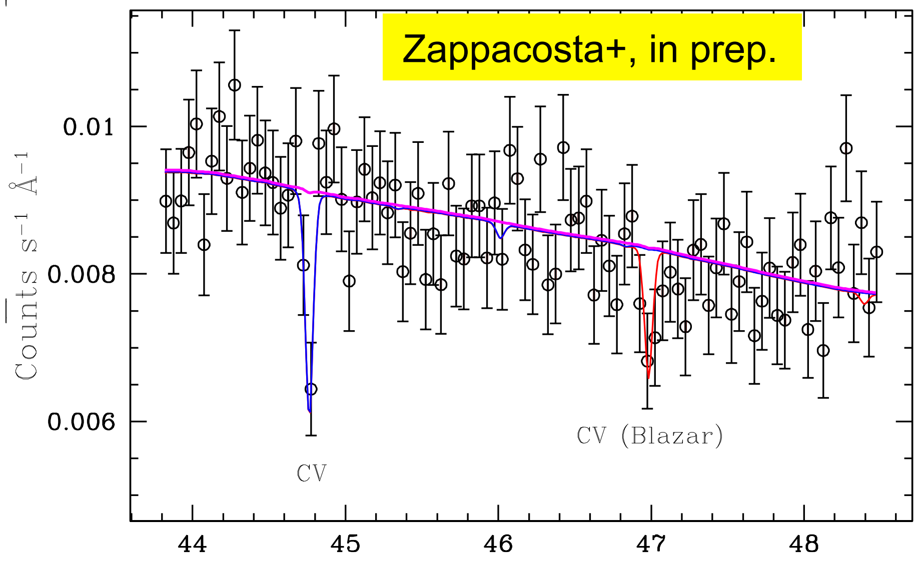
0

Cours

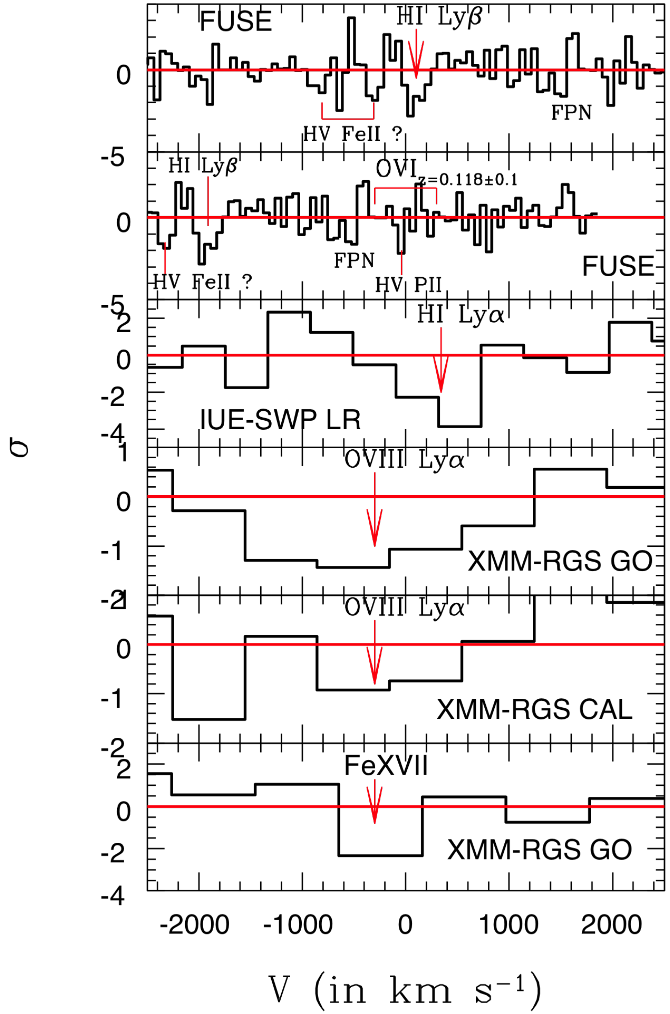
Galaxy concentrations as WHIM tracers







A Serendipitous hot X-Ray/BLA Filament at z=0.118?



From X-rays ➔ $\log T < 6.75$; $\log N_H = 21.5 \pm 0.3\ (Z/Z_{0.01\odot})^{-1}$

From lack of OVI ➔ $\log T > 6.52$

From HI and T ➔ $Z = (1\text{-}4)\%\ Z_\odot$

From Z and T and Theory ➔ $\delta \approx 300$

From δ and N_H ➔ D=4-7 Mpc

Combined Statistical Significance = 5.2σ (5σ if FUSE systematics are included) [Nicastro+10]

3

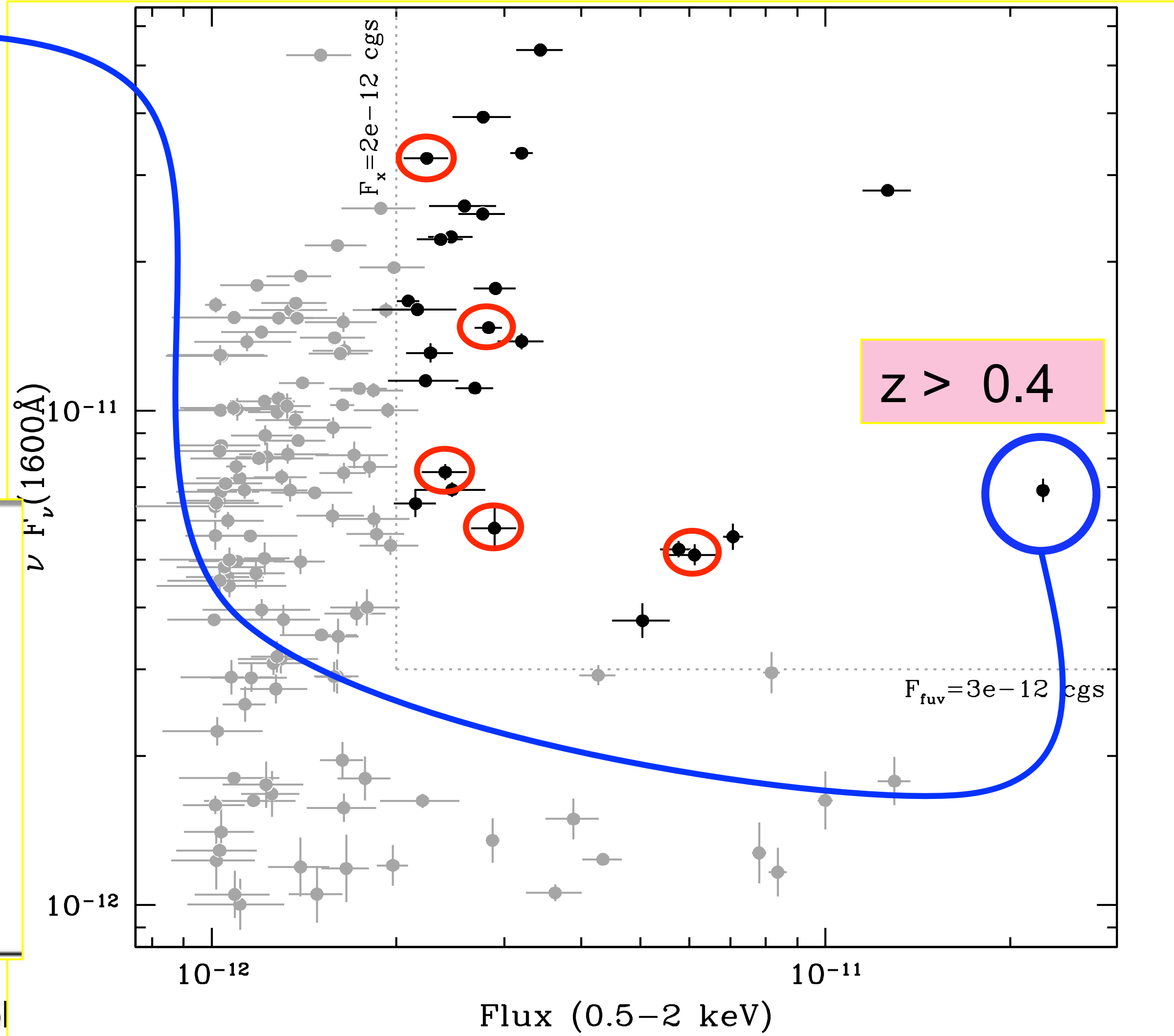
Optimizing the Observational Strategy

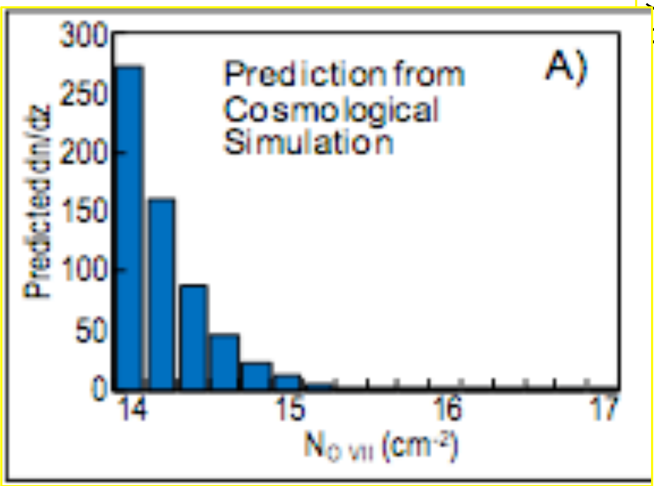
The WHIM is hard to detect

- Only 4 systems at $z<0.4$ and $N_{OVII}> 10^{15}cm^{-2}$
  ➔ Needs high-z targets
- $N_{OVII}=10^{15}cm^{-2}$ ⇔ EW(OVII Kα)=3 mA
  ➔ Needs bright X-ray targets (> 1 mCrab)
- ~170 REs at $z<0.4$ in Chandra: ~10 by chance at $< -2\sigma$ ➔ Needs "Signposts"

Best WHIM Targets

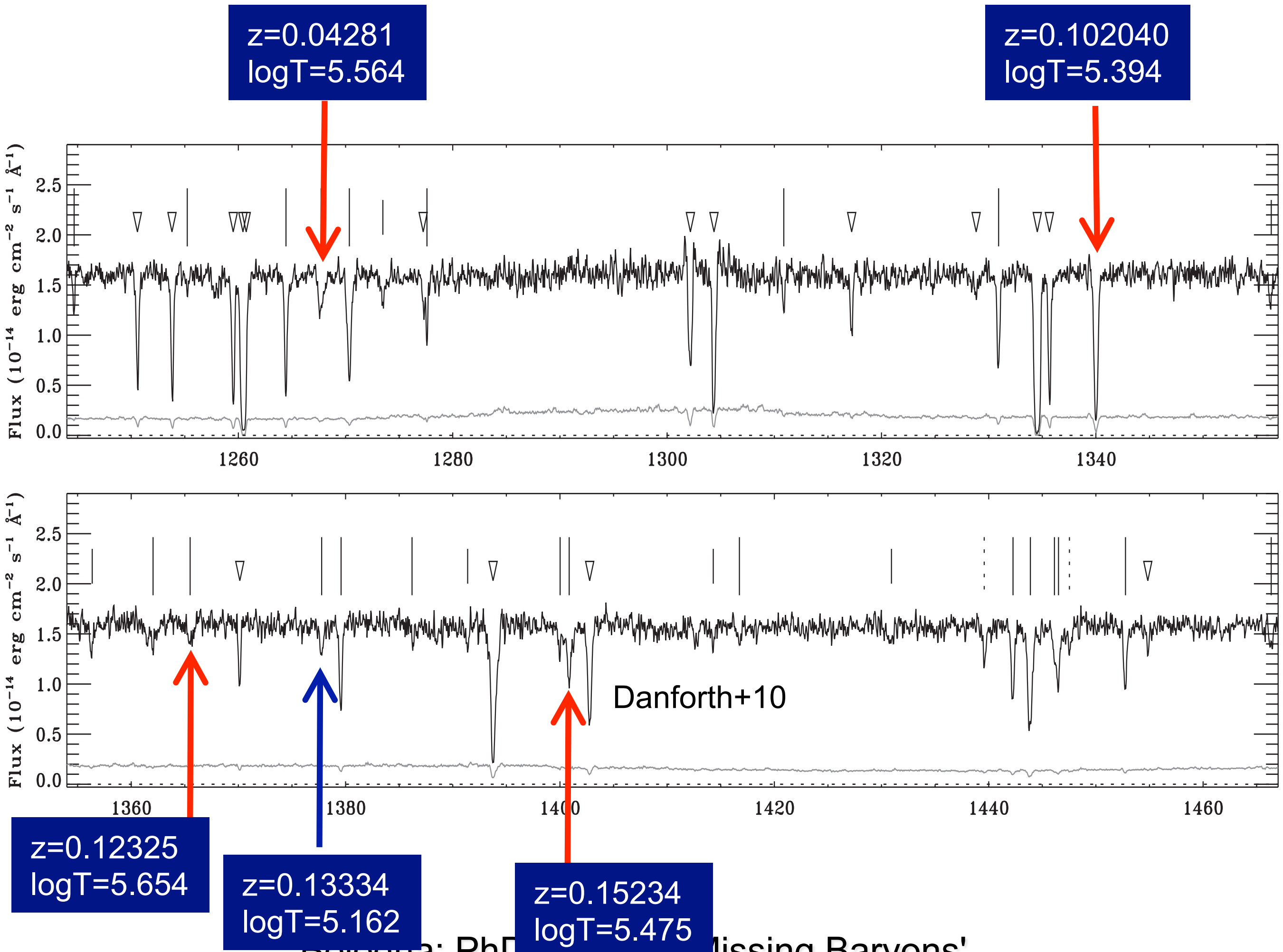
1ES 1553+115: the Best WHIM Target in the Universe!





FUV Signposts: BLAs and Ly α

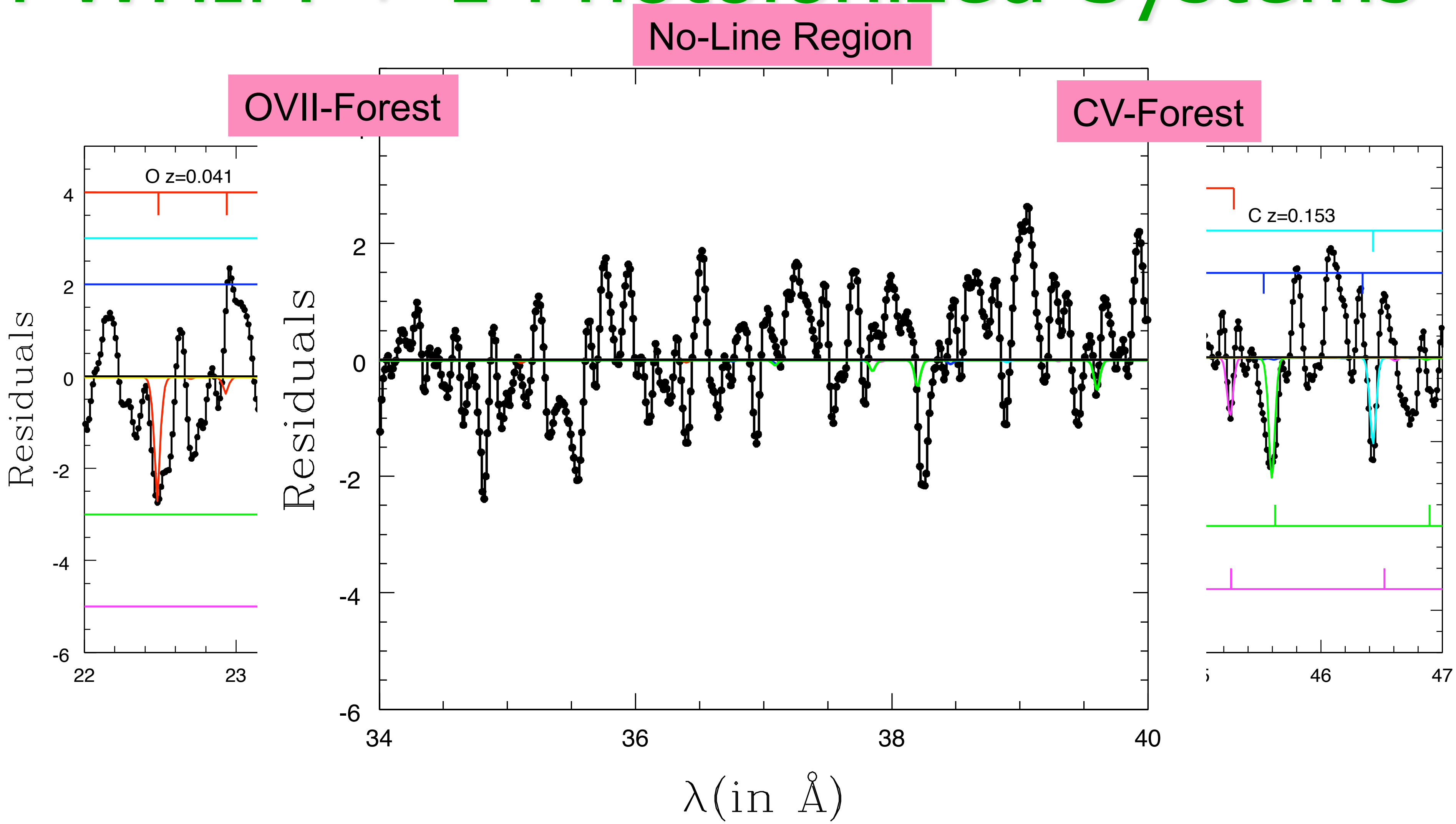
42 Ly α systems in COS: 4(5) Broad (b>52(46) km s^{-1} ➔ b_{th}>40(35) km s^{-1})



Chandra 500 ks of 1ES 1553+113

- 3 Observations: (a) 2011, May 4-6 (166 ks); (b) 2011, May 6-9 (175 ks); (c) 2011, June 18-20 (154 ks)
- Total Exposure: 495 ks
- Confirm average flux: $F_{0.5-2}$(a)=1.1 mCrab; $F_{0.5-2}$(b)=1.2 mCrab; $F_{0.5-2}$(c)=0.6 mCrab
- Sensitivity to Absorption Line EW>4 mA (1σ) in 18-28 A (~300 Ct/R.E.)
- Detects several ISM/IGM absorption lines

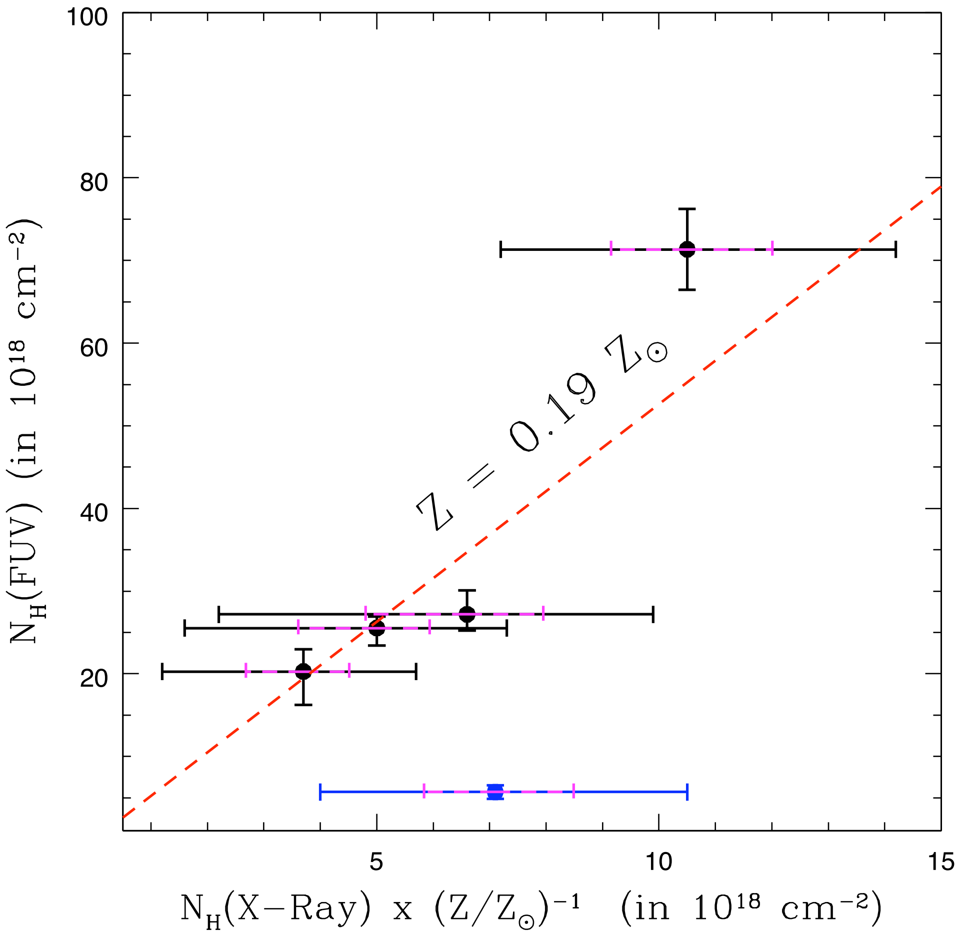
LETG LSF-Smoothed Residuals:
4 WHIM + 1 Photoionized Systems

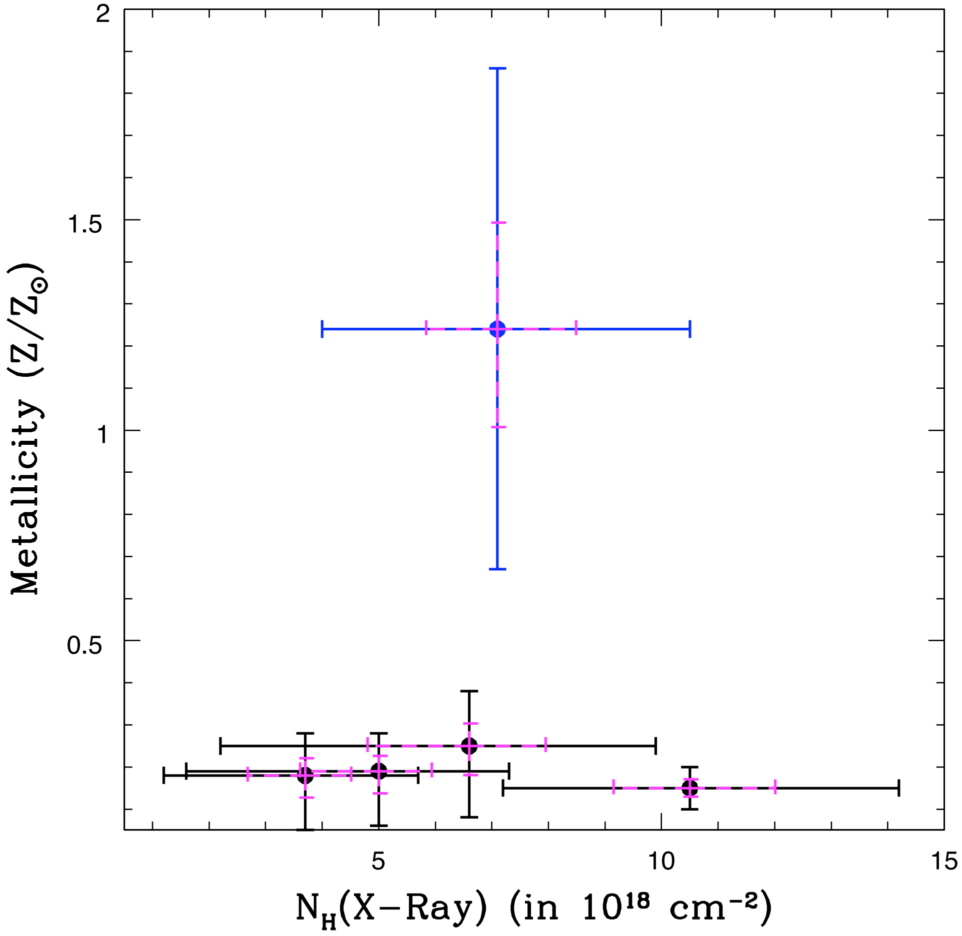


Physical Properties and Metallicities

Redshift X/FUV	b_{th} (km s^{-1})	logT (K)	f(HI) (10^{-6})	$N_H(X)$ (10^{18} cm^{-2})	N_{HI} (10^{13} cm^{-2})	$Z/Z_\odot$	Stat. Sign. (σ) X/FUV
0.041 0.04281	56 ± 5	5.564	1.03	$6.6^{+4.4}_{-3.3}$	$2.8^{+0.2}_{-0.3}$	$0.25^{+0.17}_{-0.13}$	3/23.9
0.100 0.10230	40 ± 1	5.394	1.85	$10.5^{+3.3}_{-3.7}$	13.2 ± 0.09	0.15 ±0.05	2.6/90
0.123 0.12325	62 ± 12	5.654	0.74	$3.7^{+2.5}_{-2.0}$	$1.5^{+0.3}_{-0.2}$	$0.18^{+0.13}_{-0.10}$	2/4.5
0.153 0.15234	51 ± 4	5.475	1.41	$5.0^{+3.4}_{-2.3}$	$3.6^{+0.3}_{-0.2}$	$0.19^{+0.13}_{-0.09}$	2/13.3
0.132 0.13334	35 ± 6	5.327	2.46	$7.1^{+3.1}_{-3.4}$	$1.4^{+0.2}_{-0.2}$	$1.24^{+0.57}_{-0.62}$	2/5.4

Physical Properties and Metallicities





4

The Missing Baryons in and around the Milky Way

Hot Gas in the Local Group

> 1.5 x 10^{12} $M_{\odot}$ are needed to stabilize the Local Group

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INTERGALACTIC MATTER AND THE GALAXY

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Received May 18, 1959

ABSTRACT

It is shown that the Local Group of galaxies can be dynamically stable only if it contains an appreciable amount of intergalactic matter. A detailed discussion shows that this matter consists mainly of ionized hydrogen and that stars can contribute only a small fraction to its total mass. The most likely values for the intergalactic temperature and density are found to be 5×10^5 degrees and 1×10^{-4} proton/cm^3, respectively. It is thought that this gas confines the halo. The distortion of the disk of the Galaxy, revealed by 21-cm observations, is analyzed. This effect cannot be regarded as a relic from a primeval distortion, which occurred at the time of formation of the Galaxy; a more promising explanation for it can be given in terms of the flow pattern of the intergalactic gas past the Galaxy and of the resulting pressure distribution on the halo.

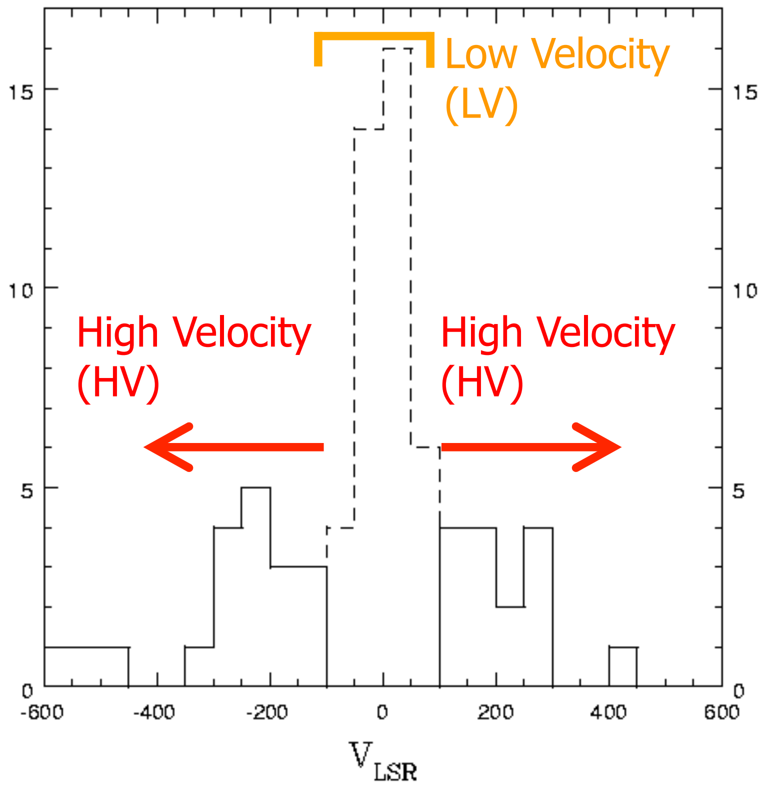
OVI Velocity Distribution in the LSR

(Nicastro+03, Nature)

The Sample:

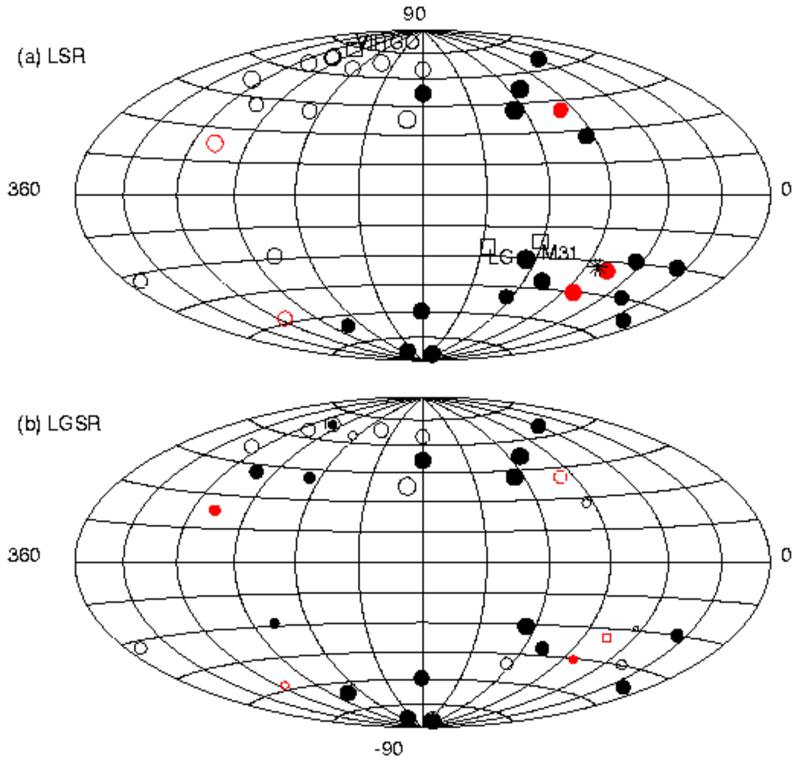
- 103 FUSE Obs. Of AGN
- 54 with S/N ≥ 5 per Res. El., at 1032 Å
- 45 show at least 1 OVI abs. at z~0, at our detection threshold
(7 of the remaining 9 have poor S/N spectra)

- 38/45 LV-OVI
- 32/45 HV-OVI
- 21 both
- High Covering Factor
(could be 90 % down to 20 mÅ, Sembach+02)

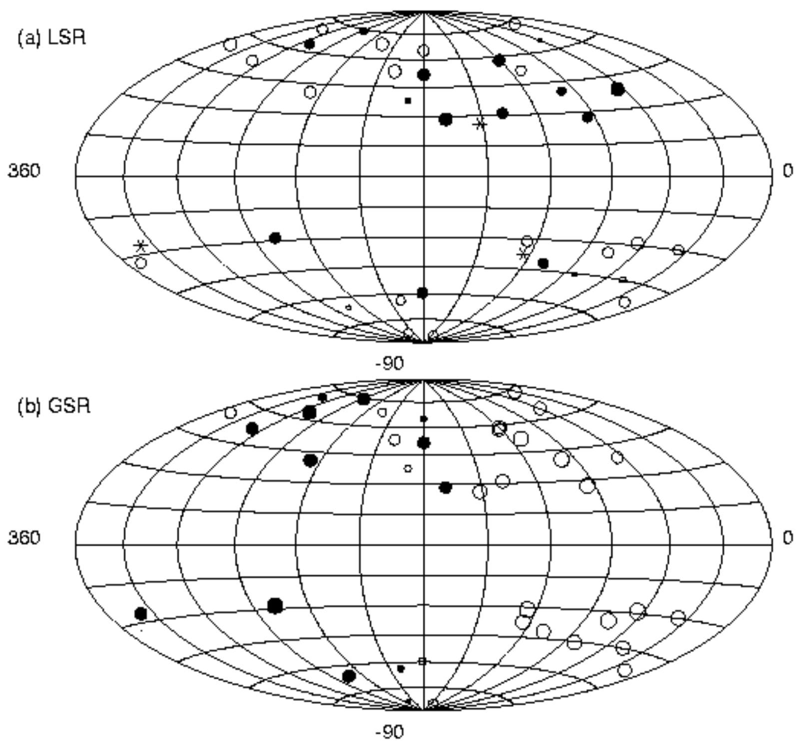


Velocity Segregation

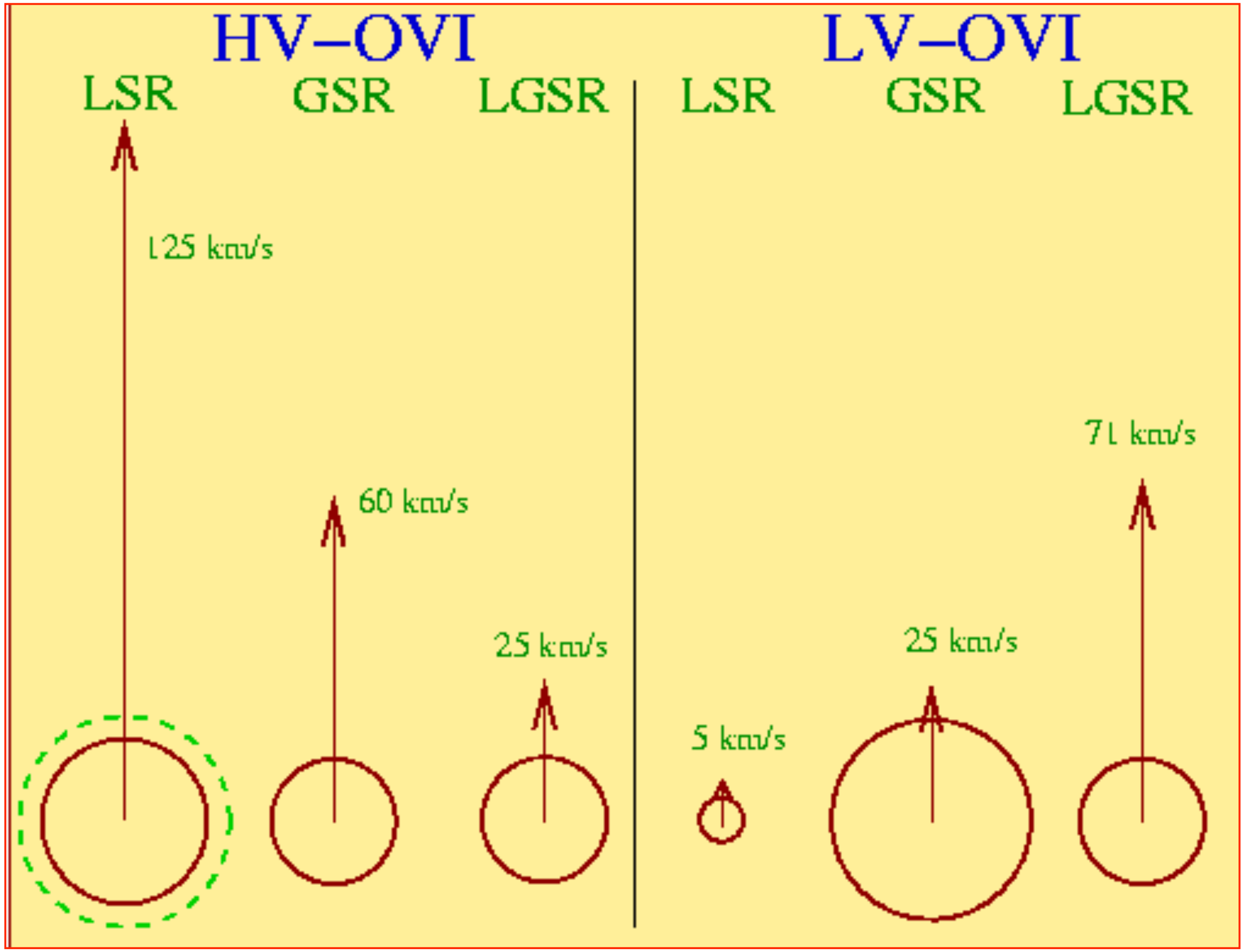
HV-OVI
Strong Segregation in the LSR



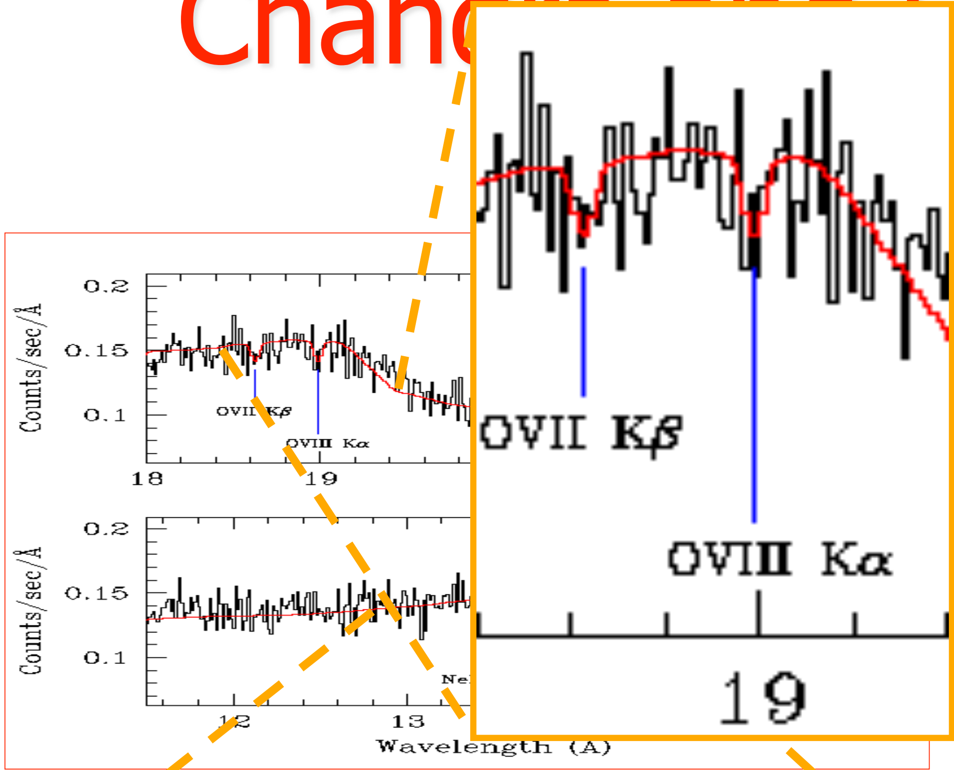
LV-OVI
Strong Segregation in the GSR

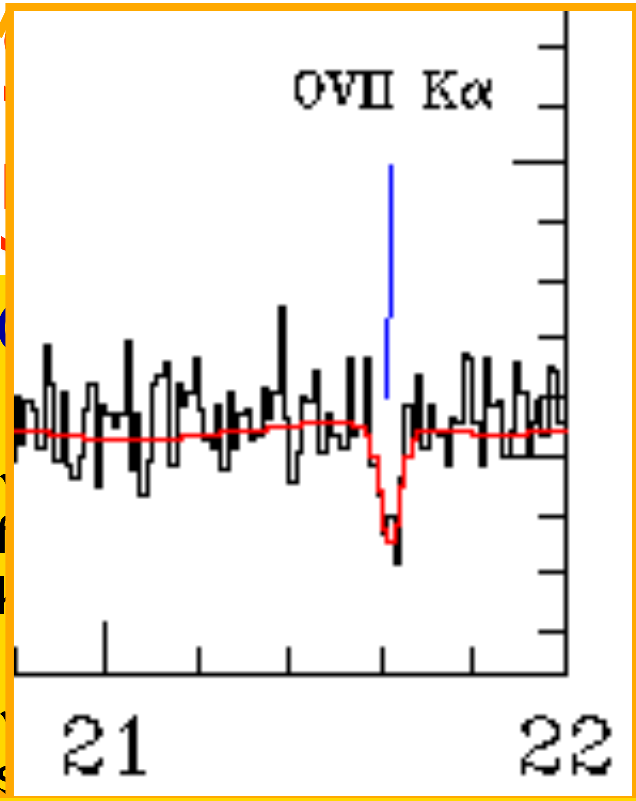


Average Velocity Vectors



Chand… and FU… of …5…





…1999
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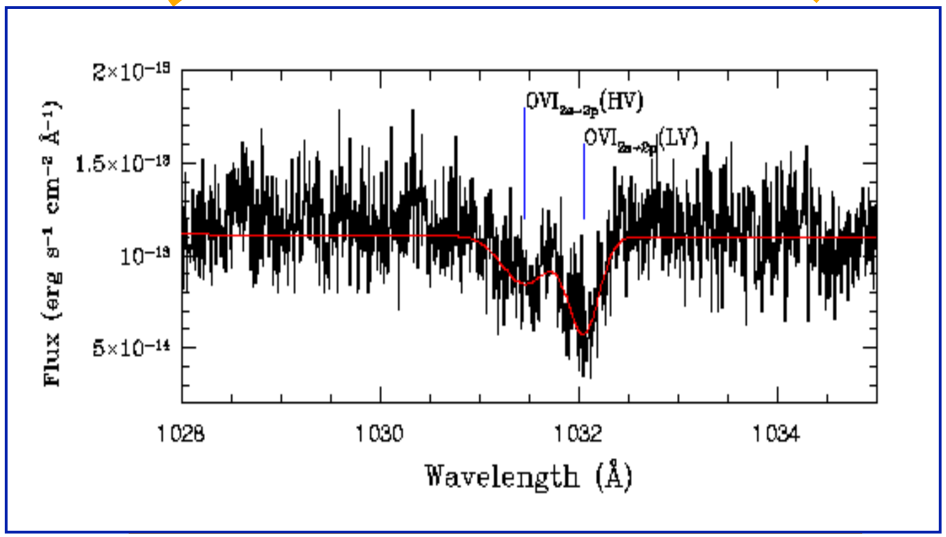
FUSE Spectrum

Resolution: Δλ ~ 65 mÅ
➔~ 20 km s^{-1} @ 1000 Å

✓Observed on 24 October 1999 for ~ 39 ks



Galactic vs Extragalactic Solutions

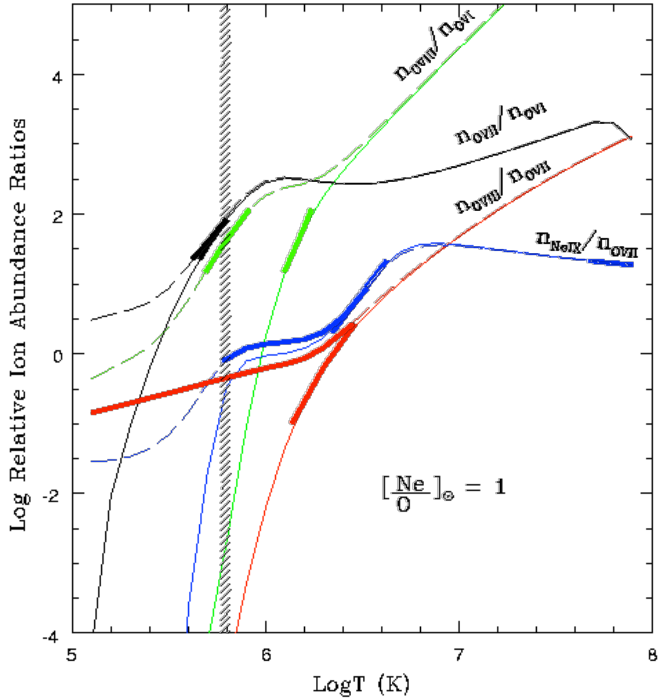
Galactic = High Density (typical ISM densities) ➔ No Phot. Contr. ➔ Gas in collisional equilibrium: 3-cloud Galactic solution.

Extragalactic = Low Density ($n_e < 10^{-5}$ cm^{-3}) ➔ XRB contribution becomes important: it populates OVII-OVIII species event at relatively low temperature ($T \sim 10^6$ K) ➔ Local Group WHIM solution

WHIM Solution:

logT = 5.8; $[Ne/O]_{\odot} = 2.5$
$n_e = 4\text{-}6 \times 10^{-6}$ cm^{-3} = 20-30 δ
$N_H = 4.5 \times 10^{19}$ $[H/O]_{0.3}$ cm^{-2}
All consistent with WHIM predictions
==> D = $(2\text{-}4)[H/O]_{0.3}$ Mpc
Well Beyond the Milky Way

(Nicastro et al., 2002, ApJ, 573, 157)



Implication

- Assuming a transverse size of $1\times[H/O]_{0.3}$ Mpc

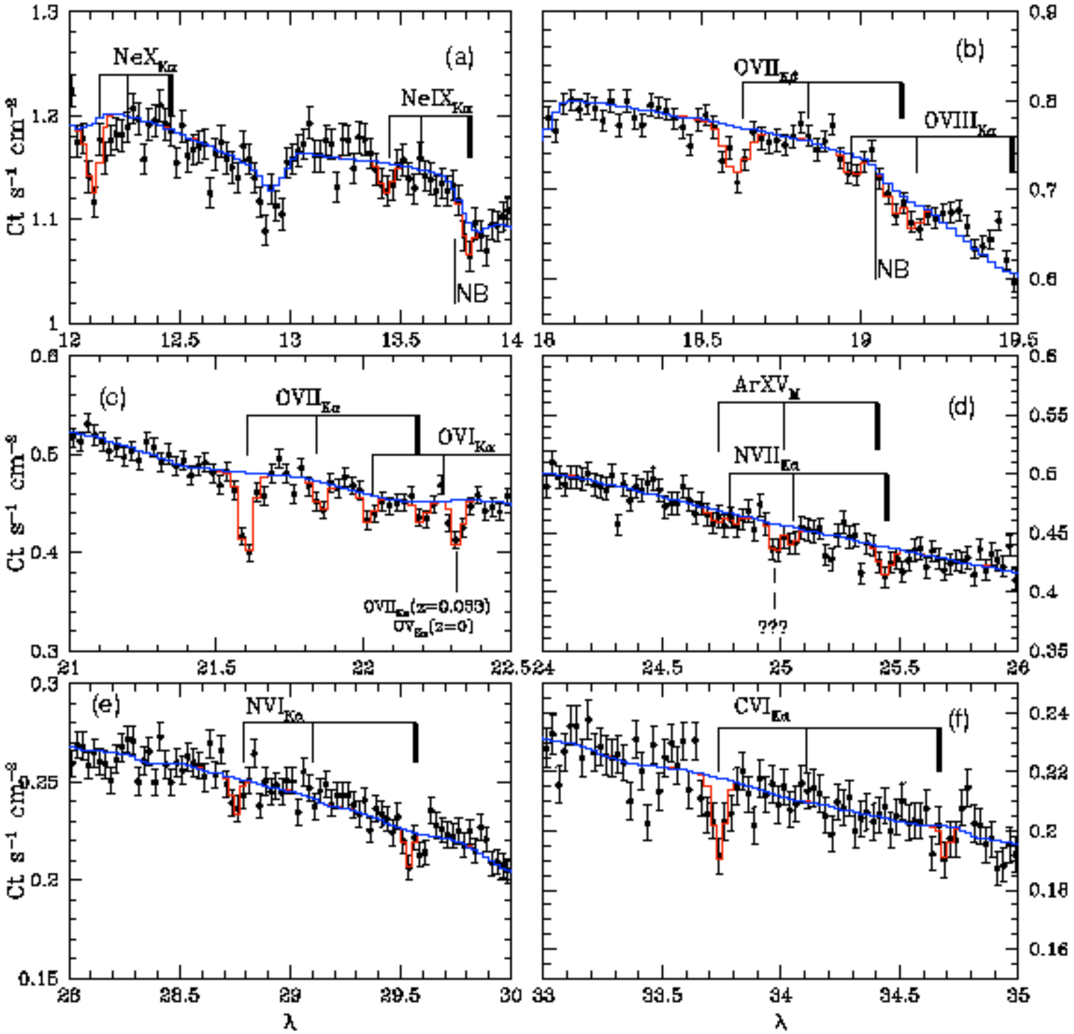
$$M = (0.6 - 2)\times 10^{12} M_{\odot}$$

Assumes High Covering Factors

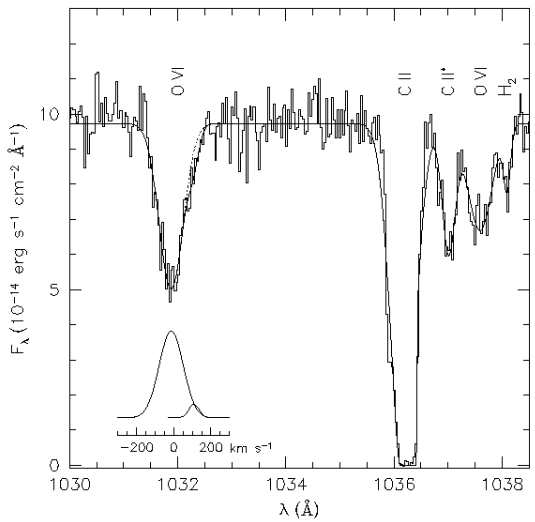
Z=0 Absorption

Chandra-LETG spectrum of Mkn 421

(Williams+05)

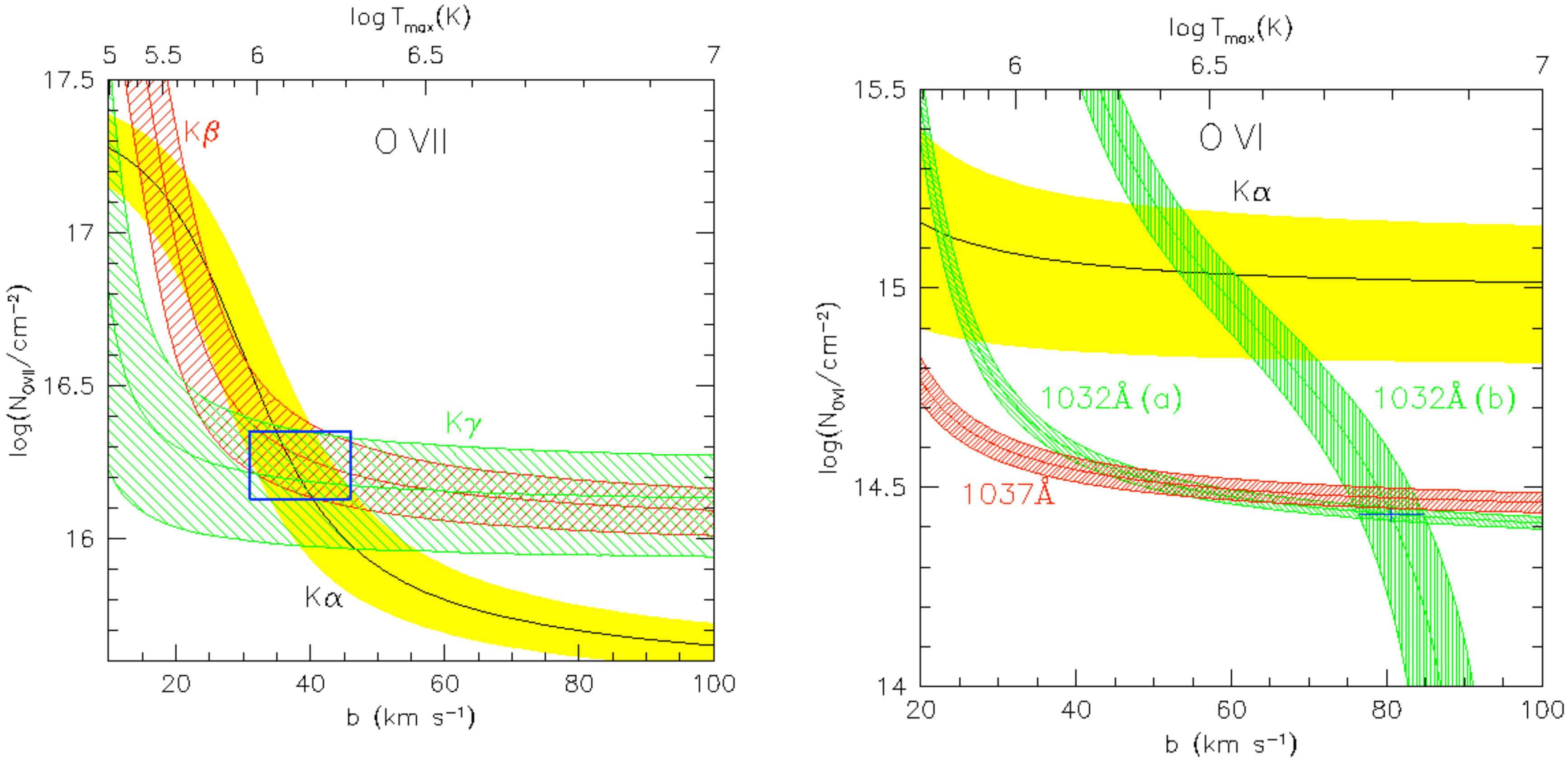


FUSE



Doppler Parameter

OVII Gas ≠LV-OVI Gas



(Williams+05)

Ionization Balance

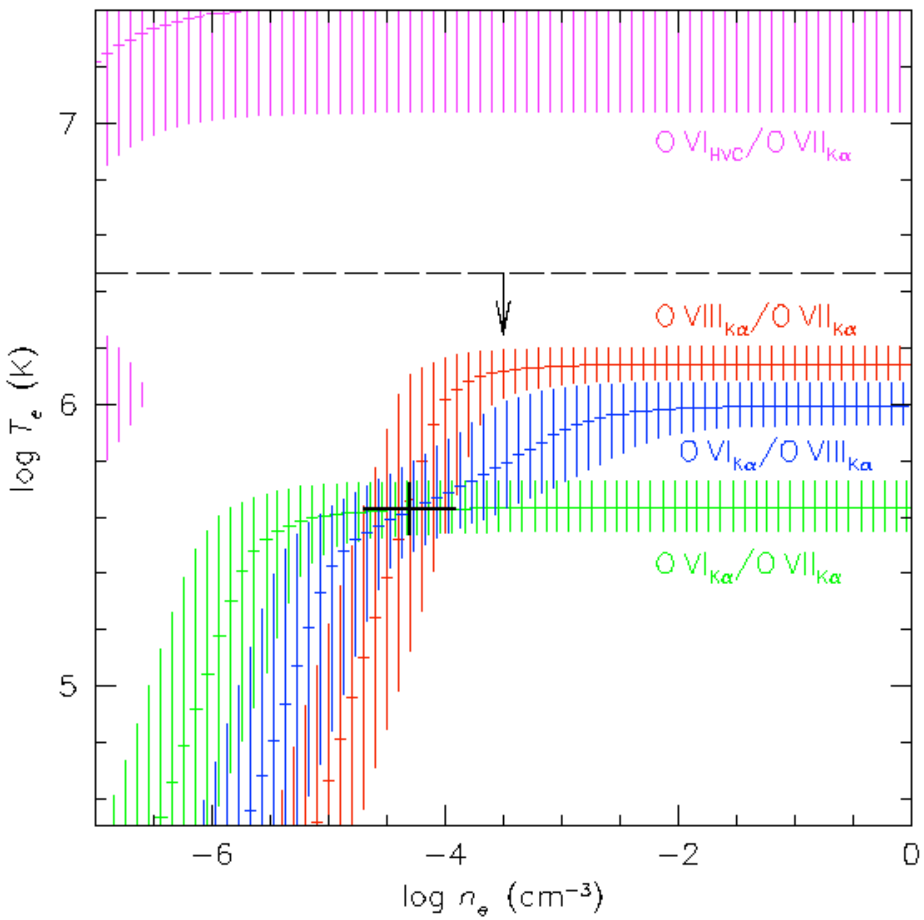
For 2 ions from the same element

$$\frac{\xi_{X^i}}{\xi_{X^{[i+n]}}} = \frac{N_{X^i}}{N_{X^{[i+n]}}} \propto \frac{EW^b_{X^i}}{EW^b_{X^{[i+n]}}}$$

For 2 ions from different elements

$$\frac{\xi_{X^i}}{\xi_{Y^j}} = \frac{N_{X^i}}{N_{Y^j}} \times \frac{A_Y}{A_X} \propto \frac{EW^b_{X^i}}{EW^b_{Y^j}} \times \frac{A_Y}{A_X}$$

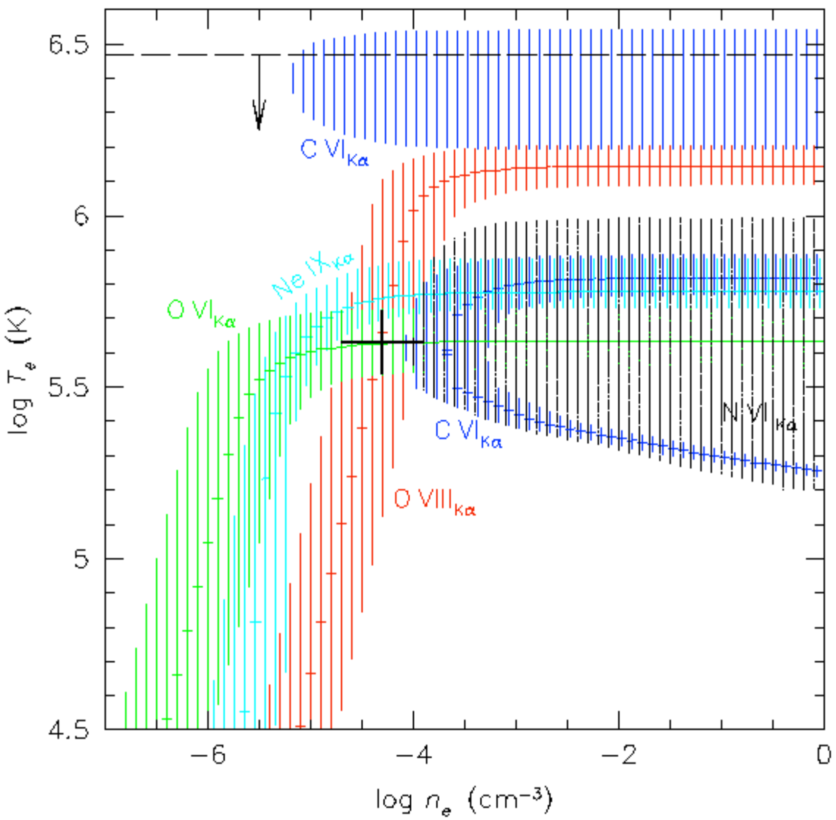
Low-Density Solution
The OVI Problem



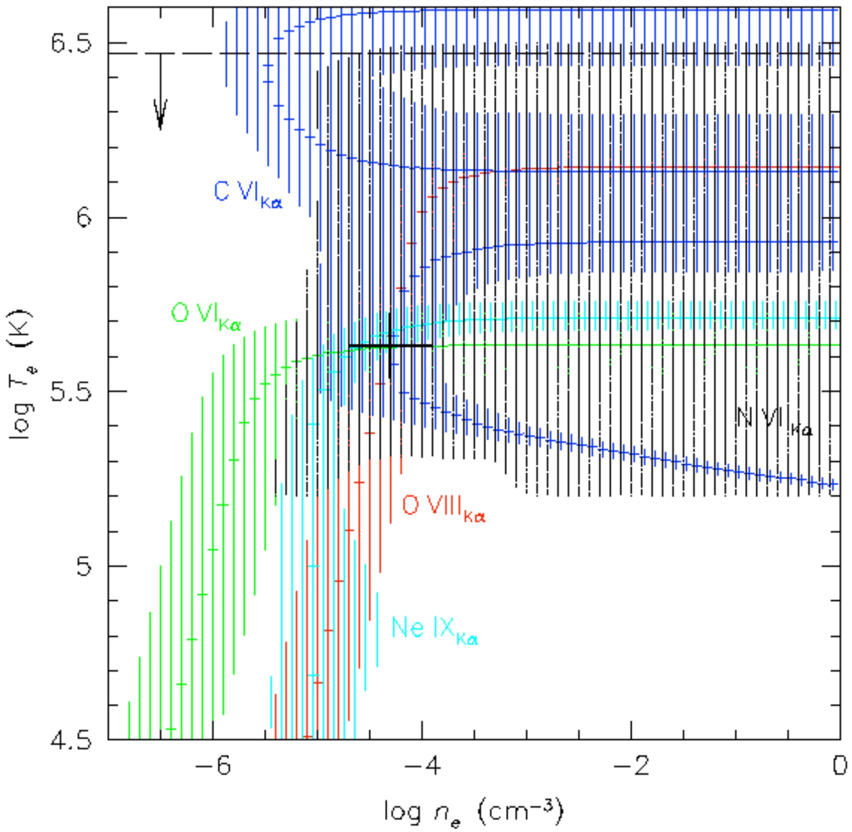
(Williams+05)

The [Ne/O] Problem

[Ne/O] = 0



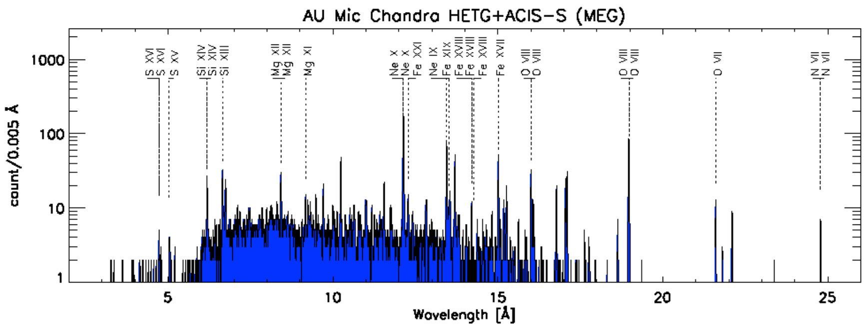
[Ne/O] = 1

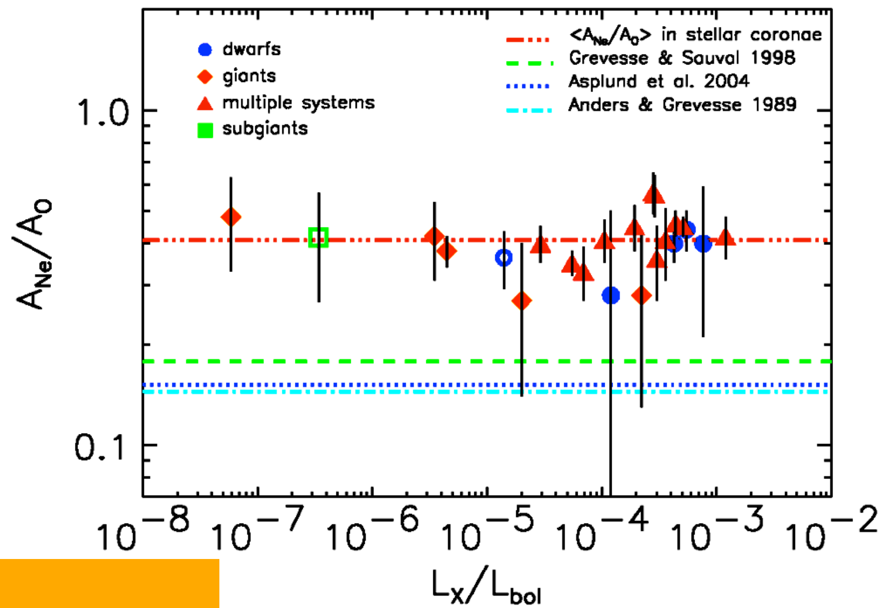


(Williams+05)

Sun Structure and Metallicity

22 nearby stars observed with Chandra-HETG





[Ne/O] = 0.43 (2.7 x Solar)

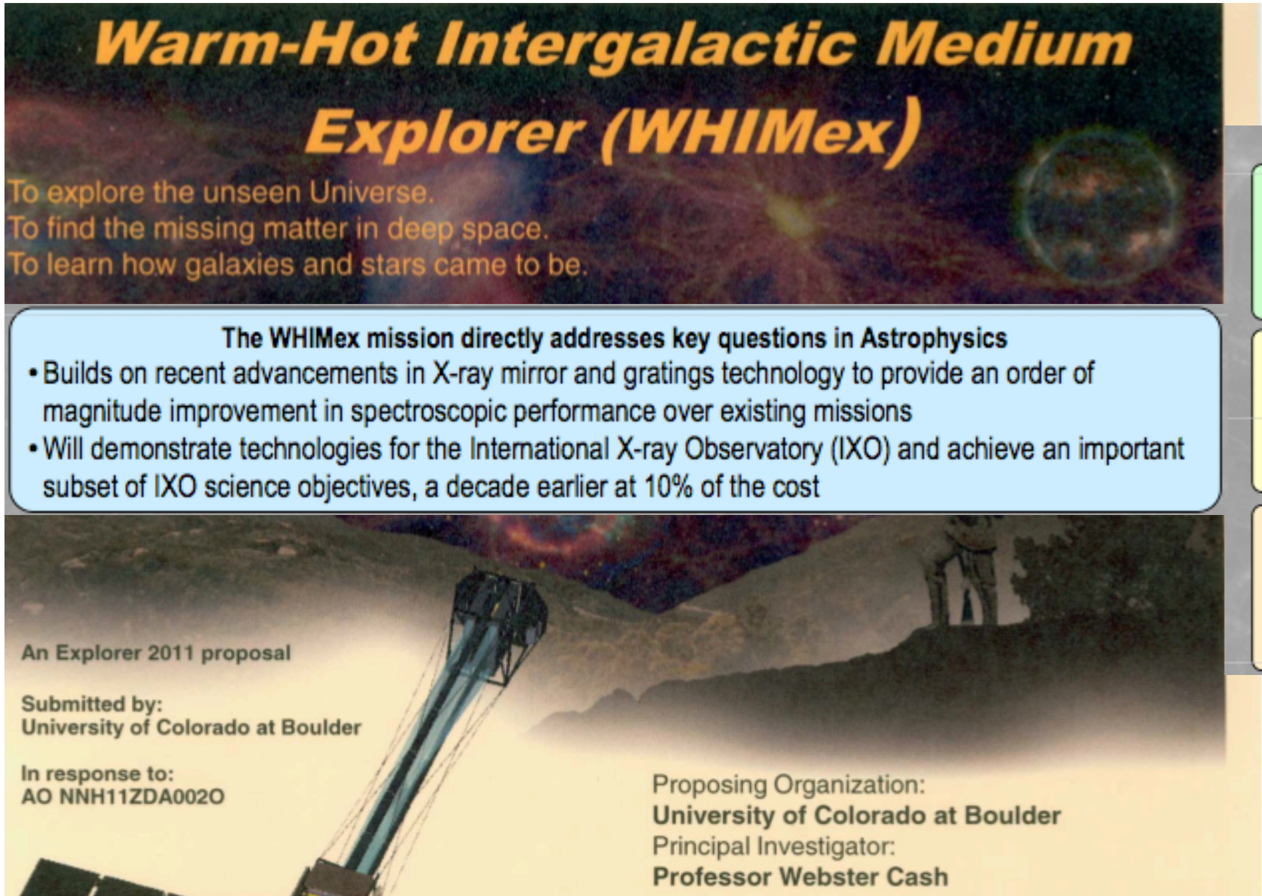
together with the recently revised C, N, O abundances (Asplund+04) brings the solar model back into agreement with Helioseismology

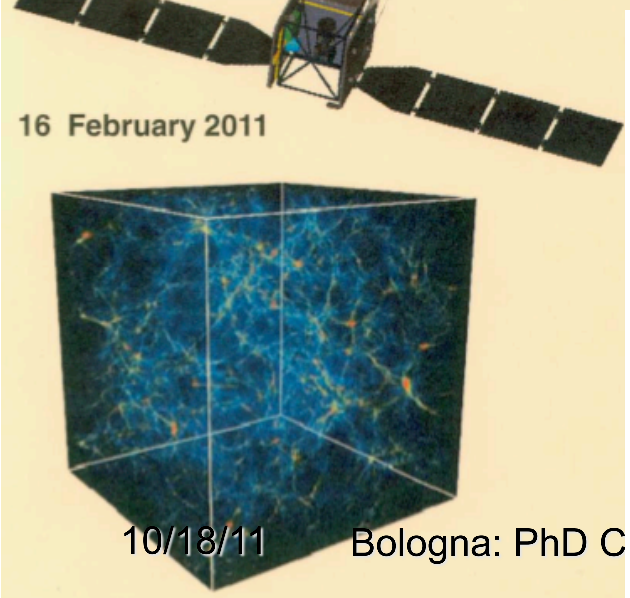
(Drake & Testa, 2005, Nature)

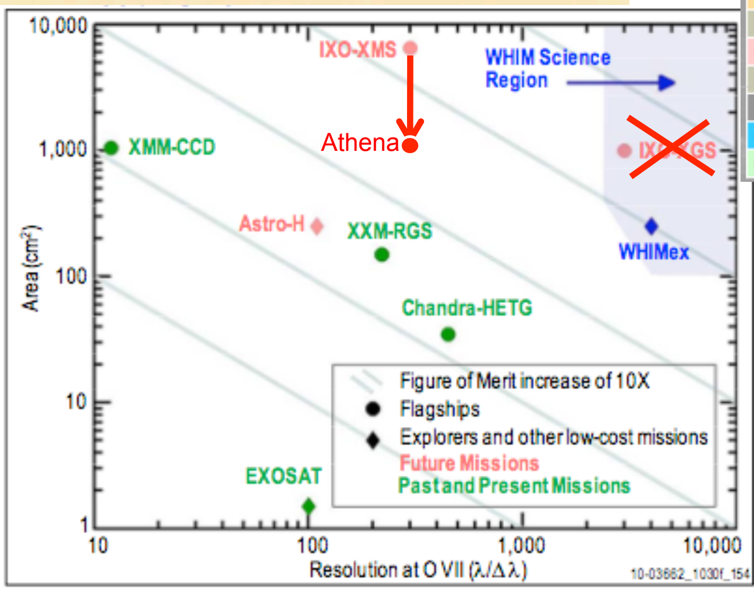
4

The Future: Need for a Large- Throughput High-Resolution X-Ray Spectrometer

WHIMex







Science Objectives

Warm-Hot Intergalactic Medium (WHIM)

- Find the missing baryons in the low-mid-redshift universe.
- Understand the cycles of matter on a cosmological scale.
- Constrain models for the evolution of large-scale structure

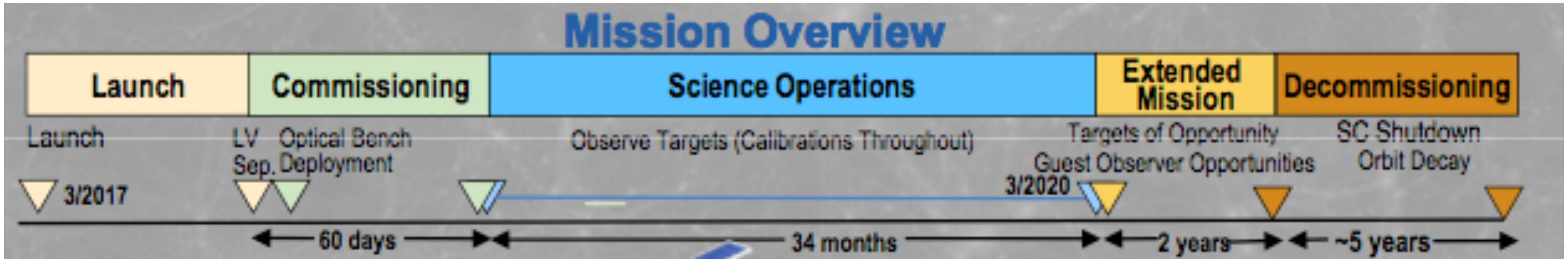
Active Galactic Nuclei (AGN)

- Measure the outflow of matter from the nuclei of galaxies
- Examine the role of feedback for the chemical enrichment and heating of interstellar and intergalactic media

Galactic Sources

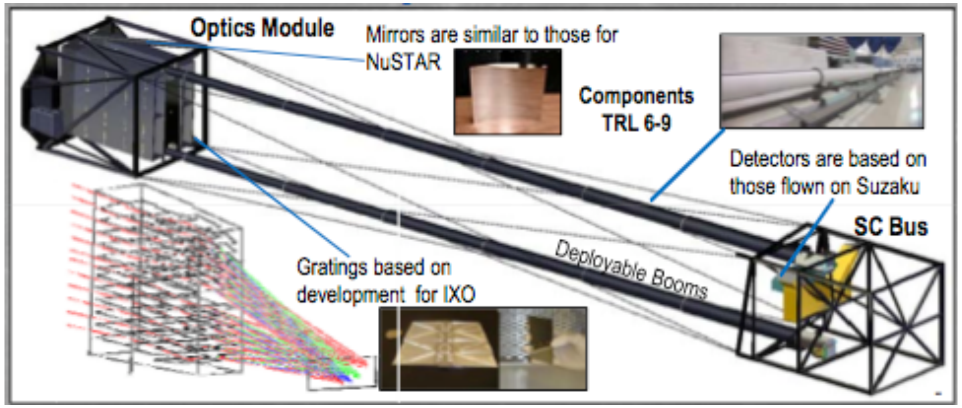
- Probe shocks, winds, coronae, and accretion disks of stars
- Study exotic (black-hole & neutron) stars and environs
- Characterize the hot component of the interstellar medium

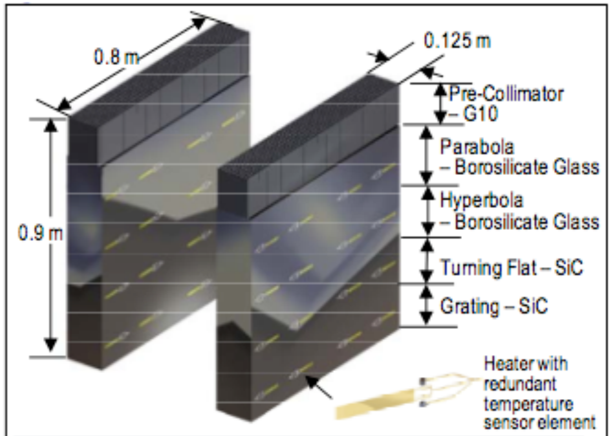
U Colorado	Principal Investigator (PI) Responsibility for the scientific success of WHIMex
MSFC	Project Office; Calibration of X-ray Spectrometer
U Iowa	Deputy PI; Instrument PI for X-ray spectrograph
GSFC	Production of Optics Modules, mirror fabrication & alignment
NG	Development & Integration of the entire Flight System; extensible bench
MIT	Grating replication & testing; support for detector acquisition
Sierra Nevada Corp.	Development & integration of Spacecraft Bus.
CASA	Science Operations Center (SOC)
LASP	Mission Operations Center (MOC)
SAO	Public Data Archive (Science Enhancement Option)
Open U	International Partner (UK), detector electronics & assembly
Osaka U	International Partner (Japan), CCD procurement & screening



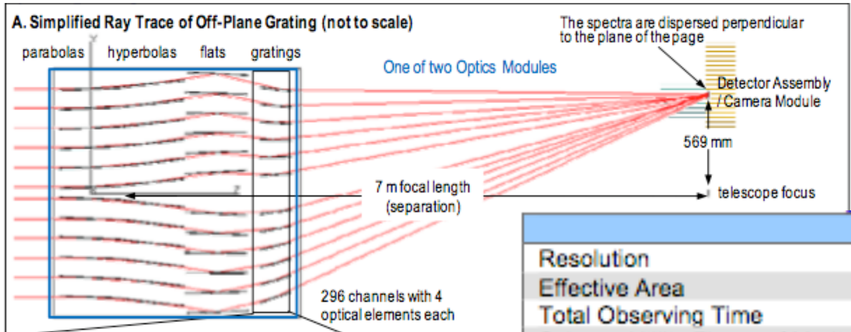
Key Instrument Payload Characteristics:

- Spectrograph with resolving power R ≈ 4000 and effective area A_{eff} ≈ 360 cm^2 around 0.5 keV
- Telescope focal length F= 7 m, using an extensible optical bench
- Two Optics Modules, each with ≈ 300 sets of primary, secondary, and flat mirrors plus radial groove gratings
- Spectrograph read-out detector (CCD array) giving high efficiency and separation of spectral orders





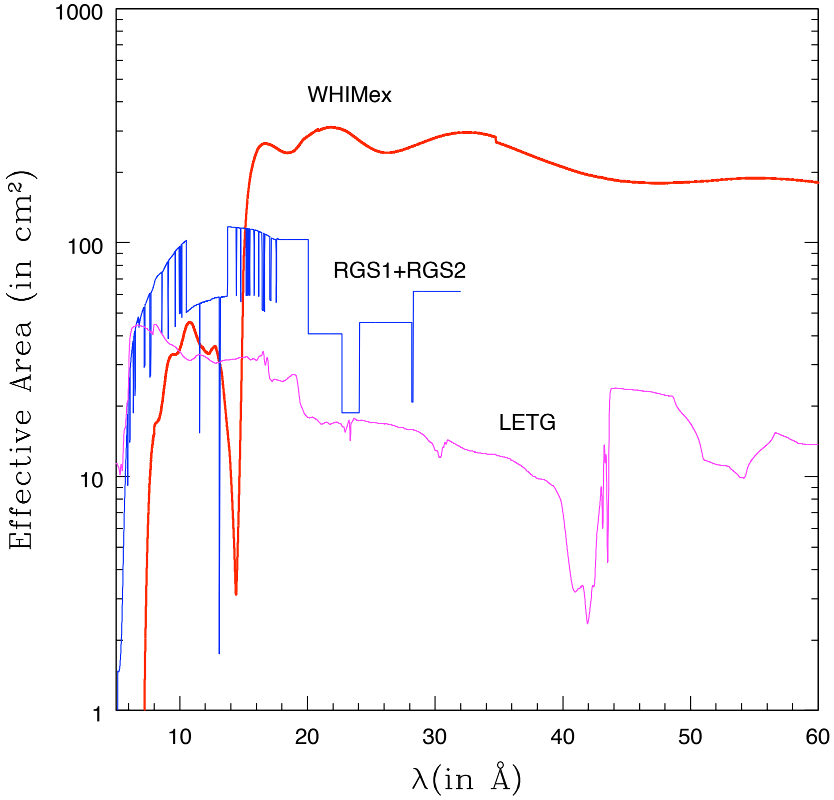
Component	Number
Precollimator	2
Parabola/Hyperbola pairs (X-ray mirrors, 0.4 mm thick)	592 pairs, 1184 elements
Turning flats (1 mm thick)	592
Gratings (1 mm thick)	592
Thermal Control Subsystem	64 heaters, 128 sensors
Structure	2

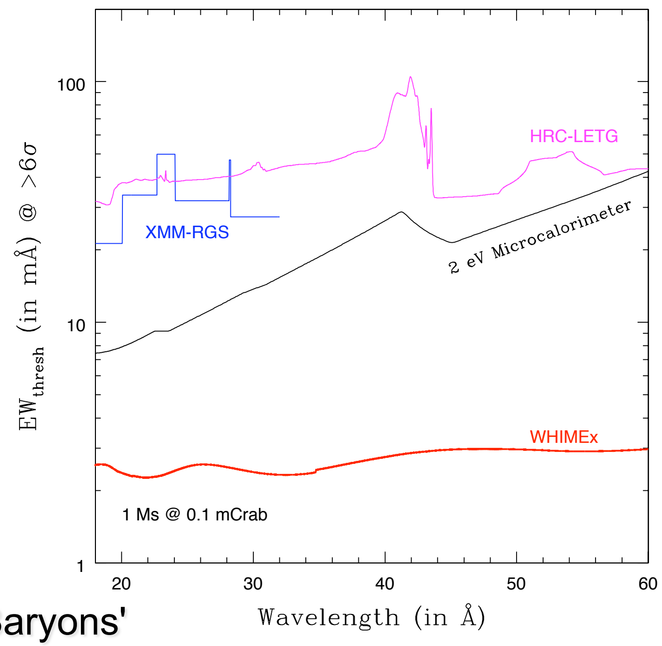


		Threshold	Baseline	Enhanced	Comment
Resolution	λ/Δλ	2,500	4,000	4,000	Average over band
Effective Area	cm^2	100	250	500	
Total Observing Time	Ms	15	45	100	At 66% observing efficiency
Science Utility Figure of Merit	$x10^6$	6	45	200	Resolution*Area*Time
Number of Targets	WHIM	12	26	50	

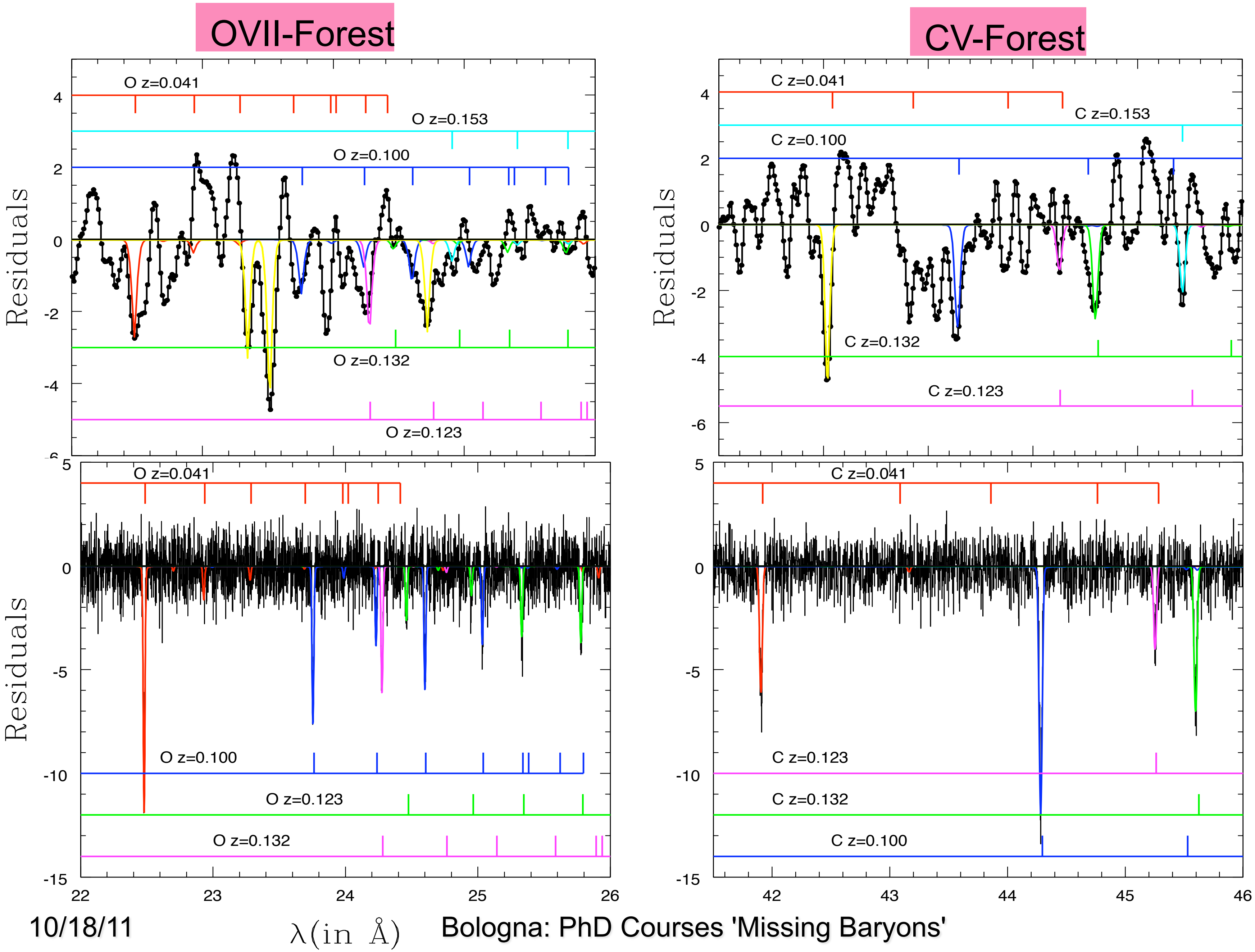
WHIMex Eff. Area & FOM X-Ray Spectral Diagnostics

Line	E in keV (z=0-0.5)	Science Value Derived from Line
O VIIα	0.57-0.38	The strongest WHIM line and the key line for WHIM science. Number of absorbers per unit redshift (dn/dz)
O VIIIα	0.65-0.44	Ionization parameter (U) and temperature (T) and hence density
C Vα	0.31-0.2	Strong WHIM line: dn/dz and T
O VIIβ	0.67-0.44	Bulk motion (b) and column density (Nion); Needed for saturation
C Vβ	0.35-0.23	b and Nion; b from 2 elements gives T
C VIα	0.37-0.24	Absorption ratio, U, and T. Strong at high T
C Vγ	0.37-0.24	b and Nion
O VIIγ	0.7-0.45	b and Nion
Si X/Si X*	0.245	Nion, Electron number density (ne), distance to Black Hole
Mg VIII/Mg VIII*	0.21	Nion, ne, distance to Black Hole

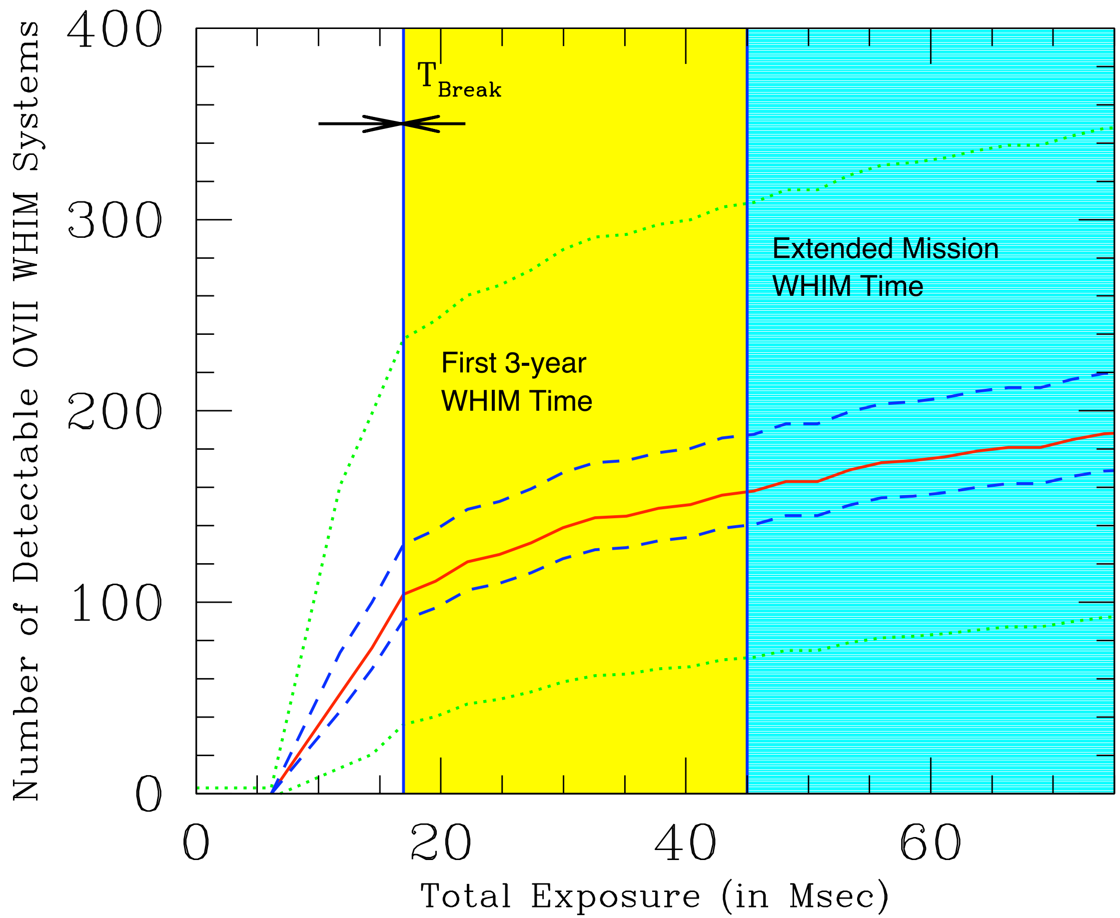




The WHIM with WHIM-Ex



The WHIM with WHIMex



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