The WHIM Associated with Galaxy Clusters

Probing WHIM Associated with the Virgo Cluster using an Oxygen

Absorption Line, Fujimoto et al. (2004)

and

The WHIM associated with the Coma Cluster, Takei et al. (2007)

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Background for presentation is image of Coma Cluster from 0.5- 2 keV, from Finogenov et al., 2003

Motivation

- Settle missing baryon problem- by detecting the WHIM where they can reside
- Further understanding of large scale cosmological structure

What's the WHIM?

- Large scale structure simulations predict a gas of 10^5 - 10^7 K
- Associated with clusters and groups of galaxies- sometimes filamentary
- Simulations indicate higher density of WHIM near clusters
- Heated via shock heating
- Predicted to house missing baryons

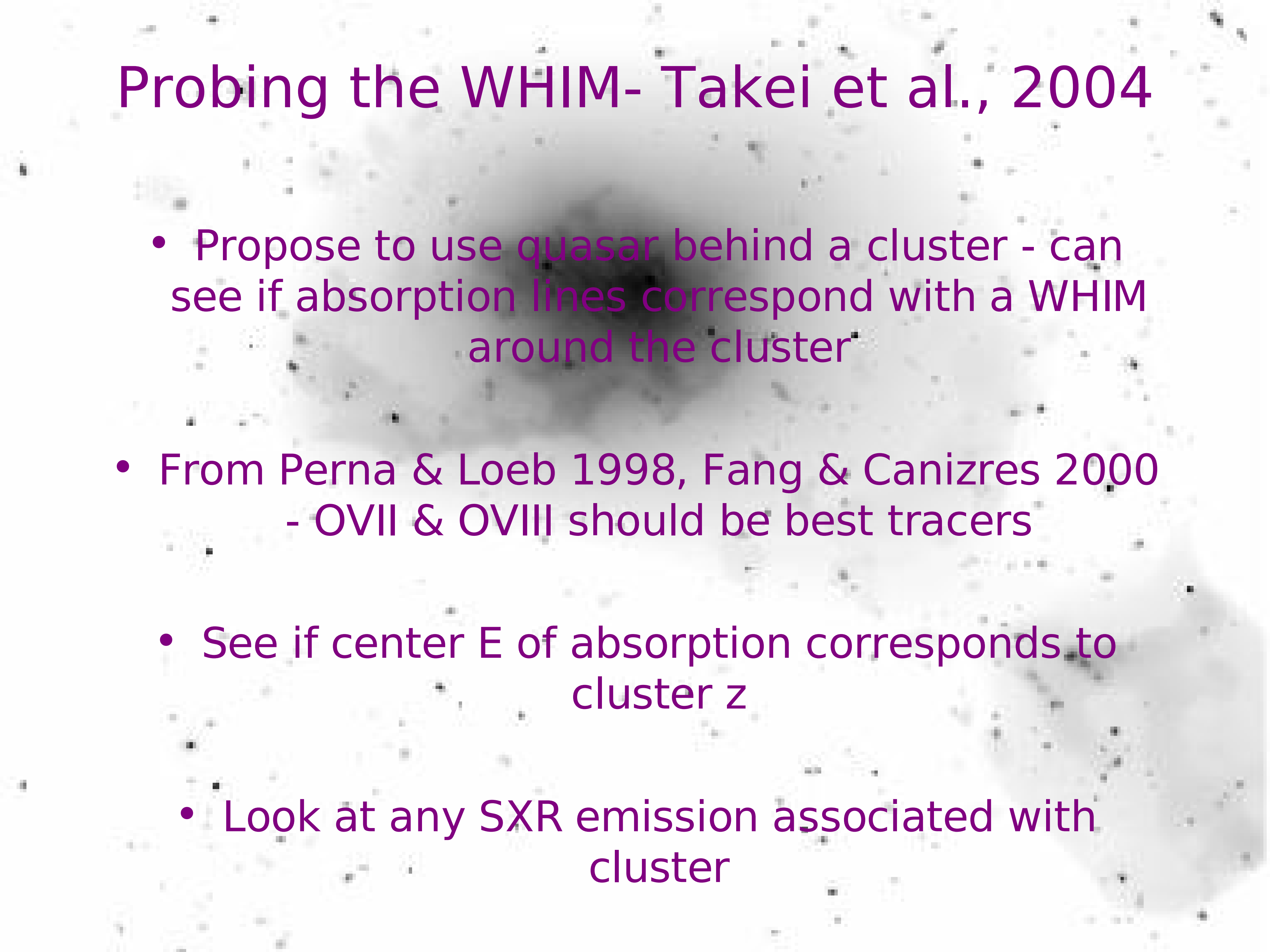
What are “missing baryons?”

From Sparke and Gallagher:

- We know $.03 < \Omega_B < .07$
- Galaxies- (stars & cool gas)don’t contribute enough
- Hot X-ray gas in clusters contributes some additional amt.- still not enough to satisfy Ω_B

From Fujimoto et al.:

- Simulations predict up to 50% of baryons could reside in a WHIM (Cen, Ostricker 1999)



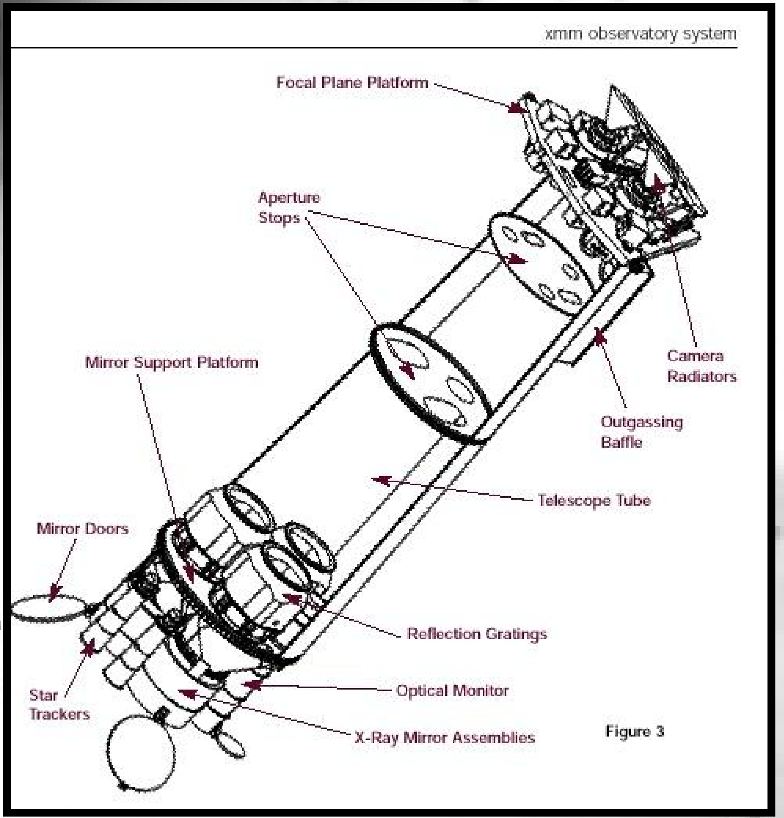
Probing the WHIM- Takei et al., 2004

- Propose to use quasar behind a cluster - can see if absorption lines correspond with a WHIM around the cluster
- From Perna & Loeb 1998, Fang & Canizres 2000 - OVII & OVIII should be best tracers
- See if center E of absorption corresponds to cluster z
- Look at any SXR emission associated with cluster

Instrumentation

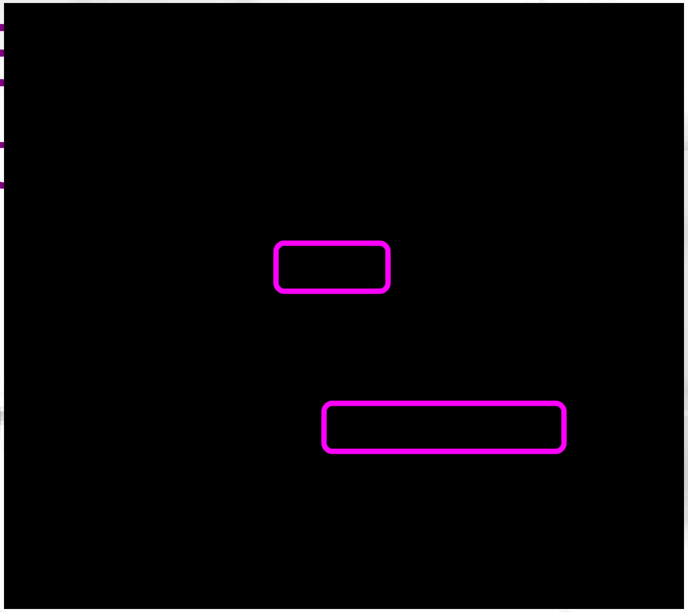
X-ray Multi Mirror- Newton from ESA:

- 3 telescopes w/ CCD detectors in the focus of the 3 telescopes
- Behind two of the telescopes, ~ 1/2 of X-rays are utilized by the Reflection Grating Spectrometers (RGS)
- three X-ray CCD cameras make up the European Photon Imaging Camera (EPIC)
- Two cameras are MOS (Metal Oxide Semi-conductor) CCD arrays- behind the RGS equipped telescopes.
- The third X-ray telescope has an unobstructed beam- third EPIC camera is here, called the pn camera.



Data

- Quasar LBQS 1228 + 1116, at z=.237
- Behind Virgo Cluster (M87), at z= .00436
- RGS, EPIC-MOS and E
taken with XMM- Newt
2003



Data Preparation

RGS Data

- Data Reduction with XMM-Newton SAS- standard parameters
- check for background flares in source-free regions- don't use data if flare(s) present
  - Produce background spectrum & absorption spectrum
- Fit spectra with power law, negative Gaussian, & account for Galactic absorption

EPIC Data

- Subtract internal background
- Exclude quasar and other point sources for analysis
- Then look at accumulated photons in .3-3 keV (SXR)range for spectrum
- Model spectrum with ICM, CXB, MWH, and LHB components

RGS (absorption) results

- Decide to only use OVIII
- Observed line center energy = $650^{+0.8}_{-1.9}$ eV
- EW = $2.8^{+1.3}_{-2.0}$ eV
- Assuming OVIII is source: Energy shift from rest frame = $2.7^{+0.8}_{-1.9}$ km s^{-1}
- This corresponds to cz = 1253^{+881}_{-369} km s^{-1}
- For M87, cz = 1307 km s^{-1}
- Good agreement with location of cluster since cz of quasar would be 71100 km s^{-1}
- Also checked archives for any instrumental effects at the OVIII wavelength - none found

Best fits for RGS1 and RGS2- power law, negative Gaussian and galactic absorption

QuickTime and a decompressor are needed to see this picture.

Background levels fitted w/constant model

OVIII absorption trough

Evaluating Stat. Significance of the abs. line:

- Produce 10000 simulation spectra
- Compare C-statistic (maximum likelihood) results of simulation to actual spectrum
- Actual spectrum produces ΔC of 4.33 between fit with absorption line and fit w/o abs. line
- Only 3.6% of simulation spectra produce a $\Delta C \geq 4.33$
- So chance probability of detecting “an absorption at the very wavelength corresponding to OVIII at the cluster rs is 3.6%”
- In other words- confidence of line is 96.4%

EPIC (emission) results

- Looking for diffuse, low energy emission- only used pn results
- MWH, LHB, & CXB values for fit fixed to those of Lumb et al., 2002
- To fit spectrum two more components required --> ICM and optically thin thermal plasma (SXR source from WHIM?)
- Can only take emission intensity as upper limit- cannot rule out possible contamination from N. Polar Spur
- Further spectroscopic observation need to distinguish WHIM emission from galactic contribution

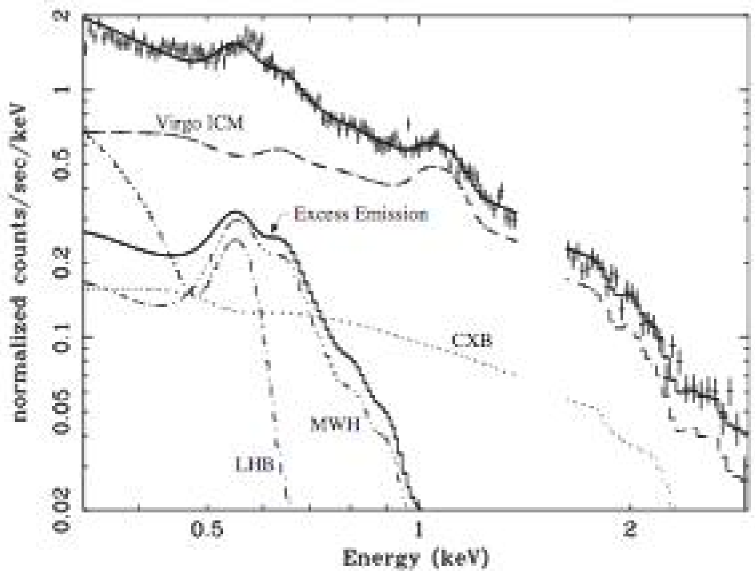


Fig. 3. Soft X-ray spectrum of the diffuse emission obtained with EPIC pn. The aluminum line region was masked. Internal background was subtracted using data taken with a filter wheel in the closed position. The parameters of the cosmic X-ray background (CXB), Milky Way halo (MWH), and Local Hot Bubble (LHB) were fixed to those obtained by Lumb et al. (2002). The data require another component that can be modeled with an optically thin thermal plasma with $kT = 0.21$ keV.

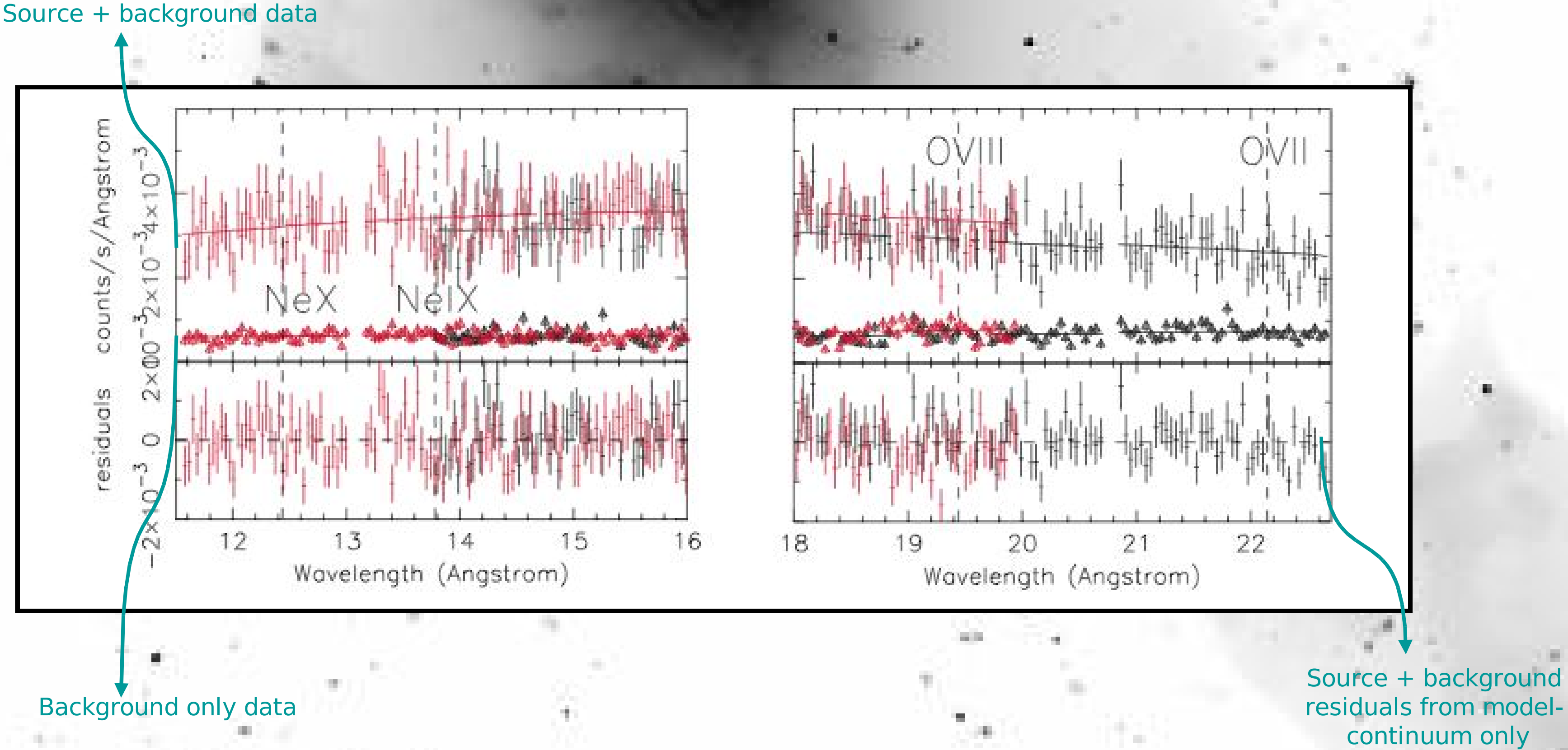
Finals thoughts- Good early attempt at this method and development of techniques, confident results for OVIII only, emission results dubious

WHIM associated w/ the Coma Cluster
Takei et al., 2007

- Same instrumentation - XMM Newton (RGS, EPIC)
- Expand search for absorption to OVII, OVIII, NeX, NeIX
- Now looking at Coma Cluster (at z=.0231)instead of Virgo
- Chosen x-ray object is now the Seyfert 1 AGN X Comae (at z=.091±.001)

Absorption Lines in RGS Spectra

- Almost identical reduction process- extract spectrum and background spectrum
- Also made background model to look at significance of absorption features



Fitting absorption and determining EW: Ratio Method

- Ratio = (source+background data)- (background data) / (source + background model) - (background model)

Where source model is a broken power law multiplied by galactic absorption (Dickey & Lockman, 1990)

And

Background model is different broken power law w/o Galactic absorption.

Figure at right -->

- Shows ratios of data to continuum model against z
- Dashed lines are z_{coma} and $z_{coma} \pm 2.5\sigma_{gal}$
- NeIX has deepest abs., next is OVIII,
- NeX and OVII barely significant

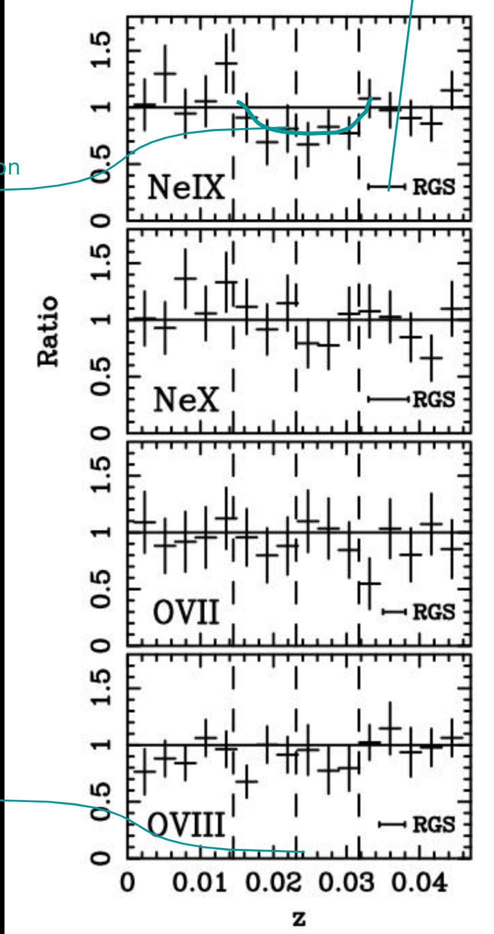


FIG. 3.—Ratios of the data to the continuum model (as defined in eq. [1]) vs. z for Ne IX, Ne X, O VII, and O VIII (*from top to bottom*). Vertical dashed lines indicate z_{Coma} and $z_{Coma} \pm 2.5\sigma_{gal}$. The average RGS1 and RGS2 instrumental resolution of 0.067 Å (FWHM) corresponds to a redshift resolution of 0.0050, 0.0055, 0.0031, and 0.0035 (*from top to bottom*), which is indicated as a horizontal line at the lower right of each panel.

TABLE 4

RATIO FOR CONTINUUM AND ABSORPTION SPECTRAL REGIONS

Line	Continuum Region[a]	Absorption Region[a,b]	EW[c] (eV)
Ne IX	1.027 ± 0.058	0.782 ± 0.071 (98.0%)	3.3 ± 1.8
Ne X	1.011 ± 0.073	0.950 ± 0.092 (42.7%)	0.8 (<3.9)
O VII	0.908 ± 0.080	0.927 ± 0.103 (50.0%)	0.7 (<2.6)
O VIII	0.963 ± 0.054	0.845 ± 0.071 (94.1%)	1.7 ± 1.3
Average of Ne IX and O VIII	0.993 ± 0.039	0.813 ± 0.050 (99.7%)	...

[a] Errors are quoted at 68% confidence level.
[b] Probability that a simulated spectrum without absorption yields a smaller discrepancy from unity.
[c] Errors are quoted at 90% confidence level, while upper limits are 2 σ.

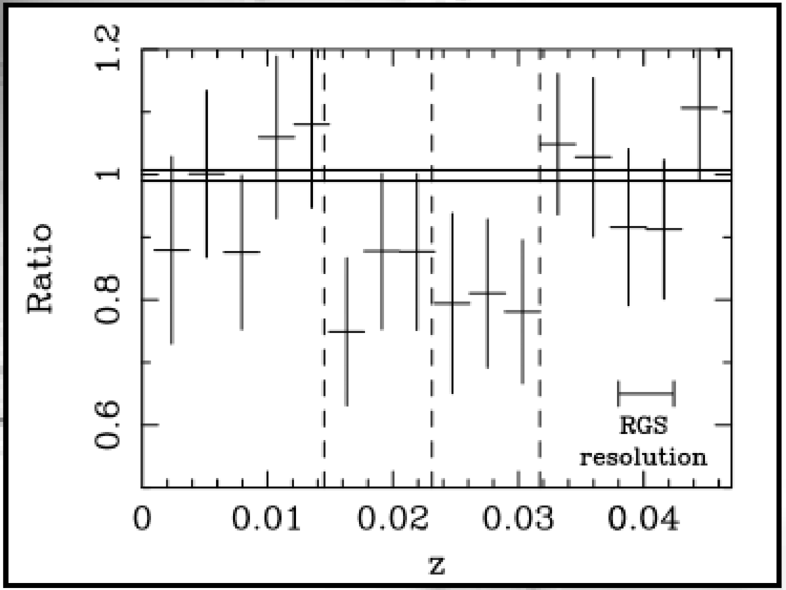
Ratio Method cont...

- Also created grand error weighted average for NeIX and OVIII to calculate combined significance - reducing signal to noise (see fig. at right)

Checking significance:

- Compared ratios previously found to 1000 ratios from simulated spectra with no absorption
- NeIX + OVIII average has significance 99.7%
- NeIX is 98%
- OVIII is 94.1%

- Conclusion: have detected actual absorption associated with Coma Cluster & abs. lines match what is expected for WHIM



Fitting Absorption, Determining EW: Model Fitting

- Same continuum model as used for ratio method
  - Assume boxcar profile fitting to describe absorption- so multiply continuum by:

$$\begin{cases} (1-F) \text{ for } \lambda_{notch} - W_{notch}/2 < \lambda < \lambda_{notch} + W_{notch}/2 \\ 1 \text{ for all others} \end{cases}$$

λ_{notch}, W_{notch}, F are central λ, width and absorption factor, respectively

For the fitting, λ_{notch} is fixed to .0231 (z of Coma), W_{notch} is fixed to best fit of NeIX and EW is given by $W_{notch}F$

Best fit results are shown at right -->

TABLE 5

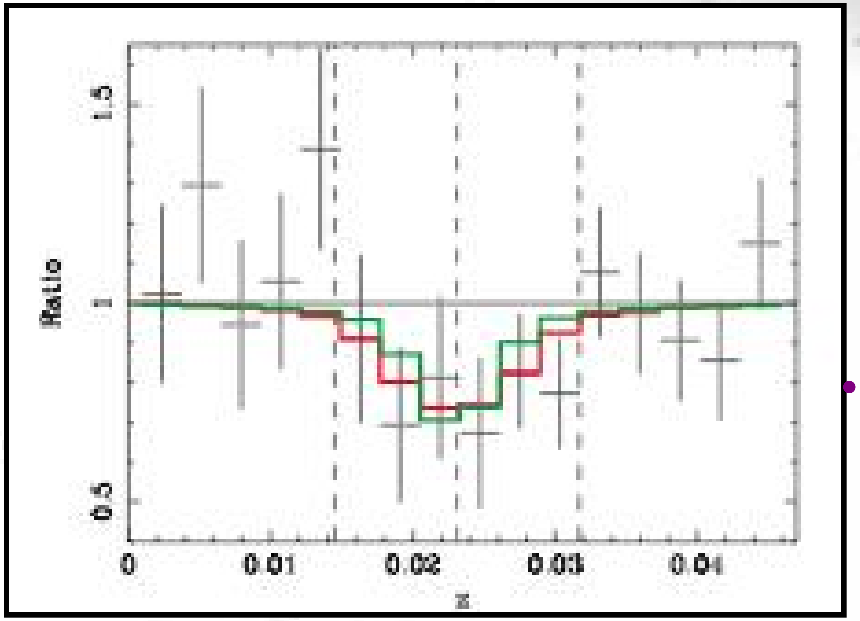
Results of Fitting the RGS Spectra of X Com with Broken Power Law Plus Boxcar Absorption Models

Component	Value
Continuum	
N_H (cm^{-2})	9.3×10^{19} (fixed)
Source Γ ($E < 0.75$ keV)	$1.71^{+0.21}_{-0.26}$
Source Γ ($E > 0.75$ keV)	2.35 ± 0.24
Source normalization[a]	$6.92^{+0.62}_{-0.35} \times 10^{-4}$
Background Γ ($E > 0.75$ keV)	$3.64^{+0.31}_{-0.39}$
Background Γ ($E < 0.75$ keV)	2.01 ± 0.21
Background normalization[a]	$(0.82 \pm 0.07) \times 10^{-4}$
Ne IX λ13.447	
λ_{notch}[b]	0.0231 (fixed)
W_{notch}[b]	9.79×10^{-3}
F	0.41
EW[c] (eV)	$3.7^{+2.0}_{-2.1}$
N_{ion}[c] (cm^{-2})	$4.7^{+2.6}_{-2.9} \times 10^{16}$
Ne X λ12.134	
λ_{notch}[b]	0.0231 (fixed)
W_{notch}[b]	9.79×10^{-3} (fixed to the Ne IX value)
F	0.09
EW[c,d] (eV)	0.8 (<4.7)
N_{ion}[c,d] (cm^{-2})	1.9 (<10.5) $\times 10^{16}$
EW/EW$_{Ne\ IX}$[d]	0.2 (<1.3)
$N_{ion}/N_{Ne\ IX}$[d]	0.4 (<2.3)
O VII λ21.602	
λ_{notch}[b]	0.0231 (fixed)
W_{notch}[b]	9.79×10^{-3} (fixed to the Ne IX value)
F	0.04
EW[c,d] (eV)	0.2 (<2.2)
N_{ion}[c,d] (cm^{-2})	0.3 (<2.9) $\times 10^{16}$
EW/EW$_{Ne\ IX}$[d]	0.06 (<0.59)
$N_{ion}/N_{Ne\ IX}$[d]	0.06 (<0.63)
O VIII λ18.969	
λ_{notch}[b]	0.0231 (fixed)
W_{notch}[b]	9.79×10^{-3} (fixed to the Ne IX value)
F	0.08
EW[c,d] (eV)	0.4 (<2.2)
N_{ion}[c,d] (cm^{-2})	0.8 (<4.9) $\times 10^{16}$
EW/EW$_{Ne\ IX}$[d]	0.10 (<0.59)
$N_{ion}/N_{Ne\ IX}$[d]	0.2 (<1.0)
Statistics	
C-statistic	834.33
Free parameters	11
Degrees of freedom	745

[a] In units of photons keV^{-1} cm^{-2} s^{-1} at 1 keV.
[b] Wavelength converted to redshift.
[c] Errors include covariance of W_{notch} and F.
[d] Upper limit is at 2 σ confidence.

Absorption lines: Model fitting cont…

- Results are shown for NeIX fitting
- Red line is best fit model (from previous table)
- Green line is $(F, W_{notch}) = (1.0, 3.1\text{x } 10^{-3})$
- Background plot is ratio of data to continuum for NeIX shown previously - for NeIX both methods produce similar results



- Monte Carlo simulations used again for significance
- Result is 99.2% for NeIX- better than ratio
- For OVIII results less significant with boxcar profile than w/ratio method (only 82.4%)
- NeIX+OVIII gives 98.5%(compared to 99.7% in ratio method)

Emission Lines: EPIC Spectra

- pn Exposure for this run is one of largest ever made of a Cluster using XMM-Newton
- Determining reliable background is crucial step needed to proceed- to improve on previous papers, authors use other XMM-Newton observations located around Coma and excised one particularly bright spot
- Basically same processing as Fujimoto paper- excised point sources, excise diffuse sources, subtracted detector background levels
- Fit spectrum with ionized thermal plasma component (Coma hot gas), component for MW background, and component for CXB.

Emission Line Results

- Clear detection of OVII, OVIII, NeIX lines in excess of the continuum
  - O lines do not vary with position
  - O lines likely from MW soft background.
- Determine that NeIX intensity varies as function of position (stronger approaching Coma center)
- ICM too hot to produce the NeIX line seen, Solar wind origin unlikely (shouldn't vary w/position)
- Conclude NeIX emission is actually associated with Coma Cluster from some source cooler than the ICM

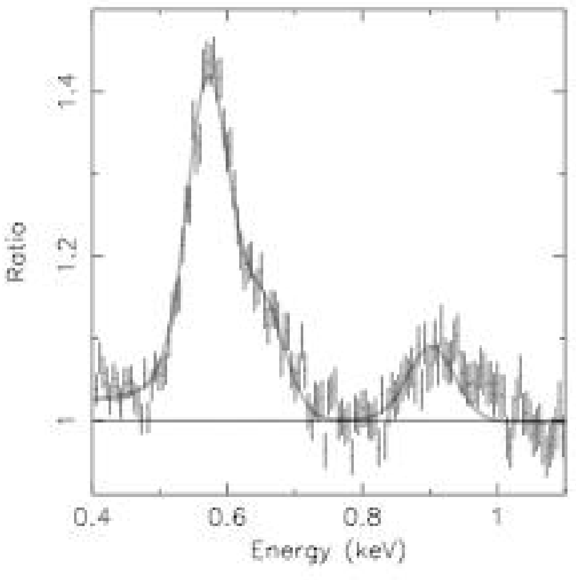


Fig. 8.—EPIC pn spectrum from the entire X Com field. Plotted is the ratio of the data to the smooth continuum with parameters in Table 7. The gray line is a fit of three narrow-width Gaussians to the residuals. The centers of the lower energy Gaussians are fixed to O vii and O viii at zero redshift, and that of the higher energy Gaussian is fixed to Ne ix at the Coma redshift.

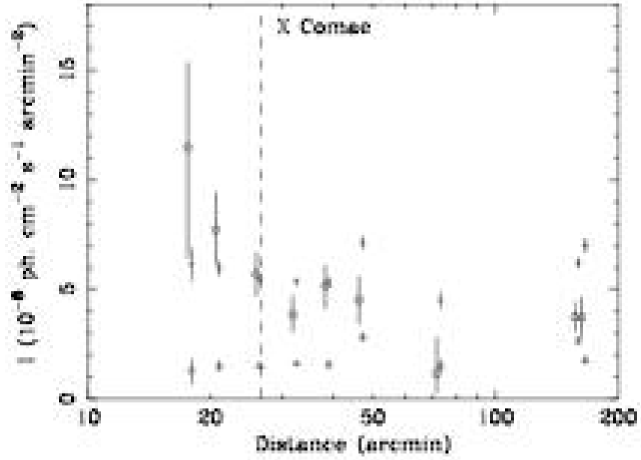


Fig. 9.—Surface brightness of O vii and O viii (*plus signs and triangles, respectively; divided by 10*) and Ne ix (*circles*) vs. distance from NGC 4874, which we take as the center of the Coma Cluster.

TABLE 7
Results of Fitting the EPIC pn Spectrum of Diffuse Gas at the Position of X Com

Component	Value
Galactic Absorption	
N_H (cm^{-2})	8.0×10^{19} (fixed)
Coma Hot ICM	
kT (keV)	$3.75^{+0.32}_{-0.30}$
Abundance (solar)	0.47 ± 0.09
z	0.0231 (fixed)
Normalization[a]	$7.77^{+0.70}_{-0.48} \times 10^{-6}$
Milky Way Warm ISM	
kT (keV)	$0.174^{+0.002}_{-0.001}$
Abundance (solar)	0, 1 (fixed)[b]
z	0 (fixed)
Normalization[a]	$(5.5 \pm 0.2) \times 10^{-5}$
Cosmic X-Ray Background	
Γ	1.40 (fixed)
Normalization[c]	$4.05^{+0.23}_{-0.18} \times 10^{-6}$
O vii Emission Line	
E (keV)	0.574 (fixed)
I[d]	$55.6^{+2.1}_{-1.4} \times 10^{-8}$
O viii Emission Line	
E (keV)	0.654 (fixed)
I[d]	$15.4^{+1.1}_{-1.4} \times 10^{-8}$
Ne ix Emission Line	
E	0.901 (fixed)
I[d]	$(6.0 \pm 0.9) \times 10^{-8}$
Statistics	
χ^2	1305.15
Free parameters	9
Degrees of freedom	1272

Note.—Entire X Com field (456.9 arcmin^2).
[a] The normalization is $\int n_e n_H \, dV / 4\pi [D_A(1+z)]^2$ per solid angle in units of 10^{14} cm^{-5} arcmin^{-2}, where D_A is the angular size distance to the source, n_e is the electron density, n_H is the hydrogen density, and V is the volume.
[b] The abundance of He, C, Fe, and Ni is fixed to 1.0, while that of all other elements, including O and Ne, is fixed to 0.0.
[c] In units of photons keV^{-1} cm^{-2} s^{-1} arcmin^{-2} at 1 keV.
[d] In units of photons cm^{-2} s^{-1} arcmin^{-2}.

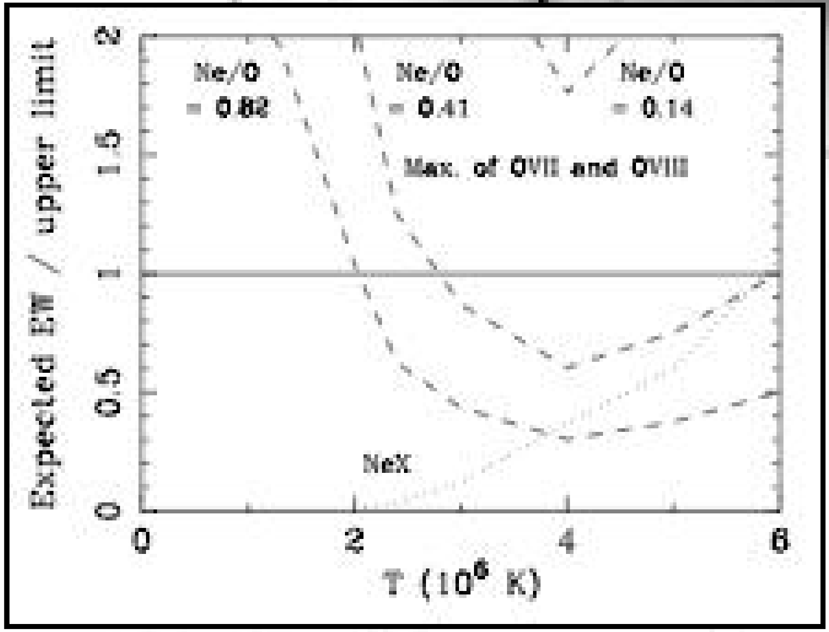
So what does all this say about the WHIM?

- So far have detected absorption feature with confidence of 99.7% @ z that matches with Coma Cluster
- Detected line emission features at the 3.4σ confidence level @ the position of X Com
- Finding both absorption and emission, both with redshift or position correlations to Coma, increases likelihood of features being true detections of some thermal component
- What can be deduced about gas that created these features?

So what does all this say about the WHIM?

- Can constrain temp of a plasma in ionization eq. based on absorption ratios of EW between different ionization states of the same species

- Similarly, ratios of different species can constrain number density ratios



From Boxcar results:

- Plot shows theoretically expected Ews of NeX, OVII and OVIII to NeIX (Chen et al., 2003) divided by upper limit of observed ratios
- Theoretical O values depend on number density ration Ne/O

- Allowed temperatures are when all curves < 1

- Resulting temperature range is $2\times 10^6 - 5.8\times 10^6$

So what does all this say about the WHIM?

From ratio results:

- Again used expected ratios from Chen et al.
- Plot shows expected ratios from Chen (curves) and upper limits from observations (horizontal lines)
- Allowed temperatures are where curves are below upper limits
- Extracted temperature range is $2.2\text{x}\ 10^6 - 5.7\text{x}\ 10^6$ K
- From observed NeIX/OVIII ratio- can investigate Ne/O number density ratio as fxn. of T since this wasn't well constrained on previous slide

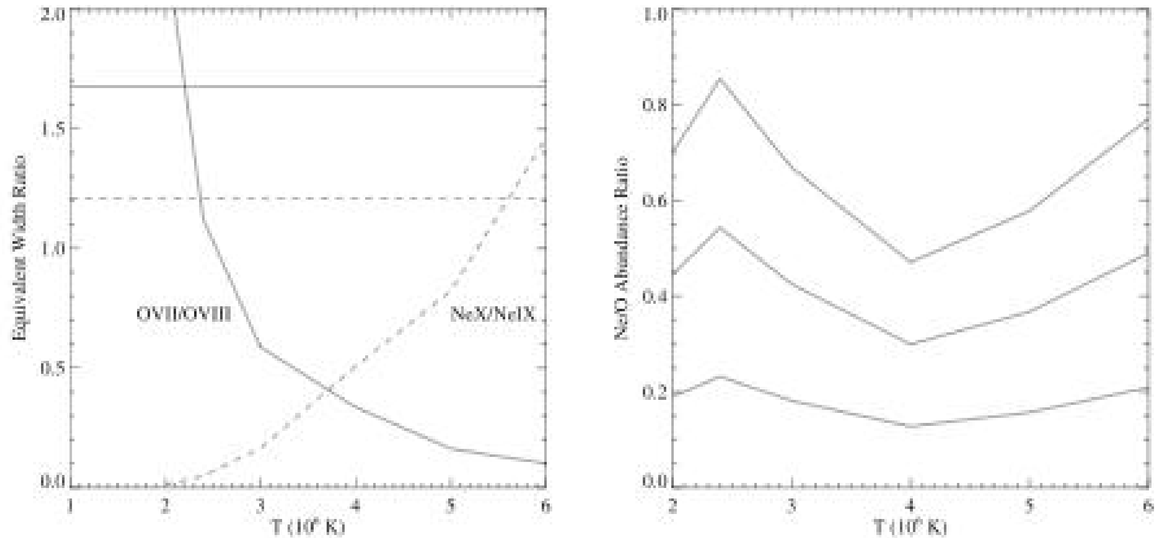


FIG. 11.—*Left*: Equivalent width ratio as a function of temperature *T*, based on Figs. 2 and 3 of Chen et al. (2003) in the collisional ionization equilibrium case. The solid and dashed curves correspond to O VII/O VIII and Ne X/Ne IX, respectively. The horizontal lines represent the upper limits determined by this work. The allowed temperature is that for which the curves are below the horizontal upper limit lines of the same style, i.e., $T > 2.2 \times 10^6$ K for O VII/O VIII (*solid line*) and $T < 5.7 \times 10^6$ K for Ne X/Ne IX (*dashed line*). *Right*: Ne/O number density ratio as a function of temperature *T*. The three curves correspond to the best-fit values and $\pm 1\ \sigma$ errors, respectively, obtained from the observed Ne IX/O VIII ratio.

So what does all this say about the WHIM?

- Can constrain average n_H if you have absorption and emission observations for an ion - so authors use NeIX

Combine equations for column density and surface brightness:

$N_{ion} = f_{ion} Z n_H L$ $\quad\quad$ $I = (C/(1+z)^3) Z n_H^2 L$

Result gives you two equations:

$n_H = (f_{ion}(1+z)^3 I)/(C N_{ion})$ $\quad\quad$ $ZL = (C N_{ion}^2)/(f_{ion}^2 (1+z)^3 I)$

Evaluate ZL and n_H over allowed temperature range to constrain their possible values, input of a T gives a value for C and f_{ion}, then ZL and n_H can be found:

Constraints on n_H:

$2 \times 10^{-6} < n_H < 8.5 \times 10^{-3}$

Constraints on ZL:

1Z Mpc < ZL < 300 Z

Constraints on L

$L > (6\text{Mpc})(Z/0.16Z)^{-1}$

Conclusion:

Properties similar to those predicted for WHIM- probably have detected a filament (due to geometry of Coma-X Comae) and filaments are also expected for WHIM

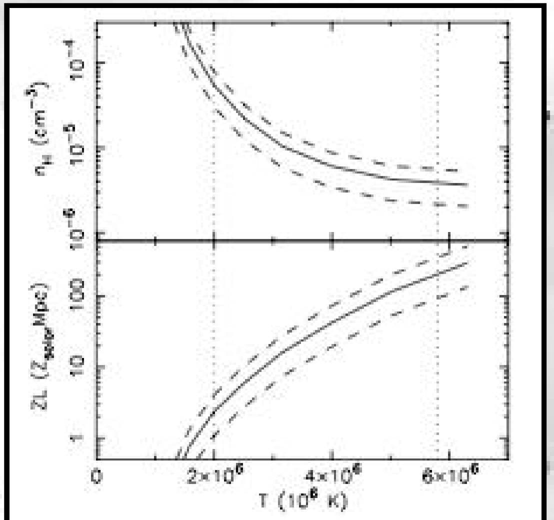


Fig. 12.—Derived n_H (top) and ZL (bottom) as a function of T. Solid and dashed curves represent best-fit values and 1 σ confidence regions, respectively. Vertical dotted lines indicate the allowed temperature range, 2.0×10^6 K $< T <$ 5.8×10^6 K (see Fig. 11).