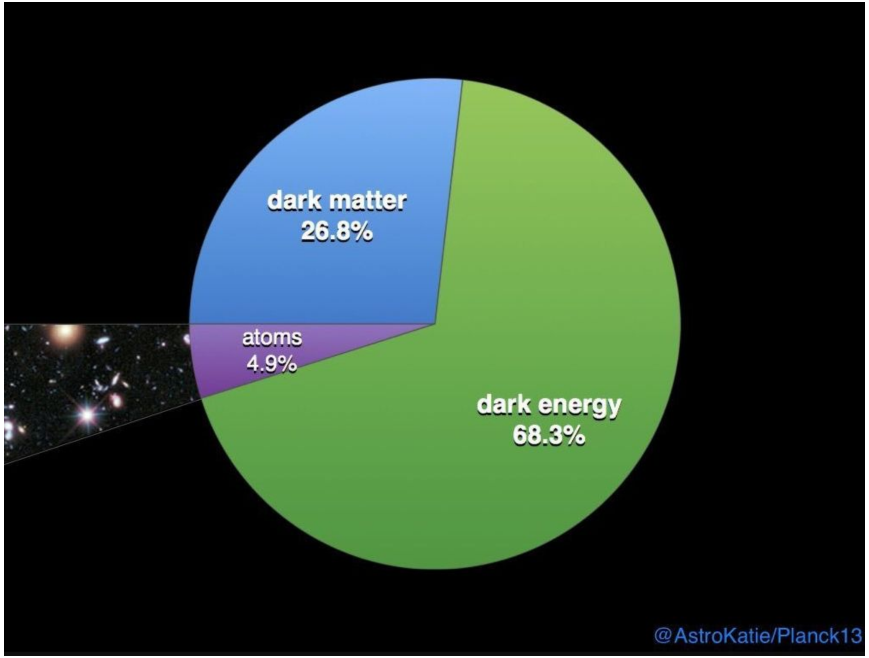
Baryons in the IGM, the ‘missing baryon’ problem and its possible solution(s)

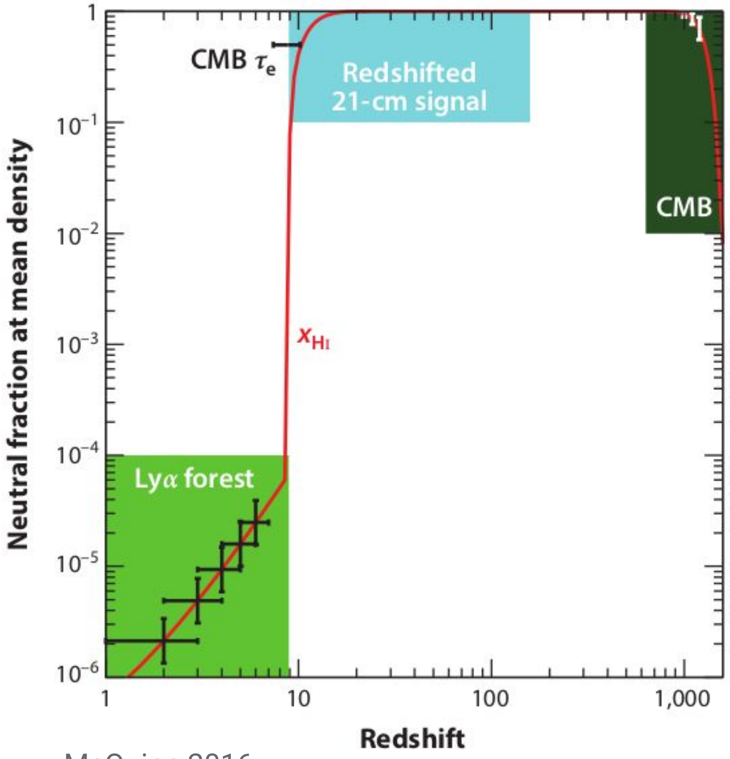
Aurélien Verdier
Observing the Cosmic Dawn: How did the first stars and galaxies form?
Fall 2023

Bregman 2007, McQuinn 2016, Shull 2012

Universe Energy pie chart



InterGalactic Medium (IGM)



McQuinn 2016

Most cosmic matter resides in the void between galaxies known as the intergalactic medium (IGM)

Measurements:

- High redshift: Primordial nucleosynthesis
- Near z = 3: Lyα lines
- CMB studies

The latter is confirmed with high accuracy

↳ Low redshift baryons are missing

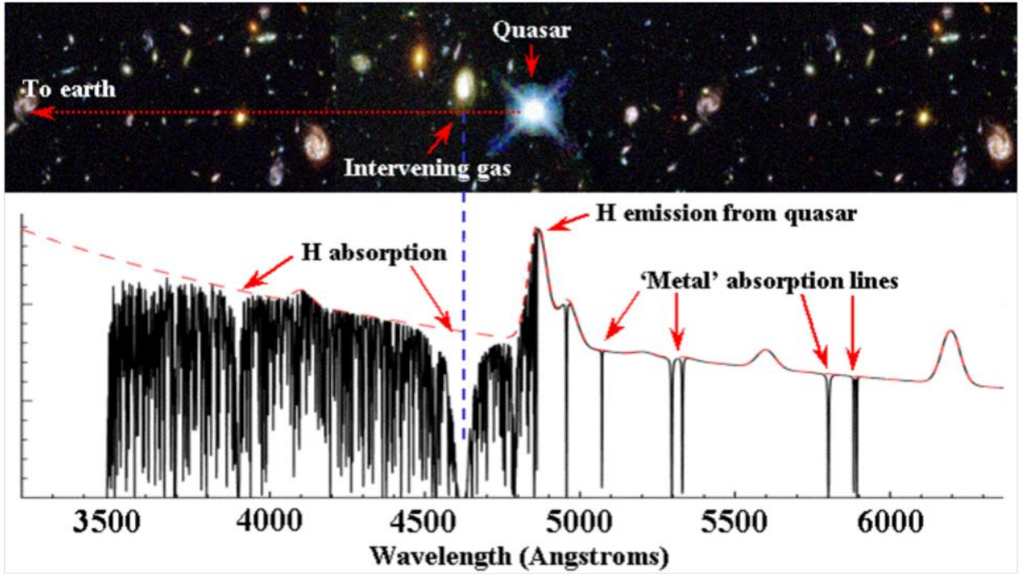
Lyman-alpha Absorbers

$$\tau_{\rm eff}(\nu, z, z') = \int_z^{z'} dz'' \int_0^\infty dN_{\rm HI} \frac{\partial^2 N_{\rm HI}}{\partial N_{\rm HI} \partial z''} [1 - \exp(-\tau_{\rm cloud}(\nu, N_{\rm HI}))]$$

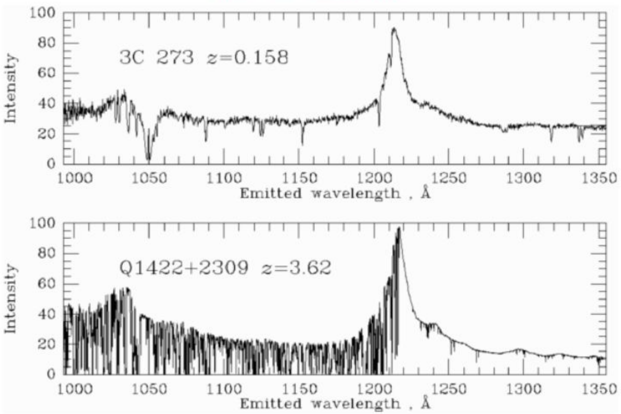
τ_eff: Effective optical depth

N_HI: Column density distribution

τ_cloud = **σ**_HI * N_HI



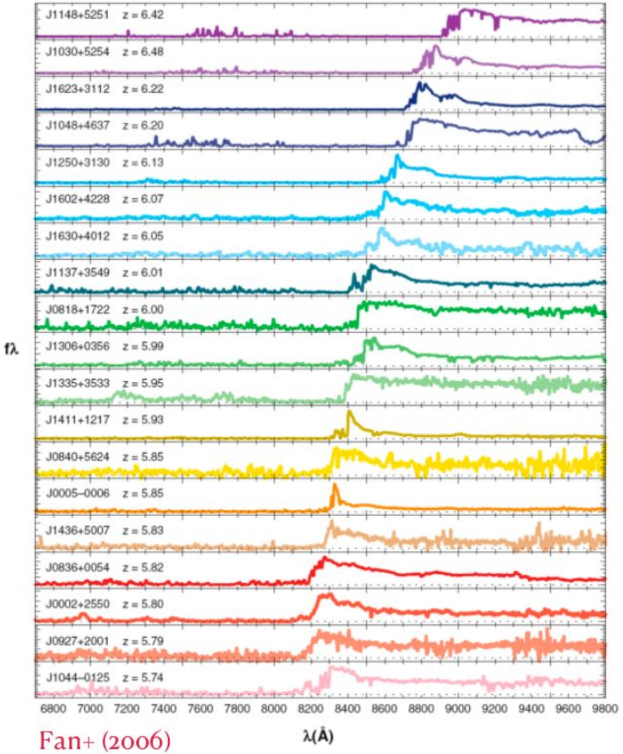
https://www.astro.ucla.edu/



Gunn–Peterson Effect

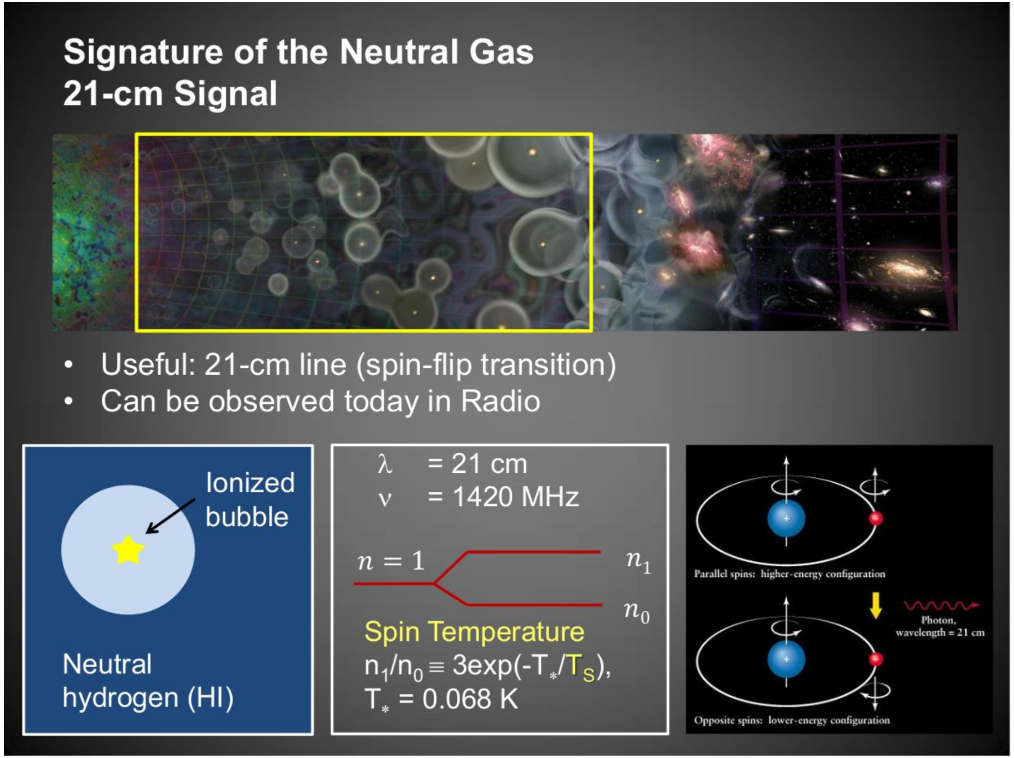
$$\tau_\alpha = 1.6 * 10^5 \, \chi_{HI} (1+\delta) \left(\frac{1+z}{4}\right)^{3/2}$$

IGM opaque even if neutral fraction is small



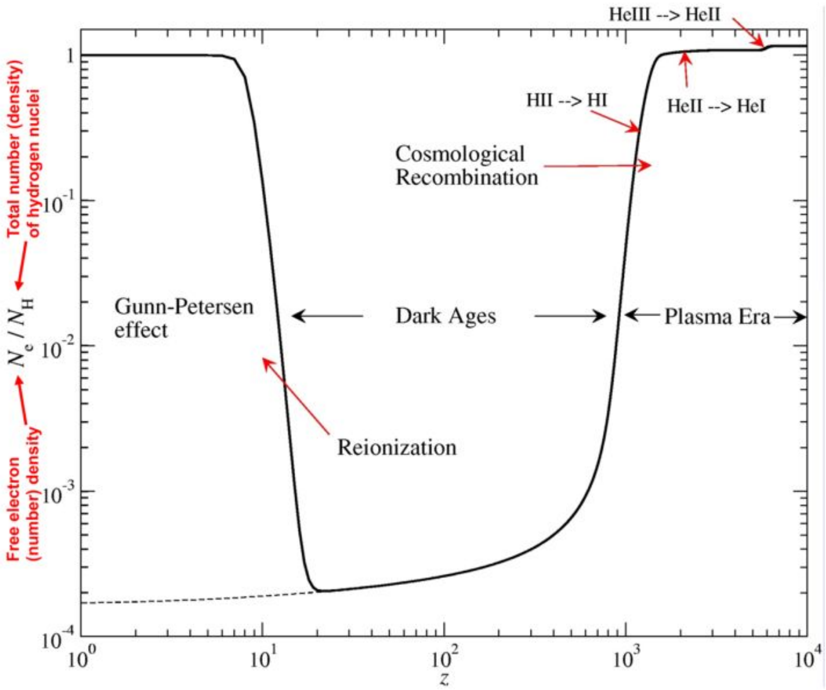
Fan+ (2006)

21cm Signal



Slide credit: Anastasia Fialkov

Dark Ages

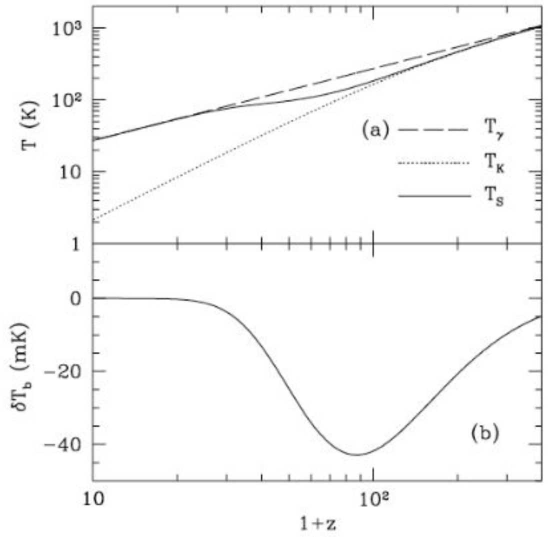


Residuals electrons are tightly coupled to the CMB via Compton scattering

[Sunyaev and Chluba (2010)]

Observable:

$$\delta T_b(\nu) = \frac{T_S - T_\gamma(z)}{(1+z)}(1 - e^{-\tau_0})$$



With First Stars

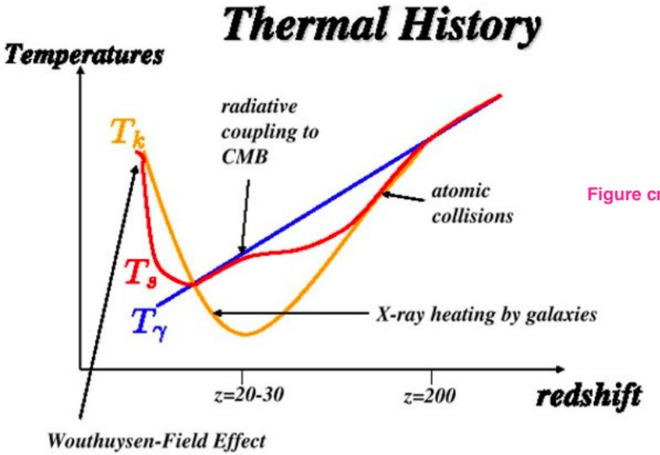


Figure credit: A. Loeb, *First Light*

21cm Observation

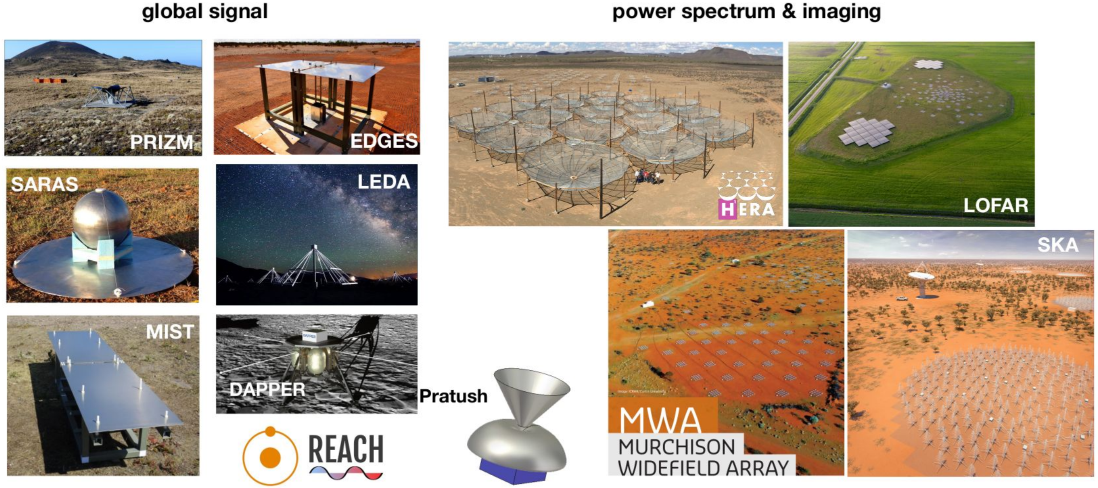
δT_b Measurement constrains high-redshift star-formation

However: Signal hard to detect

Need to be able to do the observation, remove foregrounds, add a 21-cm model ….

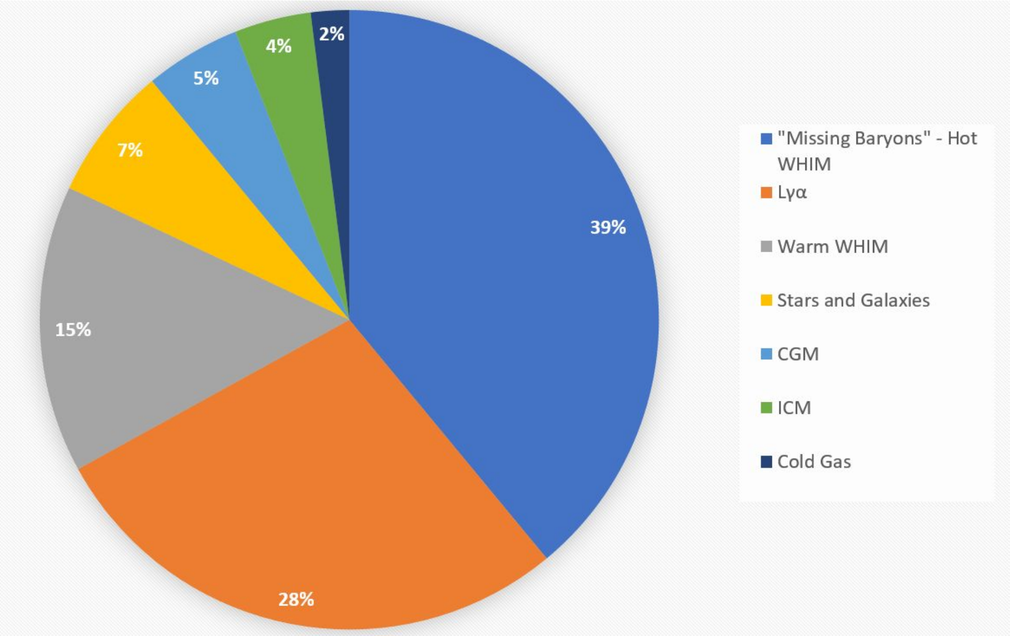
Might have instrument systematics…

More and more instruments and data acquisition techniques are developed !



credit: Jordan Mirocha

Baryon pie chart



Via Wikipedia (Nosborn1)

Contributions to Baryon content

1) Estimating Stellar Mass with white dwarfs, neutron stars, black holes, and substellar objects: 6% (Fukugita & Peebles, 2004)
2) Mass in neutral gas: 1.7% (Zwaan et al., 2003)

More than 90% of the baryons lie outside galaxies !

↳ ‘Missing’ Baryon Problem

Rich clusters of galaxies do not have missing baryon but only contributes about 4% of the total baryon content

Undetectable baryons

Gaseous mass in outer parts of clusters and groups is still increasing at least linearly with radius at the last observable radius

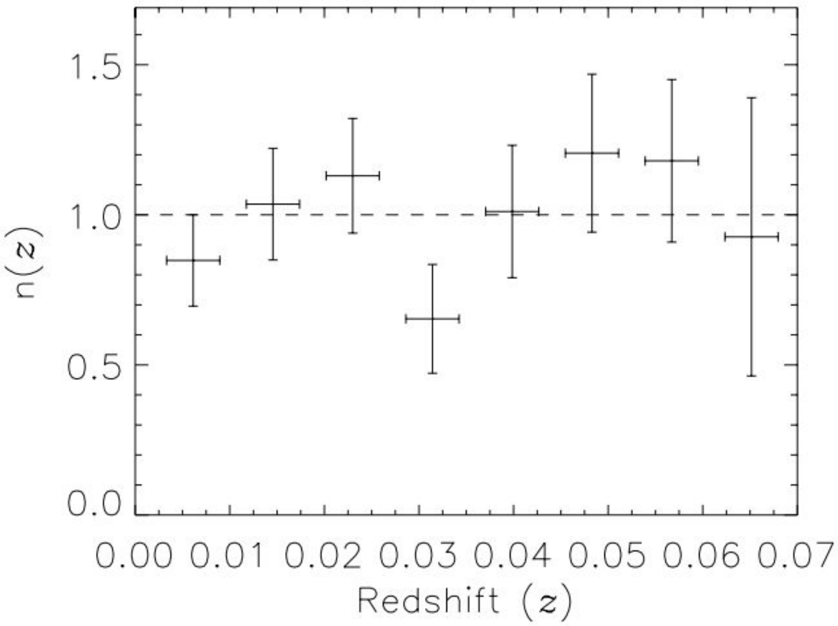
Then X-ray surface brightness falls below detectable levels

It is possible that a significant fraction of baryons lie in the outer parts

At present: Sum of galaxies and hot gas constitutes 12%

Lyman alpha absorbers at Low Redshift

Penton et al. 2004



Measuring baryon content through the Lyα absorbers

Technique for higher redshift

Applied at lower redshift

Result: 29 ± 4% of the baryon content

→ Still 60% of the baryon 'missing'

A possible solution ?

New model: gas occupies low overdensity regions in the Universe and has a temperature in the 10^5 - 10^7 K range called the Warm Hot Intergalactic Medium (WHIM)

WHIM Model

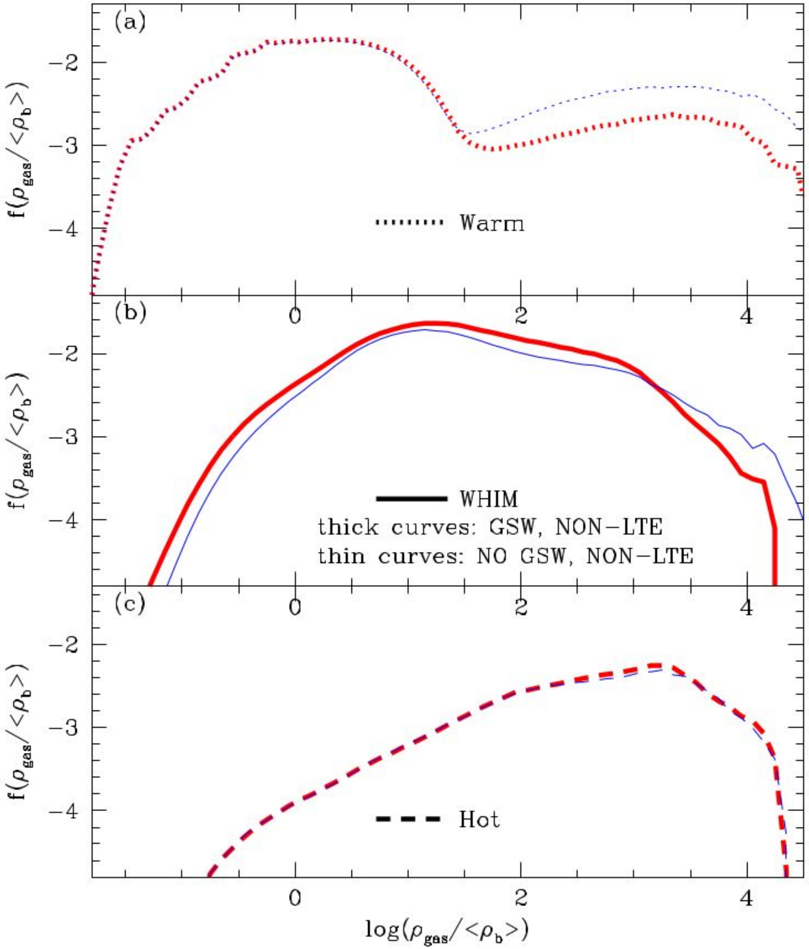
Cen & Ostriker, 2006

Heating mechanism: shocks

Without star formation and stellar feedback

Fraction of gas in the 10^5 - 10^7 K range: 40%

Warm: T < 10^5 K
WHIM: 10^5 < T < 10^7 K
Hot: T > 10^7 K



How to simulate WHIM ?

Observations involve non-primordial elements, such as oxygen

→ Need to include formation and dispersion of the heavier elements in simulation

Model for:

- galaxy and star formation
- supernova rate
- leakage of radiation from galaxy
- galactic wind
- … No cosmological simulation

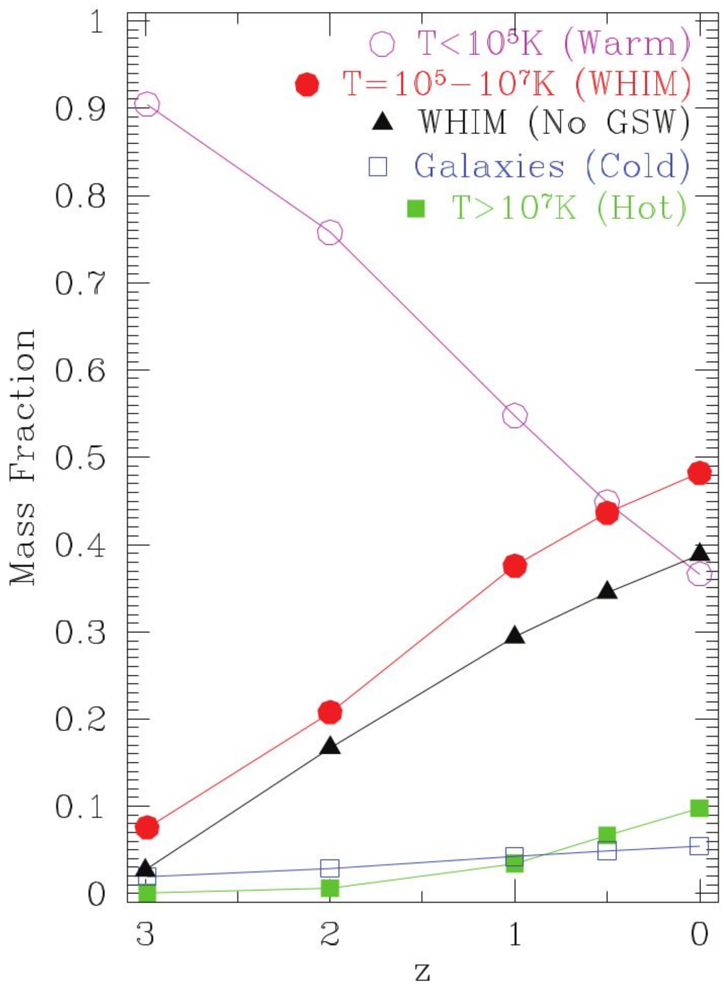
Educated Guess

Cen & Ostriker, 2006

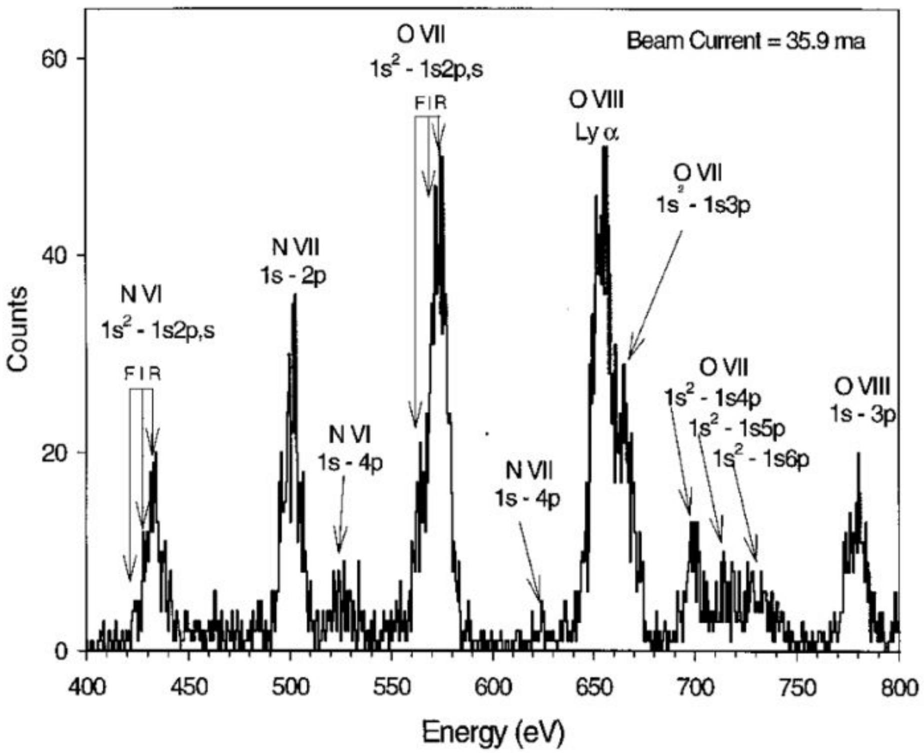
With Galactic superwinds (GSW), predicted mass fraction for the WHIM rises from 40% to 50% at z = 0

Feedback from galaxies increases the metallicity of the gas that constitutes WHIM (by a factor 2)

Hard to constrain



Observations

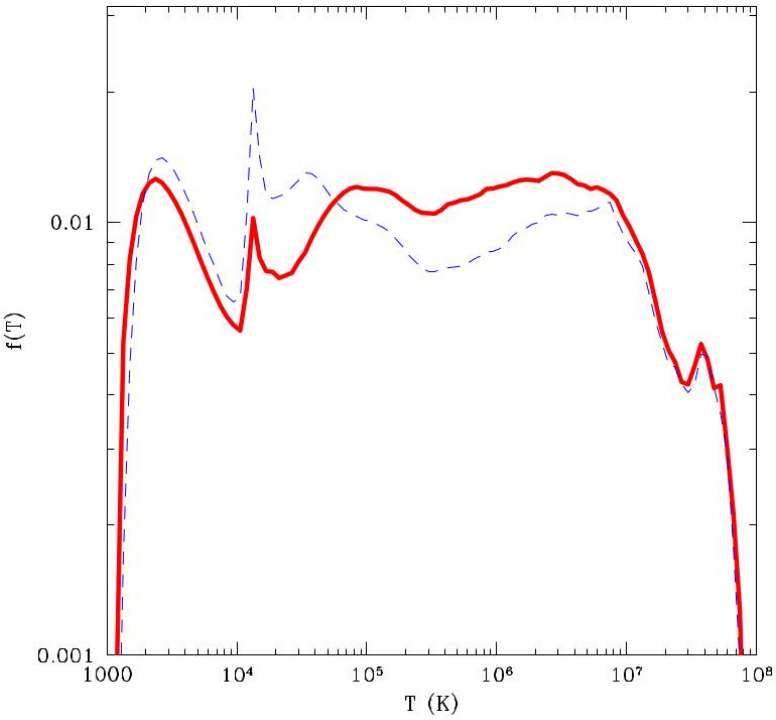


Most common heavy element: oxygen

Important lines: OⅥ, OⅦ and OⅧ

- OⅥ line reaches a peak fractional abundance near $3x10^5$K (1032 & 1038Å)
- OⅦ strongest lines near 10^6K (21.60, 21.80 & 22.1Å)
- OⅧ higher temperature (18.97Å)

Models vs Data



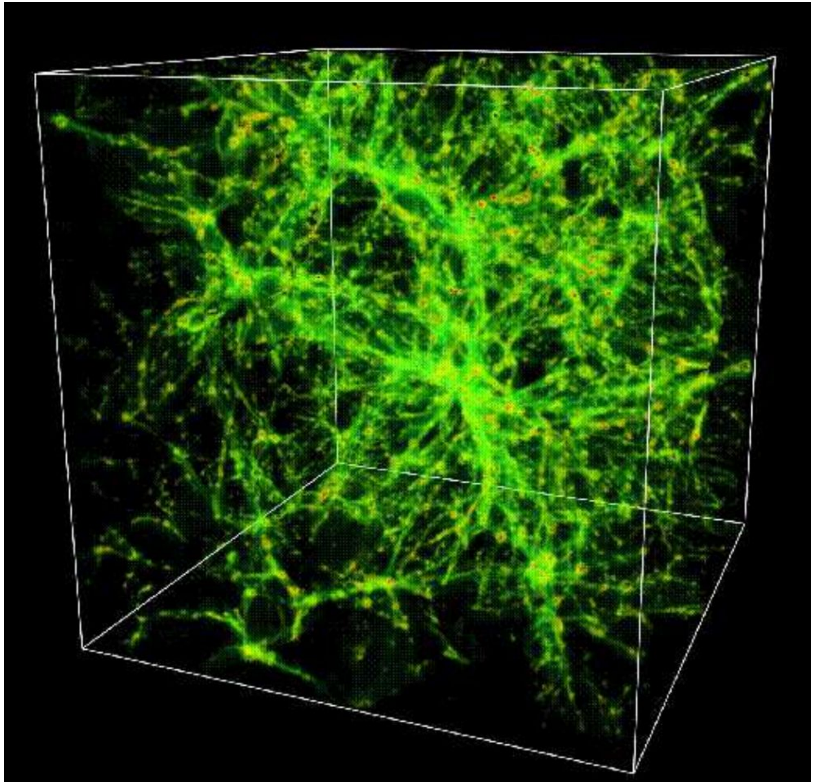
Cen & Ostriker, 2006

Galactic superwind model in red

Mass of the WHIM fairly evenly distributed

Local minimum near 3×10^5 K

In a perfect world...



Density distribution for WHIM from a cosmological ΛCDM simulation (Cen & Ostriker, 2006)

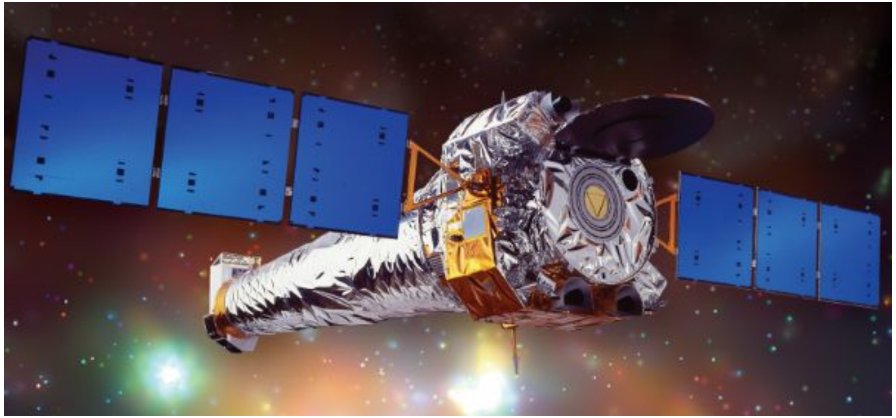
Obtaining an observational description of the structure of the cosmic web would give powerful constraints on the models

Inclusion of galactic feedback for metallicity distribution would be valuable

X-ray Instrumentation

Single photon devices: energy of the photon is proportional to the number of holes created in the CCD

At energies below 1keV (10^7 K), XMM and Chandra have sufficient resolutions



X-ray Instrumentation

Sensitivity:

- Low sensitivity region from 0.28 keV to 0.4 keV
- Below 0.3 keV Chandra Backside Illuminated CCDs has no sensitivity
- XMM Epic camera can detect photons to below 0.2 keV (declining)

Calibration:

- Deposition on the mirror
- No ideal celestial calibration source

Flat-fielding:

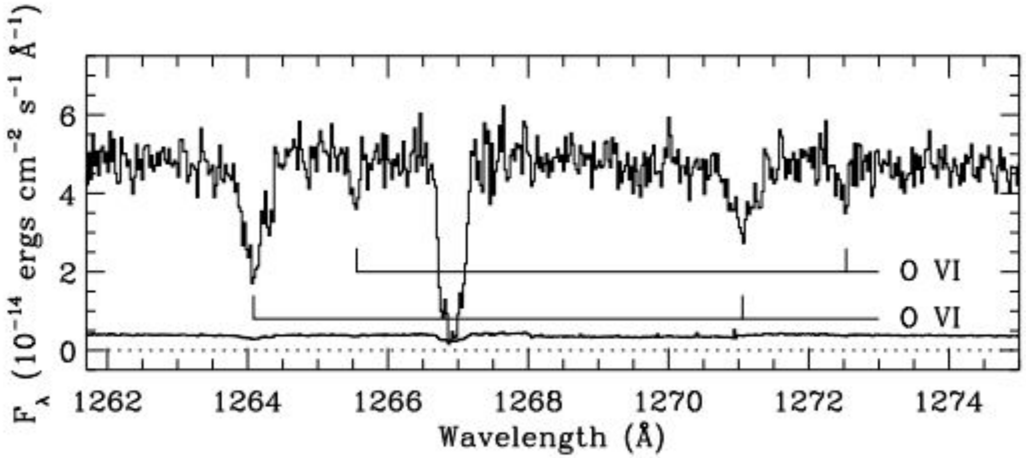
- Unfocused background (varies in time)
- Plasma process in the Solar System (varies in time)
- Diffuse gas in the Local Bubble (varies in space)
- AGNs

Detection of the 1–5x10^5 K WHIM

Preferred Wavelength: Ultraviolet

Two strong lines: O VI & hydrogen Lyα line

First Detection at low redshift: Tripp et al. 2000 (z = 0.22637)



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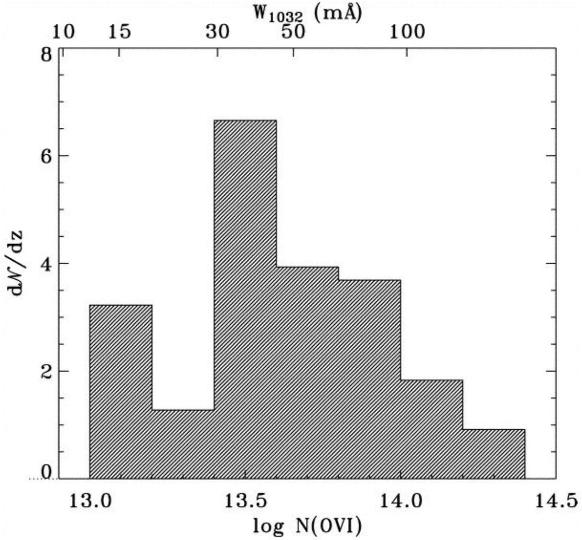
Large statistical sample: Danforth & Shull 2005 (z < 0.15)

40 systems detected
5% of the baryon content

Lower limit ! (lower
column density missing)



Detection of the 1–5x10^5 K WHIM

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Two strong lines: OⅥ & hydrogen Lyα line

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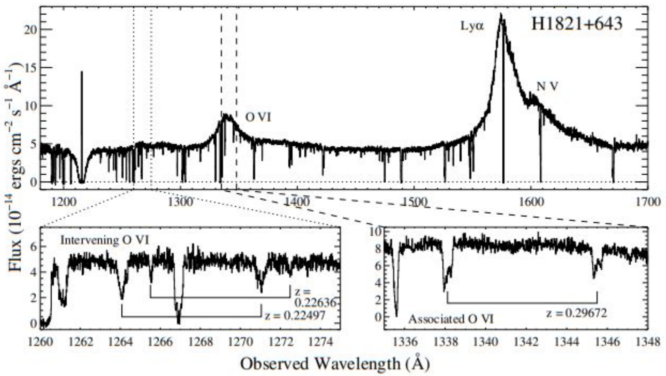
Different but larger sample: Tripp et al. 2006 (0.12 < z < 0.57)



44 OⅥ absorbers → greater than 7% baryon fraction

!!! Fraction of WHIM expected to decrease with redshift !!!

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Neutral Hydrogen: Lehner et al. 2007: 20% of the local baryons may be associated with ionized hydrogen

Problem: broad lines due to turbulences
However can be reliable and would be a
valuable tool in measuring he WHIM near 10^5K

Detection of the 1–5x10^5 K WHIM

Preferred Wavelength: Ultraviolet

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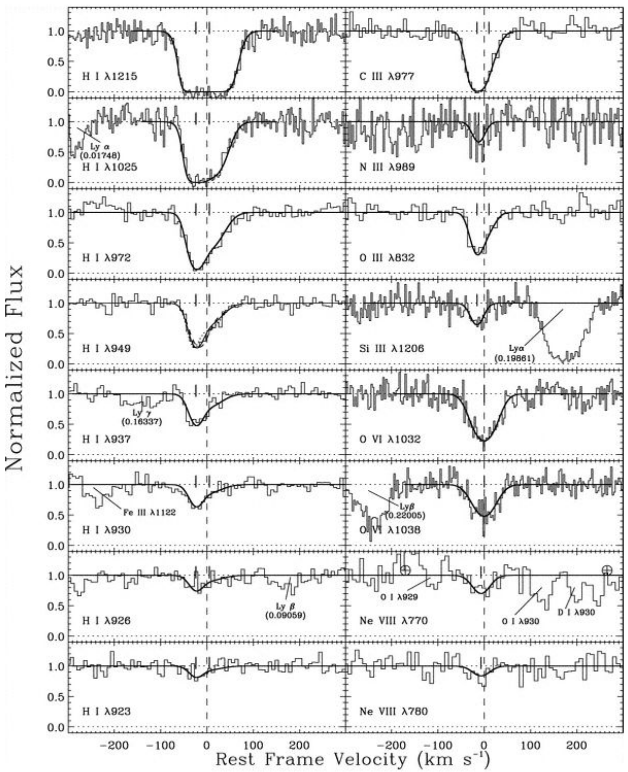
Neutral Hydrogen: Lehner et al. 2007

NeⅧ: Savage et al. 2005



WHIM content in the local group

Modest contribution to the total baryon content…

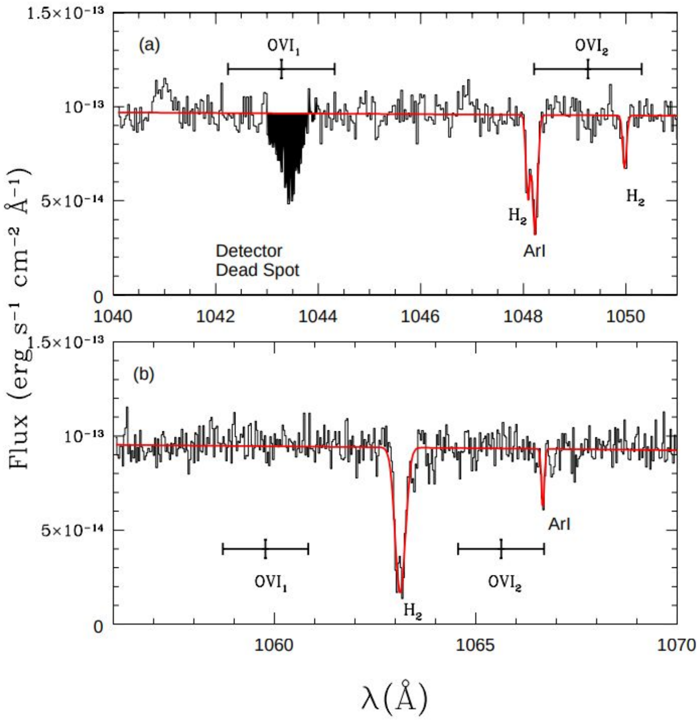
X-Ray Absorption ?

Would reveal gas at 10^6 to 10^7K

New line of research complementary to UV

Primary claim of detection: Mrk 421, brightest AGN at X-ray wavelengths, Nicastro et al. 2005 (z = 0.011 & z = 0.027)

If this is correct, it constitutes the discovery of the hot missing baryons !



X-Ray Absorption ?

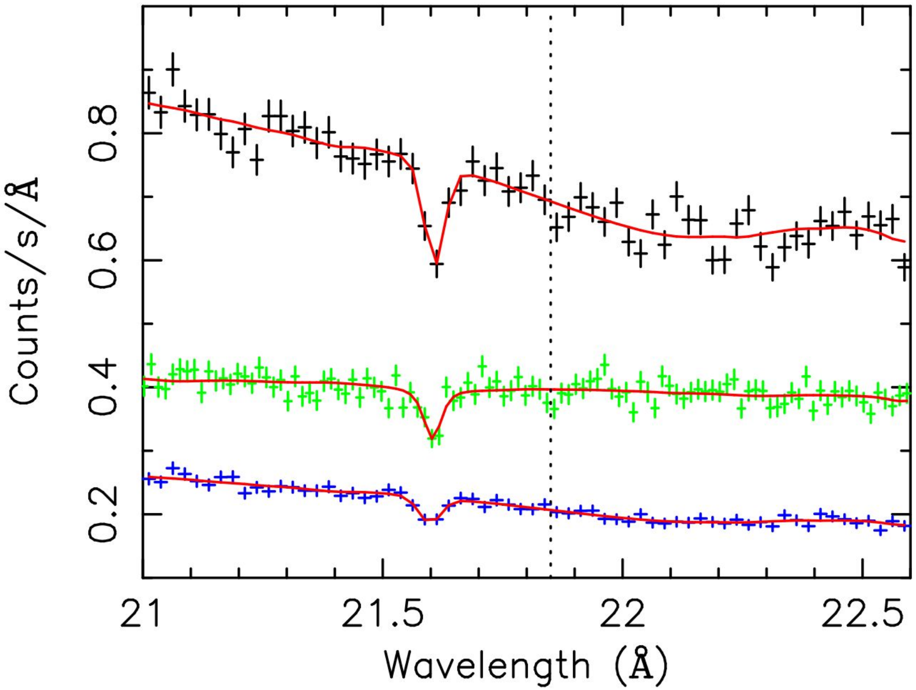
Would reveal gas at 10^6 to 10^7K

New line of research complementary to UV

Primary claim of detection:
Nicastro et al. 2005 (z = 0.011 & z = 0.027)

Questioned by Kaastra et al. 2006

Top: LETG/ACIS
Middle: LETG and HRC-S
Bottom: more recent LETG/ACIS
OⅦ Kα at 21.60 Å
Dotted line: z=0.011



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After 2006: Instrumental features near 21.83Å (detected line at 21.85Å)

X-Ray Absorption ?

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After 2006: Instrumental features near 21.83Å (detectedline at 21.85Å)

Rasmussen et al. 2006: High-quality spectra (using a complete map of all problematic pixels)

→ no detection

X-ray emission from the WHIM

Within the virial radius of galaxy clusters → cannot be claimed

Coma Cluster → Excess of X-ray emission, unlikely to come from a 10^6K medium within the cluster

Coma and Virgo Clusters → No detection of OVI (no WHIM ?)

Beyond the virial radius of galaxy clusters → No definitive detection of a filament in the 10^6-10^7K range

Other Detection techniques

- Dispersion measures
  - Would use pulsars
  - Arrival time of different pulses at different frequencies related to electron column density
  - No pulsars further than LMC…

- Radio hyperfin lines
  - Equivalent of 21cm hyperfin transition but for heavier elements
  - Most of common elements do not produce such transition
  - Except for Nitrogen (53.3 GHz), atmosphere opaque…

- Sunyaev-Zeldovich effect
  - CMB through hot cloud of electrons
  - CMB temperature decreases
  - Need WHIM in the form of filaments…

Recent project

Nicastro et al. 2023

Milky-Way-like galaxy

Well known redshifts of absorbers

4.2 - 5.6σ detection of associated O Ⅶ

Hot medium at logT ≃ 5.8 - 6.3K

X-Ray Detection of the Galaxy's Missing Baryons in the Circum-Galactic Medium of L^* Galaxies

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[11] *Columbus State Community College, Columbus, OH, USA*

Sample Selection

Absorbers of galaxies with luminosity of a Milky-Way-like galaxy

Three quasars

- PG 1407+265 (XMM Newton)
- PKS 0405-123 (Chandra & XMM Newton)
- PG 1116+215 (Chandra & XMM Newton)

Cross known absorbers at

- $z = 0.6828$
- $z = 0.1671$
- $z = 0.1385$

3 detection methods

- Absorption along individual sightlines
- Simultaneous Fit
- Stacked Spectrum

Single Spectra

Table 1. *Best-fitting parameters of the X-ray-halo lines in the single spectra of the three targets*

X-Ray Spectrum	$\lambda^{O\ vii\ K\alpha}_{LLS-frame}$ (Å)	$EW^{O\ vii\ K\alpha}_{LLS-frame}$ (mÅ)	Δv (km s^{-1})	Significance
Fits to Individuals Spectra				
1: PG 1407+265 RGS	21.59 ± 0.03	59 ± 35	$-(140 \pm 420)$	1.7σ
2: PKS 0405-123 RGS	21.54 ± 0.03	15.7 ± 7.1	$-(830 \pm 420)$	2.2σ
3: PKS 0405-123 LETG	21.57 ± 0.05	69 ± 25	$-(420 \pm 690)$	2.8σ
4: PG 1116+215 RGS	21.54 ± 0.03	20.8 ± 8.0	$-(830 \pm 420)$	2.6σ
5: PG 1116+215 LETG	21.48 ± 0.05	29.0 ± 14.5	$-(1670 \pm 690)$	2.0σ
Joint-fits to RGS+LETG spectra with EWs linked to the same value				
PKS 0405-123 RGS+LETG	21.56 ± 0.04	20.5 ± 7.3	$-(560 \pm 560)$	2.8σ
PG 1116+215 RGS+LETG	21.51 ± 0.04	18.1 ± 6.5	$-(1250 \pm 560)$	2.8σ
Weighted averages and coadded significance				
X-Ray halo	21.55 ± 0.04	28.5 ± 6.6	$-(690 \pm 560)$	4.3

Simultaneous Fit

Table 2. *Best-fitting parameters of the X-ray halo absoprtion lines from the simultaneous fits*

Method	$< \lambda^{\mathrm{O}\,vii\ K\alpha}_{LLS-frame} >$ (Å)	$< \lambda^{\mathrm{O}\,vii\ K\beta}_{LLS-frame} >$ (Å)	$<\mathrm{EW}^{\mathrm{O}\,vii\ K\alpha}_{LLS-frame}>$ (mÅ)	$<\mathrm{EW}^{\mathrm{O}\,vii\ K\beta}_{LLS-frame}>$ (mÅ)	Δv km s^{-1}	Significance of the X-ray halo
A	21.54 ± 0.04	[a]18.58	39.1 ± 7.4	9.4 ± 5.2	$-(830 \pm 560)$	5.6σ
B	21.55 ± 0.04	[a]18.59	28.5 ± 6.7	16.4 ± 10.3	$-(690 \pm 560)$	4.6σ
C	21.55 ± 0.04	[a]18.59	26.4 ± 7.1	17.3 ± 8.7	$-(690 \pm 560$	4.2σ

[a] Linked to the Kα position through the ratio of the rest-frame line positions.

Stacked Spectrum

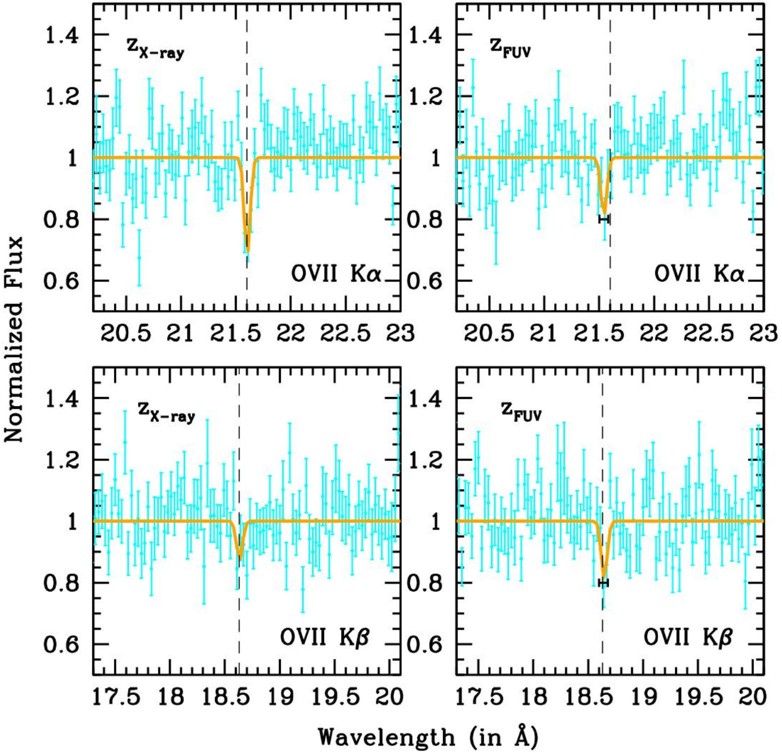
X-Ray-LLS Spectrum: Each spectrum shifted by its own X-ray redshift

FUV-LLS Spectrum: Each spectrum shifted by the redshifts of absorbers in the spectra

Table 3. *Best-fitting X-ray halo absorption line parameters*

Line Parameter	O VII Kα	O VII Kβ	O VIII Kα
X-Ray-LLS Spectrum			
Centroid (in Å)	$21.604^{+0.007}_{-0.006}$	$18.64^{+0.08}_{-0.02}$	[a]18.97
EW (in mÅ)	21.6 ± 3.4	8.6 ± 4.0	≤ 7.9
Significance	6.4σ	2.2σ	90%
Combined Significance		6.8σ	
FUV-LLS Spectrum			
Centroid (in Å)	$21.54^{+0.02}_{-0.01}$	$18.647^{+0.009}_{-0.010}$	[a]18.97
EW (in mÅ)	12.9 ± 3.9	12.9 ± 3.8	≤ 11.4
Significance	3.3σ	3.4σ	90%
Combined Significance		4.7σ	

[a] Frozen in the fit.



Thank you for your attention !