

Tracing Baryons in the Warm Hot Intergalactic Medium using Broad Lyman- α Absorbers

Thesis Phase-II

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SC19B161

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Indian Institute of Space Science and Technology

Supervisors : Dr. Vikram Khaire and Dr. Anand Narayanan



Motivation & Objective

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- ▶ The missing baryon problem

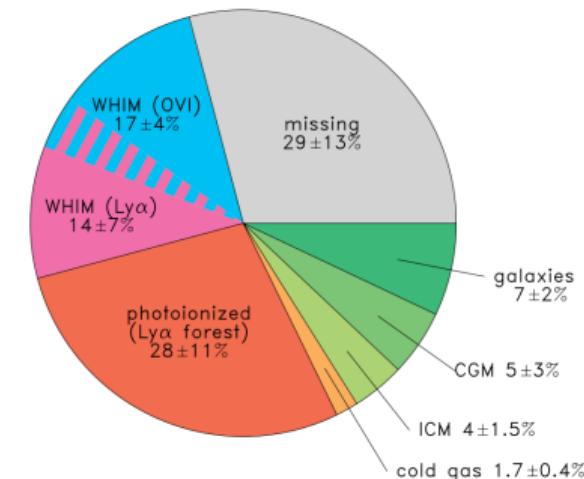


Figure 1: Baryon budget at $z \sim 0$.
Shull et al. (2012)

Ref. : Shull et al. (2012)

Motivation & Objective

- ▶ The missing baryon problem
- ▶ WHIM : $T \sim 10^5 - 10^7$ K
 $n_H \sim 10^{-6} - 10^{-4}$ cm $^{-3}$

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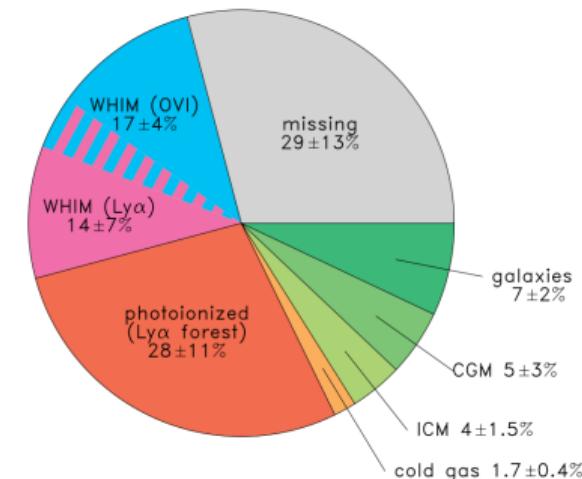


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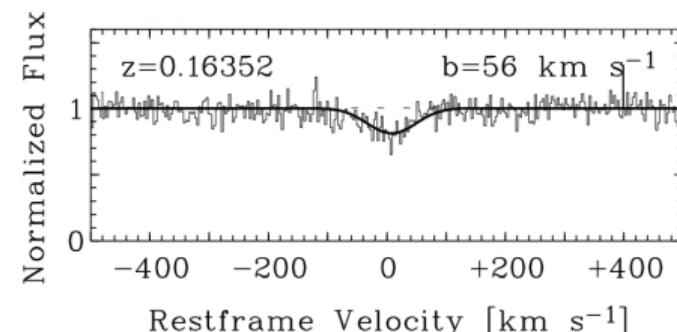


Figure 2: A BLA towards the LOS of quasar H 1821+643.
Philipp Richter (2005)

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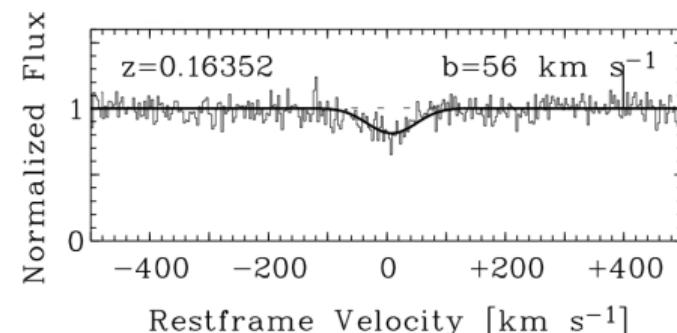


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- ▶ **Baryon content in BLAs ($\Omega_b(\text{BLA})$)**

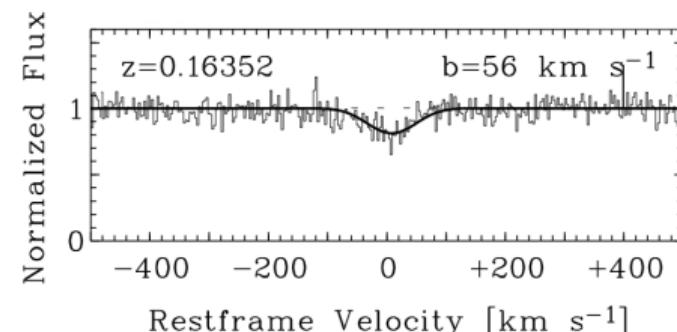


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Thesis Phase-I : Recap

Recap

Recap

- ▶ Absorber towards PG 0003+158

Recap

- ▶ Absorber towards PG 0003+158
 - Voigt profile fitting

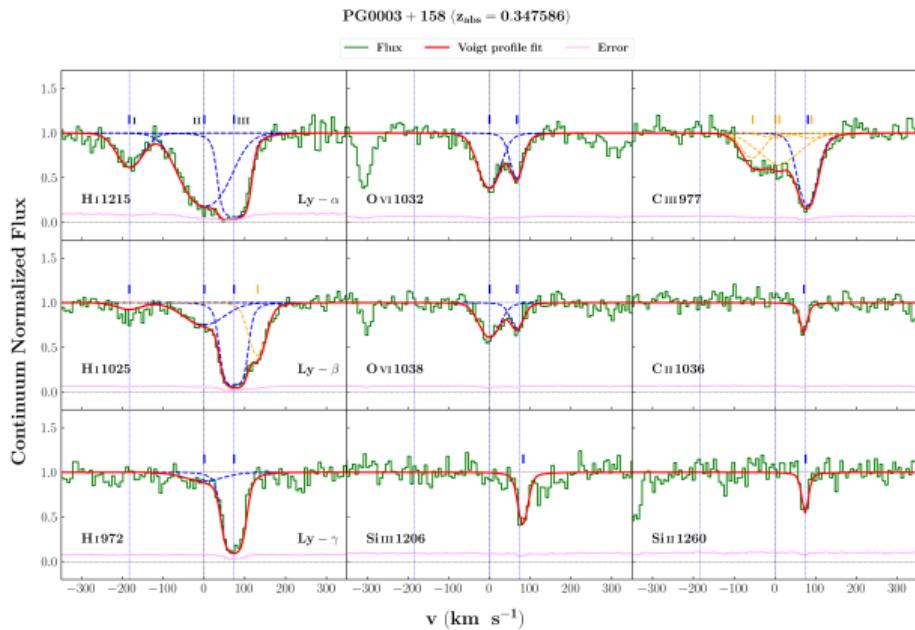


Figure 3: System plot of the absorber system towards PG 0003+158. Velocity is taken zero at $z = 0.347586$

Recap

- ▶ Absorber towards PG 0003+158
 - Voigt profile fitting
 - **Ionisation modelling**

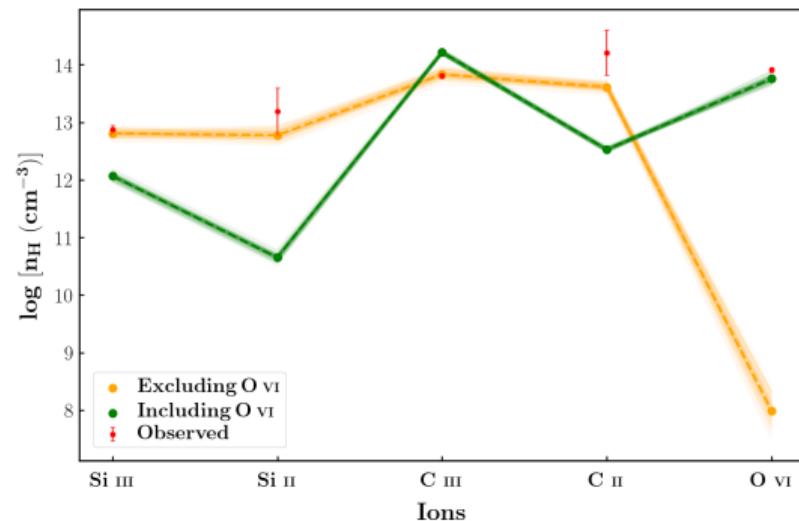


Figure 4: Photoionization modelling of component-III in absorber towards PG 0003+158

Recap

- ▶ Absorber towards PG 0003+158
 - Voigt profile fitting
 - Ionisation modelling
 - Galaxy environment

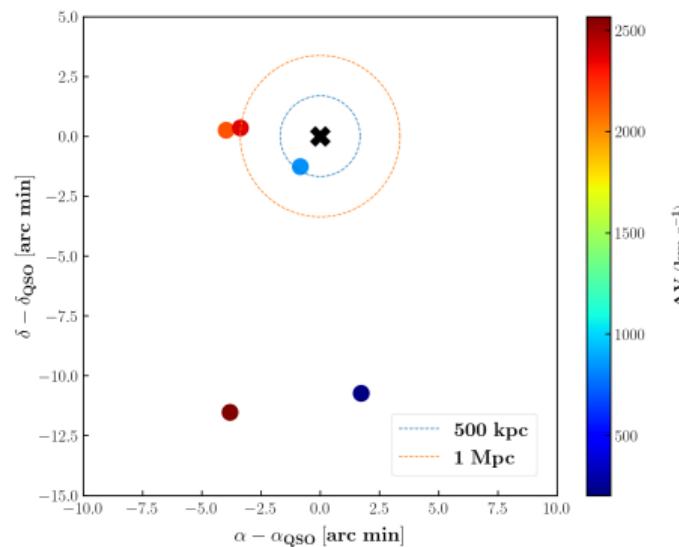
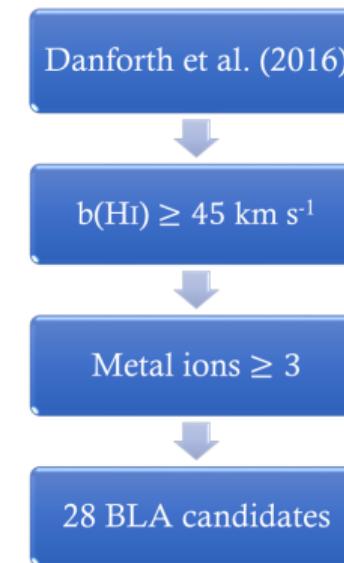


Figure 5: Galaxy neighbourhood of absorber towards PG 0003+158

Recap

- ▶ Absorber towards PG 0003+158
 - Voigt profile fitting
 - Ionisation modelling
 - Galaxy environment
- ▶ **BLA survey**



Ref. : Danforth et al. (2016)

Figure 6: Shortlisting the BLA candidates for survey

The BLA Survey

Some numbers

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- ▶ **22 sight lines** : $\Delta z_{\text{Ly}\alpha} = 5.561$

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- ▶ **29 absorbers** : 17 (O VI) + 12 (non-O VI)

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- ▶ 22 sight lines : $\Delta z_{\text{Ly}\alpha} = 5.561$
- ▶ 29 absorbers : 17 (O VI) + 12 (non-O VI)
- ▶ Voigt profile fitting : 686 absorption lines - 97 H I components
- ▶ **Ionisation modelling** : 39 components

Voigt profile fitting

Absorption species

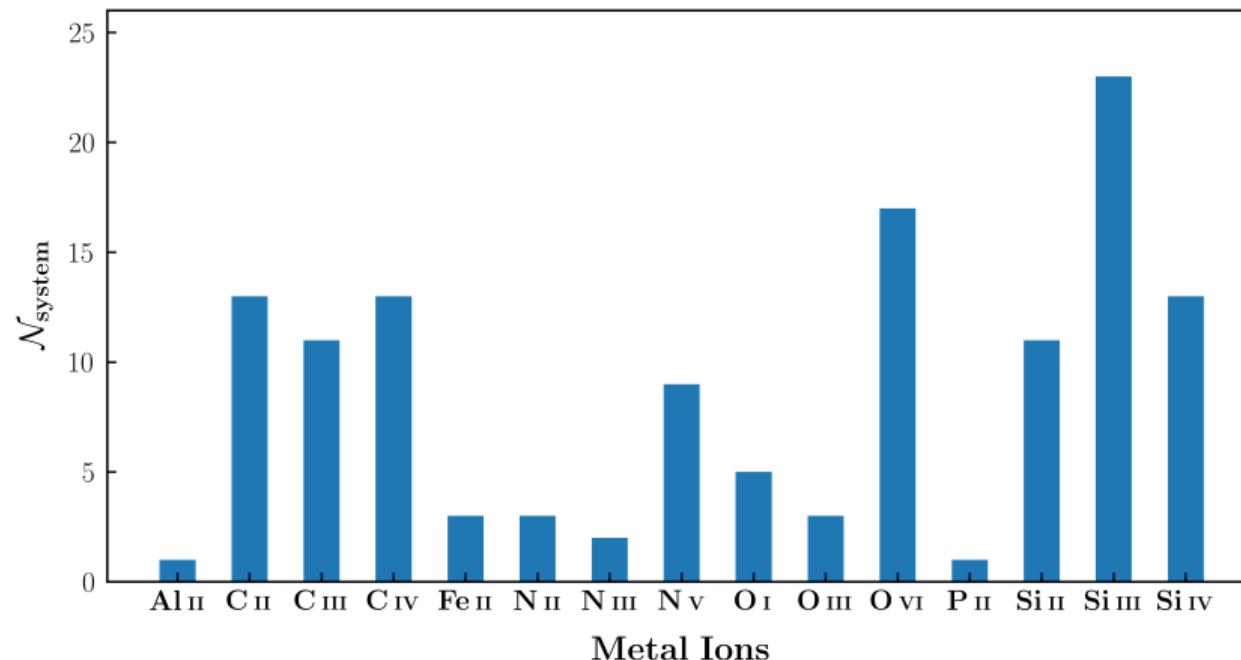


Figure 7: Distribution of metal species in 29 BLA candidates

Absorption species

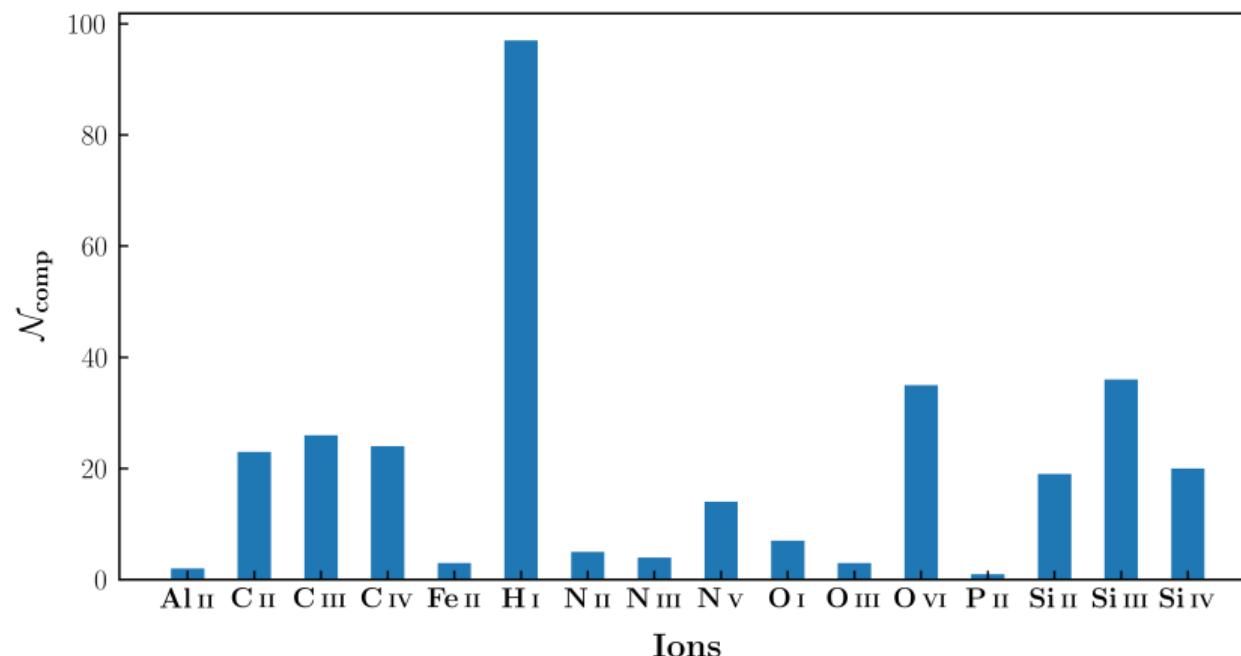


Figure 8: Distribution of components of absorption species in 29 BLA candidates

N(H I) and b (H I)

N(H I) and b (H I)

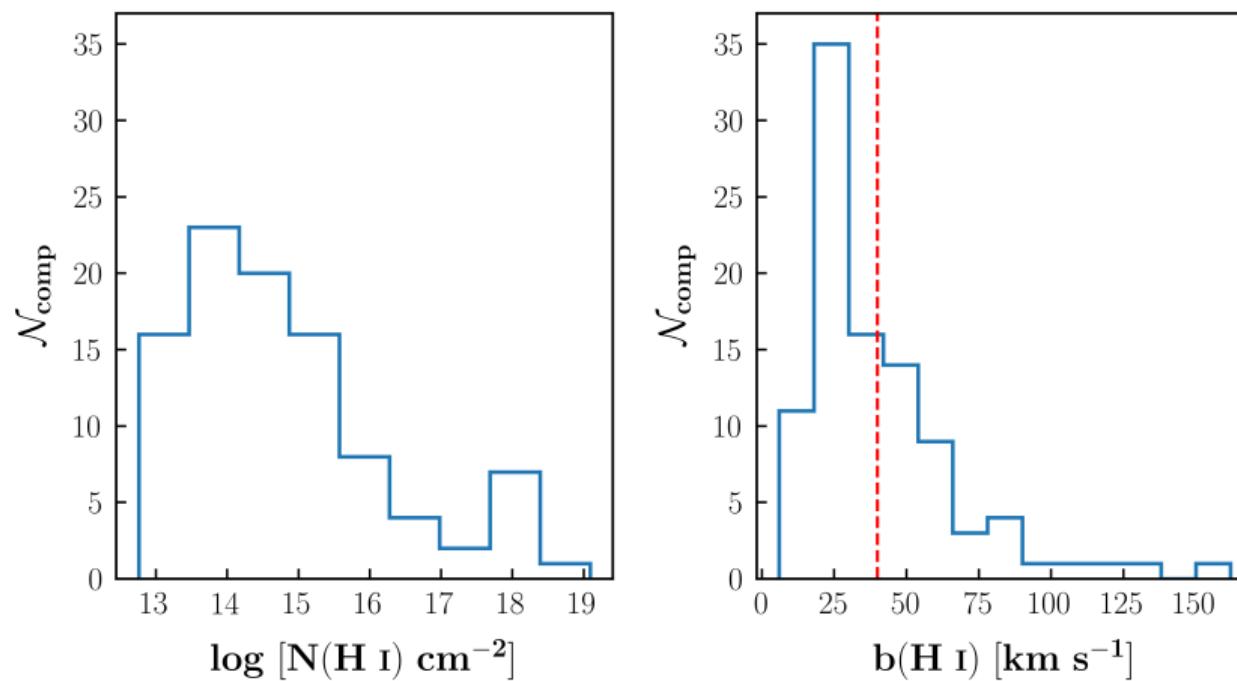


Figure 9: Distribution of column densities and Doppler widths of 97 H I components

N(H I) and b (H I)

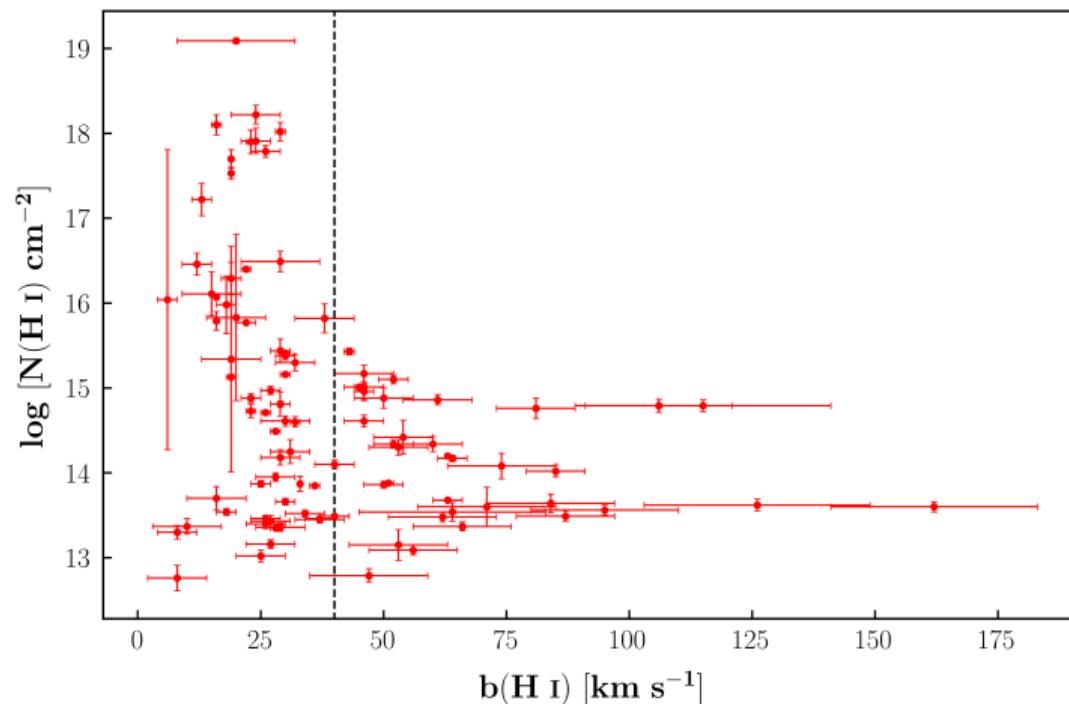


Figure 10: H I column density v/s Doppler width for 97 H I components

Ionisation Modelling

Method

Method

- ▶ Grid of PI CLOUDY models : Density and Metallicity

Ref. : Acharya and Khaire (2021)

Method

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- ▶ $\log(n_{\text{H}}/\text{cm}^{-3})$: -5 to 1 in steps of 0.02

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Method

- ▶ Grid of PI CLOUDY models : Density and Metallicity
- ▶ $\log(n_H/\text{cm}^{-3})$: -5 to 1 in steps of 0.02
- ▶ $\log(Z/Z_\odot)$: -3 to 2 in steps of 0.05

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Method

- ▶ Grid of PI CLOUDY models : Density and Metallicity
- ▶ $\log(n_H/\text{cm}^{-3})$: -5 to 1 in steps of 0.02
- ▶ $\log(Z/Z\odot)$: -3 to 2 in steps of 0.04
- ▶ **Solution : Model that best predicts the observed column densities**

Ref. : Acharya and Khaire (2021)

Results

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- ▶ 17 O VI absorbers : 25 components

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- ▶ **12 non-O VI absorbers : 14 components**

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- ▶ 12 non-O VI absorbers : 14 components
- ▶ **Origin of O VI**

Solutions

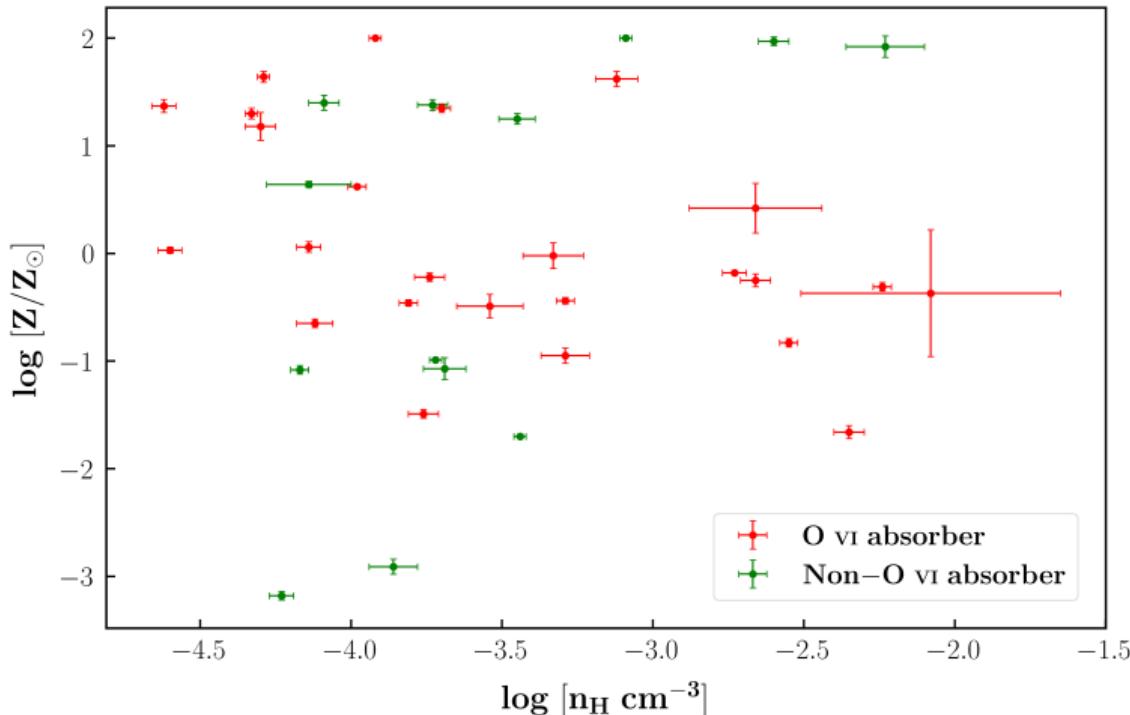


Figure 11: Ionisation modelling solutions (n_H , Z) for all 39 components.

+ve correlation

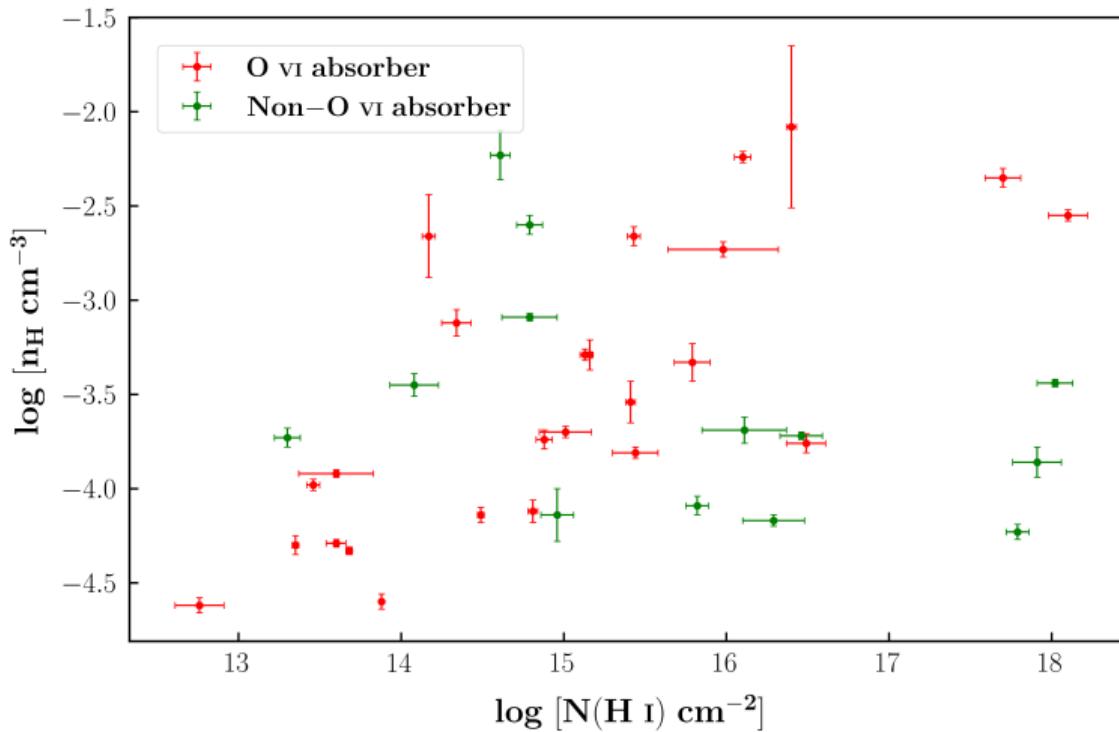
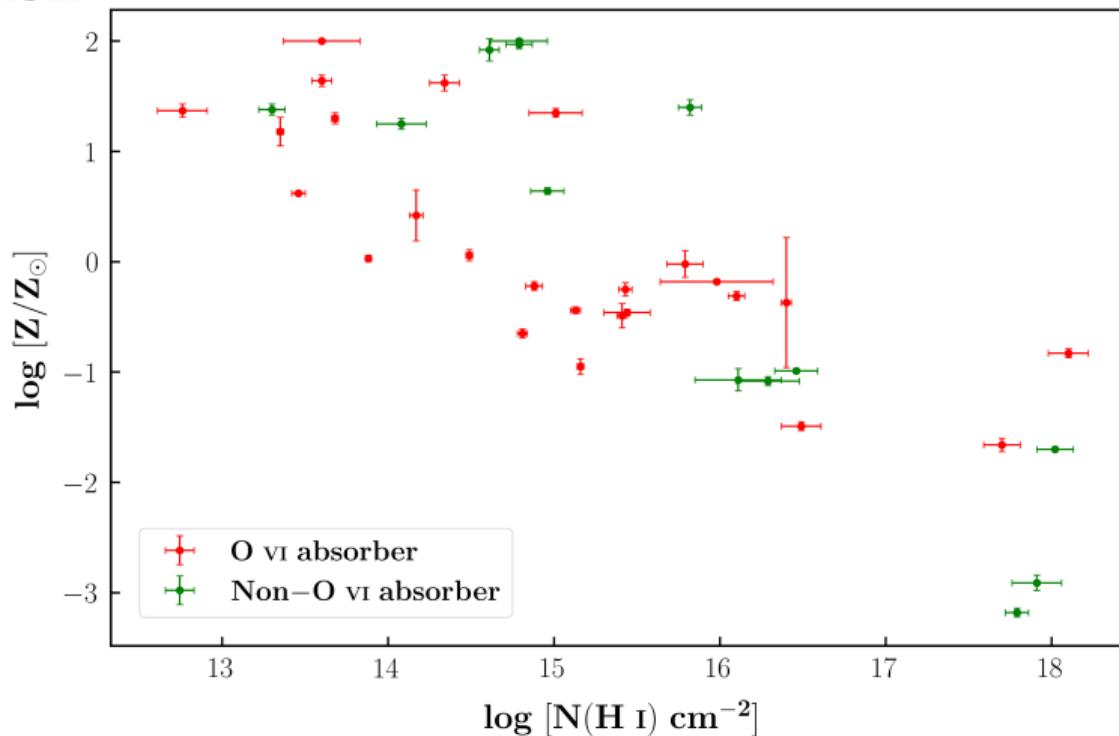


Figure 12: Variation of n_H with $N(H I)$

-ve correlation



Origin of O VI

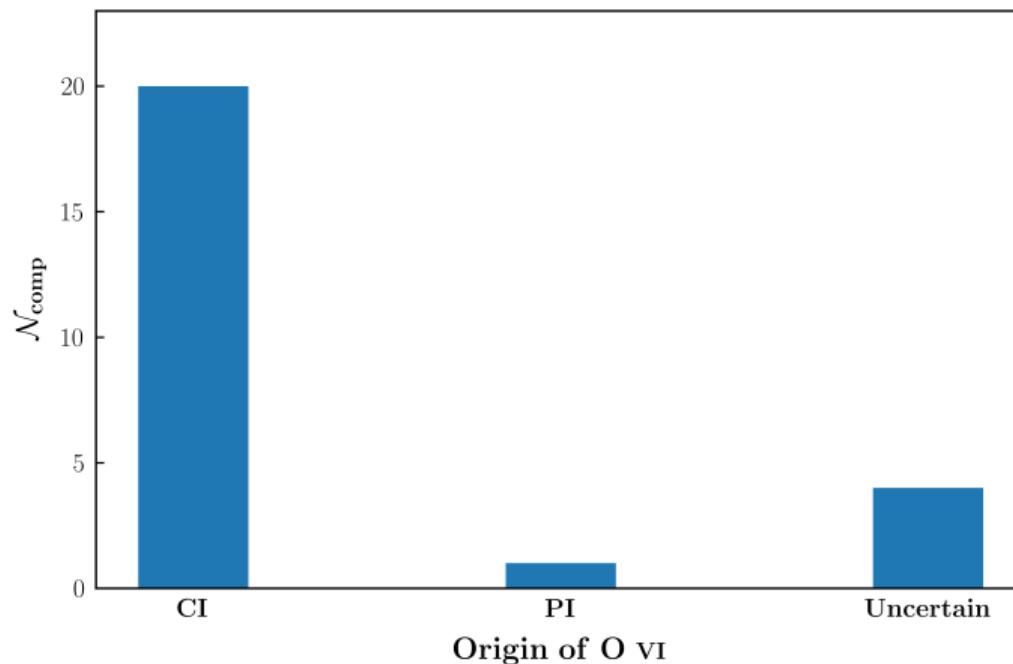
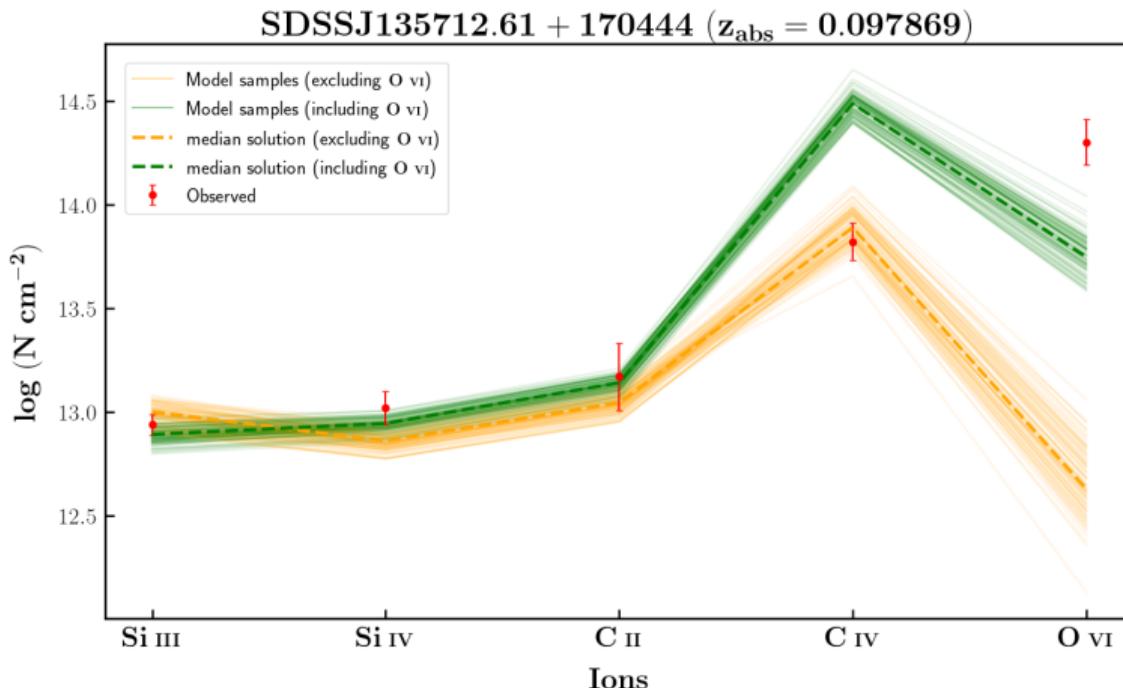
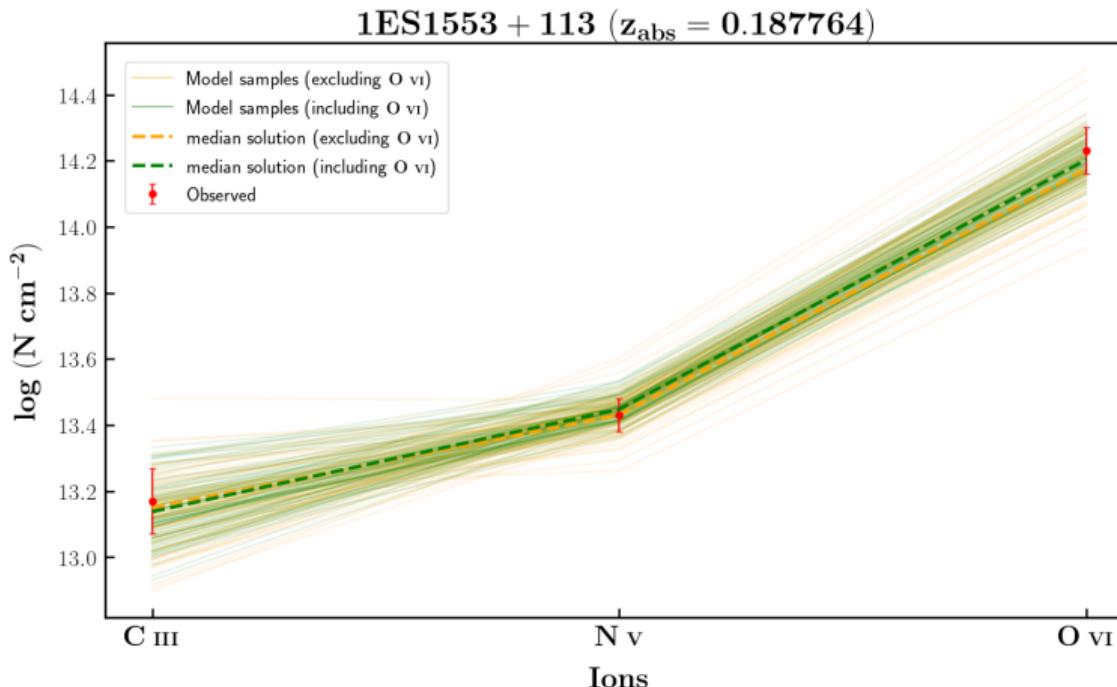


Figure 14: Ionisation state of O VI inferred from ionisation modelling

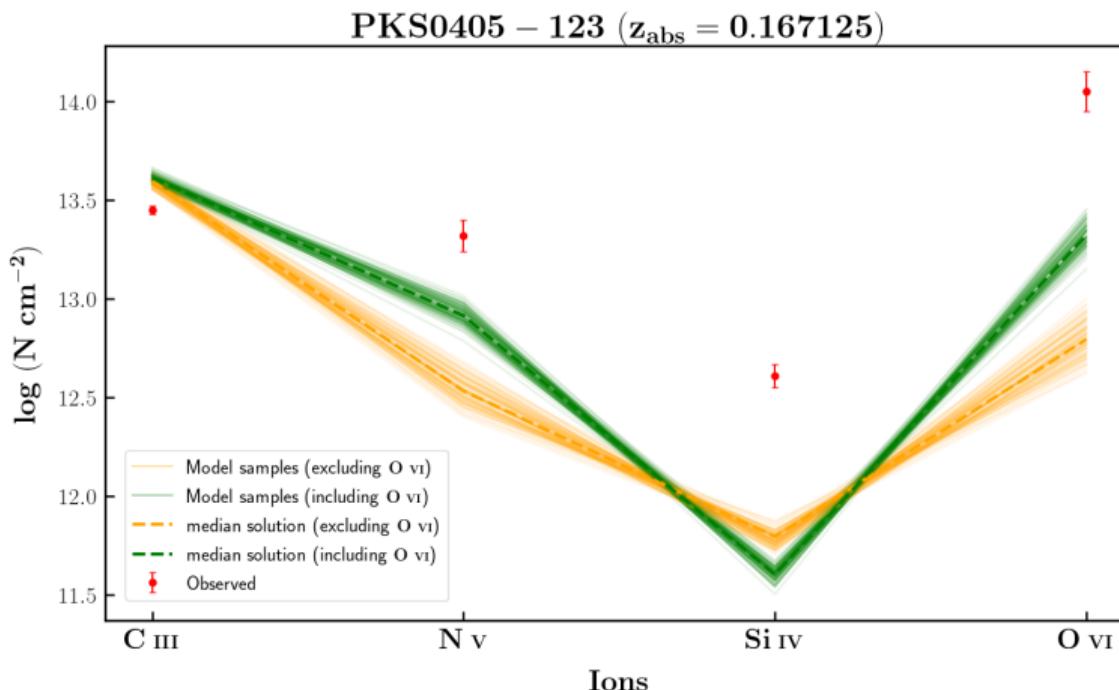
Ex : CI

Figure 15: $\log N(\text{H I}) [\text{cm}^{-2}] = 16.49$

Ex : PI

Figure 16: $\log N(\text{H I}) [\text{cm}^{-2}] = 12.76$

Ex : Uncertain

Figure 17: $\log N(\text{H I}) [\text{cm}^{-2}] = 13.46$

Estimating $\Omega_b(\text{BLA})$

Method

Method

$$\Omega_{\text{ion}} = \frac{H_0 m_{\text{ion}}}{c \rho_{\text{cr}}} \int \frac{\partial^2 \mathcal{N}}{\partial N \partial X} N dN \quad (\text{Becker et al. 2011})$$

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H_0 : current value of Hubble's constant

m_{ion} : mass of ion

c : speed of light in vacuum

ρ_{cr} : current critical density of universe

\mathcal{N} : no. of absorbers at column density N and absorption path length X

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$$X(z) = \int_0^z (1+z')^2 \frac{H_0}{H(z')} dz' \quad (\text{Bahcall \& Peebles 1969})$$

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$$\int \frac{\partial^2 \mathcal{N}}{\partial N \partial X} N dN \simeq \frac{\sum N_{\text{obs}}}{\Delta X}$$

Method

Method

$$\Omega_b(\text{BLA}) = \frac{H_0 \mu m_H}{c \rho_{\text{cr}}} \sum_{i,j} N(H)_{i,j} \left/ \sum_j \Delta X_j \right.$$

Method

$$\Omega_b(\text{BLA}) = \frac{H_0 \mu m_H}{c \rho_{\text{cr}}} \sum_{i,j} N(H)_{i,j} \left/ \sum_j \Delta X_j \right.$$

$$\Rightarrow \Omega_b(\text{BLA}) = \frac{H_0 \mu m_H}{c \rho_{\text{cr}}} \sum_{i,j} f_{H,i,j} N(\text{HI})_{i,j} \left/ \sum_j \Delta X_j \right.$$

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CIE :

Method

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CIE : $\log f_H \approx 5.4 \log T - 0.33(\log T)^2 - 13.9$ (Sutherland & Dopita 1993)

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- ▶ Photoionization important at low densities ($< 10^{-5} \text{ cm}^{-3}$)

Ref. : Richter et al. (2006)

Selecting the BLA sample

Selecting the BLA sample

- ▶ Sample A
- ▶ Sample B
- ▶ Sample C

Selecting the BLA sample

- ▶ **Sample A** : $T > 10^5 \text{ K}$ and O VI is CI
- ▶ **Sample B**
- ▶ **Sample C**

Selecting the BLA sample

- ▶ **Sample A** : $T > 10^5$ K and O VI is CI
 - 5 components
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Selecting the BLA sample

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- ▶ **Sample B** : O VI is CI
 - 20 components
- ▶ **Sample C**

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Selecting the BLA sample

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- ▶ **Sample B** : O VI is CI
 - 20 components
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 - 39 components

$\Omega_b(\text{BLA})$

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- $\Omega_b = (45.7 \pm 0.2) \times 10^{-3} h_{70}^{-2}$

Ref. : Planck Collaboration et al. (2020)

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| Sample | $\Omega_b(\text{BLA})$ ($\times 10^{-3} h_{70}^{-1}$) | $\Omega_b(\text{BLA})/\Omega_b$ ($\times h_{70} \%$) |
|----------------|--|---|
| A | 1.8 ± 0.5 | 4 ± 1 |
| B | 7.2 ± 1.3 | 16 ± 3 |
| C | 27.1 ± 13.8 | 60 ± 30 |
| C ^a | 10.0 ± 2.2 | 22 ± 5 |

^a Excluding high uncertainty sight lines from sample C

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Outcomes

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- Poster presentation at ASI-2024 meet titled "Tracing Baryons in WHIM using BLAs"¹

Tracing Baryons in the Warm-Hot Intergalactic Medium using Broad Lyman- α Absorbers

Sameer Patidar¹, Vikram Khatri^{1,2}, Anand Narayanan¹

¹ Indian Institute of Space Science and Technology, Thiruvananthapuram, Kerala

² University of California, Santa Barbara, CA, USA

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Introduction

- More than 90% of baryons reside in IGM and CGM at $z \sim 0$.
- Out of these 90% baryons, more than 30% are still unaccounted for in observations (Shull et al. 2012).
- Structure formation simulations show that these missing baryons reside in Warm Hot phase of Intergalactic Medium (WHIM).
- WHIM : Difficult to observe - low density and high temperature
- Broad Lyman- α Absorbers (BLAs) are expected to be large reservoirs of baryons.
- We probe WHIM using BLAs and estimate their contribution in the total baryonic energy density of universe.

Objectives

- Comprehensive survey of BLAs
- To estimate contribution of BLAs to the total cosmic baryon inventory

Observations

- HST/COS data in FUV channel : 1130-1790 Å
- High S/N > 15 per resolution element
- $\Delta z / \Delta v = 17,000$ (17 km s $^{-1}$)

Studying an Absorber system : Methods

- Vaigt profile fitting - VIPFIT
 - Gives positions, widths and column densities of ions
- Ionization Modelling – CLOUDY
 - To infer ionization state of the absorber cloud
 - To determine physical conditions prevailing in the absorber system
- Galaxy neighborhood
 - To deduce origins of the absorber system

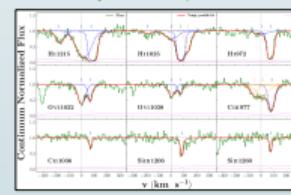


Fig. 1 : System plot of an absorber in $z \sim 0.347$ towards the line of sight of quasar PG0003+158 ($v = 0$ at $z = 0.34759$)

Absorber towards PG 0003+158 : Results

- Vaigt profile analysis (fig. 1)
 - 3 component system at $z \sim 0.347$
 - Component I : Ly α and Ly β at $v \sim -180$ km s $^{-1}$
 - Component II : Ly α - Ly β , O VI at $v = 0$ km s $^{-1}$; $T = 10^{12}$ K (BLA)
 - Component III : H I 1215-914, O VI, C II, C III, Si II, Si III at $v = 70$ km s $^{-1}$

- Ionization Modelling
 - All ions in component III can be explained using previous physical conditions except O VI (fig. 2)
 - So, O VI could be missing collisionally ionized gas phase.

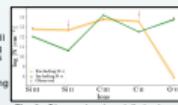
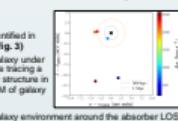


Fig. 2 : Observed and modelled column densities of ions in component III

- Galaxy Environment
 - VIMOS : 5 galaxies identified in the field - $L \leq 0.07 L^*$ (fig. 3)
 - Absorber residing in galaxy under absorption could be tracing a large scale filamentary structure in the cosmic web or CGM of galaxy fainter than $0.07 L^*$



BLA Survey : Ongoing work

- Presented results are part of our ongoing large survey of BLAs
- Identified 28 more BLA candidates for the survey
- Methods described currently are being carried out on these 28 BLA candidates.
- Results from these 28 systems will be used to estimate contribution of BLAs in the total cosmic baryon inventory.

Conclusion

- Addressed uncertainties in Baryon census in WHIM using BLAs
- Studied an interesting absorber system, possibly tracing a large scale filamentary structure or a CGM of sub- L^* galaxy.
- Results are awaited from the whole survey of additional 28 absorbers.

References

- Shull J. M., Smith B. D., Donofrio C. W., 2012, ApJ, 759, 23
- Donofrio C. W. et al., 2016, ApJ, 817, 111
- Acharya A., Khatri V., 2021, MNRAS, 509, 5559
- Khatri V., Srivani R., 2019, MNRAS, 484, 4274

¹ <https://ui.adsabs.harvard.edu/abs/2024asi..confP..78P/abstract>

Outcomes

- ▶ Poster presentation at ASI-2024 meet titled "**Tracing Baryons in WHIM using BLAs**"¹

- ▶ Manuscript titled "**A BLA candidate towards PG 0003+158 tracing a filamentary structure in the cosmic web**"
to be submitted to MNRAS

MNRAS **000**, 1–10 (2024)

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A BLA candidate towards PG 0003+158 tracing a filamentary structure in the cosmic web

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ABSTRACT

Quasar line spectroscopy allows us to probe the circumgalactic medium of galaxies and the intergalactic medium between us and the distant quasars. In this work, we use quasar line spectroscopy to study a broad Lyman- α absorber (BLA) candidate system towards the line of sight of quasar PG 0003+158 ($z_{\text{em}} = 0.4509$) at $z \sim 0.347$. These BLAs are excellent tracers of the warm-hot intergalactic medium (WHIM), where around 50% of the baryons in the present universe are expected to be found. For the current study, we utilize HST/COS observations in the FUV channel available in the Hubble Spectral Legacy Archive. To study the absorber system, we first do the Voigt profile measurements on the identified absorption lines using a Voigt profile fitting code called VPFIT. We identified three components in the absorber system and observed H I and metal absorption to different extents in different components. Component I shows only H I absorption, component II, which is our BLA candidate, exhibits H I and a concurrent O VI absorption, whereas component III shows metal absorption in the form of C II, C III, Si II, Si III and O VI along with H I absorption. We estimate the temperature of component II to be $\sim 10^{3.3}$ K, indicating the presence of a warm gas phase. We also perform ionisation modeling to infer the ionisation state in the absorber cloud. We find that O VI absorption in the component III possibly traces a collisionally ionised gas phase, whereas other ions arise from a photoionised gas. We also analyzed the galaxy environment of the absorber and found that the absorber resides in a galaxy under-dense region, likely tracing a filamentary structure in the cosmic web or a CGM of a faint galaxy.

Key words: galaxies: halos – intergalactic medium – quasars: absorption lines – quasars: individual (PG 0003+158)

¹ <https://ui.adsabs.harvard.edu/abs/2024asi..confP..78P/abstract>

Summary

- ▶ Missing baryon problem
- ▶ BLA survey : 29 BLA candidates - 22 LOS
- ▶ Voigt profile fitting : 686 Voigt profiles
- ▶ Ionisation modelling : 39 components
- ▶ BLA + O VI : WHIM
- ▶ **BLAs can contribute around 20% to Ω_b**

References

Acharya A., Khaire V., 2021, MNRAS, 509, 5559

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(The End is the Beginning)

Additional slides

$b(\text{O VI})$ vs. $b(\text{H I})$

$$b^2 = b_{th}^2 + b_{nt}^2$$

$$b_{th}^2 = \frac{2kT}{m}$$

$$T = \frac{8m}{15k} (b_{\text{H I}}^2 - b_{\text{O VI}}^2)$$

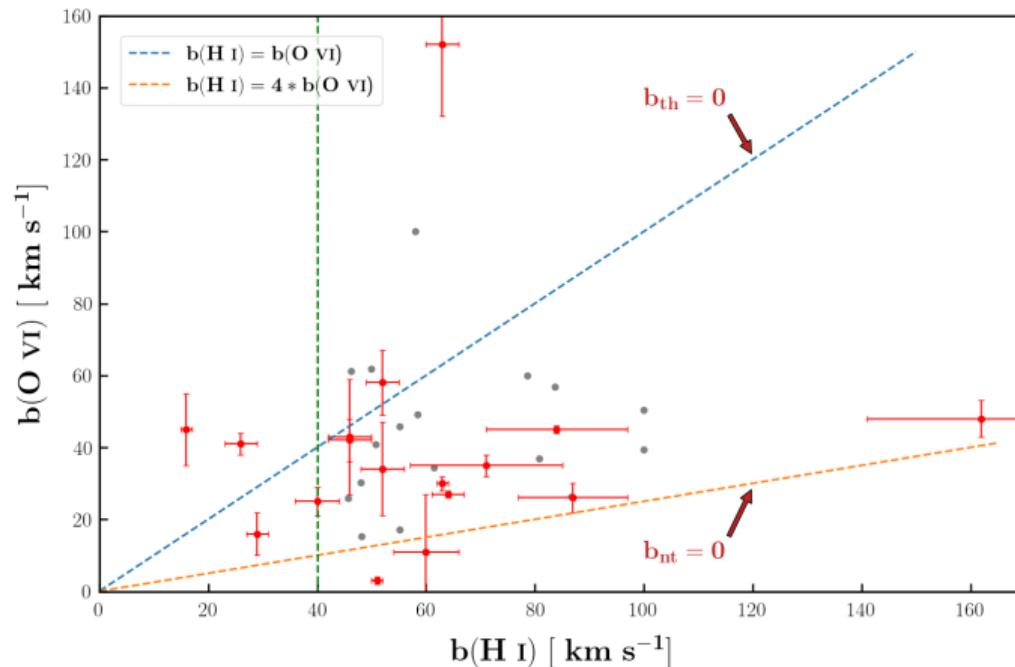


Figure 18: $b(\text{O VI})$ vs. $b(\text{H I})$. Grey filled circles are measurements from Danforth et al. (2016).

- ▶ Outlier b(O VI)

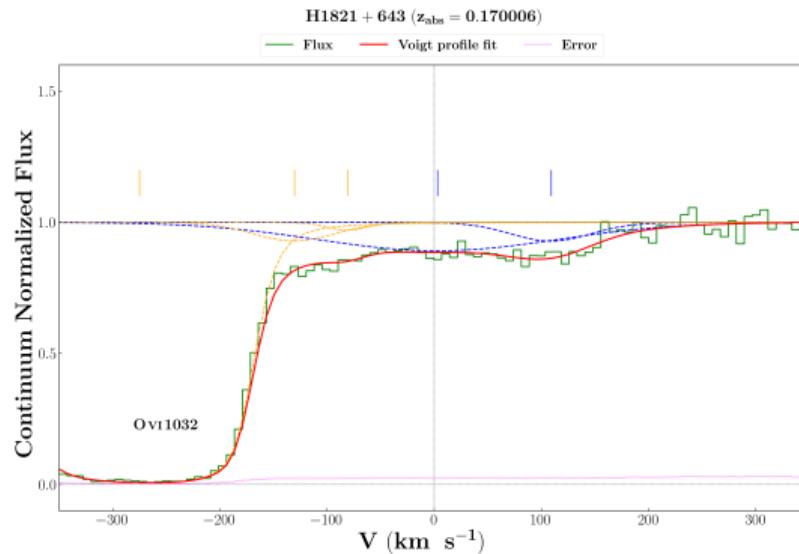


Figure 19: Voigt profile fit of O VI 1032 line in absorber system towards H1821+643 at $z_{abs} = 0.170006$