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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Motivation & Objective

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- **The missing baryon problem**

Ref. : Shull et al. (2012)

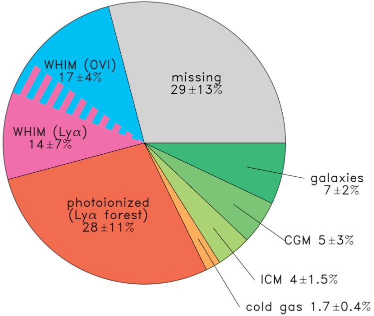

Figure 1: Baryon budget at $z \sim 0$. Shull et al. (2012)

Motivation & Objective

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

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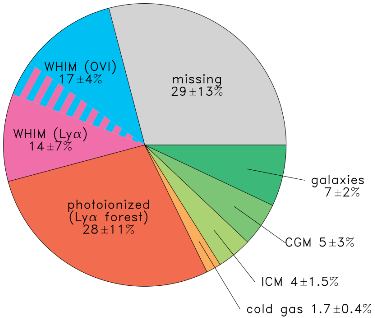

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- **BLAs : Way to probe WHIM**

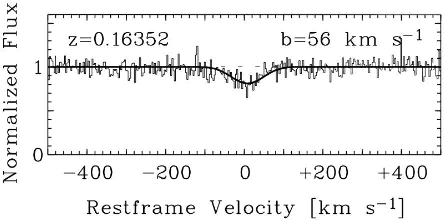

Figure 2: A BLA towards the LOS of quasar H 1821+643. Philipp Richter (2005)

Ref. : Shull et al. (2012)
Lehner et al. (2007)

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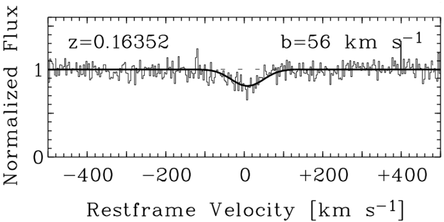
- **Survey of BLAs**



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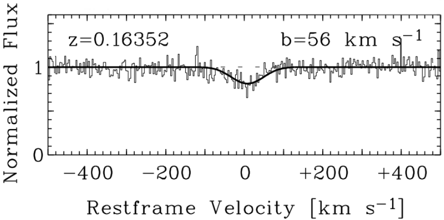
- **Baryon content in BLAs (Ω_b(BLA))**



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Thesis Phase-I : Recap

Recap

Recap

- **Absorber towards PG 0003+158**

Recap

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

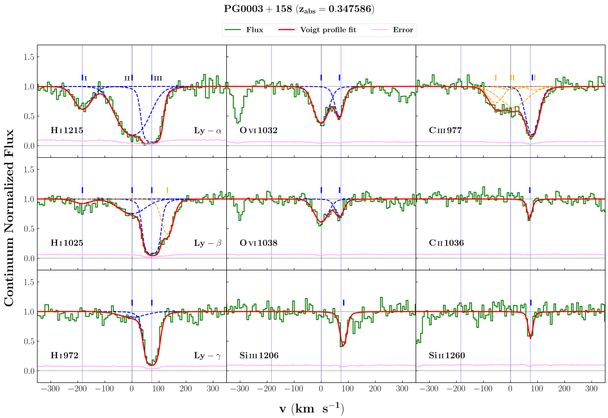

Figure 3: System plot of the absorber system towards PG 0003+158. Velocity is taken zero at z = 0.347586

Recap

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

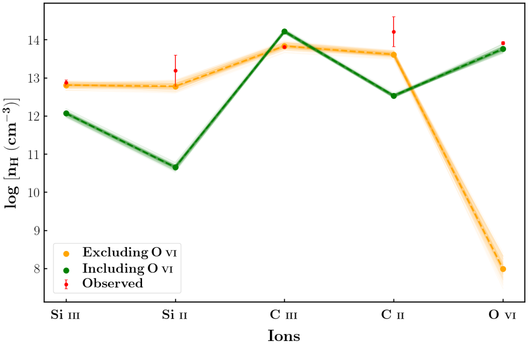

Figure 4: Photoionization modelling of component-III in absorber towards PG 0003+158

Recap

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

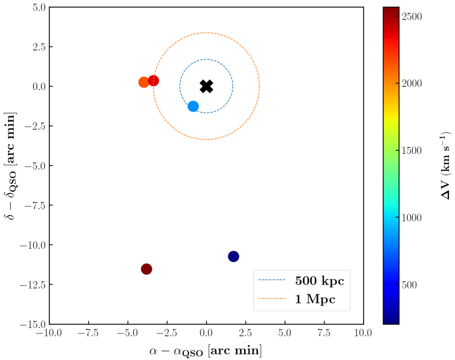

Figure 5: Galaxy neighbourhood of absorber towards PG 0003+158

Recap

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

Ref. : Danforth et al. (2016)

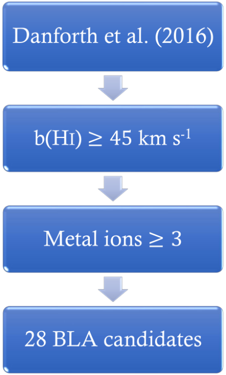

Figure 6: Shortlisting the BLA candidates for survey

The BLA Survey

Some numbers

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

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

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- 22 sight lines : $\Delta z_{\mathrm{Ly}\alpha} = 5.561$
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- **Ionisation modelling** : 39 components

Voigt profile fitting

Absorption species

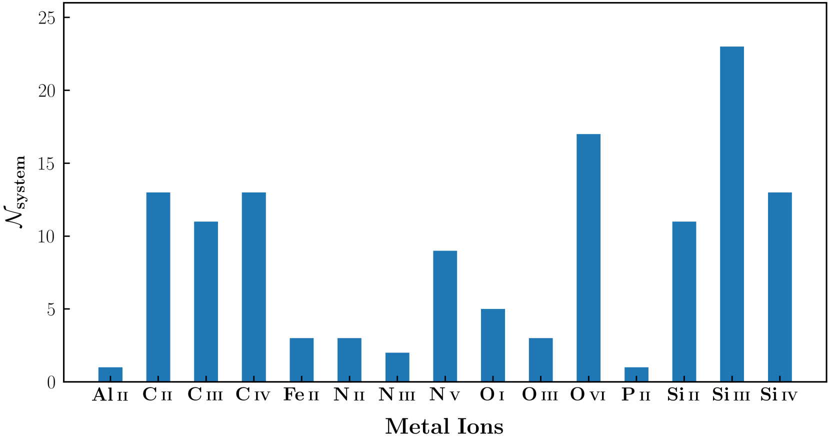

Figure 7: Distribution of metal species in 29 BLA candidates

Absorption species

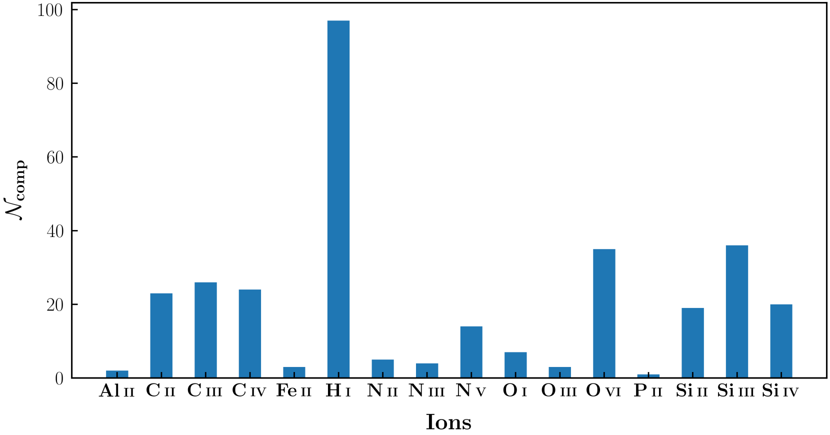

Figure 8: Distribution of components of absorption species in 29 BLA candidates

N(H I) and b(H I)

N(H I) and *b*(H I)

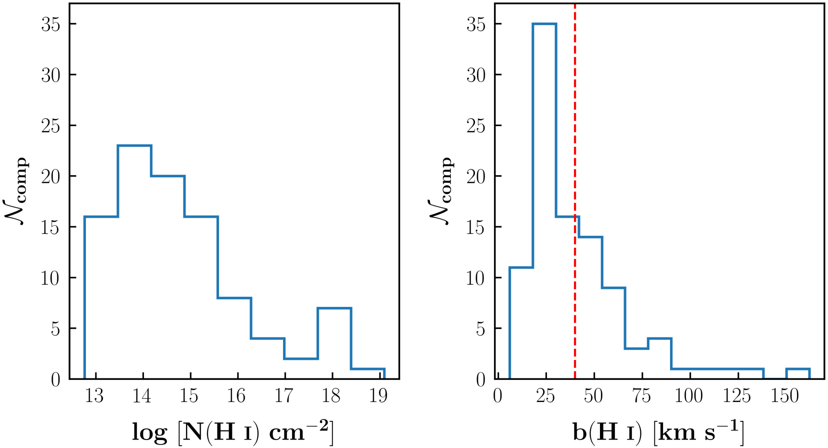

Figure 9: Distribution of column densities and Doppler widths of 97 H I components

N(H I) and *b*(H I)

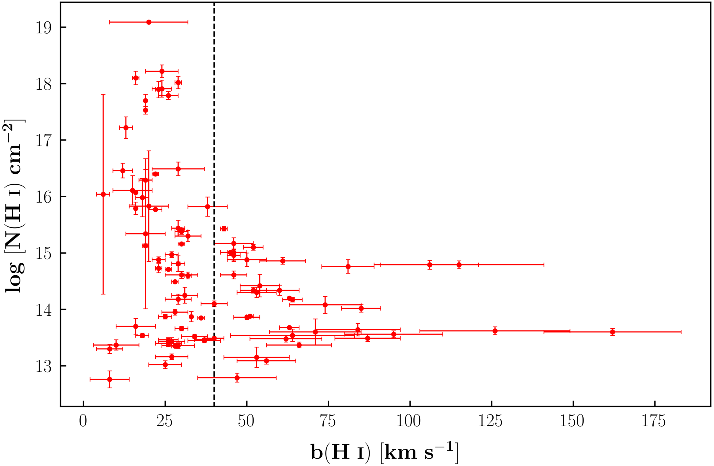

Figure 10: H I column density v/s Doppler width for 97 H I components

Ionisation Modelling

Method

Method

- **Grid of PI CLOUDY models : Density and Metallicity**

Ref. : Acharya and Khaire (2021)

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- log (n_H/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/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

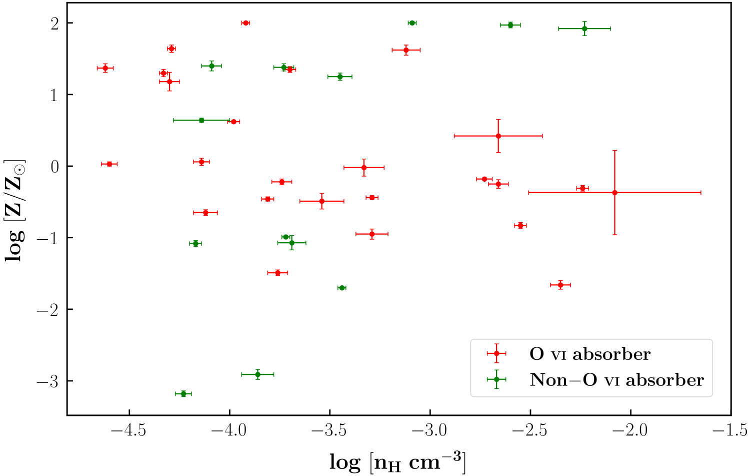

Figure 11: Ionisation modelling solutions (n_H, Z) for all 39 components.

+ve correlation

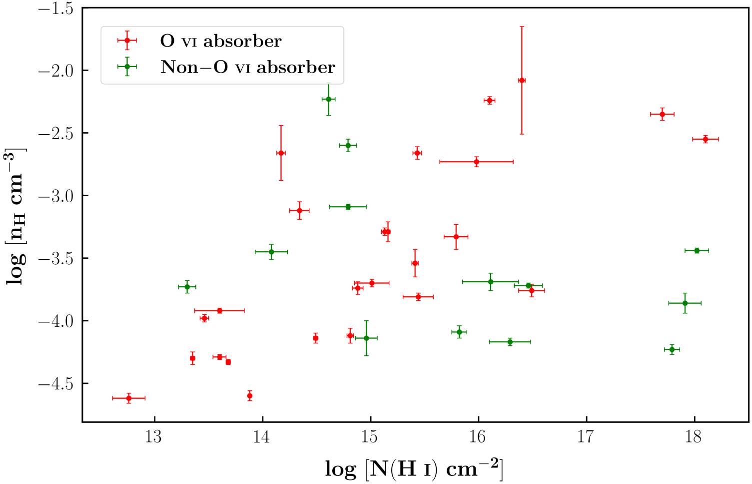

Figure 12: Variation of n_H with N(H I)

-ve correlation

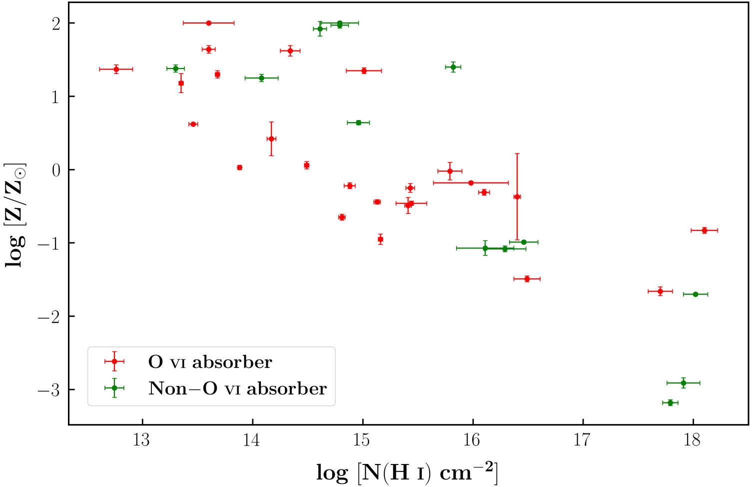

Figure 13: Variation of Z with N(H I)

Origin of O VI

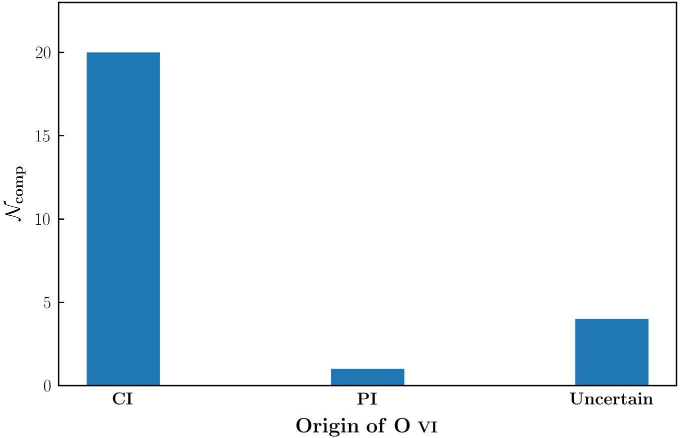

Figure 14: Ionisation state of O VI inferred from ionisation modelling

Ex : CI

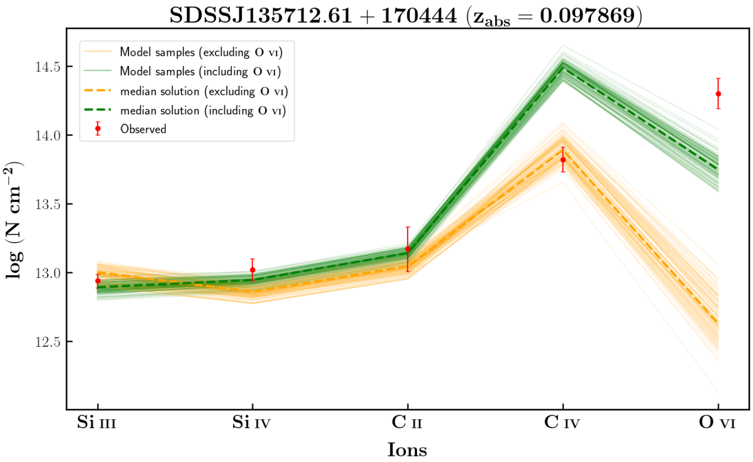

Figure 15: log N(H I) [cm^{-2}]=16.49

Ex : PI

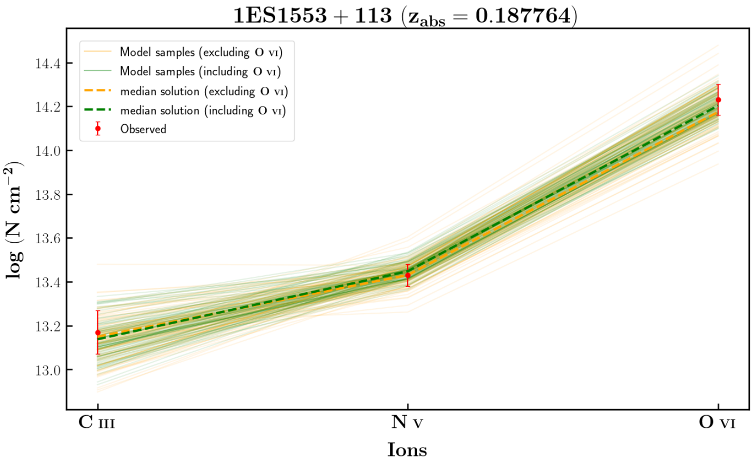

Figure 16: log N(H I) [cm^{-2}]=12.76

Ex : Uncertain

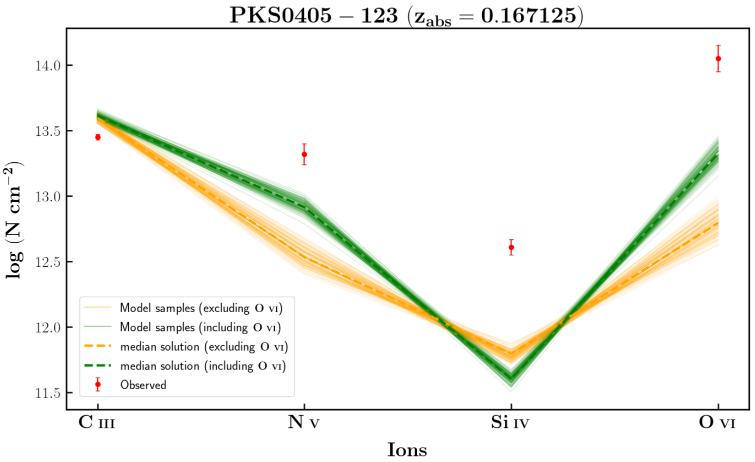

Figure 17: log N(H I) [cm^{-2}]=13.46

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

Method

Method

$$\Omega_{\text{ion}} = \frac{H_0 m_{\text{ion}}}{c\rho_{\text{cr}}} \int \frac{\partial^2 \mathcal{N}}{\partial N \partial X} N dN$$

(Becker et al. 2011)

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(Becker et al. 2011)

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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$$X(z) = \int_0^z (1+z')^2 \frac{H_0}{H(z')} dz'$$

(Bahcall & Peebles 1969)

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

Method

Method

$$\Omega_{\mathrm{b}}(\mathrm{BLA}) = \frac{H_0\ \mu m_H}{c\rho_{\mathrm{cr}}} \sum_{i,j} N(H)_{i,j} \bigg/ \sum_j \Delta X_j$$

Method

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

$$\Rightarrow \Omega_b(\mathrm{BLA}) = \frac{H_0\ \mu m_H}{c\rho_{\mathrm{cr}}} \sum_{i,j} f_{H_{i,j}} N(\mathrm{H\,I})_{i,j} \Bigg/ \sum_j \Delta X_j$$

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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 ($< 10^{-5}$ cm^{-3})**

Ref. : Richter et al. (2006)

Selecting the BLA sample

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- **Sample A**
- **Sample B**
- **Sample C**

Selecting the BLA sample

- **Sample A** : T > 10^5 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
- **Sample B**
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Selecting the BLA sample

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- **Sample C**

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- **Sample C** : All

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  - 5 components
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  - 20 components
- **Sample C** : All
  - 39 components

Ω_b(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	Ω_b(BLA) ($\times 10^{-3}\, {h_{70}}^{-1}$)	Ω_b(BLA)/Ω_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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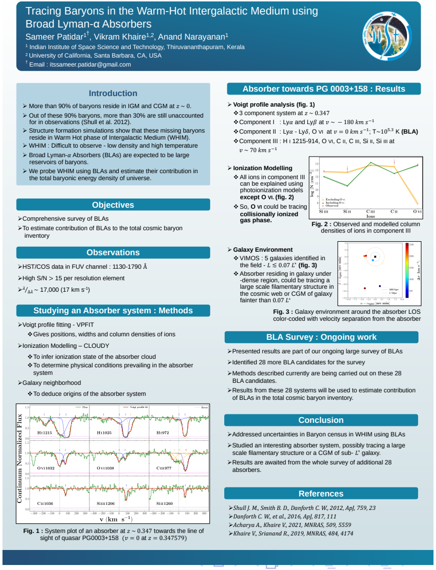
- Poster presentation at ASI-2024 meet titled "**Tracing Baryons in WHIM using BLAs**" [1]



[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) Preprint 21 May 2024 Compiled using MNRAS LaTeX style file v3.0

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

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[2] *Physics Department, Broida Hall, University of California Santa Barbara, Santa Barbara 93106-9530, CA , USA*
[3] *Centre for Extragalactic Astronomy, Department of Physics, Durham University, South Road, Durham DH1 3LE, UK*
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Accepted XXX. Received YYY; in original form ZZZ

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 ($z_{em} = 0.4509$) 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 $\sim 10^{5.3}$ 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

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अंतःअस्ति प्रारंभः

(The End is the Beginning)

Additional slides

b(O VI) vs. b(H I)

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

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

$$\mathrm{T} = \frac{8m}{15k}\left({b^2}_{\mathrm{H\,I}} - {b^2}_{\mathrm{O\,VI}}\right)$$

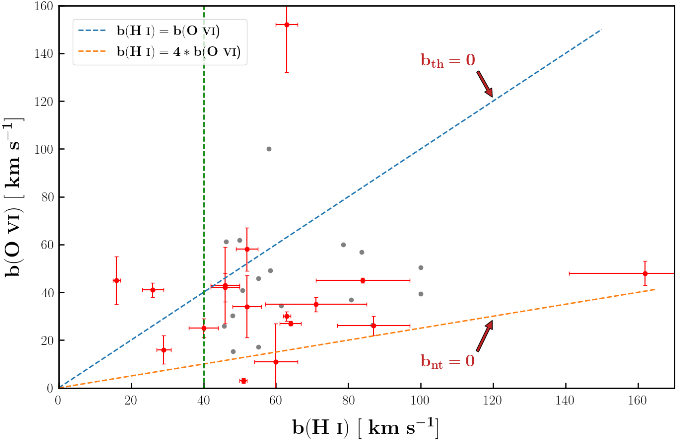

Figure 18: b(O VI) vs. b(H I). Grey filled circles are measurements from Danforth et al. (2016).

- Outlier b(O VI)

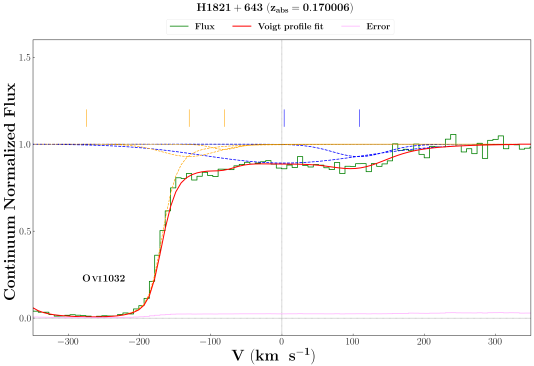

Figure 19: Voigt profile fit of O VI 1032 line in absorber system towards H1821+643 at $z_{abs} = 0.170006$