

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

Mid-Term 2

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Thesis Phase I : Recap

Recap

- ▶ The missing baryon problem
- ▶ BLAs : Way to probe WHIM
- ▶ Absorber towards PG 0003+158
- ▶ BLA survey : 28 BLA candidates

Ref. : Shull et al. (2012)

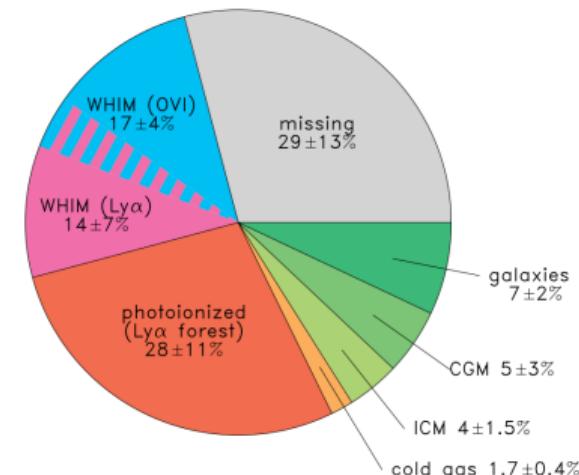


Figure 1: Baryon budget at $z \sim 0$.
Shull et al. (2012)

Recap

- ▶ The missing baryon problem
- ▶ **BLAs : Way to probe WHIM**
- ▶ Absorber towards PG 0003+158
- ▶ BLA survey : 28 BLA candidates

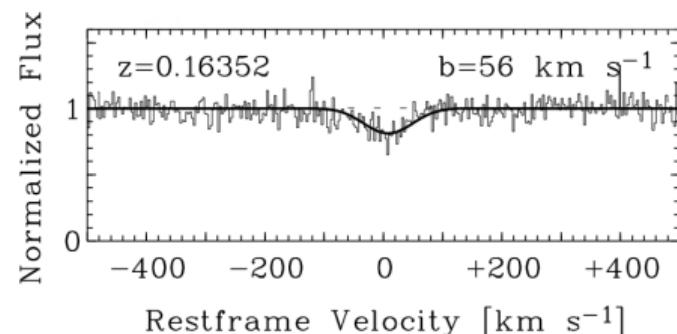


Figure 2: A BLA towards the LOS of quasar H 1821+643.
Philipp Richter (2005)

Ref. : Shull et al. (2012)

Recap

- ▶ The missing baryon problem
- ▶ BLAs : Way to probe WHIM
- ▶ **Absorber towards PG 0003+158**
- ▶ BLA survey : 28 BLA candidates

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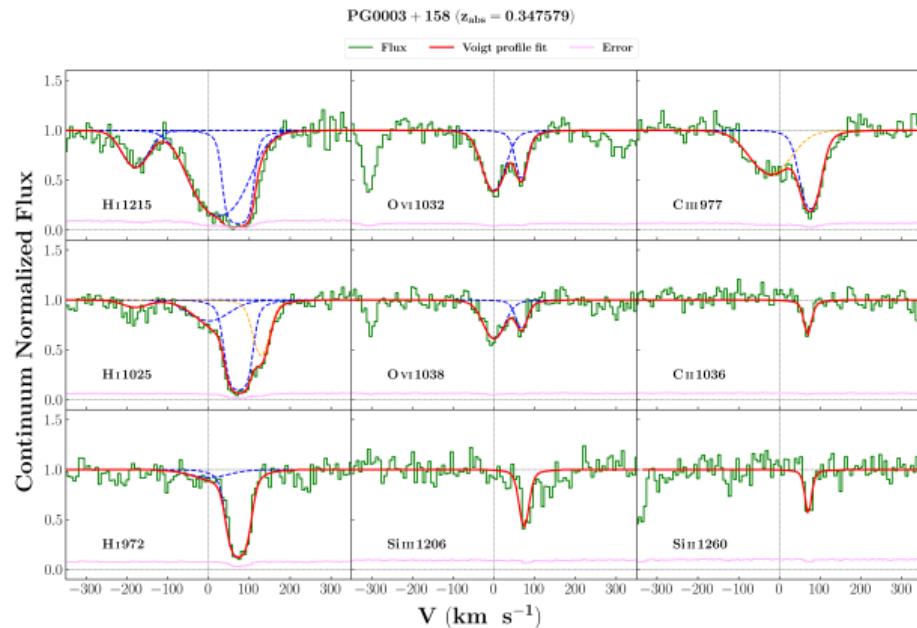


Figure 3: System plot of the absorber system towards PG 0003+158. Velocity is taken zero at $z = 0.347579$

Recap

- ▶ The missing baryon problem
- ▶ BLAs : Way to probe WHIM
- ▶ Absorber towards PG 0003+158
- ▶ **BLA survey : 28 BLA candidates**

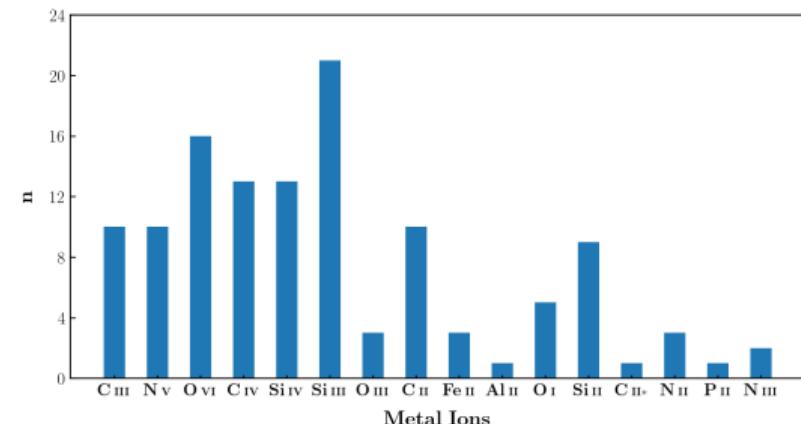


Figure 4: Distribution of metal ions in all 28 candidate BLAs

Ref. : Shull et al. (2012)
Danforth et al. (2016)

The BLA Survey

Survey so far...

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- ▶ Voigt profile fitting : 16 (O VI) + 6

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- ▶ Ionisation Modelling : **16 (O VI)**

Insights

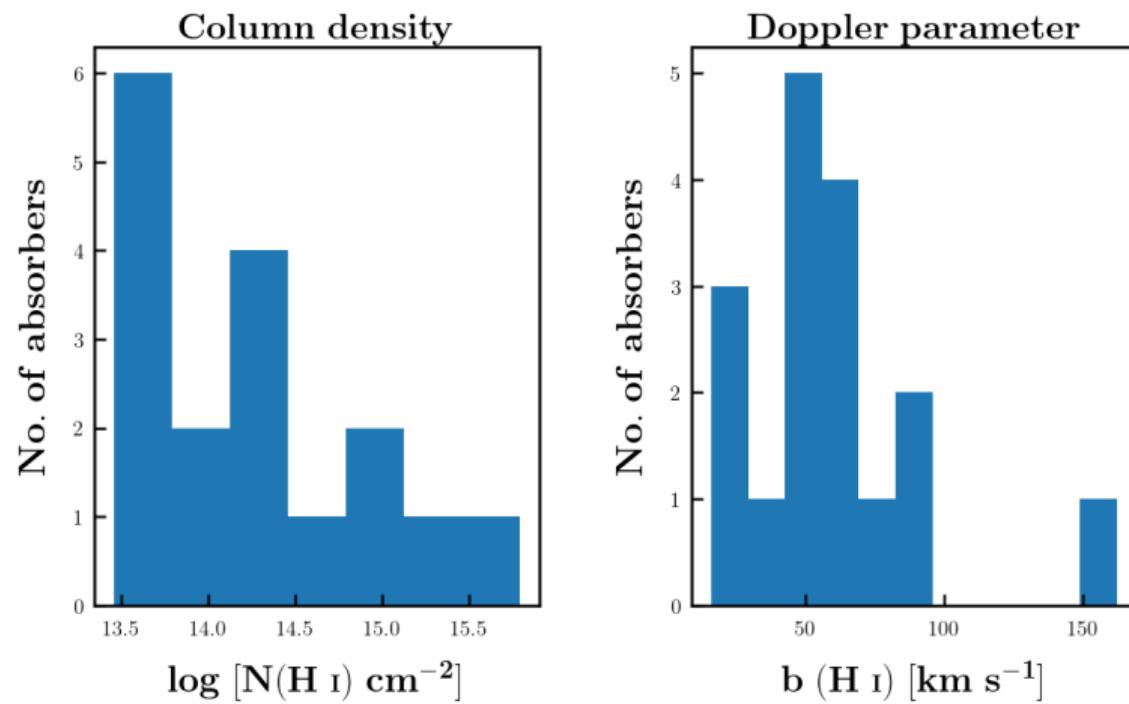


Figure 5: Distribution of HI column densities and Doppler parameters.

Insights

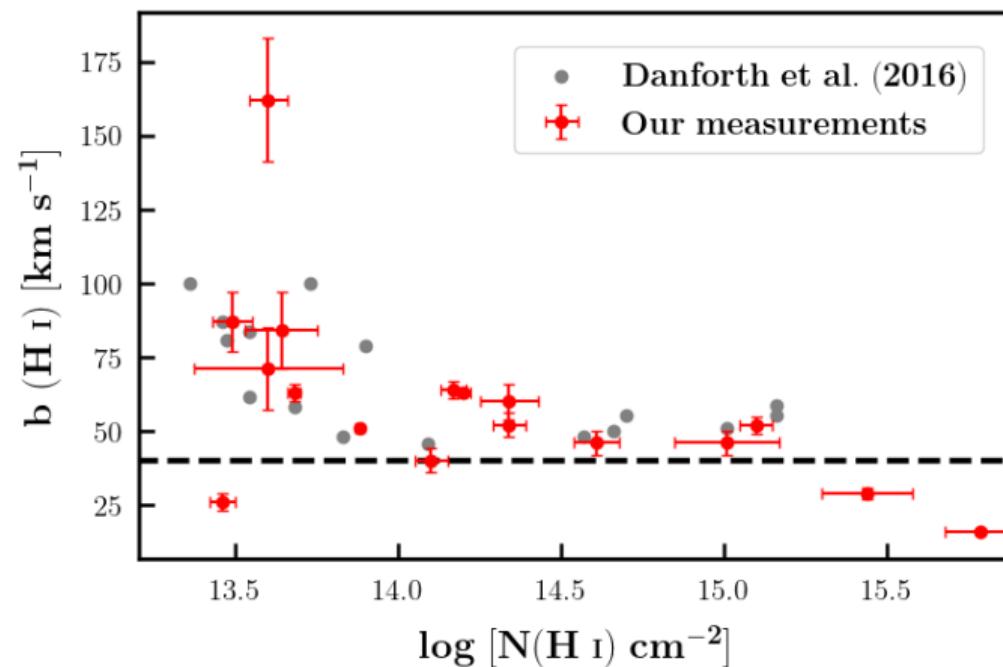


Figure 6: HI column density vs. Doppler parameter

Insights

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

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

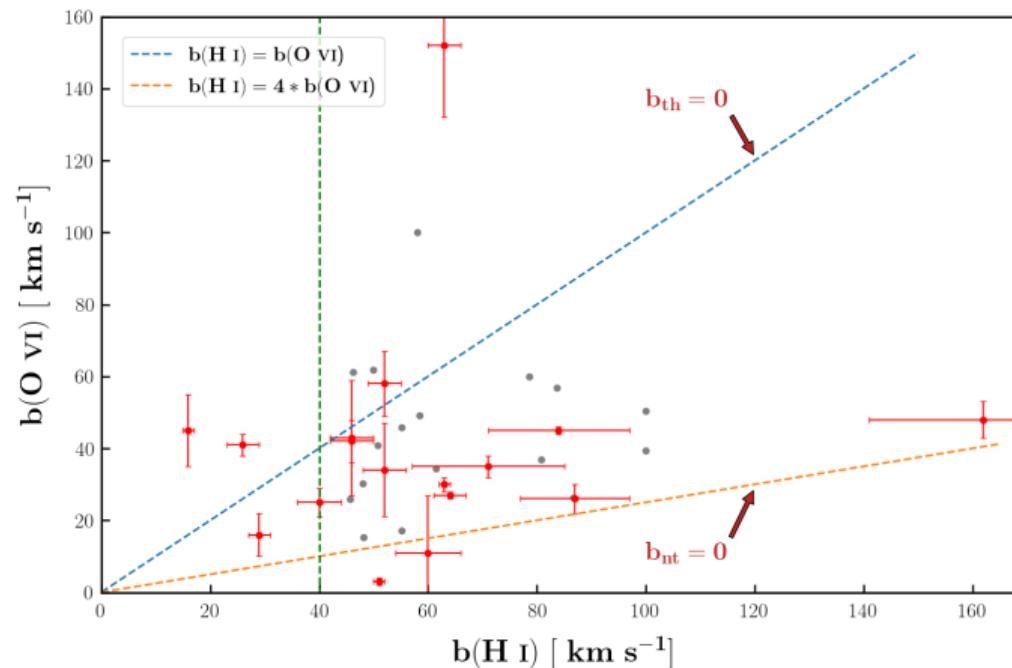


Figure 7: $b(\text{O VI})$ vs. $b(\text{H I})$. Grey filled circles are measurements from Danforth et al. (2016).

Insights

$$T = \frac{8m}{15k} (b_{\text{H}\alpha}^2 - b_{\text{OVI}}^2)$$

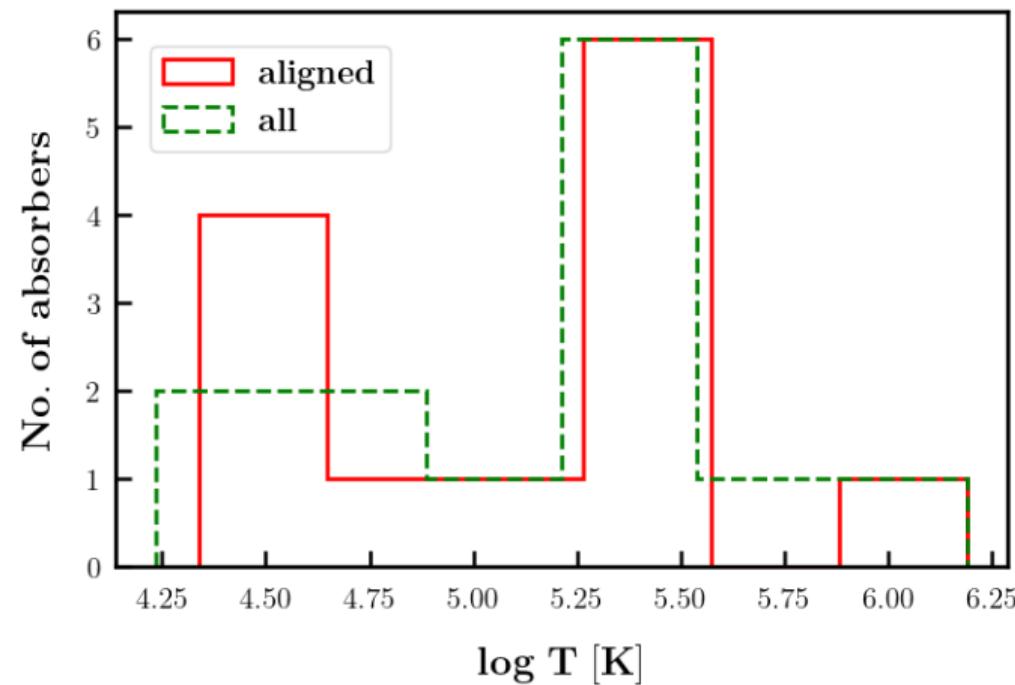


Figure 8: Distribution of temperature calculated from Doppler parameters of H_I and O_{VI} lines.

Ionisation Modelling

Method

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- ▶ Grid of PI CLOUDY models : Density and Metallicity

Ref. : Acharya and Khaire (2021)

Method

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

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Method

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- ▶ $\log(n_{\text{H}}/\text{cm}^{-3})$: -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
- ▶ $\log(n_{\text{H}}/\text{cm}^{-3})$: -5 to 1 in steps of 0.02
- ▶ $\log(Z/Z_{\odot})$: -3 to 2 in steps of 0.05
- ▶ Solution : Model that best predicts the observed column densities

Ref. : Acharya and Khaire (2021)

Results

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- ▶ 26 components

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- ▶ 26 components
- ▶ Origin of O VI

Solutions

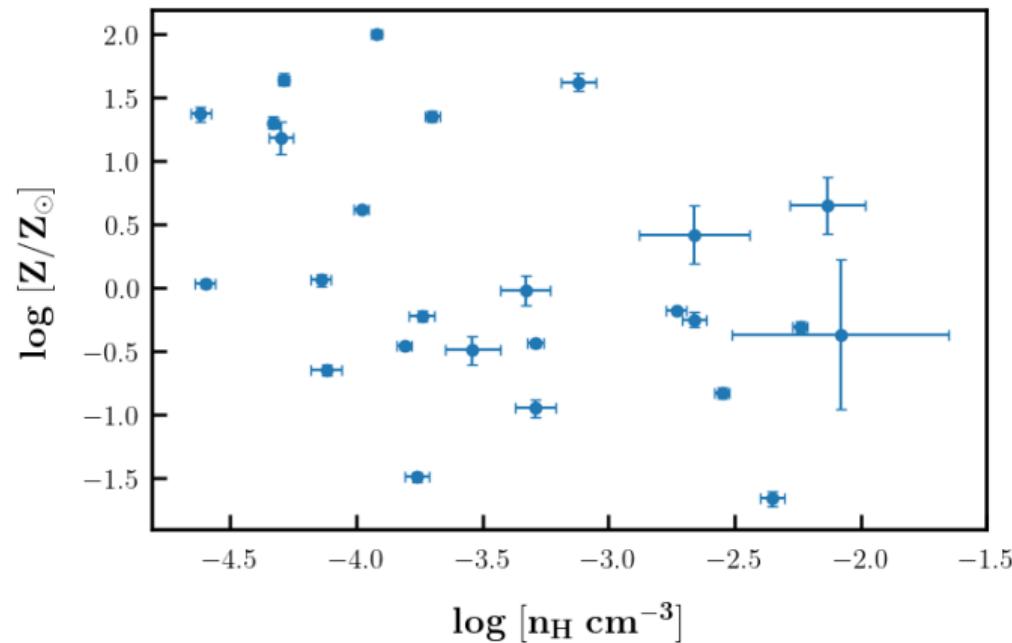


Figure 9: Ionisation modelling solutions (n_H , Z) for all 26 components.

+ve correlation

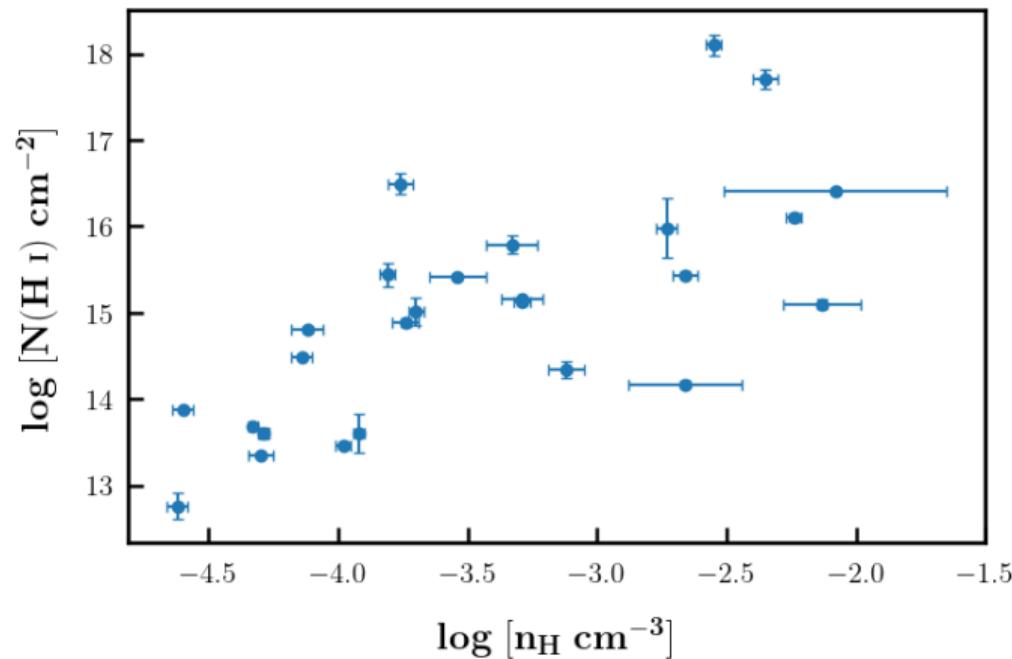


Figure 10: Variation of $N(\text{HI})$ with n_{H}

O VI cases

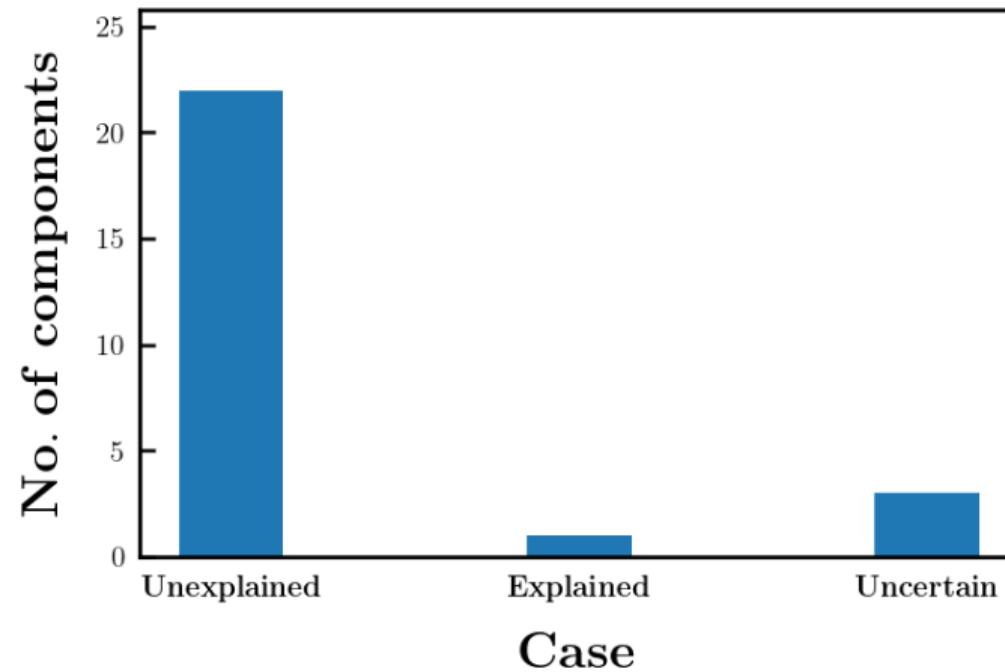


Figure 11: O VI column density predictions.

Ex : Unexplained

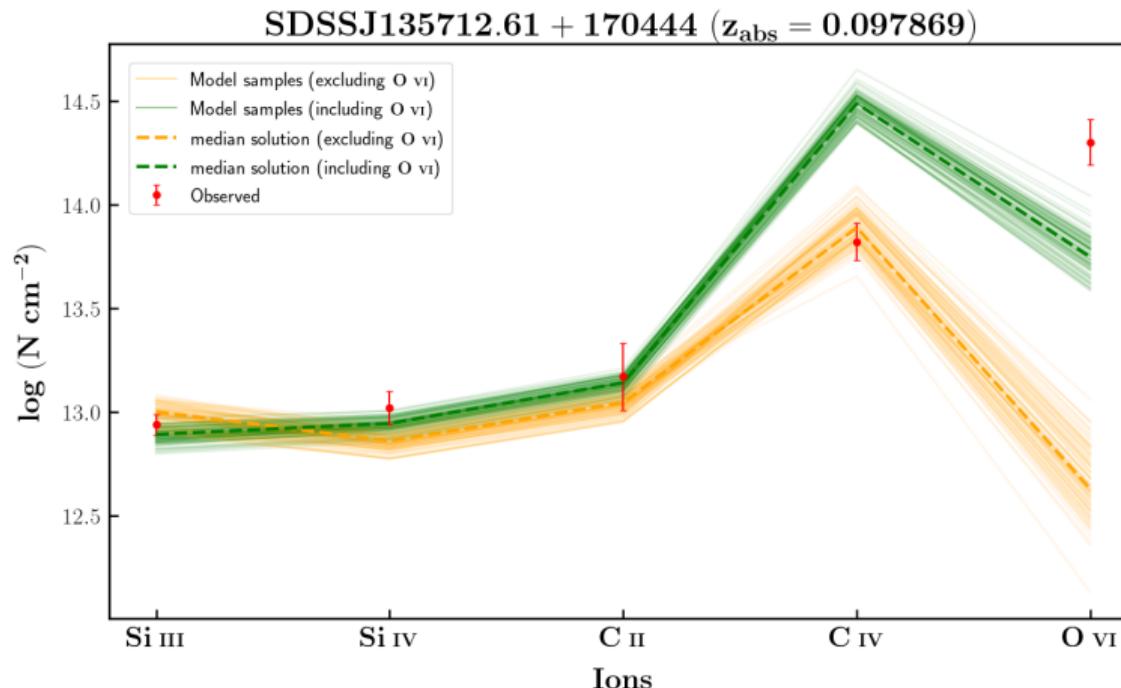


Figure 12: $N(\text{H I})=16.49 \text{ cm}^{-2}$

Ex : Explained

1ES1553 + 113 ($z_{\text{abs}} = 0.187764$)

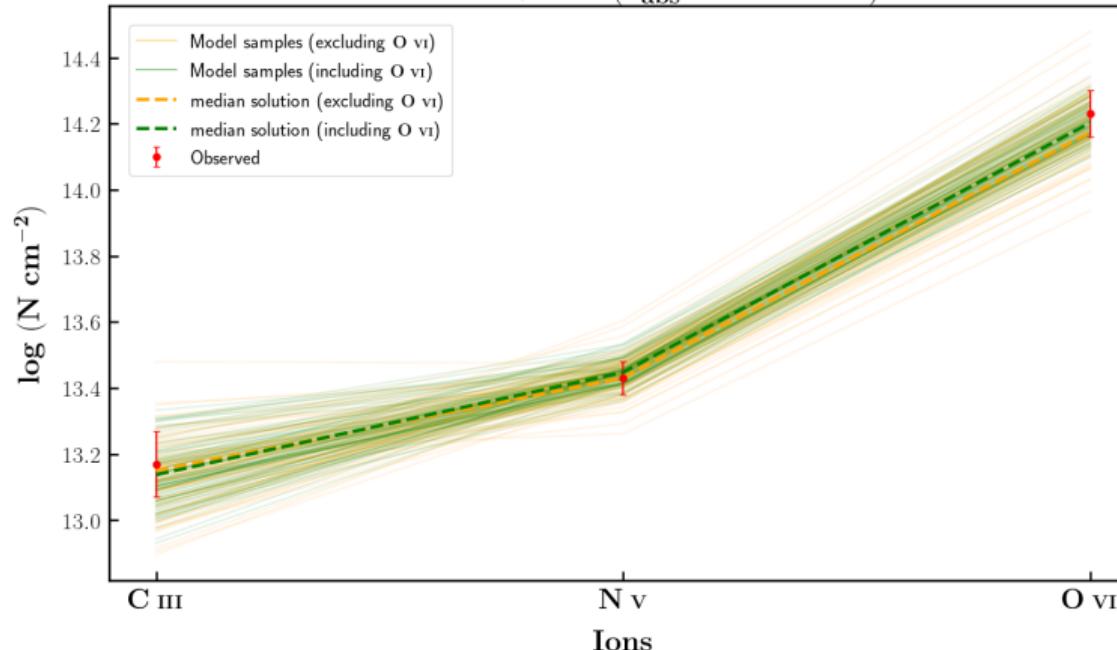


Figure 13: $N(\text{H I})=12.76 \text{ cm}^{-2}$

Ex : Uncertain

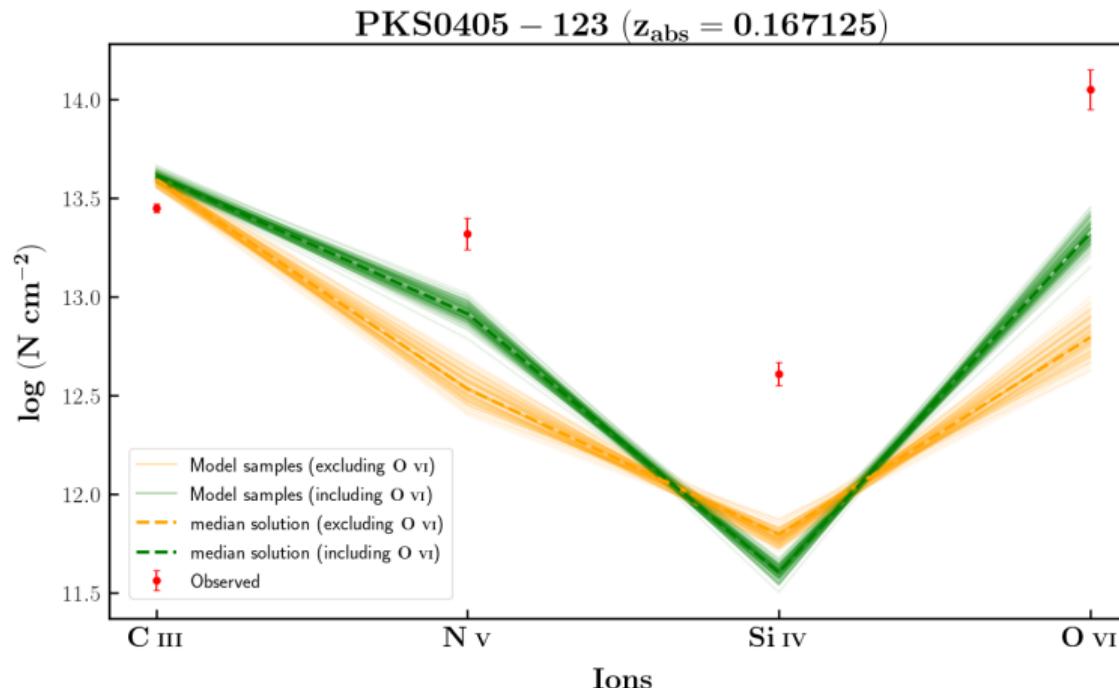


Figure 14: $N(\text{H I})=13.46 \text{ cm}^{-2}$

Towards *the end*

Ongoing and Future Work

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- ▶ Voigt profile fitting : 6

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- ▶ Voigt profile fitting : 6
- ▶ Ionisation modelling : 12
- ▶ Exploring the survey results
- ▶ *Finally, calculating $\Omega_b(BLA)$*

Outcomes

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

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

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Introduction

- More than 90% of baryons reside in iGM and CGM at $z \sim 0$.
- Out of these 90%, about 30% are still unaccounted for in observations (Shull et al. 2012).
- Structure formation simulations show 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 : 1130-1700 Å
- High S/N > 15 per resolution element
- $\lambda_{\text{Ly}\alpha} = 17,000$ (17 km s $^{-1}$)

Studying an Absorber system : Methods

- Voigt profile fitting - VPFIT
 - Gives positions, widths and column densities of ions
- Ionization Modeling - 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

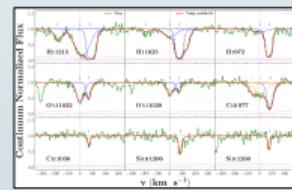


Fig. 1 : System plot of an absorber at $z = 0.347$ towards the line of sight of quasar PG0003+158 ($v = 0$ at $z = 0.347579$)

Absorber towards PG 0003+158 : Results

- Voigt profile analysis (Fig. 1)
 - 3 component system at $z = 0.347$
 - Component I : Ly α and Ly β at $v = -180$ km s $^{-1}$
 - Component II : Ly α - Ly β , O VI at $v = 0$ km s $^{-1}$, T = 10 $^{8.2}$ 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 are explained using photoionization models except O VI (Fig. 2)
- So, O VI could be tracing collisionally ionized gas phase.

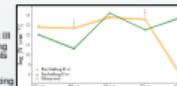


Fig. 2 : Observed and modelled column densities of ions in component III

Galaxy Environment

- VIMOS - 5 galaxies identified in the field - $L \leq 0.07 L^*$ (Fig. 3)
- Absorber residing in galaxy under consideration - suggesting traces of large scale filamentary structures in the cosmic web or CGM of galaxy fainter than $0.07 L^*$

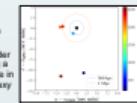


Fig. 3 : Galaxy environment around the absorber LOS color-coded with velocity separation from the absorber

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., Denforth C. W., 2012, ApJ, 759, 23
- Denforth C. W., et al., 2016, ApJ, 817, 111
- Acharya A., Khaire V., 2021, MNRAS, 509, 5559
- Khaire V., Srikanth R., 2019, MNRAS, 484, 4179

Summary

- ▶ Voigt profile fitting : 22 absorbers - 231 Voigt profiles
- ▶ Ionisation modelling : 16 absorbers - 26 components
- ▶ O VI couldn't be explained with photoionization models
- ▶ BLA survey towards completion

References

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

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Lehner N., Savage B. D., Richter P., Sembach K. R., Tripp T. M., Wakker B. P., 2007, ApJ, 658, 680

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So much universe, and so little time...

Appendix

- ▶ Outlier b(O VI)

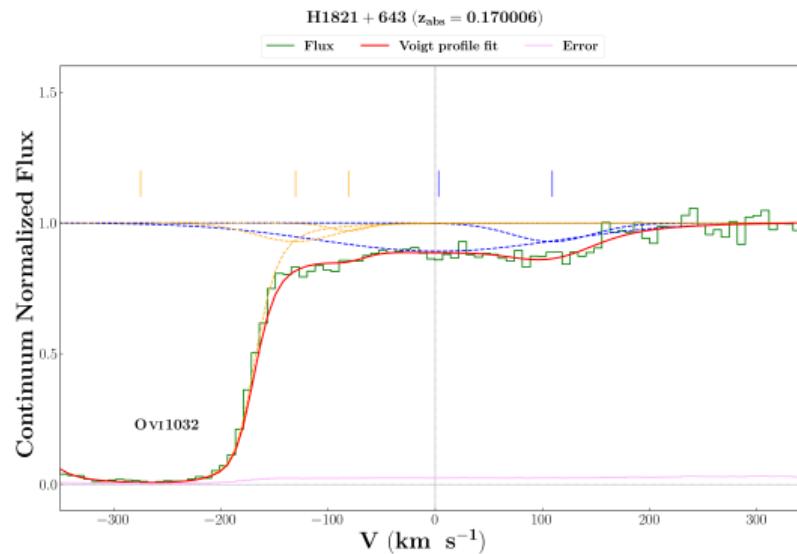


Figure 15: Voigt profile fit of O VI 1032 line in absorber system towards H1821+643 at $z_{abs} = 0.170006$