CAN WE DETECT THE CHEMICAL SIGNATURE OF POP III STARS AT $z\sim6$? A VIEW FROM THE XQR-30 SURVEY

Alessio Sodini

INAF – Osservatorio Astronomico di Trieste

Valentina D’Odorico, Guido Cupani, Stefania Salvadori, Irene Vanni, Manuela Bischetti, Rebecca Davies and the XQR-30 collaboration.

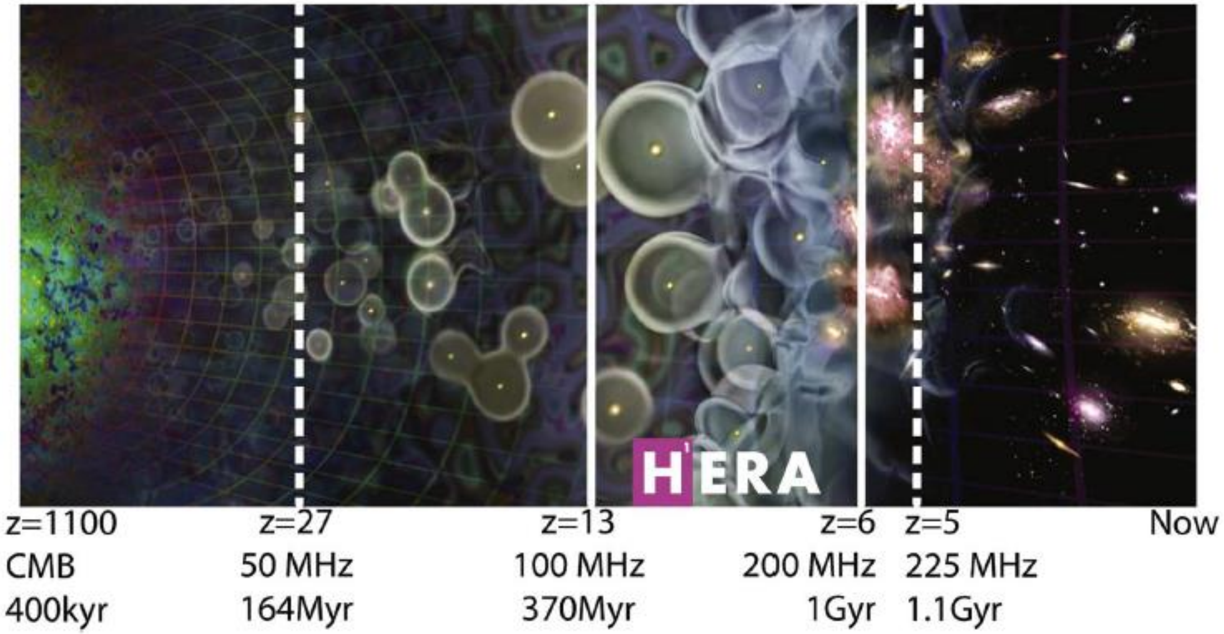
INTRODUCTION

Study of the abundances of the elements present in the gas associated with cosmological structures at redshift $z{\sim}6$, when the Universe was going through the final stages of the reionization epoch.

The objective of this study is:

- Look for the nucleosynthetic traces of the Pop III stars.
- Place constraints on the generations of stars that contributed to the enrichment of metals in the gas.

Depending on the mass and the stellar population, the characteristics of the final explosion are different and therefore the ratio of the chemical elements produced is different.



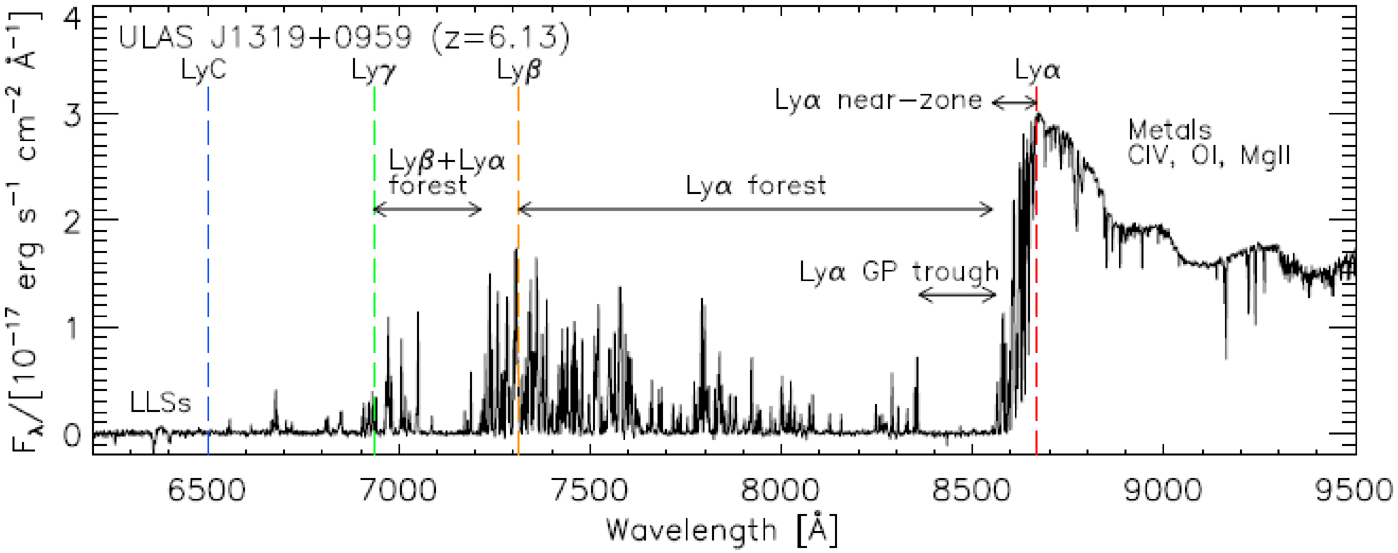
Cosmic evolution from recombination to today (De Boer et al. 2017).

QUASAR ABSORPTION SPECTRA

Elemental abundances can be measured by studying the absorption lines of metals observed in the spectra of high redshift quasars (QSOs).

- The radiation emitted by the QSOs passes through the IGM and the cosmological structures that are located along the line of sight.

- The atoms found in these structures create systems of absorption lines in the QSO spectra, which provide valuable information on their nature.



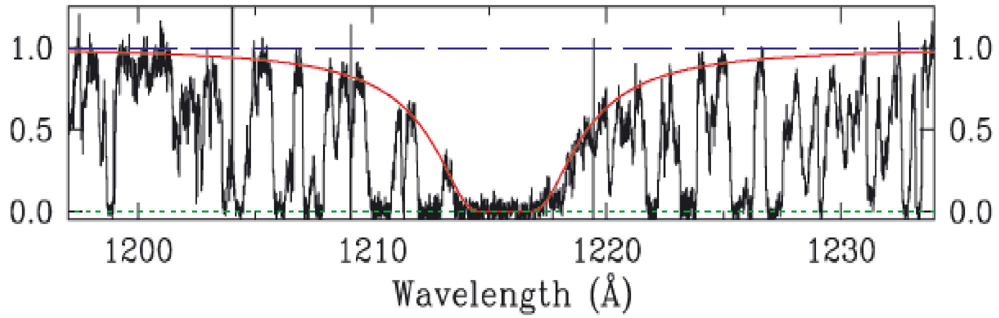
Spectrum of QSO ULAS J1319+0959 at redshift $z = 6.13$ (Becker, Bolton & Lidz 2015).

DAMPED LYMAN-α SYSTEM

Damped Lyman-α systems (DLAs) have a column density of neutral hydrogen (HI) $\log N_{HI} \geq 20.3$ and providing information on the ISM of galaxies lying along the line of sight of the QSOs.

The outer layer of hydrogen absorbs radiation with energy $\geq 13.6\ eV$, and shields the innermost gas, where:

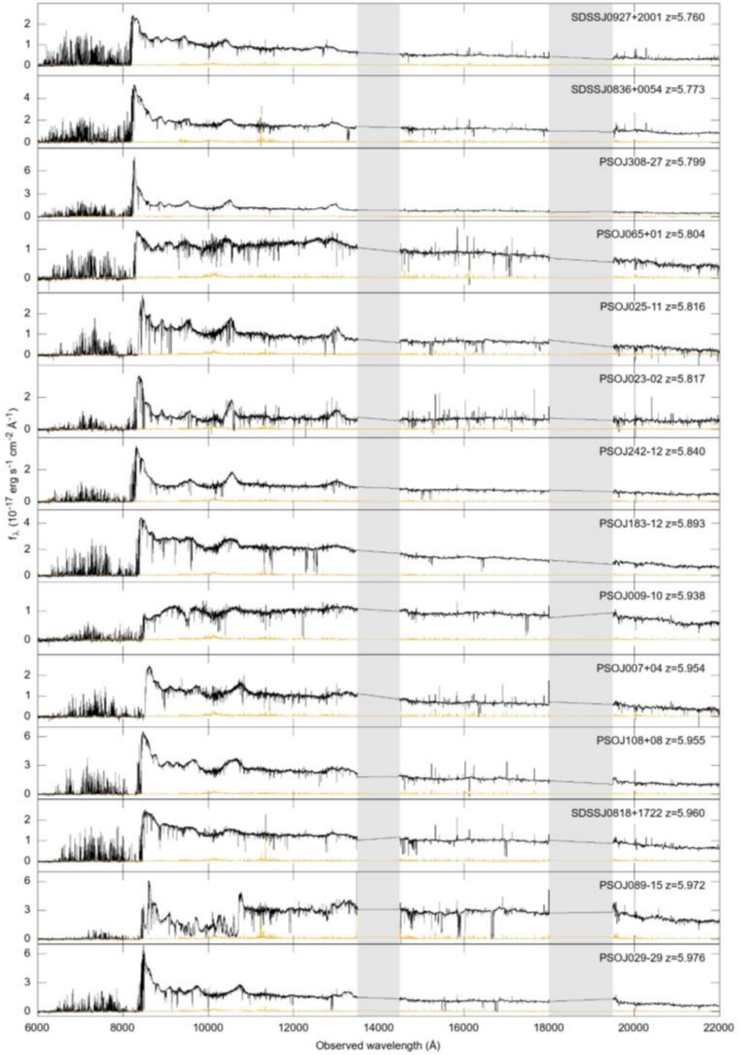
- Hydrogen is predominantly neutral (HI);
- Oxygen will be predominantly neutral (OI);
- Carbon, silicon, aluminum, iron and magnesium will be present in the single ionization state (CII, SiII, AlII, FeII, MgII).



Absorption line of HI in a DLA (Cooke et al. 2011b).

At high redshift ($z > 5$), the HI absorption line is hardly observable, and DLA systems (or sub-DLA $19 \leq \log N_{HI} < 20.3$) are **identified by the presence of OI**.

THE E-XQR-30 SAMPLE



D'Odorico et al. 2023

We analyzed absorption spectra of 42 high redshift QSOs from the XQR-30 observation program and literature.

- XQR-30 is the «acronym» of the observing program «XQR-30: the ultimate X-Shooter legacy survey of quasars at $z{\sim}5.8-6.6$ » (P.I. Valentina D'Odorico). This program obtained 248 hours of observations with the X-Shooter spectrograph of ESO's Very Large Telescope, to collect high signal-to-noise optical and infrared spectra of 30 bright QSOs in the redshift range $5.8 < z < 6.6$.

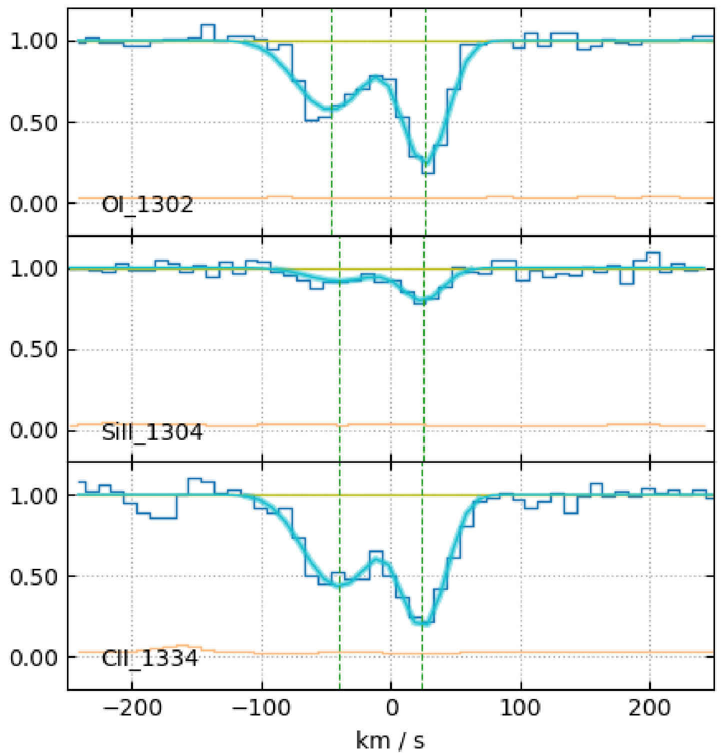
- The other 12 QSOs were obtained from the X-Shooter archive and have similar characteristics as XQR-30.

The total sample is dubbed the **Enlarged XQR-30** sample (E-XQR-30).

DATA ANALYSIS

We associated the absorption lines present in the QSO spectra with specific ion transitions, and then we performed the fits with Voigt profiles to determine:

- The absorption redshift z;
- The column density of the ion $N\ (cm^{-2})$;
- The Doppler parameter $b\ (km/s)$, i.e. the broadening of the line.

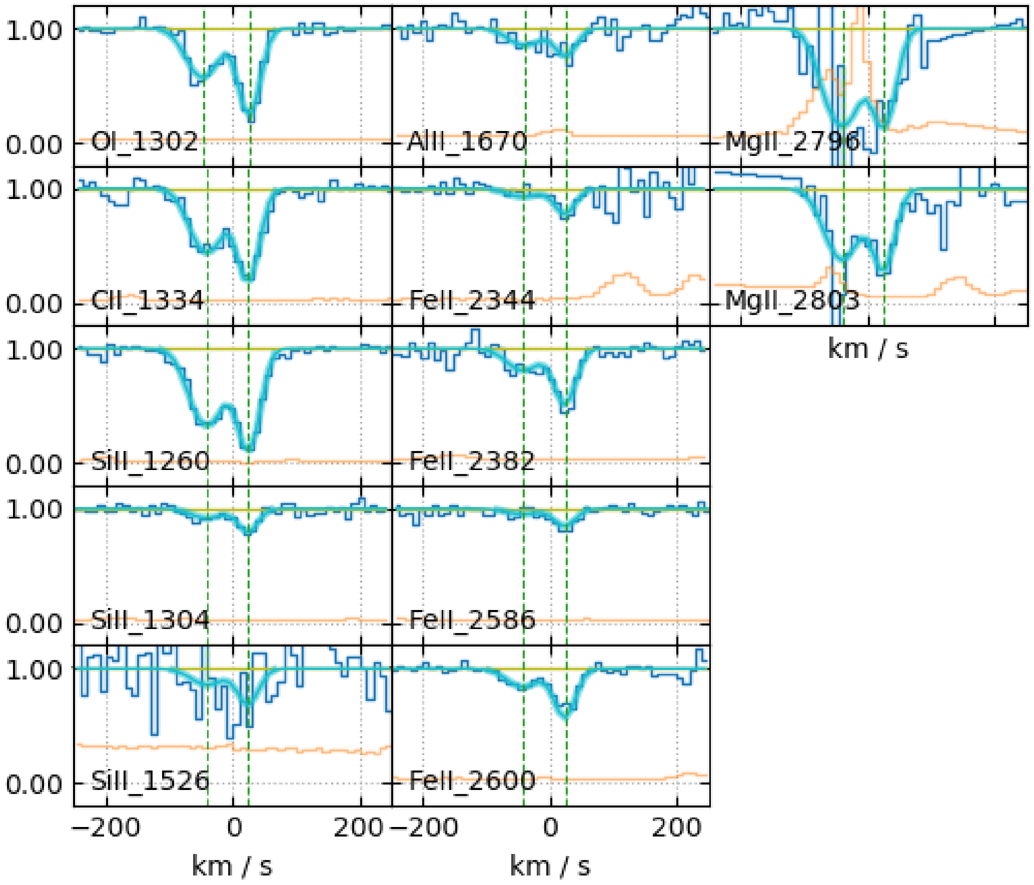


We identified low ionization systems, characterized by the presence of OI at 1302 Å, looking for a correspondence between the absorptions detected in the spectrum and the transitions due to OI at 1302 Å, SiII at 1304 Å and CII at 1334 Å present at the same redshift.

DATA ANALYSIS

We looked for the other lines associated with the identified low ionization systems, i.e. with the same absorption redshift:

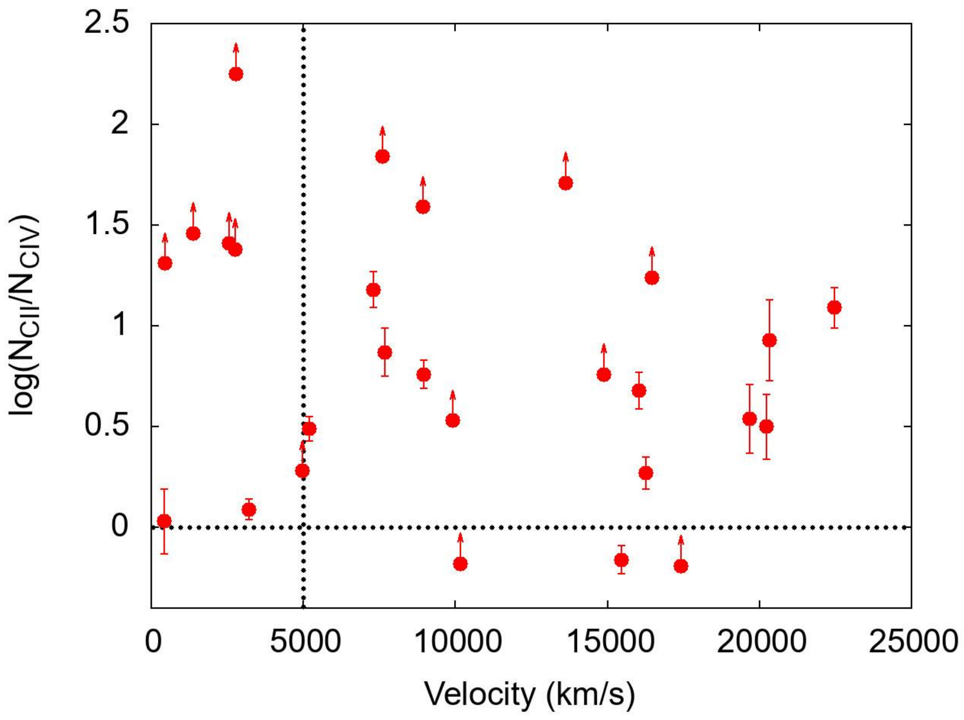
- The line of SiII at 1260 Å and at 1526 Å;
- The doublet of MgII at 2796 Å and at 2803 Å;
- The line of AlII at 1670 Å;
- The multiplet of FeII, whose strongest lines have a wavelength of 1608 Å, 2344 Å, 2374 Å, 2382 Å, 2586 Å e 2600 Å.
- The high ionization lines: the CIV doublet at 1548 Å and at 1550 Å, and the SiIV doublet at 1392 Å and at 1402 Å.



LOW IONIZATION SYSTEMS

Based on the separation in velocity from the QSO's emission redshift, we have distinguished two types of absorption systems:

- The systems «associated» to the QSO, called **proximate DLAs (PDLAs)**, which have $v < 5000\ km/s$;
- The **intervening DLAs**, which they have $v > 5000\ km/s$.



In the spectra of the 42 QSOs analyzed we found 27 low ionization systems, characterized by the presence of OI, along the line of sight of 18 QSOs:

- 8 are PDLAs;
- 19 are intervening DLAs.

We found no systematic differences in chemical abundances and ionization state measured in the PDLA and in the intervening DLA systems.

RELATIVE ABUNDANCES

Starting from the column density of the ions obtained from the fit of the absorption lines we calculated the relative abundances between two elements X and Y from the relation:

$$\left[\frac{X}{Y}\right] = \log\frac{N_X}{N_Y} - \log\frac{n_{X\odot}}{n_{Y\odot}}$$

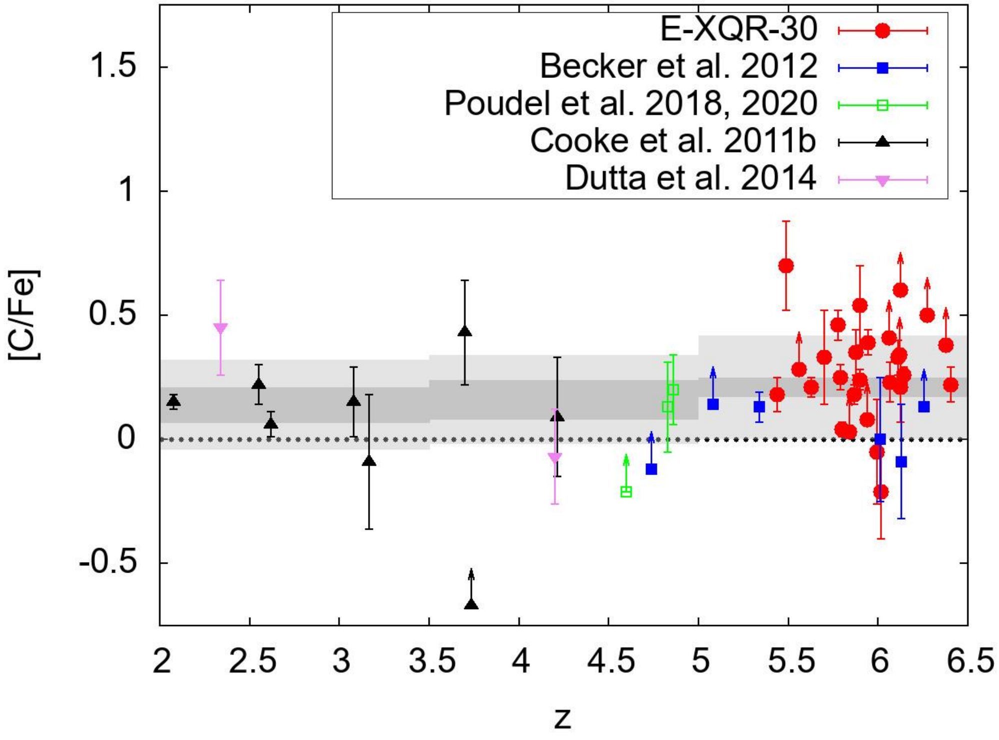
compared to the solar photospheric values of Asplund et al. 2009.

In this calculation we have neglected:

- The depletion of elements from the gas due to the formation of dust grains;
- The effects due to ionization.

COMPARISON WITH THE LITERATURE

We compared the relative abundances of the elements present in the low ionization systems identified with those of similar systems found in the literature at various redshift.

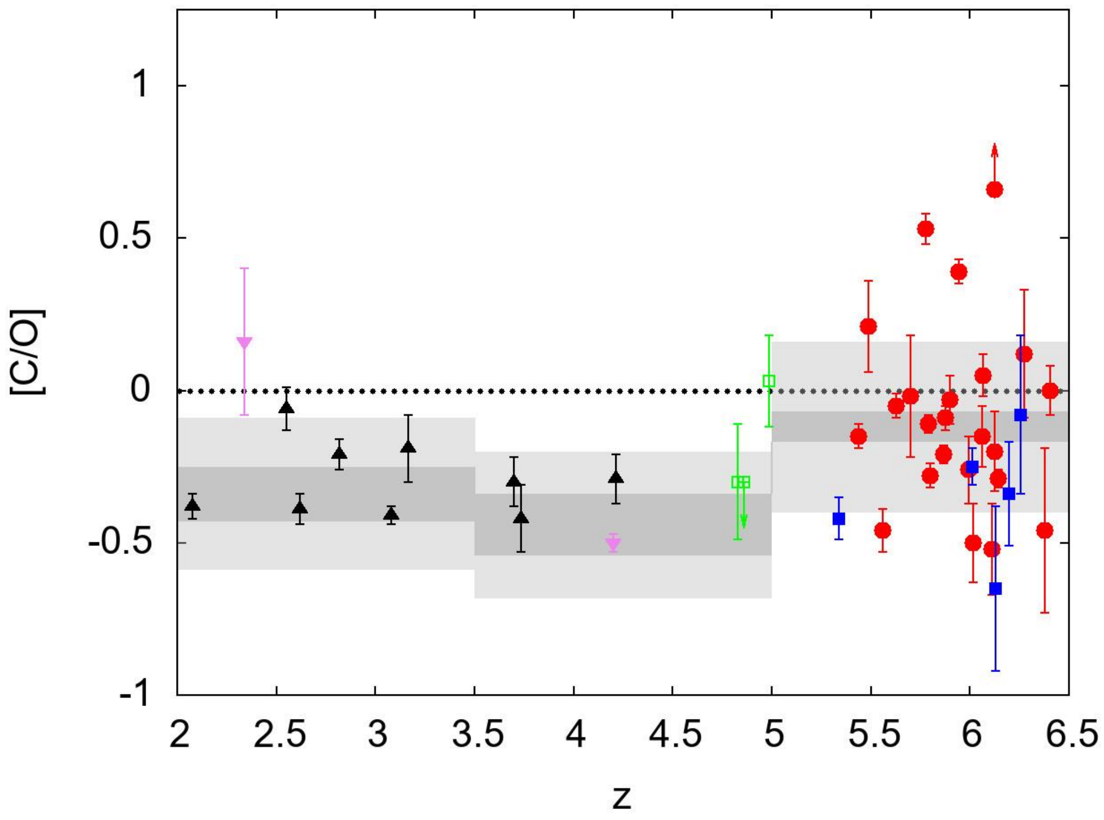


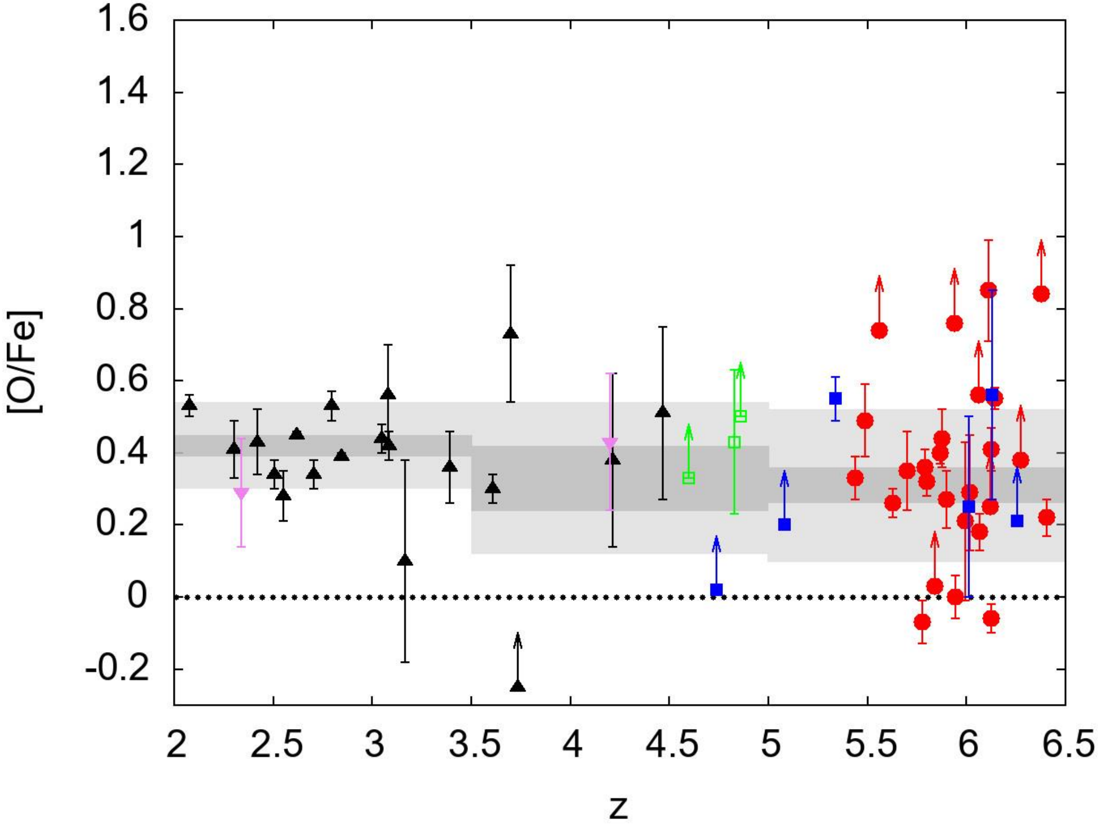
We have computed the average values of the measurements (excluding upper and lower limits) in three redshift intervals.

The abundances detected in the low redshift VMP-DLAs are in agreement with an enrichment due to type II SNe originating from stars with a metallicity up to $0.3Z_{\odot}$, with a possible contribution also from SNe of the same type coming from stars without metals (Cooke et al. 2011b).

COMPARISON WITH THE LITERATURE

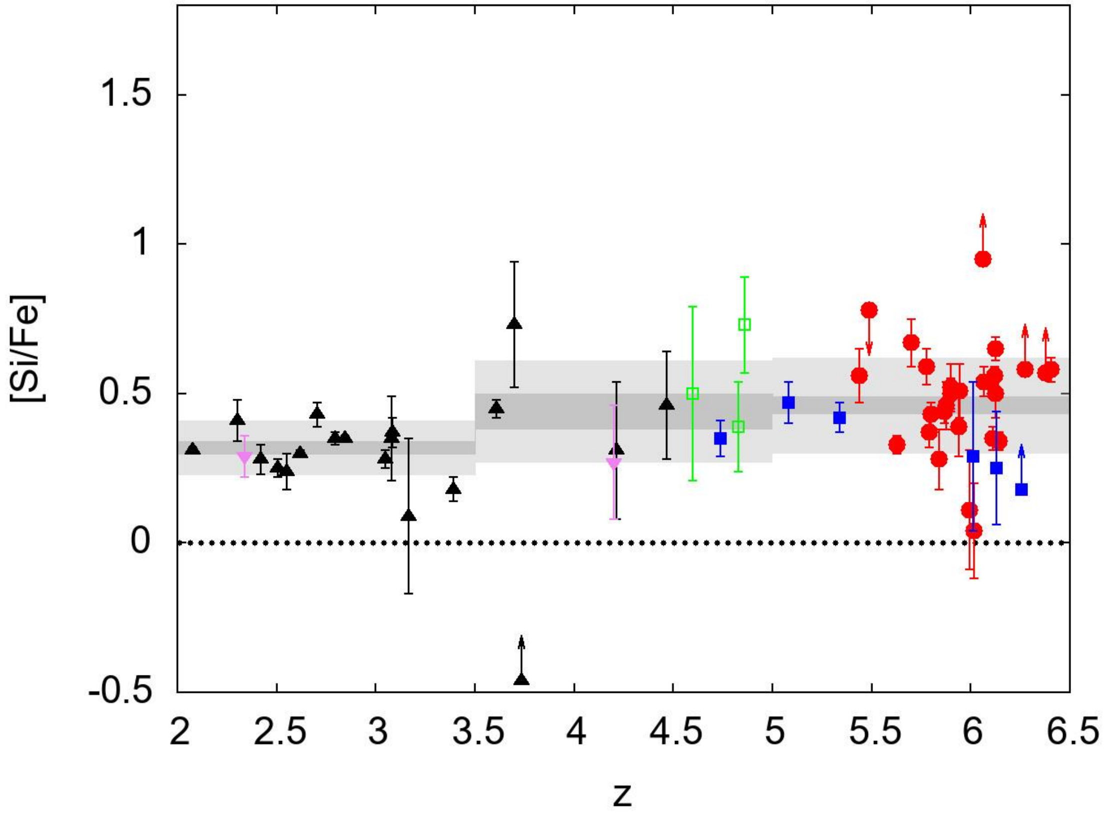
We compared the relative abundances of the elements present in the low ionization systems identified with those of similar systems found in the literature at various redshift.

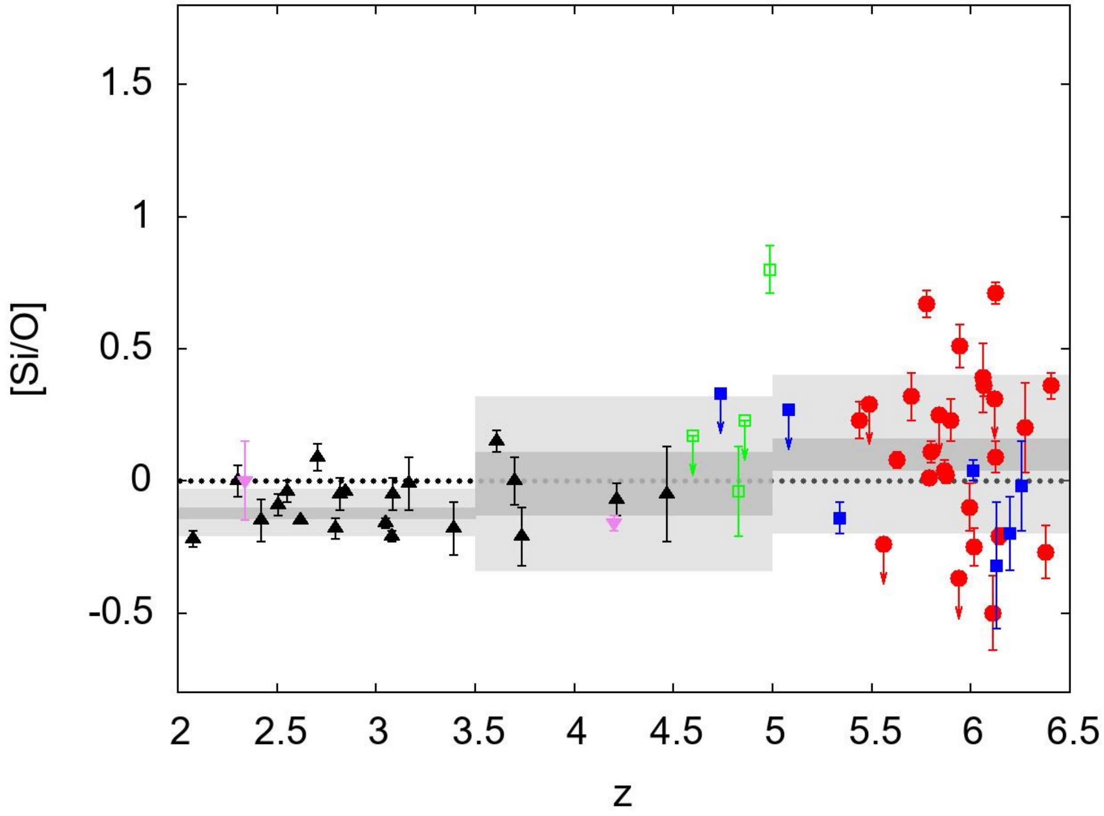




COMPARISON WITH THE LITERATURE

We compared the relative abundances of the elements present in the low ionization systems identified with those of similar systems found in the literature at various redshift.





ARE WE OBSERVING THE FIRST STARS' SIGNATURE?

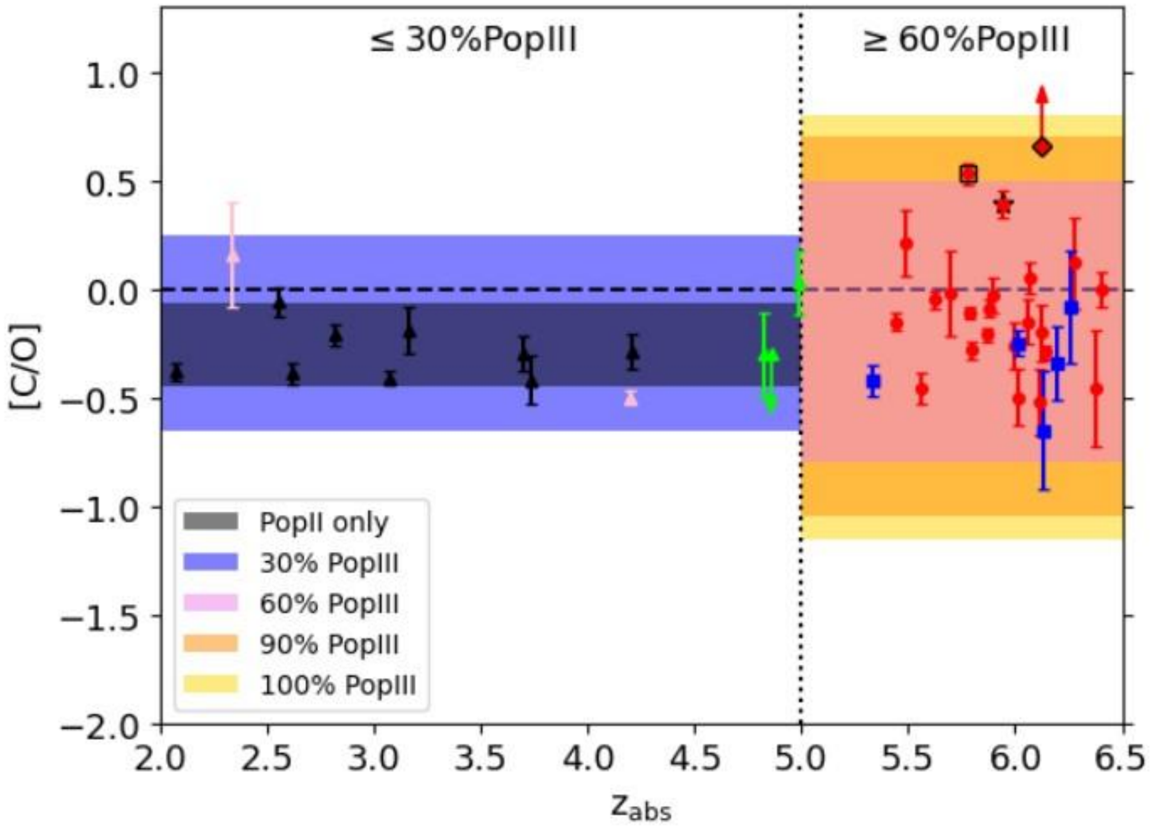
We compare the measured chemical abundance ratios with the ones predicted by the simple and general parametric study first developed by Salvadori et al. (2019) and recently refined by Vanni et al. (2023, and in prep.).

This model investigates the chemical abundance pattern of an ISM polluted by the first Pop III SNe with:

- Explosion energies $E = (0.3 - 100) \times 10^{51}\ erg$
- Progenitor masses $m_* = (10 - 1000) M_\odot$
- yields by Heger & Woosley (2002); Heger & Woosley (2010).

Furthermore, it investigates how does the ISM chemical enrichment vary when considering the contribution of subsequent generation of "normal" Pop II stars exploding as core-collapse SNe (Limongi & Chieffi 2018).

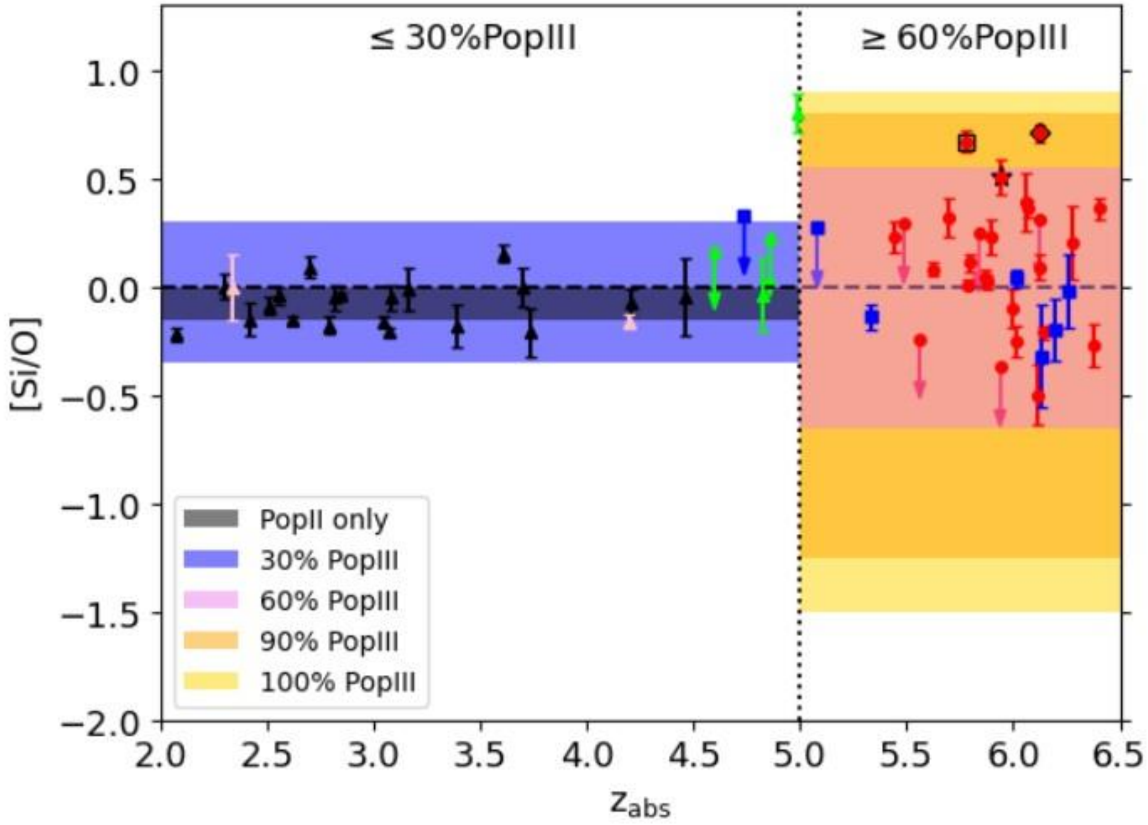
ARE WE OBSERVING THE FIRST STARS' SIGNATURE?



- $z < 5$ absorbers exhibit a small [C/O] and [Si/O] scatter, which is consistent with an enrichment predominantly driven by Pop II SNe (≤ 30% metals from Pop III stars).

- $z \geq 5$ absorbers show an increase of the scatter: while some absorbers are still consistent with a ≤ 30% imprint from Pop III stars, we see some systems could suggest that Pop III stars likely contributed to ≥ 60% of their metals.

ARE WE OBSERVING THE FIRST STARS' SIGNATURE?



- z < 5 absorbers exhibit a small [C/O] and [Si/O] scatter, which is consistent with an enrichment predominantly driven by Pop II SNe (≤ 30% metals from Pop III stars).

- z ≥ 5 absorbers show an increase of the scatter: while some absorbers are still consistent with a ≤ 30% imprint from Pop III stars, we see some systems could suggest that Pop III stars likely contributed to ≥ 60% of their metals.

CONCLUSION

- We have compiled the largest sample of low ionization systems at z>5.4 from the E-XQR-30 survey: 27 OI systems of which 8 are proximate systems.

- In the sample of low ionization absorbing systems analyzed we found no systematic differences in the chemical abundances measured in the PDLA and in the intervening DLA systems.

- There seems to be good agreement between the average abundances of observed systems and those in the literature, and there does not appear to be an obvious evolution of the chemical composition of the gas with the redshift. This suggests that the gas was similarly enriched in each DLAs.

- However, the scatter in the abundance ratio increases at $z > 5$. This could indicate an inhomogeneous chemical enrichment driven by different stellar populations and most likely also including SNs of Pop III stars, which could account for more than 60% of metals in the ISM.

- Unfortunately, the scatter could also be due to a higher ionization state of the systems detected at high redshift; due to the large uncertainty on the HI column density determination we cannot be sure that the observed low ionization systems are indeed DLAs as those at lower redshifts.

THANKS FOR YOUR ATTENTION