Research Proposal : Intergalactic Medium

The gravitational collapse of the overdense regions in the initial density field leads to the formation of large scale structures in the Universe. A significant fraction of the diffuse gas is in the "Intergalactic Medium" (IGM) that is not associated with collapsed objects (galaxies). The IGM fills most of the volume and exhibits a distinct filamentary structure that has imprints of cosmological initial conditions. Observations indicate that the IGM continuously interacts with galaxies through the exchange of matter and radiation. Pristine intergalactic gas flows into the galaxies, while metal-enriched outflows of gas pollute the IGM. These exchanges play a significant role in shaping the physical, chemical, and dynamical properties of galaxies, as the IGM closely intertwine with these processes. The emission of ionizing radiation from galaxies plays a central role in driving the reionization of hydrogen and helium. The reionization, in turn, alters the thermal and ionization state of the IGM, exerting an influence on subsequent galaxy formation and evolution. Thus, studying the IGM becomes vital from both a cosmological perspective, enabling us to understand large-scale structures ($\sim$ 100 Mpc), and an astrophysical viewpoint, unraveling the intricacies of galaxy formation (< 1 Mpc).

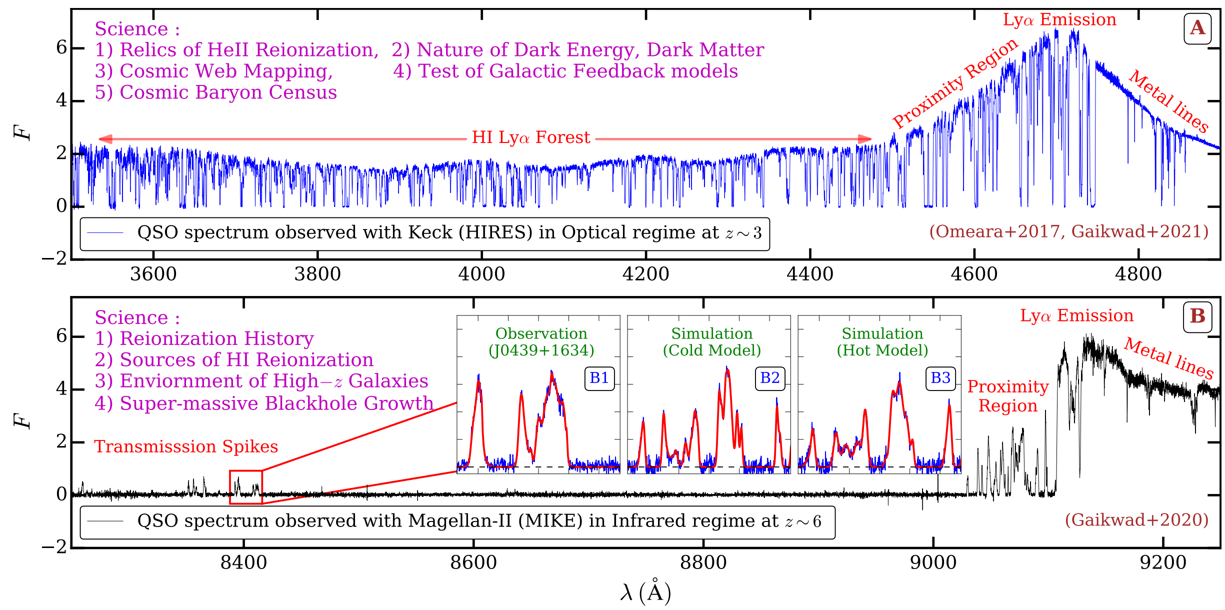

Figure 1: QSO absorption spectra at low ($0 < z < 4$, panel A) and high redshifts ($z > 5$, panel B) exhibit significant evolution in absorption systems, reflecting the changing ionization state of the IGM over cosmic time. The Lyα forest is used to constrain the nature of dark energy, dark matter and the thermal and ionization state of the IGM. The metal absorption systems helps us to understand feedback processes in galaxies, while proximity regions provide insights into AGN properties. Panel B1 to B3 illustrate that the transmission spikes are broader when the IGM is hot and has been used to measure the IGM temperature.

The unprecedented quality quasar absorption spectroscopy from ultra-violet to infrared wavelengths obtained using ground and space-based telescopes, has significantly advanced our understanding of the IGM. The observational progress is matched similarly by advancements from cosmological hydro-dynamical simulations, providing valuable insights in to the astrophysical processes that play a crucial role in the IGM. Despite these advances, there are still three important questions that remain to be answered for a deeper understanding of the universe.

1. When exactly and how did reionization occur in the timeline of the universe?
2. How do galaxies interact with their surrounding environment, and to what extent does this feedback influence large scale structures in the universe?
3. What are the fundamental properties of dark matter that governs the dynamics of the large scale structure in the universe?

The primary objective of my research plan is to address these three core questions. The abundance of spectroscopic data that we will be acquiring from present and forthcoming observing facilities, coupled with the current progress in cosmological simulations that I have developed in recent years, will provide the necessary tools to contribute significantly in answering these questions.

Recent developments in the field:

The observations of QSO absorption spectra at various redshifts have greatly improved our understanding of the evolving IGM as shown in Fig. 1. The series of absorption lines blueward of the Lyα emission, known as the Lyα forest, traces the neutral IGM along the sightlines. The distant QSO absorption spectra are composed of three regions: (i) the Lyα forest, (ii) intergalactic metal absorption systems, and (iii) the proximity region close to the QSO. My research has been focused on using Lyα forest to study the H I and He II reionization. Fig. 2 depicts the process of reionization. Reionization is driven by ionizing photons emitted by sources that produce the ionizing radiation field (right slice). This leads to inhomogeneous photo-ionization (bottom slice) and photo-heating of the IGM, increasing its temperature (left slice). The IGM temperature influences the cosmic density field through pressure smoothing, impacting further structure formation (top slice). QSO absorption spectra offer valuable insights into the thermal and ionization state of the IGM. Panel B1 to B3 in Fig. 1 illustrates that the width of the absorption system increases with increasing IGM temperature. By using such broadening effects, we have demonstrated that the IGM is hotter than previously thought, and we have successfully measured the temperature and neutral fraction of the IGM (Gaikwad et al., 2020, 2023). These findings strongly support the late completion of H I reionization at redshift $z \sim 5.2$. Similar study at $2 < z < 4$ reveal a rapid and late He II reionization by QSOs (Gaikwad et al., 2018, 2021). By better measuring the photo-ionization rate from the Lyα forest at $z < 0.5$, we have resolved the photon-underproduction crises in cosmology (Gaikwad et al., 2017a,b). These measurements are widely recognized and contribute to understanding of late-ending reionization scenarios. In this research proposal, I aim to expand my investigation to include the study of metal line systems, proximity regions and galaxy surveys around QSO sightlines.

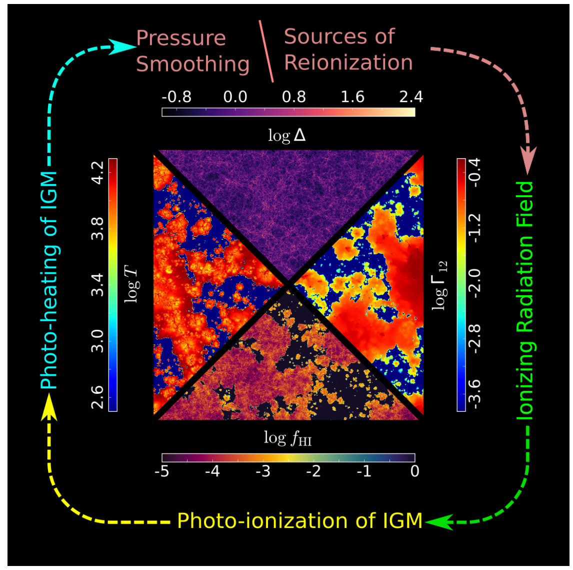

Figure 2: Processes of reionization

Research Plan

In the upcoming years, my research will center on exploring the connection between the IGM, galaxy formation and large-scale structures.

1 Lyα forest 1D flux power spectrum (P1D) measurements from ESPRESSO spectra:

Small-scale fluctuations in the Lyα forest offer valuable information about the thermal state of the IGM and provide constraints on the nature of dark matter (Gaikwad et al., 2020, 2021; Iršič et al., 2023). The thermal relics of H I reionization are imprinted on the Lyα forest as temperature fluctuations, exhibiting enhanced power on larger scales (Molaro et al., 2022). Therefore, accurate measurement of P1D is essential to gain insights into galaxy formation processes within the broader context of cosmology. The unprecedented quality of ESPRESSO spectra offers an excellent opportunity to measure P1D at scales previously unattainable with spectrographs like UVES or HIRES (Boera et al., 2019). The most stringent constraints on reionization and dark matter models arise from small scales (large k modes) in P1D, as shown in Fig. 3.

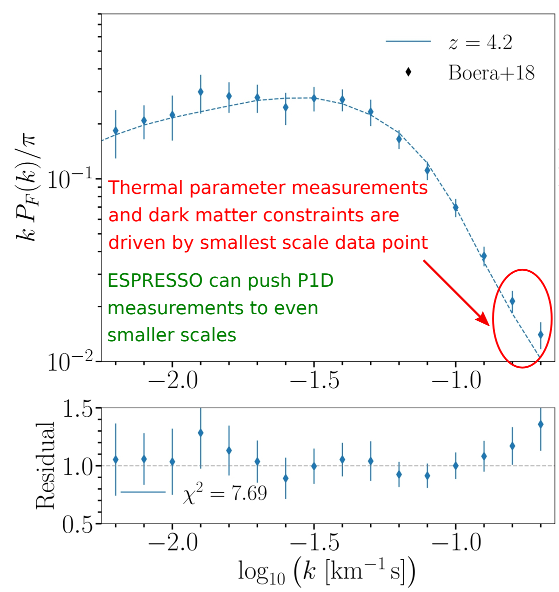

Figure 3: Lyα forest P1D measurements in literature

In this research proposal, I aim to precisely measure

P1D from ESPRESSO *data at* $3.5 < z < 4.5$*, a redshift range crucial for understanding the onset of HeII reionization following HI reionization.* Estimating the contribution of various uncertainties in P1D measurements is equally important, as it will provide the ability to distinguish between models. I plan to perform an analysis involving a hybrid approach, combining data-driven and simulation modeling to evaluate the contributions of correlated noise, instrumental broadening, and metal line contributions to the P1D measurements. In recent years, I have developed my own versatile software pipeline to perform such measurements using observed and synthetic spectra. I plan to use this pipeline to assess the impact of various uncertainties on P1D measurements. The measured P1D will be employed in the subsequent project to determine the temperature of the IGM and the properties of dark matter.

2 Probing Thermal Parameters and Warm Dark Matter Mass with ESPRESSO

Our previous work successfully measured thermal parameters at redshift ranges $2 < z < 4$ and $5 < z < 6$ (Gaikwad et al., 2020, 2021). The evolution of these thermal parameters hints at a somewhat higher temperature, which aligns with the expectation of a later reionization. However, earlier measurements at $4 < z < 5$ suggested a relatively cooler intergalactic medium (IGM), considering the limited time for the IGM to cool from $z = 5.5$ to $z = 4.8$. The discrepancy in these temperature measurements may arise from their dependence on the smallest scales in the power spectrum.

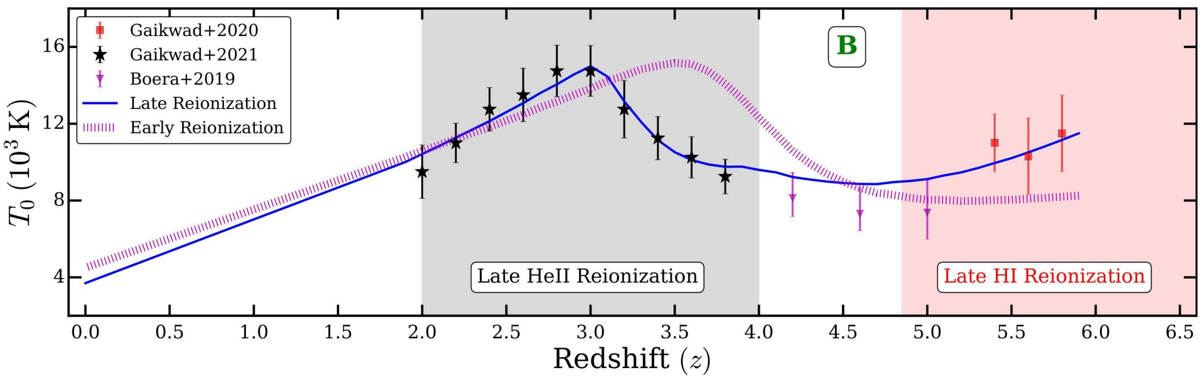

Figure 4: Figure shows evolution of temperature at cosmic mean density measured from the observations in literature. The T_0 favours a late ending reionization model. However, the T_0 measurement at $4 < z < 5$ suggest a cooler IGM. The high resolution ESPRESSO data can potentially resolve this discrepancy.

With the capabilities of ESPRESSO, we can now measure the P1D at small scales, potentially mitigating this discrepancy. I plan to utilize the P1D data obtained in previous project to infer the thermal parameters of the IGM. Additionally, these same P1D measurements offer the opportunity to constrain the mass of warm dark matter. The thermal parameters derived from the previous step will serve as a valuable prior in our efforts to constrain the mass of warm dark matter. In this way, we aim to derive a more comprehensive understanding of the thermal and ionization state of the IGM and the properties of warm dark matter.

3 Constraining reionization history using Lyα forest at $z < 5$ with ESPRESSO spectra

The timing and inhomogeneity of reionization can be characterized by measuring the evolution of the neutral fraction, temperature of the IGM and mean free path of ionizing photons. The complexities in modeling the reionization, as shown in Fig. 2, have posed considerable difficulties in measuring these parameters from observations. We have recently advanced our simulations to capture all the necessary physical effects for accurate modeling of reionization, allowing us to measure these parameters from observations with finite uncertainty at $5 < z < 6$ (Gaikwad et al., 2023).

To rule out various models of reionization requires extending these measurements to higher redshifts ($z > 6$). However this approach is difficult as the observations are extremely challenging. In this research plan, I propose an alternate approach of using $z < 5$ Lyα forest properties to constrain the reionization history. Reionization has a profound effect on the inhomogeneous photo-heating of the IGM, leading to temperature fluctuations. Fig. 5 demonstrates that the temperature fluctuations at $z < 5$ are significantly different for two different reionization histories. Detecting these fluctuations in observations has proven challenging due to limited number of Lyα forest sightlines (Gaikwad et al., 2020).

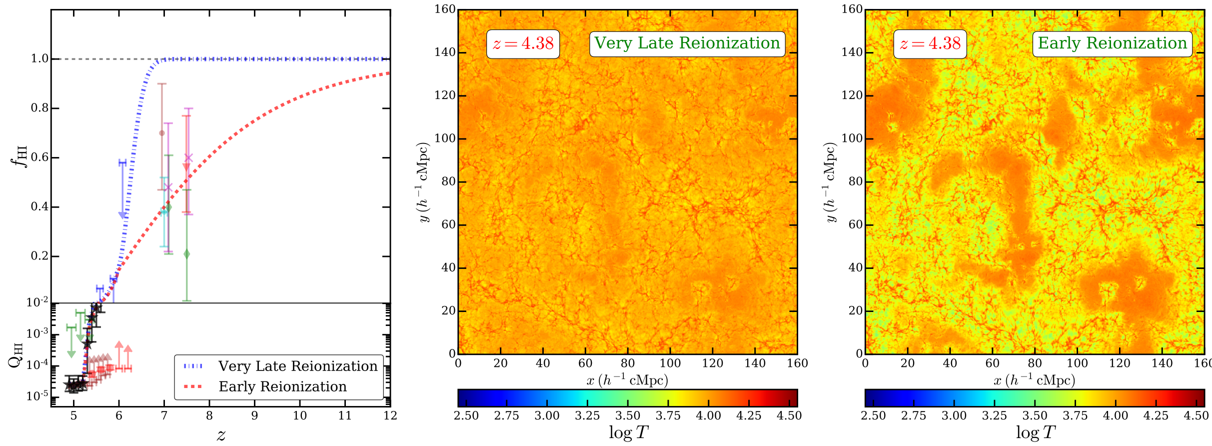

Figure 5: Figure illustrates the effect of reionization history on temperature fluctuations at $z < 4.5$. Left panel shows the evolution of neutral fraction in late (blue dotted curve) and early (red dashed curve) reionization scenario. The two reionization histories match at $z < 6$ while they are significantly different at $z > 6$. Middle and right panel shows that such a difference in reionization history produces a statistically different fluctuations in temperature. Detecting and quantifying these temperature fluctuations can give us valuable constraints on reionization histories. The high resolution ESPRESSO observations can be useful to detect the temperature fluctuation in post reionization Lyα forest.

To tackle this, I propose using high resolution spectroscopic data from ESPRESSO survey. We have recently developed the simulations necessary for conducting these studies, enabling us to effortlessly generate a large number of models for the analysis as shown in Fig. 5. I plan to use the statistics of the Lyα forest based on Voigt decomposition (see Fig. 6) of observed and simulated spectra to constrain models of reionization allowed by low-z Lyα forest data. In addition, I also intend to perform similar analysis of detecting thermal relics due to He II reionization at $2 < z < 4$ from low-z ESPRESSO, SQUAD (UVES) and KODIAQ (HIRES) sample.

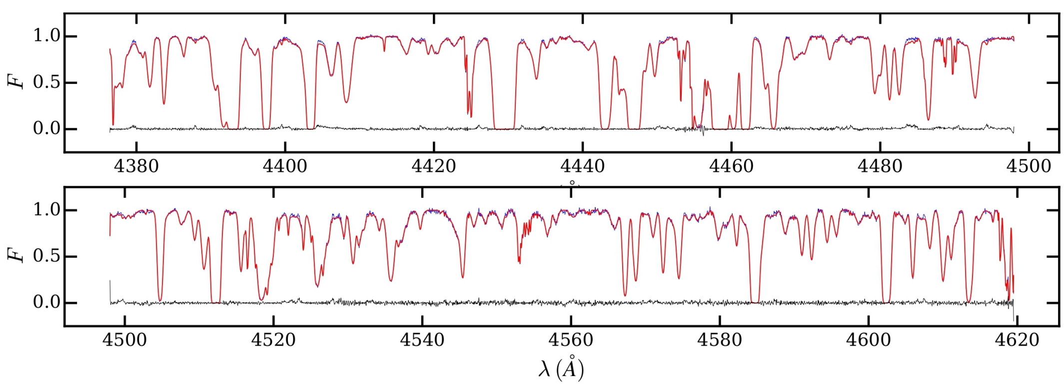

Figure 6: Example of observed Ultra-High S/N spectra (HE0940-1050, blue curve) automatically fitted with VIPER (red curve, residual shown with black curve). I plan to use VIPER (developed in Gaikwad et al., 2017b) for deriving $b - N_{\rm HI}$ statistics and constrain the thermal relics of reionization.

4 Statistical detection of density ring in ESPRESSO spectra

Reionization is an inhomogeneous process such that some regions experience early ionization, while others are ionized later. When the ionization front passes through the IGM, rapid photo-heating of gas occurs. The amount of photo-heating is greatly influenced by the ionization front's speed. In the late stages of reionization, ionization fronts can reach very high speeds of $\sim 10000\ {\rm km\,s^{-1}}$. However, the hydrodynamical response of the gas to this sudden photo-heating is delayed due to relatively large pressure smoothing time scales. Consequently, distinct ring-like (in 3d spherical shell) features in the density distribution persist long after the ionization front's passage, creating characteristic wiggles in the Lyα forest spectra as shown in Fig. 7.

Self-consistent radiative hydrodynamic simulations predict the presence of these density rings in the Lyα forest at redshifts $z < 5$, post H I reionization. Detecting these ring-like features statistically demands the observations of high-resolution QSO absorption spectra with instruments like ESPRESSO. In this research proposal, my plan involves developing a statistical framework to analyze and detect the presence density rings within ESPRESSO data. In addition to traditional

Bayesian techniques of analyzing signal, I aim to use machine learning techniques that are more sensitive to detecting these tiny variations. It is noteworthy that such ring like features are also expected to be present at $z < 2.7$ after He II reionization. If successful, this will mark the first detection of density rings in the data, underscoring the remarkable capabilities of ESPRESSO and advancement in understanding the process of reionization.

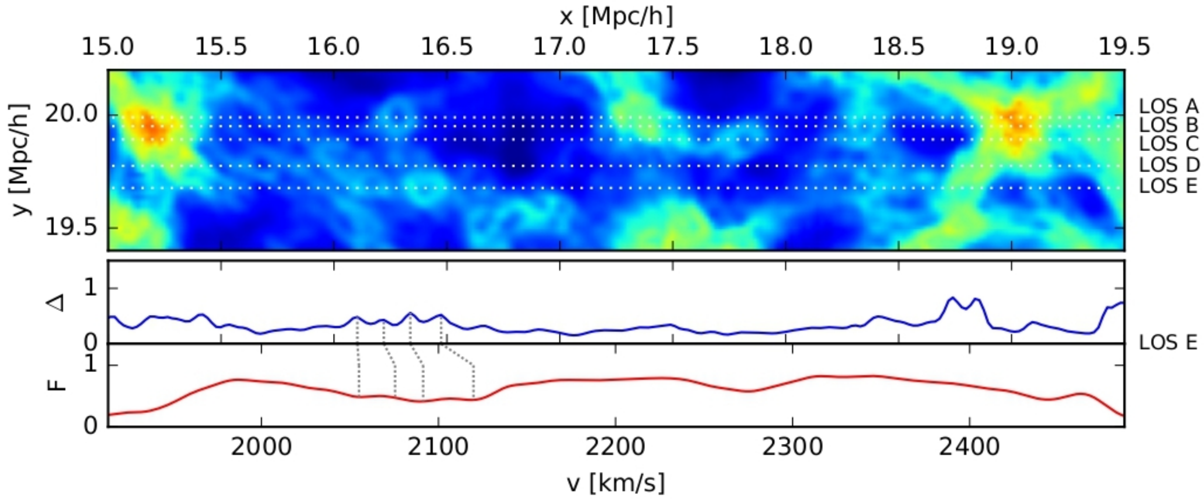

Figure 7: The photo-heating of the IGM due to reionization leads to distinct peaks in overdensity. The rings like structure produces wiggles in Lyα forest flux that can be statistically detected by high resolution spectra from instruments like ESPRESSO. Such a ring like structure are also expected to be present at $z < 2.5$ after He II reionization.

5 Quantifying density ring dynamics with Sandage test observations from ESPRESSO

While previous approach for detecting density rings have been primarily statistical and static, these rings are also expected to exhibit dynamic expansion at velocities of a few km/s. In a few years, the extent of these rings will have grown significantly, enabling their detection in the absorption spectra of the QSO Sandage test experiment. The spectra obtained at different time intervals during the Sandage test can serve as a valuable resource for identifying the real-time expansion of these density rings. It's important to note that this expansion is localized to specific regions within the spectra, unlike the uniform Hubble expansion. The regions identified in previous statistical ring detection project will be the focal points of this endeavor. What's particularly intriguing is that no additional data collection is required, as the existing Sandage test experiment data may suffice for this purpose, maximizing the information extracted from the same dataset.

I plan to conduct a thorough analysis to assess the feasibility of detecting this signal. This exploration will not only enhance our understanding of the observational and astrophysical systematics in Sandage test data analysis but also quantify the potential impact of these signals or systematics on the primary objective of the Sandage test experiment, which is to measure the Hubble expansion of the universe. Consequently, this project promises to yield scientifically valuable insights and contribute to a more comprehensive understanding of the universe's dynamics.

6 How galaxies interact with their environment? (IGM Metal enrichment in ESPRESSO, XQR-30)

Recent observations have shown substantial metal enrichment of IGM at $5 < z < 6$, highlighting the significance of stellar feedback mechanisms in high-redshift galaxies. Notably, the observed mass content of O I and C IV increases significantly at $z > 5$ which is difficult to reproduce in simulations (see Fig. 8, Davies et al., 2023). There are two main difficulties in understanding metal evolution (i) limited observations of the environment surrounding high-redshift galaxies and (ii) the computationally expensive cosmological simulations to model galactic feedback. To address the

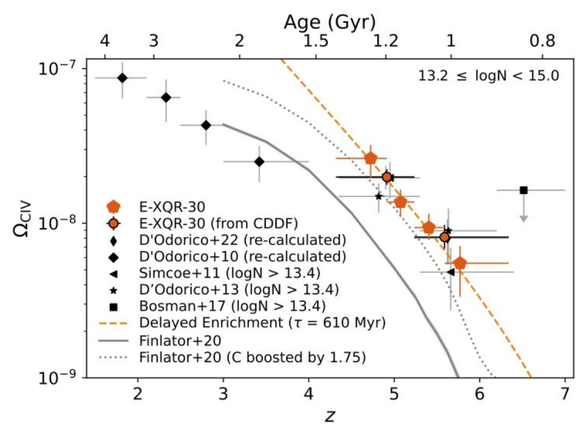

Figure 8: Observed cosmic C IV evolution

first issue, we have a valuable metal absorber catalog from XQR-30 (and ESPRESSO in future) to aid in constraining feedback models. Additionally, our MUSE large program proposal, focused on studying the environment of high-redshift galaxies, has been accepted. To tackle the second challenge, I plan to model metal absorption systems in the IGM using various galaxy feedback models in Sherwood simulation suite. These simulations will enable to quantify the amount of feedback present in high-redshift galaxies, potentially offering insights into the properties of Pop-III stars, where observational constraints are currently limited.

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