

Tracing first-star imprints in a metal-poor galaxy overdensity near the end of reionization

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This manuscript has been previously reviewed at another journal. This document only contains information relating to versions considered at Nature Astronomy.

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Comments for the Author)

This paper presents the discovery of a metal deficient protocluster around redshift ~ 5.9 . The interesting aspect of this protocluster is that it is found near a metal-poor absorption system, identified in a high-redshift quasar sightline. This work uses a valuable, and novel, combination of quasar absorption spectroscopy and JWST slitless spectroscopy, to analyze a metal-poor system both in emission and absorption. The identification of the galaxy overdensity surrounding this metal-poor absorption system is especially useful in inferring the halo mass for the absorption system, directly addressing the possibility of Pop III star formation in minihalos or on the outskirts of larger halos, which to my knowledge has not been done before. Overall this work consists of an interesting technique applied to an interesting system. However, as the topic of Pop III star searches is "in" right now, I would like to see more clarity on what is and what isn't a detection of Pop III stars (in both the absorption system as well as, and perhaps more importantly, in the galaxy overdensity whose discovery is reported here) and how reliable Pop III enrichment models are in establishing the presence of Pop III stars in a robust way. As Nature Astronomy is a journal targeting broad scientific audience, this manuscript would also benefit from a better contextualization of this system and a clearer highlighting of the novelty and contribution here.

General comments and suggestions:

- One point of confusion that could be better addressed throughout the manuscript is the relation between the galaxy overdensity and the absorption system. For instance, the title of the manuscript implies a focus on the galaxy overdensity, however, much of the main text is focused on the absorption system. Second, the title seems to imply that the galaxies in the overdensity have been enriched by first stars, however, the metallicity of the overdensity is already at the percent-solar level, which to my knowledge is not enough to claim the presence of Pop III stars or their enrichment. My understanding upon reading the manuscript is that the strongest evidence for enrichment by Pop III stars comes from the abundance pattern of the absorption system, not the galaxies themselves. How is this link exactly established? It would be helpful if this could be made more obvious.
- To increase general readability, it would be helpful if the authors could put this system into a clearer context. For example, the mean metallicity of the galaxy overdensity is mentioned in the abstract and shown in Fig. 2b - could the authors discuss more how this compares to other metal-poor galaxies that have been found and why this system is worth the reader's attention?
- How is a "protocluster" defined? The group of galaxies identified in this work is sometimes referred to as a protocluster, sometimes as overdensity, so it would be helpful to be clearer about what is meant here (and how it compares to other protoclusters that have been identified e.g. via the ASPIRE survey).
- Since we know so little about Pop III stars as is, it is crucial for the literature to be very explicit about terminology such that we all have a clearer picture of what we know and what we don't. In this spirit, I'd like to encourage the authors to be more pedantic about the difference between "Pop III stars" and "enrichment by Pop III stars", and more specific about what is referred to when "Pop III star signatures" are mentioned (see more on this topic below).

Lines 58-59: It is not known if Pop III stars initiated reionization - this still remains a theoretical prediction. I'd suggest to make this clear in this sentence.

Paragraph beginning with line 62 (this is also a more general comment throughout the paper): Since much is still unknown about Pop III stars and there have not yet been any conclusive detections of this population, I'd strongly suggest that the authors clearly specify and distinguish whether they are referring to "detecting Pop III stars" or "detecting the signatures of Pop III stars" throughout the paper (and what exact signatures are being referred to). Detecting Pop III stars themselves really requires detecting a truly metal-free, star-forming environment. On the other hand, detecting enhanced abundances that hint at PISN still require the detection of metals, meaning that one is not likely detecting Pop III stars themselves, but their subsequent imprint on their environment.

(related comment) Abstract + e.g. line 94 or line 107: I would suggest that the authors caution the reader somewhere early on about the reference to the "Pop III absorber" not being an actual Pop III absorber. In other words, this absorption system is probing the CGM/ISM that has already been enriched, possibly by Pop III stars, but does not represent Pop III stars themselves. I think this would be good to make clear from the beginning, since it could cause confusion as this absorber is identified through its associated metal lines and so does not represent a metal-free medium. Here, I'd like to see a clearer separation of "Pop III stars" and "enrichment due to Pop III stars".

Line 87 and Table 1: Could you please clarify what is meant by "distinct types of metal absorbers"? What types are being referred to? I suppose it is referring to enrichment that is expected to arise due to pollution by Pop III vs Pop II supernovae - I would suggest that this is made clearer in the text.

Fig. 2a and more generally: In the literature, specific abundance patterns have become frequently used to establish hints at Pop III star enrichment, as is done in this work. I wonder - how reliable are the models that lead to these predictions on the abundance patterns, given that we do not know much, observationally, about Pop III stars and the supernovae they undergo? Could the authors please briefly comment on this somewhere in the manuscript?

Fig. 2b + text beginning with line 111: Could the authors briefly comment on the Cullen+25 data point that lies even lower in metallicity, at a comparable halo mass, than the measurements from the current work? How is this system different from the discovery presented here? Does this make the Cullen+25 system a stronger candidate for Pop III star formation, and if not, why?

Line 146 and further: It is not immediately obvious why two transmission peaks that are offset from the absorber should indicate that the absorber is being exposed to ionizing radiation. Could the authors expand on this more?

Reviewer #2

(Comments for the Author)

I have reviewed the paper "A very metal-poor galaxy overdensity near the end of reionization enriched by the first stars" by Li et al. The paper presents evidence of a protocluster at the same redshift as a previously discovered low metallicity absorber along the line of sight of QSO SDSS J0100+2802 with Carbon and Silicon overabundance. Given that the absorber might have been enriched by Pop III the paper concludes that Pop IIIs might be able to form at the outskirts of a cluster.

The detection of a metal-poor protocluster close to the line of sight of a metal-poor absorber with C and Si overabundance, possibly explainable by Pop III enrichment, is a new and important result. On this basis, I find the paper suitable for acceptance after revisions needed to address the comments below.

Major comments:

In multiple area the draft is not sufficiently crisp in separating what are the new results reported here, and how they were obtained, from what was already known from, e.g., Sodini et al. [their reference 6]. Namely:

I. The values of [C/O] and [Si/O] reported in Table 1 are slightly different from those that can be derived from Sodini et al. which suggests that they were rederived. If this is true, it should be stated explicitly that the authors did that, also stating explicitly on which data [presumably the same as Sodini et al.]. If the data are the same, what changed to give slightly different results? I would like to see a clear statement that a reanalysis was carried out and what were the differences from Sodini et al. Alternatively, if there was no reanalysis, the numbers in Table 1 should be derived from Sodini et al. and the corresponding section in the Methods should be significantly shortened.

II. It is also not clear how the sample of two absorbers was selected. Sodini et al. include many objects and so do GO-2078 and GO-1243. Is it just serendipity that these two absorbers had been observed by the JWST programs? whether or not this is a serendipitous sample is important information for the reader to be able to assess the significance of the result. I would like to see an explicit comment on sample selection.

III. Finally, the paper mentions multiple times First Stars and Pop III. However, no new data here point directly to Pop III stars. My understanding is that the whole evidence comes from a reanalysis and modelling effort on the already published Sodini et al. data. The new data presented here simply show that the metal poor absorber with abundance anomalies is located at similar redshifts as a proto-cluster of low-metallicity galaxies. Thus, in essence, the paper is composed of two logical parts: the discovery of the proto-cluster, and the modelling of the C and Si overabundance. The paper would benefit if these two parts were disentangled more clearly.

Assuming I understood what is going on, I would also like to see a clear statement that the authors, given the presence of the

metal-poor proto-cluster, remodel the absorber abundances to strengthen the interpretation as possibly due to Pop III enrichment.

This is potentially an important paper and I urge to authors to improve its clarity along the lines suggested above.

Minor comments:

1. in line 45 they should not define the C and Si abundances as "excessive" but simply as over-abundant compared to solar.
2. in line 53, "massive halos" is overstated. The authors prove that the halo has $\text{LogM} > 9$ so it is firmly in the atomic hydrogen cooling regime. They should replace "massive" with "atomic hydrogen cooling" consistently with what discussed in the paper.
3. both panels of Figure 2 are important and deserve better visibility. All information presented there is important and should be retained. An obvious, and probably sufficient, way to improve visibility would be to use larger single panel figures but it is possible that other solutions would work as well. For instance, the circles and triangles in 2a are not jumping to the eye. Perhaps using a filled symbol for one of the two would help.
4. this is more of a matter of personal taste but the notation Pop III.2 is not really a standard and is a rather ugly combination of roman and arabic numerals. I would recommend the authors not to use it. If they insist in using this notation, I would urge them to replace "commonly referred to" in line 128 with "hereafter indicated as" which acknowledges that some of the readers not deep in Pop III literature may have never seen it before.
5. I suggest rephrasing, in line 170, the words "provides tentative observational evidence". Tentative evidence sounds very weak. Perhaps something like "is suggestive" or "provides an example" would work better,

Reviewer #3

(Comments for the Author)

The manuscript "A Very Metal-poor Galaxy Overdensity Near the End of Reionization Enriched by the First Stars" reports the detection of a metal-deficient protocluster composed of 17 galaxies with a mean metallicity of 3% solar, found in the vicinity of a PopIII absorber in the sightline of SDSS J0100+2802 at $z = 5.945$.

This metal deficient environment is interpreted as a primordial site preserving traces of late PopIII star formation occurring in the outskirts of a massive halo.

I want to congratulate the authors for this important result, which reinforces previous findings and theories on possible low-metallicity hosts at the end of the epoch of cosmic reionization (EoR). Overall the discovery is well described, the adopted method well documented and the impact clearly explained.

My main concern regards the theoretical interpretation of the results which is certainly plausible but not without alternatives, which are never explored with sufficient care.

I perfectly understand that the authors want to adopt a reference model for their interpretation but considering the difficulty in identifying POPIII stars or their relics, I reckon that the reader should be provided with the entire spectrum of possible theoretical alternatives; this approach will also strengthen and broaden the importance of the present discovery.

I therefore reserve the right to provide suggestions on the possible publication of the manuscript after its second revision. More details are provided below.

1. Please provide a clear indication of the metallicity threshold adopted by your models to disentangle a PopIII from a PopII stellar population. Are you adopting the usual value $1d-4 Z_{\text{sun}}$. Also provide a value for the adopted Z_{sun} in absolute units.

Line 43: "Detecting the chemical enrichment of circumgalactic gas offers a promising way to trace the signature of Pop iii stars" -> This is misleading. The CGM is enriched by the integrated contributions of all stellar populations present in its halo. You want to say "very metal poor clouds of the CGM" probably?

Line 49: "We reveal that the member galaxies are on average ~ 0.4 dex more metal-poor than coeval galaxies in similar protocluster environments. Such a metal-deficient nature indicates a primordial environment well preserving the relics of Pop iii star-formation"

This is also inaccurate. A low metallicity environment indicates low metallicity stars, without a threshold definition the sentence is simply inaccurate.

Line 52: "consistent with late-time Pop iii formation at the outskirts of massive halos". In the paper the word halo is often used in a confusing way. Please specify Dark MAter halo or refer to galaxies, groups, protoclusters. Moreover, citing Venditti 2023 at the end of this sentence is confusing as well. Venditti finds POPIII star formation in the outskirts of the central galaxy, not of the DM halo. They certainly claim late POPIII star formation in external galactic regions. Please be more accurate with scientific terminology.

Line: 55 " $z \sim 30$ ".. the way things are presented here is also puzzling... this value remains strictly model dependent,.. and probably facilities like the ET could help exploring these redshifts throughout GW coalescence.. I suggest to indicate a range

of possible values of redshifts and to say models predict the epoch of cosmic dawn or the first stars to appear... Similar indication for the peak.. either you say "... predicts the peak" or you have to explain that it remains model dependent ..

Line 57: should I interpret your Pop III definition as strictly at $z=0$? Here you say metal-free. Same for the IMF.. a top heavy is a widely adopted prescription but still unconstrained now.

Line 60: What is your definition of supernova explosions enriching the ISM? Do you assume only PISN POPIII can enrich the medium or in which mass regime you consider POPIII enriching the surrounding gas?

Line 70: Similar comment as above: "supernova-driven...", Which mechanism are you referring to? Local POPIII or standard SNe explosions contaminating the ISM or the integrated effect of galaxy winds polluting the CGM/ISM? In this case linking supernovae explosions to galactic winds is still debated.

Line 80: are the systems you are referring to also star forming or just detected in their metallicity but with no clear signatures of star formation? Which class of QSO absorbers are you referring to?

Line 93 and Figure 2 (both panels). Here is the main point. Your claim is clear but according to the adopted model (The GAMETE model or some variant I guess). Are there alternatives? Or if any, what are the indications you can provide to favour the GAMETE predictions? Do you know massive star very metal poor models (Cameron, Charbonnel) or late AGB contributions? Moreover, what about the impact of WR stars (Schaerer et al.) or fast rotators present at very low metallicity, not necessarily PopIII...(Meynet..)

One technical question: the GAMETE model is known as a reference tool for stellar archaeology and provides good statistical references, accurate chemistry implementation and flexibility in parameter exploration. On the other hand I think it still relies on semi-analytic merger trees and simplified inhomogeneous enrichment,.. which seems less appropriate than hydrodynamical simulations for an accurate claim on external POPIII in metal free pockets at the end of EOR . This would in fact require an accurate inhomogeneous metal enrichment model and there is a strong debate on its effects along the redshift depending on the scale and numerical scheme (see Venditti 2023 for example). Why do you consider GAMETE appropriate for this specific investigation?

Line 104: "The estimated halo mass is consistent with that of typical [O iii]-emitting galaxies at similar redshifts". This is also confusing.. Why typical? OIII emission comes from a larger range of main sequence galaxies at the end of EoR with an equivalent spread in their halo masses... am I missing something here?

Line 114: The fact that it is a low metallicity environment does not imply PopIII.

Line 118: Here probably citing Venditti 2023 is appropriate within the other models. Is the model of Pallottini predicting late POPIII? Do they properly model POPIII stars? Please check the literature, or maybe 52,54 instead of 52-54. I am confused by this as Venditti is one co-author. Please check your references.

Line 132: to be(?) self-shielded?

Line 133: Referring to the POPIII host or POPIII candidate is misleading. You do not have any direct evidence of a living POPIII population. Just relics... There are no He line detections and they could also not be a direct indication. Please restate your nomenclature. There is no POPIII detection I guess...

Line 147: Background radiation is consistent with star formation of certain type.. not POPIII star formation ... which is a chemically related question, first.

Line 153: Which part of the POPIII IMF should remain intact? A massive POPIII has a lifetime of 3 Myr on average... what is your popiii IMF mass range?

Line 178: This is one possibility.. for sure there is evidence of a very low metallicity environment in which either internal feedback is inefficient or external pollution is inefficient. A direct link to PopIII is one possibility.

Line 183: I do not agree. The evidence is that a POPIII compatible environment exists at the end of EoR. Not POPIII star forming environment. This would require other detections ...

Line 185: This is also inaccurate. If you refer to the POPIII-> POPII transition this is a statistical concept regulating the dominating population. What you find here is the "sporadic episodes of POPIII are possible as fund by Venditti 2023 and others (THESAN..)"

Line 491: Specify the FoF is applied to baryonic structures, it is usually referred to DM structures..

Line 526: Is this a "local" IGM temperature right? A global IGM is at different scales.. What is the ratio between the estimated background in this region and the predicted global HM background value at this redshift?

Line 543: I do not agree. It supports very low-metallicity star formation. Not necessarily POPIII

Lines 551-555: the star formation efficiency quantifies,... the dilution factor establishes,.. which quantifies if referred to the fraction..

Line 616: Which background? Local or global?

Line 620 : hydrogen number density, not density I guess.. How overdense is the -2 value at this redshift?

Version 1:

Reviewer comments:

Reviewer #2

(Comments for the Author)

I have reviewed the revised version of the manuscript "First-star-enriched gas within a very metal-poor galaxy overdensity near the end of reionization" by Li et al. and I find this version sufficiently improved to be now acceptable for publication.

Reviewer #3

(Comments for the Author)

I thank the authors for their detailed answers and comments, which I generally agree with, except for the points detailed below. Here, I also avoid repeating my previous comments regarding guidelines points 2, 3, 4, and 5 in the form.

(Q11) Why do you consider GAMETE appropriate for this specific investigation?

Response: We clarify again that GAMETE is not used in this work.

My reply: This is now clear, thank you.

Our goal is instead to adopt a simple and flexible framework that captures the key physical ingredients relevant to the chemical imprint of individual Pop III supernovae, including inhomogeneous enrichment through a parametric treatment.

My reply: This explanation, however, raises further concerns. The problem suffers from so many degeneracies that lacking a proper cosmological framework makes the predictions even more model-dependent.

We agree that fully hydrodynamical cosmological simulations provide a more detailed description of structure formation and metal mixing. However, current simulations face important trade-offs and do not yet simultaneously resolve (i) minihalos hosting the first stars,

My reply: This depends on the scale of the simulated volume. While it is true that a multi-scale approach is still missing, there are simulations capable of resolving minihalos in Local Volume groups (i.e., semi-cosmological approaches). See, for example, the Renaissance simulations for a full hydrodynamical case, or the GAMESH pipeline for a hybrid approach. Therefore, your statement is inaccurate.

(ii) the full range of Pop III progenitor masses and explosion energies, and (iii) detailed multi-element chemical yields.

My reply: This is also inaccurate. There are models featuring a flexible IMF and multi-element yields (e.g., dustyGadget), which the authors should be familiar with.

As a result, they typically probe more massive halos and environments enriched by multiple supernovae.

My reply: That is a choice linked strictly to the volume (and its corresponding mass resolution), not to the inherent limitations of the numerical schemes.

Our approach is therefore complementary.

My reply: I agree that your approach is a complementary and interesting attempt. However, I do not agree that it can be conclusive in any way on such a complex problem. You should therefore soften your strong statements, as you have already partially done in the revised manuscript.

Having said that, your new suggested title cannot be supported:

"First-star-enriched gas within a very metal-poor galaxy overdensity near the end of reionization."

I suggest something like:

"Detection of an unusually metal enriched gas region within a very metal-poor galaxy overdensity near the end of reionization. A possible detection of first star chemical signatures?"

This formulation better describes this interesting and promising discovery with an appropriate level of uncertainty in the conclusions, which is primarily dictated by the limitations of the theoretical modelling.

I therefore recommend the paper for publication only subject to a clear modification of the message in the title, though it does not necessarily have to be identical to the one suggested above.

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The authors sincerely appreciate the insightful comments from the anonymous referees, which have significantly improved the paper. We have revised our manuscript according to these comments. We list our detailed point-by-point response below, and the main changes in the manuscript are marked in red.

1 Response to Referee 1

General comments and suggestions:

(Q1) One point of confusion that could be better addressed throughout the manuscript is the relation between the galaxy overdensity and the absorption system. For instance, the title of the manuscript implies a focus on the galaxy overdensity, however, much of the main text is focused on the absorption system. Second, the title seems to imply that the galaxies in the overdensity have been enriched by first stars, however, the metallicity of the overdensity is already at the percent-solar level, which to my knowledge is not enough to claim the presence of Pop iii stars or their enrichment. My understanding upon reading the manuscript is that the strongest evidence for enrichment by Pop iii stars comes from the abundance pattern of the absorption system, not the galaxies themselves. How is this link exactly established? It would be helpful if this could be made more obvious.

Response: We thank the reviewer for this insightful comment. We agree that the direct evidence for Pop III enrichment comes from the chemical abundance pattern of the absorption system, not the metallicity of the member galaxies. To address this, we have changed the title to “*First-star-enriched gas in a very metal-poor galaxy overdensity near the end of reionization*” to better reflect our findings. Furthermore, we have further clarified in the main text to explicitly state how the two are linked: the absorber provides the nucleosynthetic signature of Pop III stars, while the unusually metal-poor galaxy overdensity provides the environmental context that allowed these Pop III relics to survive at $z \sim 6$.

The galaxies are not solely enriched by Pop III stars, but they reside in the metal-poor structure that may host the Pop III formation.

(Q2) To increase general readability, it would be helpful if the authors could put this system into a clearer context. For example, the mean metallicity of the galaxy overdensity is mentioned in the abstract and shown in Fig. 2b - could the authors discuss more how this compares to other metal-poor galaxies that have been found and why this system is worth the reader's attention?

Response: We thank the referee for this helpful suggestion. We agree that the significance of this system should be placed in a clearer broader context. In the revised manuscript, we have expanded the discussion around Fig. 2b and in the Discussion section to clarify why this overdensity is noteworthy.

The member galaxies in the overdensity are not individually extreme in all of their observable properties. Rather, the large-scale environment shows a systematically lower metallicity than galaxies in the coeval overdense environments, in comparison with the overdensity associated with a Pop II absorber. This indicates that the property of the system is a coherent environmental metal deficiency, rather than the presence of a single unusual galaxy.

We now clarify that this makes the system complementary to previously reported extremely metal-poor galaxies in the literature. Many earlier examples are individual galaxies or star-forming complexes identified because of their exceptionally low metallicities (Nakajima et al., 2025; Morishita et al., 2025; Maiolino et al., 2026). In contrast, our system is distinguished by the combination of: (1) a large-scale overdensity of galaxies, (2) an averaged metallicity that is low for its stellar mass, and (3) its spatial association with a metal absorber whose abundance pattern is consistent with Pop III enrichment. Taken together, these observations suggest that we may be seeing not just an isolated chemically primitive galaxy, but a larger-scale chemically young environment in which metal mixing has remained inefficient or cold gas accretion has continued to replenish the

pristine star formation at $z \sim 6$. This discovery provides observational and theoretical insights into the conditions for Pop III formation at $z \sim 6$.

We have therefore revised the manuscript to better emphasize that the physical significance of this system lies in the fact that metallicity provides information not captured by the other bulk galaxy properties: although the galaxies are otherwise broadly similar to typical [OIII] emitters, their collective chemical state appears unusually primitive. This is what makes the system relevant for understanding patchy metal enrichment, pristine gas survival, and possible late-time Pop III star formation channels.

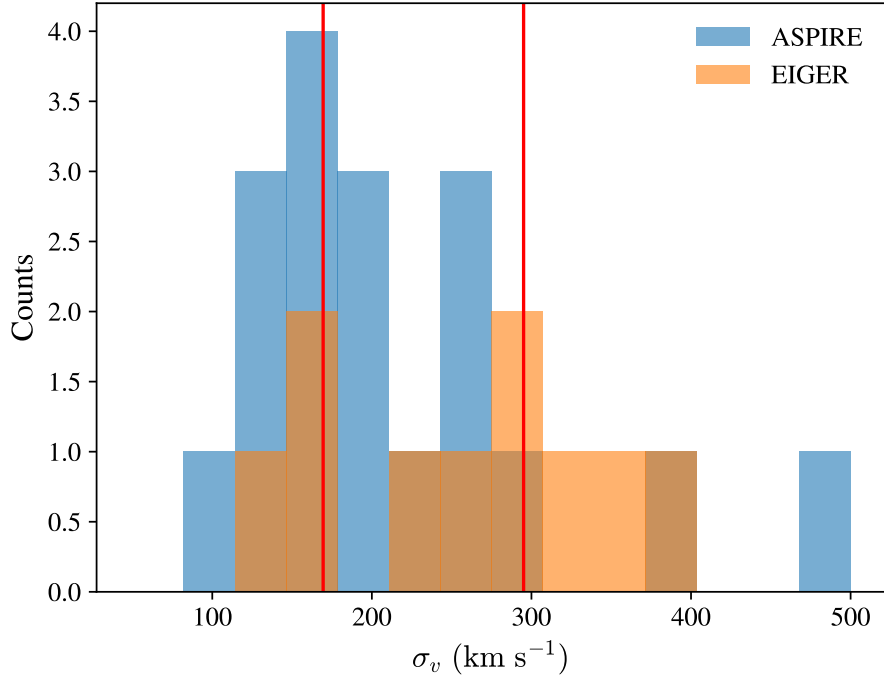
(Q3) How is a “protocluster” defined? The group of galaxies identified in this work is sometimes referred to as a protocluster, sometimes as overdensity, so it would be helpful to be clearer about what is meant here (and how it compares to other protoclusters that have been identified e.g. via the ASPIRE survey).

Response: We thank the reviewer for this constructive suggestion. We recognize that the interchangeable use of “overdensity” and “protocluster” may cause confusion. We have clarified these definitions in the revised manuscript as follows:

We now consistently use “galaxy overdensity” to refer to the specific structure identified observationally via the Friends-of-friends (FoF) algorithm (linking parameters: $d_{link} = 500$ kpc, $\sigma_{link} = 500$ km/s). The term “protocluster” is reserved for the physical interpretation of this system as a progenitor of a massive galaxy cluster, characterized by its large spatial extent (≈ 1400 kpc) and member count.

The total velocity dispersion of 1253 ± 133 km/s for all 17 members is driven by the velocity offset between two distinct substructures at $z \approx 5.94$ and $z \approx 5.99$. This is likely characteristic of dynamically young, non-virialized systems at high redshift, where multiple groups are still assembling into a common large-scale environment.

To provide context, we measured the internal velocity dispersions of the two substructures separately, yielding $\sigma_v \approx 300$ km/s and $\sigma_v \approx 170$ km/s. As shown in Response Figure 1, these values are consistent with other protocluster candidates identified in the



Response Figure 1: Velocity dispersion of member galaxies in overdensities identified in the ASPIRE and EIGER surveys. The red lines mark the two substructures associated with the Pop III absorber in this work.

ASPIRE and EIGER surveys. While our system is typical in size and internal dynamics, its metal-deficient nature suggests it may be influenced by stronger pristine gas inflows along its connected filamentary structures.

We have revised Section “Overdensity characterization” to explicitly define these terms at first mention. We now refer to the system as an “overdensity” when discussing direct observational identification and have ensured terminology is uniform throughout the paper.

(Q4) Since we know so little about Pop iii stars as is, it is crucial for the literature to be very explicit about terminology such that we all have a clearer picture of what we know and what we don’t. In this spirit, I’d like to encourage the authors to be more pedantic about the difference between “Pop iii stars” and “enrichment by Pop iii stars”, and more specific about what is referred to

when "Pop iii star signatures" are mentioned (see more on this topic below).

Response: Thanks for this suggestion. We have revised the manuscript accordingly, using terms such as "Pop III enrichment", "Pop III-like abundance pattern", and "Pop III-enriched gas" when discussing the absorber, while reserving "Pop III stars" for cases involving actual metal-free star formation.

(Q5) Lines 58-59: It is not known if Pop iii stars initiated reionization - this still remains a theoretical prediction. I'd suggest to make this clear in this sentence.

Response: Thanks for noting this. We agree that it remains a theoretical prediction. In the revised version, we have rephrased this sentence to avoid overstatement:

"Those stars are predicted to have played an important role in the onset of cosmic reionization through their intense ultraviolet radiation, which ionized the surrounding intergalactic medium (IGM)"

(Q6) Paragraph beginning with line 62 (this is also a more general comment throughout the paper): Since much is still unknown about Pop iii stars and there have not yet been any conclusive detections of this population, I'd strongly suggest that the authors clearly specify and distinguish whether they are referring to "detecting Pop iii stars" or "detecting the signatures of Pop iii stars" throughout the paper (and what exact signatures are being referred to). Detecting Pop iii stars themselves really requires detecting a truly metal-free, star-forming environment. On the other hand, detecting enhanced abundances that hint at PISN still require the detection of metals, meaning that one is not likely detecting Pop iii stars themselves, but their subsequent imprint on their environment.

Response: Thanks for this important suggestion. In the revised manuscript, we have clarified this distinction throughout. In particular, we now reserve wording such as "Pop III stars" for cases involving direct evidence of a truly metal-free star-forming envi-

ronment, while using “Pop III enrichment” when referring to metal abundance patterns that may trace the nucleosynthetic impact of Pop III stars. We have revised the paragraph accordingly and made the terminology more consistent throughout the paper.

(Q7) (related comment) Abstract + e.g. line 94 or line 107: I would suggest that the authors caution the reader somewhere early on about the reference to the “Pop iii absorber” not being an actual Pop iii absorber. In other words, this absorption system is probing the CGM/ISM that has already been enriched, possibly by Pop iii stars, but does not represent Pop iii stars themselves. I think this would be good to make clear from the beginning, since it could cause confusion as this absorber is identified through its associated metal lines and so does not represent a metal-free medium. Here, I’d like to see a clearer separation of “Pop iii stars” and “enrichment due to Pop iii stars”.

Response: In the revised manuscript, we have clarified the definition, and the term “Pop III absorber” is used only as a brief shorthand for absorbed enriched by Pop III SN ejecta. We have also avoided using the term “Pop III absorber” in the abstract and only used it in the main text after clearly defining it.

The definition on page 4 reads as:

“... predominantly enriched by the chemical products of Pop III SNe, and we denote this as a “Pop III absorber” for simplicity.”

(Q8) Line 87 and Table 1: Could you please clarify what is meant by “distinct types of metal absorbers”? What types are being referred to? I suppose it is referring to enrichment that is expected to arise due to pollution by Pop iii vs Pop II supernovae - I would suggest that this is made clearer in the text.

Response: Thanks for this suggestion. We have clarified this. The revised sentence now reads:

“By comparing with chemical enrichment models (Vanni et al., 2023), we identified

two metal absorbers with abundance patterns consistent with enrichment from Pop III and Pop II supernovae, respectively.”

And we have also clarified the definition of “type” in Table 1:

“The type is determined by consistency with Pop III or Pop II enrichment models (Vanni et al., 2024).”

(Q9) Fig. 2a and more generally: In the literature, specific abundance patterns have become frequently used to establish hints at Pop iii star enrichment, as is done in this work. I wonder - how reliable are the models that lead to these predictions on the abundance patterns, given that we do not know much, observationally, about Pop iii stars and the supernovae they undergo? Could the authors please briefly comment on this somewhere in the manuscript?

Response:

We thank the referee for raising this important point. We agree that the predictive power of Pop III nucleosynthesis models is fundamentally limited by the lack of direct observations of the first stars and their explosions. We have clarified this caveat in the manuscript. The model adopted here (Salvadori et al., 2019; Vanni et al., 2023) is intentionally designed to minimize assumptions and instead explore a broad parameter space, including progenitor masses (10–100 Msun and 140–260 Msun), explosion energies ($0.1\text{--}100 \times 10^{51}$ erg), and variations in star formation efficiency and metal dilution. No specific Pop III initial mass function is assumed. Despite these uncertainties, indirect observational support exists: abundance patterns of some extremely metal-poor stars are consistent with enrichment by individual low-energy (faint) and high-energy Pop III supernovae (e.g., Iwamoto et al., 2005; Placco et al., 2011; Keller et al., 2014; Frebel et al., 2015; Skúladóttir et al., 2024). In addition, independent theoretical models of Galactic halo stars and ultra-faint dwarf galaxies recover similar ranges of progenitor masses and explosion energies (e.g., Cooke & Madau, 2014; Ishigaki et al., 2018; Rossi et al., 2025). At the high-mass end, we note that while no clear chemical signatures of pair-instability

supernovae have been robustly identified in second-generation stars, recent observations of a candidate Pop III galaxy at $z \approx 11$ (Hebe; Maiolino et al., 2026) suggest the presence of very massive zero-metallicity stars. This is supported by theoretical work indicating that the Pop III mass spectrum may extend beyond $250 M_{\odot}$ (Rusta et al., 2026). Although indirect, these results provide motivation for including the pair-instability mass range in our parameter space. We emphasize that individual abundance patterns are not uniquely diagnostic; rather, our approach assesses the robustness of inferred signatures across a wide and physically motivated parameter space.

On the observational side, similarly enhanced C/O abundance patterns have been reported in chemically primitive systems such as LAP1-B (Nakajima et al., 2025). Its extremely low oxygen abundance is consistent with the Pop III regime, providing an observational consistency check for our model. However, we admit that a single source cannot by itself validate the model predictions.

In the main text, we have added the following discussion about the consistency check:

“A similarly enhanced C/O ratio has also been reported in the chemically primitive galaxy LAP1-B (Nakajima et al., 2025), whose extremely low oxygen abundance places it in the Pop III regime. This agreement provides an observational consistency check for C/O as a Pop III-sensitive abundance diagnostic.”

In addition, we have added more discussions at the end of the section “Chemical enrichment model” about the model reliability.

(Q10) Fig. 2b + text beginning with line 111: Could the authors briefly comment on the Cullen+25 data point that lies even lower in metallicity, at a comparable halo mass, than the measurements from the current work? How is this system different from the discovery presented here? Does this make the Cullen+25 system a stronger candidate for Pop iii star formation, and if not, why?

Response: We thank the referee for raising this important comparison. We agree that

EXCELS-63107 from Cullen et al. (2025) is a relevant system, as it lies at even lower metallicity than our measurements at a comparable mass scale. However, the nature of the two systems is different. EXCELS-63107 is a single, compact, and isolated galaxy whose interpretation is driven by its internal nebular properties and unusually hard ionizing spectrum. Cullen et al. (2025) suggests that a top-heavy IMF is considered a plausible explanation, while Pop III star formation is discussed as another possible scenario. By contrast, our result is based on the joint presence of a Pop III-like absorber abundance pattern and a chemically primitive galaxy overdensity, which together point to a low-metallicity large-scale environment preserving signatures of Pop III enrichment. By contrast, our observations do not directly identify Pop III stars, and we instead find evidence for a Pop III enrichment signature at the outskirts of atomic-cooling halos, to support previous theoretical predictions (e.g., Venditti et al., 2023). We therefore view the two systems as complementary rather than interpreting EXCELS-63107 as necessarily a stronger Pop III candidate.

In the revised manuscript, we have added a brief discussion about the comparison. It reads:

“For comparison, we show EXCELS-63107 in Fig. 2, an extremely metal-poor galaxy in a comparable stellar-mass regime reported in the literature (Cullen et al., 2025). Its spectrum indicates an unusually hard ionizing source, suggesting that Pop III stars may form within mildly enriched halos. In our observations, the metal-deficient nature of the overdensity points to a relatively chemically primitive environment in which early enrichment signatures could be more readily preserved. When considered together with the Pop III-like abundance pattern of the absorber, this environment supports the interpretation that the absorber may point to Pop III star formation in the outskirts of a mildly enriched dark matter halo.”

(Q11) Line 146 and further: It is not immediately obvious why two transmission peaks that are offset from the absorber should indicate that the absorber

is being exposed to ionizing radiation. Could the authors expand on this more?

Response: We thank the referee for pointing this out. We agree that our original wording was too concise. Our interpretation is not that the two transmission peaks directly prove that the absorber itself is exposed to ionizing radiation. Rather, the peaks indicate enhanced $\text{Ly}\alpha/\text{Ly}\beta$ transmission in the surrounding large-scale IGM, which is most naturally explained by a local ionized bubble in the absorber environment.

The offset of the transmission peaks is expected due to the fact that in the immediate vicinity of the absorber/host-galaxy environment, the gas density is higher, which increases the $\text{Ly}\alpha$ optical depth and suppresses transmission. Therefore, transmission maxima are expected to appear offset from the overdense core, and Kakiichi et al. (2025) suggests an excess $\text{Ly}\alpha$ transmission at a distance $\sim 20 - 40$ cMpc/h around OIII emitters (their Fig. 12). In our case, the two spikes occur at ~ -20 and $\sim +16$ h cMpc/h relative to the absorber, and the corresponding $\text{Ly}\beta$ spikes support the interpretation that they trace an ionized region rather than noise fluctuations.

We have revised the text to clarify that these peaks imply that the large-scale environment around the absorber may reside in an ionized bubble and is exposed to ionizing radiation. We have added the clarification in the text as:

“Since the immediate absorber and host galaxy environment is likely associated with a gas overdensity that enhances the $\text{Ly}\alpha$ optical depth and suppresses transmission locally (Kakiichi et al., 2025), the transmission maximum is not expected to coincide with the exact location of galaxy overdensity. Instead, the $\text{Ly}\alpha$ and $\text{Ly}\beta$ peaks suggest that the absorber is embedded in a larger-scale ionized region, indicating that its surrounding environment is exposed to radiation. This provides environmental context compatible with the theoretical Pop III formation pathway under the UV background (Jeong et al., 2026)”

2 Response to Referee 2

Major comments:

In multiple area the draft is not sufficiently crisp in separating what are the new results reported here, and how they were obtained, from what was already known from, e.g., Sodini et al. [their reference 6]. Namely:

(Q1) The values of [C/O] and [Si/O] reported in Table 1 are slightly different from those that can be derived from Sodini et al. which suggests that they were rederived. If this is true, it should be stated explicitly that the authors did that, also stating explicitly on which data [presumably the same as Sodini et al.]. If the data are the same, what changed to give slightly different results? I would like to see a clear statement that a reanalysis was carried out and what were the differences from Sodini et al. Alternatively, if there was no reanalysis, the numbers in Table 1 should be derived from Sodini et al. and the corresponding section in the Methods should be significantly shortened.

Response:

We thank the referee for pointing this out. We did not perform an independent spectroscopic re-analysis of the absorption systems. Instead, we adopted the column density measurements directly from the official XQR-30 public metal absorber catalog to ensure reproducibility and consistency with the broader survey (Davies et al., 2023). In addition, Sodini et al. (2024) has noted that they carried out their own detection and fitting procedures, and their results are in agreement with the official catalog within 1σ , which leads to the difference in our Table 1.

While the column density fitting procedure is indeed detailed in Davies et al. (2023), we have maintained the current Methods section because the original catalog primarily reports column densities rather than the specific relative abundance ratios, such as [Si/O] and [C/O], utilized in our analysis. The Methods section provides the necessary documentation and the specific derivation of these ratios, which are essential for comparing

the observed data with the Pop III chemical enrichment models. We believe keeping this detail is critical for clarity, as it allows readers to understand the precise steps taken to translate raw catalog data into the diagnostic physical quantities presented in Figure 2.

In the revised manuscript, we have noted that the values in Table 1 differ from those reported by [Sodini et al. \(2024\)](#) to avoid potential confusion for readers.

(Q2) It is also not clear how the sample of two absorbers was selected. Sodini et al. include many objects and so do GO-2078 and GO-1243. Is it just serendipity that these two absorbers had been observed by the JWST programs? whether or not this is a serendipitous sample is important information for the reader to be able to assess the significance of the result. I would like to see an explicit comment on sample selection.

Response: We thank the referee for this important suggestion. We apologize that we did not explicitly discuss about the sample selection in the last version. Here we clarify that this is a targeted sample defined by the overlap between (i) reliable abundance measurements from XQR-30, (ii) existing JWST coverage, and (iii) identifiable host-galaxy environments.

In the revised manuscript, we have added one section “Absorber-galaxy sample selection” to clarify this. It reads as:

“We started from the XQR-30 metal-absorber catalog and required detections of C II, O I, and Si II in order to derive robust [C/O] and [Si/O] abundance ratios. We compared these ratios with Pop III enrichment models (Fig. 2a) and cross-matched the corresponding absorbers with quasar sightlines covered by JWST/NIRCam grism observations from ASPIRE and EIGER. The absorber at $z = 5.945$ toward SDSS J0100+2802 is the only system in this set with abundance ratios consistent with Pop III enrichment, and its JWST data reveal an associated galaxy overdensity. To place this system in context, we aimed to select comparison absorbers from the same parent sample with similar large scale environments but without Pop III enriched abundances. After excluding the $z = 6.06$ ab-

sorber toward PSO J036+03, which is associated with a single isolated galaxy (Zou et al., 2024), and the $z = 6.11$ and $z = 6.14$ absorbers toward SDSS J0100+2802, for which no associated galaxies are identified (Kashino et al., 2025), the final sample consists of two absorbers associated with galaxy overdensities: the Pop III-enriched system toward SDSS J0100+2802 and the non-Pop III comparison system toward VDES J0224-4711.”

(Q3) Finally, the paper mentions multiple times First Stars and Pop iii. However, no new data here point directly to Pop iii stars. My understanding is that the whole evidence comes from a reanalysis and modelling effort on the already published Sodini et al. data. The new data presented here simply show that the metal poor absorber with abundance anomalies is located at similar redshifts as a proto-cluster of low-metallicity galaxies. Thus, in essence, the paper is composed of two logical parts: the discovery of the proto-cluster, and the modelling of the C and Si overabundance. The paper would benefit if these two parts were disentangled more clearly. Assuming I understood what is going on, I would also like to see a clear statement that the authors, given the presence of the metal-poor proto-cluster, remodel the absorber abundances to strengthen the interpretation as possibly due to Pop iii enrichment.

Response: We thank the referee for this important and constructive comment. We agree that our new JWST data do not provide a direct detection of Pop III stars themselves. The interpretation of the absorber as possibly influenced by Pop III enrichment is indeed based on abundance measurements previously reported by Sodini et al. (2024), which we revisit here in the context of the newly identified environment.

We have revised the manuscript to make this distinction clearer. The absorber abundance modeling and the JWST overdensity discovery are now presented as two separate pieces of evidence, which are combined at the interpretation stage: the absorber provides the chemical-enrichment signature, whereas the overdensity provides the environmental context in which such signatures may be preserved. We have also revised the title, ab-

stract, and main text to avoid implying that the member galaxies themselves are directly enriched by Pop III stars.

Minor comments:

(Q4) In line 45 they should not define the C and Si abundances as “excessive” but simply as over-abundant compared to solar.

Response: Thanks for this suggestion. We have rephrased the wording accordingly.

(Q5) In line 53, “massive halos” is overstated. The authors prove that the halo has $\text{Log}M > 9$ so it is firmly in the atomic hydrogen cooling regime. They should replace “massive” with “atomic hydrogen cooling” consistently with what discussed in the paper.

Response: Thanks for this suggestion. We have rephrased the wording accordingly.

(Q6) Both panels of Figure 2 are important and deserve better visibility. All information presented there is important and should be retained. An obvious, and probably sufficient, way to improve visibility would be to use larger single panel figures but it is possible that other solutions would work as well. For instance, the circles and triangles in 2a are not jumping to the eye. Perhaps using a filled symbol for one of the two would help.

Response: Thanks for the suggestions. Since figure sizes and placements may change during production, we think that it is more practical at this stage to make the symbols more prominent, as suggested. In the revised manuscript, we have updated Figures 2a and 2b by increasing the size of both circle and triangle symbols, and by using filled triangles in Figure 2a.

(Q7) This is more of a matter of personal taste but the notation Pop iii.2 is not really a standard and is a rather ugly combination of roman and arabic numerals. I would recommend the authors not to use it. If they insist in using this notation, I would urge them to replace “commonly refered to” in line 128 with “hereafter indicated as” which acknowledges that some of the readers

not deep in Pop iii literature may have never seen it before.

Response: Thanks for this suggestion. We agree that, although the notation “Pop III.2” appears in some literature, it may be confusing for readers, as the distinction is based on their proposed formation mechanisms rather than their intrinsic properties. Therefore, we have chosen not to use “Pop III.2” and instead refer only to “Pop III ” with a clear definition.

(Q8) I suggest rephrasing, in line 170, the words “provides tentative observational evidence”. Tentative evidence sounds very weak. Perhaps something like “is suggestive” or “provides an example” would work better.

Response: Thanks for this suggestion. We have rephrased this sentence as suggested.

3 Response to Referee 3

(Q1) Please provide a clear indication of the metallicity threshold adopted by your models to disentangle a PopIII from a PopII stellar population. Are you adopting the usual value $1d-4 Z_{\text{sun}}$. Also provide a value for the adopted Z_{sun} in absolute units.

Response: We thank the referee for pointing this out. To distinguish Pop III from Pop II star formation, we adopt the same critical metallicity of Vanni et al. (2023), $Z_{\text{cr}} = 10^{-4.5} Z_{\odot}$, which is based on the observation of the most metal-poor star in the Galactic halo (de Bennassuti et al., 2017). In the revised manuscript, we now explicitly state this in the section “Chemical enrichment model”: “Specifically, we adopt a critical metallicity of $Z_{\text{cr}} = 10^{-4.5} Z_{\odot}$ to distinguish Pop III from Pop II star formation (Vanni et al., 2023). The adopted solar metallicity is $Z_{\odot} = 0.0126$ in absolute mass fraction (Asplund et al., 2009).”

(Q2) Line 43: “Detecting the chemical enrichment of circumgalactic gas offers a promising way to trace the signature of Pop iii stars” – > This is misleading. The CGM is enriched by the integrated contributions of all stellar populations

present in its halo. You want to say “very metal poor clouds of the CGM” probably?

Response:

Thank you for raising this issue. We agree that the original statement was inaccurate. The enrichment signature of Pop III stars should only be expected in very metal-poor CGM that has experienced minimal enrichment from later stellar generations. In the revised manuscript, we have rephrased this sentence accordingly.

(Q3) Line 49: “We reveal that the member galaxies are on average ~ 0.4 dex more metal-poor than coeval galaxies in similar protocluster environments. Such a metal-deficient nature indicates a primordial environment well preserving the relics of Pop iii star-formation”. This is also inaccurate. A low metallicity environment indicates low metallicity stars, without a threshold definition the sentence is simply inaccurate.

Response: We agree with the referee. The original sentence overstated the implication of the metallicity measurement. Low metallicity alone does not constitute evidence for preserved Pop III relics. We have therefore revised the sentence to state only that the overdensity is chemically less evolved than comparable coeval overdense environments, which may provide a favorable environment for Pop III enrichment signatures. It now reads as:

“This less chemically evolved system may have provided favorable conditions for preserving the Pop III enrichment absorption signatures.”

(Q4) Line 52: “consistent with late-time Pop iii formation at the outskirts of massive halos”. In the paper the word halo is often used in a confusing way. Please specify Dark Matter halo or refer to galaxies, groups, protoclusters. Moreover, citing Venditti 2023 at the end of this sentence is confusing as well. Vendittio finds POPIII star formation in the outskirts of the central galaxy, not of the DM halo. They certainly claim late POPIII star formation in

external galactic regions. Please be more accurate with scientific terminology.

Response: We apologize for the confusion. We specify that it refers to the “dark matter halos”. We agree that [Venditti et al. \(2023\)](#) discusses late Pop III star formation in the outskirts of the central galaxy, rather than at the outskirts of the full dark matter halo. We have therefore removed this citation at the end of this sentence. We have rephrased the relevant sentences accordingly, and ensured the consistency of terminology throughout the manuscript.

(Q5) Line: 55 “ $z \sim 30$ ”.. the way things are presented here is also puzzling... this value remains strictly model dependent,.. and probably facilities like the ET could help exploring these redshifts throughout GW coalescence.. I suggest to indicate a range of possible values of redshifts and to say models predict the epoch of cosmic dawn or the first stars to appear... Similar indication for the peak.. either you say “.. predicts the peak” or you have to explain that it remains model dependent ..

Response: We thank the referee for this important comment. We agree that quoting a specific value without clarification may give the misleading impression of a well-determined quantity, while in reality this remains strongly model dependent. In response, we have revised the text to better reflect the theoretical uncertainties.

The revised sentence now reads:

“The Pop III stars are theoretically predicted to emerge during the cosmic dawn, with typical estimates spanning $z \approx 20 - 30$, depending on the model ([Klessen & Glover, 2023](#)). Although still model-dependent ([Liu & Bromm, 2020](#)) and not fully observationally constrained ([Fujimoto et al., 2025](#)), the peak of Pop III star formation is predicted to occur at $z \gtrsim 10$, while direct detection by JWST at $z > 10$ is predicted to be challenging ([Schauer et al., 2020](#)), and may be more feasible under extreme conditions, such as in highly overdense regions ([Jeon et al., 2026](#)).”

(Q6) Line 57: should I interpret your Pop iii definition as strictly at $z=0$?

Here you say metal-free. Same for the IMF.. a top heavy is a widely adopted prescription but still unconstrained now.

Response: Thank you for this comment. We agree that the Pop III IMF remains poorly constrained, and that a top-heavy IMF should not be presented as a definitive property. We have therefore revised the sentence to avoid an overly strong statement and to emphasize that this is a theoretical expectation rather than an established fact.

In the revised version, this sentence now reads as:

“Formed from metal-free gas, those stars lacked efficient cooling via metals and are therefore theoretically expected to have an initial mass function (IMF) distinct from that of metal-enriched stellar populations.”

(Q7) Line 60: What is your definition of supernova explosions enriching the ISM? Do you assume only PISN POPIII can enrich the medium or in which mass regime you consider POPIII enriching the surrounding gas?

Response: Thank you for pointing this out. We did not intend to imply that only PISN Pop III stars enrich the surrounding gas. As it is a general introduction, we aimed to refer broadly to metal ejection from Pop III stars that end their lives as SNe, including core-collapse supernovae and pair-instability supernovae, depending on the progenitor mass and explosion energy. We have revised the sentence to clarify this point and to avoid implying a specific Pop III mass regime.

In the revised version, this sentence now reads as:

“Depending on their progenitor masses, they ended their lives as supernova explosions, such as core-collapse supernovae (CCSNe) and pair-instability supernovae (PISNe), enriching the interstellar medium (ISM) and beyond, thereby seeding the early universe with the first heavy elements.”

(Q8) Line 70: Similar comment as above: ”supernova-driven...”, Which mechanism are you referring to? Local POPIII or standard SNe explosions contaminating the ISM or the integrated effect of galaxy winds polluting the

CGM/ISM? In this case linking supernovae explosions to galactic winds is still debated.

Response: Thank you for this helpful comment. We agree that the original wording was too broad and imprecise. Here, we would like to refer generally to metal transport from early stellar populations into the surrounding gas, which may occur through local supernova explosions, and/or the cumulative effect of galactic-scale gas outflows. We have revised the sentence to avoid implying a specific mechanism that is still in debate.

The revised sentence now reads as:

“Indirect Pop III detection can be achieved through the observation of their nucleosynthetic products as metal absorbers which were dispersed in the environment by stellar winds, supernova explosions and on larger radii, by galactic scale outflows.”

(Q9) Line 80: are the systems you are referring to also star forming or just detected in their metallicity but with no clear signatures of star formation? Which class of QSO absorbers are you referring to?

Response: Thank you for pointing this out. The “extremely metal-poor systems” we referred to here is not a conventional metal absorber with detected metal absorption lines. It is the $z \approx 6$ Lyman alpha emitter candidate reported by [Ďurovčáková et al. \(2025\)](#), which is associated with a sub-DLA absorption system toward the quasar PSO J158-14. Its extremely low metallicity is inferred from the non-detection of low-ionization metal absorption lines at the LAE redshift in the quasar spectrum, yielding an upper limit of metallicity $[Z/H] < -3$. Therefore, this system has a possible LAE counterpart, but the metallicity constraint itself comes from absorption spectroscopy of the CGM, rather than from direct nebular metallicity measurements of the galaxy.

(Q10) Line 93 and Figure 2 (both panels). Here is the main point. Your claim is clear but according to the adopted model (The GAMETE model or some variant I guess). Are there alternatives? Or if any, what are the indications you can provide to favour the GAMETE predictions? Do you

know massive star very metal poor models (Cameron, Charbonnel) or late AGB contributions? Moreover, what about the impact of WR stars (Schaerer et al.) or fast rotators present at very low metallicity, not necessarily Pop III... (Meynet..)

Response: Thanks for the questions. We first clarify that we do not use the semi-analytical code GAMETE. Instead, we adopt the more general parametric model of Salvadori et al. (2019) and Vanni et al. (2023), specifically designed to explore the chemical signatures of individual Pop III supernovae and their evolution under subsequent Pop II enrichment. When applied to Galactic metal-poor stars, our framework yields conclusions consistent with more complex semi-analytical models that include hierarchical assembly and inhomogeneous enrichment (e.g., Koutsouridou et al., 2023). In particular, both approaches find that the most iron-poor and strongly carbon-enhanced stars ($[C/Fe] > +2.5$) are best explained as second-generation objects enriched by one or a few Pop III supernovae. This agreement supports the robustness of the inferred abundance signatures.

We agree that AGB stars represent a potential enrichment channel. However, their contribution is unlikely to dominate in the environments considered here, as they produce negligible Si and evolve on longer timescales, making them less compatible with early second-generation enrichment scenarios. AGB stars are mainly discussed as sources of He, C, N, Na, Mg, and s-process material, while silicon is not a dominant AGB product. Therefore, AGB stars alone cannot explain the enhanced Si/O abundance as we observed. In recent high-redshift literature, the AGB models were used to explain the enhanced N/O pattern in GN-z11 (D’Antona et al., 2023; Cameron et al., 2023), which is different from our C/O and Si/O enhancement.

Massive very metal-poor stars, including rapidly rotating models (e.g. in the framework of Charbonnel et al., 2023), can produce enhanced C, O. These models therefore provide a plausible alternative, or an additional contribution, to the observed carbon enhancement. However, they generally require prior enrichment and often predict additional

signatures, such as elevated N abundances, which can distinguish them from classical Pop III supernova yields. Fast rotators may help explain enhanced C/O, and especially N/O, but their winds alone do not naturally produce a high Si/O pattern. Since Si is mainly synthesized in deeper layers and/or during the supernova phase, it is not expected to be efficiently released in wind-dominated SMS scenarios and is therefore often not included in such models. Thus, SMS/fast-rotator winds cannot fully reproduce the simultaneous C/O and Si/O enhancement observed in this Pop III-like absorber without an additional SN component. Charbonnel et al. (2023) explains GN-z11 with hot-H-burning in a supermassive star, and the key observables in that framework are N/O, C/O, and Ne/O, which is not built around Si/O as the discriminant observable.

Wolf-Rayet stars (e.g., Daniel Schaerer) can eject significant amounts of C and O through stellar winds, but their formation is expected to be strongly suppressed at very low metallicity unless rapid rotation or prior enrichment is present. Moreover, their contribution to Si is limited, as this element is also primarily produced during the supernova phase. So WR enrichment is best described as another CNO-dominated wind channel, not as a natural origin of a combined C/O and Si/O anomaly.

We have added a brief discussion in the section “Chemical enrichment model” regarding the above points. It reads as:

“We caution that Pop III nucleosynthesis models remain uncertain, as the first stars and their explosions have not been directly observed. Other enrichment channels may also contribute to parts of the observed pattern, but they are less likely to explain the combined C/O and Si/O enhancement on their own. AGB stars mainly produce C, N, Na, Mg, and *s*-process material, and evolve on longer timescales. They are more relevant to explain the enhanced N/O patterns, such as those discussed for GN-z11 (D’Antona et al., 2023; Cameron et al., 2023). Similarly, very metal-poor fast rotators (Meynet et al., 2006), supermassive stars (Charbonnel et al., 2023), and Wolf-Rayet channels can provide CNO-rich material and may contribute to the carbon enhancement, but they do not naturally

release large amounts of Si through winds alone. Since Si is mainly synthesized in deeper layers and/or during the supernova phase, the simultaneous enhancement of C/O and Si/O in this Pop III-like absorber is more naturally explained by a supernova contribution. We therefore interpret individual abundance patterns cautiously, focusing not on a unique diagnostic solution but on whether the inferred Pop III-like signatures remain robust across a broad, physically motivated parameter space.”

(Q11) One technical question: the GAMETE model is known as a reference tool for stellar archaeology and provides good statistical references, accurate chemistry implementation and flexibility in parameter exploration. On the other hand I think it still relies on semi-analytic merger trees and simplified inhomogeneous enrichment,.. which seems less appropriate than hydrodynamical simulations for an accurate claim on external POPIII in metal free pockets at the end of EOR. This would in fact require an accurate inhomogeneous metal enrichment model and there is a strong debate on its effects along the redshift depending on the scale and numerical scheme (see Venditti 2023 for example). Why do you consider GAMETE appropriate for this specific investigation?

Response: We clarify again that GAMETE is not used in this work. Our goal is instead to adopt a simple and flexible framework that captures the key physical ingredients relevant to the chemical imprint of individual Pop III supernovae, including inhomogeneous enrichment through a parametric treatment. We agree that fully hydrodynamical cosmological simulations provide a more detailed description of structure formation and metal mixing. However, current simulations face important trade-offs and do not yet simultaneously resolve (i) minihalos hosting the first stars, (ii) the full range of Pop III progenitor masses and explosion energies, and (iii) detailed multi-element chemical yields. As a result, they typically probe more massive halos and environments enriched by multiple supernovae. Our approach is therefore complementary: it is designed to isolate and

interpret the chemical signatures of individual or few Pop III supernovae across a wide parameter space, including regimes that remain challenging for current simulations.

(Q12) Line 104: “The estimated halo mass is consistent with that of typical [O III]-emitting galaxies at similar redshifts”. This is also confusing.. Why typical? OIII emission comes from a larger range of main sequence galaxies at the end of EoR with an equivalent spread in their halo masses... am I missing something here?

Response: Thank you for pointing this out. We apologize for the confusion. The value we referred to comes from the clustering analysis of Eilers et al. (2024), in which the authors measured the galaxy–galaxy auto-correlation function of a luminosity-limited sample of [O III] emitters using a halo occupation model. The quoted value represents the minimum host halo mass threshold for the [O III] emitter population, $\log(M_{\text{h,min}}/M_{\odot})$, rather than the halo mass of each galaxy. We used the same HOD prescription in our absorber–galaxy cross-correlation analysis. We find that this comparison may be confusing to general readers and does not provide a clear physical interpretation of our results. We have therefore removed the comparison from the revised manuscript. In the revised version, we also clarify that the “halo mass” refers to the minimum host halo mass inferred from the HOD model, rather than the halo mass of an individual object.

(Q13) Line 114: The fact that it is a low metallicity environment does not imply PopIII.

Response: We thank the reviewer for pointing this out. We agree that a low-metallicity environment alone does not imply Pop III enrichment. To avoid overstatement, we have revised the sentence as follows:

“In our observations, the metal-deficient nature of the overdensity points to a relatively chemically primitive environment in which early enrichment signatures could be more readily preserved. When considered together with the Pop III-like abundance pattern of the absorber, this environment supports the interpretation that the absorber may point

to Pop III star formation in the outskirts of a mildly enriched dark matter halo.”

(Q14) Line 118: Here probably citing Venditti 2023 is appropriate within the other models. Is the model of Pallottini predicting late POPIII? Do they properly model POPIII stars? Please check the literature, or maybe 52,54 instead of 52-54. I am confused by this as Venditti is one co-author. Please check your references.

Response: We thank the reviewer for pointing this out. We agree that the original citation range was not sufficiently precise. Pallottini et al. (2014) is mainly relevant to the cosmic metal-enrichment history and the Pop III–Pop II transition. We agree that it is not the most direct reference for late Pop III star formation persisting to the end of reionization. We have changed the reference to Venditti et al. (2023), as they explicitly discussed the late time Pop III scenario.

(Q15) Line 132: to be(?) self-shielded?

Response: Thanks for noting this typo. We corrected it in the revised manuscript.

(Q16) Line 133: Referring to the POPIII host or POPIII candidate is misleading. You do not have any direct evidence of a living POPIII population. Just relics... There are no He line detections and they could also not be a direct indication. Please restate your nomenclature. There is no POPIII detection I guess...

Response: Thank you for this clarification. We agree with the referee that expressions such as “Pop III host” or “Pop III candidate” can be misleading. We have rephrased the relevant sentences to avoid misleading terminology both in the line and throughout the manuscript. In particular, we now refer to the system as an “absorber associated with Pop III-like enrichment,” “Pop III-enriched gas,” or “halo associated with Pop III-enriched gas,” depending on the context.

The revised line now reads:

“Given our measured lower limit on the halo mass associated with the absorber,

$\log(M_{\text{h,min}}/M_{\odot}) > 9$, the absorber is likely to trace gas in an atomic-cooling halo. This is consistent with a scenario in which the Pop III-enriched gas is preserved in the outskirts of relatively massive, mildly enriched halos hosting more evolved Pop II and/or Pop I stellar populations.”

(Q17) Line 147: Background radiation is consistent with star formation of certain type.. not POPIII star formation ... which is a chemically related question, first.

Response: Thank you for pointing this out. We intended to show that the absorber lies in an ionized large-scale environment and may have been exposed to a LW radiation field from nearby star-forming galaxies. This environmental context is compatible with theoretical Pop III formation under LW radiation (e.g., Jeong et al., 2026), but it does not constitute direct evidence for Pop III star formation. We have revised the text to clarify this point and to avoid implying that the radiation field itself indicates Pop III formation. The revised text now reads as:

“This provides environmental context compatible with the theoretical Pop III formation pathway in the presence of the LW background (Jeong et al., 2026).”

(Q18) Line 153: Which part of the POPIII IMF should remain intact? A massive POPIII has a lifetime of 3 Myr on average... what is your popiii IMF mass range?

Response: Thank you for this question. We agree that the original wording was not sufficiently clear. Since our observations do not constrain the Pop III IMF, and the onset of Pop III star formation is also unknown, this point can only be discussed qualitatively. For example, if the first Pop III starburst occurred at $z \sim 20$, it would take ~ 750 Myr to reach the observed redshift of $z \sim 6$. Over this timescale, only low-mass stars ($\lesssim 3M_{\odot}$) could survive, whereas higher-mass stars ($\gtrsim 10M_{\odot}$) would have much shorter lifetimes (< 30 Myr) and would rapidly enrich the surrounding gas if they exploded as SNe.

In our Pop III enrichment model, we consider an IMF mass range of $[0.8, 1000] M_{\odot}$

(Vanni et al., 2023). However, the chemical enrichment pattern only considers short-lived massive stars ($\gtrsim 10 M_{\odot}$), rather than by any surviving low-mass stars. We have therefore revised the text to clarify that what may remain preserved is the relic Pop III-enriched gas, not the massive Pop III stars themselves. Since long-lived low-mass Pop III stars have not been observationally identified either in this work or in the literature, we consider it more appropriate here to focus on the relic chemical signatures produced by massive Pop III stars.

The revised text now reads as:

“Although the short-lived massive Pop III stars themselves would have quickly ended their lives, their SN ejecta may remain chemically distinguishable if they avoid substantial mixing with metals produced by subsequent Pop II supernovae. As hierarchical merging proceeds, the minihaloes can be incorporated into central systems, allowing Pop III relics to persist in the outskirts of relatively massive dark matter haloes at lower redshifts. By the end of reionization, photoevaporation may suppress further star formation in these minihaloes.”

(Q19) Line 178: This is one possibility.. for sure there is evidence of a very low metallicity environment in which either internal feedback is inefficient or external pollution is inefficient. A direct link to PopIII is one possibility.

Response: We thank the reviewer for this helpful comment. We admit that the Pop III explanation is only one possibility, and not direct evidence. We have revised the text to avoid overstatement. It now reads as:

“In summary, our observations reveal a very low-metallicity overdensity at $z \sim 6$, where continuous replenishment by pristine gas or inefficient internal metal mixing may allow both pristine gas and Pop III-enriched gas to persist. These conditions provide a natural physical context for theoretical scenarios in which Pop III star formation might persist until $z \sim 6$ in the outskirts of evolved massive halos.”

(Q20) Line 183: I do not agree. The evidence is that a POPIII compatible

environment exists at the end of EoR. Not POPIII star forming environment. This would require other detections ...

Response: We thank the reviewer for this important clarification. We have rephrased the statement, and it now reads as:

“Although the absorbers are not expected to show direct Pop III stellar or nebular emission, they may preserve the chemical imprint of earlier Pop III supernova enrichment. Searching for such enrichment signatures in metal absorbing systems therefore provides a complementary avenue for probing the legacy of Pop III stars.”

(Q21) Line 185: This is also inaccurate. If you refer to the POPIII $\rightarrow$ POPII transition this is a statistical concept regulating the dominating population. What you find here is the “sporadic episodes of POPIII are possible as found by Venditti 2023 and others (THESAN..)”

Response: We thank the reviewer for this clarification. We have revised the text to avoid this implication, and it now reads as:

“In this context, our findings are consistent with scenarios in which sporadic episodes of Pop III star formation, or the survival of Pop III-enriched gas, may occur even after Pop II star formation has become dominant, as found in simulations (Venditti et al., 2023; Zier et al., 2025)”

(Q22) Line 491: Specify the FoF is applied to baryonic structures, it is usually referred to DM structures..

Response: Thanks for this suggestion. We have specified it as suggested, which reads as:

“This method has been widely applied to dark matter halos (More et al., 2011), and here we apply it to galaxies.”

(Q23) Line 526: Is this a “local” IGM temperature right? A global IGM is at different scales.. What is the ratio between the estimated background in this region and the predicted global HM background value at this redshift?

Response: Thanks for this question. Yes, it is assumed to be the local temperature, and we clarified it in the revised manuscript. For comparison, the [Haardt & Madau \(2012\)](#) predicts $\Gamma_{\text{HI}}(z = 6) = 2.67 \times 10^{-13} \text{ s}^{-1}$. Our inferred value, $\Gamma_{\text{HI}} = (1.00 - 1.69) \times 10^{-13} \text{ s}^{-1}$, corresponds to $\Gamma_{\text{HI}}^{\text{local}}/\Gamma_{\text{HI}}^{\text{HM12}} \simeq 0.4 - 0.6$, suggesting that any enhanced ionizing emissivity in the overdense region may be partly balanced by the higher gas density of the local IGM.

(Q24) Line 543: I do not agree. It supports very low-metallicity star formation. Not necessarily POPIII

Response: We thank the reviewer for this clarification. We have revised this sentence as:

“These results support the presence of low-metallicity star formation in a chemically primitive environment, which may also provide favorable conditions for theoretical scenarios in which Pop III star formation is delayed by LW radiation.”

(Q25) Lines 551-555: the star formation efficiency quantifies,... the dilution factor establishes,.. which quantifies if referred to the fraction..

Response: Thanks for the suggestion. We have revised the definitions of these parameters for clarity and grammatical consistency.

(Q26) Line 616: Which background? Local or global?

Response: We thank the referee for pointing this out. We have revised the text to clarify that this refers to the local ionizing radiation field incident on the absorber in the Cloudy modeling.

(Q27) Line 620: hydrogen number density, not density I guess.. How overdense is the -2 value at this redshift?

Response: We thank the referee for this comment. We have clarified that the relevant quantity here is the hydrogen number density. Using the cosmic mean hydrogen number density, $\bar{n}_H(z) = 2.057 \times 10^{-7}(1+z)^3(\Omega_b h^2/0.023), \text{ cm}^{-3}$, we find $\bar{n}_H(z = 5.95) \approx 10^{-4}, \text{ cm}^{-3}$. Therefore, $n_H = 10^{-2} \text{ cm}^{-3}$ corresponds to a local overdensity of order 10^2 .

We further clarify that this refers to the local gas density of the absorber used in the ionization modeling, and not to the large-scale overdense environment.

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The authors sincerely appreciate the insightful comments from the anonymous referees, which have significantly improved the paper. We have revised our manuscript according to these comments. We list our detailed point-by-point response below.

1 Response to Referee 3

Referee’s comments:

(Q1) I thank the authors for their detailed answers and comments, which I generally agree with, except for the points detailed below. Here, I also avoid repeating my previous comments regarding guidelines points 2, 3, 4, and 5 in the form.

(Q11) Why do you consider GAMETE appropriate for this specific investigation? Response: We clarify again that GAMETE is not used in this work.

My reply: This is now clear, thank you.

Our goal is instead to adopt a simple and flexible framework that captures the key physical ingredients relevant to the chemical imprint of individual Pop III supernovae, including inhomogeneous enrichment through a parametric treatment.

My reply: This explanation, however, raises further concerns. The problem suffers from so many degeneracies that lacking a proper cosmological framework makes the predictions even more model-dependent.

We agree that fully hydrodynamical cosmological simulations provide a more detailed description of structure formation and metal mixing. However, current simulations face important trade-offs and do not yet simultaneously resolve (i) minihalos hosting the first stars,

My reply: This depends on the scale of the simulated volume. While it is true that a multi-scale approach is still missing, there are simulations capable of resolving minihalos in Local Volume groups (i.e., semi-cosmological

approaches). See, for example, the Renaissance simulations for a full hydrodynamical case, or the GAMESH pipeline for a hybrid approach. Therefore, your statement is inaccurate.

(ii) the full range of Pop III progenitor masses and explosion energies, and
(iii) detailed multi-element chemical yields.

My reply: This is also inaccurate. There are models featuring a flexible IMF and multi-element yields (e.g., dustyGadget), which the authors should be familiar with.

As a result, they typically probe more massive halos and environments enriched by multiple supernovae.

My reply: That is a choice linked strictly to the volume (and its corresponding mass resolution), not to the inherent limitations of the numerical schemes.

Our approach is therefore complementary.

My reply: I agree that your approach is a complementary and interesting attempt. However, I do not agree that it can be conclusive in any way on such a complex problem. You should therefore soften your strong statements, as you have already partially done in the revised manuscript.

Having said that, your new suggested title cannot be supported:

“First-star-enriched gas within a very metal-poor galaxy overdensity near the end of reionization.”

I suggest something like:

“Detection of an unusually metal enriched gas region within a very metal-poor galaxy overdensity near the end of reionization. A possible detection of first star chemical signatures?”

This formulation better describes this interesting and promising discovery with an appropriate level of uncertainty in the conclusions, which is primarily

dictated by the limitations of the theoretical modelling.

I therefore recommend the paper for publication only subject to a clear modification of the message in the title, though it does not necessarily have to be identical to the one suggested above.

Response: We thank the reviewer for this constructive comment. We agree that our framework should be regarded as a complementary, model-dependent approach rather than a conclusive treatment of this complex problem. We have therefore revised the title and softened the relevant statements about our model to better reflect the associated limitations and uncertainties.

To also comply with the editor’s request for a shorter title, we have revised it to: “Tracing first-star imprints in a metal-poor galaxy overdensity near the end of reionization.” We believe that this title more appropriately reflects the level of uncertainty in our interpretation and avoids conveying the impression of a direct detection of Pop III stars.